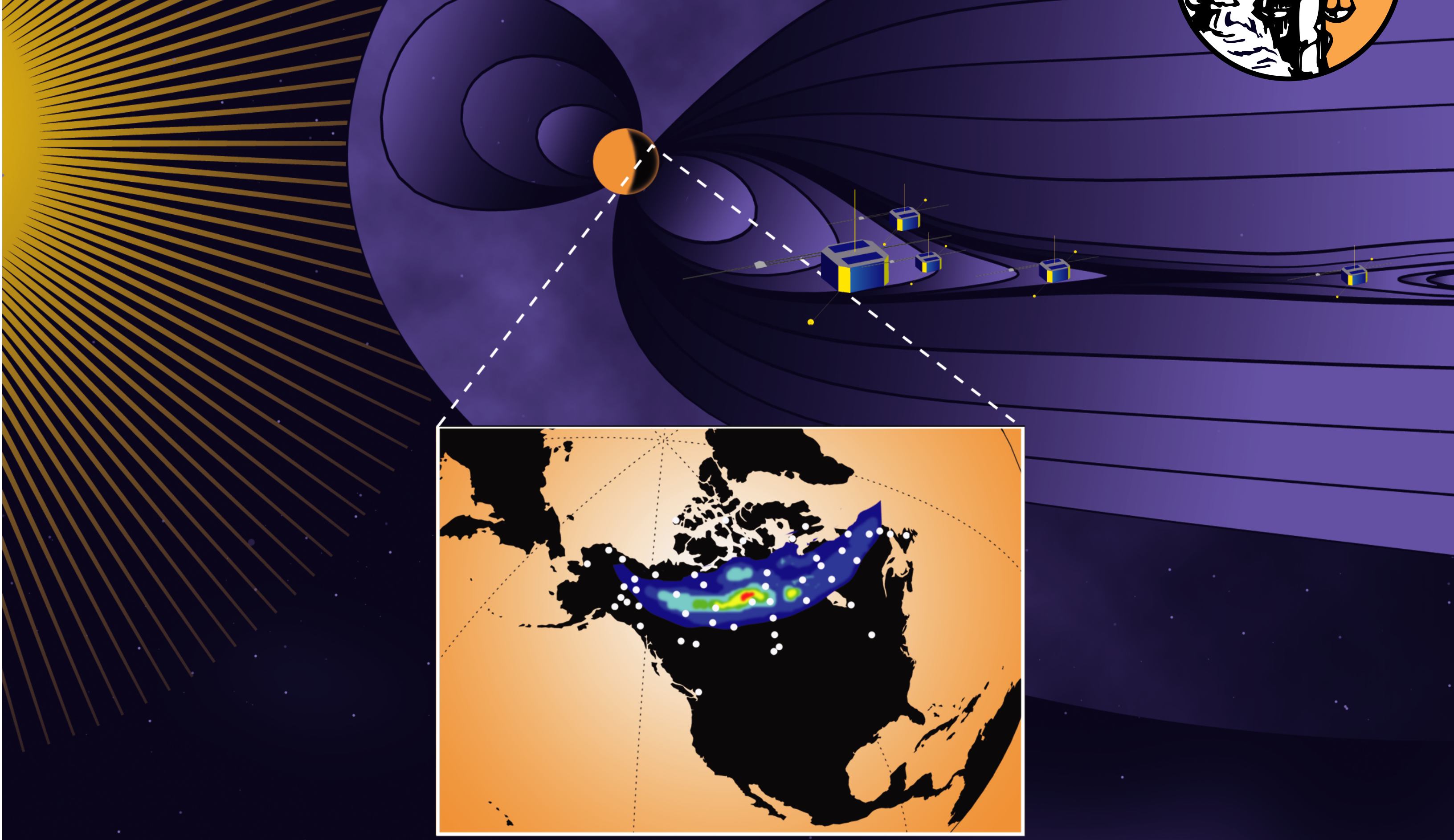
Time History of Events and Macroscale Interactions during Substorms

THEMIS



A NASA MEDIUM-CLASS EXPLORER MISSION
PHASE A CONCEPT STUDY REPORT

SUBMITTED BY THE
REGENTS OF THE UNIVERSITY OF CALIFORNIA
OCTOBER 16, 2002

Cover Page and Investigation Summary

Phase A Concept Study Report for a NASA Medium-Class Explorer Mission (MIDEX)

October 16, 2002

THEMIS: Time History of Events and Macroscale Interactions during Substorms.

The Regents of the University of California

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Total NASA Cost: $158,374,000 (FY02 dollars)

Investigation Summary:

THEMIS answers fundamental outstanding questions regarding the magnetospheric substorm instability, a dominant mechanism of transport and explosive release of solar wind energy within Geospace. THEMIS will elucidate which magnetotail process is responsible for substorm onset at the region where substorm auroras map (~10Re): (i) a local disruption of the plasma sheet current or (ii) that current interaction with the rapid influx of plasma emanating from lobe flux annihilation at ~25Re. Correlative observations from long-baseline (2-25 Re) probe conjunctions, will delineate the causal relationship and macroscale interaction between the substorm components. THEMIS five identical probes measure particles and fields on orbits which optimize tail-aligned conjunctions over North America. Ground observatories time auroral breakup onset. Three inner probes at ~10Re monitor current disruption onset, while two outer probes, at 20 and 30Re respectively, remotely monitor plasma acceleration due to lobe flux dissipation. In addition to addressing its primary objective, THEMIS answers critical questions in radiation belt physics and solar wind - magnetosphere energy coupling. THEMIS probes use flight-proven instruments and subsystems, yet demonstrate spacecraft design strategies ideal for Constellation class missions. THEMIS is complementary to MMS and a science and a technology pathfinder for future STP missions.

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Restriction on Use and Disclosure of Proposal Information (Data)

The information (data) contained in Section J-4 (Johns Hopkins University [APL] Budget Detail) and Section J-5 (Swales Aerospace Budget Detail) of this proposal constitutes a trade secret and/or information that is commercial or financial and confidential or privileged of Johns Hopkins University (Sec. J-4) and Swales Aerospace (Sec. J-5). It is furnished to the Government in confidence with the understanding that it will not, without permission of Johns Hopkins University or Swales Aerospace, as applicable, be used or disclosed for other than evaluation purposes; provided, however, that in the event a contract is awarded on the basis of this proposal the Goverment shall have the right to use and disclose this information (data) to the extent provided in the contract. This restriction does not limit the Goverment's right to use or disclose this information (data), if obtained from another source without restriction.

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October 4, 2002

Letter of Agreement Between the University of California, Berkeley (UCB) and the Jet Propulsion Laboratory (JPL) on the participation of Dr. Vassilis Angelopoulos on the THEMIS Mission

Since August 2002, Dr. Angelopoulos, the PI of the THEMIS mission, has been employed at JPL as a part-time employee at the 30% level. The majority of his time (70%) is spent as an employee of the Space Sciences Laboratory (SSL) of the University of California, Berkeley. This Letter of Agreement describes the institutional commitments that will permit Dr. Angelopoulos to discharge his responsibilities as THEMIS PI.

1. Dr. Angelopoulos shall remain a fully vested SSL employee working at a fixed 70% level at SSL with full responsibility for THEMIS.
2. SSL shall retain full management and institutional responsibility for the THEMIS mission. As described in the THEMIS proposal, an experienced project manager, Mr. Peter Harvey, will have day-to-day responsibility for the execution of the THEMIS project.
3. Dr. Angelopoulos shall be supported for the 30% of his time at JPL by his NASA SR&T grant on Cluster (THEMIS-related data analysis), or by his NASA/THEMIS Phase B-E activities.
4. To support the selection, development, and operation of THEMIS, JPL provides office space and computer facilities to Dr. Angelopoulos. JPL shall make available appropriate engineering expertise and advanced technology, e.g. TRIO chips, as requested by the THEMIS project.

JPL is supportive of the fact that Dr. Angelopoulos will need to physically be at SSL 100% of the time on occasion. UCB is appreciative of JPL's accommodation to the PI's family needs, which led to this arrangement, and is looking forward to future collaborative work with JPL after the completion of the THEMIS program. JPL views THEMIS as enhancing the experience of JPL for future low-cost multi spacecraft missions and wishes SSL success on the THEMIS mission.

Prof. Beth Burnside	Prof. Robert Lin	Dr. Larry Simmons
Vice Chancellor for Research University of California, Berkeley	Director Space Sciences Laboratory University of California	Director, Astronomy and Physics Jet Propulsion Laboratory California Inst. of Technology

B. TABLE OF CONTENTS

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Time History of Events and Macroscale Interactions during Substorms

THEMIS Science Objectives:

- Onset and evolution of the macroscale *substorm instability,* a fundamental mode of mass, and energy transport throughout Geospace.
- Production of storm-time MeV electrons.
- Control of the solar wind-magnetosphere coupling by the bow shock, magnetosheath, and magnetopause.

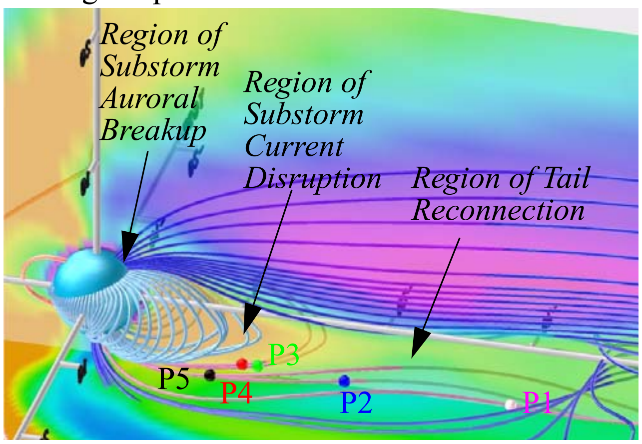


Figure C-1. *THEMIS objectives are addressed by >300 hrs/yr of four or five-probe conjunctions.*

Alignment with NASA Strategic Objectives:

- How does our planet respond to solar variations? (Quest II of NASA SEC Theme).
- How does solar variability affect society? (Quest IV of NASA SEC Theme).

THEMIS is essential for understanding Earth's space environment and a prerequisite to understanding space weather.

Relationship to MMS:

THEMIS is a macroscale mission, with objectives and orbits complementary to those of micro/meso scale mission MMS.

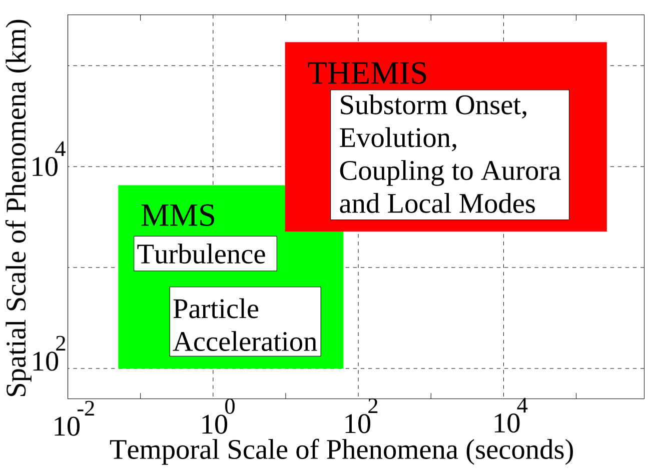


Figure C-2. *Outline of THEMIS and MMS target processes at the inner edge of the plasma sheet.*

Insti-tution	Science Team Member	Insti-tution	Science Team Member
NASA Funded		Non-NASA funded	
UCB	V. Angelopoulos	TUBS	*U. Auster*
	C. W. Carlson†		K.-H. Glassmeier
	G. T. Delory	IWF	W. Baumjohann
	R. P. Lin		R. Nakamura
	S. Mende		*K. Schwingenschuh*
	F. S. Mozer	MPAe	J. Buechner
	G. Parks	CETP	O. Le Contel
	T. D. Phan		*A. Roux*
	M. A. Temerin	UC	E. Donovan
UCLA	K. K. Khurana	ESTEC	*P. Escoubet*
	M. G. Kivelson		H. Laakso
	J. Raeder	TITech	M. Fujimoto
	C. T. Russell	CESR	C. J. Jacquey
CU	*R. E. Ergun*		D. LeQueau
	X. Li	UA	J. Samson
APL	A. T. Y. Lui		I. Voronkov
GSFC	D. Sibeck	USP	V. Sergeev
		NOAA	H. J. Singer
†Co-Is responsible for hardware delivery are italicized			

Table C-1. *THEMIS science team.*

Mission Primary Objectives:

- Establish when and where substorms start.
- Determine how the individual substorm components interact macroscopically.
- Determine how substorms power the aurora.
- Identify how the substorm instability couples dynamically to local current disruption modes.

Mission Characteristics:

- Five-probe, 2yr lifetime baseline mission.
- Four-probe, 1yr minimum mission.
- Each tail-phase (winter) apogees align over US/Canada without routine stationkeeping.
- Ground-based determination of auroral onset.
- Instruments identical to ones recently built and flown by high-heritage institutions (Table C-1).
- Team members are leaders in substorm studies.

Science Payload:

- 3D FluxGate and Search Coil Magnetometers (FGM, SCM) obtain 1024 vector/s waveforms.
- 3D Electric Field Instrument (EFI) obtains DC to 1024 vector/s waveforms.
- Electrostatic Analyzer (ESA) measures i^+/e^- of energy 5eV-30keV (over 4π str once per spin).
- Solid State Telescope (SST) measures i^+/e^- of 20keV-1MeV (over $108^o \times 360^o$ once per spin).

Spacecraft Characteristics:

- Spin-stabilized (T_{spin}=3s) probes dynamically stable even during deployment fault scenarios.
- All components have flight heritage and are currently in production.
- Single string probe design with selective functional redundancy. Significant fault tolerance arises from redundancy of the fifth probe.
- Single instrument data processing unit (IDPU) and a bus processor identical to the IDPU's (UCB/STEREO heritage) simplify interfaces.
- Modular blowdown N_2H_4 propulsion system with selective redundancy and passive fuel balancing provides a simple, robust probe RCS.
- Instrument and sub-system heritage coupled with LV capability provide for a mature design.

Payload Accommodation:

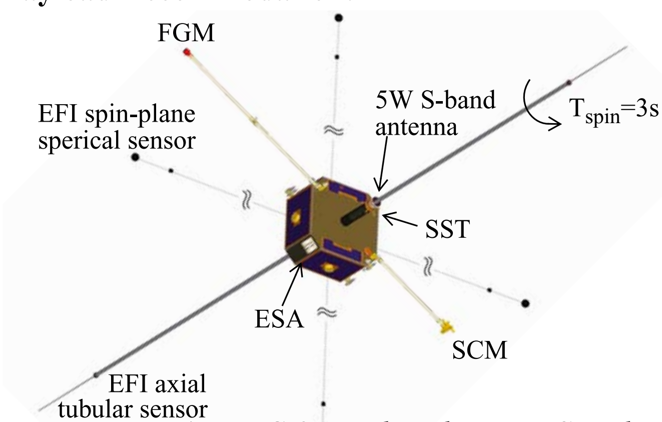


Figure C-3. *Deployed THEMIS probe.*

Launch:

- Delta II 2925-10 launched at CCAS (Launch window: 55min/ day every day of year).
- Direct injection to parking orbit; small orbit adjusts thereafter.
- Probe Carrier Assembly (PCA) uses a 3rd stage fixture ("PC") to carry probes; dispenses them via low-shock, heritage "Light-Band" separation system.

Figure C-4. *PCA on 3rd stage.*

Management:

- PI Institution has a combined 150 person-years of successful track-record in management of NASA SEC instruments and missions.
- Probe busses built by Swales, commercialization company of the SMEX-Lite & EO-SB busses with flight-demonstrated spacecraft development and launch operations experience.
- Instruments provided by a highly experienced team with proven working relationships.
- Centralized parts-buy/build program at two main institutions (UCB, Swales) reduces risk, minimizes costs (Table C-2) and optimizes schedule (Figure C-5).
- Instrument and Mission I&T at Swales with participation of UCB mission operations team.
- International co-I team of leaders in substorm, radiation belt and magnetopause research and a rapid data dissemination plan stimulate high-quality interactions and optimal science return.
- $4M for GI program and non-co-I training in analysis software boosts NASA science return.

Resources and Margins:

	[kg] Instr. Mass	[W] Instr. Power	[kg] Bus Mass	[W] Bus Power	[kg] Probe Fuel	[kg] Carrier Mass	[kg] Launch Mass	Base schedule includes costed & distributed reserves
Design	21.0	12.1	41.0	12.4	21.0	89.7	505	42 mo.
Reserve	13%	22%	15%	17%	15%	15%	15%	15% (6 mo)
Margin	41%	42%	41%	42%	43%	33%	40%	n/a

Table C-2. *THEMIS has heritage subsystems, a robust design and ample margins. Its NASA cost of $159M fits comfortably within the MIDEX cap.*

Education and Public Outreach:

- Ground observatories at rural schools permit project-based activities & science data access.
- Leverages existing mature programs.
- UCB's successful SEGWay program develops informal education materials on main SEC themes and distributes them to large audiences through its established museum partnerships.

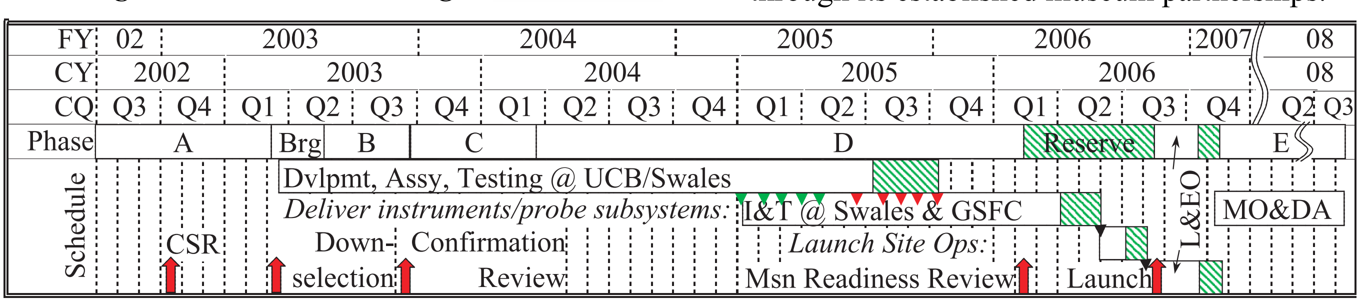


Figure C-5. *THEMIS has budgeted a six month schedule reserve and parallel I&T teams.*

D. EXECUTIVE SUMMARY

D1. SCIENCE

a. THEMIS answers a main strategic question of space physics.

The primary objective for the THEMIS project is to understand the onset and macroscale evolution of magnetospheric substorms. A substorm is an instability in the circulation of magnetic flux and plasma through the solar wind-magnetospheric system ultimately linked to the familiar auroral eruptions on Earth's polar ionosphere. These eruptions are evidence of a fundamental mode of mass and energy transport throughout Geospace. The substorm instability is evidenced not only during development of large magnetic storms, but is rather ubiquitous at all levels of solar wind energy throughput, irrespective of solar cycle phase. Understanding the substorm instability is crucial for space science, basic plasma physics and space weather, and has been identified by the National Research Council as one of the main strategic questions in space physics.

b. THEMIS will provide a rich, coordinated dataset and has a pre-eminent science team to achieve its science goals.

THEMIS will determine for the first time when and where in the magnetosphere substorms start, and how they evolve macroscopically. It will do so by timing well-known plasma particle and field signatures at several locations in the Earth's magnetotail while simultaneously determining the time and location of substorm onset at Earth using a dense network of ground observatories.

The THEMIS science objectives are achieved by five space probes in high earth orbits (HEO) with similar perigee altitudes (1.16 to 1.5 earth radii, R_E) and varying apogee altitudes. Probe 1 (P1) has an apogee of ~30 R_E, P2 at ~20 R_E, and P3, P4, & P5 at ~12 R_E with corresponding periods of ~ 4, 2, and 1 days, respectively. This choice of periods results in multi-point conjunctions at apogee, allowing the probes to simultaneously measure substorm signatures over long distances along the magnetotail, while simplifying ground communication scheduling. The probe conjunctions are tightly coordinated with the ground-based observatories during the ~4-mo. prime geotail season, which is centered around mid-February each year. This maximizes the dark skies available to the ground sensors, simplifies orbital maintenance and optimizes the yield of substorm events.

The ground observatories monitor the auroral light and ionospheric currents in order to localize the time, location, and evolution of the auroral manifestation of the substorm. The space probes align within the plane of the substorm instability and monitor the reputed sites of instability onset directly above the ground observatories as a result of THEMIS's orbit design and probe placement strategy. Routine probe alignments are used to determine when the near-Earth tail current sheet destabilizes (Current Disruption) and when the magnetic flux in the lobes begins to dissipate (Near-Earth Reconnection), while the ground instruments pinpoint the location and time of Substorm Onset. The relative timing between current disruption, near-Earth reconnection, and auroral substorm onset, when performed near the substorm meridian, determine where and when a substorm starts.

Spacecraft alignments from previous missions during the past thirty years in situ investigation have only resulted in a handful of un-optimized hours of conjunction. As a result, the causal link between these three important, primary manifestations of the substorm instability remains obscure to this day. THEMIS provides >300hrs/yr of probe-probe and probe-ground conjunctions and answers this fundamental question in space physics.

The nominal THEMIS mission captures data from two full tail seasons within a mission design life of 2 years. A robust replacement strategy permits THEMIS's minimum performance floor to be satisfied with 4 of the 5 probes capturing data from one full tail season. THEMIS is the first mission to benefit directly from Constellation reliability.

Leaders from several key areas in Geospace science bring crucial knowledge from the driving processes (solar and solar-wind science), the interactive processes (magnetopause and tail dynamics) and the response processes (auroral and ground effects) into an integrated investigation. A strong international component to the team engages the entire vibrant substorm community and leverages knowledge and analyses methods gained from Cluster, Interball and Geotail. THEMIS's open data distribution policy and a GI program accompanied by community training in THEMIS software and analysis packages ensure maximum benefit to the US science community.

c. THEMIS is complementary to Cluster and MMS and a pathfinder to SEC missions.

While Cluster and MMS, in tetrahedral spacecraft configurations, study local plasma boundaries, THEMIS provides the macroscale vantage point necessary to study the global evolution of the magnetosphere during substorms. The THEMIS orbits are ideal for conjunctions with Cluster and MMS if THEMIS is launched as the first MIDEX. Lessons learned from THEMIS's science discoveries and technical implementation will have immediate application to the planning of MMS and MagCon, as well as other proposed constellation missions in the SEC discipline.

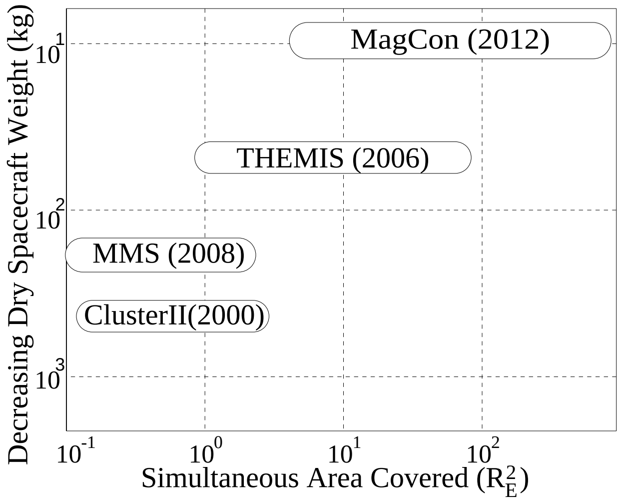


Figure D-1. *Evolutionary process of SEC missions. THEMIS expands SEC's capability to effectively monitor simultaneously an increasing volume of space. While utilizing existing technologies it provides a much needed heritage for microspacecraft design, deployment and operations.*

D2. Technical approach

a. Mission design: Simple and fault tolerant.

THEMIS is launched (planned for August 2006) on a Delta II 2925-10, from CCAS, with a daily launch window of 40 minutes into a direct injection orbit near the final (science) orbit of P3/4/5 (3 inner probes) in a stable 1.1 x 12.1 R_e orbit. The probe carrier (PC), a simple mechanical fixture (PC stays attached to L/V 3rd stage), dispenses the probes (via low-shock, heritage separation systems), spin-stabilized, directly into this common initial orbit. An on-board hydrazine propulsion reaction control system (RCS) performs the final placement of each probe into its final orbit with minor trimming prior to the prime science tail seasons.

The spin-stabilized probes (T_{spin}=3s) are dynamically stable even under worst-case scenarios (as demonstrated by fault tolerance analyses). The single-string probe design is further simplified by a minimal hardware complement, inherent functional redundancy, strong instrument heritage and with the instruments and the bus designed for graceful degradation. Our probabilistic risk assessment and contingency analyses demonstrate that either P3 or P4 can replace any other probe during the mission, including dry mass reserves and margins.THEMIS's heritage parts selection and constellation redundancy bestow it with >93% reliability for the minimum performance mission which can be accomplished by four probes within 1 year.

b. Instrumentation: Heritage, manufacturability and testability.

The five THEMIS flight-instruments (FGM, ESA, SST, SCM and EFI) are near-identical to units which have been built in production quantities and flown successfully on previous space missions by the same THEMIS lead engineering and scientific staff. As a result they already have embedded design-features which allow for ease in manufacturing, calibration, integration and testing (I&T). They easily exceed the mission requirements while providing programmatic confidence. The instruments have comfortable data rates (~5kbps avg) and utilize WIND and FAST experience for burst-trigger and burst-data-collection strategies controlled by the instrument data processing unit (IDPU). The IDPU which is the single electrical and data interface to the bus, simplifies bus interfaces and I&T procedures. All instruments (plus the flight IDPU, booms and harnesses) are integrated into a single instrument suite and tested at UCB with a Swales-provided probe simulator. This occurs prior to delivery at Swales for probe-integration, thus further simplifying the I&T process. The team's experience, the mature designs, and a detailed grass-roots schedule and cost result in high-confidence, strong margins, and low-risk.

The ground-based observatory development and deployment of all-sky cameras and magnetometers (in Alaska & Canada) is performed by a team with decades of experience in building, deploying, and operating such instrument networks in far more remote locations and adverse climatic conditions than required for THEMIS.

c. Probes and Probe Carrier: Reliability and cost effectiveness.

The probe bus has a simple, low-rate S-band communication system with a store-and-downlink (near perigee) strategy. It is supported by an 80196 computer (identical to the processor in the IDPU), hosting heritage-software to perform data handling and minor fault detection activities. The power system is comprised of simple body-mounted solar panels and a small battery controlled by a direct energy transfer controller. A passive thermal design simplifies probe operations. The bus structure utilizes a single primary load-path, i.e., a stiff baseplate for mounting most bus and instrument elements. The RCS is a fault-tolerant cross-strapped mono-propellant hydrazine blow-down system and the spin-stabilized attitude control system (ACS) is simplified by ground-based attitude and orbit determination. All maneuver sequences are formed, checked (via high-fidelity operational testbed), uploaded, and executed during real-time ground communications. Heritage components (currently in production) are used on the probe bus and minimize risk, simplify instrument-bus interfaces, and reduce cost.

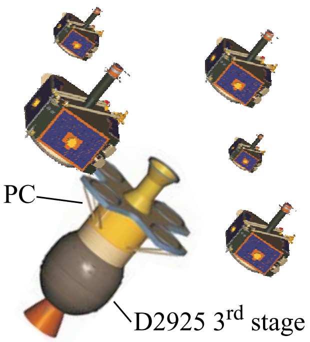


Figure D-2. *THEMIS probes upon release by the probe carrier (PC).*

The L/V injection orbit and the probe operations were analyzed extensively and optimized to minimize lunar, solar, and environmental effects during the mission phase. The L/V 3rd stage (with PC attached) passively re-enters Earth's atmosphere and each probe, at end-of-mission, has a minor maneuver, with burn to depletion, for subsequent passive re-entry. All flight elements meet the NASA orbital debris guidelines of re-entry in <25 yrs and debris footprints < 8 m^2.

d. Integration and test plan: Modular, fault-tolerant and with clear interfaces.

During instrument complement I&T with the flight IDPU and the bus simulator at UCB, Swales integration personnel train and help formulate the instrument test procedures on-site, with the same integration test & operations system (ITOS) used in subsequent I&T and in flight operations.

The instrument suite is subsequently delivered to Swales, and is accompanied by UCB personnel who participate in further testing during probe I&T. The ITOS procedures flow forward from UCB to Swales upon instrument delivery and the tightly coupled UCB/Swales test team, with rotating work assignments, ensure hands-on, efficient training of the UCB mission and flight operation team on bus system functions.

The instrument I&T process at UCB is mirrored by a centralized probe bus I&T at Swales with a UCB instrument simulator. Probe bus integration, instrument-to-probe I&T, and mission integration take place at Swales; environmental tests utilize the GSFC facilities. A two parallel line I&T production approach, with migration of instrument and bus subsystem developers and selected mission operations team into the I&T environment, allows for continuity, cross-training, and mentoring of the core I&T test conductors and technicians. This results in a time-phased probe integration and builds the team's understanding of the system's behavior into subsequent processes and test trend databases.

The software team performs build-testing on a hi-fidelity stand-alone testbed prior to software integration. The mission operations team also utilizes this testbed for mission simulation rehearsals prior to formal simulation with flight probes. This testbed is moved to UCB prior to launch and is used to verify command sequences (prior to upload) during flight operations.

D3. Management: Experienced teams with clear lines of authority and responsibility.

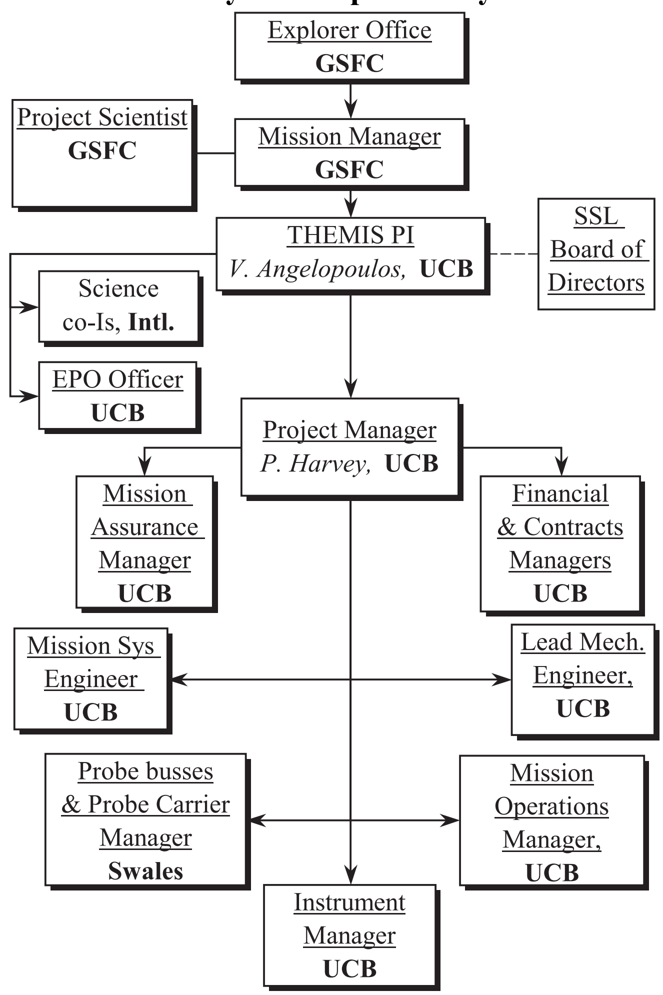


Figure D-3 *THEMIS organizational structure.*

The mission is managed by UCB, an institution that has successfully led three previous Explorer missions (EUVE, FAST and HESSI) and has >30 years of experience in managing large programs for NASA and other organizations. THEMIS core team members have decades of experience in leadership of similar programs and a solid track record of on-time, on budget delivery and in-flight performance. The THEMIS PI, Dr. Vassilis Angelopoulos is the single point of contact for the Explorers office and a leading figure in space physics research. He has been honored by the AGU Macelwane medal and the Russian Academy of Sciences Zeldovich medal. He has been working with the core UCB THEMIS science and engineering team leading THEMIS-related technical studies since 1996. Angelopoulos benefits from the long institutional experience at UCB through advice from the Space Sciences Laboratory's Board of Directors. The mission Program Manager (PM), Mr. Peter Harvey reports directly to the PI. He is responsible for the day-to-day management activities and coordinates the overall program implementation, including space and ground segment developments. He has nearly 30 years of experience in flight projects. He was the PM for HESSI, which was successfully launched in February of 2002.

The THEMIS industrial team partner, Swales Aerospace (the SMEX-Lite technology commercialization company), brings their recent MIDEX class spacecraft manufacturing, bus and mission I&T management, and launch operations leadership experience from FUSE, EO-1, MAP, and Triana to the THEMIS team. Facilities needed for THEMIS are in place and have been used on previous programs. Our centralized parts-buy/build plan (with the main institutions, UCB & Swales) reduces risk, minimizes cost, improves program parts quality & traceability, reduces parts count, and improves schedule for long-lead parts.

The strong system engineering function at both institutions is evident form the results of key trade studies, performed during Phase A, further increasing the robustness of an already fault tolerant mission design. The present direct-injection launch strategy is a simplification from the AO proposed design. The step-1 proposal solid kick motor, coast phase operations and associated electronics have been removed allowing the mission management to transfer the costs of these items towards a more capable NASA/NLS Delta vehicle. This reduced mission risk and development time and further simplified flight operations. The same change allowed the mechanical design to optimize all static and dynamic clearances during probe dispense. Phase A trade studies reduced dry mass, complexity and risk, yet improved science performance, mission reliability and production simplicity.

D4. Cost and Schedule: Grass-roots development matched by parametric models.

The heritage of instruments and bus components and the experience of the developers and their organizations resulted in a high fidelity, bottom-up, and cross-linked schedule plan, used to derive costs. Part and component costs reflect formal industry responses to requests for quotations (using component specifications and statements of work); labor costs reflect actual identified personnel. Basis of estimates are formed from recent flight experience. Instrument parametric models of SSL-delivered hardware match our mass, power, cost and schedule estimates. Analogous and parametric cost validations also demonstrate probe bus and mission I&T correlation to <10% variance with the industry standard Aerospace Corp. Small Satellite Cost Model (SSCM).

In summary, THEMIS has a mature and robust mission design, a highly-experienced and tightly-coupled development team and is led by an organization with an excellent record for on-time and on-budget delivery and in-orbit performance on previous Explorers. THEMIS is a low risk mission.

D5. Education and public outreach.

A mature EPO team of national partners, led by the Center for Science Education at UCB, leverages current UCB activities on FAST, IMAGE, HESSI, STEREO and CHIPS as well as NASA resources through the Space Grant consortium. By establishing ground-based magnetometer stations at rural schools or tribal colleges in traditionally underserved, under-represented communities, THEMIS provides students and teachers project-based activities that support inquiry and promote access to real scientific data. Utilizing the heritage of the SEGway program at UCB THEMIS develops classroom modules, teacher professional training and materials and planetarium shows. THEMIS conducts a sustained, well-evaluated EPO program that builds on the involvement of scientists and their research in education for the benefit of broad audiences.

D6. New Technology

No new technology is necessary for THEMIS. In recognition of its pathfinding role for future Constellations THEMIS is testing two new technology items which have no risk-impact to the mission. These are implemented at, or after the end of the 2-yr mission. They are (i) a low cost ranging technique (similar to ST-5) and (ii) a Celestial Navigation software (developed by GSFC). They are implemented with little effort and require no hardware or software change to the probe architecture.

D7. SDB plans.

The Space Sciences Laboratory utilizes the UCB Office of Small Business Development (OSBD) and maintains a strong relationship with a number of small, disadvantaged businesses (SDBs). It is committed to coordinate with OSDB and, as in previous programs, it expects to have no problem providing a subcontracting plan that will be readily acceptable to NASA.

SCIENCE IMPLEMENTATION CHANGES PAGE

There is no change to the baseline mission or the minimum mission science objectives. Over the Phase A period a number of trade studies were performed on science implementation; those studies have resulted in enhancing the mission implementation (science yield improved by >50% relative to step-1 proposal; see Section E3.e), while at the same time reducing mission risk and increasing margins. These improvements are tabulated below along with their position in the text. They are in complete agreement with the program's stated primary science requirements.

CSR location	Change	Reason	Adherence to Mission Requirements (Fig. E-1/A_I)
Figure E-6	Now for Feb-21	Section E3.a	Optimizes quality and number of substorm observations
Figure E-6	Caption: P5f gains 6hrs/day	Section E3.b	Optimizes scale-size distribution of conjunctions
Figure E-7	Tail center on Feb-21; 4 month tail season	Section E3.a	Optimizes quality, number and distribution of substorm observations. Gradual loss of conjunctions in flanks.
Figure E-8	Canadian/Alaskan locations	Section E3.i	Locations benefit from infrastructure; reduced risk/cost
Figure E-8	jpeg compression reduces ASI data volume	Section E3.i	Baseline data transmitted via VSAT, local data compression via jpeg and recovery by disk-swapping
E1.i, ¶5, L.5	Removed statement that solar wind density and temperature will be measured by electron ESA	Section E3.g	Optimized ESA to obtain higher quality solar wind measurements, within mass, power, cost in accordance with FAST and WIND heritage. Now ion/electron ESA can operate nominally also in SW.
E1.i, ¶6, L.5	Added explanation of orbits	Section E3	Optimized orbit to minimize P3,4,5 differential drift and simultaneously enhance quality of dayside observations
E1.k, ¶1, L.15	B-angle to spin plane large for different reasons.	Section E3.a4	B-field angle to spin plane still large (20^o-30^o) and exceeds requirement of >10^o for obtaining 3^{rd} (axial) E-field component from spin-plane components.
E1.g, ¶3, L.1; ¶5, L.1; ¶8, L.1	Added implementation details on orbit strategy	Section E3.b	Optimized nightside observation implementation (dZ probe separation with minimal fuel) and improved dayside observation strategy.
E1.h, ¶1, L5	Minimum mission is 1 yr	Section E3.e	Full adherence to mission goals
E1.h, ¶1, L5	From X and Z the 2^{nd} year to Y and Z the 2^{nd} year	Section E3.b	Improved CD monitoring by Y-separated rather than X-separated probes. Eliminate risk of missing CD.
Table E-5	Minor mass, power changes	Section F	Full adherence to mission requirements and within step-1 proposal specifications
E2.a1, ¶2, L6	FGM boom is FAST and Lunar Prospector heritage but copy of neither	Section E3.h	Optimized boom design: Eliminated risk of latching from centrifugal force opposing release sping tension.
E2.a2, ¶2, L20	ESA attenuator added	Section E3.g	Dayside science improved, no effect on tail science.
E2.a2, ¶3, L4	Intercalibrate ESA on fluxes	step-1 review	This is a clarification, no science effect
E2.a5, ¶1, L4	EFI stacer element detail	clarification	The 5m axial is 4 m stacer element + 1m tubular sensor
E2.a5, ¶3, L5	Angle between spin-plane and magnetic equator	Section E3.a4	Angle nominal value unchanged, seasonal range larger, low limit still >10^o as per requirement and step 1 proposal
Table E-6 and E1.b, ¶2, L5	Data rate internal allocation	Section E3.j	Data volume same. Optimized routine/burst allocation.
E2.b, ¶3, L10	USN replaced WGS, DSN	Section F	USN station Perth (secondary) compatible with BGS (primary) in collecting all mission data.
Table E-7, and E2.d, ¶1, L21; ¶1, L26	Added key persons Abiad, Turin	Senior engineers Curtis, Harvey, Pankow involved in management; take supervisory role. Experienced developers committed to THEMIS program from Phase A.	
Table E-7, and E2.d, ¶1, L25	Added D. Larson as SST key person	R. Campbell passed away	Based on Larson experience on WIND and similar role on STEREO

E. SCIENCE INVESTIGATION

THEMIS ["Time History of Events and their Macroscopic Interactions during Substorms"] will determine the onset of the macroscale substorm instability. The primary quest of THEMIS, "where and how are substorms triggered", has been identified by the National Research Council (NRC) as one of the main strategic questions in space physics[1]. Five identical microspacecraft (probes) with carefully designed orbits near the equatorial magnetotail provide prolonged tail-aligned, cross-tail and cross-sheet conjunctions. In each of those ideal conjunctions THEMIS has the opportunity to study 50-100 substorms. Comprehensive in-situ particles and fields measurements in space together with simultaneous, ground-based, global measurements of auroral onset will establish macroscale plasma interactions over scales ranging from 0.3 to 20 R_E. The primary focus of THEMIS is the region of 8-10R_E (where onset auroras likely map). Although THEMIS does not visit the tail reconnection region (which will be studied in situ by MMS) because it is not concerned with the reconnection process itself, it remotely senses reconnection onset to place substorm onset in the context of global circulation. Thus, in terms of the processes studied, the scale-size of those processes and the region visited THEMIS is complementary to MMS. UC Berkeley has managed three Explorer missions (EUVE, FAST and HESSI) and has a 30 yr-long history of on-time, on-budget development and successful flight of instruments on SEC missions. THEMIS addresses unique science objectives and is a technological pathfinder to future NASA STP missions.

E1. SCIENTIFIC GOALS AND OBJECTIVES

a. Goals and objectives of investigation

A substorm is an avalanche of small-scale magnetotail energy surges[2] feeding from solar wind energy previously stored in the magnetotail lobes. During its course auroral arcs intensify, move poleward and break up into smaller formations[3]. A substorm has well demarcated global evolutionary phases corresponding to unique stages of an instability of the coupled solar wind-magnetospheric circulation of energy and magnetic flux. These unique stages are: energy storage (growth phase), explosive release (onset) and eventual ionospheric dissipation (late expansion and recovery phases). Thus a substorm represents a fundamental mode of global circulation of energy and magnetic flux transport throughout Geospace. This global, macroscopic instability is as central to space physics and space weather as the extratropical cyclone is to meteorology and weather. Despite the elemental nature of the substorm process lack of appropriate spacecraft conjunctions from previous missions resulted in a contentious set of theories for its description. At question is not simply which is the operant plasma micro-instability at onset. Rather, even the location, onset time, extent and motion of the magnetotail energization process leading to the macroscopic substorm phenomenon are still unknown[4].

	Science Objective	Science Goal
Primary	Onset and evolution of substorm instability	Time history of auroral breakup, current disruption, and lobe flux dissipation at the substorm meridian by timing: • Onset time of auroral breakup, current disruption and reconnection within <10s. • Ground onset location within 0.5^o in longitude and in space within 1R_E.
		Macroscale interaction between current disruption and near-Earth reconnection.
		Coupling between the substorm current and the auroral ionosphere.
		Cross-scale energy coupling between the macroscale substorm instability and local processes at the current disruption site.
Secondary	At radiation belts: Production of storm-time MeV electrons	Source and acceleration mechanism of storm-time MeV electrons
Tertiary	At dayside: Control of solar wind-magnetosphere coupling by upstream processes	The nature, extent and cause of magnetopause transient events.

Table E-1. *THEMIS baseline goals and objectives*

Resolving the substorm problem requires accurate timing of three disparate but well defined processes: ground auroral onset, current disruption onset at 8-10R_E and reconnection onset at 20-30R_E. Since these processes expand rapidly with time, knowledge of the onset location is as important as timing. THEMIS is the first mission specifically designed to determine the onset and evolution of the substorm instability. Towards this primary objective, THEMIS utilizes conjunctions between 5 identical probes on multiple period, near-equatorial orbits. Three inner probes (~1day periods) monitor current disruption and two outer probes (~2day and ~4 day periods) monitor lobe flux dissipation. The conjunctions occur near-midnight (i.e., near the substorm meridian) when a dense network of ground observatories monitors ground onset. The objectives and goals are summarized in Table E-1. The primary mission requirements and mission capabilities are tabulated in Figure E-1/A_I, while THEMIS's orbits are depicted in Figure E-1/B.

b. Significance of science objectives.

Substorms are ubiquitous at all solar phases and appear within all types of magnetospheric responses to solar wind input: Embedded within large

A Primary Science Closure

A_I THEMIS science goals, mission requirements and capabilities

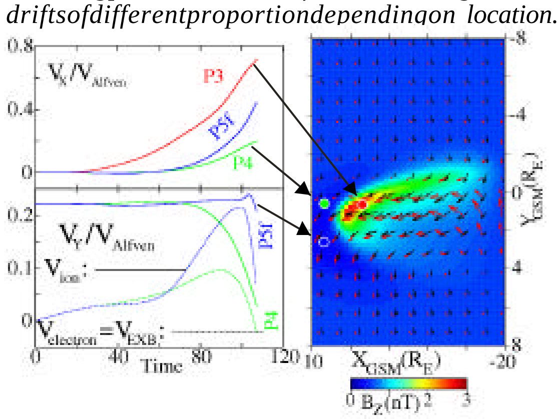
GOAL	MISSION REQUIREMENT	MISSION CAPABILITY
G1. Time history of Breakup, CD, Rx at the substorm onset meridian. (**Section E1.f1**)	**MR1i** An ASI, a high latitude and a mid latitude magnetometer station per MLT hour pin-point onset at δMLT<6°, t_{res}<30s. **MR1ii** 2 equatorial probes at ~10R_E, separated by δXY~2R_E monitor CD onset at t_{res}<30s. **MR1iii** Two orbits bracketing Rx region, separated by δY~2R_E and at apogee within 5R_E of neutral sheet (one at 20R_E and one at 30R_E, inc<7°) measure Rx(fast flow) onset t_{res}<30s. **MR1iv** CD and Rx monitors align (within ±2R_E) during >10 substorms in winter ±2mo. **MR1v** SST measures on ecliptic plane (axis control ~±30°) i^+/e^- fluxes (40-100keV), t_{res}=10s. **MR1vi** $\delta B/B$ ~ 10%, or δB~1nT absolute.	**MC1i** 2 ground ASIs, 2 high lat./mid lat. magnetometers provide onset detection within δMLT<0.5°, δt=1s. Even when cloudy, PiBs provide δt=1s and mid-lat. magnetometers determine onset meridian within δMLT<5°. **MC1ii** P3 & P4 (δXY~2R_E): CD onset at t_{res}<10s. **MC1iii** P1 & P2 at required orbits; once per 4 days at δY~2R_E (δX~6-10R_E) time Rx onset with t_{res}<10s. **MC1iv** P1, P2, P3 & P4 align once per 4 days. P5 also part of alignment strategy (Avg. ~12 hrs/alignment). 80 substorms/year; 16 substorm-alignments/yr. **MC1v** Spin-plane-mounted SST (20keV to >1MeV) at t_{res}=3s, covers required FOV at all seasons. Spin-axis normal to ecliptic. ACS control~0.5°. **MC1vi** δB~0.6nT absolute, routinely at 4 vectors/s.
G2. CD-Rx coupling (**Section E1.f2**)	**MR2i** Track rarefaction wave (1600km/s) in B. **MR2ii** Track Earthward flows (400 km/s) in V. **MR2iii** δB~1nT absolute, $\delta V/V$~10%	**MC2i,2 ii** P3 & P2 determine delays at $\delta X/\delta t$=6R_E/3s=12000km/s for 160 substorms (32-alignments)/yr. **MC2iii** δB~0.6nT absolute and $\delta V/V$~10%
G2. Substorm coupling to auroral ionosphere (**Section E1.f3**)	**MR3i** Measure radial/cross-sheet pressure gradients ($\delta P/\delta XY$~0.1nPa/R_E); flow vorticity/deceleration ($\delta V/\delta XY$ ~100km/sR_E). Requires 10% accuracy in δV, δP on 1R_E scales ($\delta P/P$~$\delta V/V$~1). **MR3ii** Measure $J_{current\_sheet}$ (planar approximation, $\delta J/J$~10%, $\delta B/B$~10% or δB~1nT absolute, 0.1nT relative, over δZ~0.5R_E) and incoming flows **MR3iii** E field (t_{res}=10s) for non-MHD part of flow. **MR3iv** Study >10 events in each δX, δY, and δZ.	**MC3i** δXY conjunctions between P3, P4, P5f over ranges of 0.3-10R_E provide δP, δV with 10% absolute accuracy. Modeling provides curlV, gradP. **MC3ii** P4 & P5u δZ-conjunctions provide δB~0.6nT absolute, 0.03nT relative while P2 measures flows. **MC3iii** E field measured at 4vectors/s routinely. **MC3iv** Cross-tail, cross-sheet or tail-aligned separations: 320 substorms/yr. P2 (incoming flows) available during 160 of those. Simultaneity in δX-δY or δY-δZ observations (not required) is possible.
G3. Substorm coupling to local modes at ~10R_E (**Section E1.f4**)	**MR4i** Cross-tail pairs to measure FLRs, KH and ballooning waves in B, P, V and E at δY~0.5-10R_E, t_{res}=10s. **MR4ii** Cross-sheet pairs to measure $J_{current\_sheet}$ (as before) as free energy for cross-field current instabilities at 6Hz, on E field @ spin-plane (2D), B-field in 3D. **MR4iii** Study 10 substorms or more.	**MC4i** P3, P5f measure B, P, V and E at separations δY~0.3-10R_E, at t_{res}=3s or better. **MC4ii** P3 & P5u δZ-conjunctions measure sheet density (B~0.6nT absolute). **MC4iii** 160 substorms/yr (P3, P5f/u). P2 aligns and times flows for 64 substorms/yr.

A_{II} THEMIS baseline minus minimum mission descopes

DESCOPE	PRIMARY SCIENCE EFFECT/RECOVERY	MISSION EFFECT	DATE
2 EFI axials	3rd DC component from E*B=0. Can still identify high frequency modes	Saves 4kg, 1W, \$0.4M per probe	Phase D
One ground observatory/ MLT	One station/MLT-hour can identify most onsets. Impairs detection of only the (rare) high latitude/ early evening/late morning onsets.	Saves \$0.6M	Phase D
SCM	*FGM recovers waves (<10Hz) at lower sensitivity. *Primary science (requires 6Hz waves) recovered.	Saves 1.5kg, 2.0W, \$0.1M / probe	Phase C
One probe (P4)	*δX, δY, δZ (P5f, P3 pair does all types, separately) * Full recovery of 4day, 4probe tail-alignments, and 2probe cross-tail and cross-sheet alignments.	Saves 95kg (max. expected probe mass), 2mo. schedule, \$4.5M recurring costs.	Phase C
Total value of descopes: 117kg (at PCA level), 3.0W/probe, \$7.0M in cost and 2mo. in schedule			

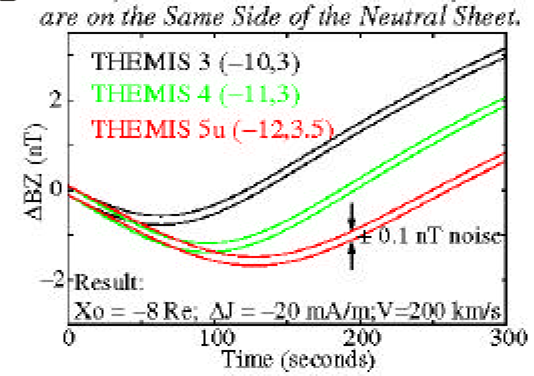
A_{VI}

THEMIS-specific hybrid simulations show how the incoming plasma consists of both EXB and gradP drifts of different proportion depending on location.

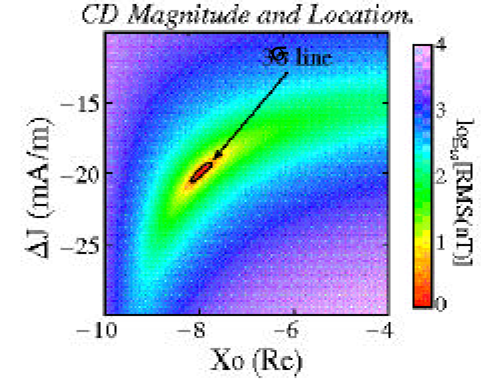


A_V

Modeling Current Disruption Propagation Seen by THEMIS s/c Even When they all are on the Same Side of the Neutral Sheet.

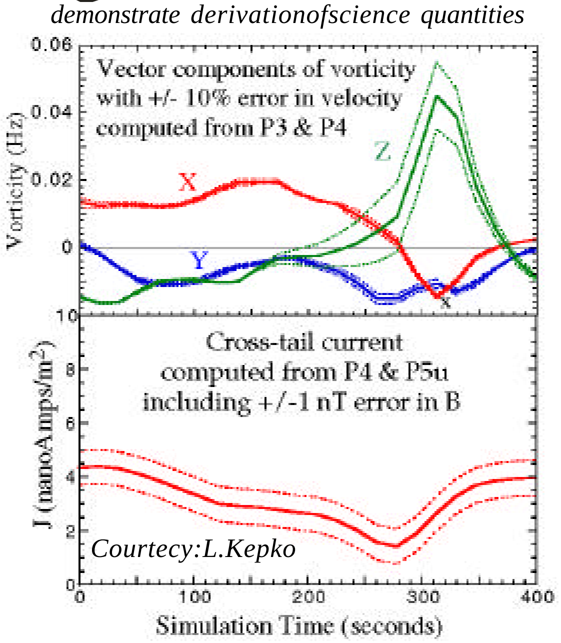


Evaluation of Uncertainty in CD Magnitude and Location.



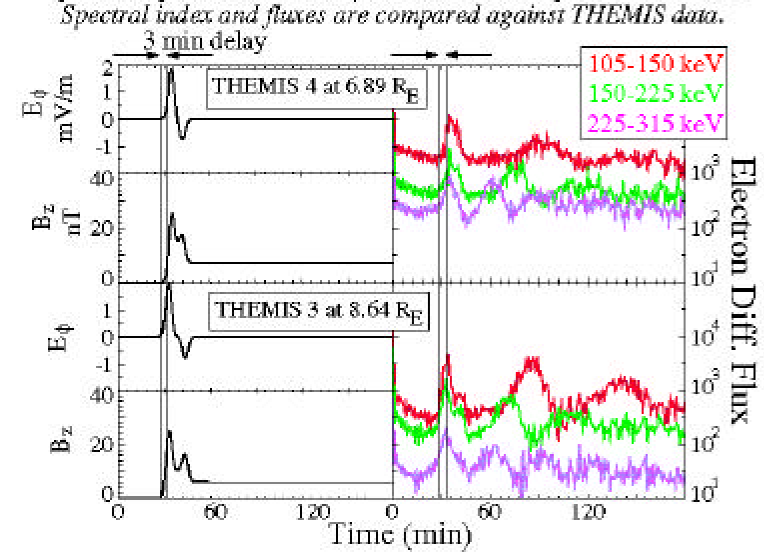
A_{III}

Realistic orbits through MHD model demonstrate derivation of science quantities



A_{IV}

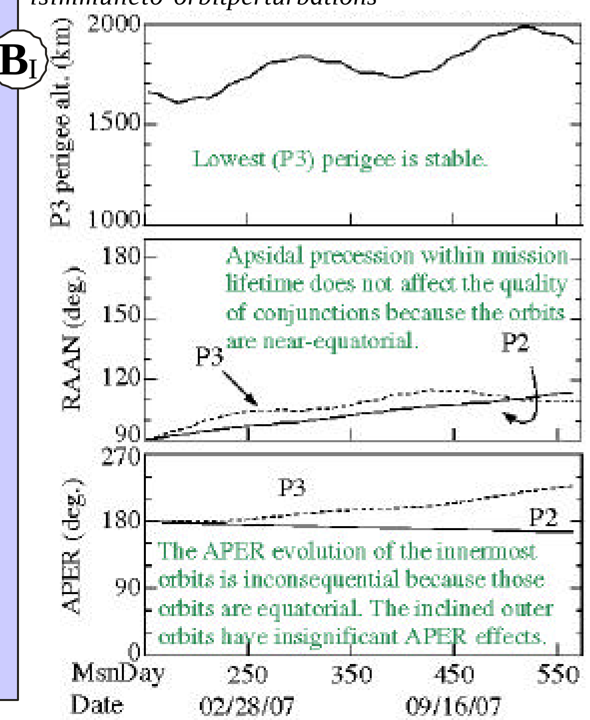
An electric field pulse through a realistic model field produces particle spectra that evolve from one THEMIS probe to another. Spectral index and fluxes are compared against THEMIS data.



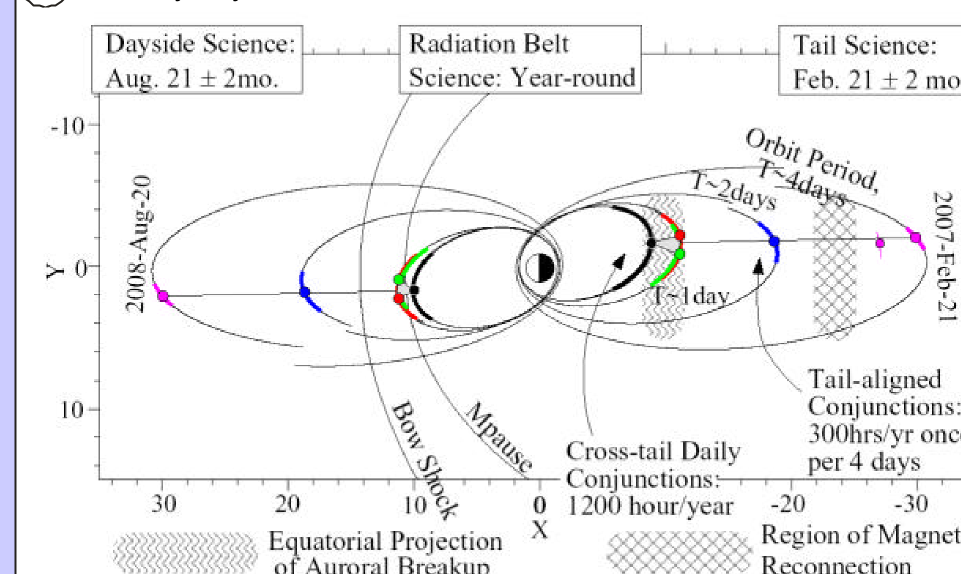
B Orbit

B_I

Evolution of typical probe P2 and P3 orbits for 14 mo. (including 2 tail seasons) with model GTDS.J2, lunar, solar, and drag terms are included. THEMIS is immune to orbit perturbations



B_{II} THEMIS yearly evolution



B_{III} THEMIS orbits and ΔV requirements

#	Probe Name	T (hrs)	r_a (R_E)	r_p (R_E)	inc (deg)	ΔV (m/s)	How?
i	PCA	23.9	12.1	1.100	9.0	n/a	D2925
1	P1	92.0	30.9	1.500	7.0	569	On-board Hydrazine
2	P2	47.7	19.8	1.168	7.0	350	
3	P3	23.9	12.1	1.118	9.0	39	
4	P4	23.9	12.1	1.118	9.0	39	
5	P5f	18.0	9.8	1.118	4.0	470	
	P5u	23.9	12.1	1.118	4.0		

***FIGURE E-1** THEMIS Science Closure and Orbit (Foldout-1)* storms they influence storm development[5] and geoeffectiveness[6]. They bound the beginning and end phases of magnetospheric convection bays[7]. They are closely related to pseudo-breakups[8]. Understanding the substorm process is a prerequisite to understanding the geo-magnetospheric response to all levels of solar wind energy throughput. However, the objective of deciphering the mechanism of the substorm instability transcends its geophysical interest. It relates intimately to broader scientific questions, because it addresses basic plasma physics processes, such as cross-scale coupling between MHD and kinetic plasma instabilities[9,10]. Beyond purely scientific applications are matters of more practical value to society, related to space weather processes (such as storms), which affect satellite communications and ground electrical distribution, and are inextricably linked to substorms[5,6]. In summary, *substorms represent a fundamental mode of global magnetospheric circulation, a macroscopic instability whose phenomenological and theoretical understanding is crucial for space science, basic plasma physics and space weather.*

c. THEMIS's alignment with NASA SEC goals.

The THEMIS science is directly aligned with the Space Science Enterprise Objective[11] to "understand our changing Sun and its effects throughout the Solar system" and Research Focus[12] to "understand the space environment of Earth". The primary and tertiary THEMIS objectives are aligned with Quests II of the NASA Sun-Earth Connections Theme: How does our planet respond to solar variations? THEMIS's secondary objective is important for Quest IV of NASA's SEC Theme: How does solar variability affect society? In particular THEMIS's primary objective to understand the fundamental mode of energy, mass and flux transport in Geospace is a basic SEC question identified in the SEC Roadmap[13]. THEMIS builds on a close relationship between US academia and US industry. It leverages significant foreign instrument and science contributions. These practices are in accordance with SEC strategic plans[14]. An open data policy and a $4M guest-investigator program maximize benefits from the US science community.

d. Substorm phenomenology.

d1. What is known about substorms.

The components of the substorm instability i.e., Auroral Breakup, Current Disruption and Reconnection, evolve on a meso-scale range but interact over macroscales. Previous missions and fortuitous spacecraft conjunctions have provided a wealth of information regarding these substorm components.

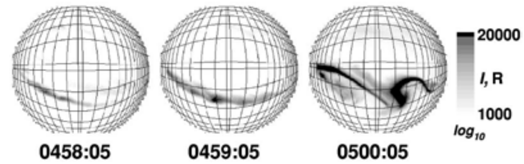


Figure E-2. *Substorm onset as seen from a ground all sky camera station[15]. Each line is 0.5 degrees in latitude (or 56km) and in longitude (or 31km).*

Auroral Breakup. High-sensitivity all sky imagers (ASIs) show that the pre-onset equatorward arcs undergo large-scale undulations with wavelengths of hundreds of kilometers (Figure E-2). This is ~6° in longitude, which maps to a region of $\delta Y \sim 1R_E$ at the inner edge of the plasma sheet. Onset erupts in 10s at a folding of one such undulation.

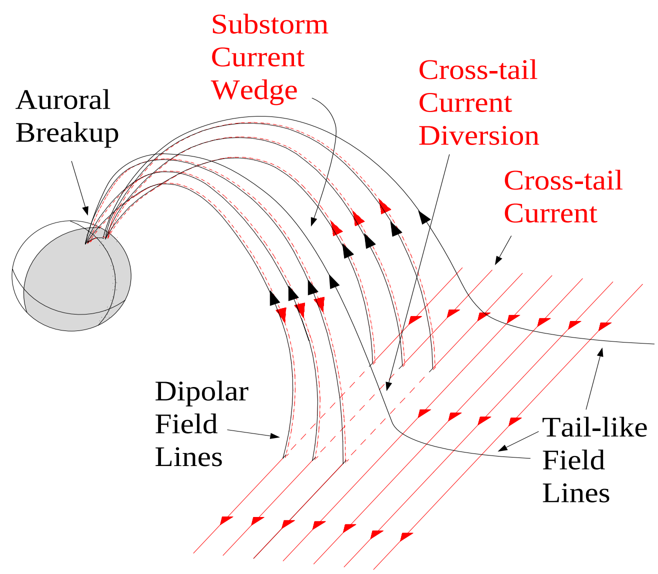


Figure E-3. *Development of the substorm current wedge through a reduction of the cross-tail current at 8-10R_E in the equatorial plasma sheet.*

Current Disruption (CD). An intense cross-tail current[16] (tens of nA/m^2), mainly supported by a duskward anisotropy in thermal ions (2-10keV), provides substantial free energy at growth phase at $\sim 10R_E$. At substorm onset the *current wedge* forms there (Figure E-3). This is an abrupt increase in the Z_{GSM} component of the magnetic field, accompanied by plasma heating. This morphological change of the field is consistent with a current-carrying particle distribution change[17]. It is modeled as a partial disruption of the cross-tail current and diversion *along* the field lines, *into* the auroral ionosphere[18,19] where it feeds into the breakup arc. It is often termed the current disruption (CD) process[20]. The hot, dipolar plasma originates in a small[21] equatorial area (~1R_E^2) and expands azimuthally[22] by ~10^o of magnetic local time (MLT) per min and radially[23,24] at ~200 km/s.

Reconnection (Rx). Further downtail, at ~25 R_E, there is evidence that *magnetic reconnection* takes place[25]. Fast, bursty, bulk ion flows presumably emanating from the reconnection site at Earthward speeds comparable to the Alfven velocity (1000 km/s), are also interpreted[26,27] as evidence of that process. Seen[28,29] as close to Earth as 10 R_E, such flows are often localized[30,31,32] (1-3 R_E) but are very efficient in energy and flux transport[33].

d2. The main question in substorm research.

Previous fortuitous spacecraft conjunctions have been unable to determine where and how the substorm instability starts because of their unoptimized vantage points. Presently all possible causal sequences involving auroral breakup, Rx onset, CD onset and external triggers are viable hypotheses[34]. In particular, CD and Rx might be causally linked, or proceed independent of each other. As an impartial and experienced researcher summarizes[35]: "*Observations are gradually leading to a coherent picture of the interrelations among these various onset phenomena, but their cause remains a controversial question. The abrupt nature of substorm onsets suggests a magnetospheric instability, but doubt remains as to its nature and place of origin. Measurements increasingly suggest the region of 7-10R_E near midnight as the likely point of origin*".

A number of substorm onset paradigms exist, but two of them can help epitomize the main ideas and reveal the primary observational requirements. These are the "*current disruption"* and the *"Near-Earth Neutral Line" (NENL)* paradigms.

Current Disruption paradigm. According to this paradigm an instability *local* to the current disruption region (8-10 R_E) is responsible for substorm onset[16]. The paradigm stems from two basic observations: First, the breakup arc maps near-Earth[36]. This has been reinforced by advanced mapping of auroral images from Viking[37], POLAR[38,39] and ground-based photometers[40,41]. Second, the cross-tail current density reaches tens of nA/m^2 and peaks near 8-10 R_E prior to substorm onset[42]. This happens explosively[43] suggesting that it is in *that* region that the free-energy source and trigger for the substorm auroral surges reside.

This paradigm suggests (Figure E-4) that Rx and fast Earthward flows are triggered by a CD-initiated fast mode rarefaction wave (V_x=-1600km/s) once it reaches ~25R_E. Flows cause neither the CD nor the auroral breakup itself. The relevant substorm component chronology appears in Table E-2.

Recent observational evidence in support of this paradigm comes from the observation that the particles energized first at the CCE spacecraft (located at 8-9 R_E) at onset are those with gyrocenters Earthward of CCE[20,45]. Finite gyroradius remote sensing applied on equatorial pitch angles produces the CD expansion's speed and direction ($\mathbf{V}_{xy}$). However, performing accurate CD onset timing requires knowledge of the CD expansion velocity at two probes which bracket the onset location. The probes should be at the neutral sheet (±2R_E) and near the CD location itself (±2R_E) so that the expansion speed will not vary significantly during its motion. Such timing has not been performed to date.

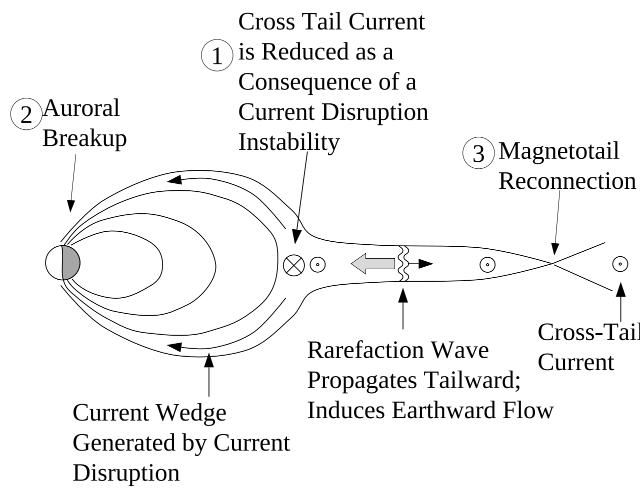


Figure E-4. *Time-history of events at the substorm meridian according to the Current Disruption model for substorms[44] (numbers indicate proposed chronological and causal sequence).*

Order	Time (s)	Event
1	t=0	Current Disruption
2	t=30	Auroral Breakup
3	t=60	Reconnection

Table E-2. *CD model event chronology.*

Near Earth Neutral Line paradigm. According to this paradigm[46,47], bursty flows generated by near-Earth reconnection[48] (~25 R_E) are responsible for substorm onset (Figure E-5). Observations pivotal for this model's development at the substorm meridian include fast tailward/Earthward flows [26,27] and plasmoid ejection[49,50] both timed to start within 1-2 minutes from ground onset.

This paradigm suggests that the flow kinetic energy is converted to particle thermal energy at the CD region. While heating generates a steep pressure gradient, the flow decelerates and deflects around Earth. The field aligned current created locally by these processes[52,53,54] leads to current disruption and auroral breakup. The recent observation that fast Earthward flows at 12-18R_E occur within 1min from substorm onset[31,51,55,56,57] has spurred renewed interest in field-aligned current generation in the NENL context. The NENL substorm component chronology is distinctly different from current disruption model's (Table E-3).

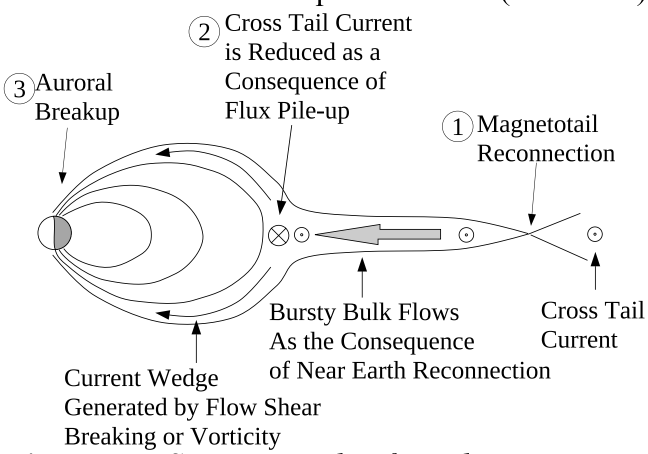


Figure E-5. *Same as E-4 but from the viewpoint of the NENL model for substorms[51]. Note the difference in the sequence of events.*

Order	Time (s)	Event
1	t=0	Reconnection
2	t=90	Current Disruption
3	t=120	Auroral Breakup

Table E-3. *NENL model event chronology.*

The NENL-predicted flow protrusion at 8-10R_E has never been reported at substorm onset, but has been seen during pseudobreakups, auroral streamer events[58,59] and at substorm recovery[60,61]. This has led to the suggestion[62] that pseudobreakup flows are CD onset triggers / substorm precursors. Alternatively: (i) The incoming flow may decelerate to compensate for the increasing magnetic field[63] or (ii) The flow may dissipate through field-aligned Poynting flux[64] along high latitude field lines[65,66]. The flow evolution and causal relationship (if any) to substorm onset is unclear, largely due to lack of tail-aligned spacecraft conjunctions.

Additionally, like for the case of CD onset detection, accurate Rx onset timing requires *two* probes at the plasma sheet, or its boundary, measuring velocity dispersed, field aligned, 30-300 keV particles. A strictly temporal interpretation of the dispersion provides L, the distance to the source[76,77]. A spatial interpretation[78,79] provides $L*V_E/V_B$. Here, V_E is the convection velocity along the flight path of the particles (inferred by the dawn-dusk electric field component or measured by the plasma detector). V_B is the Z_{GSM} component of the boundary velocity measured by finite gyroradius remote sensing on East-West particles fluxes. The latter is the more general interpretation (when $V_E = V_B$ we retrieve the temporal one), but can only be used if the Rx site is nearby (within ~5-10R_E), because the locally measured V_E/V_B is not necessarily constant along distant flight paths. Thus two probes at distances of 5-10R_E from each other should *bracket* the nominal Rx site. Oppositely-directed fluxes at the probes establish that the reconnection site is between them (nearby), justifying the assumption of a constant V_E/V_B. The two probes should observe the particles as the boundary expands over. Thus the two Rx monitors need not be at the neutral sheet but within δZ_{GSM}~5R_E of it. Plasma sheet Z-fluctuations affect little the timing capability because the active plasma sheet expansions are large relative to those fluctuations. Such accurate Rx timing has not been performed to date.

Other substorm models. Distinguishing between the CD and NENL models imposes similar observational requirements on timing and location as distinguishing between all substorm models. For example the Magnetosphere-Ionosphere (MI) coupling model[67] suggests that the substorm starts due to breaking of the Earthward flows at a rate >3mV/m/R_E, and the ensuing Alfven wave bouncing. Here the flows come first, as a result of mid-tail or distant tail processes and the remaining sequence of events is similar to the current disruption scenario. As in the current disruption model, Rx is not a necessary condition for onset triggering. But contrary to the current disruption model, the flows come first, as a result of mid-tail or distant tail processes.

Solar Wind triggering. Spontaneous[68] onsets and externally triggered[69,70] onsets (stimulated by sudden impulses, northward turnings or rotational discontinuities[71]) may exhibit different destabilization scenaria[72]. It is possible, e.g., that external triggers result in a NENL-like path to onset, whereas spontaneous onset substorms follow the CD paradigm prescription. It is thus important to classify substorms according to the external conditions in order to distinguish between different scenaria.

e. Mission requirements and mission design.

The science goals and objectives of Table E-1, and the previous discussion on substorm phenomenology lead to a set of mission requirements. These requirements are tabulated in Figure E-1/A_I.

For example, ground onset timing should be performed along the substorm onset meridian (δMLT~6° which corresponds to $1R_E$ at the CD site) and must be better than the time scale of interaction of those processes (30s). Since CD onset is limited in $\delta XY \sim 1R_E^2$ the CD monitors should be no more than $\delta Y \sim \delta X \sim \pm 2R_E$ apart. Rx monitors should be around $20R_E$ and $30R_E$, i.e., within $\pm 5R_E$ of the nominal Rx site to ensure constancy of the measured V_E/V_B ratio. The neutral sheet location (maximum Z_{GSM} distance in winter solstice) determines the orbit inclination of both the CD and the Rx monitors. Diurnal fluctuations at $10R_E$ ($\delta Z \pm 2R_E$) have little effect on the capability of the CD monitors to determine CD expansion speeds. Plasma sheet diurnal fluctuations at 20 and $30R_E$ ($\delta Z \pm 3R_E$) are small compared to the $\pm 5R_E$ tolerance. Additionally, the two inner probes in combination should permit cross-tail ($\delta Y \sim 0.5\text{-}5R_E$) or cross-sheet ($\delta Z \sim 1R_E$) conjunctions (not necessarily simultaneously).

The objective to time auroral onset using <30s time resolution ASIs in the US/Canada fixes our probe apogees to US winter season, at central US midnight, i.e., ~6:30 UT (best performance of ASIs in winter). This in turn calls for orbit periods which are multiples of a day. Remote sensing requirements for both CD and Rx monitors are to measure near-equatorial fluxes. ACS control of 11.25° is derived from the SST technical specifications. δB/B~10% requirements arise from the need to monitor the rarefaction wave (also the cross-tail current within δJ/J~10%, given a ΔB~B between probes at separation $\delta Z \sim 1R_E$) In a minimum field of 10nT this renders the absolute stability requirement 1nT.

THEMIS should measure at least a few solar-wind triggered and a few spontaneous onset substorms (assumed equal chances to observe each). Thus at least 5 substorms should be observed in each probe conjunction configuration. Given a 3-6hr recurrence time for substorms[73], this necessitates 30hrs of useful data in each conjunction type.

THEMIS's orbit strategy accounts for >300 hrs of conjunctions in each conjunction type. We recognize that significant losses of useful events may occur due to plasma sheet fluctuations, lack of solar wind data, possible extreme event localization, and early evening/late morning substorms. Clear evidence that tail-aligned spacecraft equipped with THEMIS-like instrumentation can indeed monitor the progression of the incoming flows despite their $\delta Y \sim 1\text{-}3R_E$ localization comes from fortuitous ISTP conjunctions during north-south arcs at late substorm recovery[58,59]. We anticipate that a number of events much larger than the required 5 will be available for study. Of those, a few high quality, clear and effective conjunctions will receive attention by a large number of people (like CDAW events).

The above strategy defines the mission design. Orbits are shown in Figure E-1/B_{II} and are tabulated in Figure E-1/B_{II}. Stability to J2 and lunar perturbations is established in Figure E-1/B_I. In particular THEMIS is immune to the differential precession of the line of apsides between the high and low altitude orbits, because it relies on mean anomaly phasing to obtain tail-alignments. Relative apsidal drifts of as much as 60 degrees can be balanced by mean-anomaly phasing.

THEMIS's orbits, instrumentation and time resolution are specifically geared towards resolving the present impasse on the onset and evolution of the substorm instability.

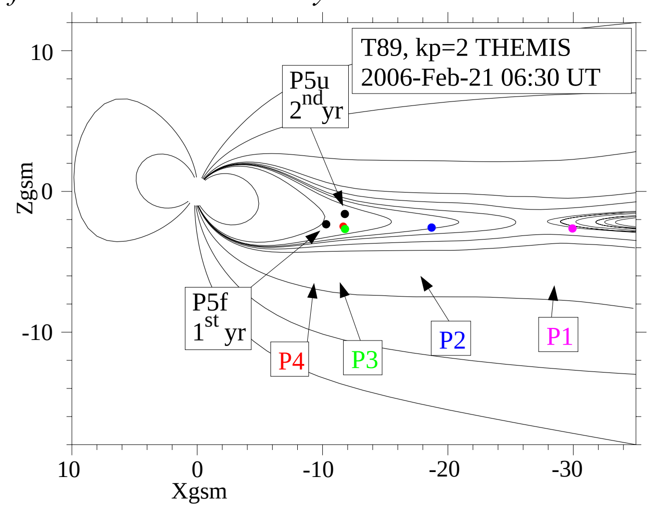


Figure E-6. *Meridional view of the THEMIS probe locations at midnight over North America. P5f (fast) gains 6hours/day over P4, in year#1. P5u (up), is $1R_E$ above P4 at apogee in year#2. Tail seasons are centered on Feb.-14, 2006/2007. Useful conjunctions occur nominally ±2mo. around that.*

f. Expected results

f1. Time history of events.

THEMIS probes will form more than 300hrs/yr (50-100 substorms/yr[73]) of tail-aligned conjunctions (all within $\delta Y=2R_E$ from P1) and will delineate the time history of events that compose the substorm process. In addition to WIND, ACE and SOHO, solar wind data from TRIANA and Solar Stereo will likely be available in THEMIS's time frame. With such data *THEMIS will account for the* *external conditions and distinguish between the different paths to substorm onset.*

CD onset determination. At speeds of 200km/s a current disruption onset 1R_E away expands over the THEMIS probes within 30s. THEMIS probes P4 & P3 (Figure E-6) will obtain timing information from the remote sensing (finite gyroradius) technique[20,45] applied to energetic ions. Boundary expansion speeds to within 10km/s and directions good to a fraction of the angular resolution of the ion detector[74,75] will be obtained. The onset time will be determined from the expansion velocities on the two nearby probes to a temporal resolution as good as the temporal resolution on the probes (3s). *THEMIS's temporal resolution provides current disruption onset timing to within 10s or better.*

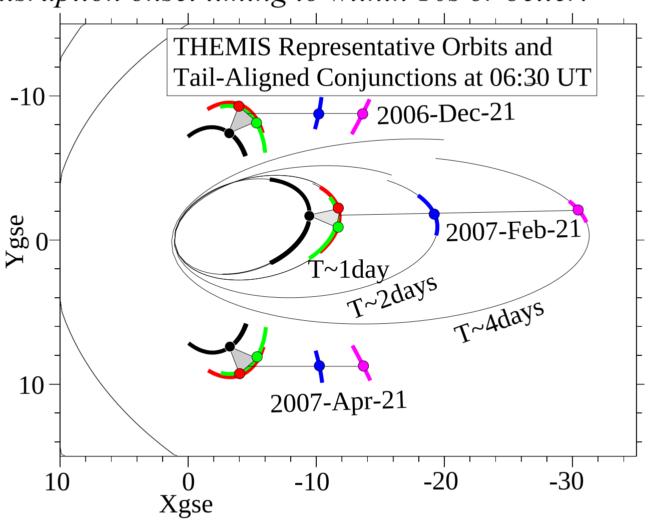


Figure E-7. *Equatorial view of THEMIS probe locations during tail-aligned conjunctions. Full orbits are shown only near tail center. Six-hour-long orbit segments centered at 6:30 UT are shown in color, approximately two months apart. Colors denote the different probes as in Figure E-6.*

Reconnection onset determination. THEMIS will time Rx onset by monitoring the arrival times of field aligned energetic particles from the reconnection site at its two outer probes (P2 & P1). Those are within 5R_E from the nominal site of reconnection (25R_E). Ancillary timing information will be obtained from the measured flow speed and other local observations[77,56] (electrons, waves, MHD pulse). *THEMIS's probe locations, temporal resolution (3s) and instrumentation will ensure reconnection onset timing to within 10s or better.*

Auroral breakup onset determination. Imagers or ground magnetometers can time onset far better than mid-latitude global Pi2 onsets[80,81]. THEMIS's dense network of white-light all sky imager and ground magnetometer stations in Alaska, Canada and the US at 1s resolution will ensure accurate determination of onset to within 0.5^o in magnetic local time (Figure E-8). Cloudy skies or moonlight can obscure, at times, part of those images. At those times, PiB (1-40s period, 3s nominal) pulsations[82], which are good substorm indicators[83,84], will determine onset time to within a few seconds. Substorm current wedge modelling from a dense North American network of auroral and mid-latitude magnetometer stations provides determination of the substorm meridian to within 5^o or better (still fulfilling the science goal of 6^o). Such modelling is routinely performed using data from the existing network of mid-latitude stations[85,86,87,88] and has been validated using global imaging[89]. In short *THEMIS's ground network of all sky imager and ground magnetometer stations has the density and time resolution to detect auroral breakup onset meridian and onset time nominally within* $\delta MLT<0.5°$, $\delta t<10s$.

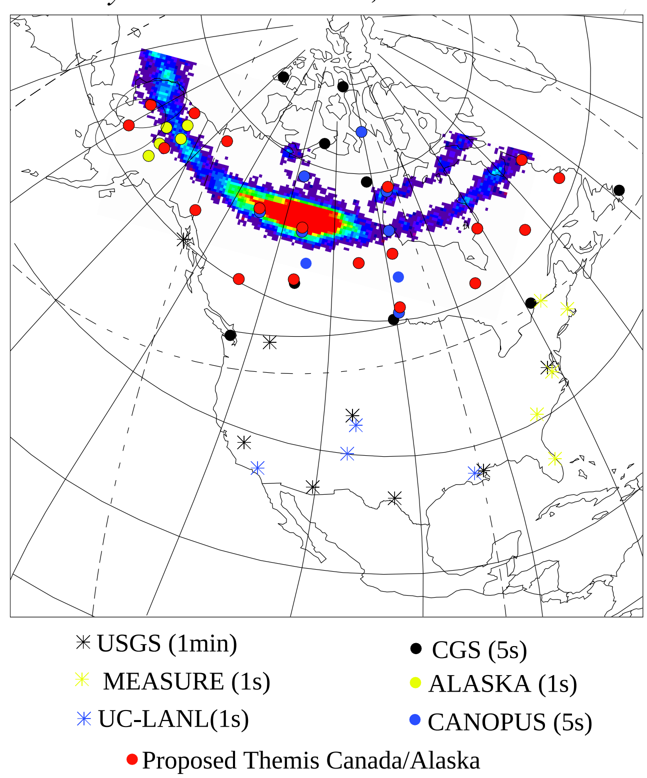


Figure E-8. *Existing and proposed auroral and mid-latitude magnetometer stations. Most THEMIS stations supplement existing instrumentation at the proposed sites. Each station includes a white-light All Sky Imager (ASI) and a ground magnetometer with time resolution of 1s. An auroral snapshot of a substorm onset by IMAGE is overlaid. Circles around the West-Alaska stations denote typical ASI field of view. Simple jpeg (e.g., jpeg2000) compression renders ASI local data storage manageable.*

f2. Macroscale Interactions

A THEMIS objective is to address how the localized, mesoscale substorm components interact over macroscale ranges:

In the context of the CD paradigm, THEMIS will measure the *tailward* motion of the rarefaction wave in δP, δB, δV, at speeds comparable to the local fast mode speed[90] (1600km/s). Probes P4 and P3 will first observe fast Earthward flows at onset, but P2 will not observe them until 20s later. P1 will observe no Rx signature until at least another 20-25s. *THEMIS probes P4, P3 and P2 will measure the outward motion of the rarefaction wave that links lobe flux dissipation to current disruption.*

In the context of the NENL paradigm, THEMIS will monitor the *Earthward* motion of the fast flows (typically[91] ~400km/s) by observing the anticipated >90s flow-onset time delay between P2 and P3 or P4. In the second year, probe P5u (see Figure E-6) at higher latitudes will determine if flow-driven boundary layer waves carry substantial Poynting flux. *THEMIS probes P2, P3 and P4 will monitor the Earthward flow and establish the link between current disrupt onset and reconnection.*

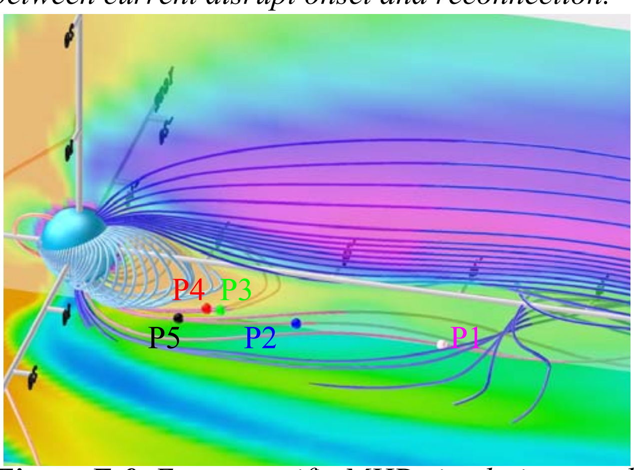


Figure E-9. *Event-specific MHD simulations model the substorm evolution in response to external conditions (probe colors same as in Figure E-6).*

Event-specific MHD and particle modeling. In the context of all paradigms, macroscale interactions will be modelled using event-specific MHD runs[92] driven by measured solar wind (Figure E-9). Additionally, particle modelling in prescribed **E** and **B** fields will validate[93] the outgoing rarefaction wave or the incoming flow hypothesis (Figure E-1/A_{IV}). *Using MHD and particle simulations THEMIS will strengthen closure on the macroscale interaction of components of the substorm instability.*

f3. Means of ionospheric coupling.

THEMIS will remotely infer (i) cross-tail current evolution and (ii) field aligned current generation. Studying 100-200 substorms, the mission will establish the macroscale coupling between the global substorm instability and auroral arc formation.

Cross-tail current reduction. THEMIS probes P4 & P5u will routinely straddle the current sheet at separations 0.2-1R_E and measure the cross tail current and its evolution (one to tens nA/m^2), using a planar approximation. Tail flapping due to solar wind buffeting[94], and diurnal effects[95] ensure multiple neutral sheet crossings. The cross-tail current modeled under worst case absolute δB noise from P4 & P5u data through an MHD run is shown in Figure E-1/A_{III}. The relationship to the incoming flows is simultaneously monitored by probe P2.

Additionally, the inner THEMIS probes will occasionally be away from the neutral sheet and will obtain magnetic field measurements across and along the tail. The current disruption process can then be remotely sensed with methods established on ISEE[23], and Interball[96]. Figure E-1/A_V shows such a reconstruction by THEMIS probes using simulated input of worst case noise amplitude.

Field aligned current generation. In MHD the field aligned current generated by the bursty flows can be due to[97,53,54] the flow vorticity, the flow braking, the radial pressure gradient or the cross-sheet pressure gradient. Pair conjunctions between probes P4, P3, P5f or P5u across the path of a (laterally expanding) flow channel or a (tailward expanding) pressure gradient will determine the *curl*V and *grad*P. For example, the vorticity modeled using worst case (~10%) detector noise as a flow channel moves past P4 & P5f in the context of an MHD run is shown in Figure E-1/A_{III}. Data from P2 during 100-200 substorms place the field aligned current generated in the global context.

The incoming flow interacts with Earth's dipole in a region of strong **B** field gradient and of high ion temperature. There, ion diamagnetic drifts become pronounced, and non-MHD effects are apparent. The splitting between the ions (drifting duskward) and electrons (which obey the plasma approximation, $V_e=E \times B/B^2$) calls for Hall MHD (hybrid) codes to model the observations and affects profoundly the generation of field aligned currents[57]. Such effects necessitate electric field measurements in addition to the ion flow data[29]. THEMIS will measure both plasma and the E×B flow independently and will be able to determine the (non-MHD) component of the ion drifts.

Event-specific hybrid modeling. Hybrid simulations in support of THEMIS design show (Figure E-1/A_{VI}) that probes P3 P4 & P5 can fully assess if the observed CD is due to electron acceleration (accompanied by flux transport) or due to an ion drifts reduction. *The THEMIS team will interpret its data on current wedge formation hand-in-hand with event-specific hybrid simulations.*

f4. Cross-scale coupling to local modes at $10R_E$.

The substorm operates over a variety of coupled scale-lengths (Table E-4) applicable to all paradigms. Identifying these coupling processes is just as important to the substorm problem as identifying the local modes at play.

Ballooning modes. These have been identified by geosynchronous[98] and ionospheric[37] observations. Their free energy source is the near-Earth pressure gradient ($1nPa/R_E$). The modes have wavelengths $\lambda=2*\pi*\rho_i\sim2000$-12000km, move azimuthally at the ion drift speed (50-100s of km/s) and have a Doppler-shifted ($\omega=V_d*k_y$) period T~0.3-2 min. Coherent waves are expected on spacecraft traversing the near-Earth region at the ($\sim1R_E^2$) onset location[99]. Classical ballooning is near marginal stability for typical tail parameters[100,101]. This has led to non-linear ballooning mode theories[102], and linear but absolute instabilities[103].

Scale	Size (R_E)	Process
Macro	10	Rx/CD coupling. Current Wedge formation. Field line resonances.
Meso	1	CD onset size. Ballooning modes. Kelvin-Helmholz waves.
Micro	0.1	Cross-field current instabilities. Aflven waves.

Table E-4. *Scales of processes at substorm onset.*

An alternative approach, the shear-flow ballooning, suggests that ballooning is part of a larger cross-scale coupling process[10,104]. It proposes that field line resonances[105] ($\lambda\sim2$-$10R_E$, T~5min) drive Kelvin-Helmholtz (KH) waves ($\lambda\sim0.2$-$1R_E$) which in turn become non-linearly unstable within ~1min. KH waves drive smaller ($\delta Y\sim0.1\ R_E$) Alfvenic currents dissipating energy through the ionosphere. The (East-West) cross-field flow shear driver has $\delta V\sim200$km/s; the waves have phase speeds V_ϕ ~50km/s. Independent Poynting vector calculations show[106,107] the bouncing Alfven waves, but their association with ballooning is not confirmed.

Ballooning modes and resonances will be apparent on THEMIS probes as coherent waves in cross-tail pairs P4 and P5f, and will be studied using cross-spectral, wave-telescope[108] and Poynting vector techniques. Phase speeds measured using probe pairs will be compared to flow speeds measured on both probes. Using cross-tail probe pairs (P4 & P5f) at separations of 0.3-10 R_E THEMIS will identify the properties of the ballooning mode waves. MHD simulations will be used to model observations[104]. Coupling to the global substorm instability is simultaneously monitored by P2.

Cross-field current instabilities. These are driven unstable when the cross tail current exceeds an instability threshold[16] (10 nA/m^2, or 100 mA/m). They have frequencies 0.01-0.1 f_{LH} (f_{LH}, the low hybrid frequency is 60Hz at $8R_E$), wavelengths 300-2000 km and exhibit no cross-tail spectral coherence. THEMIS's **E** and **B** field instrument data and their phase relations will identify the unstable wavevector direction and mode. Cross-tail probe pairs (P3, P4, P5) will ascertain the lack of spectral coherence. Particle-in-cell simulations[109] will establish if the observed wave amplitudes and particle streaming compare favorably with non-linear saturation amplitudes of the unstable modes. Again, P2 monitors coupling to the global substorm process.

THEMIS probe P2 along with pairs of P3, P4 and P5f or P5u determine during 100-200 substorm events the local mode type, free energy source and cross-scale coupling to the global substorm.

g. Additional tail science.

THEMIS can contribute towards understanding other important phenomena indirectly related to substorms. These goals are not primary mission goals and do not drive the mission design.

Flux-tube evolution along streamlines. Adiabatic[110] convection does not match the average lobe pressure profile[111] resulting in a "pressure balance inconsistency". Bubbles generated by uneven density loading in the tail[112] and propagating rapidly Earthward[113] have been proposed as the solution to this crisis, but their observations are limited to late substorm recovery[30]. Is the bubble evolution applicable to all fast Earthward moving flux tubes? *THEMIS probes P4/P3, P2 and P1 will determine the flux-tube evolution of fast flows along their streamlines and their importance in resolving the pressure balance inconsistency.*

High frequency modes. Waves in the Pi1 pulsation range[114] or beyond[115] exist during substorms. They may be driven unstable by low energy [0.5-2 keV] electrons[116], or by free energy sources due to the kinetic structure of a thin plasma sheet[117]. Bursty and broadbanded they extend to $f\sim4*f_{LH}$ about 10-20% of the time. They are occasionally (1/5 of the time) accompanied by whistlers at 1-10*f_{LH}. Burst waveform collection of **E** and **B** data up to 10*f_{LH}, or 600 Hz (f_{LH}~60Hz at 8R_E) on *THEMIS will identify these modes, and place them in the context of substorm evolution.*

h. Radiation Belt (Secondary objective).

At storm main phase, MeV energy electrons are abruptly (1-4hrs) lost; they reappear also abruptly at storm recovery with fluxes higher than prior to the storm (Figure E-10). This MeV electron flux increase represents the main electron flux increase of electrons during a storm.

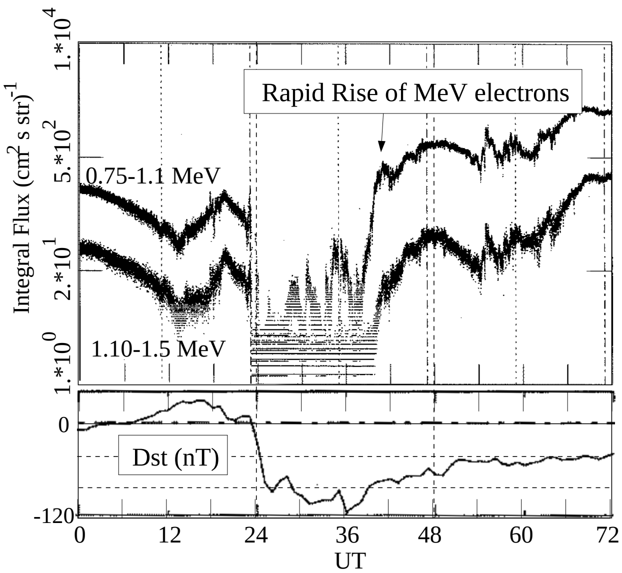


Figure E-10. *LANL satellite data on November 3, 1993 storm exemplify the rapid loss and reappearance of storm time electron flux at geostationary orbit at storm onset and rapid (1-4 hr) reappearance at recovery*[118].

The observed *rapid* increase of MeV electron flux inside of geosynchronous altitude cannot be accounted for by the *relatively slow* diffusion of solar wind plasma. The "Dst effect" *alone* cannot account for this process either, since the electrons reappear at much higher fluxes than before the storm. Electron fluxes are therefore likely enhanced at L=11 before being transported inwards. Daily variations of MeV electrons are modeled successfully under that assumption[121], but it is unclear whether such an electron source is indeed present beyond geosynchronous altitude at storm recovery.

The instantaneous radial profile of the electron flux at constant μ and the transport process fully determine the evolution of the outer belt. But no single satellite traversing the equatorial radiation belt and its sources (i.e., L-values from 3.5 to 11) can measure the radial profile of the electron fluxes faster than once per ten hours, due to its orbital period. Low altitude (polar) satellites measure near-loss-cone fluxes and underestimate the true equatorial flux value which peaks at 90^o at active times. Multiple, eccentric, equatorial satellites are needed, displaced sufficiently along their orbit to provide repetitive cuts through the radiation belt. MMS spacecraft are too closely spaced for such a task; they will move together through the belt region.

THEMIS probes traverse the inner magnetosphere from L=3.5 to L=11 with a median recurrence rate of 3.8 hours. Thus, *THEMIS will determine the radial profile of the electron phase space density at constant* μ*, on a time scale commensurate with the storm-time radiation belt MeV electron loss and re-appearance.* Based on the slope of the obtained flux profiles with L-shell, *THEMIS will determine whether there is a sufficient source of electrons at the outer boundary.* If the answer to this question is affirmative, THEMIS will identify the primary transport mechanism. The Dst-effect will be readily evaluated from individual radial flux profiles. The radial diffusion coefficient will be obtained from first order differencing of consecutive profiles while the plasma convection will be directly measured on each probe. *If radial transport alone cannot account for the MeV electron enhancement*[122]*, THEMIS, equipped with comprehensive fields instrumentation, will determine whether other proposed mechanisms (e.g., waves) are responsible for local electron heating.*

Finally, THEMIS's ground observatories and its tail flow monitor P2 along with the radiation belt monitors P3, P4 and P5 promise to advance our knowledge on storm-substorm[123] relationships.

i. Dayside (Tertiary objective).

Observations near the equatorial magnetopause provide strong evidence for the predicted signatures of transient solar wind-magnetosphere coupling, namely fast flows[124] and flux transfer events (FTEs)[125]. These may be either triggered by solar wind features[126] or occur in response to intrinsic instabilities[127]. A number of other externally driven transient phenomena also contribute to the variations observed on single spacecraft. *Efforts to discriminate between the causes of magnetopause transients and determine the significance of each phenomenon to the solar wind-magnetosphere interaction have been hampered by several obstacles:*

First, observations near the L1 point or several 10s of R_E off the Sun-Earth line are of limited use because solar wind features transverse to the Sun-Earth line are on the order of ~20 R_E[128,129] and lag time uncertainties increase with distance[130].

Second, foreshock and magnetosheath processes affect the magnetopause. These cannot be observed within the pristine solar wind[131,132] (Figure E-11) and must be observed in place. Examples are: Hot flow anomalies transmitted across the bow shock[133,134] and sheath[135,136]; externally-driven, propagating slow shocks[137] or standing slow shocks[138] in the magnetosheath.

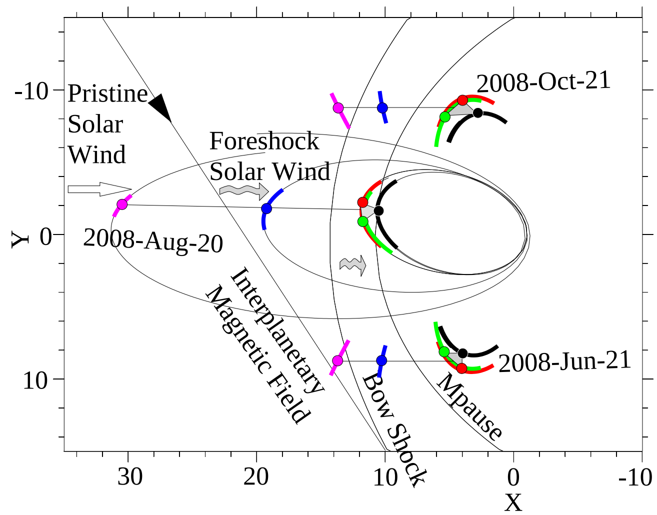


Figure E-11. *Same as in Fig. E-5 but for the dayside equatorial magnetosphere.*

Third, the significance of individual events depends upon their azimuthal dimensions. FTEs range from 0.5 to 5 R_E[139]. Events with similar features include solar wind/foreshock pressure-driven waves[140] or Kelvin-Helmholtz[141] waves.

Thanks to its unique Sun-Earth aligned probe conjunctions (Figure E-11), THEMIS will overcome the aforementioned obstacles and decisively determine the response of the coupled dayside solar wind-magnetosphere system to varying incident conditions. With particle and magnetic field instrumentation similar to that flown on AMPTE/IRM, THEMIS probes P1 and P2 will not only characterize the solar wind but also will determine its modification within the foreshock[135,140]. Hundreds of hours of conjunctions will enable us to conduct statistics of event occurrence patterns and characteristics as a function of the solar wind conditions.

An observation strategy that simultaneously optimizes the nightside second year observations and the dayside observations (Section E3.b) calls for P5's dayside apogee to be at 13R_E during the 1st year (T_{P5}=9/8*$T_{P3,4}$ ~ 27hrs) and at 11R_E during the 2nd year (T_{P5}=7/8*$T_{P3,4}$ ~ 21hrs). Four probe conjunctions recur every 4 days and five-probe conjunctions recur once per 8 days. This permits exploring the *flank* magnetopause/magnetosheath interaction the first year and the *subsolar* magnetopause/magnetosheath interaction during the second year of the investigation.

Probes P3 (or P4) and P5 will discriminate between standing waves and time-dependent shocks propagating through the sheath in response to upstream features measured by P2. Probe pairs P3 (or P4) and P5, monitoring the magnetopause over scale sizes from 0.5 to 6 R_E will determine the propagation direction, speed and azimuthal dimensions of transient events. Aided by global MHD modeling the THEMIS team will use simultaneous magnetosheath (P3, P4 or P5), and solar wind (P2 & P1) observations to determine the ultimate triggers of these events along the solar wind streamlines. The combination of P5 and P3, P4 monitoring simultaneously the magnetopause and adjacent magnetosheath will validate previously used remote sensing techniques (e.g., Walthour et al.[142]) and enable a systematic survey of transient events at the magnetopause, in both THEMIS's and in previous datasets. Thus, *THEMIS will establish the nature, cause and extent of magnetopause transient events.* Whereas MMS and CLUSTER will define the internal structure of individual magnetopause reconnection events, *THEMIS will provide the context in which they occur, identify the trigger (if any), and determine their significance to the solar wind-magnetosphere interaction.*

j. The Need for the Investigation in Light of Past, Present and Future missions.

Past missions. Rare, fortuitous spacecraft alignments have led to contradictory answers because of unoptimized satellite locations or inadequate instrumentation[34].

Present missions. CLUSTER due to its orbit cannot study the equatorial region where auroras map (10R_E, nightside plasma sheet). Upcoming tail-aligned conjunctions between POLAR (9R_E) and CLUSTER (19R_E) are limited to <27hours, only in 2003 (δMLT>1.5hours in other years) due to the different precession of the orbits; for those POLAR does not provide multi-point measurements at 9R_E.

Relationship to MMS. While THEMIS makes the macroscale measurements necessary to study the substorm instability, MMS will be making the micro- and meso-scale measurements to address physics of plasma boundaries, in general, and magnetic reconnection in particular. As evident from Figure B-2 THEMIS is complementary in scale-size and temporal resolution to MMS's planned 3-month survey of the 10R_E magnetotail region[144].

There MMS will advance our understanding of some of the micro/meso scale phenomena involved in the substorm process from complementary scales to THEMIS's macroscale vantage point. However, there is no provision in MMS for a simultaneous downtail monitor that would place these in a global substorm context. While MMS studies reconnection at $25R_E$, THEMIS does not visit that region locally and aims at remotely sensing Rx onset time to identify the role of lobe flux dissipation in substorm onset. Only one of many candidate substorm models advocates that Rx is the trigger of substorms (NENL), while all others advocate that Rx is either an immediate effect, or a parallel independent process. In summary MMS and THEMIS are independent, self-sufficient and fully complementary.

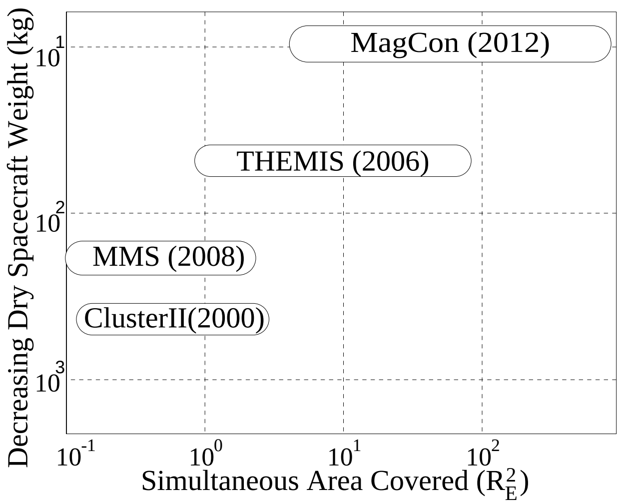


Figure E-12. *Evolutionary process of SEC missions. THEMIS expands SEC's capability to effectively monitor simultaneously an increasing volume of space. While utilizing existing technologies it provides a much needed heritage for microspacecraft design, deployment and operations.*

Future missions. MMS cannot address the substorm onset, global evolution and cross-scale coupling problem because it lacks the large baseline measurements needed. The Magnetospheric Constellation mission is expected to study global transport phenomena (including substorms) over a range of scales similar to THEMIS, but will lack the complete instrumentation afforded by a small fleet of satellites and necessary to link local instabilities to global interactions. THEMIS's unique science goals and mission design presents the only viable candidate for resolving the important substorm problem. THEMIS is an evolutionary step between Cluster / MMS and MagCon (Figure E-12).

k. History and Basis for the Proposal.

The THEMIS team has been improving its observation strategy since 1996. It originally proposed a UNEX mission (QUATRO) with minimal instrumentation and a piggyback launch. It received excellent science reviews but was deemed inappropriate for the UNEX category. The mission was proposed under a SMEX opportunity as a dual-launch on a Delta-II. It received excellent technical evaluation but the instrumentation suffered from a one-dimensional electric field measurement. The major and minor recommendations of the SMEX proposal can only be addressed adequately with a MIDEX class mission. More specifically: 1) THEMIS probes now are equipped with 3 dimensional electric field sensors. This measurement is aided by the following three factors: *First,* a phasing of the tail investigation during the winter season over North America when the dipole tilt is large and the magnetic field is at a large angle to the spin plane. *Second*, following traditional practices that minimize sphere shadowing by the spacecraft we choose an angle between the spin and the ecliptic normal of 10^o. *Third,* observations are made at and near 6:30 UT, at a time of day when the Earth's magnetic dipole tilt is maximum i.e., 11^o. As explained in Section E3.a4 at all times of interest (tail observations) the angle between the instantaneous magnetic field and the spin plane will be 10^o-30^o. Thus, the traditionally elusive spin axis component of the DC **E**-field can be accurately inferred at P3, P4 and P5 also from the spin plane components. 2) The same orbit phasing responds to a recommendation for ground onset determination. 3) A recommendation to directly monitor the Rx process simultaneously with the CD region is addressed by bracketing the Rx site with THEMIS probes P2 and P1. The MIDEX AO permits a comprehensive science implementation, a high reliability approach, a dedicated launch vehicle, and a fault tolerant mission design.

g. Baseline mission overview.

THEMIS will achieve its goals in two years using five identical spacecraft (*probes*) routinely measuring in-situ the electric and magnetic fields at 32 vectors per second and ion and electron distributions once every three seconds (spin period). The five probes will be placed in near-equatorial, highly eccentric orbits with apogees between 10 & 30 R_E.

Choice of orbit. The orbit strategy follows naturally from the requirements of Section E1.e. Probes are tabulated in Figure E-1/B_{III}.

In the 1st tail season, P1 has apogee ~$30R_E$ and a ~4 day period, while probe P2 has apogee ~$19R_E$ and a ~2 day period. Once per 4 days these probes align near apogee and bracket the reconnection site. Probes P4 and P3 have apogees at $12R_E$ and differ in their mean anomaly by 5^o such that at apogee they are separated by ~$2R_E$. At or near apogee these probes routinely monitor the CD using the finite gyroradius technique. The third innermost probe (P5f, or fast) has an apogee of $10R_E$ but during the first tail season it has a faster-than-synchronous period, gaining 6hrs/day along is orbit relative to P3, P4. Once every four days the inner probes cluster near apogee. Cross-tail separations between P3/4 and P5f range between 0.3 and 10 R_E permitting studies of low frequency MHD modes. Additionally, P5 is given an inclination change of 5^o relative to P3,4. This affects little the apogee conjunctions during the 1^{st} tail season, when the argument of perigee (APER) is small, but creates the inner probe Z-separation in the 2^{nd} tail season, when APER is large (inner probes drift by ~90^o/yr due to J2 terms).

In preparation for 1^{st} year dayside observations P5's apogee is raised to ~$13R_E$ with the same perigee, thereby increasing its period T_{P5} to 9/8 $T_{P3,4}$. Now, P5 monitors the *magnetosheath* near the flanks, whereas P3, P4 monitor the magnetopause. P5 becomes P5s (for sheath). Orbits recur near the flank magnetopause once per 8 days.

Prior to the 2^{nd} year tail season, P5's apogee and mean anomaly are made identical to P3, P4's by a perigee maneuver at the appropriate time. P5's inclination difference (5^o) relative to P3/4 and the common inner probe APER (~90^o) ensures an ~$1R_E$ difference in the Z-direction between P3,4 and P5u (up). This permits studies of the thin cross-tail current during substorms. P5 becomes P5u (up).

Prior to the 2^{nd} year dayside season, P5's apogee is reduced to $11R_E$, (same perigee), thereby decreasing its period T_{P5} to 7/8 $T_{P3,4}$. The 2^{nd} year probe conjunctions recur at the magnetopause once per 8 days again, just like in the 1^{st} year, but P5 is the *magnetopause* monitor at the subsolar region, whereas P3,4 are the *magnetosheath* monitors. P5 becomes P5p (for pause).

Measurements. The primary science objectives call for 3D measurements of thermal ions and electrons at 3s resolution, and magnetic and electric fields at 12vectors/s resolution. Additionally superthermal ions and electrons along the spin plane are required, for CD and Rx timing. Sensitivity should permit differential measurements of average cross-tail current, pressure gradients and flow vorticity to within 10%. Since inter-probe distances are planned to be comparable to the variation scale-lengths of B ($0.5R_E$ in Z), P and V ($1R_E$ in X,Y) the plasma moments and magnetic field should be known to within 10%. This accuracy can be easily achieved by instruments flown on previous missions. THEMIS instruments are shown in Figure E-13. Requirements and adherence to them are summarized in the table inserts.

h. Baseline versus minimum mission.

THEMIS depends on four tail-aligned probe conjunctions and on cross-tail or cross-sheet probe pairs to address its main question. Science closure can be achieved by a minimum mission of four probes, in one year of tail crossings (Figure E-1/A_{II}). Inclusion of a fifth probe in the baseline mission reduces risk and increases science return. Lower risk comes from the fact that probe P3 (or P4) has sufficient fuel reserves to replace any other probe during the mission. Science increase from the fifth probe allows two-probe measurements in both X and Y dimensions the first year (Y and Z dimensions the second year). Additionally, THEMIS's primary science can be achieved, in principle[145], with a 3D, fluxgate magnetometer and a 2D, spin-plane, electric field measurement. The increased sensitivity of the SCM in the range of ~10Hz and above, and the robustness in mode identification through a 3D EFI experiment are descopes of the baseline mission.

E2. SCIENCE IMPLEMENTATION

The five spin-stabilized (T_{spin}=3s) probes carry identical instruments which exceed the requirements of the primary science objective. The guiding principles are: 1) Selection of existing, low power, low weight units, to ensure no new development costs. 2) Common instrument DPU (IDPU) electronics to maximize science and simplify interfaces, motivated by FAST. 3) "Common buy" parts procurement to minimize expenditures. 4) Significant foreign contributions in instruments and analysis, ensuring wide international community participation. 5) Rapid, web-based dissemination of data and IDL analysis code accompanied by a $4M guest investigator program to ensure maximum benefits for the US science community.

a. Instrumentation

THEMIS instruments are summarized in Table E-5. Detailed specifications and accommodation are provided in Figure E-13. The five high-heritage instruments are identical (or require minor modifications) to ones flown recently. Two of those (FGM, SCM) are provided by foreign institutions, two by UCB (EFI, ESA) and one is a collaboration between UCB and a foreign institution (SST). THEMIS builds on existing close working relationships of its team members with each other and/or

Figure E-13 THEMIS instruments: Performance & heritage (Foldout-2)

Search CoilMagnetometer(SCM) *Roux(CETP,France)*

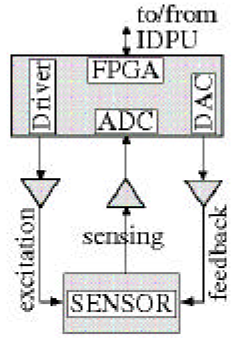
Performance	Req'ment	Capability
†Frequency range:	1-6 Hz	1 Hz-8 kHz
Sensitivity @10Hz	1pT/$\sqrt{Hz}$	<0.4pT /$\sqrt{Hz}$
Components	3D	3D
Requirements Accommodation in Rate/Range Wave-Captures (@16bits)		Routine: 4 Hz, full range Particle burst:128Hz ±15nT range Wave burst 1: 1kHz ±1nT range Wave burst 2: 4kHz ±1nT range
FFT Spectra: Range; δf/f Dynamic range		†16Hz-8kHz; ~50% (16 steps) 10^0-10^{-5} nT /$\sqrt{Hz}$
Mechanical	Dimension	Weight (gr)
Sensor	17cm×2cm	600
Pre-amps	7×4×2cm^3	200
Boom	1 m	500
Electrical		Power (mW)
Sensor Pre-amps		80*
Data Accumulation		Rate (bps)
Survey mode: RMS power (|**B**|, Bx,y,z @ 4 Hz)		192
Particle burst Bx,y,z@16bits, 128 Hz		6144
Wave Burst 1 Bx,y,z@16bits, 1024 Hz		49152
Wave Burst 2 Bx,y,z@16bits, 4096 Hz		196608
Particle, Wave Bursts 1,2 include FFT spectra (Bx,y,z) at 0.125-0.512s resolution, 16 frequencies		

† Nyquist frequency
*Filtering, digitization power accounted for in EFI system

FluxgateMagnetometer(FGM) *Auster(TUB,Germany) Schwingenschuh(IWF,Austria)*

A

Electronicsidentical toRosetta's

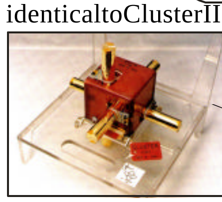


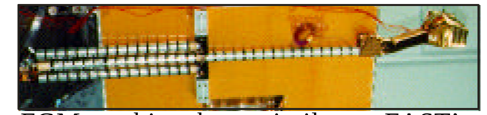
Sensor identical to Equator-S's & Rosetta's

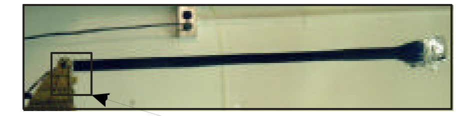
Performance	Requirement	Capability
Absolute stability	1nT	<0.8nT
Relative stability	<0.1nT	<0.05 nT
Resolution	<0.1nT	10pT
Noise Level at 1Hz	<0.1nT	5pT/$\sqrt{Hz}$
Orthogonality	<1°	<0.03°/120 days
Range. Science:	0-1000 nT	0-32000 nT
Frequency range:	DC-1Hz	DC-128 Hz
Mechanical	Dimension	Weight (gr)
Sensor	5×5×5 cm^3	70
Boom harness	2 m	30
Boom (deployed)	2 m	1200
Electronics	10×12 cm^2	120
Electrical		Power (mW)
Routine collection (@4Hz)		650
Burst collection (@128 Hz)		800
Orbit avg (75% burst enable)		<600
Data Accumulation		Rate (bps)
Survey (DC-2Hz & spin fits)		283
Particle Burst (@128 Hz)		8192
Wave Burst (@128Hz)		8192

E

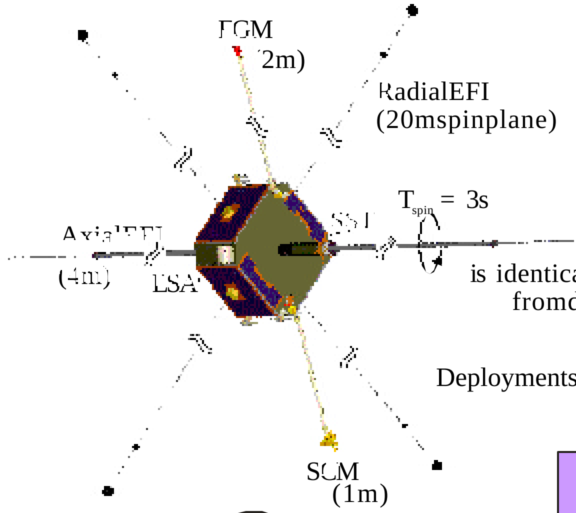
SCM sensor is identicaltoClusterII's



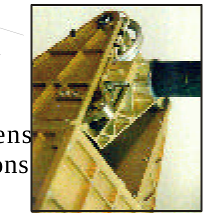




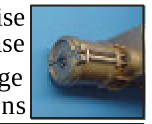
FGMtwo-hingeboomsimilar to FAST's



B

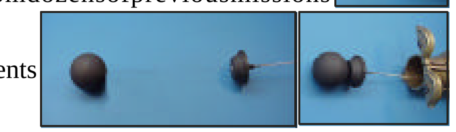


Thehingeand latchmecha-nismshave flownondozens ofpast missions



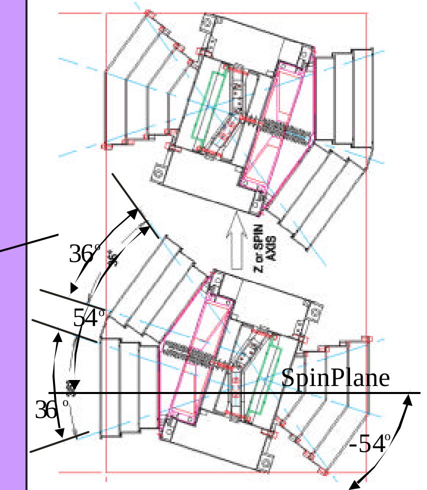
EFIcablestep-wise (unwind+respin)release is identicaltoClusteII's withheritage fromdozensofpreviousmissions

Deployments



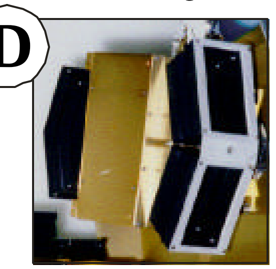
Ion&ElectronSolidStateTelescope(SST) *Lin(UCB);Escoubet(ESTEC,TheNetherlands)*

Performance	Requirement	Capability
Energy range, keV	i: 30-300 e: 30-100	i:20-6000 e: 25-1000
Energy Sampling: Resolution, δE/E:	i,e: 8,1 30%, 100%	Raw: i, e: 32 i,e: 20%; 15%
g-factor (cm^2 str) per detector	i: ~0.5-0.05 e: ~0.5-0.05	i: 0.11/0.005 e: 0.11/0.005
E-flux per detector, (keV/cm^{2}s str keV)	i: 10^2-5x10^6 e:10^3-10^7	i:5x10^{-1}-5x10^8 i:5x10^{-1}-5x10^8
Elevation×Azi-muth FOV, degrees	i, e: 45×45	Raw: i, e: 108×22.5
Solid angle @ Time resolution	Sun, Dusk, Dawn @ 10s	92%×4π str @3s
Mechanical	Dimension	Weight (gr)
Sensors & electron-ics (2 units)	15×17×5 cm^3	1200
Electronics (IDPU)	4×10 cm^2	70
Electrical		Power (mW)
Sensor Electronics		850
I/F Electronics in IDPU		200
Data Accumulation		Rate (bps or bsSpin)
Digitization×Angles×Energies		
Full distribution function (FDF): (8 bits × 48 angles ×16 energies) Averaged distribution function: (8 bits × 16 angles × 6 energies)		24576 bpSpin 1536 bpSpin
Survey data accumulation i,e averaged distribution/spin: 1 ion & electron FDF/16 spins:		 512 bps 512 bps
Particle Burst accumulation 1 electron, 1 ion FDF/spin:		 8192 bps
Wave Burst data rates same as Particle Burst		



SSTmountingandview angles

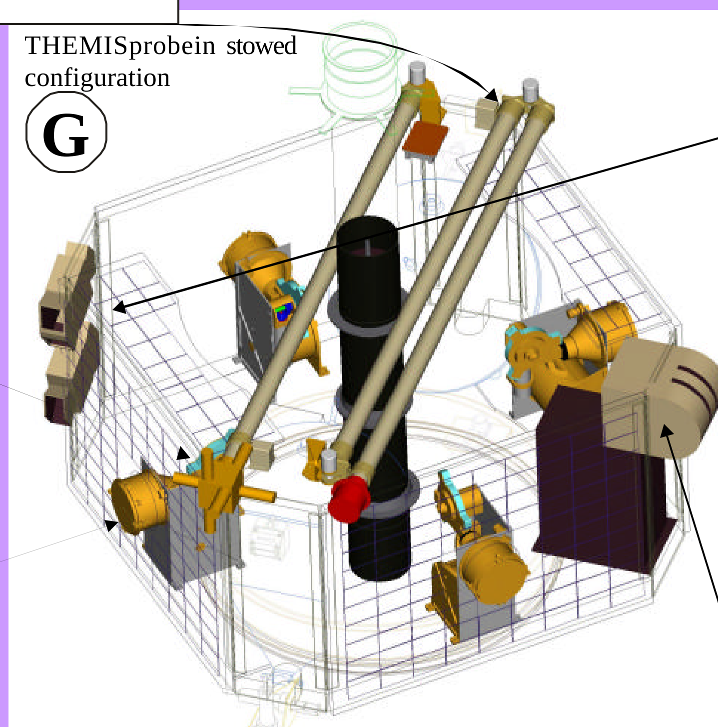
D



THEMIS's twoSSTpairs areidentical toWIND's

THEMISprobein stowed configuration

G



ElectricField Instrument(EFI), *Mozer(UCB)*

Mechanical	Dimension	Weight (gr)
Sensor	25×22×13cm^3	4 × 1750 (radials) 2 × 2000 (axials)
Digital Fields Board (in IDPU)	16×20 cm^2	360g*
Electrical		Power (mW)
Boom Electronics Board		2090
Digital Fields Board (in IDPU)		650
Data Accumulation		Rates (bps)
Survey mode **E** @ 16 bits×6 vectors/spin: 1 component spin fit: s/c V, Ne, HF RMS:		 192 27 64
Particle Burst **E** @16bits×64 vectors/spin FFT spectra at 0.5s res: s/c V, Ne, HF RMS:		 6144 1024 1024
Wave burst 1 waveforms: **E** @16bit×512 vectors/spin FFT spectra at 0.125s res: s/c V, Ne, HF RMS:		 49152 4096 12288
Wave burst 2 waveforms: **E** @16bit×2048 vectors/spin FFT spectra at 0.125s res: s/c V, Ne, HF RMS:		 196608 4096 61440

†Nyquist frequency
*Includes filtering, digitization for SCM instrument

EFIspin-planesensors identical toClusterII's. CommonIDPUresults insimplerelectronics, andlighterEFI housing.

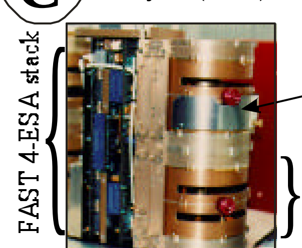
EFIstaggeredstacers are derived fromPOLAR's, but arelighter(shorter,no sphere)andsimpler(one lessstacerpersensor)

Performance	Requirement	Capability
†Frequency range	DC@10s/3D AC@ 6Hz	DC@3s/3D, AC@8 kHz,RMS @ 512kHz
Requirements accommodation in rate/range (16bits)		Survey: 6 **E**/spin ±640mV/m Particle burst: 128Hz ±150mV/m Wave burst 1: 32 Hz - 1 kHz Wave burst 2: 128 Hz - 4 kHz
FFT spectra Range; δf/f Dynamic range		 †16Hz-8kHz~50% (16 steps) 10^{-4}-10^1mV/m /$\sqrt{Hz}$
HF RMS (Log power)		100-500 kHz bandwidth @ max 8 kHz resolution

F

Ion&ElectronElectrostatic Analyzer(ESA)*Carlson(UCB)*

C



THEMIS's5(i,e)ESApairs,oneper probeareidenticaltoFAST's.FAST had8pairsarrangedin4stacks.

Performance	Requirement	Capability
Energy range, keV	i: 0.01-30 e: 0.01-30	i:0.01-40 e: 0.005-30
Energy Sampling Resolution, δE/E	e, i: 16 e, i: 50%	Raw: e,i:32 i: 20%; e: 15%
g-factor per anode (cm^{2}str keV/keV)	i: ~0.5-1.×10^{-3} e: ~0.1-0.5×10^{-3}	i: 0.875×10^{-3} e: 0.313×10^{-3}
Energy flux/anode (keV/cm^{2}s str keV)	i: 10^4-10^7 e: 10^5-10^8	i: 10^3-10^9 e: 10^4-10^{10}
Elevation×Azi-muth FOV, degrees	e, i: 180×22.5	Raw data: e,i: 180×11.25
Solid angle	4π str @ <10s	4π str @ 3s

Mechanical	Dimension	Weight (gr)
Sensor	14×14×18 cm^3	2020
Electronics (IDPU)	6×12 cm^2	150
Electrical		Power (mW)
Electronics (at sensor)		1870
Electronics (in IDPU)		600
Data Accumulation		Rate (bps or bsSpin)
i,e Full Distribution Function (FDF): (8 bits × 88 angles × 32 energies) i,e Averaged distribution function: (8 bits × 88 angles × 16 energies) i,e Moments (N, Vx,y,z, P-tensor) @ 16 bits:		45056 bpSpin 22528 bpSpin 416 bpSpin
Survey data accumulation Ion and electron moments/spin: 1 ion & 1 electron FDF / 16 spins		 138 bps 470 bps
Particle Burst data accumulation 1 ion, 1 electron FDF/spin		 15019 bps
Wave Burst data rate same as Particle Burst rate		

with UCB on Cluster, WIND, FAST, POLAR and Equator-S.

Instrument	Mass (kg)	Power (W)	Recent Flight	Insti-tute
FGM @ sensor	0.1	Equator-S		TUBS
FGM boom	1.2	Fast, Lunar Prospector		UCB
FGM @ DPU	0.3	0.8	MIR	IWF
ESA @ sensor	2.1	1.9	FAST	UCB
ESA @ DPU	0.3	0.6	FAST	UCB
SST @ sensor	1.3	0.9	WIND	UCB, ESTEC
SST @ DPU	0.1	0.2	WIND	UCB
SCM @ sensor	0.7		Cluster	CETP
SCM boom	0.5	Lunar Prospector		UCB
SCM pre-amps	0.3	0.1	Cluster	CETP
EFI (4) @ spin-plane	7.2	0.3	Cluster	UCB
EFI (2) @ axials	4.1	0.2	POLAR	UCB
EFI/SCM @ DPU	1.7	2.8	FAST	UCB
DPU process, compress & store	1.2	4.5	FAST, Lunar Prospector	UCB
Total	21.0	12.1		
Maximum expected	23.6	14.8		
Average reserve	13%	22%		

Table E-5. *Summary of each probe's instrument characteristics. Sensors include harness and MLI. Power includes power conversion and conditioning. Maximum expected values derived from grassroots, based on maturity level of each subsystem.*

a1. Fluxgate magnetometer (FGM)

A triaxial fluxgate magnetometer built to the heritage of units flown on AMPTE/IRM (1985), Phobos (1988), Interball (1992), Equator-S (1997) and MIR (1998) will measure the 3D ambient magnetic field. The sensor and electronics are identical to ones of the ROMAP instrument package delivered for the Rosetta mission (launch 2003), and similar to the ones flown[146] on Equator-S and MIR. The sensors will be built by TUBS, and the electronics breadboarding will be performed by IWF. The same team has delivered the ROMAP unit and has the expertise, and established working relationships to perform the task seamlessly. The flight electronics will be implemented at UCB. In-flight calibration will be performed by UCLA, deriving from Galileo and CLUSTER practices. The science requirements are to: 1) Measure DC and low frequency perturbations of the magnetic field, 2) Time wave and structure propagation between probes, 3) Provide information on plasma currents based on instantaneous magnetic field differences on two or more probes, separated by >0.2 R_E. Adherence to them is summarized in Figure E-13/A.

FGM specifications. The unit (Figure E-13/A) consists of two orthogonal ringcore elements of different diameter, made of an ultra-stable 6-81-Mo permalloy band (2mm×20μm), fixed within a bobbin. The unit is mounted on a 2 m double-hinge carbon epoxy boom with FAST and Lunar Prospector heritage (Figure E-13/B). The electronics consist of the driver and control circuits (Figure E-13/A), on a 10x12 cm^2 board within the IDPU. The controller controls digital excitation[147], data acquisition, feedback and compensation making the device low power. Its low noise permits easy intercalibration with the search-coil magnetometer at frequencies ~10Hz. Specifications and in-flight sensitivity are shown in Figure E-13/A.

Early establishment of a magnetic cleanliness program is commensurate with a low cost, high performance flight unit. THEMIS will benefit from the IWF, TUBS, UCLA and UCB experience in magnetic characterization, modeling and compensation of panel currents and latch valve/SST magnets.

FGM calibration. Although a 1 nT absolute accuracy requirement is achievable with independent sensor calibration, it is important to ascertain that two separate probes provide identical values when properties of the medium are steady. Once per orbit we will acquire calibration data at 32Hz to determine (on individual probes) zero levels, gains, and sensor orientation[148]. After Khurana et al.[149] we will also intercalibrate the magnetometers on all five probes during the early part of the mission (L&EO) using traversals of current-free (or low current density) regions of the magnetosphere. If the divergence-free approximation cannot be easily met then time-lagged data from probes traversing the same region will be compared for trend-recognition after long-term averaging.

a2. Electrostatic analyzer (ESA).

A "top hat" back-to-back pair of hemispherical ESAs will be built at UCB to the heritage of AMPTE/IRM, Giotto, FAST, Wind and CLUSTER, to measure the thermal ions and electrons. The proposed pair of units is of identical design to that flown on FAST (Figure E-13/C). It has geometric factors ideal for the fluxes expected at the THEMIS orbit. THEMIS's science requirements are to measure: 1) Plasma moments to within 10%, at high time resolution (10s or better) for inter-probe timing studies. 2) Instantaneous differences in velocity and ion pressure between probes, to estimate the scale size of transport, the size and strength of flow vortices and the pressure gradient. 3) Distribution functions of ions and electrons, to ascertain the presence of free energy sources. Adherence to those is summarized in Figure E-13/C.

ESA specifications. Both the ion and the electron ESA (Figure E-13/C) have a look direction of 180° in elevation, split in eight, 22.5° bins (one per anode). Measurements over a 4π str, are made once per spin as the probe rotates. The particles are selected in E/q (where q is the charge) by a sweeping potential applied in 32 steps, 32 times/spin (32 azimuths) between the outer (0 kV) and inner (~0-3 kV) concentric spheres and are focussed onto an MCP pair arranged in a Chevron configuration. The proposed ESA already has significant shielding to avoid MeV electron penetration and employs scalloping of both hemispheres for improved secondary-electron rejection. On-board moment, pitch angle and averaging computations are implemented at the IDPU. These operations routinely utilize FGM data and SST data (to ensure correct values when the peak flux extends beyond the plasma instrument energy range). An attenuator built to the heritage of a UCB-built (Lunar-Prospector) TiNi device, improves the P1, P2 ESA performance in the dayside seasons (Section E3.g).

ESA calibration. Science requirement of 10% accuracy on moment computation can be met by independent calibration of the ESAs. However by inter-calibrating hour-long averages of routinely-collected particle distributions during quiet-time probe-conjunctions we expected to surpass the accuracy obtained from independent ESA calibration.

a3. Solid state telescope (SST).

A solid state telescope unit, built by UCB to the heritage of ISEE1/2/3 and WIND (Figure E-13/D) will measure the super-thermal part of the ion and electron distributions. The detectors are identical to the SST telescope pairs flown on WIND[150]. Each probe carries two such pairs. The SST geometric factors are optimized for THEMIS. The electronics are comprised of miniaturized hybrid electronics on a VLSI chip, developed for ESTEC by a commercial outfit. The chip is undergoing testing at ESTEC and will be delivered for flight on the IMPACT/SEPT telescopes on Solar Stereo in March 2003. ESTEC has been a traditional collaborator of UCB, with most recent joint work on WIND/3DP in similar roles to the ones proposed herein. The primary science needs for the SST are: 1) To perform remote sensing of the tailward-moving current disruption boundary (at P3, P4, P5). 2) To measure the time-of-arrival of superthermal ions and electrons (30-300 keV, at 10s resolution or better) during injections, and ascertain the Rx onset time (P1, P2).

SST specifications. Each double-ended telescope unit is equipped with three stacked, fully depleted, passivated, ion-implanted, 1.5 cm² silicon detectors (Figure E-14). The center (T) detector is 500 μ thick, while the outside (O & F) detectors are 300 μ thick. The two detector pairs are mounted such that two telescope units point on the spin-plane (~ecliptic), one points above and the other below the spin-plane. One of the two spin-plane telescopes has detectors of area 0.075cm² and provides a geometric factor 20 times smaller that all the others to ensure no saturation at times of very high flux levels near the radiation belts. Specifications are tabulated in Figure E-13/D.

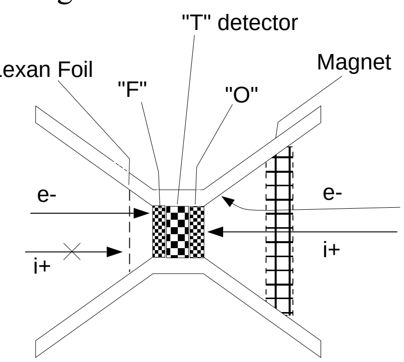


Figure E-14. *SST telescope operation.*

UV avoidance, i.e., the requirement that sunlight is to remain >7° away from the field of view (FOV), is guaranteed for the up- and down-looking telescopes with a tolerance of ±11.25° by virtue of the mounting angles (Figure E-13/D). For the spin-plane-mounted, large geometric factor detector fast recovery electronics (100 ns) ensures that no more than 2 sectors will be UV-saturated. This approach was successfully implemented on WIND. The spin-plane, low geometric factor ion detector is covered by a 1300Å Lexan foil with 900Å of Al deposited on either side, preventing direct sunlight from hitting the detector, while still enabling >30keV ions to be detected.

SST calibration. Absolute calibration points are determined by monitoring the highest energy of protons stopped and by placing the pairs (or triplets) of detectors in coincidence and monitoring the minimum ionizing energy for penetrating particles. Such practices have led to superb agreement between SST and ESA fluxes on WIND, and result to <10% absolute flux uncertainty. Inter-probe calibration will also be performed at times of low plasma sheet activity, when the flux anisotropy is low.

a4. Search coil magnetometer (SCM).

The SCM instrument built by CETP to the heritage of GEOS 1&2, Galileo, Ulysses, Cassini, Freja and CLUSTER will extend with appropriate sensitivity the measurements of the FGM beyond the 1 Hz range. The sensor (Figure E-13/E) is similar to the one flown on the CLUSTER/STAFF instrument and identical to the one flown on Interball, while its electronics are a simplification of the ones flown on the FAST IDPU. The science requirements derive from the need to measure with appropriate sensitivity (<$1pT/\sqrt{Hz}$ @ 10Hz); the cross-field current disruption waves (~$0.1f_{LH}$) at least as close to Earth as $8R_E$ (f_{LH}=60Hz). Adherence to those is summarized in Figure E-13/E.

SCM specifications. The SCM measures the variation of the magnetic flux threading three orthogonal high permeability μ-metal rods. The unit sensitivity is $0.5pT/\sqrt{Hz}$ @ 10Hz. A flux feedback loop is employed to ensure phase stability. The tri-axial sensor is mounted on a single-hinge, 1m graphite epoxy boom (Figure E-13/B) identical to the one flown on Lunar Prospector. The unit specifications are shown in Figure E-13/E. The signals from the three sensors are pre-amplified and then processed together with EFI data at the IDPU. The IDPU consists of one analog and one digital board. The analog board serves primarily the **B**- and **E**-fields processing and includes the SCM pre-amplifiers. The analog signal is pre-amplified and then filtered (together with the E-fields signals) and processed for routine waveform (DC-32samples/second) and for burst waveform (128Hz-8kHz) production. The Digital Signal Processor (DSP) takes 2^n continuous segments (n=0...7, commandable) of 1024 data points and performs FFTs of the data and subsequent averaging in frequency. Consecutive spectral averaging reduces noise further. These operations represent a rather small subset of the fields signal processing of the FAST IDPU; they can be implemented by low cost, rad-tolerant parts. Specifications are detailed in Figure E-13/E.

SCM calibration. Absolute amplitude and phase calibration takes place with calibration coils that create a known AC pseudo-random noise consisting of a series of discrete frequencies covering most of the bandwidth (10Hz-8kHz). Calibration switch-on is commanded by the DPU according to a pre-scheduled sequence. This procedure has negligible power and weight requirements and has been applied successfully on previous missions.

a5. Electric field instrument (EFI).

A three dimensional EFI experiment consists of 4 spin-plane spherical sensors each on a 20m deployable cable and 2 axial tubular sensors, each 1m-long and mounted on a 4m-long stacer element. The experiment is built by UCB to the heritage of S3-3, ISEE1, CRRES, POLAR and CLUSTER. The 8cm diameter spherical sensors (Figure E-13/F) are identical to the ones delivered for flight on the CLUSTER II satellites. The axial, two-stage stacer elements are identical to ones used on POLAR, FAST and rockets. The 1m long, 2mm diameter, stowable tubular sensor is of the standard STEM line built by commercial outfits (Orbital/TRW/AEC-ABLE). The sensor electronics are simplified versions of the CLUSTER design. THEMIS's simpler science and instrument interface requirements result in considerable volume, weight and power savings. The (digital) fields processing electronics are a simplified version of the FAST electronics (see SCM section). The proposed spin-plane sensor incorporates a design improvement flown on the CLUSTERII-EFW experiment: the insertion of a thin wire between the hockey-puck stub and the sphere sensor. This wire increased the CLUSTERII-EFW sensitivity (tenfold) relative to previous designs. In-flight performance data show that a wire length twelve times the spacecraft diameter is sufficient to guarantee high sensitivity electric field measurements. THEMIS baseline has wires 20 times the probe diameter. The proposed use of a tubular element, instead of a sphere, along the axial direction is afforded by the symmetry of the probes which are spinning nearly on the ecliptic plane. This design permits longer, lighter axials while the tube's thinness at its base minimizes photoelectron interaction with the stacers.

The primary science requirements are derived from the need to determine at the times of onset at 8-10R_E: 1) The plasma pure convective motion, i.e., without the effects of diamagnetic drifts that ESA measurements are subject to. 2) The low frequency (T~1min) wave mode and Poynting flux. Adherence to these is summarized Figure E-13/F.

The **E**·**B**=0 approximation, commonly used at low frequencies to derive the third electric field component is ideally applicable for the THEMIS conditions at the primary region of interest (8-10R_E). The approach is error-free when **B** is away from the spin plane by >10^o. As explained in Section E3.a4, the nominal angle between B and the spin plane will be ~20^o. Thus even under extremely thin plasma sheet conditions the inner probes will determine the axial component independently from the axial boom measurement and provide both a method for calibration of the axial measurement and a backup solution.

EFI specifications. The preamplifier electronics for the wire sensors are housed inside a hockey-puck arrangement, which also acts as a stub for the wires (Figure E-13/F). The deployment mechanism is identical to CLUSTER's but packaging is analogous to FAST due to the reduced volume requirements of the THEMIS EFI experiment. The sphere and stub release is shown in Figure E-13/B.

The boom electronics, located at the EFI housing, perform stub and guard voltage control and sphere-biasing. Signal processing takes place in the IDPU, together with the SCM. Routine waveforms (at 32samples/s) or burst waveforms (at 128 - 8192 samples/s) are captured and processed just as for the SCM data. Spectral processing of the low frequency (<8 kHz) data occurs in the DSP in a fashion identical to the SCM. The wire booms will be deployed with near real-time monitoring of a release and spin-up sequence, each lasting 1-2 hours / probe. Alternating between different THEMIS probes in science and sphere-release phase, mission-total EFI deployment lasts <10 days.

EFI calibration. The aforementioned individual probe calibration results in absolute DC measurement accuracy of 0.1 mV/m, i.e., <10% of the field value anticipated during fast flows. Increased confidence in the measurements will be obtained from inter-spacecraft calibration at quiet times.

a6. Ground observations.

The comprehensive THEMIS approach to solving the substorm problem calls for monitoring the nightside auroral oval with fast (<1s exposures), low cost and robust white-light imagers and high-time resolution (1s) magnetometers. The ASIs will be provided by UCB based on its recent experience with the Automated Geophysical Observatories (AGOs) deployed in Antarctica, while the magnetometers will be provided by UCLA based on its recent experience with the UC-LANL, MEASURE, SMALL ground magnetometer networks. Our choice of sites and instruments complements existing CANOPUS all sky stations which carry multiple filters, and space-based platforms which might be available in 2006 (IMAGE, TIMED, LWS). Proposed THEMIS stations are shown in Figure E-8. Additional dual-purpose (EPO and scientific) mid-latitude THEMIS magnetometer stations will complement the existing mid-latitude network. The proposed deployment in Canada will receive on-site technical personnel support and maintenance from the University of Calgary (UC), based on its experience with the ongoing NORSTAR all sky imager network deployment, and from the University of Alberta (UA) based on its CANOPUS experience.

The proposed deployment along with substantial contributions from ancillary ground magnetometer networks (see Section E3.i) result in a ground station density that surpasses mission requirements.

b. Mission Design.

Data accumulation. An average of ~750 Mbits per day will be collected (Table E-6). Existing methods for instrument-specific loss-less compression will be applied to reduce data volume by a factor of two (<375 Mbits). Baseline primary science can be accomplished with routine data accumulation. High-time resolution particles & fields datasets are afforded by the particle burst mode.

Burst mode can be of two types: *particle* or *wave*. Particle bursts collect high resolution distributions and low frequency waveforms. They aim at capturing the components of the global magnetospheric substorm instability (-5min to +10min from burst trigger). They will be triggered by local plasma conditions. Since substorms occur ~10% of the time (15min collection / 3hr substorm recurrence time) which is similar to the occurrence rate of bursty flows[33,29] and current disruption in the region of primary interest (X>-13R_E) our memory allocation of 15% of the observation time to particle bursts leads to full coverage of all surge intervals by this mode. *Wave* bursts are intended to capture the **E&B** field waveforms of the waves anticipated within the disruption region. Broadbanded low frequency waves occur nominally 10-20% of the bursty flow time (and proportionately less at higher frequencies). Memory allocation to wave bursts (10% of the particle burst time) results in waveform accumulation during most onset-related waves.

	Routine Accumulation Mode t_R=80% t_{total}	Particle Bursts: For 24hr orbits: t_{PB}=15% t_{total}	Wave Burst Mode t_{WB}=10% t_{PB}	Total
Collection, hrs	19.2	2.88	0.432	19.2 hrs
FGM, bps	283	8192	n/a	91 Mbits
ESA, bps	608	15019	n/a	151 Mbits
SST, bps	1024	8192	n/a	97 Mbits
SCM, bps	192	6144	49152	204 Mbits
EFI, bps	283	8192	65536	204 Mbits
Total (Mbits)	165	439	119	735 Mbits

Table E-6. *Data volume/orbit (uncompressed). For P4/P3/P5f, particle bursts occur 15% of the time. For P2 and P1, bursts occur only during days/times of tail-aligned conjunctions.*

Data collection. The THEMIS tracking needs (1370 passes/year) will be met primarily by the 11m UC Berkeley ground station BGS (1030 passes/year). USN station Perth has been budgeted as secondary (240 passes/year). Downlinks not feasible during high priority orbits at the standard transmission bit-rate will be (i) stored on board for transmission at the next contact (10 orbits/yr) (ii) downlinked on longer range, lower bit-rate sessions (90 orbits/yr).

Spacecraft performance. The requirements are outlined in Figure E-1/A_I. Absolute spin stability (and knowledge) is required to within 1^o (for current sheet measurements). The SST instrument performance spin control (ACS) to within $\pm 11.25^o$ from the ecliptic normal is derived from the need to maintain solar UV more than ~7^o away from the top and bottom SST fields of view. No attitude, but some orbit conditioning (i.e., to phase appropriately the probe mean anomalies) is required prior to each tail- and dayside- mission phase.

Mission operations concept. Data are stored on-board and dumped over a several-hour-long window of opportunity near perigee. After an early post-launch check-out period, operations are automated. Commands and time are uplinked and instrument health status downlinked once per contact (1-4 days). No real-time data link is required. The dataset is stored locally and transmitted over a dial-up ISDN line, or over the internet. This is the scheme employed on FAST. An on-call operator responds to automated paging if housekeeping data are beyond limits.

Mission operations requirements. Position knowledge is required at 10% of minimum inter-probe separation in science regions. This amounts to knowledge within 100 km, which is easily achievable using the on-board transponder for 2-way coherent ranging.

Launch and lifetime. THEMIS's baseline mission calls for a 2-year lifetime. The inertial pointing of the probes during ascent has a power-positive configuration and a healthy link margin at all epochs, resulting in no seasonal restrictions on launch date. Nominal launch date is August 21, 2006, i.e., four months prior to the prime mission phase.

c. Analysis and Archiving

Data flow. Level-zero processing at the science operations center extracts housekeeping information and produce simplified level zero ".cdf" files containing individual instrument data. Daily automatic processing will produce "level 1" calibrated data files within 3hrs of downlink. Science team validated data will be updated daily on the web along with standardized-format plots (.gif and.ps). Data will also be sent in CDROM format to co-I sites and for archival to NSSDC monthly. These practices are identical to the FAST handling. Inter-probe calibration will be performed in the early mission phase to confirm individual probe calibrations, but will be part of the data analysis efforts thereafter, so as to not hold up data dissemination.

Analysis software. Four IDL-based software suites are proposed: (1) *Single probe analysis software,* is directly transferable to THEMIS from FAST and WIND analysis. (2) *Multi-point data analysis software from* ISTP and CLUSTERII analysis to compute the flow shear/curl and pressure gradient along with their standard error will be directly implemented or modified for THEMIS. (3) *Ancillary data software.* An existing distributed database of such data will be upgraded with IDL decommutators for plotting them seamlessly relative to THEMIS quantities. These will include ground magnetometers, all sky cameras, ancillary ground chains and solar wind data. (4) *Event modeling.* IDL codes that fly virtual probes within simulation run results under specific, idealized solar wind external conditions already exist and will be fine-tuned for THEMIS use. A library of event-specific MHD, hybrid and kinetic simulations will be assembled for useful conjunctions, enabling quantitative comparisons between models and observations.

Community participation. The PI and co-Is are integral parts of the vibrant substorm, GEM and ISTP communities. They intend to spare no effort in engaging and facilitating the optimal use of the THEMIS dataset by their colleagues. A $4.0M for a guest investigator (GI) program and for non co-I training in analysis tools is planned so as to enhance the US community productivity under this GI or future SR&T programs. The active involvement of the international community through instrument and data analysis contributions further guarantees maximal THEMIS data utilization.

d. Science team

Table E-7 describes the science team members, roles, most recent pertinent experience and funding sources. At UCB, **V. Angelopoulos** will lead the science team as PI, based on his experience in magnetotail data analysis and theory over the last 12 years. He will ensure that the decisions taken during mission development will be in the best interest of science and will meet the mission objectives. The PI will lead the magnetotail data analysis efforts. Individuals responsible for instrument development are named in Figure E-13/A-F. Their experience from previous projects is detailed in Table E-7; their respective institutional heritage is described in the first paragraph of the corresponding instrument section (Section E2 a1-a5). Key instrument personnel at UCB are: **P. R. Harvey**, who will manage the EFI and SCM electronics development based on his experience in similar roles on CLUSTERII, POLAR and FAST; **D. W. Curtis**, who will advise the ESA, SST electronics development and the IDPU development based on his similar roles on FAST, Lunar Prospector, HESSI and STEREO; **R. Abiad** who will work on the design and detailed implementation of the IDPU, based on his experience in FAST, FUSE and HESSI; **D. Pankow**, who will manage the mechanical design and development of all instruments based on his similar experience on FAST and HESSI; **P. Turin**, who will work on the design and detailed implementation of the EFI, ESA and SST sensors based on his experience on FAST and HESSI; and **D. Larson**, who will be responsible for SST sensor development and ground calibrations based on his similar role on WIND and STEREO.

	THEMIS Team Member	Institution	NASA Mission Management	FGM	ESA	SST	SCM	EFI	Common IDPU	I&T, Operations and In-flight	Tail Science	Radiation Belt Science	Magnetopause Science	Theory/ Modeling	Ground Correlations	Most Recent Demonstrated Experience
NASA FUNDED																
PI	V. Angelopoulos	UCB	★								✔★				✔★	ISEE, IRM&CCE, Geotail
NASA funded co-Is/co-Es	C. W. Carlson	UCB	✔☆		✔★				✔★	✔★	✔★				✔★	FAST PI; CLUSTERII/CIS
NASA funded co-Is/co-Es	G. T. Delory	UCB						✔★	✔★	✔★						FAST, Alaska 99: PM
NASA funded co-Is/co-Es	R. P. Lin	UCB	✔☆		✔	✔★				✔☆	✔					HESSI, WIND/3DP: PI
NASA funded co-Is/co-Es	S. Mende	UCB													✔★	AGOs, IMAGE/FUV:PI
NASA funded co-Is/co-Es	F. S. Mozer	UCB	✔☆				✔☆	✔★		✔☆	✔★		✔★			S3-3, POLAR/EFI: PI
NASA funded co-Is/co-Es	G. Parks	UCB													✔★	Geotail; Polar; ClusterII
NASA funded co-Is/co-Es	T. D. Phan	UCB									✔★		✔★			Equator-S, ISTP
NASA funded co-Is/co-Es	M. A. Temerin	UCB									✔★	✔★		✔★		S3-3, POLAR, FAST
NASA funded co-Is/co-Es	K. K. Khurana	UCLA		✔						✔★	✔★			✔★		Galileo/MAG; Cluster/FGM
NASA funded co-Is/co-Es	M. G. Kivelson	UCLA		✔							✔★		✔★	✔★		Galileo/MAG; Cluster/FGM
NASA funded co-Is/co-Es	J. Raeder	UCLA									✔★		✔★	✔★		ISTP; MHD Codes
NASA funded co-Is/co-Es	C. T. Russell	UCLA		✔☆						✔★	✔★		✔★	✔★	✔★	ISTP; MEASURE; SMALL
NASA funded co-Is/co-Es	R. E. Ergun	CU					✔☆	✔☆	✔★	✔	✔					Rockets, FAST waves: co-I
NASA funded co-Is/co-Es	X. Li	CU										✔★		✔★		IRM; CRRES; SAMPEX; Polar
NASA funded co-Is/co-Es	A. T. Y. Lui	JHU/ APL									✔★			✔★	✔★	ISIS, CCE, Geotail,
NASA funded co-Is/co-Es	D. Sibeck	JHU/ APL									✔★		✔★			AMPTE/CCE, GOES, ISEE3
Instrument key persons	R. Abiad (EE)	UCB							✔★							FAST, FUSE, HESSI, ISUAL
Instrument key persons	D.W. Curtis (EE)	UCB			✔☆	✔☆			✔☆	✔☆						IRM, WIND/3DP, Cluster, FAST IDPU
Instrument key persons	P. R. Harvey (EE)	UCB	✔★				✔★	✔★	✔★	✔★						Cluster, POLAR, FAST
Instrument key persons	D. Pankow (ME)	UCB			✔★	✔★	✔★	✔★		✔★						LP, POLAR, FAST, HESSI
Instrument key persons	P. Turin (ME)	UCB			✔★	✔★	✔★	✔★								LP, POLAR, FAST, HESSI
Instrument key persons	D. Larson	UCB				✔★							✔★			WIND/3DP; Equator-S, STEREO
NON-NASA FUNDED																
	U. Auster	TUBS		✔★						✔★			✔★			MIR, Equator-S, Rosetta
	K.-H. Glassmeier	TUBS									✔★		✔★		✔★	Freja, CLUSTERII, Rosetta
Foreign co-Is	W. Baumjohann	IWF									✔★	✔★	✔		✔★	IRM, Equator-S, Geotail
Foreign co-Is	R. Nakamura	IWF									✔★	✔			✔★	Equator-S, Geotail, Sampex
Foreign co-Is	K. Schwingenschuh	IWF		✔★						✔★						Equator-S, Rosetta/ROMAP
Foreign co-Is	J. Buechner	MPAe									✔★		✔	✔★		Equator-S, Interball; PIC Codes
Foreign co-Is	O. Le Contel	CETP									✔★			✔★		CLUSTERII, GEOTAIL
Foreign co-Is	A. Roux	CETP					✔★			✔★	✔★			✔★	✔★	GEOS,CRRES, CLUSTERII
Foreign co-Is	E. Donovan	UC									✔★				✔★	NORSTAR(PI), CLUSTERII
Foreign co-Is	P. Escoubet	ESTEC				✔★				✔☆			✔★			WIND/3DP, CLUSTERII
Foreign co-Is	H. Laakso	ESTEC									✔★					POLAR/EFW, CLUSTERII/EFI
Foreign co-Is	M. Fujimoto	TITech									✔★		✔★	✔★		Geotail; Hybrid Codes
Foreign co-Is	C. J. Jacquey	CESR									✔★			✔★	✔	ISEE, Geotail, Interball
Foreign co-Is	D. LeQueau	CESR									✔★		✔★	✔★	✔	ISTP theory, CLUSTERII
Foreign co-Is	J. Samson	UA									✔★			✔★	✔★	ISTP-Canopus
Foreign co-Is	I. Voronkov	UA									✔★			✔★	✔★	ISTP-Canopus
Foreign co-Is	V. Sergeev	USP									✔★			✔★	✔★	Interball; ISTP; ClusterII
†	H. J. Singer	NOAA		✔		✔				✔	✔☆	☆				ISTP on Space Weather

†Unfunded Collaborator ✔Demonstrated experience ★Primary Function(s) ☆Advisory Role(s)

***Table E-7** Member roles and experience*

Additionally at UCB, team member **G. T. Delory** will be responsible for integration and testing of instruments with the IDPU, based on his experience in a similar role on the Alaska 99 rocket, where he was also the overall program manager; **S. Mende** will be responsible for developing the auroral ground imagers, based on his development of the AGO network; **T. D. Phan** an experienced magnetopause and magnetotail researcher (current experience: CLUSTERII), will also be responsible for analysis software development based on his similar role on Equator-S; while **M. A. Temerin** will lead the analysis of radiation belt data analysis efforts based on his 20 years of experience in radiation belt physics and wave-particle interactions.

At UCLA, **K. K. Khurana** will conduct FGM inter-calibration and data analysis (similar to his Galileo and CLUSTERII roles), **M. G. Kivelson** will study plasmoid/flux rope and sources of modulated flows based on her experience on Galileo and Geotail, **J. Raeder** will perform event-based MHD modeling deriving from his ISTP mission support and **C. T. Russell** will be responsible for ground magnetometer development and for space/ground correlative substorm studies. At CU, **R. Ergun** will design the IDPU fields processing, stemming from his experience on FAST, and **X. Li** will conduct event-based analysis and particle tracing for radiation belt physics as on CRRES and POLAR. At no cost to NASA foreign co-Is will participate in THEMIS data analysis geared towards various aspects of substorm physics phenomenology (**Baumjohann, Nakamura, Jacquey, Roux, Sergeev**), theory (**LeQueau, LeContel, Voronkov**) data analyses correlative with ground pulsations (**Glassmeier, Samson, Schwingenschuh**) and images (**Donovan**). Canadian co-Is will advise on development and support deployment of the ground stations. In addition to (and in conjunction with) Raeder's MHD simulations, co-Is **Buechner** and **Fujimoto** will conduct data-model comparisons using kinetic or hybrid simulations, based on their recent successful practices on Interball and Geotail respectively. Un-funded collaborator **Singer** will advise the team on space weather issues and Goes data usage.

E3. PHASE A SCIENCE IMPLEMENTATION TRADE STUDIES

The THEMIS science objectives have remained unchanged. Trade studies have optimized science return (50% relative to step-1 proposal, see Section E3) and reduced mission risk, as outlined below.

a. Center-tail target date.

The (1) best ASI viewing conditions and (2) the highest frequency of substorm recurrence must be traded against seasonal evolution of: (3) dark-sky duration at polar latitudes (4) magnetic field angle to the spin plane and (5) peak shadow.

a1. Cloud cover

Early winter months are notorious for cloudy skies in Alaska and Western Canada. Clear skies (Figure E-15) appear only after oceans freeze and dominate in mid- to late-winter months, with a peak in mid-February. This is a factor-of-two effect between mid-December and mid-February.

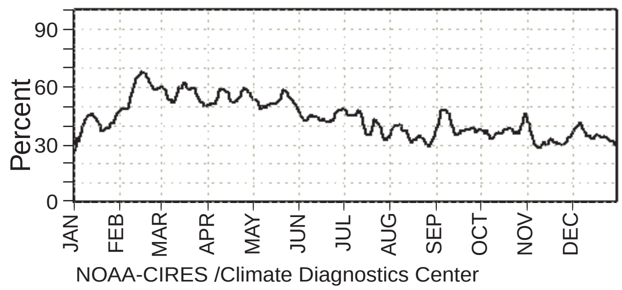


Figure E-15. *Percent clear sky obtained from 7-year records at Nome, Alaska.*

a2. Substorm recurrence

Auroral activity is well known[151,152] to depend on season. Direct evidence of activity recurrence is shown in Figure E-16 (R. Nemzek, private communication). This is a 50% effect from winter to spring. Interpolating we obtain a substorm recurrence of 3.75hrs in mid-February. Centering THEMIS tail observations in late (rather than early- or mid-) winter results in optimal yield of substorms.

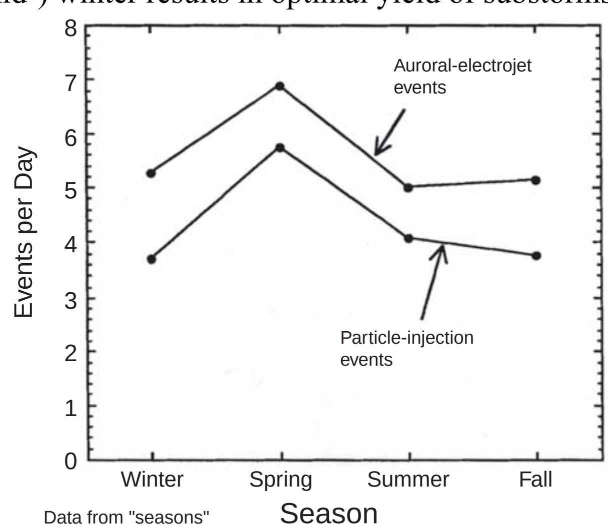


Figure E-16. *Substorm recurrence as function of season. Substorms are identified in AE (their seasonal trend also validated in injection database). Following the semi-annual trend evidenced[151,152] by auroral activity, substorm recurrence also shows a pronounced peak near equinox.*

a3. Night-time duration at polar latitudes

ASI observations necessitate dark skies (Figure

E-17). Of interest are geo*magnetic* latitudes of auroral breakup (65°-70°) which correspond to geo*graphic* latitudes of 55°-60°. Since substorms occur typically ±2hrs around 23:00MLT we require >6 hrs of useful mid-night-centered observations from each station. This happens between mid-September and end-of-April. Assuming a ±2month duration of THEMIS tail observation period we conclude that for ASIs to observe substorm onsets nominally the center-tail target date should before February 28.

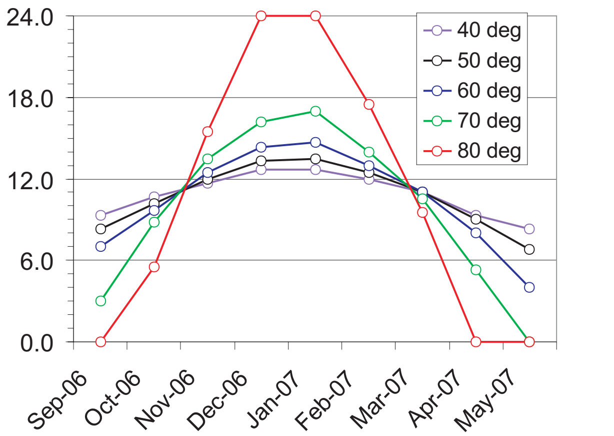


Figure E-17. *Night duration (defined as times when Sun is >10° below horizon) as function of season and geographic latitude over CANOPUS meridian chain (midnight at 6:30 UT).*

a4. Validation of the DC axial component of E.

Figure E-18 shows the instantaneous value of the angle between the spin plane and the magnetic field near apogee (mid-February center-tail target date). Prior to Apr. 21 this angle remains >10°, as required for a high fidelity reproduction of the axial component of the electric field from spin-plane components (see section E2.a5). This angle approaches the limiting case only at end of tail observation period when conjunctions are infrequent.

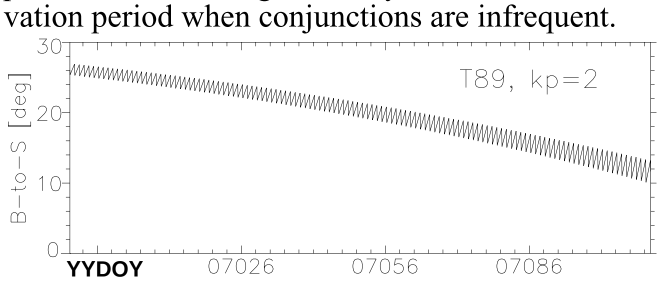


Figure E-18. *Tsyganenko model field angle to the spin plane near apogee as function of season, including satellite motion and an inertially fixed 10° angle of the spin-axis and the ecliptic normal.*

a5. Shadow duration

As the target center-tail date moves closer to equinox the Sun-Earth line gets closer to the equatorial plane; shadows of low-inclination orbits increase (Figure E-19). We seek target dates that minimize shadows and maximize conjunctions.

A given target date is characterized by the inertial location of the mission orbits' semi-major axis whose longitude, as it turns out, is least effected by lunar and L2 terms. That inertial longitude is measured by the Right Ascension of Perigee (RAP) which is the sum of the argument of perigee (APER) and the right ascension of the ascending node (RAAN). RAP is fixed for each target date (e.g., it is 330 degrees for Feb.-21).

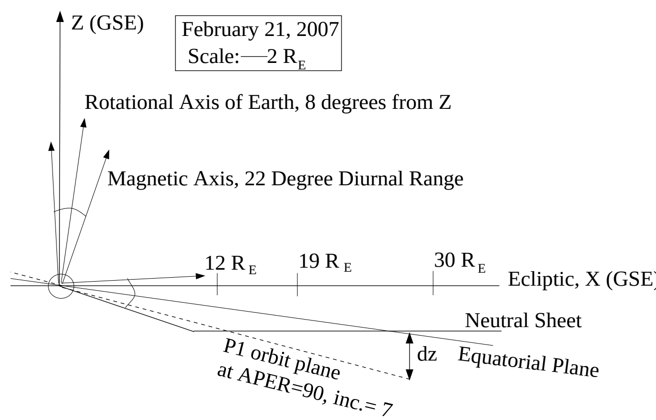


Figure E-19. *Schematic depicting observation geometry for Feb.-21, 2007 center-tail target date.*

P1 yearly peak-shadow [min] centered in winter of 06-07

RAAN[deg] / Target=	21-Dec	7-Jan	21-Jan	7-Feb	21-Feb	7-Mar	21-Mar
RAP=	269	285	298	315	330	345	180
0	100	125	150	190	250	310	340
20	140	180	235	310	345	305	240
40	160	215	275	330	305	240	185
60	150	205	270	325	305	235	175
80	135	180	250	330	320	250	190
100	115	160	215	270	320	275	205
120	100	130	175	265	330	285	205
140	85	110	145	210	260	290	260
160	80	100	120	160	225	305	315
180	75	90	105	145	195	280	335
200	80	80	95	125	165	235	310
220	90	75	90	110	145	195	260
240	100	80	80	100	125	160	215
260	120	90	75	95	115	155	205
280	140	105	85	90	110	145	185
300	155	115	95	90	110	135	175
320	160	120	100	100	115	145	185
340	145	115	100	120	150	185	240

Figure E-20. *Maximum yearly shadow for P1 (limiting probe case). RAP is APER+RAAN (ordinate). Abscissa is RAAN. APER is their difference. Orbits are integrated forward and backward using GTDS, including lunar, solar, geoid and atmospheric drag effects. For target dates ~Feb.-21 (RAP=330), peak-shadows are <180min for RAAN= 220° to 340° (i.e., for APER of -10° to +110°)*

Peak yearly shadows are comfortably below 180min under a wide range of APERs (see Figure

E-20). The number of shadows and the date of peak-shadow were also tabulated (not shown). For target dates near Feb.-21 and APER of -10 to +110 degrees shadows peak *after* Apr.-3, i.e., more than a month after the (prime) center tail observations. The low range (0^o-30^o) of that APER range for P1,P2 is compatible with high yields of neutral sheet conjunctions. (Any range of APERs for P3,4,5 is compatible with low shadows and high conjunction yields). Shadows represent <3% of the total dataset. The robust probe thermal design (Section F) ensures a passive thermal constant of 270min, well above predicted worst shadows.

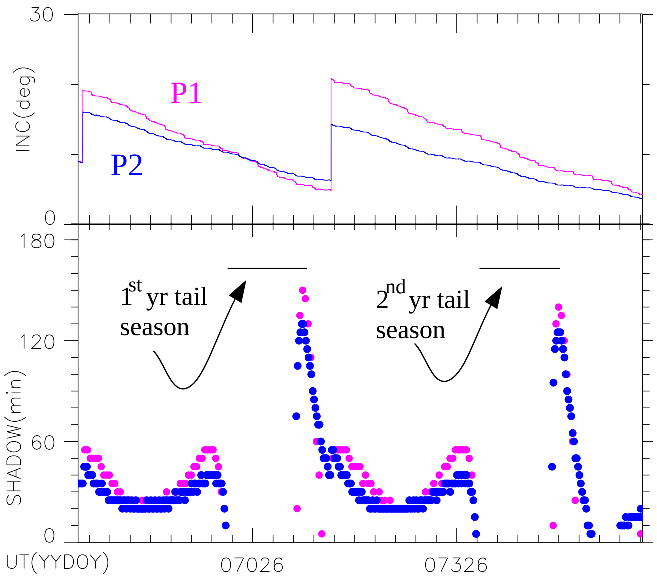


Figure E-21. *Orbit element evolution (P1 and P2) assuming shadow minimization procedure occurring outside tail season (i.e., long before tail season begins). Launch in August of 2006 results in minimal fuel consumption for shadow avoidance (no ΔV required).*

The orbit strategy for attaining the optimal orbit parameters for P1 and P2 is shown in Figure E-21 for the limiting-case launch conditions, i.e, ~1year prior to the center-tail target date. After launch to an inertially fixed RAP=330^o (APER=0^o), and an apogee raise to the target apogee, an inclination change of <16^o places P1 in an orbit which evolves due to lunar perturbations to the target elements that minimize shadows and optimize conjunctions. This inclination-change maneuver is repeated once again prior to the second year tail science season. This is the baseline plan as it brackets the mission fuel needs. A backup plan is to perform a shadow avoidance maneuver just prior to the beginning of the shadow period within each tail observation season, effectively eliminating all tail shadows. Table E-8 summarizes the two plans.

a6. Orbit maintenance considerations

At small dipole tilt angles (Figure E-19) all target orbits can have the same low inclination. This happens as the target date moves toward equinox. For mid- to late-February the corresponding inclinations are in the range of 0^o to 9^o.

Strategy	Max yearly P1 shadow	Pros	Cons
at LEO: δinc<16^o	<180min, peak in tail	ΔV in LEO not in tail	more fuel, 3% data loss
in tail: δinc<9^o	<90min peak outside tail	less fuel, no shadows	during science season

Table E-8. *Shadow minimization operational strategies. Neither approach taxes thermal design; both compatible with data return requirements.*

a7. Summary

Table E-9 summarizes the trade-space and results from each parameter. Based on that we have decided to shift the center-tail observation target date to Feb.-21±1 week (RAP=330^o±7^o).

Section	Purpose	Optimal Season	Effect magnitude
a1	Minimize cloud cover	Feb.±2mo	+100% relative to Dec.
a2	Maximize substorm recurrence	Vernal equinox	+50% relative to winter solstice. Pro-rated effect.
a3	Polar night >6hrs	Dec.±4mo.	No THEMIS effect if within
a4	**B** angle to spin plane >10^o	Dec.±4mo.	No THEMIS effect if within
a5	Minimize shadows	Solstice	P1, P2: <3% data loss, some fuel consumption if target date on Feb.-21
a6	Relative orbit maintenance	Equinox	No effect if target date in mid- to late February

Table E-9. *Trade space and considerations for decision on center-tail target date.*

b. Inner orbit apogees/periods.

These were optimized (Table E-10) in full compliance with baseline science requirements. An additional benefit from the above orbit optimizations is that there is no longer a need to have the inner orbits at vastly different perigees as was done in the original proposal. A common perigee saves fuel and simplifies ascend operations.

c. Establishing common inner orbit perigee.

Once orbit periods and approximate apogees have been established the only driver for all orbit perigees becomes orbit stability and re-entry strategy. Stability will be considered here. Re-entry strategy refers to the same type of analysis but will be discussed in Appendix M. Figure E-22 (top) shows that perigees around 1.3-1.6R_E correspond to the breakpoint between short (<5yrs) and long (>20yrs) P1 lifetimes. The bottom panel shows the effect of lunar phase (tantamount to placement at fixed ma=180^o at variable ascend dates). Interpolating we find that a perigee of 1.5R_E results in lifetimes > 10yrs under all lunar phases. This is low because lunar perturbations, for the RAPs selected, raise perigee regardless of lunar phase. We thus chose R_P(P1)=1.5R_E as the nominal P1 perigee. Similarly we get R_P(P2)=1.168R_E and R_P(P3/4/5)= 1.118R_E.

Optimization	Science driver	Implementation Effect	Risk
P4 on same orbit as P3 throughout mission, except for $\delta ma^{P3,P4}$=5^o	δX separated probes can miss CD if co-aligned with it. Optimal separation is in δY, achieved by δma	Increased fuel margin. Reduced ascend functions Reduced differential precession of P3,4	Reduced risk of CD and sub-storm event loss.
P5 at 1st year dayside pass: apogee=13R_E (T_{P5}=9/8*$T_{P3,4}$ ~ 27hrs).	Becomes magnetosheath monitor (P5s for sheath)	Small fuel margin reduction. Reduced differential precession of P3/4,5	None
P5 at 2nd year dayside pass: apogee=11R_E (T_{P5}=7/8*$T_{P3,4}$ ~ 21hrs).	Becomes magnetopause monitor (P5p for pause)	Small fuel margin reduction after completion of primary science.	None
P5f on 1st year tail pass: apogee=10R_E (T_{P5}=3/4*$T_{P3,4}$ ~ 18hrs). [Gains 6hrs/day]	Was 7min/day; had orbital bias in δY database. Separations of 0.3-10R_E now once per 4 days	Increased fuel margin assuming a common perigee.	None

Table E-10. *Orbit apogee/period optimization*

d. Conjunction optimization.

Conjunctions were simulated and tabulated (Table E-11) using GTDS to determine optimal inclinations, periods and period tweaks necessary to met science requirements ($\delta Y^{P1,2,3,4,5}$<2R_E, $\delta Z^{P1/2,NS}$ <5R_E, $\delta Z^{P3/4/5,NS}$<2R_E).

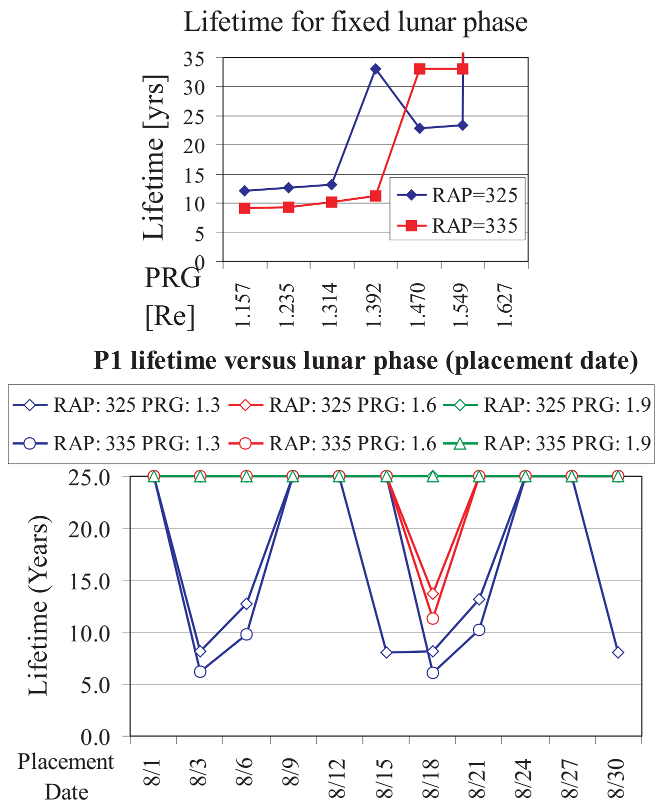


Figure E-22 *P1 lifetime vs. perigee (T_{P1}=96hrs).*

Strategy	Center-tail	Feb.-14	Feb.-21	Feb.-28
at LEO: δinc<16^o	L+6mo	266	319	335
	L+18mo	264	315	333
mid-tail δinc<9^o	L+6mo	401	397	367
	L+18mo	369	330	294

Table E-11 *Conjunction hours of realistic orbits with target date of Feb.-21 are >300hrs. Two minor period tweaks per year assumed for P1, P2.*

e. Baseline versus minimum mission.

Baseline requirements are unchanged (Figure E-1/A_I). Better understanding of the substorm recurrence rates (see section E3.a2 and Figure E-16) for the new target date (Feb.-21) produces a higher yield of events per year. The requirement of >10substorm observations is met by 188 hrs of con-

		# of events	Recurrence	Encounter probability	Hours needed	Hours have	Inner-probe pairs needed	Duration
Baseline Mission	Step-1	>10 [5 for each external solar wind condition]	<6hrs	4 in 20=1/5 (δY_{onset}=±2R_E, δY_{tail_width}=20R_E)	>300	>300/ yr	δX(P5f/4,P3: 1st yr); δY(P5f,P4: 1st yr) δZ(P5f->P5u,P3: 2nd yr)	2 yrs
	CSR		3.75hrs		>188		δX(P5f,P3/4: 1st yr); δY(P5f/P4,P3: 1st yr); δZ(P5f->P5u,P3/4: 2nd yr)	2 yrs
Minimum Mission	Step-1	>5	<6hrs		150	>300/ yr	δX(P5f,P3: 1st yr), δY(P5f->P4,P3; 2nd yr); δZ(P5f->P5u, P3)	3 yrs
	CSR		3.75hrs		94		δX,δY,δZ (P5f,P3 pair does all three types)	1 yr

Table E-12 *Baseline and minimum mission implementation with new P3, P4, P5 orbits* junctions (Table E-12). *Mission design has improved the baseline mission performance relative to the step-1 proposal by 50%.*

Minimum mission *implementation* is also been re-evaluated. The new orbit apogee implementation (Section E3.b) results in probe conjunctions that span all interprobe separations, δX, δY and δZ, with equal probability. The increased event yield from the seasonally adjusted substorm recurrence permits us to obtain the same minimum mission objectives within 1 year (Table E-12).

f. Mission desired launch date.

Owing to the 2-month shift in both the center-tail target date and the MIDEX program start date, the nominal launch date was shifted by 2 months (to August 21, 2006). (Desired but not required).

g. Ion ESA design optimization.

The step-1 proposed ESA design was identical to FAST except for the reduced number of anodes from 16 (FAST) to 8. This, and two other aspects of the design have been reconsidered resulting in science improvement and risk reduction (Table E-13).

	Technique	Heritage	Reason	Effect	Risk
geometric factor: toggle high (tail) low (dayside)	Shaped memory alloy attenuator (TiNi)	Lunar Prospector actuator (UCB)	Improves solar wind detection on P1, P2 without saturation, no effect on tail science.	Negligible power, mass, schedule effect (i.e., within step-1 *baseline* values)	Implementation: no risk Science: reduced risk
16 anodes	Fully identical to FAST (UCB)				
Run to 40keV	Higher voltage	AMPTE/IRM (UCB)	CD detection with ESA (backup to SST)		

Table E-13 *Ion ESA design optimization trade study results*

h. FGM/SCM boom design/deploy (Table E-14).

Action	Heritage	Reason	Effect
Release in swing-radially (rather than swing-over-top) fashion.	Lunar Prospector	Smaller release spring, Simpler design.	Eliminates risk from centripetal acceleration opposing motion.
Replace release breakwire with Coriolis force plus overtravel springs on FGM boom.		Development and operation simplification	Reduces complexity and associated risk.
From double to single tubular FGM boom base segment.		Simplification afforded by new release method.	

Table E-14. *A simplified FGM/SCM boom design and deploy mechanism reduces mission risk without increasing resource needs.*

i. Ground based observatory implementation.

We have: Optimized the ASI locations to benefit from existing infrastructure; Reduced the number of ground magnetometers needed from 20 down to 8; Reduced the cost/risk in deployment and maintenance by reducing the number of new installations to 6 in Quebec and 2 in Alaska; Chosen robust VSAT-satellite link for baseline data retrieval with disk-swapping /shipping as backup (over the step-1 proposed internet/telephone link); Obtained Canadian Space Agency commitment to support installation, data relay and dissemination; and Obtained commitments from complementary ground networks for logistical support, data sharing and collaboration (Table E-15).

network	location	purpose	letter from
MEASURE	Eastern US	denser American sector mid-latitude chain. Optimal substorm detection	UCLA/Moldwin
UC-LANL	Central US		UCLA/Chi
SAMBA	Central/South America		UCLA/Zesta
MACCS	Eastern Canada, high latitudes		Engebretson
U. Alberta	Canada, US	denser coverage	Ian Mann
Alaska/GI	Alaska	data and logistical support	GI/Bristow, Olson, Deehr
Iceland	Iceland	extend MLT	NIPR/Sato
DMI	Greenland	extend MLT	Waterman
CPMN	Japan, Russia, Pacific, other	extend MLT	Yumoto

Table E-15. *THEMIS ancillary ground networks*

j. Data processing and rate allocation

Moment calculations have been simplified (Table E-16) reducing processor complexity. Data rates have been duly re-distributed (Table E-5).

Action		Reason	Science effect
Eliminated reduced distribution functions (no pitch angle sorting, no angle averaging every other distribution)		Simplified on-board processing (software and hardware). Reduced risk. Facilitated analysis/interpretation.	Reduced particle bursts to 15%; Exceeds by 50% the (10%) science requirement (E2.b).
Simplified ESA/SST moment calculations	Removed on-board ESA-SST merging		None
	Partial moments computed to preset mid-point energy; added on ground		None

Table E-16. *Simplification in on-board processing.*

F. TECHNICAL APPROACH

F1. TECHNICAL APPROACH OVERVIEW

THEMIS is a five identical probe (micro-satellite) mission, built at two main institutions. UC Berkeley, the PI institution, with team members having a combined 150 person-year track-record of successfully building and managing NASA SEC missions, most recently FAST and HESSI (SMEX). Our industrial team partner, Swales Aerospace (the SMEX-Lite technology commercialization co.), has recent MIDEX class spacecraft manufacturing, mission management, and launch operations leadership experience on FUSE, EO-1 and Triana.

The THEMIS primary science emanates from probe conjunctions within a 4-month primary data-phase per year during a two year baseline mission. Probe to probe conjunctions (probe alignments mostly along the Sun-Earth line within a comfortable $\pm 2R_E$ range) and probe conjunctions with ground based observatories (in North America) result from natural orbit geometry recurrence, with the probe periods designed to be multiples of each other (1:2:4 for probes P3/4/5:P2:P1 respectively). A store-and-forward data flow scheme retrieves prime conjunction plasma and fields data during substorm events with simple, automated science operations. Four out of the five probes, operating for one year, achieve the minimum mission.

The ground-based observatory network in Alaska and Canada monitors auroral currents and optical emissions to obtain accurate timing of substorm onset. Ground observatory development and deployment of all-sky cameras and magnetometers is performed by a team who has previously built these instruments (en-masse), deployed, and operated them in far more remote locations and adverse climatic conditions than required for THEMIS.

The five flight instruments (FGM, ESA, SST, SCM and EFI) are near-identical to previous units, have been successfully flown previously by the THEMIS lead instrument scientists and engineers. They were selected because they easily exceed the mission requirements and provide programmatic confidence resulting prior multi-unit production. They adhere to THEMIS's basic philosophy of simplicity, manufacturability, and ease of testing, assuring us that the 5 probes can be developed, calibrated, and qualified within schedule and cost. The instrumenter's experience, mature designs, and a detailed grass-roots schedule and cost result in high-confidence, strong margins and low-risk.

THEMIS benefits from significant foreign contributions. Commitments from foreign institutional authorities for flight hardware have been obtained.

THEMIS is launched on a Delta II 2925-10 Expendable Launch Vehicle (ELV), from Cape Canaveral (CCAS), with no epoch restriction and a daily launch window of 40 min. The probe carrier assembly (PCA) consists of a probe carrier (PC) fixture permanently attached to launch vehicle (L/V) 3rd stage and the probes. The PC dispenses the probes via a low-shock, heritage separation systems. The probes are released spin-stabilized, near the final science orbit of P3/4/5 (3 inner probes), in a stable $1.1\times 12.1R_E$ orbit. An on-board reaction control system (RCS), comprised of a blow-down hydrazine propulsion system, performs the final probe placement and minor science-driven adjustments prior to each prime-science phase.

Key systems engineering trade studies, performed during Phase A, have further increased the robustness of an already fault tolerant mission. The launch strategy is simplified by directly injecting with the ELV into the parking orbit (includes the main inclination change). This approach removed a solid kick motor (from the step-1 proposal design) and eliminated coast phase operations and associated electronics. This allows for us to transfer the costs of these items towards a more capable launch vehicle within the NASA/NLS Delta family, thereby reducing mission risk, minimizing schedule risk, and simplifying flight operations. The probe dispense from the PCA now occurs immediately following 3rd stage burnout. The solid motor removal improves all static and dynamic clearances during probe dispense. Probes utilize industry standard components chosen to further increase probe fuel margin. Probe power margins have also increased due to slightly larger, current technology, high performance solar cells. In all, Phase A trade studies have reduced dry mass, complexity, and risk while improving mission performance, reliability, and production simplicity.

The spin-stabilized probes (T_{spin}=3s) are dynamically stable, even under the worst-case scenarios, as evaluated by our systems fault tolerance analysis. The single-string probe design has inherent functional redundancy (e.g., in ACS sensors, axial thrusters, probe dispense time & sequence). Both instruments and the bus are designed for graceful degradation (e.g. multiple solar array strings and battery cells, redundant memory blocks, and multiple EFI sensor heads). Additionally, preliminary probabilistic risk assessment (PRA) and contingency operations analyses demonstrate that either P3 or P4 can completely replace any other probe during any mission phase while fully maintaining positive fuel and dry mass reserves and margins. Since four probes can accomplish the minimum mission objectives, THEMIS benefits from constellation redundancy. Consequently, THEMIS is a low risk mission.

Heritage components (all currently in production) on the probe bus and the use of a bus processor card identical to the instrument data processor card (UCB-heritage from STEREO and ISUAL), minimize risk, simplify instrument-bus interfaces, and reduce cost. Flight operations use testbed-verified (prior to upload) ground-command sequences and benefit from the passive fail-safe control scheme, resulting in automated operations, a simplified bus avionics architecture, and minimal flight software.

F2. MISSION DESIGN

The THEMIS team has been refining its observation strategy since 1998, to ensure traceability and science closure with a robust mission implementation and operational simplicity derived from the natural progression of the THEMIS orbits. Phase A carried this philosophy forward with the tightly integrated science, instrument, operations and bus engineering team optimizing the mission design by leveraging the built-in flexibility, afforded by the step-1 proposed design, to further reduce implementation risk and increase performance margins. Primary amongst the trade-study results was the simplification of the probe-carrier-assembly (PCA) design (removed apogee-kick-motor, coast phase electronics, and operations) by the choice of a slightly more capable standard NASA/NLS launch vehicle (L/V), the Delta II 2925 (herein D2925). Our choice, the result of a detailed trade study with the participation of KSC, simplified the launch phase with a direct insertion to parking orbit, increased the injection mass margin, and further improved the on-board fuel margin.

Date:	No requirement. Desired=08/21/06±2mo. (prime science follows L&EO, fuel margins, fits schedule).
Time:	40 min window every day
Duration:	2 years
Final Orbits:	HEO (detailed in Figure E-1/B)
LV/Site	DeltaII 2925-10 from CCAS
Injection Orbit	†r_A=12.1R_E §, r_P=1.1R_E, aper=0^o, inc=9^o

†r_A, r_P are geocentric apogee and perigee in R_E
§R_E is mean Earth radius (1R_E=6378km).

Table F-1. *General orbit information.*

a. Mission profile

The operational phases of the mission from launch to end-of-mission are tabulated in Figure F-1/A (pictorial representation to its right). THEMIS has no launch date restriction and the target orbit (Table F-1) achieves 3rd stage re-entry passively, while being sufficiently stable (>1.8yrs), under all choices of orbital elements and lunar phase. This launch profile permits a comfortable probe checkout period prior to probe final-orbit placement and for unforeseen contingency operations.

Item	Maneuver Title	ΔV (m/sec)	R_A [R_E]	R_P [R_E]	Inc. [deg]
PCA	Target Parking Orbit	n/a	12.1	1.100	9.0
	Launch Vehicle Dispersions	n/a	12.0	1.099	8.5
P1	Intermediate Apg. Raise	88.3	15.0	1.099	8.5
	Intermediate Prg. Raise	16.0	15.0	1.150	8.5
	Final Apogee Raise	189.4	30.9	1.150	8.5
	prg.&inc. tune; drift to target	114.6	30.9	1.500	23.0
	period Tweak #1 (midtail-24d)	4.6	31.6	1.500	7.0
	Period Tweak #2 (midtail+24d)	4.6	30.9	1.500	7.0
	drift to 2nd yr dayside target	3.1	31.4	1.500	7.0
	inc.&prg. tune; drift to target	130.3	31.4	1.814	23.0
	drift to 2nd yr tail (midtail-2mo)	3.1	30.9	1.500	7.0
	period tweak #1 (midtail-24d)	4.6	31.6	1.500	7.0
	period tweak #2 (midtail+24d)	4.6	30.9	1.500	7.0
	re-entry maneuver	6.0	31.9	1.500	7.0
	Total	569.0			
P3 & P4	Apogee Trim	5.2	12.1	1.099	9.5
	lower inc., raise prg., place ma	10.9	12.1	1.118	9.0
	prg. tune; drift to target	14.8	12.1	1.157	9.0
	re-entry maneuver (prg tune)	6.9	12.1	1.100	9.0
	re-entry maneuver (apg tune)	1.5	12.1	1.100	9.0
	Total	39.3			

Table F-2 *ΔV for P3/4 and P1. (ΔV req's for P2 and P5 are enveloped by those of P3/4's and P1's.*

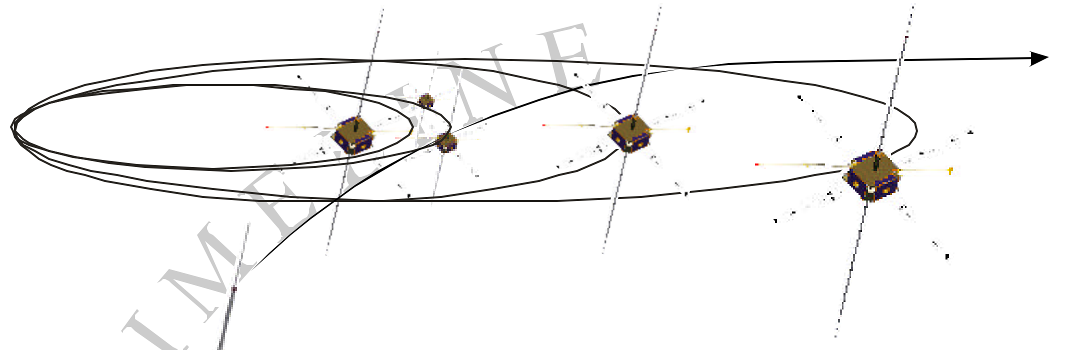
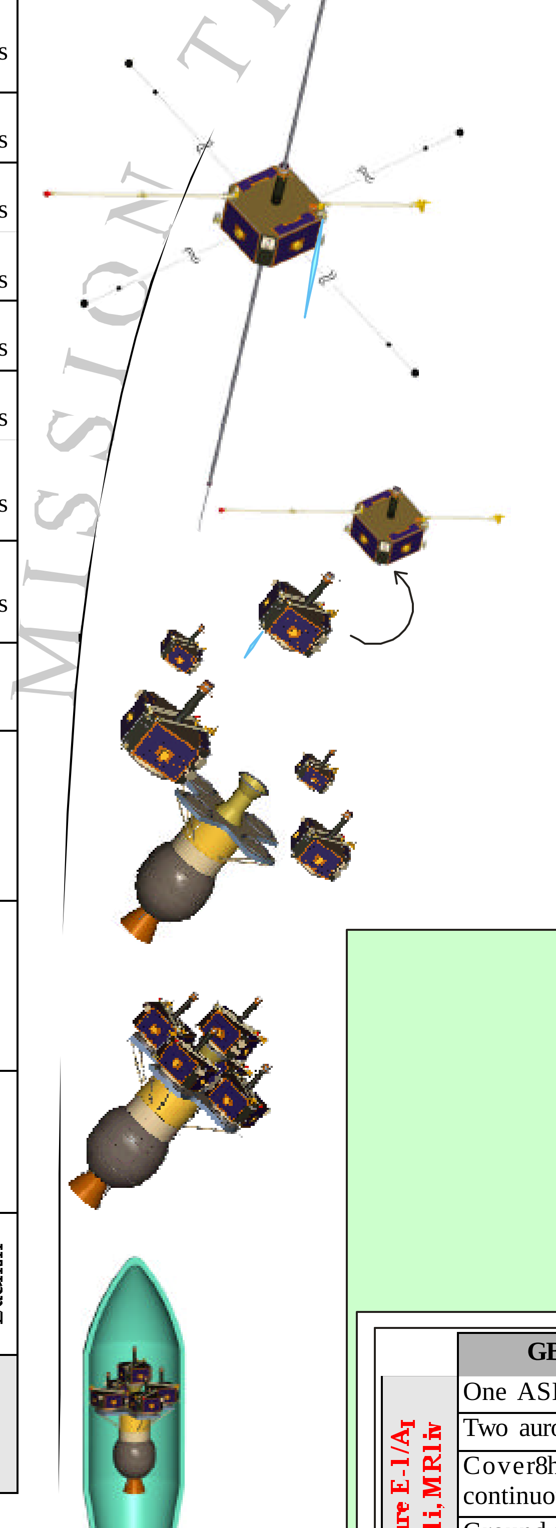
a1. Launch and early orbit (L&EO) operations

L&EO starts with count-down (Figure F-1/A) and nominal L/V insertion (probe receivers on) followed by the PC dispensing of the probes into the injection orbit. The PC is a simple structure that remains fixed on the 3rd stage solid motor. Probes are thus dispensed into a spin-stable (15RPM) state after receipt of a L/V separation signal. The probes transition into "stand-by" mode (transmitter enabled and ready) with system aliveness and state of health checkouts for each probe. Subsequently, the magnetometer booms are deployed, the ACS sensors and thrusters are calibrated, science instruments are checked out and the probes are spun-up to 30RPM. Following orbit characterization the probes use their RCS for final orbit placement (propellant budget allows this to occur independent of launch date). Orbit determination contacts are interspersed between low-thrust, incremental orbit adjustments resulting in accurate orbit convergence. ESA and SST high voltage supplies are turned-on and finally EFI spin-plane cable-booms and stacers

FIGURE F-1
Mission Profile and Traceability Matrix (Foldout-3)

Mission Profile (A)

Mode	Operation	Condition	Duration
Science Operations	3 Period Tweaks	2nd year Setup & Science	365 days
	Adjust Inclination	P1, P2: Reor/ Thrust/ Reor	6 days
	4 Period Tweaks	1st yr Setup & Science	365 days
Initial Checkout, Final Orbit Inject/Trim, Deployment & Calibration	Place on Orbit & Deploy EFI	Respin (20rpm)	10 days
		EFI AXB Dply	5 days
		EFI SPB Dply	10 days
		Orbit Adjust	30 days
		Respin (30rpm)	5 days
	Instr. Check-out	End checkout	5 days
	Deploy Mag. Booms	Standby Mode at 13rpm	5 days
	Check Health	Survival Mode	1-2 hrs
Launch	Despin & Separation	Probe release	20 sec
		3rd Stage Despin (15rpm)	
	Spin-up, Apg. Inject, & Incl. change	3rd Stage Burn	177 sec
		3rd Stage Spin-up	
	Injection	Launch thru 2nd Stage Burns	21.8 min
Pre-launch	Terminal Countdown	Checkout & Countdown	L-6 hr to Launch

Traceability & Performance Verification Matrix (B)

GOAL
G1. Time history of Breakup, CD, Rx at the substorm onset meridian. (**Section E1.f1**)
G2. CD-Rx coupling (**Section E1.f2**)
G2. Substorm coupling to auroral ionosphere (**Section E1.f3**)
G3. Substorm coupling to local modes at ~10R_E. (**Section E1.f4**)

Figure E-1/A$_I$, MR1ii-iv, MR2i-ii, MR3i-ii, MR4i-ii

ORBIT DERIVED REQUIREMENTS					
Parameter	**P1**	**P2**	**P3**	**P4**	**P5**
Period (days)	4	2	1		
Apogee (R_E)	30	19	12	12	12
Perigee (R_E)	1.5	1.2	1.16		
Inclination @ Midtail	<7°		<9°		
Drifts@Apogee 6:30 UT	δY < 1 R_E/month				
→ control δApogee (km)	400	250	150		
Knowledge @Apogee	100 km				
Conjunction Time	188 hours/total mission				

Figure E-1/A$_I$, MR1v-vi, MR2i-iii, MR3i-iii, MR4ii

INSTRUMENT DERIVED REQUIREMENTS	
FGM, SCM	• Spinning spacecraft (10-30rpm) • EMC: below sensitivity at sensor • Absolute inertial knowledge <1° • Inertial stability: <0.1°/12hrs; < 1°/5days • Spin phase knowledge <0.1° • Mountingorthogonality<1°
EFI	• Spin axis ~10° to ecliptic normal • ESC: external surface grounding, and conductive ITO such that ρ d<10^5 Ohm m^2. • I_{zz}-Z_{sc} stability <5.6°, knowledge<1°
SST, ESA	• Spin axis control <11.25° • I_{zz}-Z_{sc} stability <5.6° • FOV clear of MAG booms, EFI wire view acceptable
INSTRUMENT COMPLEMENT	• 14.7W (includes 21.6% reserve) • 23.7 kg(includes 12.8% reserve) • Unattended ops, gnd burst criteria updates • Thermal limits on bus (can do cold turn-on): Oper: -20°/+40°C; Survive: -50°/+65°C • Boom-mounted parts (can do cold turn-on): Oper: -100°/+40°C; Survive: -100°/+65°C (except EFI - same oper. limits as bus)

Figure E-1/A$_I$, MR1i, MR1iv

GBO DERIVED REQUIREMENTS	PERFORMANCE
One ASI per MLT in North American sector	Two ASIs per MLT
Two auroral GMAGs per MLT (high/low lat.)	>2 GMAGs per MLT (+contributed, +mid-latitudes)
Cover 8hrs of Geographic Local Time (allows continuous 12hr conjunctions with probes).	Covers 10hrs of Geographic LT with ASIs, 14hrs with GMAGs including contributions.
Ground obs. allocated <10s cadence/timing accuracy	<1s ASI exposures. Cadence: 1sec GMAG, 3s ASI. (baselined). Accuracy: msec (GPS)
Sensitivity <10kRayleigh (ASIs); <1nT (GMAGs)	Sensitivity: <1kR (5:1 S/N ratio); 0.1nT

Figure E-1/A$_I$, MR1i, MR1iv

Figure E-1/A$_I$, MC1iv, MC2i-ii, MC3iv, MC4iii

MISSION PROFILE REQ	PERFORMANCE
Baseline life: 2 yrs.	2yr mission design, Reliability Ps=0.8 (P3/P4 can replace any other)
Minimum life: 1yr.	Reliability=0.93
1.1×12.1R_E; $\delta prg_{3\sigma}$=10km, $\delta apg_{3\sigma}$=1000km; aper=0°±1°; raan=330°±1°; inc=9°±1°	DeltaII 2925 exceeds target req's; 40min launch window/day; 807 kg to orbit (predicted mass: 505kg.) Average mass reserve=15%, Margin = 40%.
No launch date requirement.	Six months costed schedule contingency to 8/06
End-of mission re-entry within < 25 years	PC passively reenters, P1/2/3/4/5 maneuver to reentry trajectory (< 25 years, debris < 8m^2)
Probe carrier supports probes thru launch and dispense	PC is simple 3rd stage fixture (15% mass reserve and 33% mass margin); flight proven probe release mechanism; exceeds launch load requirements.

Figure E-1/A$_I$, MC1ii-vi, MC2iii, MC3i-iii, MC4i-ii

	PROBE REQUIREMENT	PERFORMANCE
Mass	23.7kg of max. instrument mass within 99.5kg of dry probe mass.	47.2kg of max. expected bus mass (includes 15.1 kg reserve) with a 40.5% total mass margin
Power	14.7W max. expected instrument power.	14.5W max. expected bus power (includes 17W reserve) accomodates instrument power plus 41.9% power margin. 41.5W EOL power capability, 10.5 A-hr battery, peak mission DoD 50%
Fuel	ΔV=569m/s (P1 limit case)	Tank size accomodates all P1 maneuvers at max. dry mass & provides 43% fuel margin.
Replacement	P3/4 can replace any other (P3->P1 limit case)	Fuel margin allows P3/4 at max expected dry mass to replace and perform all P1 functions.
Thermal	Instrument survival through longest (3hr) eclipse.	Passive thermal design, thermostatically controlled heaters, survival in any attitude.
C&DH	Store-and-dump 375Mbits of science data / orbit. Uplink 0.1Mbits/ orbit	256 Mbytes (IDPU) and 16Mbytes (bus) permit multiple orbits' data storage and forward dump through bus communications card. 1Mbps serial interface for bus-IDPU data exchange.
GN&C	Orbit control: δV<80cm/s	Orbit control: δV<8cm/s
	Orbit knowledge <100km	Knowledge 3σ<3km (2-way Doppler)
	Spin axis control <11.25°	Spin axis control <0.5°
	Absolute attitude knowledge <1°	Absolute attitude knowledge <0.6°
	Attitude drift: <0.1°/12hrs; < 1°/5days	Attitude drift: <0.03°/12hrs; < 0.3°/5days
	Spin phase knowledge <0.1°	Spin phase knowledge <0.04°
Redundancy & Fault Tol.	Single String/Probe	Single string with functional redundancy result in graceful degradation; autonomous FDC tolerant of S/A string failures; N+1 redundancy in memory blocks, 2 axis gyro & magnetometer backup sun sensor
Radiation	2yr dose on P3 (limit case): 66kRads thru 5mm Al (includes ×2 margin, at solar max).	Effective shielding of 5mm, radiation-tolerant (100kRad), SEU-tolerant and latchup-immune electronics
Communications	BGS and USN. Downlink at 400kbps at <20,000km; Uplink 1kbps	Omni S-band toroidal antenna. All data can be downlinked any time of the year within <20min per contact. Link margins: 8.0dB downlink; 6.0dB uplink at highest apogee. TDRSS and DSN-compatible for contingency operations.

	Item	Mass [kg]	Mass [%]	Power [W]	Power (%)	Notes
Single Probe	Instruments (% is reserve)	21.0	12.8%	12.1	21.6%	Developer predicts; Percentages are reserve estimates
	Bus (% is reserve)	41.0	15.1%	12.4	17.0%	
	Total	62.0		24.5		
	Contingency (Reserve)	8.8	14.3%	4.7	19.3%	Weighted Average
	Maximum expected, dry	70.8		29.2		Sum
	Fuel for base + reserve mass	24.2			Maximum expected mass for P1 propellant usage	
	Maximum expected, wet	95.0				
	Agreed-to maximum limit, wet	134		41.50	Mass Limit Allocated; EOL Power	
	Usable Propellant Margin	10.3			Tank max. minus expected fuel max.	
	Margin	28.7	40.5%	12.3	41.9%	
	Agreed-to maximum limit,dry	99.5				
Probe Carrier	Base Mass	89.7				Developer predict
	Contingency (Reserve)	13.6	15.2%			Weighted Average
	Maximum expected	103				Sum
	Agreed-to limit value	137				Mass Limit Allocated
	Margin	34.1	33.0%			
PCA	Delta 2925-10 lift capability	807	Equals 5 limit-mass fully loaded probes on limit-mass carrier			
	Base wet mass	505				Current predict
	Contingency (Reserve)	73.9	14.6%			Weighted Average
	Margin	229	39.6%			Weighted Average

Table F-4 *THEMIS has ample mass and power margins, based on subsystem heritage.*

	P1	P2	P3	P4	P5	P3->P1
ΔV(m/s)	569	349	39	39	472	561

Table F-3 *Total mission-ΔV for probes and for P3 assuming it replaces P1 (limit case) at any point in the mission.*

are deployed, in that order. Final probe characterization and health-status checks conclude the nominal 60-day L&EO operations.

a2. Science operations

The probe orbit placements result in highest science return when the prime tail-season, a four month period, is centered approximately around Feb. 21 of each year (2007/2008 if THEMIS is the first MIDEX launched). Science operations entail simple instrument command generation and burst-trigger table uploads. Probe-probe conjunction is optimized by two small period-trims on P1 & P2, at 1 month from the center-tail target date. Dayside science is also optimized by one period tweak of P1 & P2 prior to the dayside observation season (two months after the end of the tail season). P5 is also trimmed after the first prime science season to accommodate dayside and second-year tail-season performance. All of these apogee trims are short-duration and use side-thrusting (tangential thruster pair) and have long post-thrust orbit determination intervals. Prior to the second year tail season a single inclination change burn occurs for P1 and for P2 using axial burns, to place then in the correct orbit elements that, considering lunar perturbations, will place them on scientifically optimal inclination and argument of perigee. P3 and P4 nominally remain in the same orbits throughout the mission. In the unlikely event of loss of one probe, the P3 (or P4) fuel budgets are sized so that they can replace any other probe (even at maximum expected probe dry mass).

After the 2nd year of operations the probes are positioned for a re-entry course (<25 years fully complying with NASA's orbit debris policy): P1 & P2 undergo a mean-anomaly placement to maximize lunar resonance. P3, 4, & 5 undergo a reduction in perigee. After fuel is depleted, the probes reenter passively in 1-10yrs.

All maneuvers occur in contact with ground stations with full a priori and a posteriori (near-real time) attitude and orbit determination. We have conservatively baselined a one-probe-at-a-time placement scenario allowing us to comfortably achieve higher actual maneuver efficiency.

a3. ΔV requirements

The ΔV requirements are derived from the detailed maneuver plan of Table F-2. The operational complexity, propellant usage, and ΔV of all probes are bounded by the maneuvers of P3/ P4 and P1. Table F-3 summarizes the nominal-profile ΔV requirements for all probes and for the contingency operation of P1 replacement by P3. The scenario of P1 replacement by P3 bounds the worst-case fuel requirement for any probe replacement. It can occur at any time in the mission with a positive margin even for maximum expected probe dry mass.

a4. THEMIS mass and power budgets

The THEMIS mass and power resources are shown in Table F-4. Base estimates were derived for each lowest level component by sub-system experts and from vendor-measured data. Contingencies (reserves) are a weighted average of the individual item confidence levels shown in the instrument, probe bus and PC Master Equipment Lists (MEL). Individual component contingency allocation is based on institutional experience at UCB and Swales and is summarized in Table F-5.

UCB and instrument co-Is		Swales	
Level	Reserve	Level	Reserve
Fabrication drawings	4%	COTS or build to print	10%
Prior flight hardware	8%	COTS + minor modifications	15%
Design drawings	15%	Heritage + mods.	20%
Heritage concept	25%	New design	25%

Table F-5 *Reserves are assigned to components based on their level of heritage. This assignment is in accordance to institutional practices tabulated above as assembled from recent flight experiences.*

a5. Communications

The probes use CCSDS encoding and an S-band, omni-directional antenna (FAST-like) to communicate at 400kbps downlink (nominal) and uplink at 1kbps. Section F7.d4 describes the primary (Berkeley) ground station (BGS) and Section F7.d5 describes the secondary (USN) and backup (DSN/RID, TDRSS/SA) communications paths, all fully compatible with THEMIS's NASA standard communications method.

b. Technical implementation trade studies

In addition to Phase A *science* implementation trade studies (discussed in Section E3), *technical* implementation trades resulted in increased mission fault tolerance (PCA simplification from step-1 design), mission reliability (simpler avionics, ACS/RCS design) and higher performance margins (on-board fuel, power capacity, dry mass). Table F-6 summarizes those and decisions based on them.

Our choice of the D2925 L/V originated with the probe-probe conjunction science optimization resulting in a less demanding injection orbit (see Table E-11): an injection inclination of 9^{o} is the most efficient starting point for each probe that still exceeds the science requirements (results in same or increased science conjunction hours relative to

Trade	Mass	Power	Risk Effect	Cost effect
Launch scenario: DII2925+passive fixture PC+electrically independent probes has replaced: DII2425+maneuverable PC+electrically ganged probes	Couples to new orbit implementation. No net effect on PCA launch margins.	n/a	Passive PCA is far simpler. Reduced schedule risk & mission operations complexity.	+\$5.5M (LV) -\$4.5M (PC smarts+solid savings) =+\$1M (net cost increase)
PCA architecture: 4-on-a-plane + 1-on-a-tower has replaced: 5-on-a-plane	+8kg on PC. Minimal effect	n/a	Increased deploy clearance. Eliminated failure modes.	None
Fuel: Increased capacity to ensure P3/4 replacement strategy. PSI-80321 tank has replaced PSI-80148.	Per probe: dry mass increase=0.12kg; fuel increase=7.24kg	n/a	None (both high heritage conospheres from same vendor).	-\$37Kea.×11 (#80148) +\$105Kea.×11 (#80321) =+\$750K (cost increase)
Avionics: UCB-provided bus avionics unit (BAU) processor card, identical with IDPU-card has replaced: UTMC UT131 board	No effect.	No effect.	UCB-heritage processor, software & experience. Common I&T, simpler BAU-IDPU I/F.	-\$50K×5 (UTMC) +\$10K×5 (UCB copy) = -\$200K (cost reduction)
Battery: Yardney LiIon 10.5 Ahr has replaced OSC SMEX-Lite NiCad 4Ahr (out of production).	2.75kg ea. instead of 5kg ea.	Higher capacity	Low risk, increases robustness of shadow operations.	-\$75K×5 (NiCad) +\$90K×5 (LiIon) =\$75K (cost increase)
Structure: Composite/Titanium./Aluminum hybrid structure has replaced Al/honeycomb structure	None: lighter, stiffer material reduces solar cell distortion.	n/a	No risk (Swales is industry leader in space composite structures)	None
Solar panels: Added two solar array strings at bottom face	+0.6kg	+heater power	Reduced risk: Now 4π str power-positive.	+\$165K total
ACS: Micro-gyros have replaced accelerometers	None	none	Both heritage devices. Simpler ACS solution/ops.	-\$40K (accel.) +\$85K (gyros) = +\$45Ktotal
ACS: Eliminate on-board attitude solution and "autonomous safe-mode"	None	none	Reduced on-board software; simpler design	None
RCS: Connected propellant tanks	Passively maintains fuel balance. Any thruster can access all fuel. (Increases operational simplicity. No cost/power/mass effects).			

Table F-6. *Phase A trade studies have reduced risk and increased THEMIS's fault-tolerance and margins* the step-1 design). Choosing a common initial perigee altitude (Section E3.c) results in stable initial probe orbits and allows the coupled PC/Delta 3rd stage system to passively re-enter within the NASA orbit debris limit of <25 yrs. These optimal injection parameters are the result of extensive, high-fidelity, multi-body numerical propagation analyses. They provide the highest margins on fuel and allow a D2925 direct-injection to this orbit. They yield low shadow durations and acceptable synchronization between probe orbits over the mission life (as evidenced by the high yields on conjunction hours).

Since net L/V mass to orbit is not affected in the above trade attention is focused on trading system complexity and risk versus cost. THEMIS concluded that the benefits from the simpler PCA design, and the associated schedule and risk reduction, far outweigh the additional ~$1M in cost to upgrade from the originally proposed D2425 to the D2925.

c. Traceability

The mission traceability and predicted performance verification matrix is shown in Figure F-1/B providing the "trace" between the mission requirements, tabulated in red in Figure E-1/A_I, and the predicted mission performance, tabulated in blue in Figure E-1/A_I. The matrix in Figure F-1/B first reinforces the relationship to the THEMIS primary science goals and then derives a set of requirements that each main mission element, i.e., the Orbits, the Instruments and the Ground Based Observatories (GBOs), places upon the mission profile (and L/V), the probe bus and the ground based instrumentation. Those "derived" mission-element requirements then feed into detailed mission profile and probe requirements shown on the right. Performance is verified along each row, and performance characteristics from multiple rows combine and feed back into the science closure table (Table E-1/A_I) via the blue call-outs. This matrix provides solid traceability of the mission implementation characteristics back to the science closure themes of Figure E-1/A.

F3. PROBE BUS AND PROBE CARRIER

a. Probe bus overview

THEMIS employs five simple, identical, high-heritage probes (P1, P2, P3, P4 & P5) in coordinated orbits. The probes communicate independently with the mission operations center (MOC) that operates each probe in a serial fashion. While the probes are self-sufficient, attitude and orbit determination is maintained in the ground operations center and all orbit and attitude maneuvers take place during ground contact. These elements have resulted in a robust design that utilizes a simple architecture and our team's experience building and operating small satellites (e.g., EO-1 and HESSI).

For THEMIS to capitalize at a mission-level from Constellation redundancy the RCS (propulsion system) is sized not only to ensure high margins for the nominal mission but also to allow for the worst-case (P1) replacement operations by P3/P4. The passively spin-stabilized control scheme, the 4π steradian power positive body-mounted solar panels and a near-omni-directional communication coverage allows for any probe to fail-safe with *no* required maneuvers, should an anomaly occur. Conservative design techniques result in capabilities that easily meeting the derived Level 2 requirements with ample reserves and margins. Worst-case parameter sensitivity analyses were also employed to understand the characteristics of the architecture and to evaluate all credible failure modes. A component level Probabilistic Risk Assessment (PRA) and Fault Tree Analysis have demonstrated the system's fault tolerance (see section F9.m/n) providing further confidence in the design.

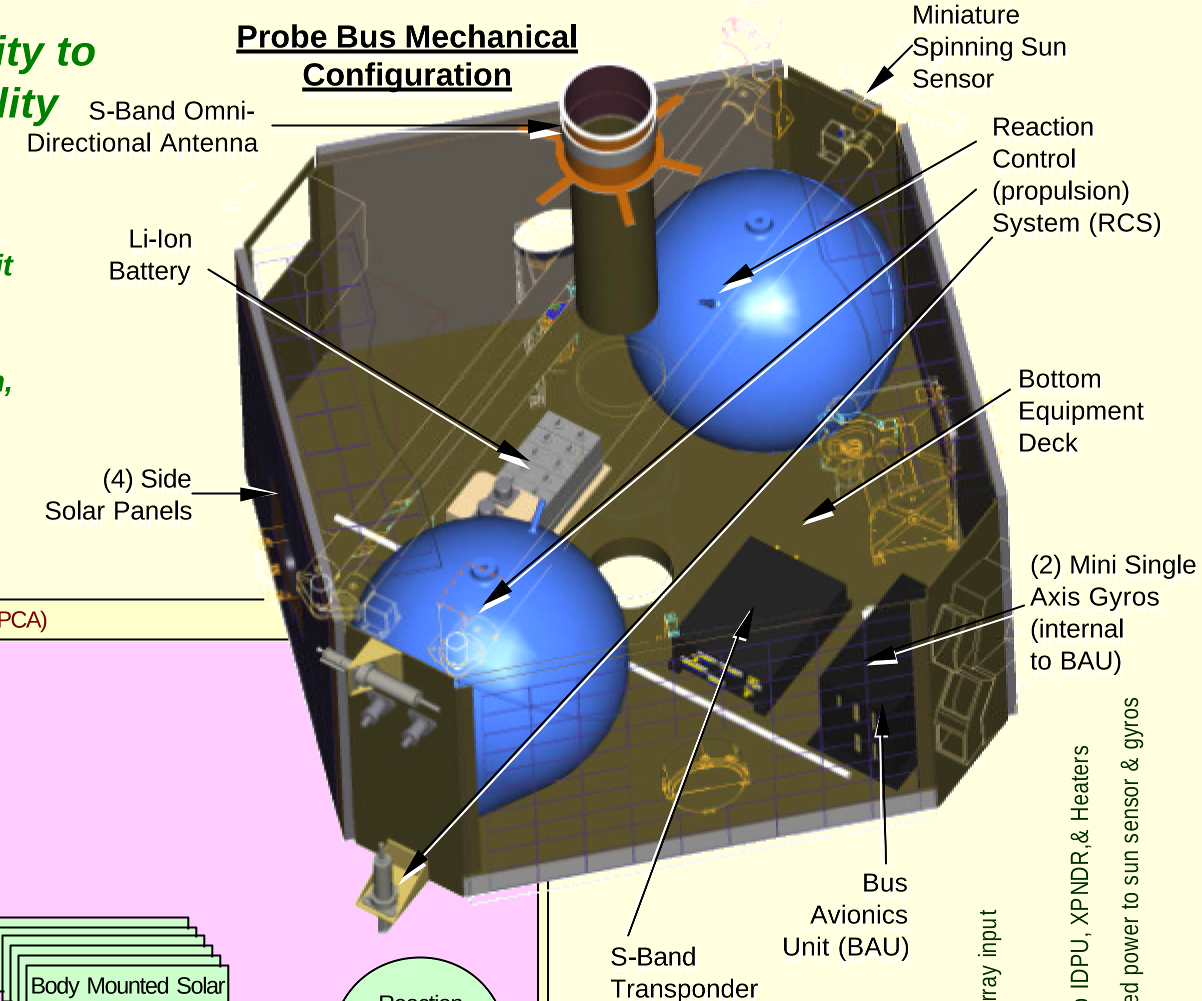
The physical and functional configuration of the probe bus is illustrated on Figure F-2 (Foldout-4). Probe bus requirements summary and predicted performance was summarized in Figure F-1 (Foldout-3). Table F-2 shows top-level probe power and mass margins.

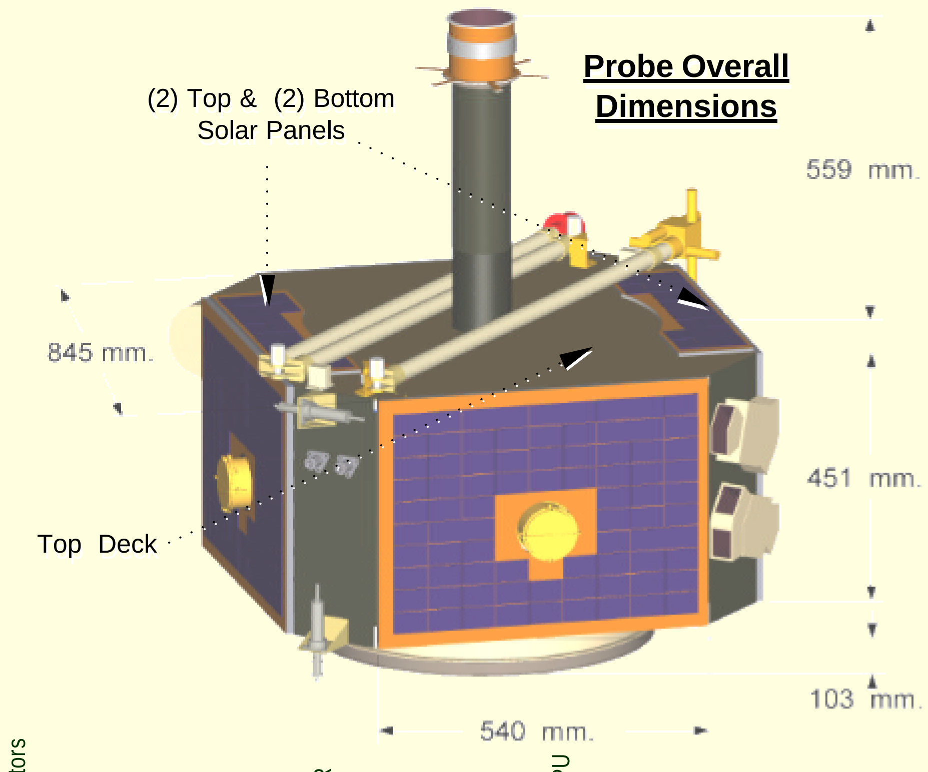
Each probe consists of the probe bus (probe) and the instrument suite (See Figure E-13/Foldout-2). The probe bus subsystems include Structural/Mechanical, Thermal, Power, RF and Communications Subsystem (RFCS), Command & Data Handling Subsystem (CDHS) and Guidance Navigation & Control (GN&C). The GN&C consists of the Attitude Control Subsystem (ACS) and the Reaction Control (propulsion) Subsystem (RCS). The electronics associated with the Power, CDHS, ACS, and RCS reside in the Bus Avionics Unit (BAU).

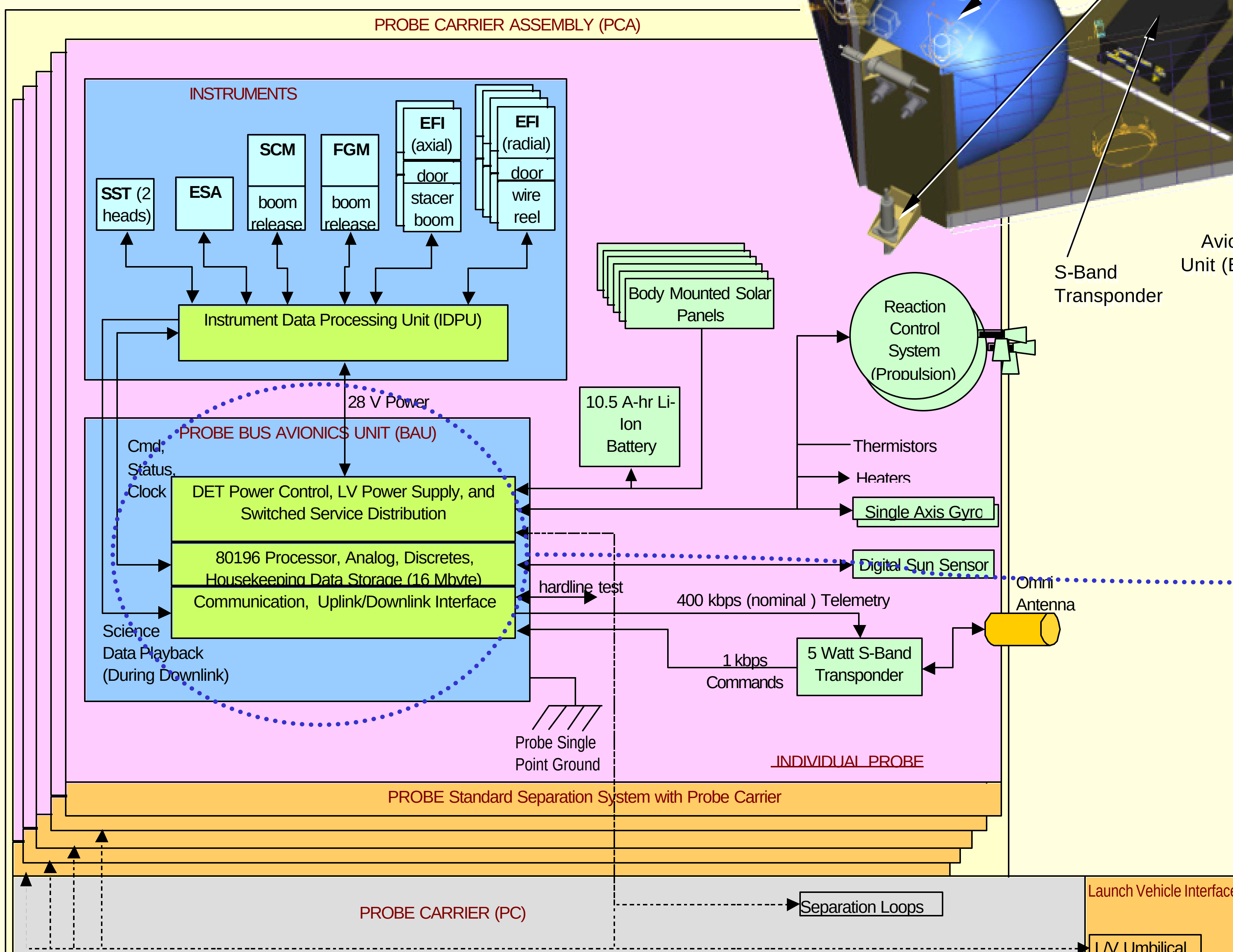
There are five main operational modes: Pre-Launch Nominal Science Operations, Maneuver, and End-of-Mission. The probe operational sequence and states are illustrated in Figure F-1 (Foldout-3). The probes are powered with the receiver ON during Pre-Launch and Launch modes with all appendages stowed during the PC dispense operation. The probe enters Nominal/Science Operation mode after dispense is complete. The probes are passively spin-stabilized upon release (even under dispense fault conditions) and full command (CMD) and telemetry (TLM) communications commence, initiated by ground command, to each probe using unique identification codes. Deployment, checkout, and power-up of each instrument is accomplished at the appropriate stages of the In Orbit Checkout (IOC) phase to verify key instrument

Simple Probe Design Minimizes Complexity to Maximize Reliability & Manufacturability

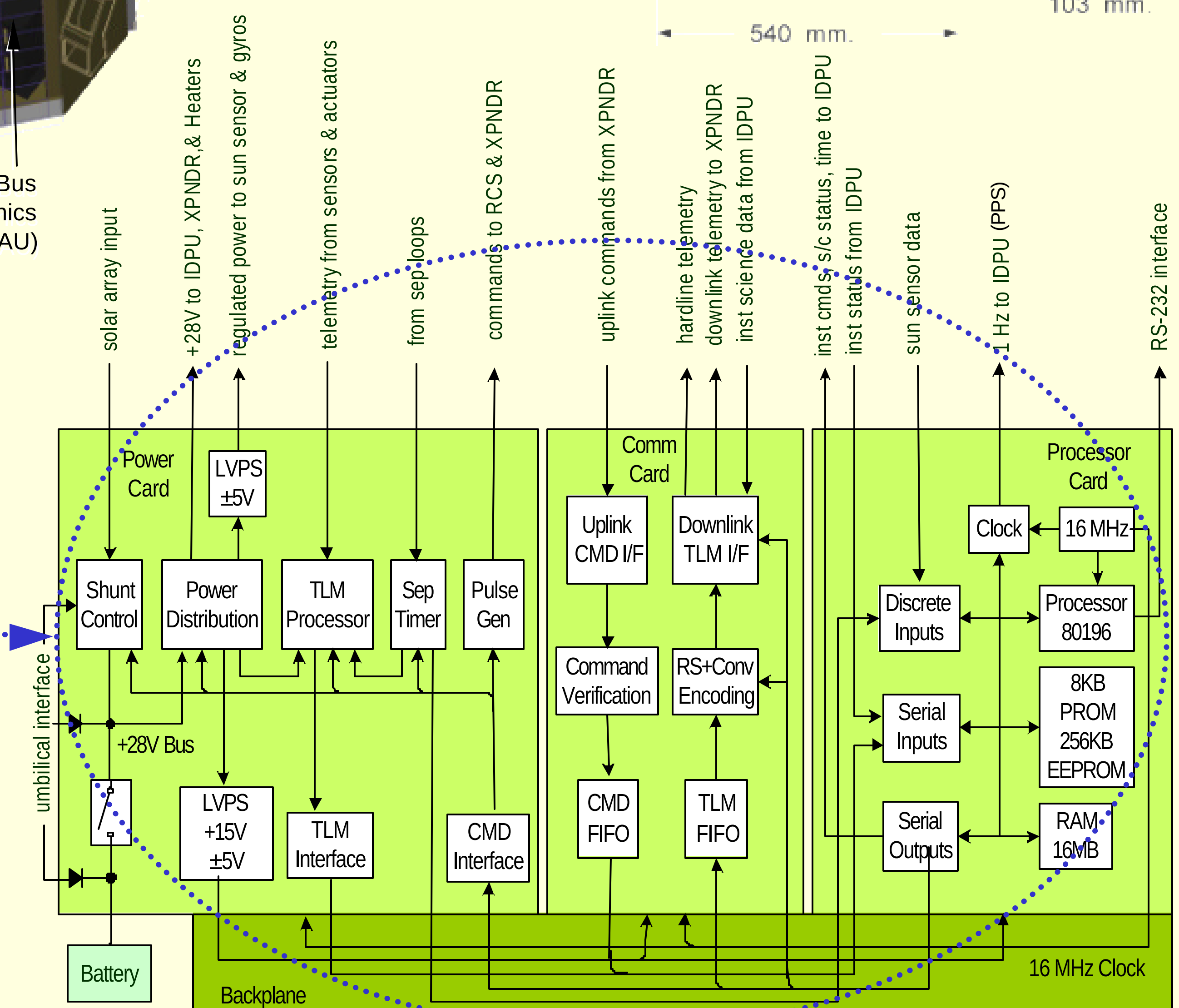
- *Power Positive in all Attitudes*
- *Passive Thermal Design Tolerant of Longest Shadows*
- *Positive Communication Availability for Every Orbit Regardless of Attitude; In View for Greatest Part of Orbit*
- *Passively Spin Stable in all Nominal and Off-Nominal Conditions*
- *Simple RCS (Propulsion) System Minimizes Fuel Motion, is Cross-Strapped to Maximize System Reliability, and Minimizes Hazardous Fueling Operations*
- *Probe Functional Simplicity allows for Minimal Flight Software*
- *Requirements Met with High Margins*







Probe (with Probe Carrier Shown) System Functional Block Diagram



Probe Bus Avionics Unit (BAU) Internal Block Diagram

Figure F-2: *THEMIS Probe Physical & Functional Design (Foldout-4)* functions and to extract body (FGM), sheath (EFI) and field (SCM) calibration data for each unique configuration during these deployments. This allows for independent decoupling and characterization of the probe body effects for use in subsequent science data analysis. Deployments are (in that order): SCM/FGM (simultaneous nominal deploy), EFI radial wire-boom pair #1, EFI radial wire-boom pair #2, and EFI axial-boom pair (simultaneous nominal deploy). The passive, spin-stabilized ACS and probe mass distribution analysis of off-nominal deployment conditions demonstrates that any of the magnetometer booms or wire-booms can deploy individually (off-nominal) with passive spin-stability preserved. The EFI axial booms can be deployed individually and still preserve passive spin stability, as long as the axial booms are deployed last in the overall sequence.

The RCS utilizes axial (2) and side (2) thrusters allowing for orbit maneuver operational flexibility. Side (tangential) thrusters also act individually for spin rate trimming, as needed. The RCS is a two-tank system with two banks of paired thrusters. The pressurant and propellant sides on both tanks are interconnected to produce a self-compensating symmetric mass distribution throughout the mission life and for added probe reliability. Latch valves between the two tanks are closed during launch and dispense operations eliminating fuel migration.

The mechanical and thermal designs provide a low conductance composite structure for isolation of the body-mounted solar panels, minimizing thermal energy effects between full-sun and shadow operations. Most of the bus and instrument components mount to the stiff honeycomb base plate (operating nominally at ~30^{o} C). This design allows for a direct transfer of launch loads into the flight heritage standard Payload Attach Fitting (PAF). The probe thermal design is a passive system with Multi-Layer Insulation (MLI) blankets on most of the exterior surfaces and around the RCS tanks, lines, and thruster bodies to minimize radiative interaction with other probe components. Thermostatically controlled film heaters control selected elements/zones and thermistors are used for housekeeping temperature monitoring.

The RFCS utilizes a NASA-standard S-Band transponder for CMD & TLM communications with a single cylindrical FAST-like, toroidal gain pattern, omni directional antenna.

The BAU includes a SMEX-Lite heritage uplink/downlink communications card, a processor card (identical to the IDPU processor card), and a Direct Energy Transfer (DET) power control card with SMEX-Lite and EO-1 heritage. The flight software is derived from prior SMEX mission modules (in C-language) and is hosted by the heritage CMX-RTX Real-Time Operating System (RTOS). Instrument and bus housekeeping data are stored in the local bus memory while science data are stored in the IDPU. During a ground communication event the housekeeping data is transmitted directly by the bus with the IDPU science data flowing through the bus (bent pipe flow), similar to the FAST implementation of the burst-data downlink.

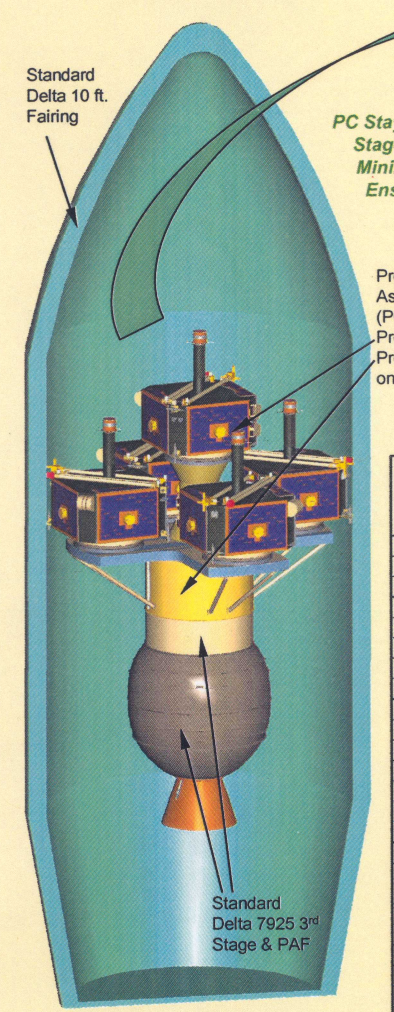
b. Probe Carrier Configuration & Launch

THEMIS utilizes the standard Delta sequence to directly inject the PCA into the target parking orbit. As shown in Figure F-3 (Foldout-4) the PCA mounts to the D2925 3rd stage via a standard 3712 Payload Attach Fitting (PAF). The PC does not separate from the 3rd stage; the probes separate from the probe carrier (using an industry standard heritage clamp band separation system) immediately after 3rd stage burnout and yo-yo despin. The direct injection represents a much simplified launch scenario from the step-1 proposal as the PC is no longer an active (4th) stage but a simple mechanical dispenser. The probes are electrically independent; each initiates separation based on built-in sequence timers and ELV separation signals, thereby eliminating any credible PCA single point failure. Multiple timers (hardware and software) are provided to protect against premature probe dispense. The ground can also backup separation via command.

Swales has integrated experience and design techniques derived from the XSS-10 micro-satellite dispenser (USAF) and the STS/SHELS (NASA) micro-satellite dispenser and converged on the baseline design illustrated in Figure F-3: Four probes directly mount to the stiffened bottom deck and the fifth mounts to the central tower. This configuration reduces the bottom deck footprint and improves the static/dynamic clearances of the PCA relative to the launch vehicle fairing and between the probes themselves. It provides a stiff launch boundary condition to each probe, thus allowing for full optimization of the probe internal structural design and minimizing probe dry mass. The design meets all Delta II fairing clearance and natural frequency requirements.

The probe dispense sequence has been chosen to maximize separation clearances. First, the top (center) probe dispenses along the spin axis followed. Following a 4sec. wait-period, the remaining four probes dispense simultaneously. This is easily implemented by simple timers built into the probes and minimizes the effect of dispense timing errors. In addition, our PC design maximizes the launch dynamic stiffness, minimizes mass, simpli-

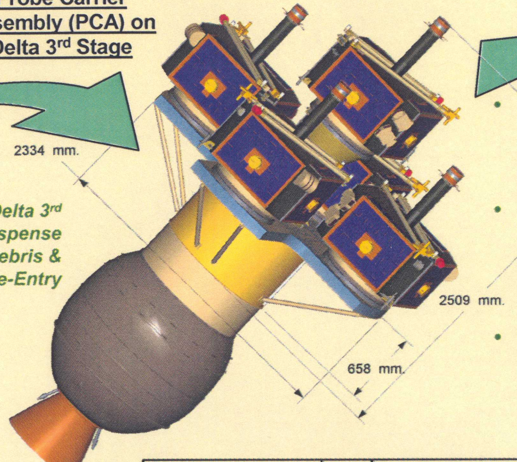
Fault Tolerant and Robust Launch Design Minimizes Mission Risk



THEMIS Launch Configuration

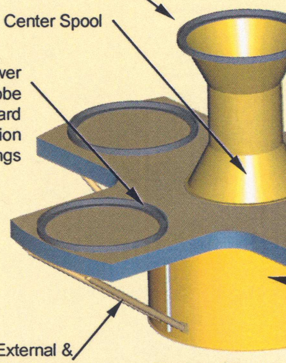
Easily Accommodated within Standard Delta 7925-10 Vehicle Configuration & Services

Probe Carrier Assembly (PCA) on Delta 3rd Stage



PC Stays Attached to Delta 3rd Stage After Probe Dispense Minimizing Orbital Debris & Ensuring < 25 yr. Re-Entry

- *Ample Positive Clearance Exists for all Dispense Configurations and Trajectories*
- *Each Probe Dispense from the PCA is Coordinated but Independent of the Other Probes*
- *Conservative Analysis Demonstrates that no Single Probe Precludes Dispense of Remaining Probes*



Probe Carrier (PC)

Simple Probe Carrier Utilizes

- Stiffened Aluminum Structure
- Standard Heritage Payload Attach Fittings for Probes
- Straight-Forward Umbilical Interconnect harness
- Multi-Layer Insulation Thermal Blanketing

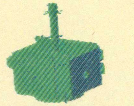
Dispense Analysis Table

Scenario	Description	Spin Rate (rpm)	Time of Release (seconds) P1	P2	P3	P4	P5	Positive Clearance	Local PAF Tip-off Rate Exacerbates Worst-Case Dynamics (Yes/No?) P1	P2	P3	P4	P5	Probe Spin-Axis (Body) Worst-Case Net Angular Change (deg) Post Dispense P1	P2	P3	P4	P5
Nominal Deploy without timing errors																		
1	low RPM P2-P5 simult.	10	4	8	8	8	8	Yes	N	N	N	N	N	0.1	1.8	1.8	1.8	1.8
2	high RPM P2-P5 simult.	20	4	8	8	8	8	Yes	N	N	N	N	N	0.1	2.5	2.5	2.5	2.5
Nominal Deploy with timing errors																		
3	high RPM P2 early	20	4	8	9	9	9	Yes	N	N	N	N	N	0.1	2.4	7.1	10.2	2.3
4	high RPM P3/P4/P5 early	20	4	9	8	8	8	Yes	N	N	N	N	N	0.1	21.7	2.3	2.5	2.3
5	low RPM P2 early	10	4	8	9	9	9	Yes	N	N	N	N	N	0.1	2.0	3.6	4.3	3.2
6	low RPM P3/P4/P5 early	10	4	9	8	8	8	Yes	N	N	N	N	N	0.1	8.3	1.7	1.9	1.5
Probe 1 (Top Probe) Does Not Deploy; Remaining 4 Probes on Deck Deploy with timing error variations																		
7	high RPM P2 early	20	NA	8	9	9	9	Yes	N	N	N	N	N	NA	2.3	4.8	5.7	0.3
8	high RPM P2/P3 early	20	NA	8	8	9	9	Yes	N	N	N	N	N	NA	2.3	2.2	9.6	5.7
9	high RPM P2/P3/P4 early	20	NA	8	8	8	9	Yes	N	N	N	N	N	NA	2.2	2.2	2.2	8.9
10	low RPM P2 early	10	NA	8	9	9	9	Yes	N	N	N	N	N	NA	1.9	2.3	3.0	2.6
11	low RPM P2/P3 early	10	NA	8	8	9	9	Yes	N	N	N	N	N	NA	1.9	1.8	3.9	4.8
12	low RPM P2/P3/P4 early	10	NA	8	8	8	9	Yes	N	N	N	N	N	NA	1.6	1.8	1.5	4.1
Probe 2 (Single Lower Probe) Does Not Deploy; Remaining 4 Probes Deploy with timing errors variations																		
13	low RPM P3 early	10	4	NA	8	9	9	Yes	N	N	N	N	N	0.1	NA	2.0	3.7	4.4
14	low RPM P3/P4 early	10	4	NA	8	8	9	Yes	N	N	N	N	N	0.1	NA	2.1	2.0	5.4
15	low RPM P3 early TO	10	4	NA	8	9	9	Yes	Y	Y	Y	Y	Y	0.7	NA	1.8	3.2	4.7
16	low RPM P3 early TO	10	4	NA	8	9	9	Yes	Y	Y	Y	Y	Y	0.7	NA	1.8	3.6	4.4
17	low RPM P3/P4 early TO	10	4	NA	8	8	9	Yes	Y	Y	Y	Y	Y	0.7	NA	1.9	2.0	5.3
18	low RPM P3/P4 early TO	10	4	NA	8	8	9	Yes	Y	Y	Y	Y	Y	0.7	NA	1.9	1.8	5.3
19	high RPM P3 early	20	4	NA	8	9	9	Yes	N	N	N	N	N	0.1	NA	2.3	7.2	10.2
20	high RPM P3/P4 early	20	4	NA	8	8	9	Yes	N	N	N	N	N	0.1	NA	2.4	2.4	19.0
21	low RPM P3 early TO	20	4	NA	8	9	9	Yes	Y	Y	Y	Y	Y	0.3	NA	0.7	15.3	14.8
22	low RPM P3 early TO	20	4	NA	8	9	9	Yes	Y	Y	Y	Y	Y	0.4	NA	2.3	7.1	10.2
23	high RPM P3/P4 early TO	20	4	NA	8	8	9	Yes	Y	Y	Y	Y	Y	0.4	NA	2.3	2.2	19.4
24	high RPM P3/P4 early TO	20	4	NA	8	8	9	Yes	Y	Y	Y	Y	Y	0.4	NA	2.4	2.4	19.2

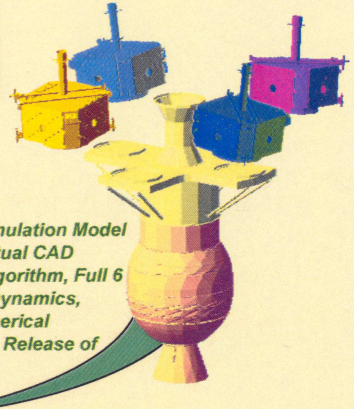
Dispense Timing Error Budget

Separation Sequence Event	Probe to Probe Variation (*msec*) Predicted	Allowed
Launch Vehicle Separation Signal (*simultaneous distribution to probes*)	0	0
Probe Hardware Timer	3.0	7.5
Separation Sequence Execution	1	2.5
Separation System Actuation	330	990
Total	334	1000
Margin	199%	

Worst Case Timing Delays and Failure Modes Evaluated in Comprehensive Time- Domain Analysis



DADS Dispense Model Dynamic Simulation Image



- *Detailed DADS Dynamic Simulation Model Integrated Pro-Engineer Actual CAD Model, Matlab Clearance Algorithm, Full 6 Degree-of-Freedom Body Dynamics, Local PAF Tip-Off, and Numerical Integration of Strain Energy Release of Separation Systems*

Figure F-3: *THEMIS Probe Carrier Assy. Launch Phase Design and Validation (Foldout-5)*

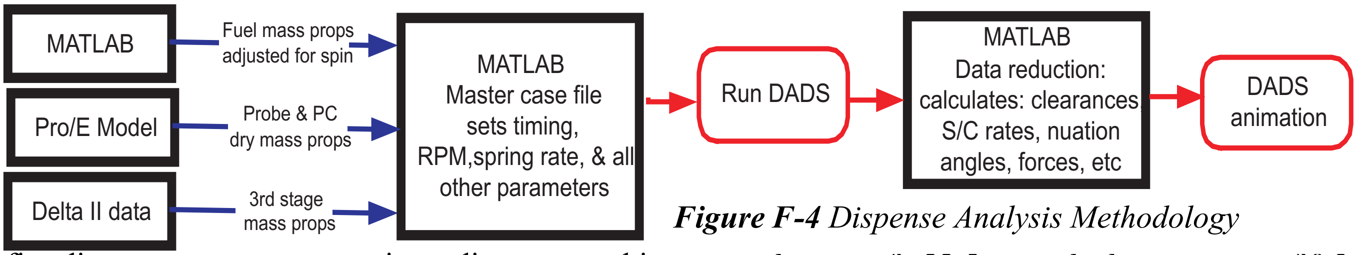


***Figure F-4** Dispense Analysis Methodology*

fies dispense sequence operations, dispenser architecture, and manufacturability. The extensive parametric sensitivity analysis results in a fault tolerant design with safe separation of all probes between each other and the PC.

b1. Separation Analysis

A detailed high-fidelity model of the system was developed using the Pro/E solid computer aided design (CAD) models, MATLAB scripts and the dynamic analysis design system (DADS) simulation software (Figure F-4). Two sources of separation tip-off were modeled. *First,* due to the probe separation system releasing its stored strain energy over 20 msec from separation time (conservatively reacts to PCA centripetal acceleration for that duration). *Second*, due to non-symmetric spring loading, manufacturing tolerances, and friction. This was modeled by applying equal and opposite torques to the probe and PC to create this conservative additional tip-off rate and was varied between ±1 deg/sec/axis to induce worst-case dynamic coupling. Multiple discrete kickoff springs were used at each separation system to dispense the probe, allowing for the springs to react to tip-off forces in a realistic asymmetric manner. Worst-case probe and PC mass properties were used in the analysis, determined from the Pro/E CAD solid models. The mass properties were calculated, via MATLAB, for the internal tank fuel shift due to the spinning of the PCA. This calculation took into account the conospherical shape of the tanks, the fill fraction, and the tank positions within the probe. Finally, the model varied each probe's dispense time to validate the separation timing error budget (see Dispense Timing Error Budget in Figure F-3).

The first set of analyses performed was a survey designed to reduce the number of overall parameters and cases under consideration including System Configuration (varied clocking and location of the probes on the PC), Deployment Rate & Sequence (varied separation system kick-off spring stiffness and associated probe deployment rates from 0.2 to 0.6m/s), PCA Initial Spin Rate (Rates varied from 10 to 60 rpm).

The survey resulted in the PCA configuration, shown in Figure F-3, with initial static clearances from probe to probe of >12.8 cm and probe to PC central tower of >22.5 cm, a deployment rate of 0.3 m/s (k=20000 N/m), and a spin rate of 15±5 rpm (±5 rpm is the standard Delta II Yo-Yo despin mechanism tolerance). This baseline configuration was evaluated further by inducing timing errors of 1 second for all probes, forcing a single probe (either the top probe or one of the lower probes) to not dispense, and by varying the tip-off configurations. The results from this large number of cases were then post-processed by two independent validation methods (Matlab-based quantitative clearance tool and DADS internal animation/collision detection module) that evaluated all clearances.

The results tabulated in the Dispense Analysis Table of Figure F-3 show that positive clearance is maintained between all bodies at all times for all cases. Extreme cases were formulated in response to the mission system fault tolerance assessment, conservatively postulating that a single probe fails to dispense. Even in this worst-case failure event the failed probe does not preclude the other probes from successfully dispensing. For various scenarios the probe nutation angles, attitude rates, and final orientation of the body spin axis were evaluated for the probes after separation. Under any dispense scenario probe nutation angles are <10^{o}; this a comfortable range of dynamic stability that naturally dampens out due to fuel friction within minutes. The final net spin axis orientation relative to the initial orientation was then calculated (<22^{o}) and was shown to result in positive communications, power, and thermal states.

c. Probe Mechanical System

The probe mechanical design is driven by the requirement to accommodate science instruments, maximize accessibility during I&T, minimize mass, and provide a fault-tolerant means of dispense from the PC with maximum clearance. It is ~84.5×84.5×45cm (Figure F-2) and consists of a lower deck, an upper deck, four corner and four side panels. The lower deck is the primary mounting surface for most of the instruments and probe components; it interfaces directly to the PAF, and allows for easy access during all integration activities. The upper deck, corner and side panels close out the probe internal cavity. The FGM and SCM booms mount to the upper deck; solar cells utilize

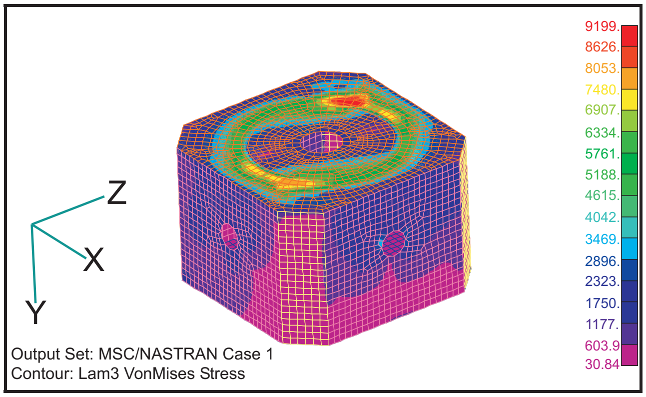


Figure F-5 *Probe FEM Peak Stress Distribution*

the exterior surface of the probe side panels as their substrate. The ESA and SST instrument, the fine sun sensor, and thruster brackets mount to two of the corner panels for clear FOVs. The lower deck is the primary structure, carrying loads from all internal components, side panels, and upper deck into the PAF and ultimately, through the probe carrier, to the L/V interface. The probe structure design allows for all side panels to be independently removable, facilitating internal component access during I&T. Small external threaded attachments on the external surfaces of the decks permit attachment of balance weights to accomplish a two-plane (minimum mass solution) dynamic balance of the probes.

The probe structure is primarily fabricated from cyanate ester fiber reinforced composite material, M55J/954-3, a high-heritage material, common in the aerospace industry and in the Swales Structural Systems (SSS) manufacturing processes. It is consolidated into sandwich panels with an aluminum honeycomb core. The advantages of this design are lightweight (lower system mass), high strength, low thermal distortion (accommodates solar cell temperature variation), and high stiffness (minimize launch load dynamics). SSS is the primary supplier of this type of composite panel to the commercial and civil aerospace markets worldwide.

A structural and dynamic analysis of the probe utilized a detailed Finite Element Model (FEM) with conservative (envelope Delta and GEVS levels) load factors of 17 g's applied to the FEM in all orientations to evaluate the strength and integrity of the structure. The model includes the equivalent interface stiffness of the PAF separation fitting, appropriate GEVS factors of safety, model uncertainty factors, and discretely modeled all components at the worst case limit probe mass of 134 kg. Maximum stresses are 63.4 MPa (9.2 ksi) and 57.9 MPa (8.4 ksi) for the panels and aluminum PAF respectively (Figure F-5). Both levels are very low, resulting in high safety margins.

The probe structural dynamics were evaluated (Figure F-6) to ensure conformance to the lateral

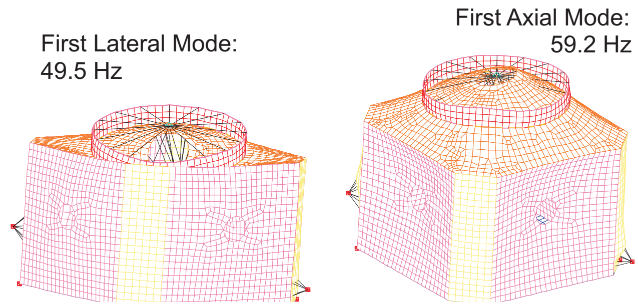


Figure F-6 *Probe Fundamental Natural Frequencies.*

and axial minimum frequency requirements of the L/V. The first lateral mode is 49.5 Hz and the first axial mode is 59.2 Hz. These show that dynamic coupling to the L/V is minimized when probes are mounted on the PCA and that the probe load factors used in the strength assessment are conservative.

The Lightband separation system (Planetary Systems) was selected as the baseline probe PAF as it provides a low mass, low shock, reliable probe dispense solution. The system was flown on the Starshine mission (Athena L/V) and has been qualified for use with the STS/SHELS and the Space Test Program MLV-05 mission on the EELV.

d. Probe Carrier (PC) Mechanical System

The PC mechanical design is driven by the requirement to provide physical support and interface for probes and L/V 3rd stage with sufficient strength and stiffness during launch while minimizing mass. It consists of the: PAF adapter ring/tube (interface to Delta 3rd stage); center spool (supports top probe); and the main deck (supports the center spool and the lower probes). The PAF adapter ring is machined aluminum with the launch vehicle 3712 standard interface at one end and a simple flange interface to the main deck. The main deck is an assembly of aluminum face sheet and core honeycomb panels simpler than many standard panels that Swales SSS currently fabricates for commercial communications satellites. The deck includes the bottom half of the lower probe separation systems and the attachment for the upper probe center spool. Aluminum struts directly stiffen the probe mounting on the main deck with the PAF adapter ring. The center spool is an assembly of three simple aluminum machinings, two conical; one cylindrical. The upper conical section interfaces to the bottom ring of the upper probe separation system. The design reflects the optimal probe mounting of Section F3.c, and the most direct load path to the L/V interface choice (thus weight efficient), amongst several structural configurations considered.

The structural and dynamic analysis of the PCA utilized a detail Finite Element Model (FEM) with the same conservative analytical conditions applied as described in the prior probe analysis summary and also assumed the worst-case probe limit masses of 134 kg. Figure F-7 illustrates that the resulting first lateral mode is 18.6 Hz (Delta requires >15 Hz) and the first major axial mode is 44.1 Hz (Delta requires >35 Hz). This demonstrates that the Delta dynamic payload responses are easily met, the acceleration load factors used in the strength analyses are valid, and that no dynamic coupling exists between the PC and any probe.

e. Guidance, Navigation, & Control (GN&C includes ACS and RCS)

e1. Attitude Control System (ACS)

Pointing Requirements and Allocations: THEMIS requires pointing control and knowledge for the spin axis and the instantaneous orientation of each instrument. Figure F-8 illustrates the relations of instruments and the probes orientation to the ecliptic plane. Requirements and allocations were specified in based on Level 1 -derived instrument requirements in Figure F-1 (Foldout-3).

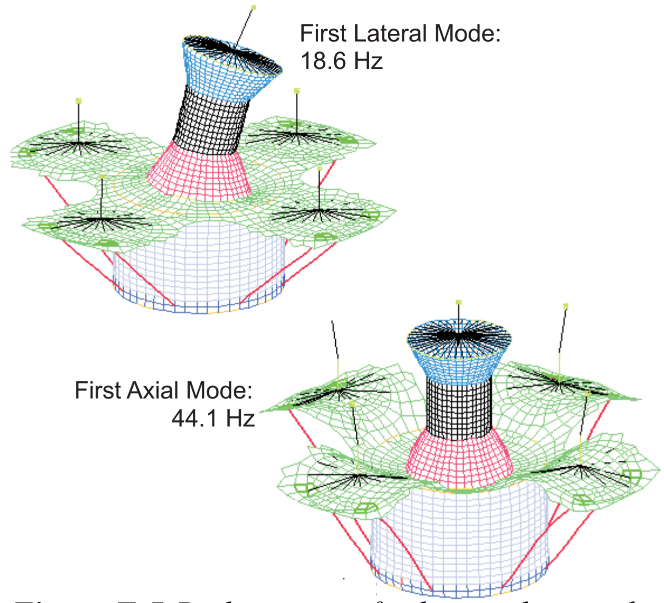


Figure F-7 *Probe carrier fundamental natural frequencies: displacements not to scale*

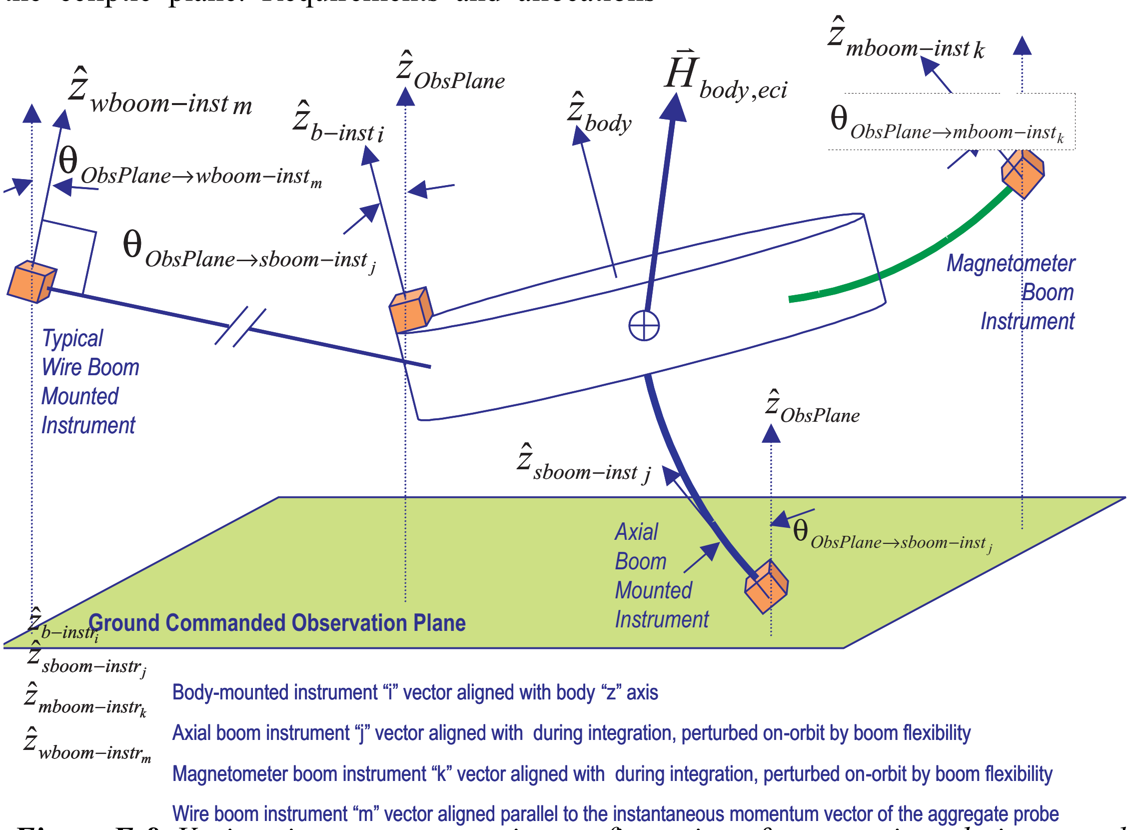


Figure F-8 *Various instrument mounting configurations & geometries relative to probe body*

Probe Pointing Budget: Table F-7 summarizes the pointing budget allocations derived from these requirements and used to validate the probe performance. The instruments are grouped together by similarity of mounting method and to delineate between their various dynamic error response characteristics. For example, EFI spin-plane booms naturally align normal to the probe principal axis while the EFI axial booms deviate due to lateral stacer boom flexure.

ACS Subsystem: Figure F-9 outlines the functional architecture of the ACS subsystem. The design utilizes a manual thruster interface driven by ground-processed estimation and command algo-

Item	FGM/ SGM		SST/ ESA		EFI-axials		EFI-spin plane	
	spin	trans	spin	trans	spin	trans	spin	trans
Instrument Errors								
Instrument Calibration Residual	**0.650**	**0.450**	**0.650**	**0.450**	**0.650**	**0.450**	**0.650**	**0.450**
Subtotal	**0.650**	**0.450**	**0.650**	**0.450**	**0.650**	**0.450**	**0.650**	**0.450**
Dynamics Errors								
PA misalignment due to imbalance	0.000	0.470	0.000	0.470	0.000	0.470	0.000	0.470
Residual wire bending stiffness	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008
Subtotal	**0.000**	**0.470**	**0.000**	**0.470**	**0.000**	**0.470**	**0.000**	**0.470**
Attitude Sensors								
MSSS survey error	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038
MSSS diurnal shift	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
MSSS hysterisis	0.000	0.021	0.000	0.021	0.000	0.021	0.000	0.021
Subtotal	**0.055**	**0.059**	**0.055**	**0.059**	**0.055**	**0.059**	**0.055**	**0.059**
Estimation Errors								
2 hr. Observation via TAM/MSSS	0.276	0.276	0.276	0.276	0.276	0.276	0.276	0.276
30 day Observation via MSSS only	0.390	0.390	0.390	0.390	0.390	0.390	0.390	0.390
Subtotal	**0.390**	**0.390**	**0.390**	**0.390**	**0.390**	**0.390**	**0.390**	**0.390**
ACS Controller Errors								
Thruster Minimum impulse of 1sec.	0.039		0.039		0.039		0.039	
Subtotal	**0.039**		**0.039**		**0.039**		**0.039**	
System Estimation Error -Required	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Prediction	**0.761**	**0.761**	**0.761**	**0.761**	**0.761**	**0.761**	**0.761**	**0.761**
Margin	**31%**	**31%**	**31%**	**31%**	**31%**	**31%**	**31%**	**31%**
12 hour stability-Required	0.100		0.100		0.100		0.100	
Prediction	**0.070**		**0.070**		**0.070**		**0.070**	
Margin	**42%**		**42%**		**42%**		**42%**	
5 day stability-Required	1.000		1.000		1.000		1.000	
Prediction	**0.352**		**0.352**		**0.352**		**0.352**	
Margin	**184%**		**184%**		**184%**		**184%**	

Table F-7 *Probe system pointing error budget allocations (all values in degrees)*

rithms with on-board limit/time-out protection. Attitude data collected from the Miniature Spinning Sun Sensor (MSSS) and the science FGM are sampled at 10 Hz and telemetered to the ground for standard, 3-axis, post-processing estimation. Ground-generated thruster command sequences are tested in a hi-fidelity probe simulator (I&T testbed migrated to mission operations center) prior to any upload. The on-board protection logic monitors real time sun aspect and the spin period, comparing them to a ground commanded reference uploaded for each maneuver. If thresholds are exceeded the maneuver is terminated. The robustness of the passive spin-stabilization along with the on-board limit/time-out protection allowed us to forgo use of a more complex autonomous acquisition scheme.

Estimation: Two existing algorithms are available for the ground-based estimation: a recursive 2-point scheme that uses the MSSS only, and the batch TRIAD algorithm that combines the MSSS and the FGM. Heritage proven algorithms currently exist and are also utilized by the ST-5 mission. Both schemes are valid over a wide attitude range.

The MSSS (identical to the ST-5 MSSS) provides precision sun line-of-sight (LOS) vector (2 axes) comprised of an azimuth angle of the sun with respect to the probe X-Y plane, and a sun crossing reference time corresponding to sun angle in this plane. Two time-separated sun sensor readings allow for the determination of the third axis with the apparent motion of the sun manifesting itself as the third angle of rotation. Figure F-10 depicts the geometry of this estimation scheme with the two azimuth readings, at t_1 and t_2, moving with respect to each other, temporally, and also to the ecliptic angle, relative to the MSSS LOS. Figure F-11 depicts a 30-day performance period of the MSSS. Attitudes consistent with the mission profile are contained in the red circle whose diameter is 11.25^o with a resulting worst-case error of 0.39^o. The azimuth angle denotes elevation with respect to the probe X/Y plane and the bore sight angle is the orientation of the ecliptic plane about the MSSS LOS.

To reduce the three-axis estimation convergence time (maneuver preparation operations), the science instrument FGM data is utilized in a batch TRIAD algorithm. Figure F-11 includes the performance for this two-sensor scheme over a two-hour period near the point of perigee passage including

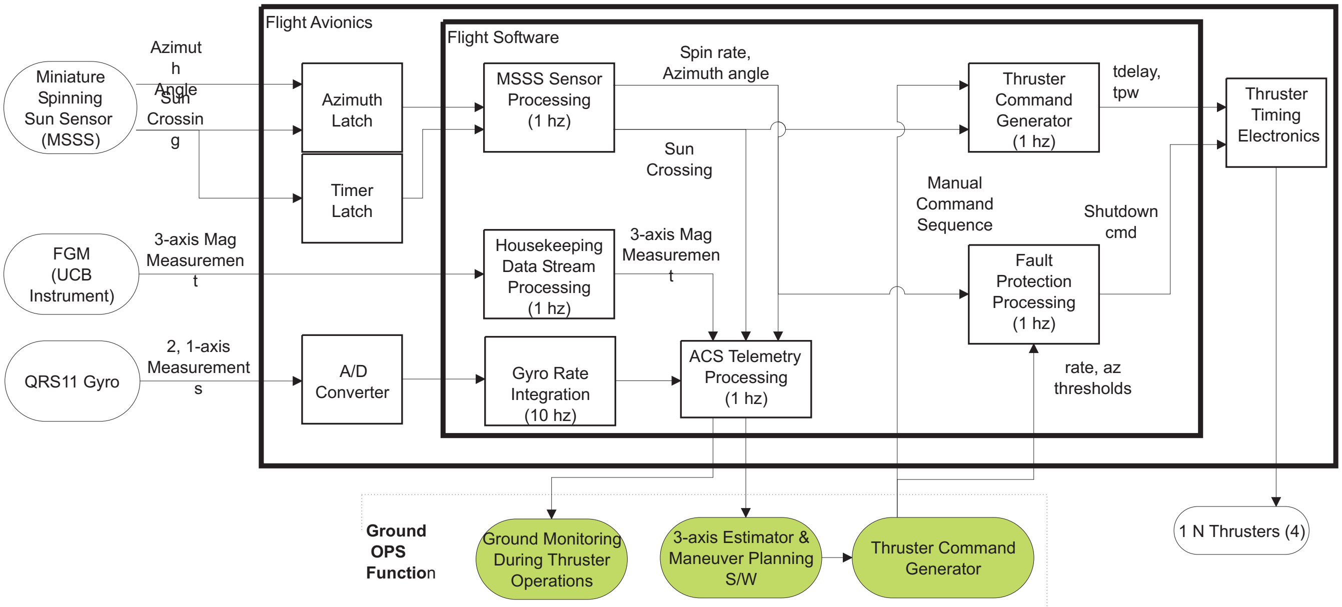


***Figure F-9** ACS subsystem block diagram*

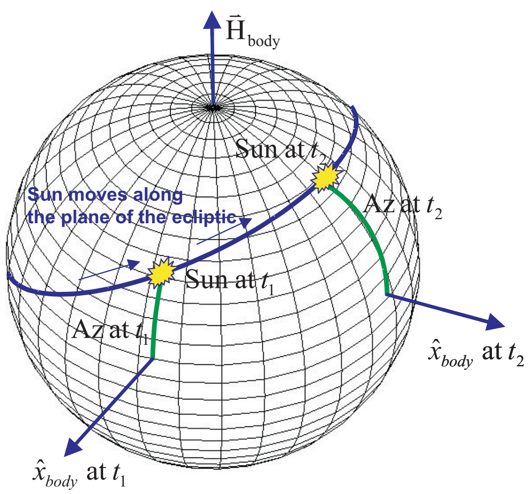


***Figure F-10** Attitude estimation scheme using two measurement points separated by an extended period of time.*

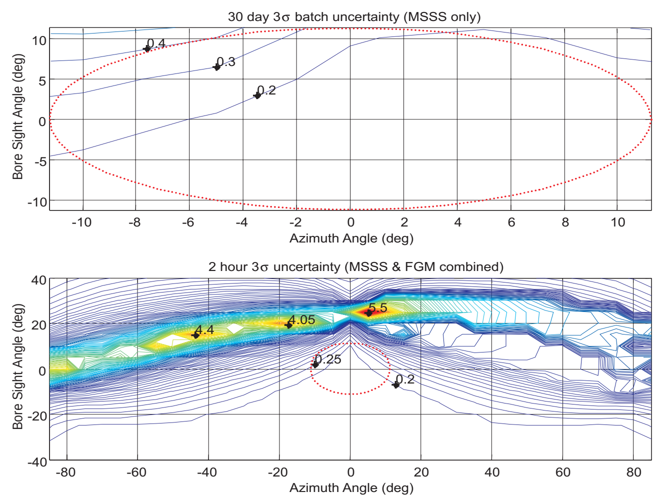


***Figure F-11** Estimation performance for the MSSS-only and the TRIAD methods*

sensor misalignment, noise, measurement inaccuracies, and data latencies. The error range for MSSS (utilized for science operations only) is narrower than that of the TRIAD approach, with the latter providing a more robust operating envelope for maneuver operations. The 11.25^{o} operational zone is also shown for the TRIAD scheme.

Two, single-axis gyros transverse to the spin provide short-term attitude verification as a separate diagnostic to TRIAD-derived rates prior to orbit maneuvers. Sampled at 10 Hz and telemetered at 1-10Hz for ground verification. This accommodates large angle changes in support of early mission orbit tuning maneuvers. The “tip-axial burn-tip” sequence can be accomplished safely in a couple hours, minimizing thermal transient effects.

Thruster Control: Thruster control is implemented using (4) 1-N thrusters: 2 oriented axially (both along +Z) for primary In Orbit Checkout (IOC) ΔV; and 2 oriented tangentially for spin up/down control and minor ΔV side-thrusting during science operations. A minimum pulse width of 1 sec is used for sizing and pulse placement (conservative, easily achieved). The tangential thrusters are placed on either side of the probe z-axis center-of-mass to decrease the potential for transverse torque disturbance during side thrusting.

The ground computed thrust command sequences utilize one of three modes: 1) Sun synchronous pulsing (triggered by MSSS sun-crossing indicator) for spin axis re-orientations and side-thrusting; 2) Continuous fire commanding for major orbit maneuvers; 3) Thruster pulse trains capable of dead-beating nutation or wire boom librations during spin adjusts.

Ground-based Command Generation and Monitoring and Flight Fault Protection: Orbit determination is accomplished via coherent ranging with the probe transponder. Thus orbit maneuvers entail a simple set of thruster commands and mode selection. Additional commanding arms and executes each sequence; all burns are executed during contact with the MOC enabling near-real-time performance monitoring. Each step is closely monitored and used in the planning of the next step; through interleaved orbit determination periods, thrusters can be calibrated to account for temporal performance variations.

ACS Performance Analysis: A high fidelity simulation included: 6 degree of free motion of the spin stabilized probe, EFI wire booms behaving as rigid rods with two degrees of freedom at their base, 4 flexible booms orientated on the probe consistent with the axial EFI's and the magnetometer booms, MSSS and FGM models, and a thruster model producing force and torque reactions. All aspects of this model have been validated against first-principles and compared with literature of analyses/data for these similar systems utilized on many prior missions (GGS, Polar, FAST, Cluster).

Passive Nutation Damping: Passive nutation damping was verified to ascertain damping time constants for the following cases: fuel frictional damping on stowed probe with 75% and 25% fill fractions, fuel damping on deployed probe case with 25% fill, and, EFI wire boom cable damping on deployed probe. Fuel damping with at 25% fuel fill fraction and an initial nutation angle of 10 degrees damps below 0.1 degrees in less than 5 minutes (stowed) and in less than 12 minutes (fully deployed). Using a conservative damping ratio of 0.05% for EFI booms, we assess the time required to damp out a conservative initial 30 deg wire boom deflection in symmetric and asymmetric orientations. Figure F-12 demonstrates acceptable damping times for the symmetric case (top, linear velocity oscillates in response to the libration) and the asymmetric case (bottom, spin rate undulates).

Mission Phase Validation: The design was evaluated relative to the full mission profile. Table F-8 outlines the results and validates the ACS subsystems capability to execute the initial ascent, deployment, and science operations.

Orbit Raising. Shows the ability to do large attitude precession and orbit maneuvers. A 75 deg precession is demonstrated to show a worst-case condition for the control system. In all cases, burn attitude was verified to < 5 degrees using the integrated gyro data. Figure F-13 shows the attitude error during this maneuver. The burn times

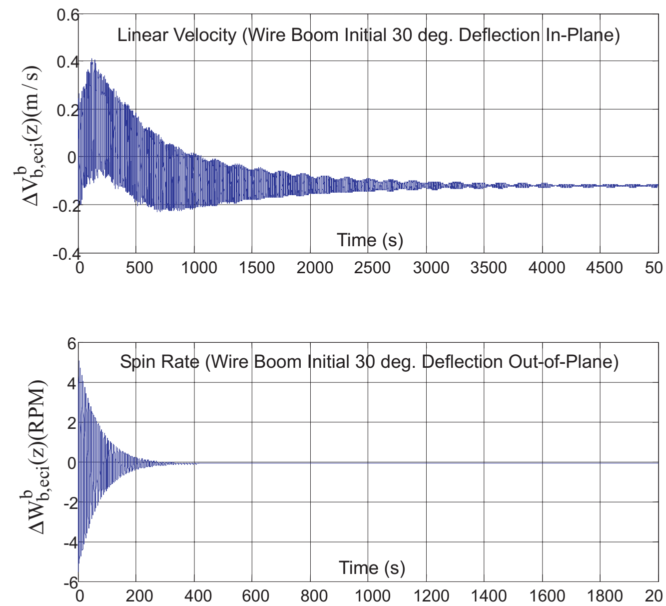


Figure F-12 *EFI wire boom damping in and out-of-plane initial deflections*

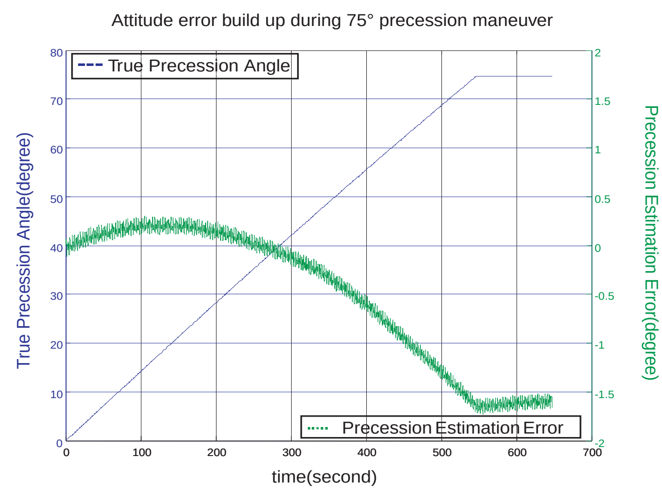


Figure F-13 *Attitude error of 75 degree precession maneuver*

conservatively reflect twice the longest burn required for P1 (limiting worst-case probe).

Mag. Boom Deployment and Spin-up. Verifies positive spin-axis stability (via favorable resultant inertia ratios) considering each boom deployed individually (failure mode case survivability).

Nominal EFI Wire Boom Deployment. Verifies positive stability and sequence during nominal EFI wire boom deploy and respin (back up to desired 30 rpm spin rate) activities. Wire-booms are deployed in pairs in six stages each to envelope the sequence and worst-case wire boom deflections

Off-Nominal EFI Wire Boom Deployment. Verifies positive stability and sequence during worst-case dynamic conditions resulting from failure mode cases. Each wire-boom was deployed in-

Run	Deployed Configuration	Initial/Final Spin (rpm)		Operational Action	Thruster Usage and (Duration:sec)	H vector (deg)	Spin (rpm)	Δv(z) (m/s)	Δv(x,y) (m/s)	WBΔ (deg)
Orbit Raising Operations in Configuration										
1a	Slowed	30.0	30.0	75° Precession, open loop	A1 w/MSSS (285)	1.30	2.50	2.10	1.60	n/a
1b	Slowed	20.0	20.0	75° Precession, open loop	A2 w/MSSS (134)	1.00	1.20	0.96	0.78	n/a
2a	Slowed	30.0	30.0	Axial ΔV, 2 max DV (P1)	A1/A2 continuous (240)	0.01	0.07	4.76	0.01	n/a
2b	Slowed	20.0	20.0	Axial ΔV, 2 max DV (P1)	A1/A2 continuous (240)	0.02	0.07	4.76	0.01	n/a
3	Slowed	30.0	15.0	Pre-Mag Boom deploy	T1 continuous (68.0)	0.17	0.05	0.05	0.01	n/a
Mag-Boom Deployment and spin-up										
4	FGM out	15.0	13.5	Show stability/ PA misalign	none	Inertia ratio computed to be 1.045				n/a
5a	FGM/SGM out	13.5	12.3	Show stability/ PA misalign	none	Inertia ratio computed to be 1.0457				n/a
5b	FGM/SGM out	12.3	30.0	Spin up for WB deployed	T2 continuous (42.5)	0.38	0.47	0.07	0.01	n/a
Nominal Wire Boom Deployment Sequence										
6a	WB 1&3 half out	10.0	30.0	Intermediate Spin-up	T2 continuous (270.5)	0.18	0.77	0.16	0.01	20.61
7a	WB 1&3 full out	10.8	30.0	Intermediate Spin-up	T2 continuous (779.4)	0.09	2.20	0.28	0.02	11.31
8a	WB 1&3 full out, WB 2&4 half out	24.2	30.0	Intermediate Spin-up	T2 continuous (281.6)	0.01	0.25	0.05	0.007	2.27
9a	All WB full out	19.8	20.0	Intermediate Spin-up	T2 continuous (15.1)	0.00	0.04	0.00	0.003	2.31
Off-Nominal Wire Boom Deployment Sequence										
6b	WB 1 out	6.4	30.0	Intermediate Spin-up	T2 modulated (544.7)	0.13	0.34	0.18	0.17	15.20
7b	WB 1&3 out	16.8	30.0	Intermediate Spin-up	T2 continuous (535.8)	0.02	0.22	0.15	0.01	5.12
8b	WB 1&2&3 out	20.8	30.0	Intermediate Spin-up	T2 continuous (534.6)	0.02	0.69	0.05	0.25	11.86
9b	WB 1&2&3&4 out	19.9	20.0	Intermediate Spin-up	T2 continuos (7.5)	0.02	0.27	0.002	0.01	2.29
Axial Boom Deployment Sequence										
10	Axial Boom 1 out	20.0	20.0	Show Stable @20 RPM	none	Inertia ratio computed to be 1.058				n/a
11	Axial Boom 2 out	20.0	20.0	Show Stable @20 RPM	none	Inertia ratio computed to be 1.062				n/a
Science Mode Operations and Passive Boom Libration Damping Verification										
12	All deployed	20.0	supply	Precession of 30 degrees	A1 w/MSSS (900)	2.70	0.10	8.20	2.30	2.30
13	All deployed	20.0	supply	Side Thrusting ΔV	T1/T2 for 140 sec	0.005	0.02	0.03	0.02	1.27
14	All deployed	20.0	supply	Axial Thrusting ΔV	A1/A2 for 140 sec	0.02	0.01	2.68	0.002	0.93
15	All deployed	20.0	supply	30° WB deflect in plane	none, 0.05% WB damping	Damping time < 0.1 deg is 16.6 min				< 0.1 deg
16	All deployed	20.0	supply	30° WB deflect out of plane	none, 0.05% WB damping	Damping time < 0.1 deg is 87 min				< 0.1 deg

Table F-8: *Analysis Results for Nominal & Extreme Probe Dynamic Configurations*

dividually to induce worst-case mass property asymmetry. Re-spin activities were performed consistent with the nominal analysis.

Axial Boom Deployment. Verify positive stability and sequencing.

Science Ops. & Passive Wire boom Libration Damping. Precession and delta-V maneuvers were executed on fully deployed probe, based upon twice the longest maneuver required by P1 during the science operations (again, P1 is the limiting worst case probe). Burns were executed via T1/T2 side thrusting and A1/A2 axial thrusting. The precession maneuvers bound the spin-axis precession adjustments (occur once/three months during science ops). Figure F-14 shows performance of a 30 deg precession (conservative without wire boom damping) resulting in excellent control stability, thus bounding actual conditions (wire boom damping adds

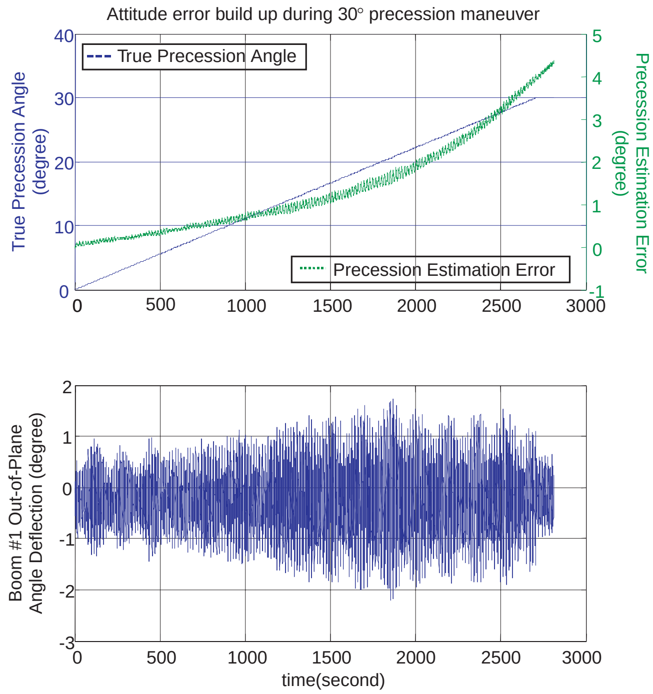


Figure F-14 *Attitude error build-up during 30^o precession maneuver*

additional stability margin).

e2. Reaction Control System (RCS)

A blow-down mono-propellant hydrazine system, with nitrogen gas as the pressurant, provides the best balance of simplicity, reliability, mass efficiency, mass symmetry, and heritage to meet the mission requirements. Two propellant tanks, two latch valves, four 1N thrusters (I_{sp}~215s), and additional ancillary fluid components are used (Figure F-15). The RCS draws its heritage from the ACE and ISEE programs and Swales's successful EO-1 mission. Although other RCS architectures (for instance, no interconnect with each tank addressing a thruster pair, the step-1 design) were analyzed, they resulted in a sub-optimal design, sacrificing one or more of mass, reliability, operational simplicity, stability, launch range safety complexity or cost.

Latch valves are located strategically to prevent propellant migration during the launch phase of the mission; Once opened, prior to first thrusting, both latch valves remain open for the duration of the mission taking advantage of the *self-stabilizing* propellant equilibration, realized on ACE and ISEE, that is inherent to this design configuration. Two heritage (PSI #80321) forged titanium propellant tanks accommodate a total propellant load of 34.52 kg and take advantage of PSI's wealth of experience in providing such propellant tanks. Propellant loading is accomplished through a single fill valve, however an additional Fill/Drain valve has been included to satisfy launch site range safety re-

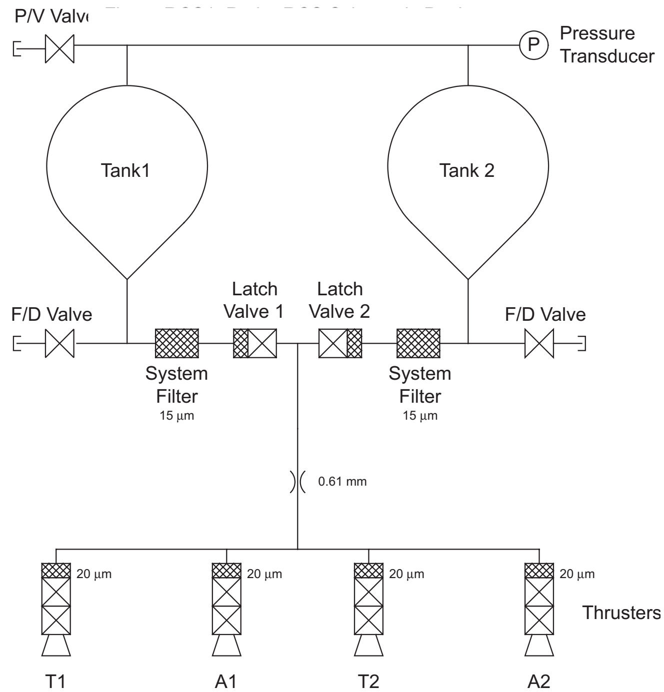


Figure F-15 *Probe RCS schematic design*

quirements for contingency propellant off load.

Thermostatically controlled tank, line and thruster heaters ensure propellant temperature maintenance comfortably above its freezing point of 0^o C. Thruster catalyst bed heaters, controlled by the BAU, preheat the catalyst bed and prevent cold-start degradation.

The RCS system has a key long-lead item (propellant tank forging purchase) that will be procured early in the program to ensure that downstream fabrication of the RCS is maintained. We have included appropriate schedule margin and I&T flow workaround strategies in our baseline schedule plan. The THEMIS orbits and ΔV budget (Table F-2) were analyzed extensively in Phase A in order to validate the RCS system sizing. The resultant propellant budget (Table F-9) shows that the propellant usage summary for each probe includes the orbit maneuver ΔV (from the ΔV budget) and ACS operations. Since all probes share a common RCS design, it is evident that P1 is the limiting ΔV case. P1 has reserve propellant associated with possible usage of the dry mass reserve and additional high levels of unallocated margin. P2-5 have much higher system reserves and margins as they have lower orbit ΔV requirements.

A P3/P4 contingency analysis verified that either probe can execute their own baseline mission maneuvers and subsequently replace any other failed probe by executing that probe's orbit maneuvers (with fully mature dry mass and fuel margin at the end), thus satisfying the THEMIS constellation reliability strategy (again, P1 is limiting case).

Analysis Condition	Probe Operational Parameter	P1	P2	P3	P4	P5
Base Mass Propellant: *(Using Predicted Probe Dry Mass and Nominal Maneuver/Operations Profile)*	**Delta-V Propellant**					
	Delta-V Total (m/sec from Delta-V Budget)	569	350	39	39	472
	Delta-V Maneuver Propellant Subtotal (kg)	***19.63***	***11.42***	***1.19***	***1.19***	***15.90***
	Attitude and Spin Control Propellant					
	(1) Initial Despin for Mag. Boom Deploy	0.05	0.05	0.05	0.05	0.05
	(1) Magnetometer Boom Deploy Respin	0.05	0.05	0.05	0.05	0.05
	(12) Orbit Maneuver Attitude Reorientation	0.47	0.47	0.47	0.47	0.47
	(1) EFI Wireboom Deploy Respin	0.59	0.59	0.59	0.59	0.59
	(8) Seasonal Precess (16 deg/3 mo's)	0.24	0.24	0.24	0.24	0.24
	Attitude and Spin Control Propellant Subtotal (kg)	***1.40***	***1.40***	***1.40***	***1.40***	***1.40***
	Base Propellant Subtotal (kg)	***21.04***	***12.82***	***2.59***	***2.59***	***17.30***
Reserve Mass Propellant: *(Accommodates Full Utilization of Dry Mass Reserve)*	***Delta-V Maneuver Propellant Subtotal (kg)***	***2.81***	***1.63***	***0.17***	***0.17***	***2.28***
	Attitude and Spin Control Propellant Subtotal (kg)	***0.37***	***0.37***	***0.37***	***0.37***	***0.37***
	Reserve Propellant Subtotal (kg)	***3.18***	***2.00***	***0.54***	***0.54***	***2.65***
	Reserve Propellant (% of combined ACS & dV fuel)	***15%***	***16%***	***21%***	***21%***	***15%***
Tank Capacity (4:1 Blowdown Ratio)	*Limit Fuel Mass (kg)*	34.52	34.52	34.52	34.52	34.52
Usable Excess Propellant in Tank (Relative to Tank Capacity)	*Fuel margin Mass (kg: Limit Fuel Mass - Reserve Propellant - Base Propellant)*	10.30	19.70	31.38	31.38	14.57
Propellant Margin	***Margin Available: Propellant Mass (kg)***	***10.30***	***19.70***	***31.38***	***31.38***	***14.57***
	Margin: Propellant (% of combined ACS& dV fuel)	***43%***	***133%***	***1001%***	***1001%***	***73%***

***Table F-9**: Probe Propellant Budget, Reserve, & Margin Summary*

Our plume impingement assessment verified that the majority of propellant products are contained within a ~30^{o} total plume angle, during continuous tangential thrusting, with thermal cooling to acceptable levels at ~0.3 meters (EFI wire boom closest item to outer edge of plume cone at 0.6m).

f. Power

The power system is a Direct Energy Transfer (DET) system with the battery and solar array connected directly to the power bus. The solar array power control and battery charging are performed using linear and sequential switching shunts.

The solar array (EMCORE), consists of eight panels, four on each side, two on each deck (Figure F-2). At nominal attitudes ~59W (EOL) are provided by the side panels. Accounting for battery recharging, increased eclipse heater power, and power control efficiencies the minimum load power available is 41.5W, easily achieving energy balance for the required load power of 31W (includes reserve). The top and bottom panels ensure survive at off-nominal attitudes in a reduced power mode (>21W EOL). High efficiency, heritage (Echostar, Insat-4, and Cryosat) triple junction Gallium Arsenide solar cells (4 x 6 cm, avg. BOL efficiency of 27.5%) are arranged in four strings per side panel and two strings each for the top and bottom. Each string has 20 series cells with integral bypass diodes to minimize shadowing effects. The overall solar array is divided into five segments, each segment consisting of four strings in parallel. Two of the segments are connected directly to the power bus for fault tolerance, and the other three segments are controlled via individual shunts to regulate the flow of power from the solar array. Power positive levels are still achieved, even under the unlikely fault condition of a single failed shunt. Their cerium doped, 8 mils thick, cover glass is treated with a UV reflective coating. External ITO coating (using a previously flight-proven vendor qualified process) provides electrical conductivity & electrostatic cleanliness.

Eclipse and peak transient loads (i.e. transmitter operation) are balanced with a 10.5 A-hr, 28V Yardney Lithium-Ion battery. LiIon is ideal due the outstanding energy density (325 WH/L) and specific energy (150 WH/kg) performance. The selected battery is based on the fully qualified Mars Exploration Rover (MER) battery (identical cells to the MER battery). Thermal management using heaters and thermistors keeps the battery at -5 to +25^{o}C.

The two-year THEMIS mission is characterized by many full sun and short eclipse orbits (durations of 0 to 60 min). There are brief periods (about 60 orbits) when eclipse durations gradually increase to a peak of 180 minutes. The battery depth-of-discharge (DOD) for this extreme case is about 50% (even with maximum heater power use and assuming baseline plus contingency power usage). The anticipated DOD and charge/discharge profiles are easily handled by Li-Ion batteries and ongoing battery life cycle tests at Yardney show over 1500 cycles at 100% DOD at room temperature and over 1000 cycles at -20°C with nominal resultant performance, easily bounding the THEMIS maximum number of shadow cycles of ~500.

The BAU power card controls solar array shunts, regulates battery charging, distributes power to loads and provides CMD/TLM interfaces to the probe C&DH subsystem. The battery is charged at a fixed rate until the battery voltage reaches a preset limit (command selectable), when the charge current switches to trickle charge. The upper voltage limit is selected conservatively so that no cell balancing is required. The BAU has the ability to shed non-critical loads from the IDPU under fault conditions (over-current or battery under-voltage).

The electrical harness uses NASA/PPL-21 flight proven wires, D connectors, braided shielding, and wide bend radii with any segment having an external braided shield tied to the probe common single point ground (SPG, emanates from the power bus). The solar cell cover glasses are interconnected by flexible conductive epoxy, consolidated to a local tie point, providing a bleed-path to SPG, to control electrostatic surface charge. Twisted shielded pairs are used for differential signals to minimize EMI noise and all signals are low voltage. The structure elements have conductive, adhesively bonded, surface charge control strips tying the structure to SPG. MLI thermal blankets have each layer conductively grounded to a local tie point, referenced to SPG. Additionally, the RF antenna has a bleed path to dissipate surface charge.

g. RF Communications Subsystem (RFCS)

The RFCS provides the RF interface between the probe and the THEMIS ground station network (BGS, USN/Perth, DSN/RID, TDRSS/SA; Section F7.d4/5). The RFCS performs command reception, telemetry modulation, and two-way ranging. The RFCS consists of an S-band transponder, diplexer, and a single spin-axis omni-directional, low gain antenna. The antenna design is based on the FAST antenna and is a wrap-around microstrip patch antenna array mounted on a standoff on the spin axis. The antenna provides sufficient gain in a 45° band about the plane perpendicular to the spin axis and enables high data rate communication. Reliable communication is achievable even outside this region (at reduced data rates), with the exception of the anomalous condition in which obscuration of the antenna from the probe body might occur. Even if such an anomalous attitude condition might occur, the outage would only last for a small fraction of the orbit ensuring, even during a failure mode, that positive communication occurs at least once per orbit.

The L-3 Conic CXS-610 transponder has extensive heritage from NASA and military missions. The uplink signal from the antenna is passively coupled to the receiver (no switches in the receive path) and is always powered. The receiver accepts the RF signals, demodulates command signals, and outputs data and timing to the BAU. The 5W transmitter accepts the base band telemetry signal, from the BAU, then directly phase modulates it onto the carrier. The transponder is also operated in a coherent mode that provides turn-around ranging capability to the MOC.

The uplink and downlink modulation and coding schemes conform to CCSDS standards. Command data at a fixed rate of 1000 bps is used to synchronously BPSK modulate a 16-kHz sinusoidal sub carrier, that in turn phase modulates the RF carrier that is transmitted to the probe. The uplink signal contains a residual carrier component that is used by the receiver to coherently recover the carrier. For the downlink, direct carrier phase modulation by telemetry data (variable rates) is employed. The downlink signal also contains a residual carrier component that can be used by the ground station to coherently recover the carrier. Error control coding for the downlink is provided by a concatenated coding scheme, with a convolutional inner code and a Reed-Solomon outer code.

Item	Value	Comment
EIRP	66.0 dBW	BGS
Space Loss	-204.5 dB	$R_a = 30.943R_e$
Receive Gain	-5.0 dBi	Antenna
Receive Loss	-0.5 dB	Circuit
Other Losses	-1.0 dB	Polarization, pointing, etc.
Received Pwr	-145.0 dBW	
Required Pwr	-151.0 dBW	1kbps, 10^{-6} BER
Margin	6.0 dB	

Table F-10: *Uplink Budget to P1 apogee (30R_E)*

Robust link margins exist for the uplink, analyzed for the worst case of P1 at apogee (see Table F-10). The downlink also has excellent link margin and is capable of multiple telemetry rates (ranging from 1 kbps to 400 kbps) with the maximum rate used for routine stored data playback at a range of <20,000 km. Alternatively, our 5 kbps downlink telemetry rate has +7.1 dB margin from P1 (highest) apogee, ensuring that all probes have a comfortable housekeeping downlink at all orbit positions.

Item	Value	Comment
EIRP	3.5 dBW	
Space Loss	-185.5 dB	$R_p = 3.25R_e$
Other Losses	-1.0 dB	Polarization, pointing, etc.
Data/Total Pwr	-1.0 dB	1.1 radian mod index
Ground G/T	24.0 dB/K	UCB Ground Station
Data Rate	400.0 kbps	
Received E_b/N_o	12.6 dB	
Required E_b/N_o	3.1 dB	RS+Conv, 10^{-6} BER
Loss	1.5 dB	Implementation
Margin	8.0 dB	

Table F-11: *Downlink Budget from 20,000 km*

h. Command and Data Handling Subsystem (CDHS)

The CDHS: 1) provides real-time and stored command capability for the bus subsystems and instruments; 2) collects, formats, and transmits, to the ground, data from the bus subsystems and the instrument; 3) provides engineering data storage; 4) distributes time to the IDPU; and 5) implements autonomous fault protection features to ensure the health and safety of the probe. The CDHS functions are implemented in flight software (see F3.h2) and hardware that reside in the BAU (see F3.h1).

The CDHS receives uplink commands from the RFCS at a fixed rate of 1000 bps using CCSDS telecommand protocols that guarantee correct, in-sequence delivery of variable-length command packets (embedded in command transfer frames) to the probe. Command transfer frames are authenticated. The CDHS is capable of accepting hardware commands (commands that do not require processor involvement) to perform critical operations such as hardware reconfiguration from the ground. Commands sent to the probe will either be executed in real time or stored for later execution. Two kinds of stored commands are provided: Absolute Time Sequence (ATS) commands and Relative Time Sequence (RTS) commands. ATS commands have time tags (expressed in UTC times, with a resolution of 1 second) specifying an absolute time of day. RTS's are command sequences that include delays (programmable) between commands.

The CDHS collects and packetizes engineering data from the bus subsystems and the instrument. The formatted real-time engineering data is stored on board and sent to the transmitter when commanded. The CDHS provides bulk memory with built-in error detection and correction (EDAC) for storage of the engineering data (science data is stored in the IDPU). Playback data stored in bulk memory can be formatted into multiple segments, called virtual recorders, which allow for easy segregation of different types of data (bus engineering data, instrument engineering data, event files, etc.). The size of the virtual recorders is modifiable by the ground (allowing memory remapping to work around failed locations). Automatic overwrite capability (ground commandable) is also provided, with programmable guard-bands. The integrity of the data stored in bulk memory is maintained by a memory scrub software task that uses the EDAC to correct single bit errors. Operating at a low priority, the memory scrub task cycles through all the data stored in bulk memory once per orbit. The CDHS also accepts playback of science data from the IDPU and routs it to the transmitter. The CDHS maintains Universal Coordinated Time (UTC) onboard the probe and distributes time to the instrument in a 1-Hz pulse (PPS), sent to the IDPU to synchronize the bus and instrument clocks.

The CDHS provides several autonomous functions to ensure the health and safety of the probe when out of ground contact. A watchdog timer continuously monitors processor operations and is capable of restarting the processor automatically. A checksum routine checks memory at low priority. A telemetry and statistics monitoring function is provided which performs “limit check” operations on the data and maintains telemetry statistics so that it can initiate the execution of a stored command sequence if pre-specified conditions occur.

The CDHS utilizes system tables to implement operational controls and to ease ground system operations. System table operations constitute the primary ground interface for probe control functions such as stored command operations and modifications of on-board parameters. The CDHS also has the ability to build “memory dwell” packets to monitor any memory location for diagnostic support.

h1. Avionics

The Bus Avionics Unit (BAU) performs the probe C&DH, Power, and GN&C computation functions. A block diagram of the BAU is shown in Figure F-2 (foldout 4). There are three circuit card assemblies (Processor, Communications and Power) with a shared backplane. The processor card performs all required C&DH and computation functions, shares an identical design to the instrument IDPU processor card, and is derived from the STEREO/IMPACT instrument processor. The card contains a UTMC 80196 rad-hard micro-controller running at 16 MHz, with 8KB of boot-PROM, 256KB EEPROM of instruction storage memory, 1MB RAM of rad-hard SEU immune instruction execution memory, 16MB of telemetry storage memory, and several rad-hard FPGA's. The telemetry storage memory, used to store probe engineering data, is protected against single-event upsets (SEUs) by the use of EDAC, memory scrubs and a built-in watchdog timer. The processor card interfaces to the comm and power cards, the fine sun sensor, and the IDPU (for instrument status and FGM data). For all command and telemetry interfaces, the UCB standard CDI serial interface is used. A serial interface for diagnostic and testing purposes is also provided

The communications (comm) card receives the command bit stream from the receiver and provides CCSDS code blocks to the processor via the backplane serial interface. It processes a limited number of hardware-decoded commands that may be received from the ground and executed without processor intervention. It provides telemetry streams to the transmitter for downlink. The data may be real-time engineering, playback engineering data, or playback science data (from the IDPU). Multiple command selectable telemetry rates (ranging from 1 kbps to 400 kbps) are provided. All data are encoded with rate 1/2 convolutional encoding, and Reed-Solomon encoding. The comm card also provides a hard-line telemetry data stream for ground testing. The comm card derives its heritage from SMEX-Lite (Triana mission).

The power card processes solar array power, controls battery charging, generates and distributes secondary voltages, generates and distributes discrete commands, monitors separation signals from the L/V, and initiates probe self-separation from the probe carrier. The card also contains circuitry needed to condition and digitize analog signals on the probe including gyro rate signals and temperature sensors. Its heritage is derived from the Swales EO-1 flight power controller.

h2. Flight Software

THEMIS flight software development is based on heritage from the NASA GSFC Small Explorer missions including SAMPEX, FAST, SWAS, TRACE, and WIRE, SMEX-Lite/Triana, and the Earth Observer-1. All, except Triana, have been in operations for the past several years. THEMIS flight software, with a reduced set of functions (virtually no on-board ACS), is simpler than any of these missions providing a low risk solution that meets the THEMIS probe requirements. Hammers Co., the THEMIS probe bus software developer, is also chartered with the systems software design, implementation, and operations review of the ST-5 software development team. Early lessons learned from the highly analogous operations and functions of ST-5 will be captured prior to the initiation of the THEMIS software development.

Command & Data Handling (C&DH) software: The C-language flight software is organized as functional tasks scheduled by a prioritized multitasking COTS operating system (OS), CMX-RTX, from CMX Systems. The flight software operates in NORMAL mode. The initial BOOT mode loads the RAM with the ROM copy of code and data for execution. The full operational NORMAL mode, which meets all the mission requirements, is entered automatically from BOOT mode. NORMAL mode software executes from the faster RAM memory and is patchable during mission operations, if needed.

Utilizing the heritage EO-1 and SMEX-Lite, bus software module communications are controlled by the central processor. The UTMC 80196 is the probe communications handler and executes attitude sensor processing and stored command sequences needed for control of the spin-stabilized system. The flight software provides the CCSDS packets for both downlink and onboard memory storage for playback. The C&DH communicates with the IDPU via a serial interface, fully supported by the CMX-RTX OS. The probe processor exchanges health & safety information and ACS ancillary data with the IDPU. Figure F-16 illustrates the C&DH software subsystems. The C&DH and ACS flight software for THEMIS is a subset of the basic software functions for the FAST mission.

Attitude Control System (ACS) software: The ACS software generates telemetry via the bus, utilizes ACS sensor input data and issues thruster actuator commands via the serial interface. A command input capability allows the ACS to accept commands from the ground as needed and a telemetry generation capability allows the ground system to monitor the health of the ACS system as needed.

No closed loop control is required since all maneuvers are performed by ground command sequences during real-time contacts. The ACS control mode manager monitors ACS attitude errors to determine if the probe is within mission attitude limit. Appropriate software status telemetry is recorded for playback and ground analysis.

ACS software also uses a modular, table-driven design to maintain its configuration. This allows for re-configuration, as needed, with a minimum of code patches during operation. It also allows for rapid system testing and easier in-orbit checkout, since new parameter values (such as scale factors or biases) may be tested on existing code without rebuilding the software. The modular and table-driven approach to the software design greatly reduces software maintenance over the mission life.

Software Heritage/Reuse Analysis: Table F-12 presents the C&DH and ACS functional descriptions, heritage analysis and CPU utilization analysis. It illustrates that the software development risk

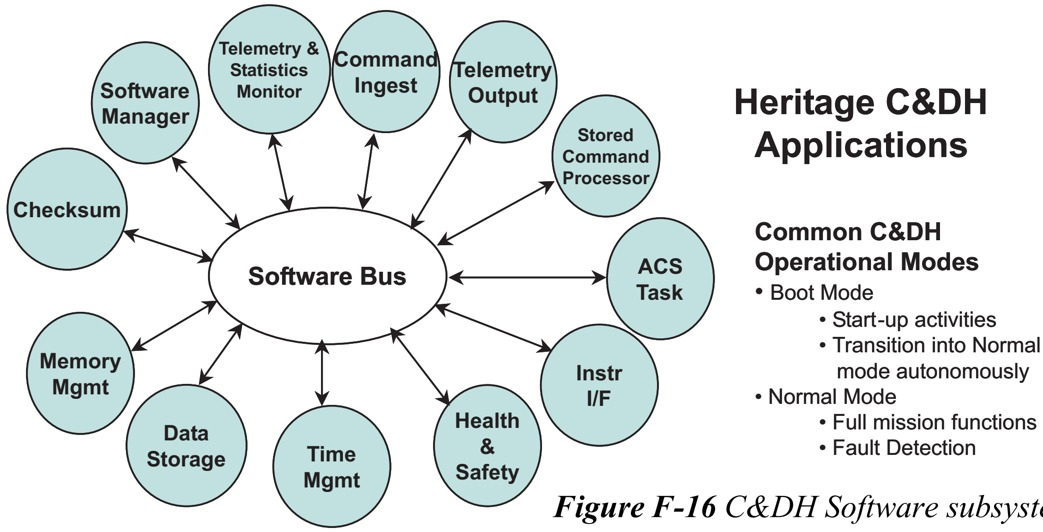


Figure F-16 *C&DH Software subsystems*

is greatly reduced by the amount of heritage from other programs.

The processor utilization is representative of our flight software system average on other NASA missions that utilized a CICS processor operating at 16 MHz. THEMIS utilizes an 80196 processor executing at 16MHz. The source lines of code (SLOC) estimate for the THEMIS flight software is ~ 40K SLOC. Percent utilization is the maximum amount of time the processor is spending in a subsystem's address space over a long-term average. Idle activities are defined as those activities that are non-essential over short time periods. Thus, we anticipate the CPU utilization to be well below 50%.

The flight software is grouped into three separate builds for the C&DH and ACS flight software subsystems. Build 1 includes the re-host of the heritage flight software reduced in complexity to fit the mission requirements, Build 2 completes the new design functions related to the ACS functions, and Build 3 is a 'clean-up' build of corrections after testing and preparation of environmental and comprehensive tests.The ACS and C&DH flight software is developed with COTS tools on a secure, networked PC-based environment. Tools include code authoring software (Codewright), compilers/linkers (CMX-RTX, GNU), version controllers (MicroSoft SourceSafe), software analyzers and metric tools (PC-Lint, PC-Metric).

We use the Internet based COTS package TeamTrack (as implemented on our work for NEMO, EO-1, Landsat 7, and ITOS projects) as our problem/issue tracking system capturing the initiation of an anomaly/change through the analysis, redesign, coding, build/regression/system-level testing, and acceptance. TeamTrack is linked to our I&T work order system.

Software Development: Our configuration management and control process activity includes the manual operations of configuration control boards to approve all changes to the requirements, design and code to the platform dependent software tools (i.e., CMS, CVS, Visual Source Save, RAZOR, etc.) needed to maintain the requirement and design documents and the source code.

Our CM system supports multiple branches of configuration controlled data (as is currently implemented for the SECCHI flight software on the STEREO mission with two probe flight and ground systems) in order to test the THEMIS probes as they progress through I&T and branch with unique table and database parameters in the flight software and ITOS ground system

i. Thermal Control System (TCS)

The main requirement on the S/C TCS is to control all subsystems within the probe central body to -15C and +60C, except the hydrazine in the RCS that has freeze protection limits described in the RCS section. A passive thermal design using Multi-Layer Insulation (MLI) and thermostatically controlled heaters has been selected as the best balance to achieve lowest mass, cost, and complexity. The probe spin axis is normal to the sun line within the ACS control limits of 11.25 providing an inherently stable thermal environment. Early orbit, delta-V maneuver, and anomalous attitude survival results are enveloped by a separate analysis case of fixing the sun directly along the spin axis; Results are within survival limits for these cases. The components with high power dissipation are mounted to the bottom avionics deck and experience a constant energy balance. The side panels have solar array cells with MLI trim and conductive isolators. Each corner panel and the top deck are covered with MLI to decouple them from the bottom panel avionics deck. The composite structure, panel isolation mounts, and internal MLI limit the conductive and radiative energy coupling paths, effectively decou-

Subsystem	Function	% Heritage Reuse	% CPU Utilization
Operating System & S/W Bus	Operating environment for defined tasks; Inter-task communication. Library functions	20	10
Stored Command Processor	Execute time based commands for instrument; activate downlink & playback of stored science & H/K data	40	2
Software Manager	Manage memory loads & dumps to accomplish flight s/w patch to NORMAL MODE CODE	20	4
Command Ingest	Receive, validate, distribute CCSDS command packets	40	2
Time Manager	Maintain & adjust time to subsecond resolution (32-bit sec., 16 bit subsec.)	40	2
Telemetry & Status Monitor	On-board health & safety monitoring	40	2
Housekeeping Telemetry Collection	Collects & formats H/K data into a CCSDS packet for storage and downlink	40	2
Data Storage	Format engineering & H/K data packets, & status, in CCSDS transfer frames for maintenance & playback	50	3
Telemetry Output (Downlink)	Control formation of real-time transfer frames containing system packet telemetry and the downlink of both real-time & playback frames interleaved	50	6
Instrument Manager	Supports interfaces with instrument for commanding and receipt of housekeeping data	New	3
Memory Scrub + Checksum	Scrubs memory and diagnostic checksums (background task)	60	1
ACS Tasks	Ingest ACS ground CMD's, initiate I/O buffers & data arrays, collect & process sensor/actuator data, ACS math functions, process thruster CMD sequences	30	8
Failure Detection & Correction	Provide ACS failure, detection and correction using health & safety data	New	2
Subtotal Average CPU% Utilization			47%

Table F-12 *Software heritage & CPU utilization.*

pling the bottom deck from the rest of the structure. Top and bottom deck solar cells are mounted on non-structural panels that are conductively insulated from those decks with G10 isolators and MLI to minimize heat loss from the bus when they are not in sun. MLI blankets cover all exposed areas of the probe exterior, decreasing the effect of on orbit en-

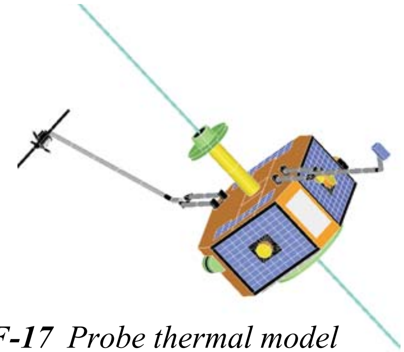


Figure F-17 *Probe thermal model*

vironmental changes leaving only sensor apertures, clamp band, and solar arrays exposed. Thermostatically controlled heaters augment the passive control as necessary for off-nominal and eclipse conditions. All thermal control hardware, coatings, and finishes have extensive heritage in similar earth orbits.

External MLI blankets are sized for hot environmental conditions and EOL properties. This design philosophy (EO-1 heritage) allows the blankets to be easily adjusted as the design matures. The majority of internal electronics have high emittance (> 0.8) coatings to enhance internal radiation exchange between these bottom deck components to minimize heater power. Since the RCS has unique thermal requirements (Survival range of 0 C to + 40 C),it is conductively and radiatively isolated from the bottom deck via G-10 isolators and MLI with its own dedicated thermostatically controlled heaters for lines, tanks, and thruster bodies.

Preliminary geometric math models (Figure F-17) utilize the Thermal Synthesis System (TSS) and thermal math models (SINDA) were constructed based on the thermal requirements and mechanical design. A simplified TSS geometric math model was created to obtain radiation exchange factors and environmental heating rates for the sink temperature calculations. The heat leakage for all six faces of the probe was used to determine the required heater power to survive the longest eclipse (P3/4/5: 3 hour shadow duration). Figure F-18 illustrates the temperature response of Probe 3/4/5 (Top Plot) and Probe 1 (Bottom Plot) and Table F-13 summarizes the P3/4/5 component temperature predictions for the longest shadow. The component temperatures are well within the required temperatures and the cold case heater power envelopes the allocation used in the power system eclipse performance evaluation.

j. Mass/Power/Heritage, Contingency/Margin, and Master Equipment List

Tables F-14 (probe carrier) and F-15 (single probe bus) are the Master Equipment Lists summarizing mass, power, reserve, and heritage by com-

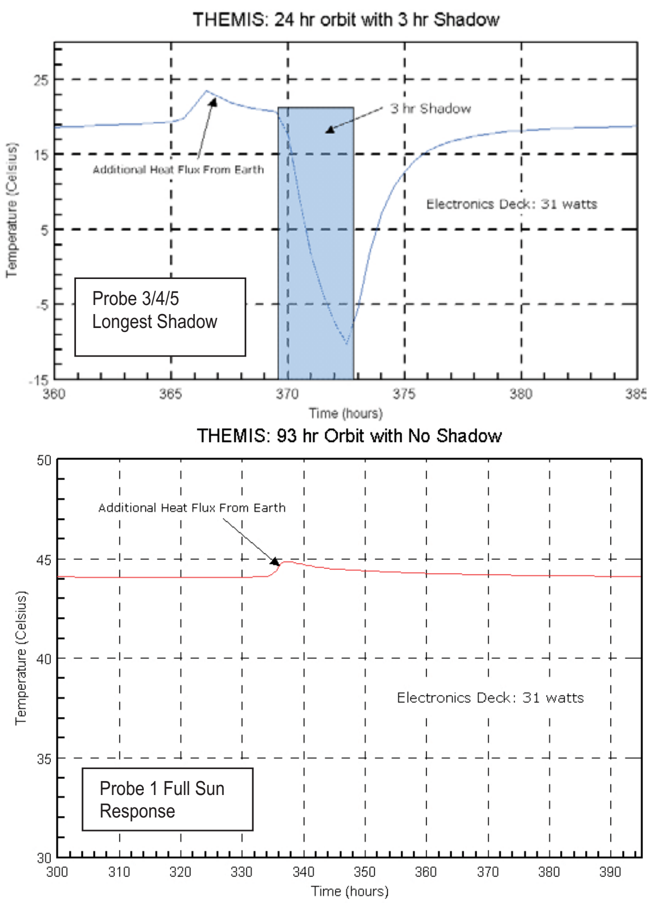


Figure F-18 *Probes 3/4/5 and Probe 1 transient thermal response of avionics deck*

ponent. Mature mass is the total mass plus the reserve shown and represents the maximum expected mass for that line item. Reserves are applied in accordance with Table F-5.

An analogous approach was used for power. These tables are a high level summary emanating from a more detailed spreadsheet. Vendor and part

Item	Hot C	Cold C	Heater Power *to Maintain Cold Case Temps* (W)
Electronics	+ 45	- 10	0
Battery	+ 25	- 5	4
RCS Tanks/Lines	+ 40	+ 10	8
Solar Array: Sides	+ 45	- 70	0
Solar Array: Top/ Bottom	+ 95	- 165	0
Instruments: Body Mounted (ESA & SST Chassis)	+ 43	+ 3	6
	Total		**18 watts**

Table F-13*: Probe 3/4/5 Temperature Predictions*

number data is shown with the most recent flight heritage. Component/subsystem heritage is a significant factor in item selection and all components are evaluated against worst-case requirements for our intended application. Additional Margin over and above the component reserves are maintained at the probe and mission level for mass and power as shown in Table F-4.

Subsystem	Component	Total Mass (kg)	Mass Reserve	Mature Mass (kg)	Total Power (W)	Power Reserve	Mature Power (W)	Vendor	Heritage
Mechanical	Deck (Al facesheets, Al core)	43.9	15%	50.49	0.00	0%	0.00	Swales	EO-1, FUSE
	Struts and Clevis Brackets	7.08	10%	7.79	0.00	0%	0.00	Swales	EO-1, FUSE, MAP
	Probe 1 Center Adapter	6.4	15%	7.36	0.00	0%	0.00	Swales	EO-1, FUSE
	PAF Adapter	14.4	15%	16.56	0.00	0%	0.00	Swales	EO-1, MAP
	Probe lower sep rings	9.05	10%	9.96	0.00	0%	0.00	Planetary Sys.	Starshine 3
	Misc.(Fasteners,insulators,etc)	4.73	30%	6.15	0.00	0%	0.00	Swales	EO-1, FUSE
	Balance Weights	1.98	20%	2.38	0.00	0%	0.00	Swales	EO-1
Thermal	Blankets	0.31	20%	0.37	0.00	0%	0.00	Swales	MAP, EO-1, FUSE
Electrical	Umbilical Harness	1.81	25%	2.26	0.00	0%	0.00	Swales	EO-1, FUSE
TOTAL		**89.66**	**15.2%**	**103.31**	**0.00**	**0%**	**0.00**	**(Reserve is a composite%)**	

Table F-14 *Probe Carrier Master Equipment List*

Subsystem	Component	Total Mass (kg)	Mass Reserve	Mature Mass (kg)	Total Power (W)	Power Reserve	Mature Power (W)	Vendor Model	Heritage
ACS	Fine Sun Sensor	0.25	10%	.28	0.13	10%	0.14	Adcole 46500	ST-5
	Gyro's	0.12	15%	.14	0.00	15%	0.00	Systron Donner QRS 11	DOD/missiles,upper stages, various S/C
BAU	CPU Board	0.50	20%	.60	1.50	20%	1.80	UCB	Stereo
	Communications Board	0.50	20%	.60	1.00	20%	1.20	Swales	SMEX-Lite,Triana
	Power Ctrl/Dist. Board	0.50	20%	.60	2.50	20%	3.00	Swales	EO-1, SMEX-Lite
	Chassis & Backplane	0.55	20%	.66	0.00	0%	0.00	Swales	EO-1, FUSE, Triana
RF/ Comm.	S-Band Antenna	0.10	15%	.12	0.00	15%	0.00	ARA or Ball	FAST
	S-Band Transponder	2.50	10%	2.75	5.25	15%	6.04	L3 Com CXS 610	EO-1, MAP, FUSE
Power	Side arrays w/o substrate	1.93	15%	2.22	0.00	0%	0.00	Swales/Emcore	Various Missions
	Deck arrays w/o substrate	1.08	15%	1.24	0.00	0%	0.00	Swales/Emcore	Various Missions
	Battery	2.75	15%	3.16	0.00	0%	0.00	Yardney	Mars Rover
Har-ness	Power, Data, RF Cables	1.45	23.5%	1.79	0.00	0%	0.00	Swales	EO-1, FUSE
RCS (propulsion)	Tanks	3.32	5%	3.49	0.00	0%	0.00	PSI: 80321	Hipparcos
	Tank Blankets	0.20	15%	0.23	0.00	0%	0.00	Swales	MAP, EO-1
	Heaters	0.04	15%	0.05	0.00	0%	0.00	Tayco	GPSII-F
	Thermostats	0.08	15%	0.09	0.00	0%	0.00	Elmwood	Bsat
	Fill/Drain Valves	0.35	15%	0.41	0.00	0%	0.00	Vacco V1E1057201	Coriolis
	Pressure Transducer	0.20	15%	0.23	0.00	0%	0.00	Paine 2137626002	TOMS-EP
	Filters	0.36	15%	0.42	0.00	0%	0.00	Vacco F1D10767-01	Iridium
	Propellant Lines	0.26	15%	0.30	0.00	0%	0.00	Various	Various Missions
	Thruster/Valve Assy	1.15	15%	1.32	0.00	0%	0.00	GD MR-103G	A2100, Iridium
	Latch Valve	0.56	15%	0.64	0.00	0%	0.00	Vacco V1E1074701	Coriolis
	N_2 Pressurant	0.35	15%	0.40	0.00	0%	0.00	Various	EO-1, MAP
Thermal	Blankets	0.60	15%	0.69	0.00	0%	0.00	Swales	FUSE, MAP, EO-1
	Heaters	0.10	15%	0.12	2.00	15%	2.30	Swales	FUSE, EO-1
	Thermostats	0.20	15%	0.23	0.00	0%	0.00	Swales	FUSE, EO-1
Mechanical	Core w/ Sep System	12.50	15%	14.38	0.00	0%	0.00	Swales	EO-1, FUSE
	Solar Array Substrate	2.75	15%	3.16	0.00	0%	0.00	Swales	FUSE, EO-1
	Brackets	0.62	25%	0.78	0.00	0%	0.00	Swales	EO-1, FUSE
	Tank Brackets	0.40	15%	0.46	0.00	0%	0.00	Swales	EO-1, FUSE
	Thruster Brackets	0.24	15%	0.27	0.00	0%	0.00	Swales	EO-1, FUSE
	Service, Connector, Latch Valve & Transducer Brackets	0.44	15%	0.50	0.00	0%	0.00	Swales	EO-1, FUSE
	Antenna Boom	0.40	25%	0.50	0.00	0%	0.00	Swales	EO-1, FUSE
	Misc. Hardware	1.66	25%	2.08	0.00	0%	0.00	Swales	EO-1, FUSE
	Balance	2.00	15%	2.30	0.00	0%	0.00	Swales	EO-1
TOTAL		41.00	15.1%	47.18	12.38	17.0%	14.48	(Reserve is a composite%)	

Table F-15 *Probe Master Equipment List*

F4. SCIENCE PAYLOAD

a. Overview

THEMIS relies on heritage instruments, provided by institutions with long record of successes in on-time, on-budget delivery and flight performance of the same instrumentation to NASA and ESA. Owing to this heritage, a clear understanding of specifications, fields of view, pointing and probe bus accommodation requirements is available. For the same reason, fabrication and I&T schedules, delivery points, test procedure, GSE and manpower needs were derived from high-confidence bottom-up estimates, backed by vendor quotations of parts, and cross-checked against previous flight-unit deliveries of multiple (in most cases of a comparable number to THEMIS) units. Probes are identical in design; a vigorous configuration management and quality assurance program assures that instruments remain perfectly characterized with changes tracked throughout the I&T process.

The five THEMIS instruments (FGM, ESA, SST, SCM, EFI) have been introduced in Section E2a (a1 through a5 in that order). They will be described in further detail in Section F4.c (c1 through c5 in the same order). A common instrument data processing unit (IDPU) is used to house most analog and all digital electronics, data processing, packetizing and storage, power conditioning and boom deployment. This enables a common-parts-buy program and facilitates integration and testing as well as interfacing with the probe bus avionics unit (BAU). This approach is based on UCB's experience with the FAST, HESSI and STEREO/Impact IDPUs. The THEMIS IDPU is described in Section F4.d.

Instrument specifications (mass, power, sensor dimensions and data rates) have been tabulated at a subsystem level in the table inserts of Figure E-13 (Foldout 2). A top-level weight and power summary of the THEMIS instrument complement appears also in Table E-5. The detailed instrument mass, power and thermal requirements appear in (this) Section F4, in Figure F-19 (Foldout-6).

Design features of the instrument complement that reduce development, integration, calibration and testing costs are summarized in Table F-16**.** The instrument build philosophy is to first take advantage of a parallel build in the manufacturing and integration process through techniques such as numerical milling and wave sauter. Subsequently the plan is to use instrument core teams of cognizant scientists and technicians, supervised by senior developers, to perform calibration and testing in a 1+2+2 fashion, minimizing T/V chamber usage with a single core I&T team per instrument. Additional design features are explained in individual instrument sections F4.c1-c5.

b. Instrument accommodations

Figure E-13 (Foldout 2) introduced the probe bus accommodation of the instruments (see THEMIS probe with instrument mounting locations shown within). The ESA and the SST instruments are body-mounted. The FGM and SCM are mounted on one-probe-diameter and two-probe-diameter carbon-epoxy booms respectively. Booms are built at UCB to the heritage of FAST and Lunar Prospector (see images in Figure E-13/B). The FGM deployment sequence is shown in Figure F-19**.**

Feature	Cost effect
Instruments chosen built in multiple copies before	Manufacturability & ease of I&T in pre-existing design
Common parts buy and electronics built program	Minimum orders, parts screening and QA efficiently used
Parallel processing: numerical milling, wave sautering	Heritage techniques (Cluster, ISUAL) ideal for multiple units
Centralized IDPU	Minimizes bus interfaces, reduces risk, controls quality
Instrument I&T w/ flight IDPU and probe simulator prior to probe I&T	Reduces: # of GSEs, # of distributed I&T teams and scale of I&T program at Swales

Table F-16 *Cost-reducing features common to all THEMIS science instruments*

The EFI sensors are mounted on spin-plane cables (EFI spherical sensors) and on axial stacers (EFI tubular sensors). The spin-plane boom cable deployment process is shown in Figure F-19**.** The EFI booms and their deployment mechanisms are built at UCB based on heritage from dozens of previous flights on rockets, balloons and spacecraft with most recent experience on Cluster I (16 units) and Cluster II (another 16). The FGM, SCM and EFI booms and deployment mechanism requirements have been included in the instrument complement requirements in Figure F-19 (Foldout 6).

The ESA and SST instrument fields of view (FOV) and the deployed EFI and FGM/SCM configurations are shown also in Figure F-19. The ESA and SST clear the deployed FGM and SCM booms by a margin of >5^{o}. Spin-plane EFI cable booms are within the FOV of the SST sensors but are thin enough such that they have no impact on the data quality of those sensors.

c. Instrument characteristics

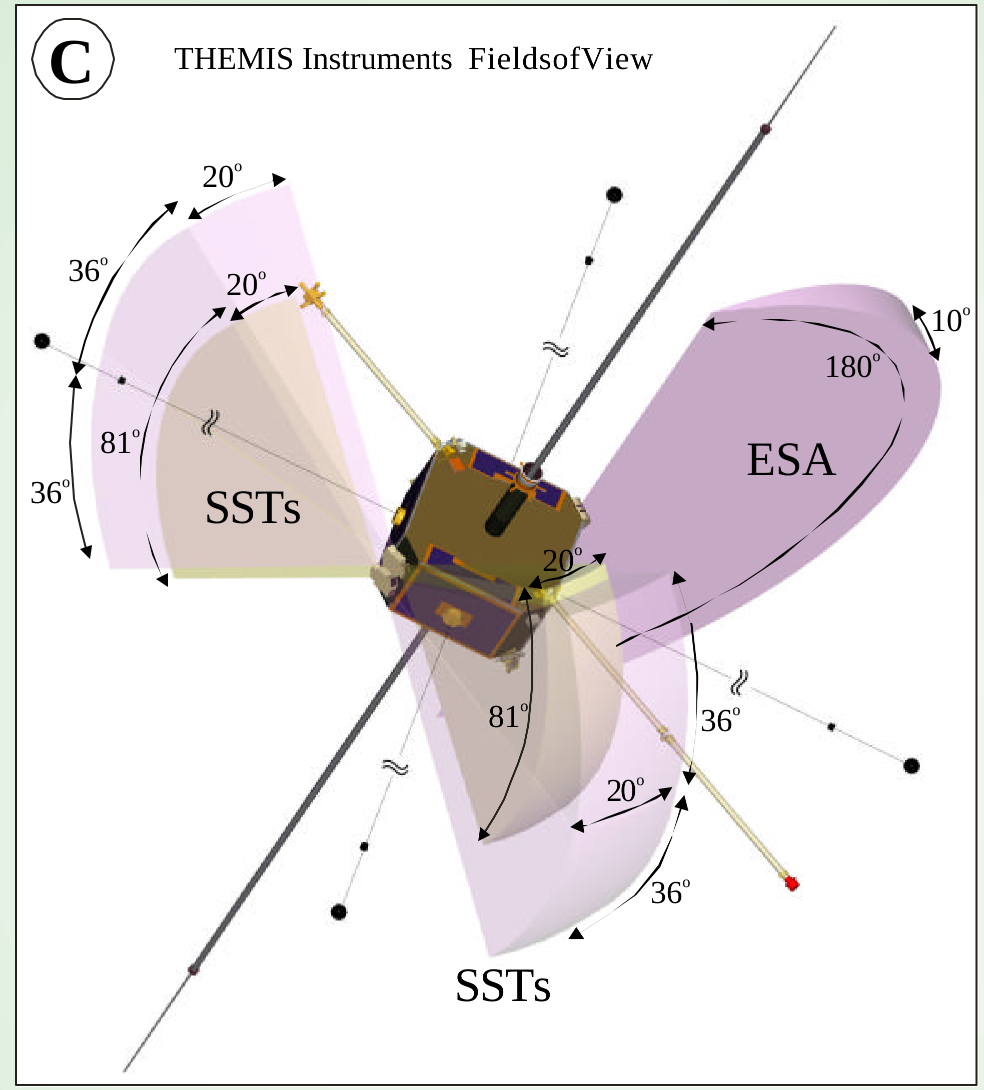
c1. Fluxgate magnetometer (FGM)

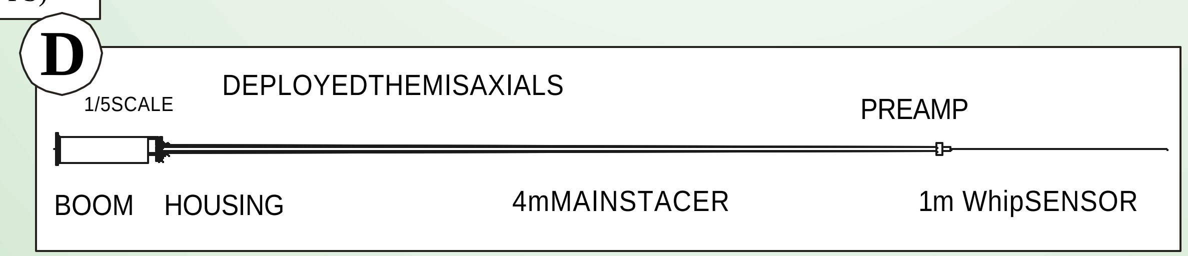
The FGM measures the 3D magnetic field in the frequency bandwidth from DC to 64 Hz (Nyquist). The FGM instrument overview is described in Section E2.a1, including the overarching measurement requirements. Mission requirements and instrument specifications in adherence to those are shown in

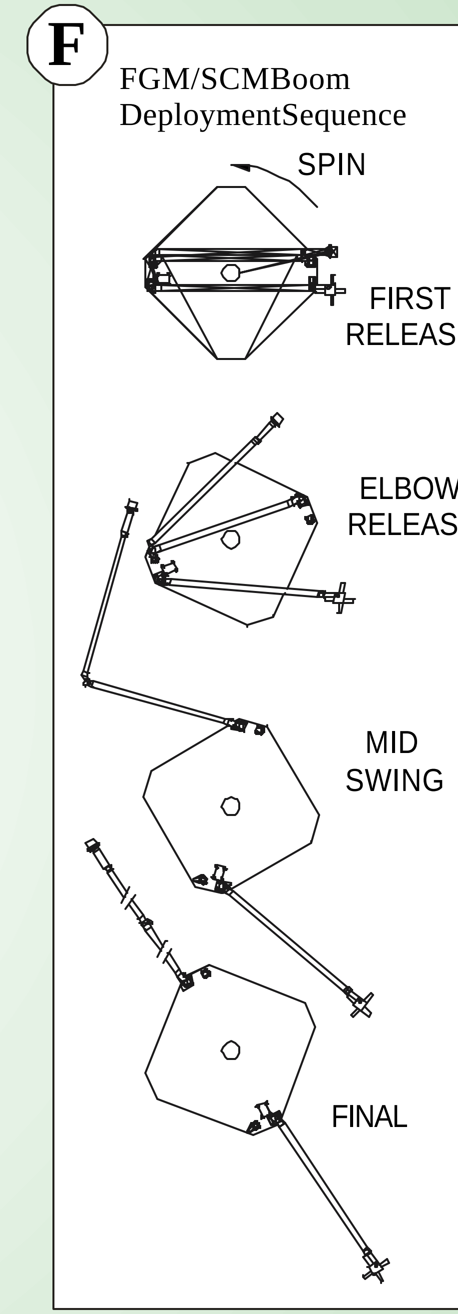
A THEMIS Instruments: Development,Resources,andRequirements

Instrument	Subsystem	Heritage	Mass Kg	Mass +Reserve	Power W	Power +Reserve	Thermal Low (degC) Surv	Thermal Low (degC) Op	Thermal High (degC) Op	Thermal High (degC) Surv
FGM	Sensor	EquatorS	0.070	0.075	0.010	0.010	-196	-110	+40	+65
	MLI and Tape		0.015	0.019						
	Boom	FAST	1.200	1.290			-50	-50	+65	+65
	Boom Harness		0.026	0.030						
	Harness to IDPU		0.037	0.046						
FGM Totals			**1.35**	**1.46**	**0.01**	**0.01**				
SCM	Sensor	Interball	0.600	0.624			-100	-100	65	+80
	MLI and Tape		0.015	0.019						
	Boom	FAST	0.500	0.575			-50	-50	+65	+65
	Boom Harness		0.130	0.170						
	Pre-Amps (PA)	EM	0.200	0.220	0.080	0.086	-50	-20	+40	+65
	Harness to IDPU		0.055	0.069						
SCM Totals			**1.50**	**1.68**	**0.08**	**0.09**				
ESA	Sensor	FAST	2.015	2.166	1.870	2.010	-50	-20	+40	+65
	Harness to IDPU		0.037	0.046						
	Thermal		0.025	0.031						
ESA Totals			**2.08**	**2.24**	**1.87**	**2.01**				
SST	Sensor	STEREO	0.900	0.968			-50	-20	+40	+65
	Harness to IDPU		0.037	0.046						
	Electronics	STEREO	0.300	0.375	0.850	1.063	-50	-20	+40	+65
	Thermal		0.025	0.031						
SST Totals			**1.26**	**1.42**	**0.85**	**1.06**				
EFI	Radial Unit 1	ClusterII	1.750	1.881	0.080	0.086	-50	-20	+40	+65
	Radial Unit 2	ClusterII	1.750	1.881	0.080	0.086	-50	-20	+40	+65
	Radial Unit 3	ClusterII	1.750	1.881	0.080	0.086	-50	-20	+40	+65
	Radial Unit 4	ClusterII	1.750	1.881	0.080	0.086	-50	-20	+40	+65
	Axial Unit 1	Polar	2.000	2.300	0.080	0.092	-50	-20	+40	+65
	Axial Unit 2	Polar	2.000	2.300	0.080	0.092	-50	-20	+40	+65
	Harness to IDPU		0.240	0.300						
EFI Totals			**11.24**	**12.43**	**0.48**	**0.53**				
IDPU	[1] SCM Filters	ClusterII	0.072	0.090	0.030	0.038	-50	-20	+40	+65
	[1] EFI Filters	ClusterII	0.072	0.090	0.100	0.125	-50	-20	+40	+65
	[1]ADC/FFT		0.216	0.270	0.530	0.663	-50	-20	+40	+65
	[2] BEB	ClusterII	0.433	0.541	2.092	2.615	-50	-20	+40	+65
	[3] FGM I/F	ROMAP	0.120	0.150	0.800	1.000	-50	-20	+40	+65
	[3] ESA I/F	FAST	0.149	0.186	0.600	0.750	-50	-20	+40	+65
	[3] SST I/F		0.075	0.093	0.200	0.250	-50	-20	+40	+65
	[4]DPMB	StereoISUAL	0.433	0.541	2.475	3.094	-50	-20	+40	+65
	[5] LVPS & Ctrl	ClusterII	0.433	0.541	2.021	2.527	-50	-20	+40	+65
	Housing		1.540	1.925						
	Thermal		0.025	0.031						
IPDU Totals			**3.57**	**4.46**	**8.85**	**11.06**				
SYSTEM TOTALS			**21.0**	**23.7**	**12.1**	**14.8**				

IDPUBoardBreakdown
[1]DigitalFieldsBoard (DFB)
[2]BoomElectronicsBoard (BEB)
[3]FGM/ESA/SSTI/F Board
[4]Data Processor/Memory Board(DPMB)
[5]Low-voltage power supply /Controlboard(LVPS)







B THEMIS Instrument Modes andDataRates

	Survey		Particle Burst		Wave Burst: Wave Burst 1		Wave Burst: Wave Burst 2	
	Measurement	bps	Measurement	bps	Measurement	bps	Measurement	bps
FGM	6 **B** vectors/spin @ 16 bits	283	|**B**|,Bx,y,z DC-128Hz	8192	|**B**|, Bx,y,zDC-128Hz	8192	|**B**|, Bx,y,z DC-128Hz	8192
SCM	Bx,y,z RMSLevel @ 4 Hz	192	Bx,y,z 10-128 Hz	6144	Bx,y,z 32-1024Hz	49152	Bx,y,z 32-4096Hz	196608
EFI	6 **E** vectors/spin @ 16 bits 1 component spin fit spacecraft V, plasmaN	283	Ex,y,z DC-128 Hz FFTs 16 bins@ 0.5s s/cV, Ne, HF RMS	8192	Ex,y,z 32-1024 Hz FFTs 16 bins@0.125s s/c V, Ne, HF RMS	65536	Ex,y,z 32-4096 Hz FFTs 16 bins @0.125s s/c V, Ne, HF RMS	262144
SST	1 Ave DF/spin* 1 FDF/16 spins*	1024	1 FDF/spin	8192	1 FDF/spin	8192	1 FDF/spin	8192
ESA	1 Ave DF/spin** 1 FDF/16 spins** N,Vxyz,P-tensor/spin	608	1 FDF/spin	15019	1 FDF/spin	15019	1 FDF/spin	15019
Totals (kbits/second)		**2.390**		**45.739**		**146.091**		**490.155**

*SSTFDF (FullDistributionFunction)= 8bits x 48anglesx32energies
SSTAve DF(Averaged DistributionFunction) = 8bits x 16anglesx6 energies

**ESA FDF(FullDistribution Function) =8bitsx88anglesx32energies
ESAAveDF(AveragedDistributionFunction)=8bitsx 88anglesx16 energies

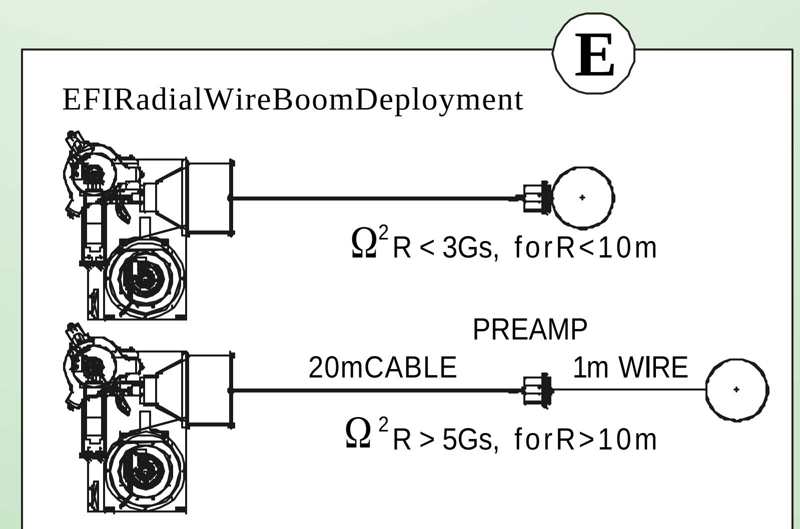


FIGURE F-19
Science Payload Accommodation (Foldout-6)

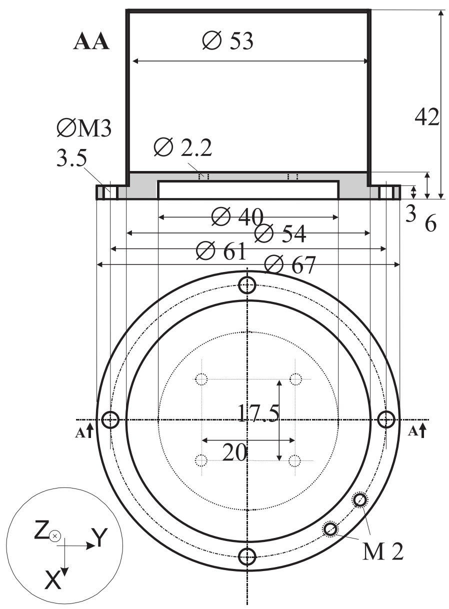


***Figure F-20** Small, rugged FGM sensor design.*

Figure E-13/A (Foldout 2). The sensor is identical to the ones of the Rosetta and MIR instrument package and similar to the ones flown on Equator-S (same soft-magnetic ringcores made of an ultra-stable 6-81-Mo permalloy band: 2 mm × 20 µm). The ringcores have been tested under extreme environmental conditions aboard numerous space missions as well as in applied geophysics. The excellent low noise and stability behavior of the sensor material has been proven aboard Equator-S.

The instrument image is shown in Figure E-13/A. The mechanical drawing and detailed FGM operation are shown in Figure F-20**.** The sensor electronics generate an excitation AC current (drive frequency at ~9kHz), which drives the soft magnetic core material of the two ringcores deep into positive and negative saturation. The external magnetic field distorts the symmetry of the magnetic flux and generates even-harmonics of the drive frequency proportional to the external field in the sense coils.

The induced voltage in the sense coil is digitized immediately after the preamplifier at four times the drive-frequency. The 'front end' signal processing (synchronous detection and integration of the sense signal and calculation of the feedback values) is done by FPGA1. A feedback field increases the overall linearity and stability of the magnetometer. This is supplied to the sensor by using two cascaded 12-bit DACs and a separate pair of feedback coils (Helmholtz coils) per sensor axis. The two 12-bit DACs guarantee simultaneously a large dynamic range (32000 nT) and a high (10 pT) resolution.

Sense and feedback signals are continuously transmitted to FPGA2 (128 Hz) which calculates the magnetic field values by scaling and adding up the received data (k1*ADC+k2*DAC). Additionally, FPGA2 averages the data for the low and high resolution telemetry link, calibrates the magnetic field data (offset and misalignment corrections) and handles the serial interface to the IDPU.

The proposed (heritage) digital concept requires analog-to-digital conversion at a higher data rate but it shows a number of advantages over the more traditional analog fluxgate magnetometer: Early digitization makes the sensed signal robust to changes of the environmental temperature and supply voltage and insensitive to EMC. This is of particular usefulness to THEMIS that utilizes a

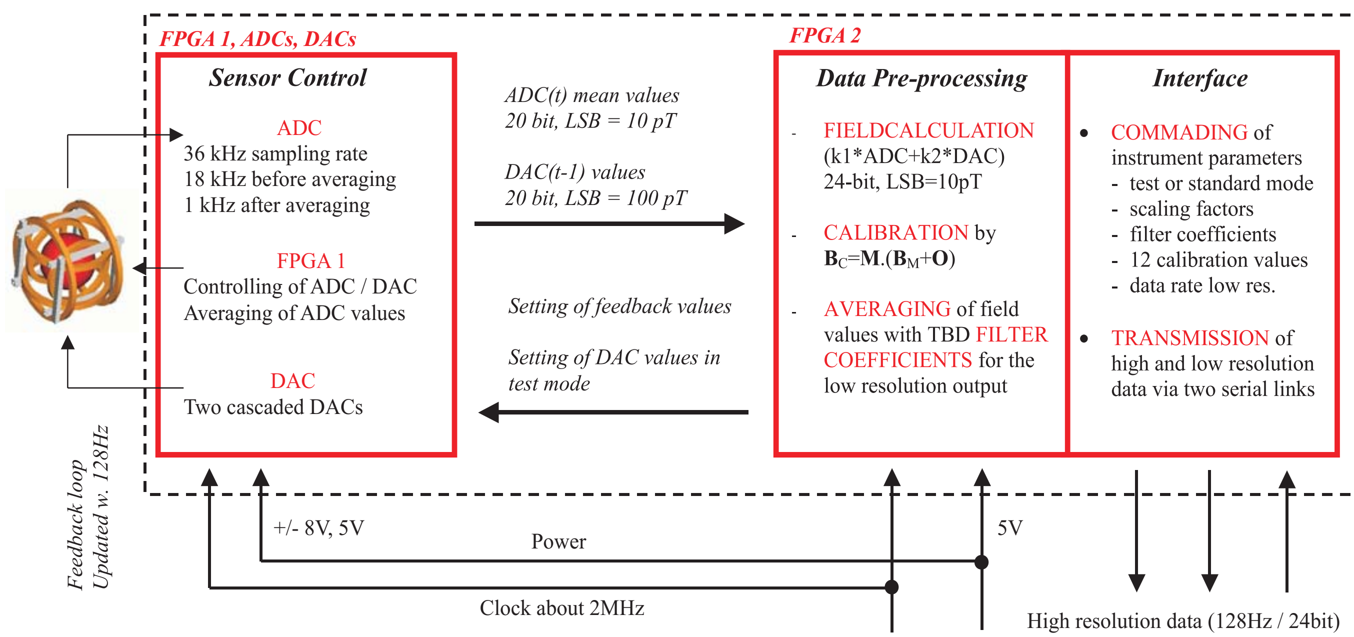


***Figure F-21** FGM block diagram.*

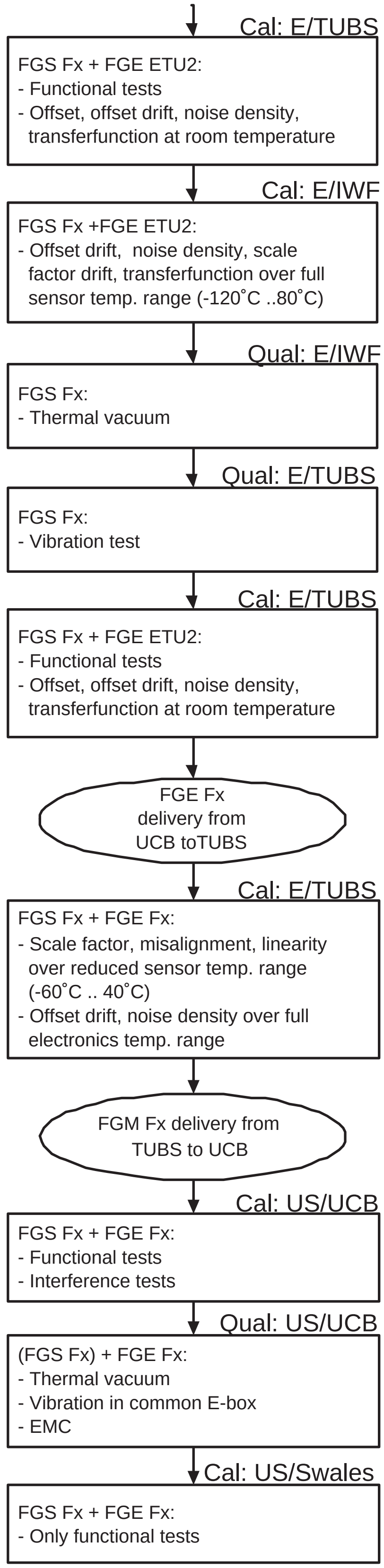


***Figure F-22** FGM F1-F5 calibration/qualification plans.*

common instrument IDPU. Furthermore, no range-switching is needed for getting the full range at full resolution, which reduces design complexity and facilitates data analysis.

No new developments are necessary; the development plans call for space qualified parts under common buy program. FGM sensor (FGS) and FGM electronics (FGE) breadboard and layouts will be developed in Europe. Boards are populated and tested at UCB. Calibration plans call for FGM sensor (FGS) calibration and FGM electronics (FGE) trimming with the breadboard and flight boards in Europe (baseline approach; backup calibration at UCB is also possible).

FGM calibration and qualification. The flowchart of Figure F-22 shows the FGM calibration and qualification plans. Before the calibration/qualification of the flight units, the FGM F6 sensor (spare) together with the first FGE Engineering and Test Unit, ETU1, will be calibrated and qualified in the same way as the flight units. The major part of the sensor qualification and calibration takes place at TUBS and IWF by using the ETU2 electronics.

Scale factor and misalignment calibrations as well as the offset drift test over the full electronics temperature range has to be done only once which simplifies the entire calibration process at UCB. Only functional tests are foreseen at Swales during S/C integration. In preparation for these UCB personnel training is planned. Calibration facilities in Europe are described in Section F8. In flight calibration is described in Section E2.a1. These calibration procedures are similar to what was done on previous programs, such as Equator-S and Cluster.

c2. Electrostatic analyzer (ESA).

The ESA instrument measures thermal electrons and ions in the range 5eV-30 keV (electrons) and 10eV-40keV (ions). The operational principle is described in Section E2.a2, including the overarching measurement requirements. Mission requirements and instrument specifications in adherence to those are shown in Figure E-13/C (Foldout 2). The basic analyzer design, and the assembly, test and calibration procedures are nearly identical to those on FAST. An image of the FAST sensor assembly (stack of 4 sensors) is shown also in Figure E-13/C. Small implementation differences from FAST include: the reduction from 4 to 2 analyzers per stack, accommodation of ACTEL chips currently in production, and digital interface to ad-

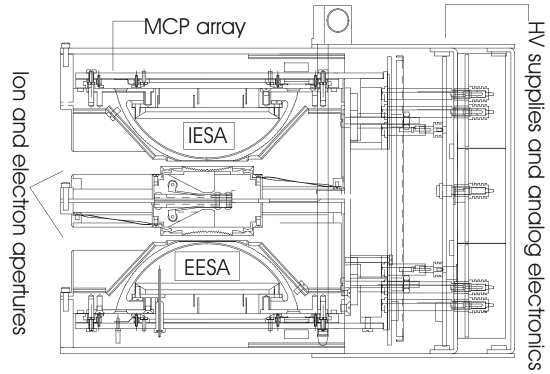


Figure F-23 *ESA mechanical design schematic.*

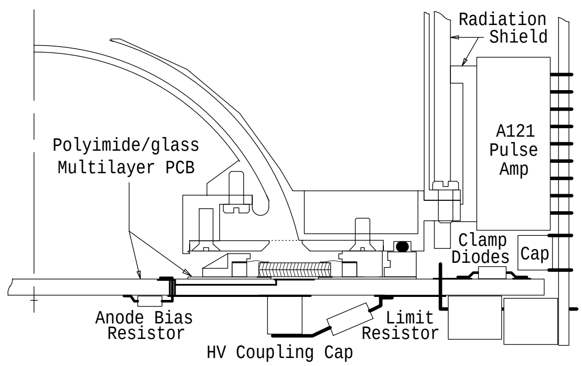


Figure F-24 *Mechanical MCP mounting and elec trical signal path from anodes to preamps.*

here to THEMIS IDPU specifications.

The sensor head (14×14×14cm^3) attaches directly to the sensor electronics (14×17.8×7.6 cm) as shown in Figure F-23. The mechanical mounting of the MCPs and the electrical signal path is shown in F-24. The stack receives regulated +/- 5 V, +/- 10 V, and +28 V from the IDPU. ESA low voltage electronics uses 0.9 W (+/- 5 V, +/- 10 V) and the high voltage supplies use 0.8 W (+28 V).

The THEMIS ESA-IDPU signal interface includes Command In, Command Clock, Data Out, Data Clock, and Spin Clock lines. Data collection and readout are spin-synchronous. An Analog Out line allows monitoring of high voltage supplies by the IDPU. Upon low voltage turn-on of the ESA, the IDPU sends the ESA Low Voltage Command Set to configure the ESA ACTELs. The IDPU enables the ESA +28 V line that powers the high voltage supplies and executes the HV Load Commands to bring the supplies to nominal voltage. The IDPU includes hardware and software safety latches to prevent accidental high voltage turn on. ESA counter readout is controlled by the IDPU, which also formats the data into spin averages and calculates onboard moments. Even with onboard averaging, the ESAs generate nearly 3 kbytes of data each spin and thus require onboard moment calculations to obtain spin period data. 3-D distributions will be transmitted at a much lower cadence accept during event bursts which will contain spin period distributions. Details of mass, power and thermal requirements are shown in Figure F-19/A and data rates are shown in Figure F-19/B (Foldout 6).

The block diagram for the ESA electronics operation is shown in Figure F-25 and is identical to FAST's. It consists of 2 anode boards, an amplifier/counter board, a board combining the main system interface functions and the HV sweep generator circuits, and HV supplies. The FAST melt wires used in the entrance aperture actuator will be replaced by an SMA actuated pin puller (TiNi Aerospace, part P5-403-10S, flight qualified), similar to that used by UCB on Lunar Prospector. The THEMIS preamplifier-counter board will require minor layout changes to accommodate current ACTEL parts. The command decoders section of the FAST ACTELs may also require minor changes depending upon the THEMIS command format. The THEMIS high voltage control board is a subset of the FAST design and requires a new board layout and some ACTEL modifications that are THEMIS-specific. The THEMIS high voltage supplies are identical to those flown on FAST.

Calibration and qualification. Sensor calibration takes place at the UCB thermal-vacuum cham-

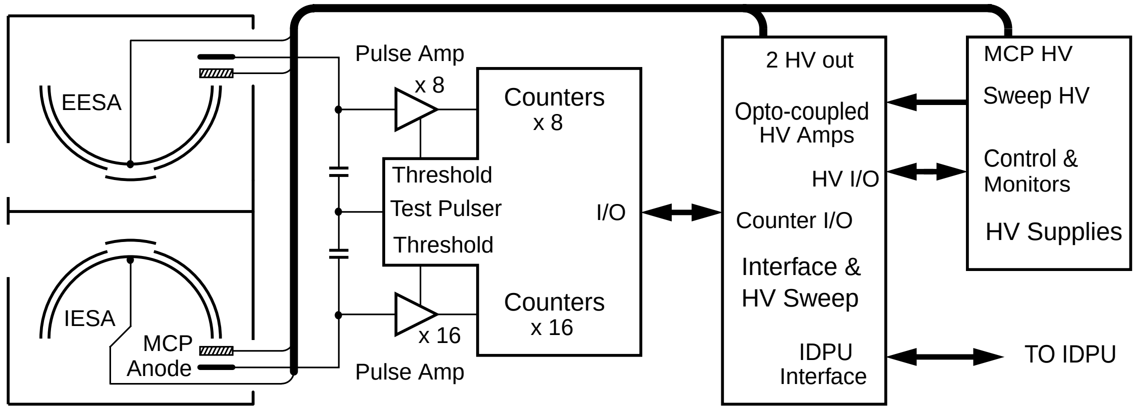


Figure F-25. *ESA block diagram.*

ber using an automated manipulator, electron/ion guns and an interactive GSE program to control the instrument. The modular detector design makes it possible to disassemble a two analyzer instrument stack down to the individual component level in about two hours in case of a need for refurbishment. The automated calibration procedure performs a complete angle/energy calibration of an instrument stack in less than one day. Calibration determines: (1) analyzer constant, uniformity of energy/angle response (2) Hemisphere concentricity (3) Optimum MCP voltage (4) Sweep voltage verification (5) relative geometric factors (6) Flight mode validation. Absolute geometric factor values are determined from computer simulations and calibration with Ni^{63} beta source. In-flight uniformity validation and inter-probe calibration is performed in accordance with the discussion in E2.a2.

c3. Solid state telescope (SST).

The SST measures the angular distribution (~3π str coverage) of superthermal ions and electrons. The instrument overview is described in Section E2.a3, including the main requirements. Mission requirements and instrument specifications in adherence to those are shown in Figure E-13D (Foldout 2). The sensor is identical to the one built and flown on the WIND spacecraft, and the electronics are implemented using an ESTEC-provided Mixed Analogue/Digital Application Specific Integrated Circuit (ASIC) which has been developed for the Space Science Dept. of ESA by the European Space Agency under its GSTP programme. This ASIC which has also been selected for use by the SEPT instrument on STEREO (part of the IMPACT suite of instruments) is currently undergoing flight qualification. The chip is in its 3rd design iteration; its performance and fidelity have been improving steadily. The final iteration is to be tested in December of 2002 and is expected to result in flight qualification for both STEREO and THEMIS. Parts procurement for THEMIS will be simultaneous with STEREO to minimize costs. Thus several test units of the flight-vintage will be available for testing at UCB prior to THEMIS selection.

The operational principle was described in Section E2.a3. Figure F-26 shows a mechanical design schematic. Each probe has two sensor heads. Each head is composed of two double-ended telescopes. Each telescope has 3 detectors: Open (magnet broom side, "O"), Foil (no magnet but foil, "F") and Thick (middle). The (2) telescope pairs are mounted as shown, to have a common field of view on the spin plane. With geometric factors varying by a factor of 20 the spin-plane telescopes at opposing fields of view ensure sensitivity in the tenuous plas-

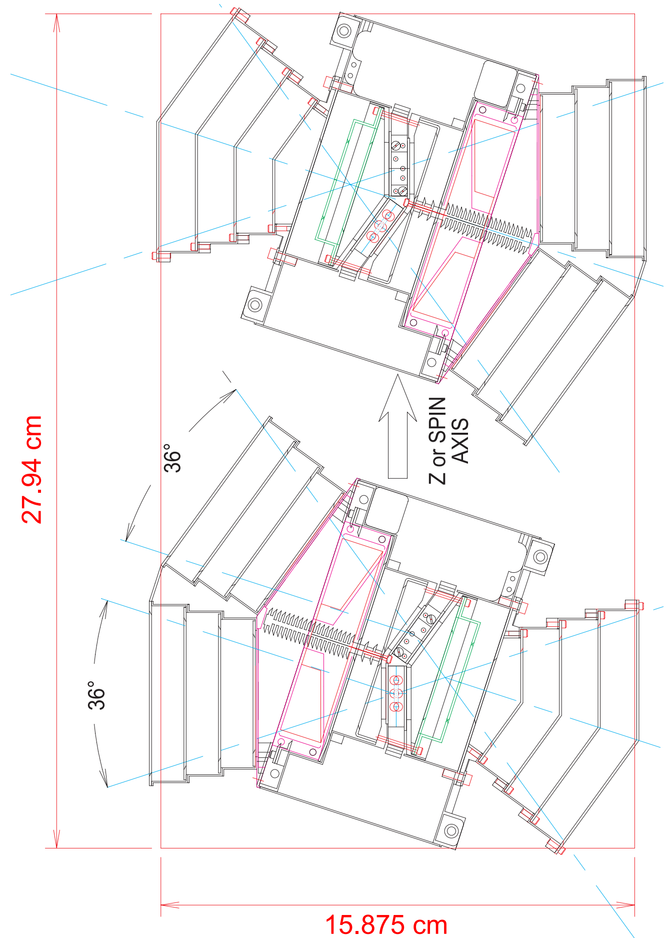


Figure F-26. *SST mechanical design and mounting orientation on the THEMIS probe.*

mas far from Earth, no saturation near Earth, and twice the cadence when they are both in nominal operation. The THEMIS SST detectors are identical to WIND's in terms of mechanical design and geometric factor, with the exception of the low geometric factor telescope pair which has a geometric factor near identical to Equator-S's detectors.

The SST electronics operation is shown in Figure F-27. Each head has an electronics unit that analyses the signals from its six solid state detectors. There are two boards per head, each board containing 3 Particle Detector Front Ends (PDFEs), one per detector. Each PDFE is effectively the ESTEC chip along with associated discrete "interface" electronics. The output of signals from the outer detectors (O and F) are run in anticoincidence mode so that energetic particles that penetrate all three detectors will not be counted. PDFE threshold values are set with 8-bit programmable discriminators. An 8-bit Analog To Digital Converter (ADC) then provides a digital output signal. Multiple PDFEs can be cascaded together and read out individually.

A Field Programable Gate Array (FPGA) is used to control the operation of the six PDFEs on

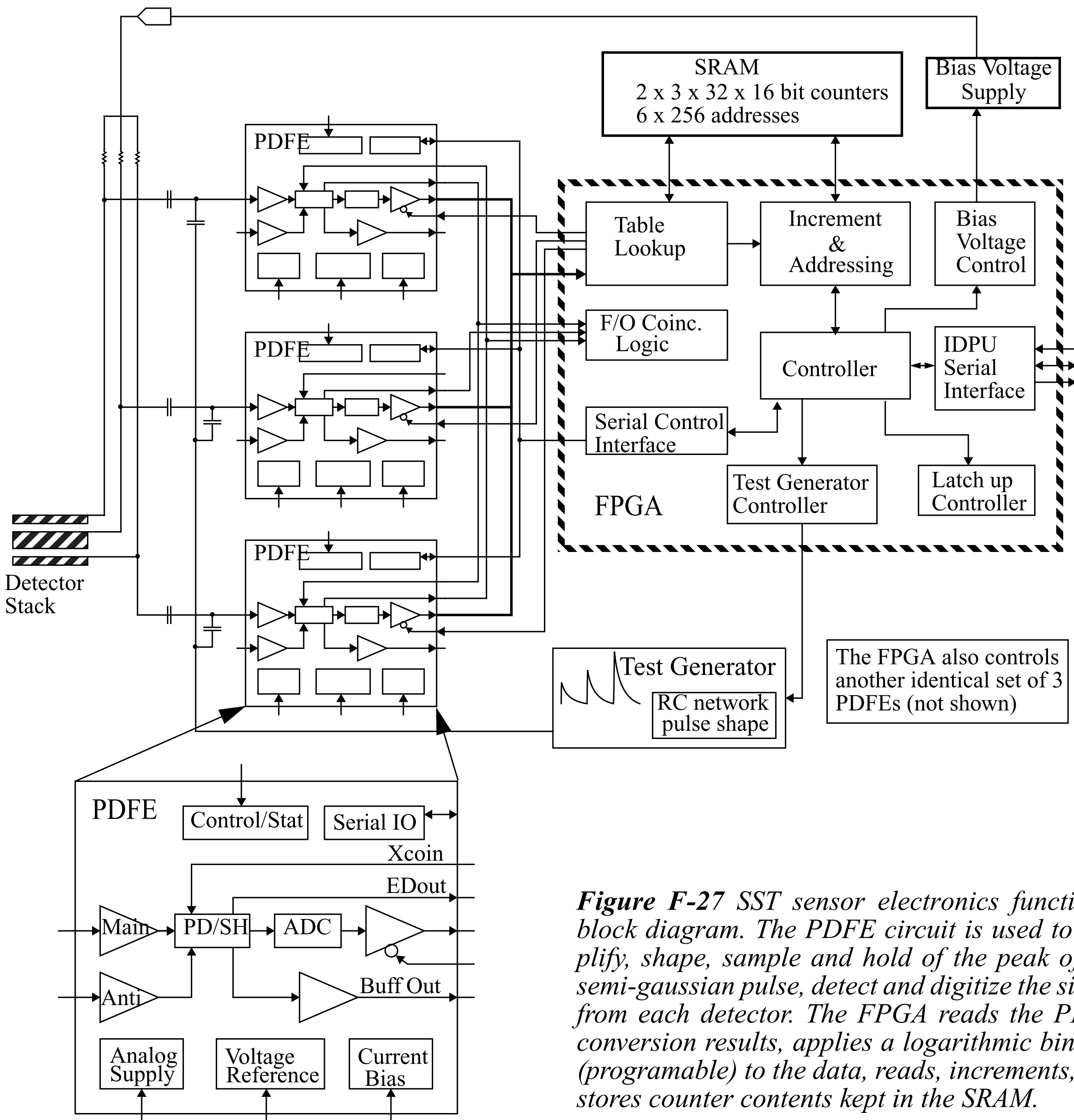


Figure F-27 *SST sensor electronics functional block diagram. The PDFE circuit is used to amplify, shape, sample and hold of the peak of the semi-gaussian pulse, detect and digitize the signal from each detector. The FPGA reads the PDFE conversion results, applies a logarithmic binning (programable) to the data, reads, increments, and stores counter contents kept in the SRAM.*

each sensor head. It handles the communication interface with the IDPU. It controls the test generator, the bias voltage and the housekeeping multiplexer.

Upon detection of a valid event, the PDFE notifies the FPGA which reads the parallel output of the PDFE. Using a binning table stored in the SRAM the appropriate counter (also contained in SRAM) is incremented. Six histograms counters are contained in each of two independent memory buffers. 16 times per spin the IDPU commands the FPGA to swap accumulator buffers and the old buffers are read out and then cleared.

Upon command the FPGA can start the test pulse generator which feeds discrete, shaped and filtered signals of growing amplitude to the 6 test inputs of the PDFEs. Upon completion the generator is automatically switched off returning the SST to the nominal operation mode. All power is supplied externally with the exception of the detector bias voltage. Each SST unit requires 3 separate +5 volt supplies (1 analog, 1 digital, 1 dual). The detector bias voltage is produced and controlled by circuitry located on the FPGA board.

The above pulse height analysis, detection and digitization were performed by discrete electronics on WIND. The ESTEC chip reduces overall system complexity and mass as seen in Figure F-28.

Calibration and qualification. The sensors will be calibrated and tested at the UCB test facilities in similar fashion to the ESA, using an electron gun and an Alpha source, automated gun manipulator and automated detector control system. On-

Figure F-28. *ESTEC chip (front) replaces discrete WIND SST electronics (back) on THEMIS.*

board absolute energy calibration points will be obtained as previously done on WIND in accordance with the discussion in Section E2.a3. Relative calibration points of energy band thresholds will be obtained with the FPGA test signal generator.

c4. Search coil magnetometer (SCM).

The SCM measures the 3D magnetic field in the frequency bandwidth from 1Hz to 8kHz. It extends with appropriate sensitivity and sufficient overlap the measurements of the FGM beyond the 1 Hz range. The SCM overview is described in Section E2.a1, including the overarching measurement requirements. Mission requirements and instrument specifications in adherence to those requirements are shown in Figure E-13/E. The identical sensor (18cm) and its kin (27cm) have been previously flown by CETP on more than 7 Earth-orbiting and interplanetary missions; most-recently it was flown as part of the CLUSTER/STAFF experiment. The identical sensor was recently flown on Interball.

The instrument is based upon the combination of a high magnetic permeability material and a large number of windings which passively detects currents induced by the changing external field (an AC-current measurement). A flux-feedback is applied to produce a flat frequency response and phase stability. The 3 SCM antennas are held orthogonally on a mechanical structure mounted on a one-probe diameter boom; they are thermally isolated and covered by MLI (Figure F-29).

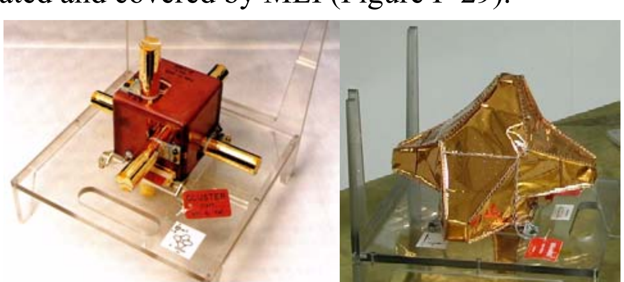


Figure F-29 *SCM sensor with and w/o MLI.*

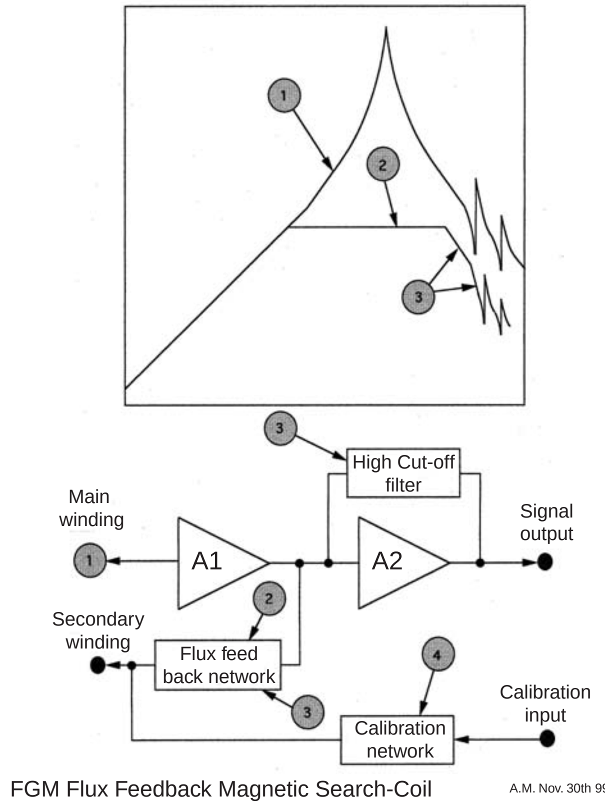


Figure F-30 *SCM sensor operation.*

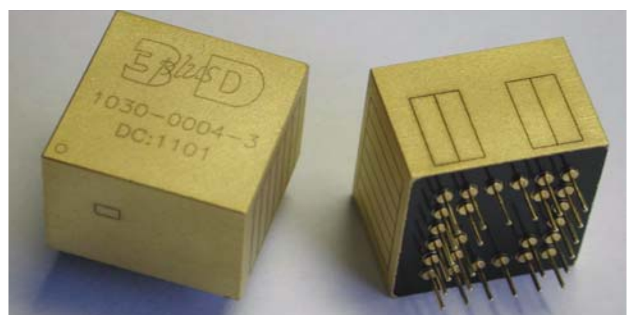


Figure F-31 *Pre-amplifier units developed under CNES funding by commercial outfit 3D+ using MCM-V technology.*

The sensor electronics block diagram for the implementation of the flux-feedback loop is shown in Figure F-30. The feedback loop as well as calibration coils are located within the preamplified unit (one per orientation, 3 total) built by a French industrial partner (3D+) using Multi Chip Module Vertical (MCM-V) technology. The electronics have already been developed under CNES funding (Figure F-31). Three of these roughly cubical (20×20×15mm) preamps (one for each direction) and one similar size power regulation unit are mounted as a unit in a dedicated Aluminum box at the base of the boom (the PA unit). The unit is rad-hard, incorporates thermal conditioning and could be used even outside the probe body.

Further signal processing takes place inside the

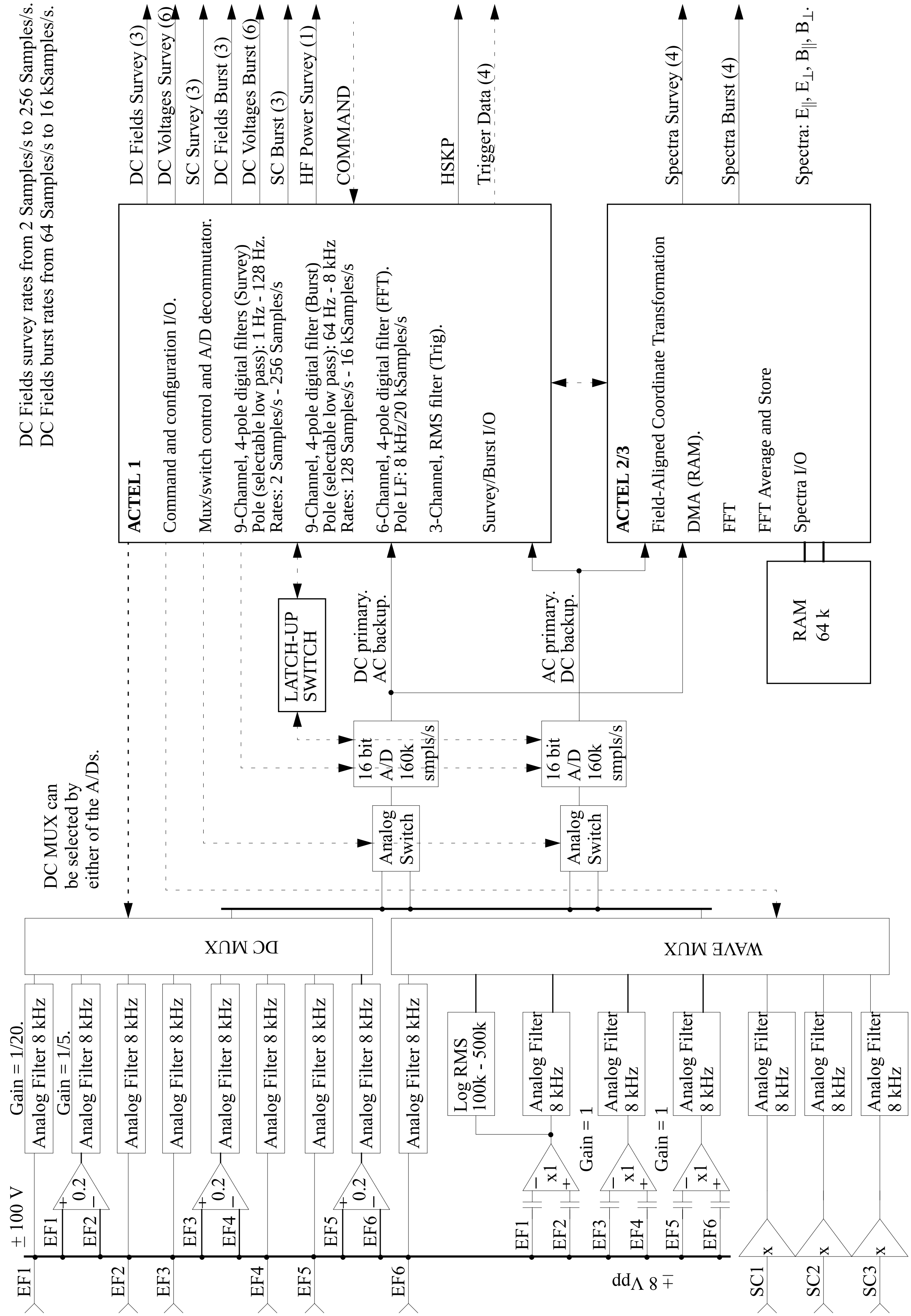


***Figure F-32** Digital fields board (DFB) in the IDPU for SCM and EFI signal processing.*

IDPU, on a single board, together with the EFI instrument (Figure F-32). The analog signal processing in the IDPU is independent from the pre-amplification of the signal of the sensor. Development and testing of the sensor and preamplifiers in France is independent of the development and testing of the IDPU fields board.

Calibration of the sensors with the pre-amplifiers takes place in a special calibration site in Chambon-la-Foret, France, where the external electrical noise is sufficiently low, as on previous programs. Mechanical, vibration, thermal/vacuum testing takes place at Interspace, Toulouse. Storage, subsystem integration and testing take place in CETP's class 10,000 facilities. After initial calibration and testing of the sensor in France the units are shipped to UCB for instrument testing with the IDPU flight boards. Mass, power, and thermal specifications are tabulated in Figure F-19 (Foldout-6).

The SCM sensor requires no new development.

c5. Electric field instrument (EFI).

The EFI measures the 3D electric field in the frequency band from DC to 300kHz. The EFI overview is described in Section E2.a5, including the overarching measurement requirements. Mission requirements and instrument specifications in adherence to those requirements are shown in Figure E-13/F. The identical sensor was previously flown by UCB on CLUSTER, the boom electronics and deployment mechanism are derived from CLUSTER, POLAR and FAST and the fields board electronics is based on FAST and POLAR design simplifications.

The four EFI spherical voltage sensors needed for the spin-plane electric field measurements are suspended on wire booms 20 meters away from the probe bus center in the spin plane, stabilized by centrifugal force. The third component of the field is measured using thin tubular sensors suspended on rigid axial booms along the probe spin axis. The resulting geometry provides a 40 meter tip-to-tip separation for the spherical sensors in the spin plane, and 10 m between the axial sensor tips (9m between the axial antenna centers). The EFI subsystems include a Boom Electronics Board (BEB) containing power supplies, motor control, and sensor biasing circuitry, and a Digital Fields Board (DFB) that provides analog-to-digital conversion, filters and wave spectra.

Requirements. Mass, power, thermal, and data rate requirements are summarized in Figure F-19/A & B (Foldout 6), and volume in Figures F-33 and Figure E-13/F (Foldout 2). Transient power needs occur during boom deployments. The radial units require a current of 0.25 Amps for EFI door-actuator initiation by the TiNi shaped memory alloy and a motor current of 250 mA at +28V. The thermal properties of the radial and axial booms are derived from experience on previous missions. Boom deployment must occur at a temperature of -20 C or greater.

A high quality EFI measurement requires mitigation of contaminating quasi-DC voltages generated by the probe bus. The probe electrostatic cleanliness specifications (Section F5) ensure this condition is met. Finally, artificial signals generated by the 1/r field of the probe, which normally resides at a positive potential due to photo-emission, force a requirement of symmetric positioning of the booms around the probe center. Centrifugal acceleration facilitate meeting that condition. Construction, mounting and deployment of the booms in accordance with this condition is also planned: For both the spin-plane booms and the axial booms, trimming the final deployed lengths is required to within <5cm, in accordance with standard UCB practices on previous missions.

The signal processing, power conversion, control, deployment, and housekeeping functions for the EFI are centralized in the IDPU. The EFI power

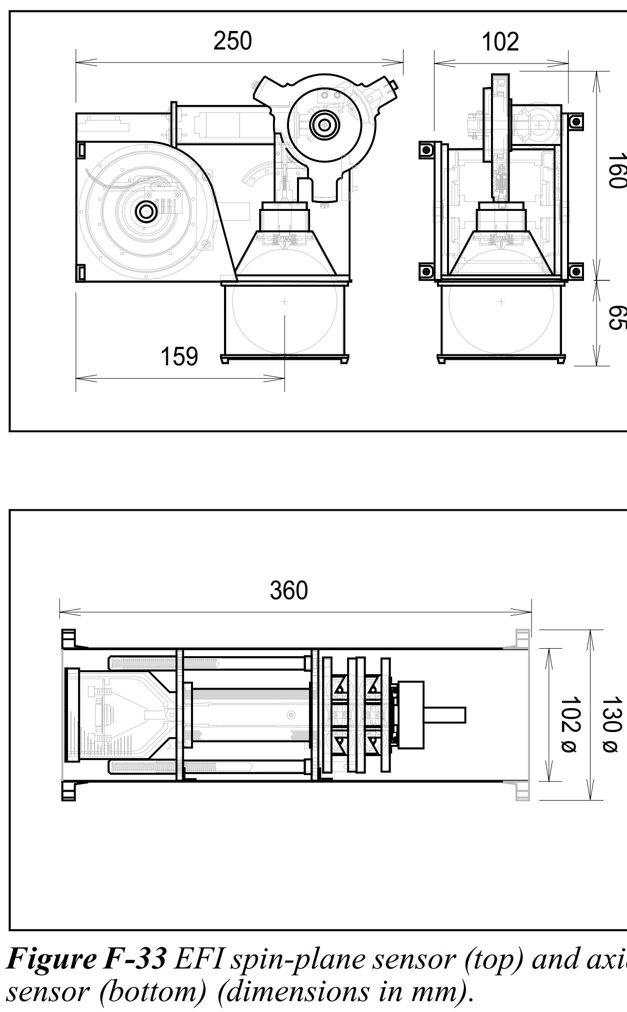


Figure F-33 *EFI spin-plane sensor (top) and axial sensor (bottom) (dimensions in mm).*

and signal processing subsystems must facilitate the measurement and distribution of DC signals with +/-100V ranges and AC signals through programmable filter channels and subsequent spectral processors. Large +/-100V probe bus-to-spherical sensor potential differences are common due to photoelectric charging of the probe surface relative to the much smaller spherical sensor surface. A floating ground power supply must be distributed to the EFI sensors to accommodate these large voltage swings, driven by high voltage amplifier circuits. In addition, surfaces near the sensors must be biased at similarly large potentials offset from the sphere DC level by a programmable amount (the “guard” and “stub” surfaces respectively.) To avoid large sphere sensor-to-plasma offset voltages, a bias current is supplied to the sphere surface itself. Subsequent signal processing for the potential measurements must filter the time series into high and low (<100 Hz) frequency components over varying dynamic ranges, and also produce real-time FFT spectra of selected channels. The IDPU data processor and memory board (DPMB; Section F4.d) conducts housekeeping monitoring, mode commanding, spin fits, and data compression for the EFI.

Operation. The operation schematic of the EFI system is shown in Figure F-34**.** The Boom Electronics Board (BEB) contains sensor biasing and control circuitry. High voltage op-amps (+/-100V) supply guard, stub, and current bias levels that are programmed via serial digital-to-analog (DAC) drivers. The sphere signal is fed back to an amplifier that controls the power ground of the sphere preamplifiers, such that for low frequencies (<100 Hz) the preamps are always at the plasma potential. For frequencies less than 100 Hz, the sphere signal is the output of the floating ground driver itself, while for higher frequencies (>100 Hz) the AC component of the preamp signal is analyzed. Separate circuits control deployment motor and TiNi actuator switching, as well as boom housekeeping and status functions.

The Digital Fields Board (DFB) provides low-pass filtering, gain, analog-to-digital conversion, programmable digital filters and spectral measurements for the EFI. Programmable filtering is implemented using FPGA-based designs that provide up to four independent filter banks for low and high frequency signals. In order to accomplish real-time spectral processing within a small resource budget, an FPGA-based FFT solution will be used to provide spectra of the parallel and perpendicular components of E (and B) in both survey and burst modes. Separate FPGA based logic will integrate FGM digital data and EFI data in order to produce the quantity $\mathbf{E}\cdot\mathbf{B}$. This will enable the FFT engine to differentiate EFI and SCM components both parallel and perpendicular to the background magnetic field and produce spectra for each quantity separately, resulting in easy wave-mode identification during subsequent visual analysis of the spectra on the ground.

The Low-Voltage Power Supply (LVPS) contains six independently floating +/-12V supplies for distribution to each sphere preamplifier. The grounds of these supplies are fed back from the preamplifier outputs below 100 Hz using a buffer in the BEB as described above. Additionally, a single +/-100V supply is accommodated in the LVPS for distribution to the high-voltage op-amps in the BEB controlling floating grounds, bias, stub, and guard settings.

Command and telemetry. Downlink data volume allocation is shown in Figure F-19/B. The EFI will require operational commands to govern boom deployment and adjustment as well as science commands to control sensor bias voltages, data sample rates, filter settings, and spectral resolution control. As in previous missions, a typical mode can be specified with ~200 commands valid over a typical operational period of ~1 month once deployment and checkout phases have completed.

Flight software consists of a simple command/mode generator, data compression, particle burst trigger initiation, and a spin-fitting routine. The spin fitting code is the same routine used on Polar and Cluster, in which a least-squares fit to a period of data is conducted. Generated products include probe spin period, offset, sine, and cosine fitting parameters, and standard deviation, requiring approximately 80 bits of data each spin and per channel. The data compression is a NASA lossless code resulting in a nominal 2x reduction in data volume. Both the data compression and the burst trigger initiation are part of a system-wide implementation in the main processor that applies to other instruments as well as the EFI.

No new developments are planned for the EFI.

Calibration and qualification. This occurs in stages, from component-level bench testing and finally end-to-end characterization during and post-I&T. Calibration begins with bench testing of the sensor preamps using both direct signal stimuli and box enclosures to simulate the plasma coupling capacitances and impedances. Cables are added to the preamp tests in order to characterize signal driving capabilities. A second phase of bench testing uses the preamps in combination with the BEB system to test the floating preamp power supply, bias, guard, and stub settings. The Digital Fields Board is tested separately using a waveform stimulator to simulate the preamp output, and a GSE IDPU simulator to

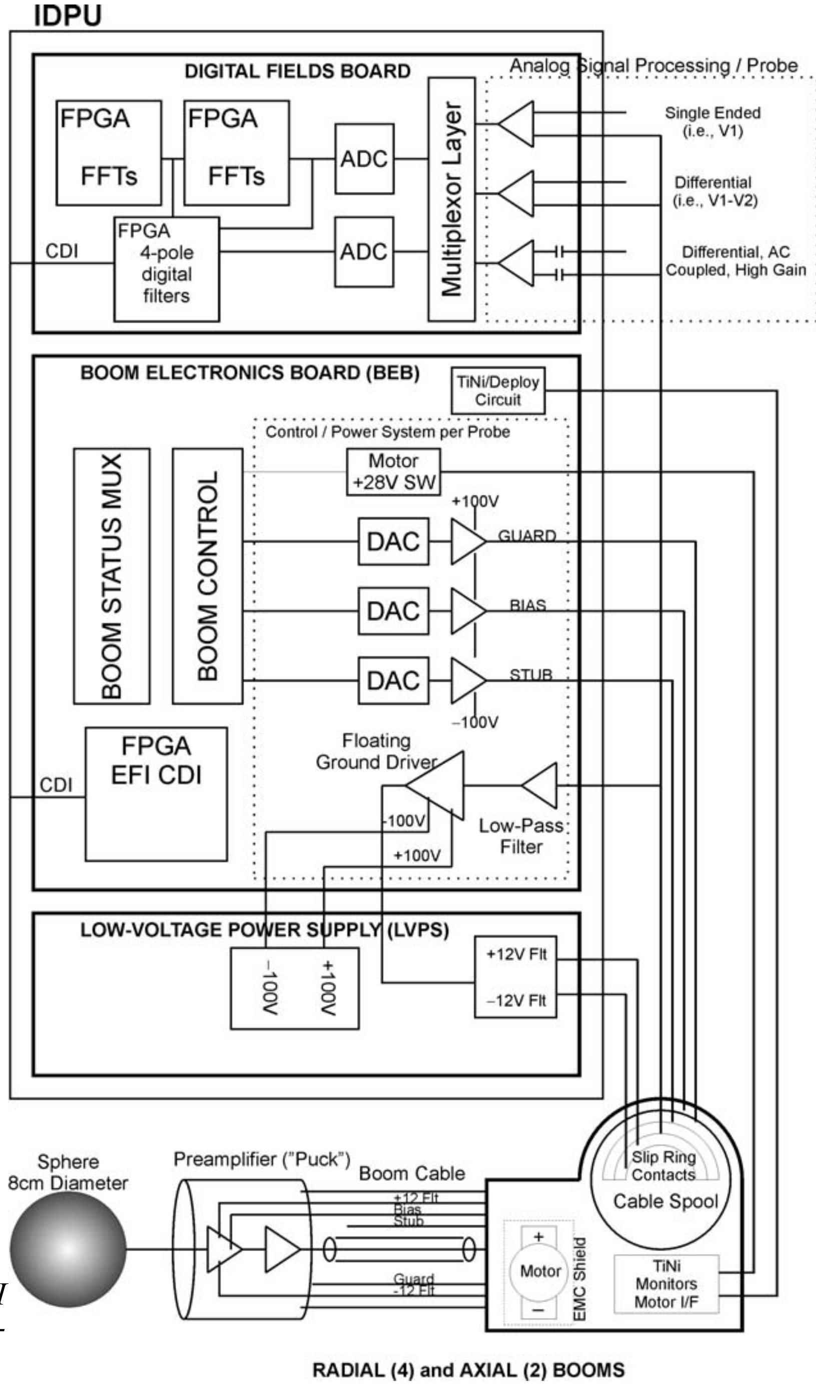


Figure F-34 *EFI operation block diagram.*

acquire and store the resulting digital data. A complete EFI calibration using the sphere preamplifier, deployed cable, boom unit, flight harness, and IDPU components is performed during deployment tests at UCB prior to probe level I&T.

Flight operations. These are divided into three phases, *deployment*, *checkout*, and *science*. The *deployment* phase consists of alternately extending each radial boom pair in predetermined increments (see Table F-17). During radial wire boom deployment and at each stop, sphere potentials are monitored in order to characterize probe charging effects (i.e., 1/r field), plasma environment, and EFI status. After the staged radial deployment, the axial booms are each deployed to their final lengths using one initiator event per boom. Assuming nominal potential measurements and probe spin rate, the checkout phase begins with final adjustments in wire boom lengths to verify that each pair deployed symmetrically relative to the probe body. These occur in near real-time sessions, monitoring the release and spin-up sequence, each lasting 1-2 hours / probe. Alternating between different THEMIS probes in science data collection and sphere-release phase, mission-total EFI deployment lasts <10 days. After boom deployment, an EFI early- *checkout* phase begins in which the photo-currents are characterized and the guards, stubs, and bias adjusted accordingly, requiring a new command load roughly once per week, per probe. Science quality data are returned during this phase which lasts ~1 month. During the nominal *science* phase, the EFI is configured roughly once each month through a command sequence.

Spin profile	Event
Spin up to 30 RPM to Wire Deployments	Deploy AB pair to 10m
	Deploy CD pair to 10m
Spin up to 26 RPM to extend sphere reels	Deploy AB pair to 12m
	Deploy CD pair to 12m
Spin up to 24 RPM	Deploy AB pair to 14m
	Deploy CD pair to 14m
Spin up to 22 RPM	Deploy AB pair to 16m
	Deploy CD pair to 16m
Spin up to 20 RPM	Deploy AB pair to 18m
	Deploy CD pair to 18m
Spin up to 20 RPM	Deploy AB pair to 20m
	Deploy CD pair to 20m (final)
	Deploy Axials (each or simultaneous)
Spin to 20 RPM	EFI deployments completed

Table F-17. *EFI deployment sequence.*

Cost-saving strategies rely on a philosophy that incorporates heritage subsystem design aspects from previous flights (S3-3, ISEE, Viking, Freja, Polar, FAST, and Cluster) that result in manufacturability and ease of assembly and testing. The fundamental wire boom mechanism is a proven design based on these missions. The bulk of the electrical components are chosen from those used on EFI systems on previous missions so that no new parts qualification efforts is required. The use of FPGA-based FFT engines for the EFI spectral processor saves the expense associated with traditional dedicated digital signal processors through both a lower component cost and power consumption.

d. Instrument Data Processing Unit (IDPU)

This unit is the heart of the instrument package: it provides instrument power, controls instrument functions, receives instrument commands and obtains housekeeping and science data, stores and processes the data and transmits data through the probe bus electronics. It is the interface between the instrument sensors and the probe BAU. It is composed of 5 separate 6U-VME sized boards (160 x 200 mm) facilitating instrument-specific control and centralized power conditioning.

The core of the IDPU system is an 80196-based processor and 256 megabyte (MB) memory card forming the Data Processor & Memory Board (DPMB). The processor design and operation relies on existing heritage with the FAST and HESSI missions as well as the currently ongoing STEREO development program. The basic design premise uses dedicated FPGAs for routine data and memory management, instrument interfaces, and other repetitive tasks in order to leave the processor free for specialized duties and less frequent, higher level functions. Instrument housekeeping and commanding is accomplished via the UCB-developed Command-Data Interface (CDI) protocol, a low-speed, (a) synchronous bi-directional serial line in a point-to-point architecture. Instrument science data is relayed over separate, high speed (1 Mbps) synchronous unidirectional serial lines to the DPMB. The DPMB accommodates two separate interfaces, one for communications with other boards using a common IPDU box backplane and a second for signals with instruments external to the IPDU box.

Card #. Subsystem/Component [Form factor]	Mass [kg]	Power [W, avg]	Power [W, peak]
#1. Digital Fields Board (DFB) [6UVME]	0.36	0.5	0.65
#2. Boom Electronics Board (BEB) [6UVME]	0.43	2.1	7
#3a. FGM Interface [3UVME]	0.27	0.8	0.8
#3b. ESA/SST Interfaces [3UVME]	0.33	0.8	0.8
#4. Data Processor & Memory Board (DPMB) [6UVME]	0.43	2.48	3.01
#5. Low Voltage Power Supply board (LVPS) [6UVME]	0.43	2.44	2.44

Table F-18. *IDPU board requirements summary*

The IDPU mass and power requirements broken down by subsystem is shown in Figure F-19/A (Foldout 6) It is also is shown by card in Table F-18. Contingency allocation is based on heritage in accordance with UCB philosophy from previous programs, as described in Section F4.a. Thermal environment must be maintained between –55 and +70 C for survival, and between –20 and +45 C for operation. During normal operations the unit will generate ~9W of power dissipation.

There are no new developments planned for the IDPU system that require a qualification program, as the majority of the subsystems and components are derived from missions with well-established heritage (FAST, POLAR, CLUSTER, HESSI). The instrument 256 MB memory is successfully undergoing a qualification program for the ISUAL project; it is scheduled to be flight-ready prior to the commencement of phase B for THEMIS.

Operation. The IDPU collects, compresses and stores instrument data and transmits the data to the ground upon command with a nominal downlink rate of 400Kbps. The IDPU-to-bus C&DH telemetry requirement is a 1 Mbps serial data stream. As in FAST and HESSI, the IDPU can mix and prioritize engineering and science frames according to operational preferences at downlink time. Flight operators can view engineering data while saving stored-engineering and science data.

Instrument data is yielded to the IDPU at continuous rates governed by the overall system mode (survey, particle burst, waveburst I or II). The data format is 24-bits, consisting of an 8-bit application identifier (ApID) followed by 16 bits of data. FPGA-based logic steers incoming instrument data to the appropriate memory locations in real-time based on instrument ApID information. FPGA-based logic performs data compression and complete packetization prior to telemetry downlink through the C&DH system in the probe BAU.

During nominal operation the DPMB provides instrument housekeeping packets to the bus which is combined with its data into CCSDS frames for downlink. Stored science data is transmitted separately after engineering data over the high speed link to the BAU when commanded from the ground.

The DPMB is responsible for monitoring instrument data and using pre-defined measurement quantities as a criteria for the overall instrument data rates. Using a command upload table, the processor steers instrument quantities into a trigger buffer section of memory based on a trigger ApID list. A real-time evaluation of a single measurement level or weighted linear combinations of several measurements are compared to pre-set thresholds as criterion for survey, particle burst, or wave burst instrument rates.

A backup ranging technique (new technology) will be implemented using a simple buffered command line from the bus to the IDPU so that uplink ranging commands can be time-tagged. The UTC of the uplinked command is telemetered back to the ground in housekeeping in order to calculate the earth-to-probe travel time.

Flight software. The IDPU software has the

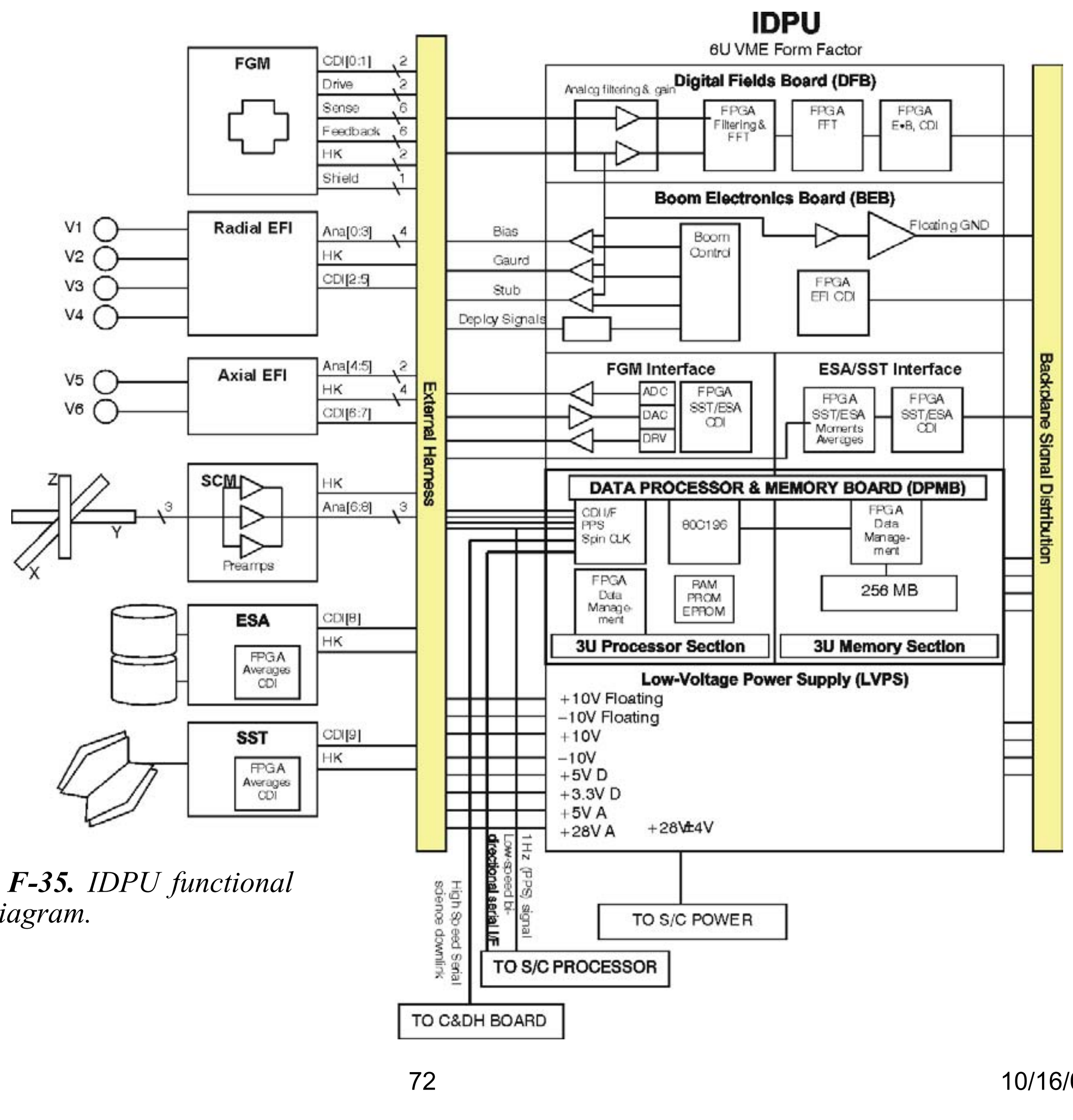


__Figure F-35.__ IDPU functional block diagram.

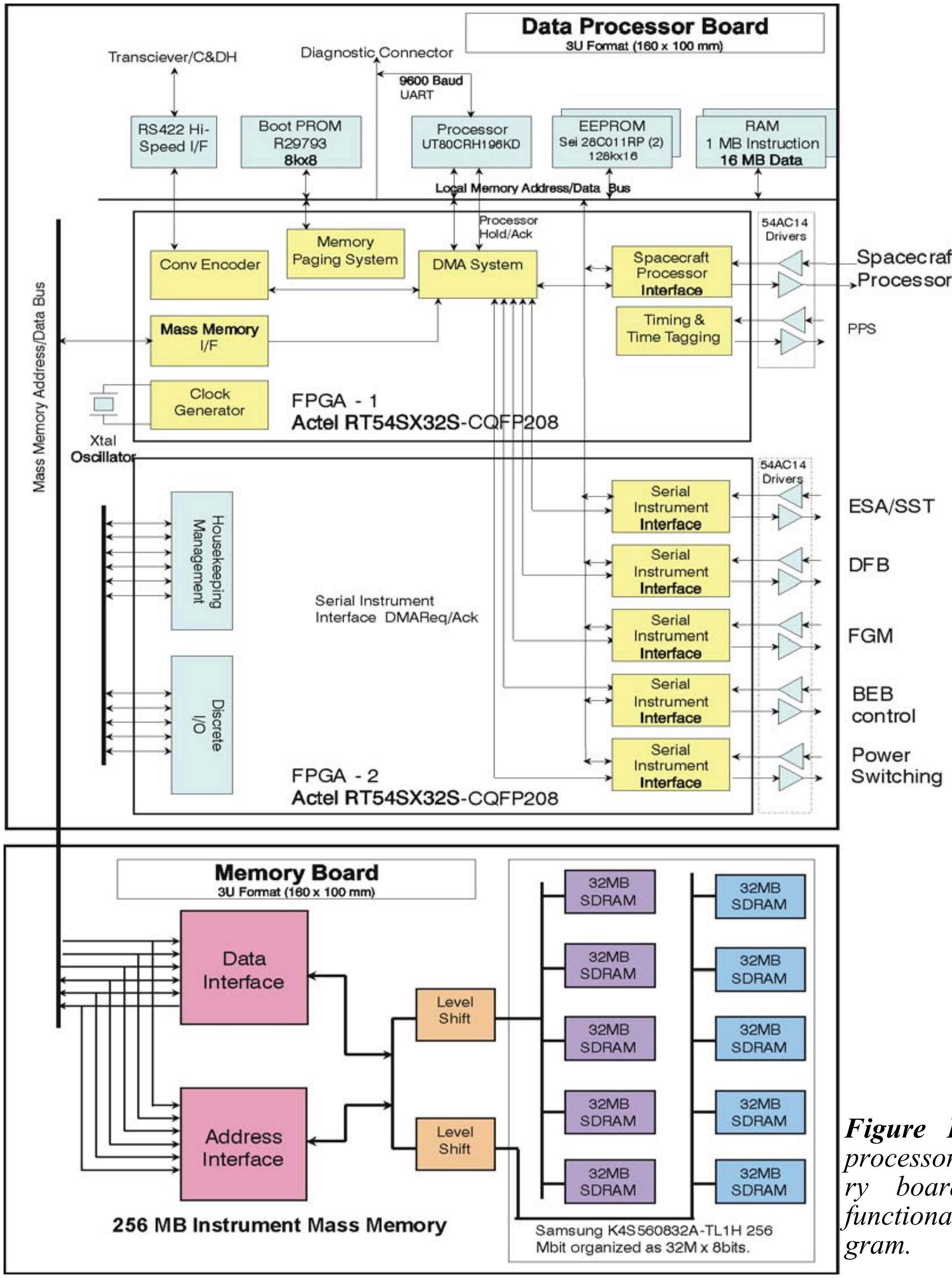


Figure F-36. Data processor and memory board (DPMB) functional block diagram.

tasks outlined in Table F-19, broken down according by CPU power usage. Flight software patches commonly occur about 2-3 months into the mission after instrument commissioning and checkout. Averaging the last six spacecraft IDPUs either built or operated by UCB, these tend to run in the 100 to 150 byte range and are insignificant contributors to the uplink.

Mode Definition tables are large macros used by the IDPU to configure instruments appropriate to the region of space being examined. As in the FAST spacecraft, the IDPU will be programmed with a number of mode definitions which are selected by an ATS command or on-board triggering logic. Assuming 32 macros of 512 bytes each, a full reload would require 16K. ESA and SST Moment Tables are calculated by IDPU FSW at system startup and loaded into the ESA and SST Moment circuitry. For contingency operations, these tables are also directly loadable from the ground. EFI biasing, FGM and SCM parameter mods are expected to be small and included in the mode definitions tables.

Task	Description	%CPU
EFI Spin Fits	Real-time least-squares fits to spin-modulated EFI data; yields spin period, standard deviations, and fit parameters.	20
ESA/SST Moments	Calculates ion/electron density (N), Velocity (**V**), and pressure (**P**).	20
Data Compression	NASA lossless, nominal ×2 reduction	10
Burst Triggering	Programmable criteria on trigger quantity packets (single-, or weighted sums of multiple-measurements)	10

Table F-19. *IDPU flight software tasks.*

The command uplink protocol is a 1 kbps, COP-1 compliant system relayed by the bus processor. Table F-20 shows the expected uplink command durations for instruments and IDPU.

Purpose	Uplink [sec] (assumes 1kbps)	
	Nominal	Contingency
IDPU FSW Updates	1.4	n/a
IDPU Mode Definitions	72.8	n/a
EFI Biasing	0.0	n/a
ESA Moment Tables	0.0	364.1
SST Moment Tables	0.0	182.0
FGM Settings (Modes)	0.0	n/a
SCM Settings	0.0	n/a

Table F-20. *Uplink duration breakdown.*

Cost saving measures. The development time of the IDPU is minimized through the use of an 80196 based processor derived from the HESSI and STEREO programs, while the mass memory is based on the ISUAL system. All boards are using either 3U- or 6U-VME form factors and are thus compatible with industry standard layouts. This form factor allows an exact copy of the existing FGM interface board to be used with minimal design changes. Further cost savings are realized through the use of nearly identical bus and instrument processor designs that fit into a 3U-VME footprint. In the instrument data processor version, the experiment mass memory occupies the remaining half of the 6U-VME IDPU board area, while in the bus version the processor stands alone in a 3U configuration without the mass memory section.

Burst mode detection and collection. This builds directly on the successful practices of WIND exactly in the same region of space (tail, magnetopause), which were modelled those of FAST. Particle burst onset is based on dipolarizations and high speed flows (WIND heritage). Wave burst collection is based on wave power in selectable bands (FAST heritage). Additionally, bursts receive orbit-dependent weights (effectively time-based), which are uploaded by ground commands (as on FAST).

F5 Payload Integration

Based upon many years of flight projects such as FAST and HESSI, the THEMIS approach to integration is to combine the electronics of the science instruments into a single package with shared data processing and storage capabilities within a single box, the IDPU. The instrument sensors have been described in Section F4. They are one each for the FGM, the SCM, the ESA and the SST instruments and six for the EFI instrument. Sensors are controlled by, and data is returned through the IDPU (Section F4.d) which has the sole electrical interface to the spacecraft. The instrument complement, including sensor harnessing to the IDPU is designed, built, and tested at UCB using a spacecraft (probe) simulator and then delivered as a single item to Swales for integration with the probe buses. While providing greater scientific capabilities in on-board power and logic sharing, the common-IDPU approach also provides a single electrical interface to the probe, streamlines instrument calibration and testing with the flight-electronics early in the I&T process and greatly simplifies probe I&T. The detailed weight, power and thermal requirements, volumetric envelopes and fields of view of the payload is given in Figure F-19 (Foldout 6).

a. Mechanical

The THEMIS science instruments have modest alignment requirements which bolt hole alignments address adequately. ESA and SST sensors require that the probe spins at 10-30RPM in order to obtain full azimuth coverage. These sensors are also contamination-sensitive, requiring that the probe propulsion plumes point away from the direction of their apertures, and set the baseline contamination requirement for the probe and launch environments (Section F5.e).

The FGM and SCM sensors are 3-axis magnetometers, mounted on rigid booms. Deployment provides a practical separation distance from the probe center body in order to provide a low noise environment. These sensors set the requirement on probe magnetic cleanliness.

The FGM and SCM booms are one-shot deployment mechanisms and will be primarily responsible for holding the sensor still with respect to the probe chassis. The maximum initial spin rate for FGM and SCM boom deployment is 15 RPM.

The EFI provides 3-axis electric field measurements once its Spin-Plane and Axial booms are deployed. These boom systems should be aligned with the probe center of mass and the probes should be spin balanced. Given that the thrusters also prefer the CG plane, these thrusters are canted a few degrees up or down from the spin plane to avoid direct impingement on the EFI cables. Likewise, the axial thrusters will be canted a few degrees outward to avoid plume impingement on the -Z Axial boom.

The EFI requires a spin rate of 30 RPM during sensor deployments.

The EFI requires that all probe surfaces are electrostatically clean to 10^{-5} Ohms/cm^2. All exterior surfaces and apertures which are not always in sunlight are subject to this requirement.

Sensor	Key Requirement on Probe
FGM	DC magnetic <1nT at sensor
SCM	AC magnetic at sensor: < 10pT/$\sqrt{Hz}$ (1Hz); <10fT/$\sqrt{Hz}$ (0.5kHz)
EFI	ESC < 10^5Ohms-m^2
ESA	Molecular <0.01 μg/cm^2
SST	Molecular <0.1 μg/cm^2

Table F-21. *Payload requirements*

b. Electrical

The IDPU to electrical interface to the probe bus consists of a low-speed bidirectional serial interface for commands, housekeeping, and status information exchange between the probe bus and instrument, as well as a high speed serial Clock and Data lines for science telemetry. A 1 Hz clock line combined with a spacecraft UTC message provides synchronization of the two systems. The probe bus provides instrument commands, time and probe status to the IDPU every second using this serial interface. Time-tagged sun-sensor data are used by the IDPU for spin-sectoring the SST and ESA data.

The IDPU provides instrument housekeeping packets to the spacecraft which is combined with its data into CCSDS frames for downlink. Stored science data is transmitted over the high speed link when commanded from the ground. Payload telemetry generation is described in Figure F-19 (Foldout 6). Uplink and downlink data rates are discussed in Section F3.

The new-technology ranging technique requires a simple buffered command line from the spacecraft to the IDPU so that uplink ranging commands can be time-tagged. The UTC of the uplinked command is telemetered back to the ground in housekeeping in order to calculate the earth-to-probe travel time.

c. Power

The bus provides the IDPU a single 28±4 VDC line on a switched service. All science instrument power is controlled internally by the IDPU.

d. Thermal

Since THEMIS probes are small, body mounted instruments will experience larger thermal extremes than in previous missions.

Shown in Figure F-19 (Foldout F6) are payload operational temperatures, which are both comfortable for the instruments and require only a passive thermal design. These instrument limits are derived from previous experience. Additional Phase B payload thermal analyses shall provide more detailed thermal limits and thermal model specifications for coupling to probe bus models. Cold survival temperatures for the instrument components are governed by the -55°C specification for most of the parts used. Practical limits for these temperatures are -50°C to +70°C survival, -20°C to +45°C operational, which are consistent with the bus thermal analysis results shown in Section F3.

e. Contamination

While several THEMIS sensors are sensitive to contamination, they have all been designed for easy handling and simple integration to the probe bus.

The ESA and SST sensors are sensitive to molecular and particulate contamination at the sub-micron level but have been successfully flown on spacecraft with a modest 0.1% TML requirement with similar on-board propulsion usage. Both have covers and an external purge provided by the instrument for integration and test.

Typical sources of spacecraft contamination are easily mitigated by standard practices to a satisfactory level for THEMIS instruments. Wire harnesses, solar array panels, thermal blankets and heaters shall be baked prior to instrument I&T. The thermal-vacuum chamber shall be baked prior to probe insertion, backfilled with GN2 at the end of the test, while its contamination level shall be monitored using a TQCM and witness plates for the duration of the test.

The EFI sensors are sensitive to “fingerprints and scratches”; i.e. asymmetries in the properties of the sphere which would generate a spin-period photo-emission. Deployment testing during the probe I&T sequence will require a class 100,000 environment and handling with gloves.

f. Integration prior to probe I&T

THEMIS instrument integration is a two step process: *In the first step*, individual instruments are calibrated and tested at the box level for unique functions. The details of sensor calibration and testing described in Section F4 for each instrument individually apply here. *In the second step*, sensors are integrated to the IDPU and flight harness at UCB. Following functional testing, the entire instrument complement is qualified as an instrument. This maximizes the instrument-level test time, while minimizing personnel and thermal-vacuum chamber resources. The tests performed at each step are tabulated in Table F-22, and are detailed in the environmental test matrix, Table F-23.

For instrument I&T, we plan to use the same clean room as was used by the HESSI and CHIPS spacecraft and install a Swales-provided probe simulator and GSE in the adjoining room. UCB will provide a probe mock-up for flight harness and sensor mounting.

Schedule and facility utilization savings can occur from parallel I&T processing of two flight units. However, performing the first flight instrument complement's ("F1") integration and testing provides invaluable experience with the nuances of the design implementation. Lessons learned from that will carry over to subsequent copies which are tested in pairs; i.e. (F2,F3) and (F4,F5). Procedures and GSEs developed for instrument I&T flow directly into probe I&T with little or no modification. This flow is shown on the schedule in section F6.

Test Description	Box	Instrument complement
Functional	✔	✔
Deployment	✔	✔
Self-Compatibility	-	✔
Cleanliness	✔	-
EMC/EMI	-	✔
DC Mag Field	✔	-
AC Mag Field	-	✔
ESC	✔	-
Vibration	✔	-
T/V (cycles)	✔(2)	✔(6)

Table F-22. *Tests performed at payload integration prior to probe I&T.*

F6. Manufacturing, Integration and Test (I&T).

a. Overview.

The THEMIS probe and ground observatory manufacturing and I&T plan is fully integrated into our overall programmatic and technical process (concurrent with design and planning). The plan is a key driver in THEMIS's selection of experienced developers, instruments and components (copies of or nearly identical to previously flown units), heritage ground system elements, and a simple mission design.

Lessons learned from engineering test units (ETU) and their application to the first probe tests reduce risk and minimize potential problems early in the schedule. To ensure uniformity, we drove the design to result in physically identical probes (minor variations contained only within design tolerances, allowable characterization differences, and in the probe unique command & telemetry (C&T) database). THEMIS's electronic configuration control process (and tools) allow the core I&T and mission operations team (MOT) to efficiently control changes, provide team-wide visibility to approved changes, and introduce them into probes under test, especially during regression test operations. This approach applies careful attention to the manufacturability, testability, repeatability, and control of the probe quality, vital to the rational I&T sequence proposed herein, thus minimizing risk of generic rework of a component in mid-probe production.

Instrument calibration, initial testing, and integration prior to probe I&T (described in Section F5.f), is performed at the instrument developer sites and at UCB using a probe bus simulator, delivered by Swales. Probe, probe carrier manufacturing, and subsequent I&T takes place at Swales, initially using instrument simulators in the probe test bed and with the flight probe buses and finally with the fully integrated instruments. A two parallel production line approach (one-core-team-per-probe) is utilized (as described in Section F3.c5.3) with I&T personnel trained and supported by subsystem developers who migrate forward into I&T and operations. The five probe production is staggered by ~one month in order to balance component delivery, personnel, facility, & equipment loading while ensuring a deterministic schedule plan with credible workaround options. Instrumenters, developers, and the MOT gain an increasing understanding of the probes' characteristic performance and ensure the most efficient utilization of the subsystem development team in test formulation, oversight, and troubleshooting. Our approach permits rapid dissemination of the experience gained from the tests of the first probe onto subsequent units, allows for parallel shift operations, and cross training within the team. The participation of key instrument personnel in I&T result in a strategy whose effectiveness was proven on prior I&T management and test activities led by Swales (FUSE and EO-1 programs) and by UCB on their HESSI program. This tightly coupled UCB/Swales effort and the rotating work assignments of test and MOT personnel, resident at both sites, ensure hands-on training and efficient transfer of bus system experience to mission and science operators.

Swales is responsible for the launch site activities including final PCA processing, integration & checkout with the L/V, and launch countdown operations.

Any instrument, component, subsystem, or system undergoes four classes of testing: 1) Comprehensive Performance Testing (CPT) exercises all functionality through parameter ranges under external stimulation, typically performed in a serial fashion for all components, instruments, and for each

Item/Assembly Level	Verification Scheme	Loads / Accel	Modal Survey	Vibration (Random/	Acoustic & Shock	Pressure Profile	Margins / Design Life	Mass Props./ Spin Balance	Conducted Emissions	Radiated Emissions	Conducted Susceptibility	Radiated Susceptibility	Number of TV Cycles	hot & cold no-Op Survial, Cold Start	TV Test Limits (deg C)	Thermal Balance	Magnetic Cleanliness	Electro-Statics & Grounding
		MECHANICAL							ELECTRICAL				THERMAL				SPECIAL	
INSTRUMENT																		
Sensors		T	T	T	A	A	A	T	self	self	self	self	Cal(2)	T	note 4	n/a	T	T
IDPU ETU	Qualification	T	T	T	A	A	A	T	T	T	T	T	CPT(2)	T	-20,55		T	T
IDPU #1-5	Acceptance	T	T	T	A	A	A	T	self	self	self	self	CPT(2)	T	-15,50	n/a	T	T
Booms		T	T	T	A	A	A	T	self	self	self	self	CPT(2)	T	note 4	n/a	T	T
Integrated Instruments		n/a	n/a	n/a	n/a	n/a	n/a	T	T	self	T	self	CPT(4)	T	-15,50	n/a	T	T
Bus Avionics ETU	Qualification	T	A	T	A	A	A	T	T	T	T	T	CPT(4)	T	-20,55	n/a	T	T
Bus Avionics #1-5	Acceptance	simil	simil	T	A	simil	simil	T	self	self	self	self	CPT(4)	T	-15,50	n/a	simil	T
Probe #1	Protoflight	T	T	T	A	A	A	T	self	T	self	T	CPT(8)	T	-20,55	T	T	T
Probes #2-5	Acceptance	simil	simil	T	A	simil	simil	T	simil	simil	simil	simil	CPT(4)	T	-15,50	simil	T	T
Probe Carrier	Protoflight	T	T	T	A	A	A	T	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
PCA (incl. 5 probes)	Acceptance	simil	T	T	T	A	simil	T	self	self	self	self	CPT(2)	T	-15,50	T	n/a	n/a

NOTES:
1. EFI & Mag Booms will be Functionally Tested (both Ambient & Vacuum) prior to Instrument Integration
2. Each Instrument will Undergo at least Two Thermal Vacuum cycles during the Individual Calibrations
3. Vibration Test Levels per GEVS-SE & Delta 2 Payload Planners Guide, Coupled Loads, and Probe Test Results
4. Thermal Vacuum Limits set by Thermal Models plus 5C (MUF) & 5C (TUF), boom & sensor limits are location dependent
5. EMI and EMC Testing per Mil-Std-461
6. Magnetic and Electrostatic Cleanliness Requirements will be Derived by the Themis Project Office
7. General - All Tests are based on pre/post system analysis

Table F-23. *THEMIS environmental test matrix.*

probe at the probe & mission test level. During thermal vacuum (T/V) temperature plateaus, the CPT is run in segments to verify performance at thermal extremes. 2) Functional testing exercises all signal path and software functionality and is performed as an integrity test during environmental testing. Functional tests occur simultaneously for combinations of instruments and bus components after each probe mode reconfiguration. 3) Aliveness testing (subset of functional test) determines the health & status of critical parameters to ensure an instrument's or a bus component's operational integrity. It provides a shortened method to assess system status after logistical operations. 4) Special tests are one-time evaluations of parameter extremes, contingency procedures, and uniquely configured stimulation conditions. These various test classes produce in-process production trend data starting with the ETU and first units' testing. Subsequent units are compared to the baseline data to flag "out of family" parameter variations. Each subsequent unit also adds to the statistical trend database to improve the quality of the baseline data.

Environmental tests, planned burn-in times, and T/V cycles for instrument, probe bus, probe, and mission levels are outlined in the environmental verification matrix (Table F-23). The THEMIS MSE works with the instrument and bus engineers to refine this matrix and compose a comprehensive test sequence. The levels and durations satisfy GEVS requirements and have been reviewed in detail at system and subsystem levels during Phase A and will continue to be a key part of subsequent subsystem peer reviews. Our thermal vacuum margins are 10^{o}C beyond predicts, vibration margins are +3dB above flight levels, and EMI and EMC limits include various margins depending on signal characteristics.

Description	EM	FLT	SPR
EFI Spin Plane Booms	2	20	2
EFI Axial Booms	1	10	1
ESA	1	5	1
SST	0	5	1
FGM	0	5	1
SCM	1	5	1
IDPU	2	5	1
Probe Bus	0	5	0
Probe Carrier	1	1	0
Ground Data System	0	1	0
ASI	1	20	2
GMAG	1	8	1
GMAG-EPO	0	10	1

Table F-24 *THEMIS end items list*

The End Items List (Table F-24) shows the expected number of completed engineering models (EM), flight-ready components (FLT) and spare units (SPR). Spare parts are typically retained at manufacturers location; with spare units delivered and ready to be used. Instrument spares include EFI wire sensors, ESA channel plates and IDPU EEE parts; bus spares include battery, spare solar panel (side), RF cable, spare processor board, propulsion tank, and spare top/bottom solar panel. Spares will be functionally tested and may be environmentally qualified as a risk reduction step.

b. Instruments

b1. Fabrication

The ESA and SST will be assembled on Class 100k clean benches (done for prior missions) and calibrated using existing dedicated T/V chambers. Both the ESA and SST are modular units consisting of several sub-assemblies, with fabrication drawings already in place. The heritage of these instruments allows for the economies of multiple unit production (marginal cost over a single unit) to be applied to the flight machined parts, etched parts, and circuit boards (manufactured, fit checked, and assembled as a batch) ensuring minimal unit-to-unit variation. Breadboard electronics testing, performed prior to proto-flight construction, and procurement of long-lead detectors and micro channel plates (MCPs), directly after program startup, reduces schedule risk. Since no optics re-design or significant electronics changes from the previous instruments is needed, breadboard testing commences upon detector and MCP arrival.

The ESA consists of the analyzer, the anode base (with MCP detectors), preamplifier-counter board, HV interface board, high voltage supplies, and the outer housing. ESAs are designed with manufacturability in mind: The final assembly of an ESA into a flight unit, ready for calibration, can be completed in several hours, based upon experience from FAST. MCP's, once installed into the anode base, require dry nitrogen purge. Thus ESA units have entrance covers internal to the unit, to contain the nitrogen purge needed to minimize contamination. These covers are opened in orbit.

The SST consists of the collimators, the detectors, the detector mounting, the magnet and yoke, the electronics housing and a pedestal. Magnetic cleanliness requires that the SST magnets are measured and paired prior to assembly in order to cancel the net dipole. Trim magnets have been used in the past to cancel any residual dipole.

EFI and FGM/SCM booms are assembled and tested, cleaned, and thermal vacuum-qualified. Standard tests include deployment in vacuum at high and low extreme temperatures. Final hot soak bake out is performed to meet contamination requirements.

EFI motors use the standard UCB design, which includes magnetic shielding of the permanent magnets. The motor magnetic field is measured and minimized prior to assembly.

Fluxgate sensor (FGS) design qualification unit (F6) and flight acceptance tests with the sensors FGS F1-F5 (vibration and thermal vacuum) are carried out by IWF and TUBS according to project specified test requirements, in their existing test facilities.

The Search Coil antennae (SCa) are built under CETP direct control and all verifications tests are performed at CETP. The Search Coil preamplifier unit (SCpa) has already been built and tested by company +3D under CNES funding and no development is needed. Fabrication of the pre-amplifiers is performed by industry using a project specified performance assurance plan independently verified by CETP. Vibration tests are performed for the SCa and the SCpa separately, according to project specifications. Total cost and test durations are reduced by vibrating 2 or 3 SCpa units simultaneously. The thermal vacuum tests are performed with a complete equipment suite (SCa + cable + Scpa).

The IDPU box includes sensor interface cards, a central computer and memory, and a power converter. CU and IWF/TUBS are providing designs for two of the electronic boards and UCB (and subcontractors) design the remaining boards. UCB purchases all EEE parts for the IDPU and assembles ETU's with internal technicians. Flight PC boards are subcontracted to qualified vendors such as UTMC and Jackson&Tull. MIL-55110 PWBs are subcontracted directly from UCB to local vendors and coupons are sent to GSFC for inspection and approval prior to flight assembly, in accordance with requirements and UCB practices on previous missions.

Instrument harnessing is built at UCB using mock-ups of the probe deck and MLI blankets are made at UCB at first item delivery. All harnessing and MLI is baked out as described in Table F6-1.

Instrument and IDPU I&T, uses a probe bus simulator, delivered by Swales, that includes the EGSE test system (ITOS) as the test command & data system.

b2. Software development.

UCB develops the IDPU software using PC-based commercial products now being used for STEREO software development. The MSE develops the THEMIS specifications in concert with the IDPU lead and places documentation under configuration control. An engineering model of the IDPU processor card is used as a test bed, and all software is "in circuit" tested. Diagnostic capabilities are included in the processor hardware design and diagnostic packet telemetry is employed.

Development and test of the software occurs in a phased-build manner. As engineering boards are finished, the software board control functions are tested and as the ETU sensors become available, instrument control module software is subsequently tested.

The bus simulator (programmed on VirtualSat (Vsat is a COTS product from our software team partner, the Hammers Co., that simulates ACS sensors, instruments, and probe dynamics and behavior) and the ITOS system allow for the instrument automated test procedure (ATP) and C&T database formation prior to instrument testing thus facilitating seamless migration into probe I&T. An expert test conductor, budgeted in the probe I&T, accompanies the bus simulator/ITOS system to UCB and resides with the instrument test team, assisting in page display tailoring, population of the C&T database, and writing unified test procedures to ensure subsequent probe integration ease of use. Conversely, an instrument interface simulator, developed by UCB, using VSat, is delivered to the probe bus team for inclusion in the test bed activities.

b3. Production personnel resources

The high heritage of the instruments and institutions allow for THEMIS to draw from an experienced pool of scientists and engineers. In all cases, whether at UCB or at the foreign developer institutions, the instrument lead is a seasoned scientist, having performed this function on many prior missions, is responsible for ensuring that the scientific and programmatic targets are met within cost and schedule. The instrument lead has an instrument manager with the technical expertise and experience to manage the day-to-day operations of the development. Scientists participate in the calibration and testing of the sensors having demonstrated, through their experience, a vested interest in the analysis of the highest quality data. They ensure optimal performance of the sensor while providing the team with immediate quality control feedback.

The production personnel at CETP are experienced with multiple builds of the SCM instrument most recently from the Cluster program. Most of the fabrication (coils, SCpa) will be performed by industry. The production personnel at IWF and TUBS have experience with multiple builds of magnetometers for ground observations (gradiometers) having similar sensitivity requirements, and also with planetary programs having similar mass and power requirements (ROSETTA). Both SCM and FGM teams each have core teams comprised of four scientists and engineers.

The core team structure is the traditional method of instrument manufacture and testing at UCB, and is based on programs such as FAST, WIND, Cluster and HESSI. The core science, engineering and technician teams for ESA, SST and EFI instrument development have been assembled. Increased staffing (already identified via industry work agreements) will draw from S.F. Bay Area industry in few key support areas, similar to our approach for previous programs of this size, using personnel who have performed similar tasks at UCB before.

b4. Instrument I&T schedule.

This section discusses the instrument I&T schedule. As was discussed in Section F5.f instruments are calibrated and tested at the developer sites at the box level, then integrated with the flight IDPU and tested at the instrument complement level prior to shipment for probe I&T and further testing at Swales. Figure F-37 shows the overall instrument manufacturing, integration and test schedule up to the point of delivery for probe I&T. Instrument testing during probe I&T is shown in Section F6.c.

c. Probe busses, probe carrier and mission I&T

c1. Fabrication

Overall fabrication and assembly of the probe bus, probe, probe carrier, and mission (PCA) I&T is shown in Figure F-38. Swales utilizes in-house production capabilities for the probe and probe carrier structural, thermal, and harness components. Swales fabricates large numbers of varying complexity structural panels (both aluminum and composite) for many commercial communications, DOD and NASA programs. Swales' thermal blanket lab fabricates MLI blankets for many commercial and NASA missions using the same materials envisioned for THEMIS. Swales's harness fabrication group (EO-1, FUSE instrument, VCL, ICEsat instrument heritage) manufactures all probe bus and PC harnesses. Probe bus electronics design is performed in-house, with PC board artwork and fabrication through a variety of local space-qualified vendors. Swales' product assurance group manages EEE parts procurement, inventory control, and kitted distribution to subcontractors for population of circuit boards. Finished boards are tested in-house in Swales's electronics lab and integrated into the BAU for box level test. Environmental component tests are performed locally (baseline at GSFC) first with the ETU BAU and followed by the flight units. Probe assembly and I&T occurs with two parallel production lines, each with its own test equipment and core test teams. Two copies of the mechanical and electrical ground support equipment (MGSE & EGSE: #1 & #2) are utilized in parallel to support the probe bus, probe, and PCA level testing activities. This enables efficient parallel operations, risk recovery workaround options, and lo-

F6. Manufacturing, Integration and Test (I&T).

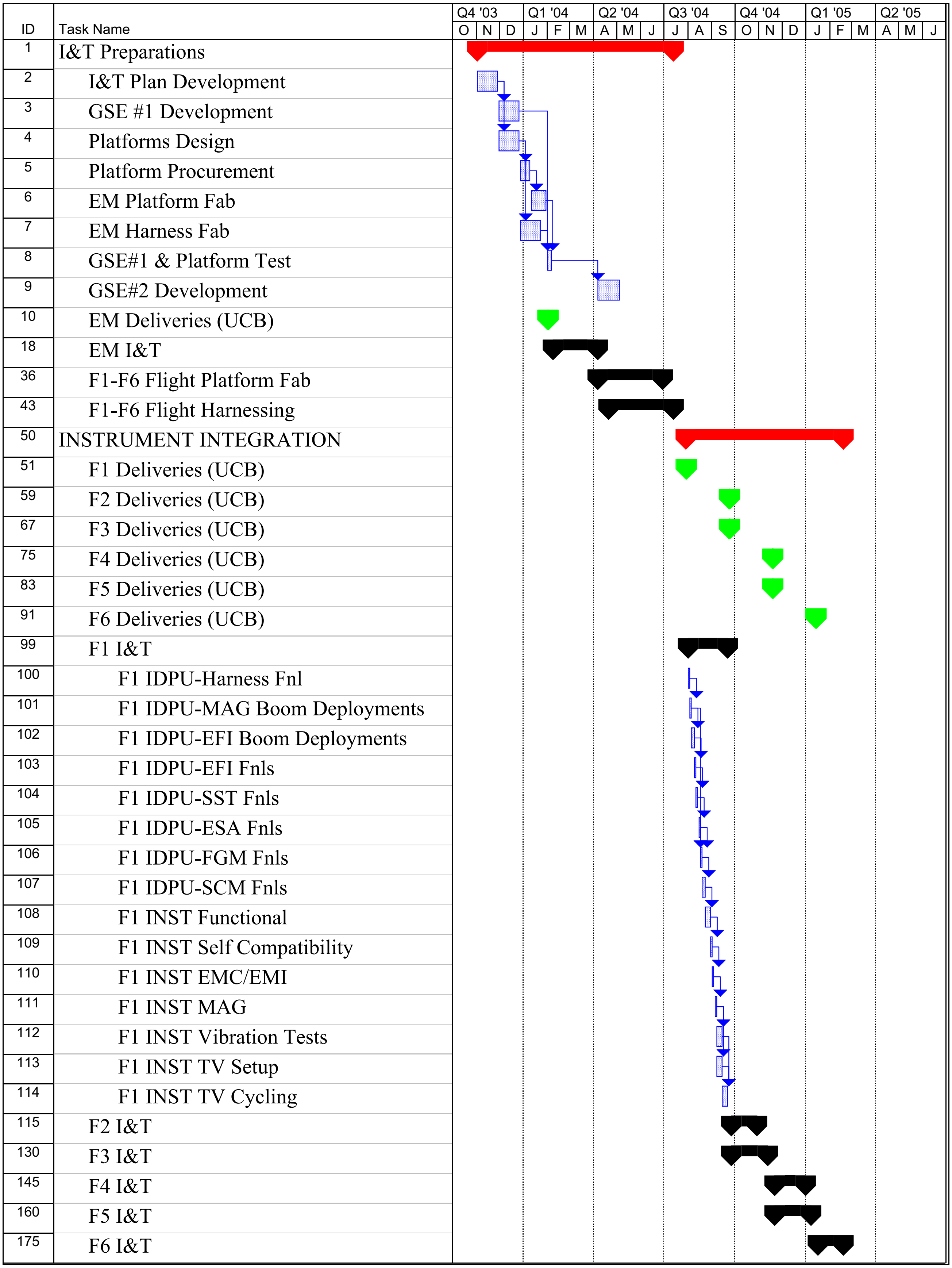


Figure F-37. *Instrument integration and testing schedule prior to delivery at Swales for probe I&T*

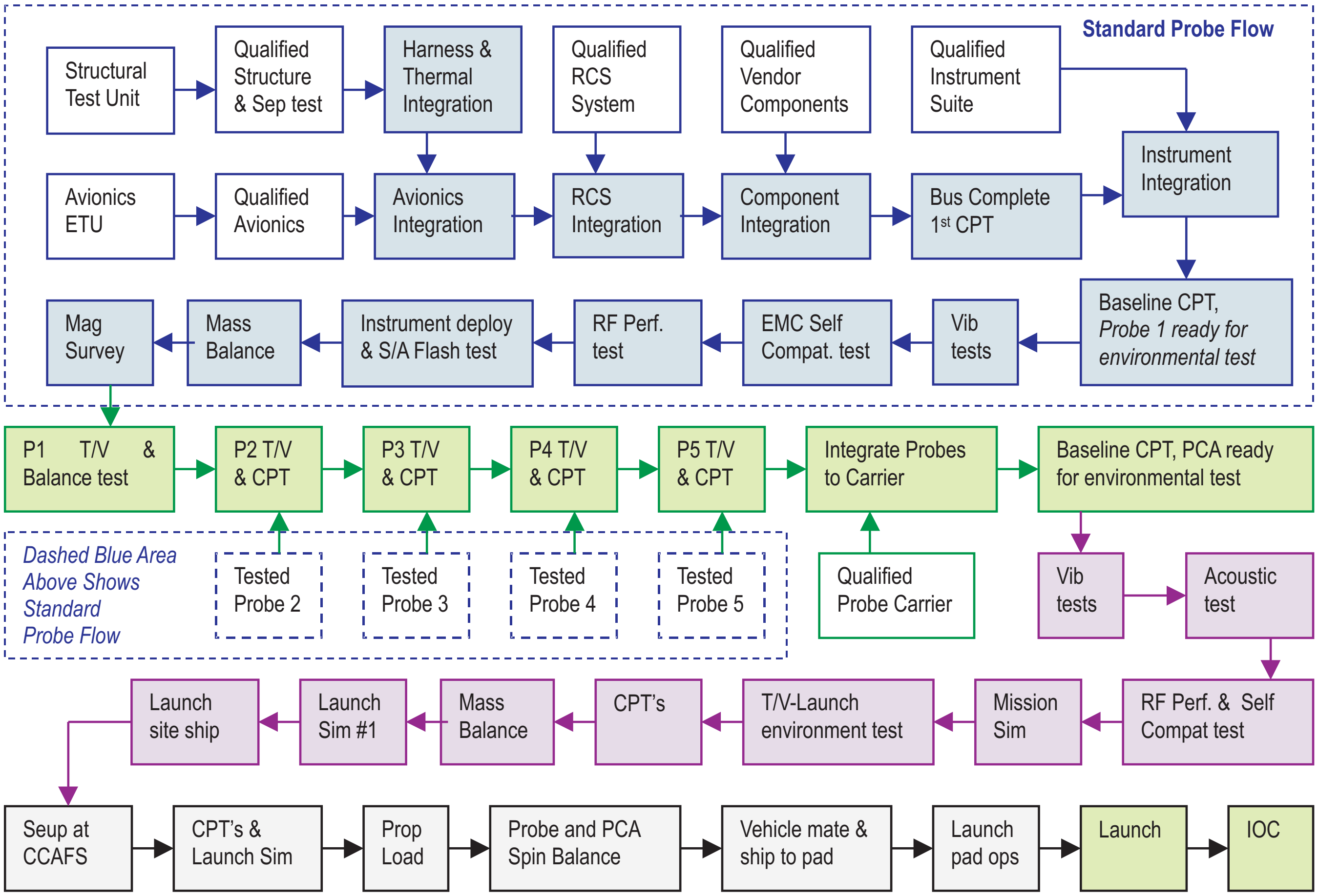


Figure F-38. *Probe and mission manufacturing, integration and test flow.*

gistical decoupling. The initial probe I&T, on these two lines, produces probes ready for environmental testing. A third full (EGSE #3) system and test-conducting group performs separately the finished probe individual T/V tests. This 3rd EGSE system is used as the central test set for PCA mission level testing through launch operations and, earlier in I&T, serves as a separate test station for contingency workarounds to debug a probe integration anomaly and/or to begin a 3rd production line as back-up to the two main production lines.

c2. Software

The flight software build process is described in section F3 as part of the design. The I&T test system utilizes the Integration Test & Operation System (ITOS) software used extensively on the GSFC/SMEX programs and in use at the UCB MOC on FAST and HESSI. A dedicated database programmer maintains the EGSE software and C&T database configurations for each probe with formal change control (using an object oriented database and file management system) to centralize test procedure usage for nominal and regression testing in both the I&T and the testbed lab. environments. The commercial, turn-key, Programmable Telemetry Processor for Windows NT (PTPNT) system is the probe front-end during I&T and the platform for ground station commanding. PTPNT is used at UCB for tracking IMAGE, and at WGS and Poker Flats (AGS) to track missions including IMAGE and LandSat. PTPNT was used at UCB for HESSI I&T and is being used in HESSI operations.

MOT training and procedure verification begins with data flow tests and abbreviated mission simulation segments utilizing the probe test-bed (includes the ETU avionics) via a commercial, dial-up, secure, command/telemetry interface between UCB and Swales. The test-bed is a dedicated schedule risk reduction system that is used for early flight software development and validation, component evaluation hardware-in-the-loop verification tests, and mission operations preliminary procedure checkout. Procedures and sequences are validated on the test-bed prior to usage in the formal mission simulations with the flight probes.

c3. Personnel

This benefits from utilization of the full depth of skills within Swales company: The personnel for probe and probe carrier integration have extensive manufacturing and test experience, most recently from the EO-1 and FUSE programs. Swales was the EO-1 prime contractor and also managed the FUSE instrument, FUSE and EO-1 I&T, and FUSE, MAP, and EO-1 Launch Operations. THEMIS Swales's large pool of experienced personnel, in all THEMIS skill areas, support many on-site GSFC, APL, and NRL programs. Thus additional resources, if needed, are available at peak times for contingency operations, in this Swales pool of resources.

Swales' bus software team partner, the Hammers Co., uses a similar philosophy and has demonstrated this modus operandi with Swales previously on EO-1 and on the SMEX-Lite commercialization test bed activity. The Swales team is co-located in a Central Design Studio (CDS) during the design phase to provide core team members immediate informal communication access, ensuring that positive progress occurs, lock step, with each other's cognizance. A daily group formal communication occurs ensuring that key items and priorities are established to balance and adjust activities to meet each upcoming milestone. The Phase A study was conducted in the CDS with the core team and the benefits of the synergy between team members was a major element allowing us to process the significant amount of work required.

As the design work concludes and manufacturing commences, this core team moves to the Swales I&T facility and takes up daily residence with interaction and daily operation basically unchanged from the design phase. The nature of the work is hands on and the team is more logistically driven, but the team interaction process, relationships, and cross-training have been established prior to the production operations, minimizing the I&T learning curve.

c4. Environmental tests

Environmental tests are summarized in Table F-23 and are performed in accordance to the flow of Figure F-38. The design qualification and parametric characterization occurs at the component level via a combination of Engineering Test Units (ETU) and/or first flight units tested in a protoflight manner. Subsequent components are, generally, tested with an acceptance test philosophy (qualification by similarity) to ensure that features subject to workmanship variation are within family for the key parameters of those components. Additionally, component calibrations occur for features/parameters that have specialized stimulation conditions and/or for items with restricted physical access or operational restrictions during higher-level system test. The first probe is subjected to a full sequence of qualification and workmanship tests prior to the subsequent production probes. This allows for issues common to each probe to be worked as soon as possible, reducing overall schedule risk. The production probes are exposed to the same test sequence as the first probe, at acceptance levels, for workmanship verification. The probe testing demonstrates compatibility with environments for the nominal and launch modes. Vendor procured components are built to performance and interface specifications and the Phase A RFQ responses verified conformance to expected test limits.

The instrument environmental tests are summarized in section F6a. The probe environmental tests include vibration, T/V, thermal balance (first unit only), electromagnetic compatibility, magnetic survey, surface conductivity, molecular/particulate contamination control, selected bake-outs, solar array flash, instrument deploy first motion, and mass properties/spin balance. RF compatibility testing with the UCB ground station and the probes will utilize the NASA compatibility test van for verification of end-to-end communications during mission I&T. Planned schedule durations and flow support >100 hours of trouble-free testing on each probe, prior to launch, with ample contingency.

The probe carrier (PC) is a single mechanical dispenser and is qualified and characterized for structural integrity, payload attach/dispense, umbilical harness continuity/isolation, and thermal blanket integrity prior to integration of the qualified probes onto it.

The PCA is comprised of 5 probes and the probe carrier (PC). The PCA is a launch specific configuration and is subjected to testing that demonstrates compatibility with the launch environment. This configuration integrates end-to-end launch countdown & injection simulations with the MOC, MOT, and the PCA in the appropriate environmental conditions. Launch dynamics, vibration loading, acoustical energy impingement, and launch mode T/V testing provides a sound basis for verification of the workmanship of all interfaces and items utilized during the injection sequence.

c5. Integration, test and verification

c5.1 Philosophy. Swales mission integration and space system production manufacturing experience has shown that the key to successful I&T schedule maintenance is a highly cross-trained core I&T team for each probe supported by a shared pool of technical specialists (described in Section c5.3 below) comprised of instrument, mission operations, systems engineering, and bus subsystem specialists. The core integration team has an individual group for each probe production line. The subsystem engineering and technician developers migrate forward into the groups to maintain program continuity, transfer subsystem design knowl-

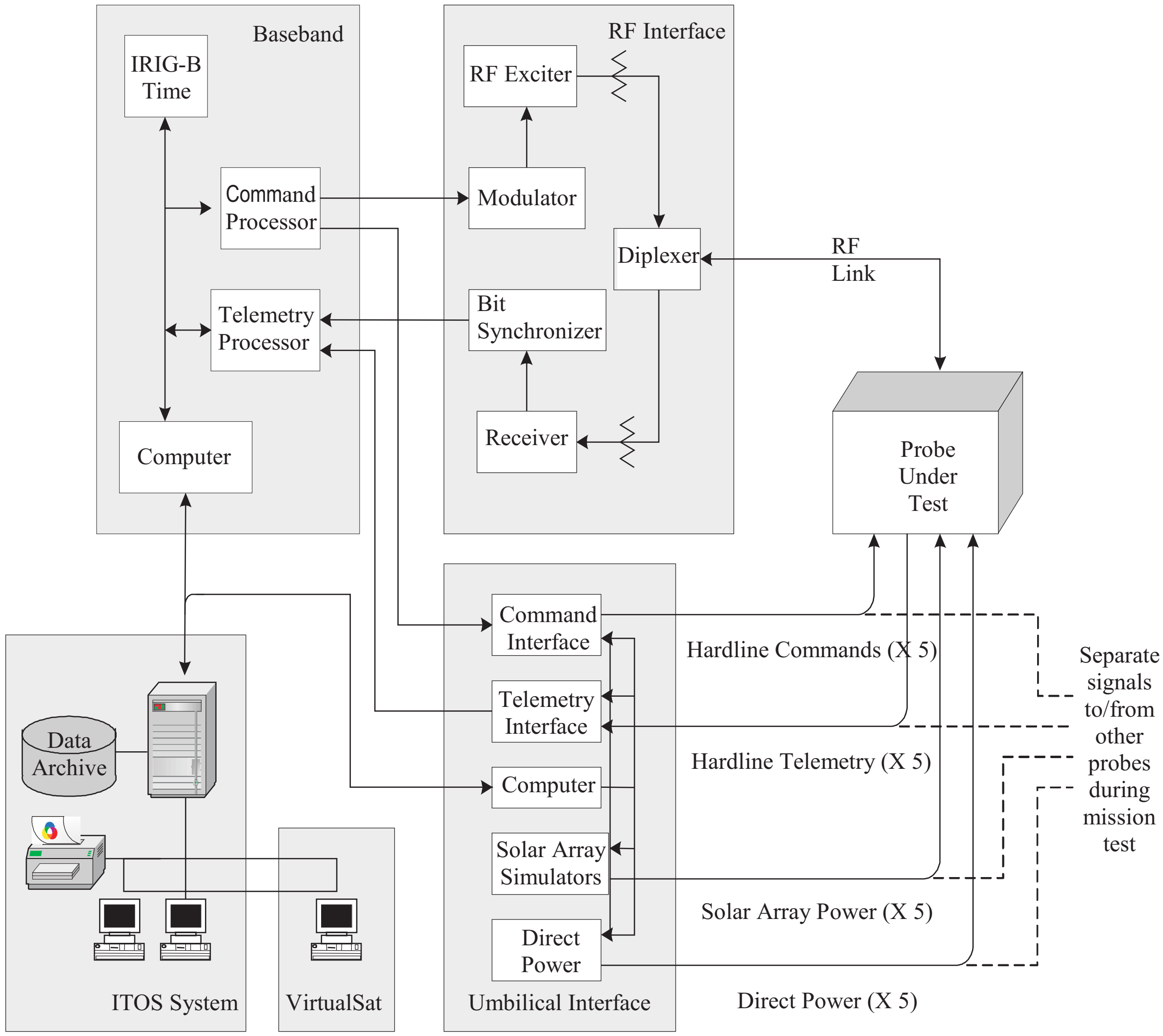


Figure F-39. *EGSE test configuration.*

edge into I&T and operations, and to provide immediate anomaly resolution. The parallel Integration Work Station (IWS) approach allows for independent shift operations for each probe group, cross-training between groups, shifting of personnel between groups to balance skill levels, and finally, during mission I&T, to provide workaround staffing capability for multi-shift operations and T/V testing. The first probe is staffed by the bulk of our core test team to ensure that the probe #1 schedule milestones are met, after which, they split into two test teams to support the parallel development of probes 2-5.

c5.2 GSE equipment. The EGSE system consists of five key elements (Table F-25): 1) the hardware/software associated with ITOS, 2) a Baseband Interface to handle command/telemetry processing, 3) an RF Interface to convert RF signals to base band, 4) an Umbilical Interface to provide power/hard-line signals to the probe(s), and 5) Vsat (described previously). These elements provide for a variety of combinations, usable for different test configurations and separate units under test. The commonality of the core elements for all EGSE copies reduces overall design complexity and development cost. The EGSE test configuration is shown in Figure F-39.

	ITOS	Virtual Sat	Base band	RF	Umbil ical
Full Function Test System (EGSE #3)	✔	✔	✔	✔	✔
Production Test System (EGSE #1 &2)	✔		✔		✔
Flatsat Simulator and Probe Simulator	✔	✔	✔		

Table F-25 *Electrical ground support equipment*

Using ITOS from the instrument and probe bus component level (as the Bench Test Equipment: BTE) up through I&T into the MOC allows for seamless migration of validated I&T procedures and the Command & Telemetry (C&T) database into the operational environment.

c5.3 I&T flow through facilities. An overview

F6. Manufacturing, Integration and Test (I&T).

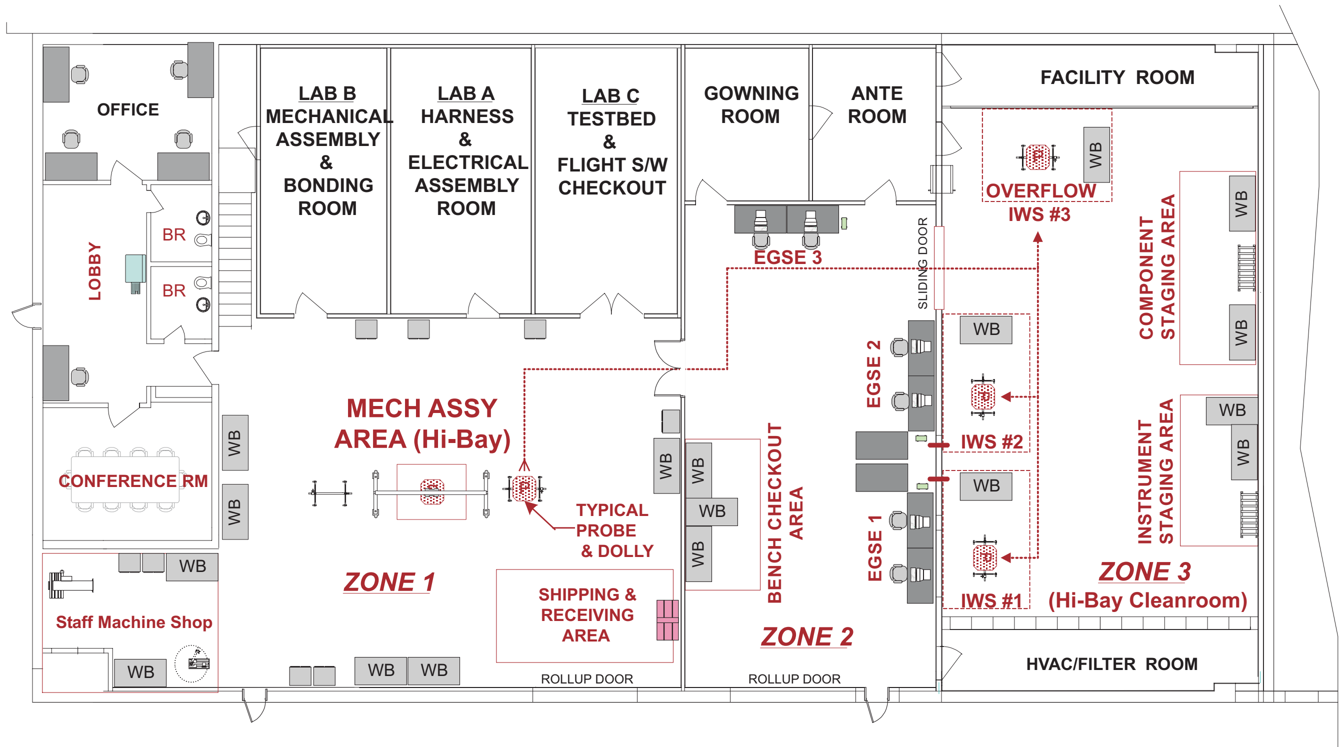


Figure F-40. *I&T facility operations and layout.*

is shown of the I&T facility operations and floor plan on Figure F-40 and the general flow of the overall I&T process appears on Figure F-41.

The integration of instruments and components onto the probe is performed in 3 adjacent work zones within the existing secure restricted access Swales I&T facility located in Beltsville, Md. The wiring harness and electrical component assy's are built up in the dedicated side room (Lab A) prior to integration. Adhesive bonding & mechanical assy (Lab B) supports controlled chemical preparations for minor bonding operations at this phase of assy. Lab C hosts the previously described probe testbed and software development team. I&T management and bonded storage is housed in a mezzanine above the labs with a conference room and restrooms are located outside of the I&T work zones. The initial integration of the probe bus occurs in zone 1, where electrical harness and thermal hardware are integrated onto the structure base plate and where general logistics, receipt, and shipping are processed. As electrical integration starts the probe is moved to Integration Work Station (IWS) #1 or #2 in zone 3, the clean room. The EGSE and test conductors supporting the IWS are located in zone 2 with electrical feed-thorough to zone 3. Instruments are processed directly into zone 3 and receipt, inspection, and post-ship functional tests are performed in the instrument staging area on work benches (WB). Other bus components are staged in the component staging area prior to their use. The cleanliness requirements of the probes are not challenging (ESA is under purge and ESA & SSTS's have protective aperture covers) and a class 100k work area and undemanding gowning protocols are sufficient to ensure maintenance of appropriate molecular and particulate levels. Instrument integration occurs in the class 10k rated clean room (used on FUSE and EO-1 previously) run at the less stringent THEMIS class 100k flow levels.

After a probe is finished it is removed from its IWS, packed, and shipped to the environmental test facility. We have baselined the GSFC environmental test facilities (formal price quotation from the ManTech reimbursable test services division) and are also capable of performing all of the probe environmental testing at backup sites (APL, NRL, Northrup/Grumman Linthicum, or OSC/Dulles) if test facility scheduling conflicts should arise within GSFC. The probes proceed to T/V testing along with the EGSE #3, leaving the #1 & #2 production lines untouched. Each probe undergoes its T/V test, a full CPT, and is declared ready for PCA integration; the next probe in line replaces it in T/V. At that point the MOT can interact with the finished probe(s) for science mode mission simulations and dataflow tests allowing for parallel validation of the MOC and training of the MOT personnel while the production of subsequent probes proceeds. The probe carrier (PC) fabrication and assy. occurs in a separate facility in the Swales Structure Systems (SSS) production facility, adjacent to the main I&T area, within the Beltsville campus. The PC is qualification tested at GSFC (baseline) as previously de-

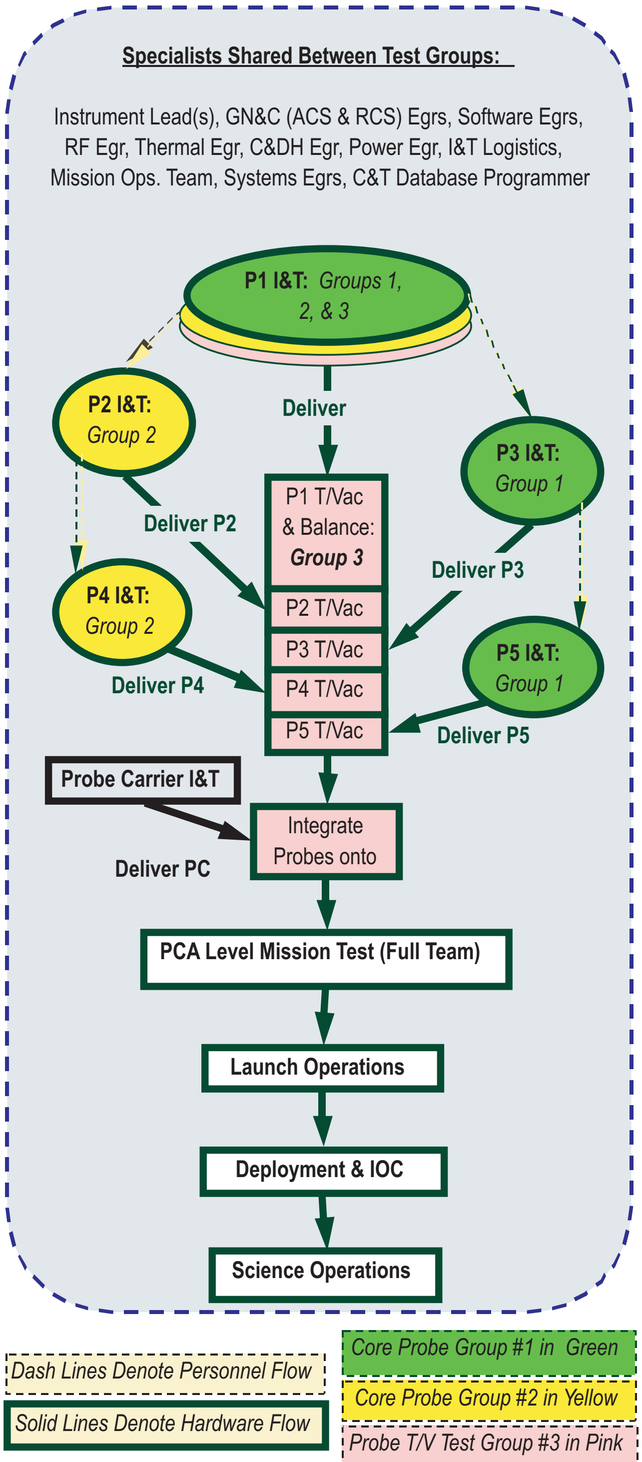


Figure F-41. *I&T flow of teams through facilities at Swales.*

scribed and stays at GSFC prior to individual probe integration onto it. Integration of individual probes to the PC can occur independently until the full PCA configuration is achieved. The previously described mission level final testing then proceeds.

c5.4 Launch site processing. Launch site activities (Swales responsibility), include PCA shipping/logistics, functional tests, RCS propellant loading, mass balance, and launch vehicle interface engineering, safety & documentation, and integration. In addition, Swales utilizes their extensive experience with the Delta II launch vehicle, gained from leading the launch site operations and teams of the FUSE, EO-1, and MAP missions, to ensure smooth processing and communication with the NASA/NLS and Boeing launch team at CCAS. Existing launch processing and countdown procedures will be leveraged from these programs to serve as a template to create THEMIS specific procedures and to train the mission team in the various launch rehearsal activities, first with the project team, prior to launch site arrival, and subsequently with the formal integrated CCAS launch simulations/rehearsals.

F7. MISSION OPERATIONS, GROUND AND DATA SYSTEMS

a. Overview

THEMIS mission operations ensure that mission goals are met and comprise pre-launch, launch and early orbit, normal, end-of-mission and contingency operations. The mission operations center performs mission planning functions, flight dynamics, orbit and attitude determination, maneuver planning, commanding and state-of-health monitoring of the five probes, recovery of science and engineering data, data trending and anomaly resolution. Science operations comprise generation of instrument schedules, data processing and archiving functions.

The THEMIS ground data system (GDS) takes advantage of the heritage developed at UCB for the FAST and HESSI SMEX missions. The scalable multi-mission architecture of the existing operations center at SSL allows straightforward expansion to also support THEMIS. As shown in Figure F-42, THEMIS operations comprise mission operations, science operations, flight dynamics and ground station operations. A variety of integrated Government and Commercial Off-the-shelf (GOTS and COTS) software products are employed to support all required functions.

A schematic of the THEMIS GDS is shown in Figure F-43 (Foldout-7). The GDS consists of several functional blocks: The ground stations required to communicate with the probes on orbit, the Mission Operations Center (MOC), the Science Operations Center (SOC) and the Flight Dynamics Center (FDC). The primary ground station for THEMIS is the Berkeley Ground Station (BGS). MOC, SOC, FDC and BGS are co-located at Space Sciences Laboratory on the UCB campus.

Secondary ground station support is provided by Universal Space Network via their station near

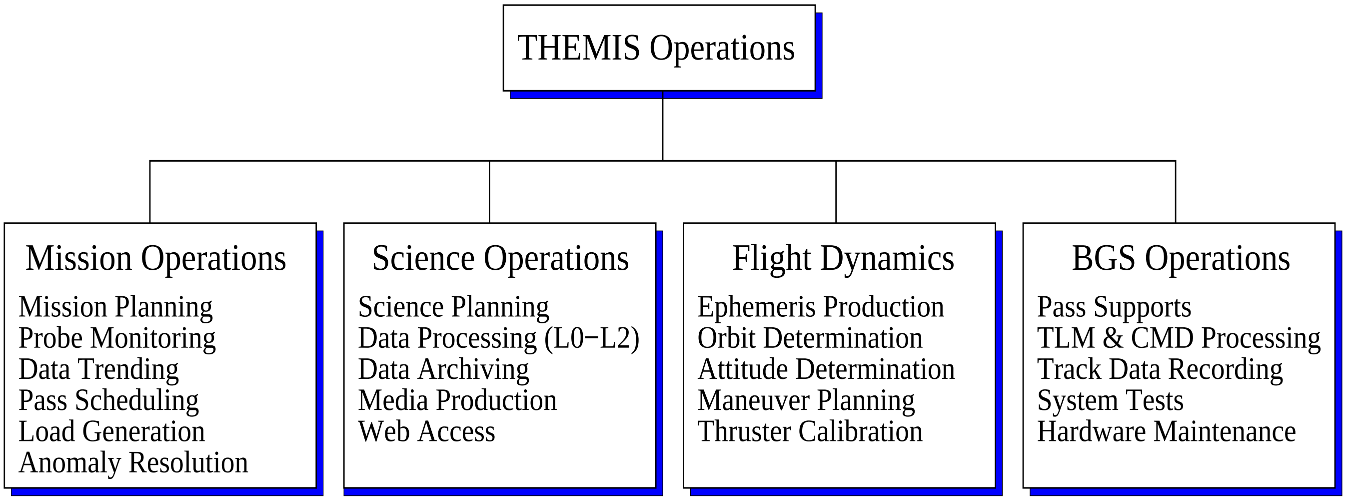


Figure F-42. *THEMIS operations functions*

Perth, Australia. TDRSS support is baselined for the launch and early orbit phase of the mission to aid in recovery from anomalous conditions. DSN and Wallops Ground Network (WGN) support is budgeted to provide additional real-time command and telemetry capabilities during critical phases of the mission. Pass schedule requests generated at the MOC are submitted to the respective scheduling offices. Confirmed pass schedules are used to build command loads and to perform mission-planning. All real-time telemetry and command data between the ground stations and the MOC are carried across secure network links. Tracking data are transferred from all ground stations and from the Space Network to the FDC to perform orbit determination in order to generate updated ephemeris products. Attitude sensor data received from the probes through the ITOS command and control system are routed to the FDC to obtain ground-based attitude solutions. Once verified, ephemeris products and attitude solutions are used to plan orbit maneuvers.

b. Mission Operations

b1. Mission Operations Center (MOC)

The MOC is part of the existing multi-mission control center, shared with the FAST, HESSI and CHIPS projects. A secure, firewall-protected network of multiple Sun workstations performs all mission planning, command and control, and flight dynamics functions. For TDRSS communications a completely isolated set of workstations and a dedicated network connection to the White Sands Ground Terminal (WSGT) are installed to fulfill the strict access requirements to the Space Network. Physical access to the MOC is restricted to essential operations personnel and is controlled by the UCB Police Department via a cardkey system. The existing IT Security Plan for the MOC is amended to include the THEMIS mission, following NPG 2810, NPD 2810.1 and the Internet Protocol Operational Network (IONet) Access Protection Policy and Requirements (GSFC document 290-004).

The probes are operated in store-and-forward mode. Transmissions are initiated by time sequence commands stored on-board. These commands are part of an Absolute Time Sequence (ATS) load generated individually for each probe with the Mission Planning System (MPS). ATS loads are uploaded several times per week and cover at least 8 days for Probe 1, 4 days for Probe 2, and 2 days for Probes 3/4/5. MPS (formerly “CMS”) is the command management software of choice with many NASA missions and has heritage at SSL with EUVE, FAST and HESSI.

The command and control system for THEMIS is ITOS. ITOS also has heritage within NASA and is currently used on FAST and HESSI. At Swales ITOS has been in use with the SMEX-Lite testbed and is employed during THEMIS I&T. The common use of ITOS at all levels of test and operations allows Flight Operations Team (FOT) members to be trained in bus and instrument operations early-on, facilitating a smooth transition from I&T to normal operations. The FOT has extensive experience with ITOS telemetry page development and scripting of manual and automated command procedures that monitor and control all probe subsystems.

THEMIS space and ground systems are tied into the Spacecraft Emergency Response System (SERS), which is a database system that regularly parses through log files generated by ITOS during real-time passes and playback of stored engineering data, and automatically checks for yellow and red limit violations. SERS also acts on email warning and error messages from other GDS elements. In case a limit-violation or another anomaly is detected, the on-call FOT members are alerted via 2-way email pagers in order to assess and resolve the problem. SERS completes the autonomous ground system and adds a high degree of reliability.

The Berkeley MOC is equipped with two SCAMA voice terminals that connect to GSFC via an existing T-1 line. These voice circuits are patched through to NASA's control centers, ground stations, and integration and test facilities for readiness-testing, simulations, launch and regular pass supports.

b2. Flight Dynamics Center (FDC)

The FDC, which is tightly coupled with the MOC, is responsible for supporting all orbit dynamics and maneuver functions, such as generation of ephemeris and mission planning products, orbit determination, ACS sensor calibration, attitude determination, maneuver planning, and analysis and calibration of thruster performance.

Four major software tools, namely GTDS, GMAN, MSASS and SatTrack generate all ephemeris and mission planning products and perform orbit and attitude determination, and maneuver planning functions. GTDS (the Goddard Trajectory Determination System), GMAN (the General Maneuver Program) and MSASS (the Multi-mission Spin Axis Stabilized Spacecraft attitude analysis system) were developed at GSFC. SatTrack is a COTS product. Probe conjunction analysis is accomplished with a combination of GTDS and an IDL-based software library that was developed inhouse at SSL. All mission critical software tools used at the MOC and the FDC are under strict version control and are verified against test data provided by GSFC's Flight Dynamics Analysis Branch (FDAB). The FDC is staffed with GSFC-trained flight dynamics analysts.

b3. Orbit determination

GTDS performs high-precision orbit propagation and orbit determination functions for THEMIS. GTDS is a keyword driven program that reads user input files. For orbit determination, GTDS ingests angle and two-way Doppler tracking data collected from the ground stations in UTDF, DSN and TDRSS format. These tracking data are obtained during regular science data transmissions at ranges of 20,000 km or less, and during additional passes at other parts of the orbit of each probe. GTDS estimates new state vectors for the five probes and generates an updated ephemeris. Once state vectors have been updated, new mission planning products are generated, and the updated vectors are distributed to the ground stations to generate new acquisition angles for upcoming pass supports.

As technology demonstration, an alternate technique for orbit determination is implemented after completion of the nominal mission. This technique is based on measuring the precise round-trip travel time of digital data packets transmitted from the ground to each probe and back to the ground. These data packets are time-stamped at the moment of transmission and reception. Achievable range measurement accuracies are expected to be of the order hundreds of meters or less, depending upon the number and duration of ranging passes scheduled throughout an orbit for each probe. Range data obtained with this technique are processed with the SatTrack Orbit Determination Tool (currently under development as an advanced technology for ST-5 mission flight demonstration).

Routine NORAD orbit determination using radar tracking data provides back-up for the primary orbit determination.

b4. Mission planning products

Mission planning products are generated by SatTrack based on GTDS ephemeris output. SatTrack has heritage with various NASA missions and generates all mission planning products for FAST, HESSI and CHIPS, comprising ground station view periods, link access periods, eclipse entry and exit times, and other orbit events required as input to MPS. Other tools in the SatTrack Suite distribute real-time event messages to various ground system elements such as ITOS and the BGS in a fully autonomous client/server network environment. Additional SatTrack tools developed for ST-5 are used to automate the process of scheduling passes with all ground stations. SatTrack also generates 2-D and 3-D real-time orbit displays to visualize conjunction, orbit and maneuver scenarios.

b5. Attitude determination

Ground based attitude determination of the probes utilizes MSASS to ingest raw sensor data from the telemetry stream that are converted into vectors expressed in spacecraft body coordinates. The suite of attitude sensors on each probe comprises a V-slit Sun sensor, two mini-gyros and the dual-use FGM three-axis magnetometer. FGM data are utilized during the near-Earth part of the probe orbits to cross-calibrate the other sensors. Reference vectors for conversion from the body frame to the inertial frame are obtained from spacecraft, solar, lunar and planetary ephemeris, and from the most current International Geophysical Reference Model (IGRF) of Earth's magnetic field. Based on these inputs, the MSASS estimator determines the inertial attitude vector at any given time for each probe. MSASS is a FDAB developed MATLAB utility that has flight heritage with the IMAGE mission.

b6. Maneuver planning

The GMAN tool performs all maneuver planning functions. Based on probe propulsion and sensor models and current and target state vectors, GMAN generates an optimized mission profile that includes spin-axis reorientation and orbit adjustment maneuvers with coast periods between thruster firings. Various constraints such as ground station view and eclipse periods are taken into account for development of the maneuver scenarios.

A typical maneuver scenario includes a reorientation of the probe from its mission attitude to the orbit maneuver attitude, followed by the orbit maneuver itself and the reorientation maneuver returning attitude back to nominal. Attitude reorientation maneuvers are performed near perigee to take advantage of the magnetometer data that allow for independent confirmation of the correct attitude for the subsequent orbit maneuver. Orbit maneuvers are executed near perigee and apogee for operational mission orbit insertion and periodic orbit maintenance. Maneuver planning functions are performed at the FDC in consultation with GSFC/FDAB.

b7. Pre-launch, Launch and Early Orbit (L&EO) operations

Pre-launch operations include end-to-end data flow tests, rehearsals and full mission simulations, integrating all ground stations and the TDRSS network. During the launch sequence, the Delta II injects the PCA into the target parking orbit, initiating release of the probes from the PCA. At this time operational command and control authority transitions from the L/V controllers to the MOC at UCB. Subsequently, each probe is polled via ground station and TDRSS contacts in a round-robin scheme to evaluate state-of-health and to obtain telemetry and tracking data for initial orbit and attitude determination. Once the orbits are well established, the MOC generates the first set of command loads that are uplinked to each probe. Further on-orbit checkout commences with deployment of the magnetometer booms and the power-up sequence of all science instruments. As soon as all probes are checked out, the final designation of Probes 1 and 2 is performed based on functional test results and magnetic signature levels. This scheme allows for implementation of mission redundancy and a probe replacement strategy that minimizes impact from off-nominal science instrument performance.

Final orbit injection begins after all probes are re-spun to a spin rate of 30 r.p.m. Calibration of the tangential thrusters occurs as part of the re-spin sequence. The orbits of each probe are then adjusted in one (P3-P5) or two (P1-P2) discrete pairs of apogee and perigee maneuvers, using the axial thrusters. Each individual maneuver is followed by careful orbit and attitude determination, allowing for calibration of the axial thrusters. Proper thruster firing is verified in real-time by monitoring telemetry data from the RCS temperature sensors, tank pressure gauges, and attitude sensors. Once placed in their final mission orbits, summarized in Table F-26, the probes are commanded to deploy the radial wire booms and subsequently the axial EFI boom.

Probe	Mission Orbit Geometry
1	1.500 x 30.943 R_e
2	1.168 x 19.756 R_e
3	1.118 x 12.103 R_e
4	1.118 x 12.103 R_e
5	1.118 x 12.103 R_e

Table F-26 *THEMIS orbits at start of mission*

b8. Normal operations

Normal operations begin with preparation of the conjunction season. During normal operations, communications with each probe are established at least once per day via the primary ground station to monitor the probe health and safety, to recover stored engineering data and to collect tracking data for precise orbit determination. Stored science data are downloaded once per orbit near perigee via the primary and secondary ground stations.

During normal operations, the orbits of P1, P2 and P5 are adjusted in few (2-4/year depending on probe) intervals to optimize conjunctions. These short-duration adjustments are nominally performed with side-thrusting. Additionally, orbit maneuvers are performed once per year with P1 and P2 to counteract the lunar effects on inclination, thus avoiding long shadow periods while optimizing science conjunction time. These longer duration burns for P1 and P2 take place outside the main science season and are performed with axial thrusting.

b9. Mission termination

At the end of the mission, all five probes undergo final orbit maneuvers (followed by RCS burn to depletion) that change their period so that lunar perturbations cause passive re-entry within the required 25 years (see Orbital Debris Analysis in Section M). The probes are left passively stabilized at 20 r.p.m. in their individual orbits with the transmitter, RCS and instruments turned off.

b10. Database and flight software maintenance

The FOT works closely with Swales engineers and instrument providers to develop the command and telemetry data base, as well as telemetry pages and related procedures for bus and instrument configuration and testing. The master telemetry and command data base is kept in one location at UCB. Updates are distributed as needed via the program configuration control process. Any flight software patches are tested carefully on a testbed system

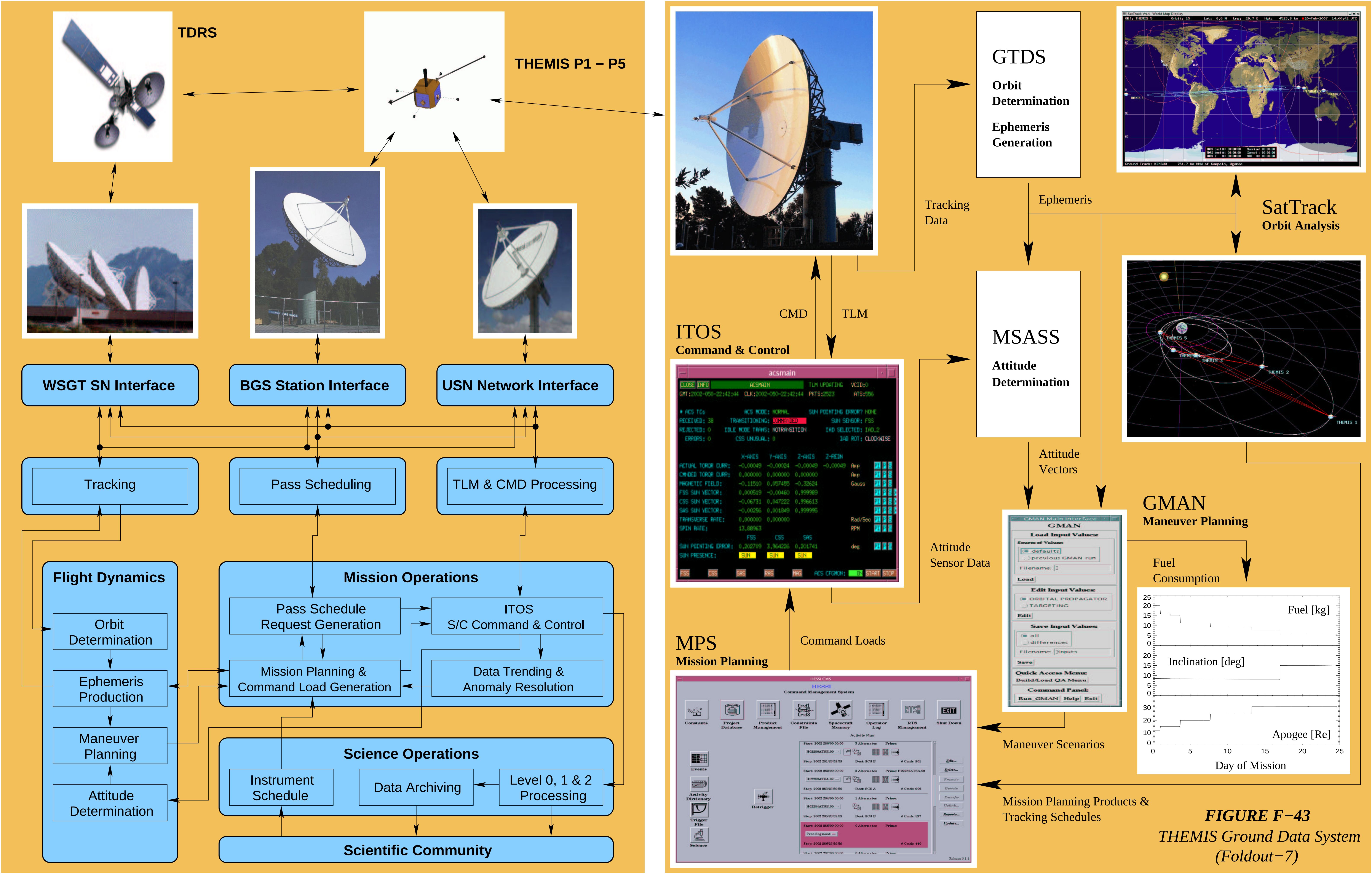


FIGURE F−43

THEMIS Ground Data System (Foldout−7)

(used during software development and I&T) that is provided by Swales prior to launch. This testbed system includes a Vsat simulator with sensor inputs, dynamics, and attitude control functions.

b11. Contingency operations

During the design phase of the mission a systems engineering assessment of mission and systems plausible failure modes is performed. Resulting products are used in the design of the probes and in the generation of I&T and flight operations procedures. These procedures are captured with an automated fault tree tool that allows FOT members to perform a rapid data base search in order to isolate potential root causes of a failure. This COTS tool features a graphical user interface with hyperlinks to procedure documents describing the corrective actions. The FOT also interacts with bus and instrument support engineers to select appropriate recovery steps. On prior missions, the most critical failure modes were used as "green cards" during I&T and mission and launch simulations as a proper test of operator readiness.

b12. Flight Operations Team (FOT)

The Berkeley FOT has >50 person-years of accumulated experience with several NASA missions, namely EUVE, FAST and HESSI. FOT members also served as test conductors during all HESSI and CHIPS I&T operations and performed numerous launch and early orbit simulations, and ground network end-to-end tests.

THEMIS routine operations carried out daily comprise probe monitor and control, real-time supports of ground station contacts and interaction with USN's Network Control Center to schedule pass supports and to transfer, verify and quality-check downloaded telemetry data. Other FOT activities include generation of command loads, data trending and software maintenance tasks. The FOT also maintains anomaly and data quality records, and generates weekly and monthly status reports.

During L&EO, the FOT staffing profile covers 24 hours, 7 days a week in one prime and two backup shifts. Probe commanding is performed only during the prime shift. During normal operations the staffing profile gradually transitions to regular 8-hour shifts.

c. Science Operations

c1. Science Operations Center (SOC)

The THEMIS SOC is divided into three entities: Level 0, 1 and 2 processing, data archiving and instrument schedule generation. The SOC works closely with the co-located MOC to guarantee seamless transfer and processing of telemetry data, and to forward science operations timelines for instrument control and configuration. Instrument commands are merged with other command and table loads for uplink to the probes.

c2. Science telemetry data

Raw telemetry data received from the ground stations are archived as annotated telemetry transfer frames. These Level 0 products are then split into individual files for each instrument, organized by instrument specific Application Process Identifiers (APIDs). These Level 1 products are saved in files containing 24 hours worth of science data each. Level 2 products are obtained by converting Level 1 products to physical units. For permanent archival, all raw and processed telemetry data are written to CD-ROMs that are distributed to the NSSDC and co-investigator institutions. A complete on-line database, stored on a Linux-based Redundant Array of Independent Disks (RAID) at SSL, allows researchers to access all mission data from their workstations.

c3. Science data processing and analysis

Data are validated by a scientist responsible for daily checks of (i) the overall data quality, (ii) housekeeping data trends (e.g., detector efficiencies and offsets) and (iii) identification and tabulation of geophysical events of special interest. IDL programs automatically produce summary information for each of the instruments. Once validated by the science team, the summary information is made available online in form of GIF plots and Common Data Format (CDF) files.

In addition to the THEMIS probe data, the SOC receives, stores and disseminates to the THEMIS team and the general public ground based observatory data (see Section F7.e). These comprise ASI and GMAG nominal data received via routine FTP-connections from the VSAT center in London, Ontario, and backup, high-resolution ASI data received on disk from the University of Calgary via the disk-swapping and mailing system.

Science data analysis is performed during the normal operations phase of the mission. Analysis software for THEMIS science data already exists in form of an extensive library of IDL programs and the Science Data Tool (SDT) developed at SSL to analyze data from FAST, WIND, CLUSTER and POLAR. The decommutator functions that allow direct access to Level 1 and 2 data products are adapted from those developed for analysis of FAST science data. The general public has access to preprocessed data via the THEMIS web site. Science software and software updates for decommunation and data analysis are periodically distributed to co-Is. Software training sessions at UCB are baselined for co-Is and guest investigators.

d. Ground stations

d1. Telemetry and command formats

The THEMIS telemetry and command formats are based on CCSDS standards and data structures. The telemetry link is encoded using concatenated rate-1/2 (K=7) convolutional and Reed-Solomon (223,255,I=5) coding to allow for error correction. The standard telemetry data rate is 400 kbps with a symbol rate of 800 kbps. Lower telemetry rates are provided for early orbit operations via TDRSS and for communications at the largest range. The command data rate is 1 kbps. This command data rate and a telemetry rate of 5 kbps allows for closing the link when the outermost probe is located at apogee.

d2. Data volumes

The five probes each acquire a science data volume of 750 Mbits per orbit. Using a compression factor of two for lossless compression, and adding 12% overhead for CCSDS frame formatting and 14% for transmission of Reed-Solomon code symbols, the data volume to be recovered is approximately 480 Mbits per orbit for each probe. At a data rate of 400 kbps, the required access time is 20 min per orbit for each probe during the *near-perigee phase* of each orbit, i.e. at a range of <20,000 km. The total corresponding number of passes amounts to 1370 per year for all probes combined. Actual link access to the five probes through the Berkeley Ground Station and the USN station in Australia is determined using a dynamic link model that takes into account line-of-sight geometry, probe attitude and antenna pattern, range, power spectral density and ground station figure of merit. The available link access times quoted in the Table F-27 represent pass averages over a period of one year with a predicted link margin in excess of 6 dB.

Telemetry downlink for all orbits combined is achieved by scheduling 1030 passes at the BGS and 340 passes at the USN-AU (Perth, Australia) site. Available link access times leave a generous margin allowing for ground station acquisition delays, retransmission of selected data and resolution of scheduling conflicts. Scheduling of pass supports by dynamic link margin rather than by plain line-of-sight geometry is employed very successfully with the HESSI mission, minimizing data loss while maximizing efficiency of ground asset usage.

d3. RF frequencies and NTIA license

Each probe contains a coherent STDN compatible transponder thus allowing two-way Doppler ranging for accurate orbit determination. All probes use the same frequency pair for telemetry and commanding. Communications are established with one probe at a time. The THEMIS team has presented this operations concept to the Spectrum Management Office at GSFC. The preliminary assessment shows that proposed S-band frequencies, data rates, modulation types and power spectral densities are in compliance with current standards and regulations. An application for the NTIA license is filed at the beginning of Phase B.

Probe	Mission Required Link Access [min/year]	BGS Available Link Access [min/year]	USN-AU Available Link Access [min/year]
1	1825	3740	3663
2	3650	6248	6952
3	7300	12153	11990
4	7300	12606	11925
5	7300	12723	14793

Table F-27. *Access times with >6dB link margin*

d4. Berkeley Ground Station (BGS)

The BGS, located at Space Sciences Laboratory, is the primary ground station supporting the THEMIS mission. The antenna consists of a pedestal with an 11-m parabolic reflector. A three-axis drive system eliminates the key hole at the zenith. The antenna is equipped with a full-duplex S-band telemetry and command system. The receiving system uses dual receivers with diversity combination and has a figure of merit (G/T) of 24.0 dB/K in each channel (LHCP and RHCP) above 5 deg elevation. A conical scan feed system provides autotrack capabilities with a typical accuracy of 0.1 deg. The transmit polarization is selectable as LHCP or RHCP, and the nominal RF output power is presently 100 W (63.0 dBW). To allow commanding the farthest probe at apogee, the high-power transmit amplifier is upgraded to 200 W (66.0 dBW). Precision Doppler tracking is performed with an Apogee Labs Doppler Measurement System. Tracking data are recorded in the common UTDF format. In addition, the ground station is equipped with a round-trip delay measurement system to allow for orbit determination based on measuring the round-trip travel time of data packets.

The BGS employs two identical front-end processors (Avtec Systems, PTP NT) for bit synchronization, Viterbi decoding, frame synchronization, Reed-Solomon decoding, and CCSDS channel routing. Data streams that carry real-time engineering and science data are typically routed directly into the ITOS workstations for real-time state-of-health monitoring and control functions. In addition, all received telemetry data are stored locally on the ground station in separate files for each virtual channel and are automatically transferred to their final destinations via FTP, once a pass support is completed.

Commanding of the probes is initiated from the

ITOS workstations and follows standard CCSDS procedures: individual commands or entire command loads are divided up into CLTUs and are forwarded to the front-end processors via secure TCP/IP network socket connections. The command data stream is then transmitted in real-time at a rate of 1 kbps and BPSK modulated onto a 16-kHz subcarrier. The subcarrier is in turn PM modulated onto the RF carrier with a modulation index of 1.0-1.3 rad. The COP-1 protocol is used to verify command reception on the probe. Once a command is sent to the probe, ITOS monitors the CLCW that is transmitted with each telemetry transfer frame and indicates the command verification status on-board the probe. ITOS automatically initiates retransmission of commands that are not verified.

The BGS performs autonomous self-tests several times per day. These end-to-end tests are automatically inserted into gaps in the tracking schedule and are treated by the ground station as regular pass supports. During these *pass supports* the system plays back real probe telemetry data through a free-space RF link within the 11-m antenna, thus exercising the command system (except for the high-power transmit amplifier), the fiber-optic links, the entire receive chain, the matrix switch and the front-end processors. RF power levels are adjusted such that the CNR is just a few dB above the minimum CNR required to decode the telemetry data with a bit error rate of 10^{-6}. Therefore any degradation in system performance will immediately cause correctable or even uncorrectable Reed-Solomon errors. These errors are detected and the engineer on duty is paged in turn to investigate and resolve the system anomaly. With this automated procedure, any system faults are typically detected and corrected in time to prevent loss of telemetry data during real spacecraft supports. Experience with IMAGE, FAST and HESSI over the past 24 months demonstrated that more than 99% of the expected telemetry volume is successfully recovered during scheduled pass supports.

d5. Secondary and back-up ground stations

Secondary ground station support for THEMIS is provided by Universal Space Network via their station near Perth, Australia. Real-time telemetry and command data are carried between the MOC and the USN Network Control Center in Horsham, PA via a secure dial-up ISDN line. Telemetry data stored on the ground are transferred to the MOC via the open Internet, the same method that is used successfully for collection of HESSI telemetry data received at Wallops Island, VA, Santiago, Chile and Weilheim, Germany.

During launch and early orbit operations, TDRSS Single Access mode allows communications with each of the probes after deploy at a low data rate at times when the individual probes are within communications range of a TDRS spacecraft. For contingency, additional pass supports may also be provided by the Wallops Ground Network and the DSN station in Madrid (RID).

The existing, dedicated T-1 line from the Berkeley MOC to GSFC is presently used to establish communications with the FAST spacecraft via WGS, AGS and MGS, and with HESSI via WGS. This T-1 line is shared with the THEMIS project to also transfer real-time THEMIS telemetry and command data to and from WGS and RID.

e. Ground Observatories

This section describes specifications, development, deployment and operations of the ground based observatories (GBOs) required to accomplish the THEMIS mission, and the EPO observatories.

e1. Overview

The THEMIS mission times substorm signatures on the ground and in space with time resolution <30s. Ground substorm onset is determined by sensing the optical (white light) signatures of erupting aurorae with UCB-built All Sky Imagers (cameras) at integration time <1s and time resolution <10s (nominally 3-5s). Additionally, existing and new ground magnetometers built by UCLA determine the signatures of the ionospheric currents induced by substorm aurorae with nominal resolution of 1s. Canadian co-Is are responsible for deployment, maintenance and data retrieval from the Canadian observatories. UCB is responsible for deployment, maintenance and data retrieval from the Alaskan sites. UCB experience on ASIs is derived from years of field development, deployment and operation of such cameras in remote locations, such as the Automatic Geophysical Observatory (AGO) sites in Antarctica, and several years of ASI

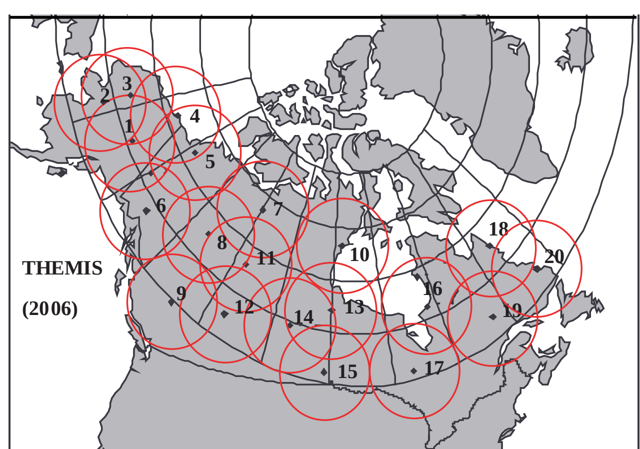


Figure F-44 *THEMIS ASI fields of view completely cover North American auroral region.*

data collection in unattended operations. UCLA's experience is derived from many years of development, deployment and operation of ground magnetometers in remote sites around the world, including the US (MEASURE, UC-LANL chains) China (CHI-MAG), Central and South America (SAMBA). Ancillary ground network data from East Russia (West) to Iceland (East) are available to THEMIS, enhancing its capability to observe substorm onset or substorm evolution at off-nominal times. International commitments to provide these data sets are outlined in Table E-15.

	#	ASI site name	gmag?	infrastructure?
Alaska	1	Poker Flat	have	observatory
	2	Galena	need	past deployment
	3	Amber	need	past deployment
	4	Kaktovic	have	observatory
Canada	5	Inuvik	have	observatory
	6	White Horse	have	observatory
	7	Contwoyto Lake	have	observatory
	8	Fort Simpson	have	observatory
	9	Prince George	need	observatory
	10	Rankin Inlet	have	observatory
	11	Fort Smith	have	observatory
	12	Meanook	have	observatory
	13	Gillam	have	observatory
	14	Flin Flon	need	observatory
	15	Pinawa	have	observatory
	16	Post-de-la Balaine	have	observatory
	17	Kapuskasing	need	observatory
	18	Hebron	need	observatory
	19	Gangon	need	observatory
	20	Cartwright	need	observatory

Table F-28. *THEMIS observatories either have current infrastructure or have been used before.*

The description of the mission requirements and the adherence to those is detailed in Section E1.f, and tabulated in the traceability matrix of Figure F-1 (Foldout-3). The locations of the ground based observatories relative to existing networks is shown in Figure E-8. Existing (non-THEMIS) sites already provide a capable magnetometer network which THEMIS enhances to meet its spatial and temporal resolution goals. The THEMIS sites are shown again with the field of view of the ASIs in Figure F-44. Canadian imager sites at the Churchill meridian also provide (or will provide by 2006) multiwavelength images of the aurora. Those imagers operate with an intensifier which limits observations far from dawn and dusk and during periods when the moon is above the horizon. THEMIS intends to overlap with that same sector with white light imagers to increase the operational time and avoid problems with lunar background light. Table F-28 shows the THEMIS ground observatory site locations, and indicates where 1s cadence magnetometers are already available or funded by CSA for installation prior to THEMIS launch.

All sites either have existing observatories or have been used in the past for magnetometer and/or all sky camera observations. There is telephone connection and power, and most of the sites have a local operator assigned to attending to the needs of the observatory site already.

e2. All Sky Imagers (ASIs)

The THEMIS ground based stations are designed for minimum maintenance. Each station includes an auroral all sky camera developed at UCB based on commercially available components. The camera environmental design is based on the heritage of the AGO sites. It also includes a GPS receiver, a magnetometer laptop, and an ASI laptop in a protective foam-cored fiberglass, ruggedized casing (Figure F-45). A heater thaws ice on the dome, ensuring good optical measurements. Controlled airflow prevents temperatures from rising in spring/summer. A photo of a prototype camera that has been built and tested is shown in Figure F-46. The camera properties are shown in Table F-29. Data from this camera were used to validate the concept of a fast (<1s exposure) panoramic optical system. Laboratory and field testing for 1s exposures has demonstrated that each CCD count is ~27 Rayleighs and that RMS dark noise is 7 CCD counts. Typical faint aurora is 1kR which gives a 5-to-1 signal-to-noise ratio.

The ASI camera looks through a heated plexi-

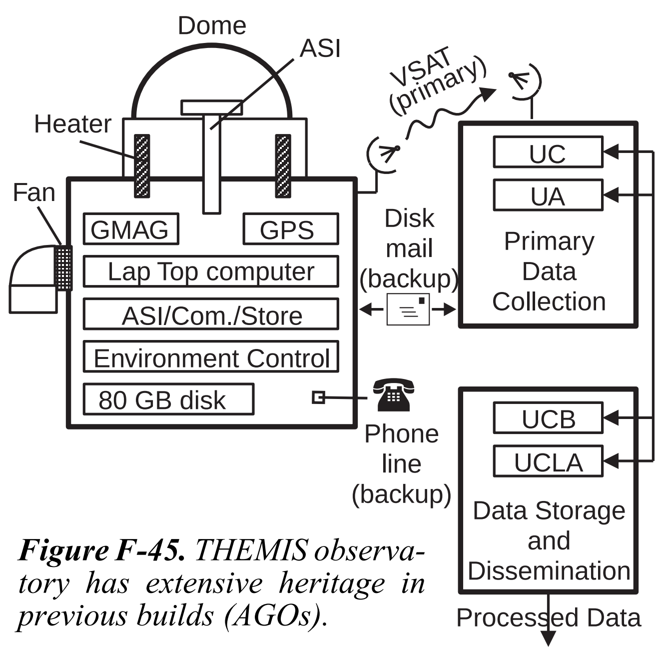


Figure F-45. *THEMIS observatory has extensive heritage in previous builds (AGOs).*

glass dome that ensures evaporation of precipitation. The AGO experience shows that this method and the additional wind scouring enhanced by the dome's mechanical shape, guarantee the dome clears a few hours after even substantial snow fall.

Property	Value
Field of view	170 degrees
Equivalent F number	0.95
Pass band	Visible (IR removed for low heating)
CCD camera/type	Sony/MX716 cooled CCD
Pixel format	361x291 (after binned 2x2)

Table F-29 *THEMIS ASI properties.*

Calibration and qualification. Each system is calibrated in the night sky against known stars and tested in extreme environments at the thermal chamber at UCB. Since all parts are currently available, the approach is to build, calibrate and qualify the first unit within a year after start of Phase B and deploy it in Canada to gather further experience in interactions with the local (Canadian) support personnel with data retrieval and dissemination, and with potential problems that might arise in the field. Ten sites shall be installed two winters before THEMIS launch. The entire THEMIS ground campaign shall be in full operation the winter before THEMIS launch. This schedule and concomitant manpower are costed into the THEMIS baseline plan.

Figure F-46. *Laboratory/field tests have validated the high cadence, large FOV THEMIS ASI camera.*

e3. Ground magnetometers (GMAGs)

The THEMIS ground based magnetometers shall be developed after the heritage of dozens of such sensors already deployed by the same UCLA team which has installed similar units at various sites internationally. There are two types of magnetometers developed for THEMIS: The EPO magnetometers to be installed for the Education and Public Outreach efforts of the program (EPO-GMAGs), and the THEMIS ground observatory magnetometers (GBO-GMAGs). Since the EPO-GMAGs are identical to previous builts, we describe those first.

EPO-GMAGS. These are 10 magnetometer stations (without ASIs) installed at sub-auroral-latitudes in the US. They are selected and deployed primarily for EPO-related reasons. The EPO-GMAG's science value is high but is not critical for the mission. The EPO-GMAGs form a network of Pi2 detection sites, ancillary to existing US mid-latitude stations already in place. EPO-GMAGs are identical to the UCLA-built sensors on previous installations. The magnetometer board (Figure F-47) fits a standard desktop PC slot and has the following major sections:

1. GPS receiver (top left)
2. DC/DC converter, regulators (bottom left)
3. A single chip controller
4. ADC & low pass filters (under shield, center)
5. Drive/sense circuits (right half).

The sensor shown in the picture above is designed to be installed in a post hole about 3 feet below the surface to minimize temperature effects. Typically the post hole is ~100 feet away from the building where the PC is housed to avoid magnetic noise from the operator/cars. It includes internal heaters which can be used to further stabilize the temperature. A protected cable connects the PC to the sensor assembly. Installation and calibration takes 2-8 hours depending on soil conditions, after logistics (hole digging, power connection, cable access from building to site) have been dealt with. The entire operation takes 2-4 days depending on availability of local support.

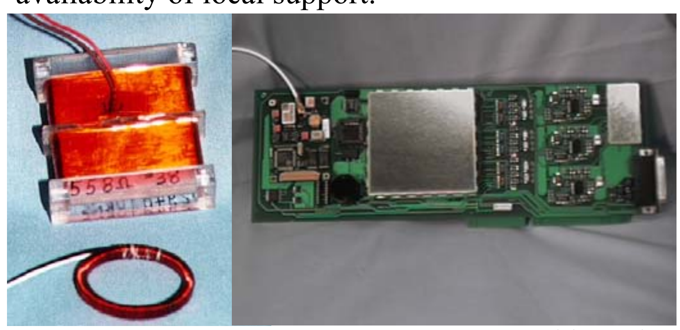


Figure F-47. *THEMIS GMAG sensor and board.*

GBO-GMAGs. There are 8 sites (2 in Alaska, 6 in Canada) that require modification relative to the standard UCLA product. The approach is to install the GMAG within the ASI, for which we repackage the magnetometer circuit board to benefit from a common data retrieval, hard drive, GPS receiver and temperature control also used by the ASI. UCLA develops an external GMAG PC board housing and cable connection so that it can be mounted externally to a laptop device. This is a small modification of the current design; the sensor design remains identical. The GMAG and ASI laptops are connected to an 80 Gbyte hard disk for local data storage, and have a common telephone and satellite link for routine, daily housekeeping and low rate data retrieval.

Calibration and qualification. The calibration and qualification procedures entail sensor temperature drift, alignment and offset measurements. This is performed in a laboratory environment within a mu-metal can prior to shipping at UCB (GBO-GMAGs) or to the appropriate school (EPO-GMAGs). Sensor integration of the ASI and GBO-GMAG, temperature extrema and field testing takes place at UCB. After that the units are shipped to the University of Calgary for deployment and operation. University of Calgary installers and operators participate extensively in GBO unit testing at UCB in order to obtain experience in calibration and troubleshooting that is bound to be invaluable during GBO installation or refurbishment. The University of Calgary is the recipient of one complete spare GBO unit for rapid and complete replacement if problems with a site are pervasive. A second spare unit remains with the developers.

ASI data rate and volume	
Number of pixels	291pix. dia. circle=266kpix
Digitization	16 bits per pixel
Avg. rep. rate	0.333 images/sec
No of bits per pixel	16
Data rate	1.8 Mbits /s with overhead
“Stream 1" rate (daily Tx).	1.4 k bit / sec
“Stream 2" rate (on disk)	180 kbit /sec
Months/season	4
Days/month (incl. moon)	24
Second in 8 hour day	28800
Tx data per day	32 Mbits + 1 Mbits H/K
Tx Baud rate (stream 1)	30 kbps
Tx time (stream 1)	1072 sec
Data volume (stream 2)	62 Gbytes/season w H/K
GMAG data rate and volume	
Digitization	16bits
Quantities	1+3 (time, Bx, By, Bz)
Rep. rate	1 sample/sec
Data rate	68bits/s w/H/K & overhead
Tx data per day	5.8Mbits
Tx Baud rate	30 kbps
Tx time (only stream 1)	193 sec
Data volume	0.265 Gbytes/year

Table F-30 *GBO data rates per station.*

e4. Data collection and dissemination

Table F-30 shows the GBO data rates and volumes. The ASIs have two data streams. Stream 1 is compressed digitally by averaging on a latitude grid of 0.5 x 0.5 degrees resulting in a data stream of 1.4 kbits/sec with overhead. This data stream is transmitted daily and complies with the needs of THEMIS to determine the onset to better than 0.5hr in MLT. The other data stream (Stream 2) contains all JPEG images and is recorded on site on a hard disk. The total data volume amounts to ~62 Gbytes annually. Primary means of “Stream 1" ASI (and GBO-GMAG) data retrieval is the VSAT satellite connection, which is to be established by Canadian funding for the Canadian Geospace Monitoring program on all THEMIS Canadian sites by 2006. This becomes also the primary means of THEMIS US sites, based on quotes received from the company. Telephone retrieval is a backup method for Stream 1 and for GMAG data; monthly disk swapping and shipping by local operators is a third, albeit slower, means of data collection that ensures retrieval of the highest spatial resolution dataset.

e5. Member responsibilities

The THEMIS primary ASI collection site is the University of Calgary (UC), whereas the primary GBO-GMAG data collection site is the University of Alberta (UA), based on their similar roles for CANOPUS. Site installation, maintenance and data retrieval of Canadian sites is the responsibility if the University of Calgary, whereas the similar roles in the US are assumed by UCB for ASIs and by UCLA for GMAGs. The primary EPO-GMAG collection site is UCLA, based on similar roles for MEASURE, SAMBA and other similar networks. UCB receives copies of the ASI disks immediately upon receipt from the field. UCLA and UCB receive all daily transmitted data on a routine and daily basis. Table F-31 shows these responsibilities.

	Develop	Install, Maintain, Retrieve Data	Primary Data Receipt Site	cc to:
ASI/Canada	UCB	UC	UC	UCB
ASI/Alaska		UCB		
GBO-GMAGs/Canada	UCLA	UC	UA	UCB, UCLA
GBO-GMAGs/Alaska		UCB		
EPO-GMAGs		UCLA	UCLA	UCB

Table F-31 *GBO team members have well defined responsibilities for deployment and data reduction.*

e6. Data processing

Each site returns ~63 GBytes/season via hard disk swapping and mail distribution. This amounts to <4TBytes for the lifetime of the mission, including full data retrieval from the two winters before the THEMIS launch. Most of this is imaging data. This data volume presents no problem for present-day RAID disk farms, in use at UC and UCB.

As soon as the bulk of the data (ASI) arrives at the University of Calgary it is copied and sent to UCB, and enters an automated database of data browsing and retrieval developed for NORSTAR’s filter camera images and based on summary keo-

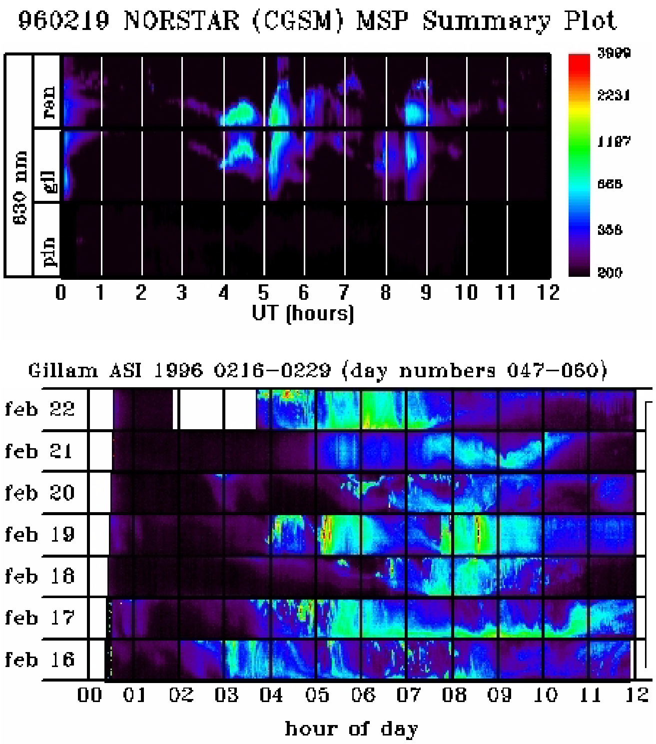


Figure F-48. *Daily multi-station keograms such as the one at the top (obtained from three Canadian filter-ASI stations) provide synoptic views of the ground based data quality, auroral activity and immediate access to the array database. Weekly (or monthly) keograms such as the one at the bottom from a single station provide quick information on a large portion of the data.*

grams (image North-South slices as a function of time). With this interactive database a user calls up a customized summary of data from one or more stations. Then by mouse-clicking on an appropriate location in the summary plot, the user is provided with a sequence of images starting from that time. Cloud detection algorithms and viewing conditions based on star counting are already in use to produce automated data quality flags that accompany them. Both keogram summary plots and composite global views provide both quick overview of data availability and a portal to data selection, decommutation and analysis. A daily three-station composite keogram from NORSTAR stations Pinawa, Gillam and Rankin Inlet is shown in Figure F-48. Local auroral electrojet indices already developed for Canopus, give similar, synoptic ground magnetometer information. With these tools already in place, THEMIS shall have no problem accessing, evaluating, comparing with space-borne measurements, and analyzing its ground observatory data.

Data are analyzed at UC and at UCB with standard IDL-based routines developed from years of experience with NORSTAR and with AGOs. Software packages for data access and analysis shall be made freely available using web-based tools. Co-Is and guest investigators receive training with these packages in similar fashion as with analysis tools of data from space-borne instrumentation.

EPO magnetometer data by local operators and schools are analyzed with standard Windows software packages (Excel import of ASCII data). THEMIS ground data, accessible to the public and to schools that host the magnetometers, are equipped with ASCII conversion routines, and web-based download functions. Thus interested students can go beyond the call of daily homework and explore correlations with spacecraft data, as well as rely on interactions with THEMIS scientists for additional assignments.

F8 Facilities

a. Instruments

Facilities for assembly and testing of THEMIS sensors already exist at the developing sites:

a1. UCB.

The ESA and SST assembly area is a Class 10K clean area with laminar flow bench operating at Class 100 (Figure F-49). This is where the 16 ESAs for FAST and the 7 SST telescopes for WIND were assembled and tested. Two thermal vacuum chambers (tanks) like the one shown in Figure F-50 (a) are used for ESA and SST calibration.

Figure F-49. *Class 100K bench for ESA and SST detector mounting and sensor assembly*

The EFI booms are assembled in the laboratory and then cleaned and T/V tested in the same room and using the same boom deployment test chamber as the 16 Cluster I and the 16 Cluster II booms.

If THEMIS is the first MIDEX launch it is prudent that an additional chamber for IDPU and boom deployment testing, as well as harness and MLI bake-outs be procured by the program in order to reduce schedule risk. Building a chamber similar to the one that was built for FAST requires ~4 months and has been budgeted early in the project.

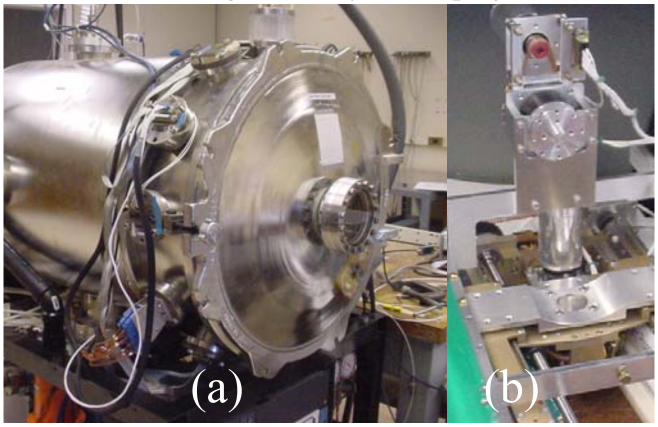


Figure F-50. *(a) One (of two) T/V tanks for sensor testing and calibration at UCB. (b) An automated manipulator stage for ESA & SST calibrations.*

Figure F-51. *Large T/V chamber to be used for full instrument complement thermal cycling.*

The UCB instrument integration area is the same as was used for HESSI and CHIPS. Equipped with HEPA filters and gowning area, this room is typically a 10000 room and is monitored daily by Mission Assurance. Instrument ground support equipment (GSE) for the THEMIS project shall be built at UCB. Although very similar to previous missions, the THEMIS sensors require unique GSEs. Depending upon the sensor, we have planned 3-6 months development time for these items. GSEs are started once the Ids are complete during Phase B. A large T/V chamber at UCB shown in Figure F-51 is used for instrument complement cycling, including the flight IDPU and cables.

a2. TUBS

The Magnetsrode, the TUBS calibration facility, is used to calibrate the FGM sensor for precise scale factor, linearity and misalignment. The facility is a triaxial Braunbek coil (Figure F-52) which provides ultra-sensitive (<1nT) dynamic compensation of Earth's field, sensed by a 3-axis fluxgate sensor in a 2 meter deep bunker, 50 meters west of

Figure F-52. *The FGM calibration system at TUBS.*

the coil system. Artificial magnetic fields up to 100 nT in any direction are generated within a homogenous field volume (<1nT variation) of 20×20×20 cm^3 and are used for gain calibration.

a3. IWF

A special temperature test facility at the Magnetometer Laboratory of IWF is used for temperature calibration of the FGM sensor. It enables calibration of offset, noise density and transfer function for especially low-range magnetic field sensors over a temperature range of +/-150^{o}C in a low-field environment. The facility consists of a three-layer magnetic shielding set, a combined low- and high-temperature equipment and an external stimulus coil. This facility was used for the MAREMF experiment then for calibrating the ROMAP/ROSETTA instrument. Recently it has been upgraded for high/low thermal tests within one test cycle and for thermal soaking in anticipation of tests required for the planned Bepi-Colombo mission to Mercury.

a4. CETP

The SCM sensor is calibrated at Chambon-la-Foret, the CETP calibration facility where the ex-

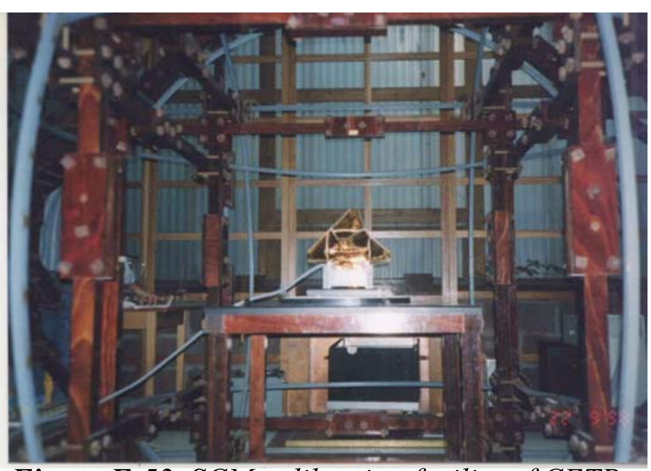


Figure F-53. *SCM calibration facility of CETP.*

ternal electromagnetic noise is extremely low. This site has been used for the development of all sensors constructed by the CETP and mounted on various satellites. Following previous practices SCM vibration and thermal vacuum tests take place at the facilities of Interspace in Toulouse. Both this and several other facilities in Europe (ESTEC, IABG, IAS) have been previously used by CETP depending on availability and schedule. For storage, equipment-testing and integration of reduced systems CETP uses a class-10000 capable clean room on its premises.

b. Probe, Probe Carrier and I&T

Figure F-54. *Swales 5051 facility.*

Swales has 113,400 ft^2 of state of the art manufacturing, integration and test facilities at our Beltsville Headquarters campus. The primary facilities for THEMIS usage (listed in Table F-32) provide the capability to build, inspect, assemble, integrate, and test the probe bus, instruments, and the probe carrier flight hardware. All of these facilities are currently in use on NASA GSFC, Naval Research Labs, and commercial programs.

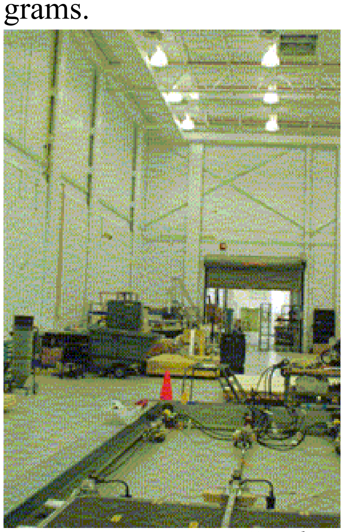


Figure F-55. *Swales Frederick Av. High Bay facility.*

Swales also has extensive facilities for the fabrication and assembly of probe bus, structures, thermal systems, harness, mechanisms and electrical components, including substantial in-house machine shops (piece part manufacturing), which facilitate quick turn around of hardware. The probe bus and Instrument integration are performed in the Swales 5015 (Figure F-54) facility (used to integrate the FUSE telescope and the EO-1 satellite) that has a 1600 square foot laminar flow clean room (rating: class 10K). The restricted access 5015 facilities contain a mechanical assembly area, harness lab, electrical integration bay, and electrical lab (for the probe testbed). The 5015 facility is central to the Beltsville Campus and provides easy access to all other Swales facilities. The small size of the probes allows for the setup of two parallel integration lines within the clean room facility with adequate staging space for completed probes and workarounds. A floor plan of the THEMIS usage of this facility with the planned equipment setups, materiel flow, and scale are shown in Figure F-39.

In 2002, Swales completed an additional 5000-ft^2 high bay assembly area (Figure F-55) on the same campus providing a workaround capability for I&T. This facility is used to assemble the probe carrier mechanical dispenser, off-line from probe I&T.

For bus component level tests, Swales has several in-house thermal vacuum chambers and uses many local test facilities, which include thermal vacuum, vibration, EMI/EMC, mass balance, and acoustics facilities. Swales has baselined the use of GSFC Environmental test facilities for probe and mission test (under a commercial reimbursement contract) and are very familiar with the operation of these facilities from our FUSE, EO-1, MAP, Hitchhiker and HST program experience. If a schedule conflict should arise, we have access to alternative facilities at either the Applied Physics Laboratory, the Naval Research Laboratory, and local commercial facilities.

Main THEMIS Facilities	Description
Frederick Ave. Structure Fab. Area: 58,400 ft2	Fab. facility for composite & aluminum probe bus & probe carrier structure
Frederick Ave. Assembly Area: 5,000 ft2	28'- highbay, class 100K, temp. & humidity control for probe carrier assy
5015 Herzel Probe I&T: 1,600 ft2	Class 10K cleanroom 30'x50'x15' high w/3 ton crane, precision cleaning, & 1050 ft2 highbay staging
5015 Herzel Central High Bay 1,600 ft2	probe structure pre-I&T area. Includes 3'x8' bakeout chamber, 3 ton crane
5015 Herzel Lab A: 350 ft2	Harness & Electrical Assy
5015 Herzel Lab B: 350 ft2	Mechanical Assy & Bonding
5015 Herzel Lab C: 350 ft2	Probe Test Bed & Software Dev.

Table F-32. *Main Swales facilities for THEMIS*

F9. Product Assurance, Mission Assurance and Safety

a. Overview

UCB leads THEMIS product and mission assurance efforts, making the essential connections between the scientific needs, the design and its implementation. The mission design benefits from Constellation redundancy, with each probe using a single-string design architecture with functional redundancy. Additionally THEMIS emphasizes modularity and rigorous testing early in the build process. Aggressive quality control and performance verification ensure THEMIS reliability during all mission phases.

The THEMIS Mission Assurance Manager (MAM), Ron Jackson at UCB, works with the Explorers Office and subcontractors to effectively communicate fabrication, reporting and inspection requirements, and to establish parts and materials review processes. The Swales performance assurance process is managed by a Quality Assurance (QA) engineer familiar with all facets of spacecraft development, resident in the same design studio as the Swales development team. The QA reports directly to the Swales Program Manager with a separate formal communication path to the THEMIS MAM and the Swales Director of Quality Assurance.

Although a majority of status reports are electronically communicated to UCB, the MAM also performs supplier audits and inspections as necessary. A monthly assurance status report is provided to NASA, referencing available on-line documentation. At all times, a transparent and versatile quality assurance program, which benefits from the recent HESSI and current STEREO practices, permits NASA to evaluate THEMIS' reliability and problem-mitigation strategy.

b. Trade studies

The PM coordinates identification, evaluation and disposition of performance, mass, power, schedule and cost. Timely decisions on alternate paths / workarounds are key to maintenance of schedule and cost resources. Trade studies explore the available resources and solutions and the decision cutoff dates for full realization of the benefits. The chief technical resource for the PM in this operation is the Mission Systems Engineer (MSE), the focal point of technical evaluations for the trade studies. Trade studies are identified and proposed by developers, the MSE, the science team, or subcontractor in-process conditions. The THEMIS PI, directing and evaluating key science trades, the PM in control of mission resources and the MSE evaluating results of technical studies is an efficient interactive team at UCB that ensures that the THEMIS science goals are met within cost and schedule. The PI is responsible for the final decisions relating to the results of trade studies. Phase A practices exemplify this process: Trade studies on science implementation (Section E3) and mission implementation (Section F2.b) involving science performance, mission cost, risk management and technical performance margins were conducted by the highly integrated and efficient THEMIS team with substantial benefits to the mission.

c. New technology

The design incorporates two new technology items supporting low cost ranging and celestial navigation. These are not essential for THEMIS, they are exercised at the end of the nominal mission and are do not divert significant effort away from the primary mission focus during Phase B/C/D.

d. Mission Assurance

THEMIS Mission Assurance will take advantage of established procedures at Swales, CETP, IWF, TUBS and flight fabrication subcontractors whose procedures meet the intent of the UCB mission assurance requirements. Swales is certified to ANSI/ISO/ASQ Q9001 (since 1999) with established standard processes and procedures, governed by the Corporate Quality Assurance Policy Manual (SAI-QAP-001), which are documented and controlled by formal Configuration Management. These documents provide employees with web-based access to requirements and sequence instructions for design, test, manufacture and interleave items such as product identification, traceability, critical process control items, inspection points, non-conformance instructions, corrective action & saving instructions, handling, and storage. Swales' Quality Manual has been reviewed and approved by UCB. Given the flight expertise in these organizations in delivering NASA and ESA flight components, THEMIS does not anticipate having to impose new requirements.

e. Performance Assurance

Early in Phase B, UCB documents the THEMIS System Reliability and Quality Assurance (SR&QA) program in the Performance Assurance Implementation Plan (PAIP). The PAIP development is modelled after the HESSI (HSI_PA_001B in ftp://apollo/pub/hessi/HESSI%20Documents.html) and STEREO PAIP development, incorporates NIAT and IV&V requirements, and fully utilizes the Explorers' office resources and experience. With it the MSE documents and coordinates the development of a comprehensive verification program, matching analyses, inspections and tests to mission requirements in a verification matrix.

The THEMIS PAIP is the performance assurance basis for all subsystems; all team members use it as a template to formulate their own PAIPs. The Swales PAIP conforms to the above THEMIS program rules and builds upon existing Swales quality standards and proven methodologies from numerous NASA projects (EO-1, FUSE, HST). The PAIP, fully compliant with GSFC-410-MIDEX-002 standards, is reviewed and approved by UCB. Additionally, the Swales PAIP addresses component and system reviews, workmanship requirements, verification and testing, parts selection, materials and process control, reliability, non-conformance and failure reporting, software assurance and system safety. Prior to PDR UCB conducts a Product Assurance audit of Swales to validate Phase C/D readiness.

f. Safety

UCB heads the THEMIS safety assurance program working with contractors early in the project to identify hazards to personnel, flight equipment, and facilities. Mitigations affecting flight and GSE designs such as interlocks, redundant systems and procedural implementation are incorporated early to minimize impact. Instrument hazards include flight high voltages and GSE radioactive sources, both handled by the UCB safety office (http://radsafe.berkeley.edu) as on previous missions.

Probe and PCA hazards include RF radiation, lifts, transportation and fueling. The Swales safety program is run by the Safety committee (includes top management, individual facility, and process control personnel) and ensures conformance to Swales' safety policies.

During mission I&T activities conducted at GSFC the I&T team conforms to all GSFC safety manual regulations with due attention on hazardous operations such as lifting, electrical isolation, material usage, and pressurization. All hazardous procedures are reviewed by the cognizant GSFC safety representative prior to first use. This procedure mirrors Swales's practices on EO-1 and FUSE.

As on HESSI, UCB subcontracts the generation of the Mission Systems Prelaunch Safety Package (MSPSP) that encompasses all flight hardware subsystems, GSE and ground operations. This is delivered to UCB within 3 mo. in advance of its first use, to allow time for safety reviews.

The MSPSP is generated by Swales, based on its EO-1, MAP, and FUSE experience. The MSPSP identifies all hazardous operations and is in compliance with the Kennedy Space Center (KSC) Safety Practices Handbook (KHB 1710.2D) with inputs integrated from the cognizant bus and instrument lead engineers. Swales also produces the Launch Site Plan identifying all required launch site resources. Prior to shipment to the launch site, Swales provides all planned launch site procedures to KSC/Range Safety for review and comment.

g. Parts

Parts selection takes place from known sources (e.g., GSFC-311-INST-001), with derating to GSFC PPL-22, Appendix B, or Mil-STD-975 H, Appendix A standards. HESSI and STEREO parts lists have been assembled and distributed to THEMIS designers for the concept study. UCB purchases all instrument parts. Swales procures all bus parts, with the exception of the BAU processor board which is identical to the IDPU processor and is provided to Swales by UCB.

In general, THEMIS expects to use GSFC 311-INST-001 Grade 3 parts with selective up-screening to grade 2 for key items in critical sub-systems. Following the experience on FAST, HESSI and other Explorer Program missions, the MAM recommends purchase of higher grade parts when it is deemed cost-effective, (such as for low cost parts). Such practices are feasible because of the small number of organizations manufacturing flight-hardware (UCB and Swales) and the resultant efficient interaction amongst the team members.

The MAM assembles and maintains comprehensive parts and materials lists, including a THEMIS-specific EEE Parts Identification List (PIL), provides them to the Explorers Office and works collaboratively with that office to identify any problem parts and materials. The MAM handles GIDEP alerts and advisories by searching the THEMIS database for matches and by communicating with subcontractors. The applicability or non-applicability of alerts is communicated directly to NASA. Swales maintains a PIL for EEE parts for all in-house developed electronics and requires all subcontractors to maintain and deliver a PIL as part of the Contract End Item (CEI) deliverable. These PILs are available to UCB electronically and updated quarterly or as required.

Incoming parts and materials are inspected and checked for conformance to specs. Discrepant items may only be used with the consent of the THEMIS Parts Control Board (PCB) and Materials Review Board (MRB), respectively. The MRB is comprised of the Program Manager, MSE, MAM, I&T Manager and, as needed, by Subsystem Lead Engineers, Instrument Leads, and a PI representative. At Swales, parts selection, application, evaluation and acceptance is under the direction of a Swales Parts Control Board (SPCB) and a Swales Materials Review Board. These are comprised of lead assurance and selected electrical/mechanical systems engineers with UCB MAM representation as necessary.

At Swales, the GSFC Preferred Parts List (PPL) is used as the initial criteria for parts selection with justification for a part not on the PPL submitted to the SPCB via a Non Standard Parts Approval Request (NSPAR). Proactive interaction with the design team ensures that the project's radiation requirements, evaluation of GIDEP Alert searches and considerations for Destructive Physical Analysis (DPA) are addressed prior to formal processing through the PCB.

Guidelines for material usage on the probe buses and probe carrier are specified in the Swales PAIP with special attention given to magnetic cleanliness and surface charging in addition to assuring compatibility of all materials properties with the mission requirements. A material and process list, electronically maintained by Swales and subcontractors with UCB interaction, outlines application, properties, source, & usage in order to enable quick forward/backward traceability during manufacturing and I&T.

h. Problem/Failure Reporting

UCB shall manage Problem/Failure Reports (PFRs) from the probe bus, ground system and instrument activities, list these in monthly status reports to the Explorers office, and track them to closure. All PFR's are expected to be closed before delivery to the next level of integration. Manufacturing travelers are used to document flight board assembly and test, and necessary revisions. Problem reports are generated for any deviation from expected performance of either the flight unit or its GSE and are reviewed by the THEMIS MRB. After a course of action is implemented and closure is verified the problem report is closed. A monthly status is generated for all open and closed problem reports and is reviewed with UCB project management.

Swales implements an internal failure reporting system described in the Corporate Quality Assurance Policy Manual (SAI-QAP-001) for piece parts and components. At higher levels of assembly (subsystem, probe, PC, etc.) Swales integrates failure reporting into the UCB process with all items having cross-project visibility and notification. All parts, components and subassemblies entering I&T are tracked via the automated Work Order Authorization (WOA) system. The intra-net based system tracks work flow and records non-conformances from the initiation of I&T through launch. Traveler information and component end-item data are inserted into the WOA prior to usage. Problem reports are identified as any departure from design, performance, testing, or handling that affects the function of flight equipment or critical ground support equipment. Problem reports are immediately documented within the WOA system and are brought forward by the cognizant engineer to the THEMIS MRB for resolution and disposition.

i. Flight Software.

UCB develops instrument software using the same development approach which put the first microprocessor-controlled instrument in space (ISEE-A Electric Field Instrument) over twenty years ago, resulting in a constant string of on-schedule developments with successful in-flight performance of ~30 processor designs on NASA instrument suites.

Based upon past experience, the THEMIS IDPU software is ~3000-4000 lines of assembly code. Instrument software requirements are specified by the MSE and IDPU software engineer, structured in 12-15 modules, written by one programmer and verified error-free by an extensive program of on-orbit-like simulation and testing.

An ETU IDPU with simulators for the sensors and analog electronics is maintained through the entire mission. All software is verified in this system to the satisfaction of the MSE before it is loaded into the flight hardware. Software reviews are parts of instrument reviews with internal UCB peer-reviews interspersed as needed and IV&V reviews, if needed, in parallel with the bus avionics unit (BAU) software. Deliverable documentation includes internal review documentation, detailed and user-level manuals for maintenance, and, as in FAST[157], a summary paper to be published.

THEMIS's probe bus BAU software requirements are specified by the spacecraft system engineer and subsequently implemented by Hammers Co. THEMIS' software quality assurance plan extends to the BAU software, addressing requirements definition, reviews, software build and coding, testing, mission-level I&T, IV&V interactions and Configuration Management. Software reviews are listed in Table F-33. In addition, peer reviews, and code walkthroughs (performed with the C&DH, systems and independent IV&V personnel) are interspersed through the project as needed. For further details on the IDPU and BAU software see Sections F4.d and F3 respectively. The THEMIS IV&V plan is described in Section G.

Concept Review (in conjunction with mission)
Requirements Review (in conjunction with mission)
Preliminary Design Review (in conjunction with mission)
Critical Design Review (in conjunction with mission)
Software Test Readiness Review
Software Acceptance Review

Table F-33 *Bus avionics unit software reviews*

j. Product Assurance Implementation.

The MAM is the centralized figure in maintaining a quality assurance program. This program is subject to internal and external reviews which parallel the general reviews of the THEMIS mission, outlined on Section G. This program includes the items listed in Table F-34. The THEMIS team places particular importance on configuration control because of the multiple copies of probe busses and instrument being built.

Document Control	Version-control via well defined system of drawing numbers and revision letters
Parts traceability	Keep master list of unique serial numbers; identify non-unique subassemblies
Procurement control	All flight unit parts and materials purchases are inspected to comply with purchase order of part model, parts marking, packaging and count.
Fabrication control	Ensures engineering drawings of fabrication and assembly flows are conducted according to program requirements. Certification logs and worker certifications for flight-segment soldering and wiring are met and in accordance to NHB 5300.4 standards.
Configuration Management	Master indented drawing list used to track the as-built subsystem configuration listing
Metrology	Verification of accuracy of lab. equipment to desired levels, per MIL-STD-45662 A.
Printed wiring boards	Built to conform to MIL-P-55110; coupons sent to GSFC for inspection and approval prior to flight assembly, in accordance with standard UCB practices.
Handling & processing	Handling, storage, marking, shipping, preservation, labeling, packaging and end-item acceptance performed according to standard (e.g., MIL-STD-129) practices

Table F-34 *THEMIS product assurance practices*

At Swales, fabrication and assembly is controlled through use of Certification Logs, Travelers, Work Instructions, hardware specific processes, procedures, and through project-specific training of THEMIS personnel prior to initiation of major activities. Materials and parts traceability are achieved through Configured Article Lists that are included in the fabrication plans. Non-conforming materials are segregated, evaluated and dispositioned. Allowable dispositions are Rework to Print, Scrap, and Submit for SMRB action (such as Repair, Use As Is, or Submit to the THEMIS MRB for Waiver). Non-conformance or change associated with controlled interfaces requires mandatory approval by UCB.

Swales's Quality Control process verifies that articles produced meet applicable design and workmanship requirements. Swales's Quality Engineering process reviews and approves each document, changes and to verifies that the instructional content is correct per the drawing and specifications. In-process inspection points are established on Travelers that contain sequential steps to complete the operation and identify in-process inspection points. The in-process inspectors confirm the configuration, dimensional features, workmanship, and recordation before testing. Testing is accomplished by the engineering Test Conductor per the applicable test procedure and is monitored by the quality engineer. The Swales closed loop non-conformance system assists in the tracking of Corrective Action Reports, Customer Deficiency Reports and Failure Reports, all made available to UCB.

The Swales Operating Procedure (OP 015-001) defines Handling, Packaging, Preservation and Transportation requirements. All Government/Customer Furnished Property is segregated, inspected, and stored under the control of the Government Property Administrator (see Swales Operating Procedure 007-001).

k. Reviews

UCB conducts THEMIS reviews in accordance with MIDEX requirements, including action-item tracking-to-closure. Reviews are conducted at the subsystem and system levels. System level reviews address critical systems, end-to-end mission level technical, safety, reliability, flight and ground operations, and programmatic issues. Major and minor reviews are listed in Table G-9. Since there are 5 probes, we anticipate five Pre-Environmental Reviews of test plans and performance results of each probe. We expect the first PER to be longer, with subsequent PERs focusing on probe readiness for environments.

The THEMIS team benefits from UCB's recent experience in multiple-review-team reviews (STEREO, HESSI). Since reviews by two independent teams can result in overlapping or conflicting action items THEMIS believes that coordinating review team dialogue can alleviate those issues and facilitate timely closures. THEMIS plans to provide a Request For Action (RFA) coordinator to work with the review teams and produce in a uniform set of recommendations. The coordinator ensures that the review teams converge and enables the THEMIS team to provide developers with clear sets of response actions emanating from the reviews.

Swales supports all major mission reviews in addition to conducting Internal Preliminary and Critical design reviews (IPDR/ICDR) for the probe bus and probe carrier. Prior to IPDR and ICDR, Swales conducts informal subsystem peer reviews with independent assessment team members that have extensive technical depth and experience to assess the subsystem under review. As on EO-1 and

FUSE, Swales strives to bring at least one member from the higher-level program-review team onto the peer review team providing insight and contextual understanding during the mission reviews. The subsystem leads conducting the peer review maintain an action item list, report on all open action items at subsequent mission reviews, and track and status resolutions as part of the formal review proceedings.

l. Continuous Risk Management.

As was successfully demonstrated on HESSI, UCB performs continuous risk management and mitigation as part of an integrated schedule, cost and science performance margin management strategy throughout the program. The Mission Manager at GSFC is fully aware of the items on the risk list, and what UCB/Swales are doing to handle potential problems. In accordance with practices on HESSI the THEMIS team openly identifies existing or emergent technical or programmatic risks so that mitigations can be arranged in a timely fashion. Continuous risk management in the HESSI project allowed UCB to deliver the spacecraft on time and on budget: For example, when the primary developer of the HESSI grids missed development-schedule milestones one year prior to delivery, UCB started a parallel effort at Tecomet. This paid dividends when the primary developer eventually failed to deliver and Tecomet did. The cost of this effort was equivalent to a week's delay in the program.

	Baseline Msn, 2 yrs					Minimum Msn, 1 yr			
	P1	P2	P3	P4	P5	P1	P2	P3	P5
FGM	✓	✓	✓	✓	✓	✓	✓	✓	✓
ESA	✗	✓	✓	✓	✓	✗	✓	✓	✓
SST (2 heads)	2	2	1	1	1	2	2	1	1
SCM	✗	✗	✓	✗	✓	✗	✗	✗	✗
EFIAXB (2)	✗	✗	2	✗	2	✗	✗	✗	✗
EFISPB (4)	2	2	4	2	4	2	2	2	2

Table F-35 *Instruments required on each probe to perform the baseline and minimum mission. It is evident that the mission is resilient to many fault scenarios, from which it fully recovers by placing the probe on which an instrument subsystem failed in an orbit where that subsystem is not critical.*

There are several components to the THEMIS risk management process for fault-recovery. *First* is the capability of the P3 and P4 probes to replace any other probe at full probe dry mass growth to their maximum expected limit, resulting in a 4-probe configuration that can accomplish the minimum performance science within 1 year, and near-baseline science goals of the mission within 2 years. *Second*, is the science resilience to partial or total sensor failure on one or more of the probes. For example, EFI axial booms (EFIAXB) are necessary only for high frequency mode recognition, and most of the baseline (and all of the minimum) science can be recovered if they are fully functional on two of the inner probes. Additionally, most of the science on P1, P2 can be recovered from one-dimensional measurements with two out of the four spin-plane EFIs (EFISPBs). Dynamic stability is maintained or even increased if contingency plans are implemented. While these items represent items of a mission fault-tolerance strategy, they also provide means for schedule risk mitigation during the development and I&T process (e.g., reduced testing on selected non-critical units after qualification of the first unit) For example, if schedule delays result in crossing important schedule milestones in the I&T process, reduced testing of selected units may take place to avoid (significant). A table of the instruments that are crucial to perform the baseline and minimum mission at each probe is shown in Table F-35. The above fault-tolerance and schedule-risk mitigation items are descope candidates (on all 5 probes). Cost and schedule savings can be realized fully if descopes are implemented prior to set trigger dates. These items, and additional descopes in the areas of mission operations and ground observatories are tabulated in Table F-36.

Descope Item	Benefit to Mission Implementation	Impact on Mission Implementation	Trigger Date	Cost Benefit ($M)
EFI stacers	Cost, mass, schedule, dyn. stability		Phase D Start	1.75
Half ground observatories	Cost		Phase D Start	0.75
SCM	Cost, mass, schedule		Phase C End	0.35
5th probe	Cost, mass, schedule	Reduced fault tolerance	Phase C End	4.5
Selective BGS, USN non-primary contacts	Cost		Phase D/E Start	0.5
Total (Still above minimum science objectives):				7.85

Table F-36 *Descope items, their effects and value*

m. Failure Mode Effects Analyses (FMEAs)

Based upon THEMIS's constellation architecture, most flight systems can be predominantly single-string designs with some areas of functional redundancy. FMEA's at the system and subsystem level are performed and maintained by the MSE in concert with probe bus and instrument engineers. These determine the basis for system robustness to potential failure modes, the data points required to detect them, and the steps that should be taken to mitigate the fault. THEMIS evaluates the design

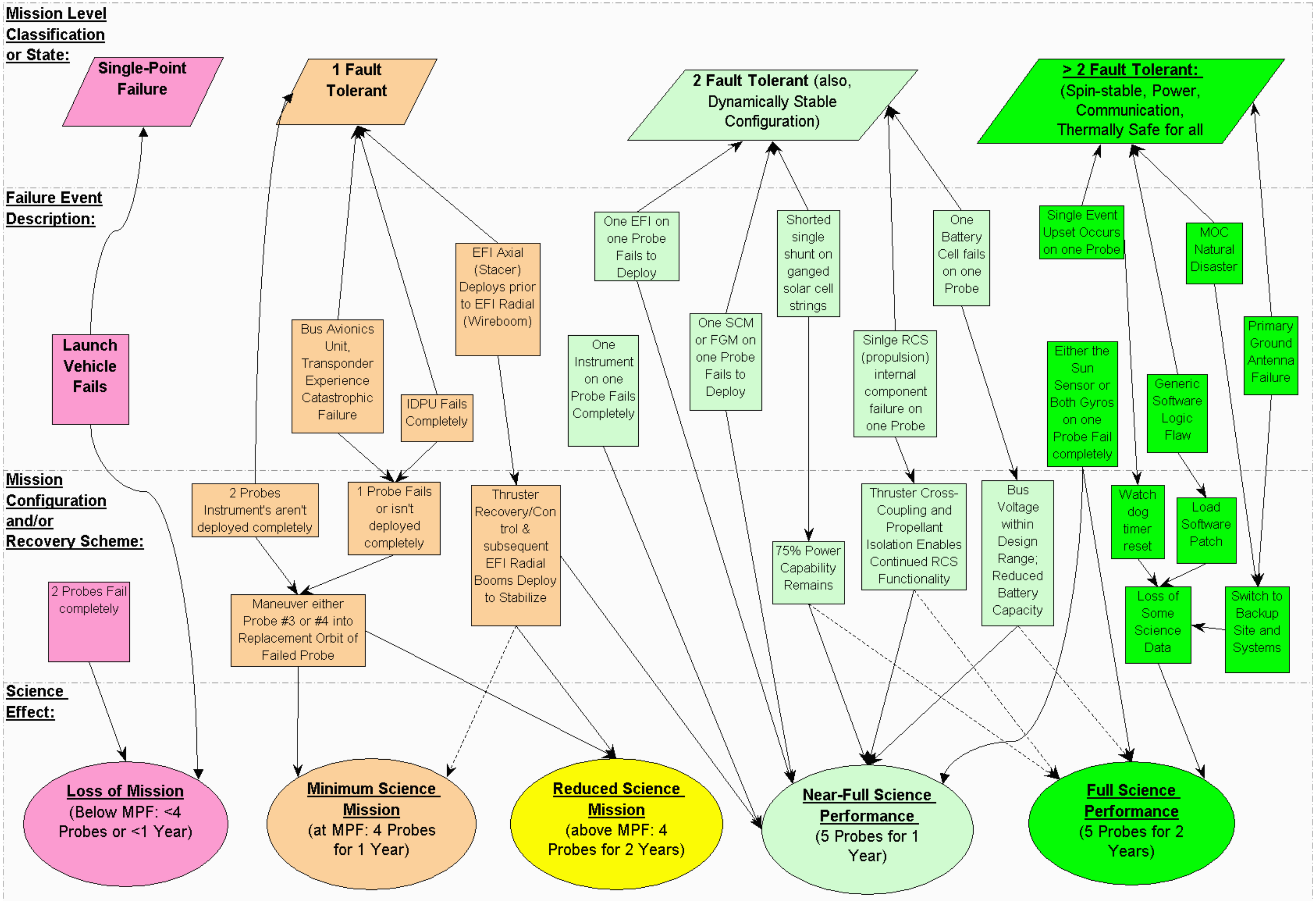


Figure F-56 *THEMIS risk assessment fault tree: Single poit failure can only occur from catastrophic loss of D2925, an unlikely scenario since D2925 is a high reliability L/V. THEMIS benefits from constellation redundancy and is a low risk mission.*

early to determine inherent functional overlap and appropriate fault recovery actions that can be handled through use of other components or software. As on FAST and HESSI these can be additional test points, redundant data paths, filtering of auxiliary telemetry data, formation of backup procedures, and additional ground software and procedures to provide failure detection and response.

THEMIS's robust system design is further evaluated and strengthened by the use of comparative reliability analyses, worst-case analyses, parts stress analyses, FMEA, PRA and fault tree analyses. These evaluate the as-designed system fault tolerance and risk profile and identify critical contingency operations. This philosophy is implemented effectively by the combined UCB-Swales systems team, as exemplified by the robust design presented herein, and as highlighted by the fault tree analysis resulting from our preliminary FMEA analysis (Figure F-56). Each major architectural topology was evaluated integrally with the FMEA process, providing us with the insight to drive simplification of the mission, probe, PC, and ground system designs while still achieving enhanced science performance.

One of the most evident examples is the simplification of the Probe Carrier design from that presented in the original AO proposal. The fault tree identified that the original approach (PC had an internal solid booster motor, sequence electronics, and a 12 hour coast phase to apogee prior to main orbit maneuver) was a source of mission risk. Our early-Phase-A assessment has revealed that utilizing a vehicle upgrade (D2925) to directly inject the probes to their initial orbits eliminates that risk. This is because the direct-inject approach simplified the PC to just a basic mechanical dispenser (that stays attached to the Delta 3rd stage) with an umbilical harness and thermal blankets. We mapped out the effects on cost (minor net increase), schedule (shorter), mass capability (no net change), operational sequence (much simpler), and on development activities (eliminated risk and contingency-bearing items). The benefits from the reliability of the larger LV are thus overwhelming at the mission risk level. The NASA/NLS office at KSC was requested to provide a validation of our entire injection and L/V configuration. The NLS assessment actually simplified our approach further, provided higher mass capability, and helped guide the team to finalize this risk reduction activity. An added direct benefit from the elimination of the internal PC solid booster was the greater clearance during probe dispense (improving fault tolerance). This risk assessment and mitigation process was utilized repeatedly on several elements of the probe and PC designs and forms the basis for our subsequent FMEA activities. The use of RELEX (COTS fault assessment tool) allows us to automate the representation and analysis of the system configuration, failure modes, and PRA of the system performance. Dynamic linkage allows for the use of the THEMIS fault tree to be transferred to the UCB MOC for use as a rapid fault isolation and root-cause analysis tool during flight operations.

n. Probabilistic Risk Assessment (PRA)

Fault tree analyses validate and depict analyzed relationships between probe components and subsystems and associated "block" failure, regardless of cause, while the PRA evaluates the likelihood of entering these potential failed states. In accordance with FAST, HESSI and STEREO practices, PRAs aid systems team gauge the relative risk associated with design options traded in the concept design and provide insight into the ability of the mission architecture to satisfy lifetime requirements.

Preliminary PRA of the probe design was performed first as a tool to trade internal bus architec-

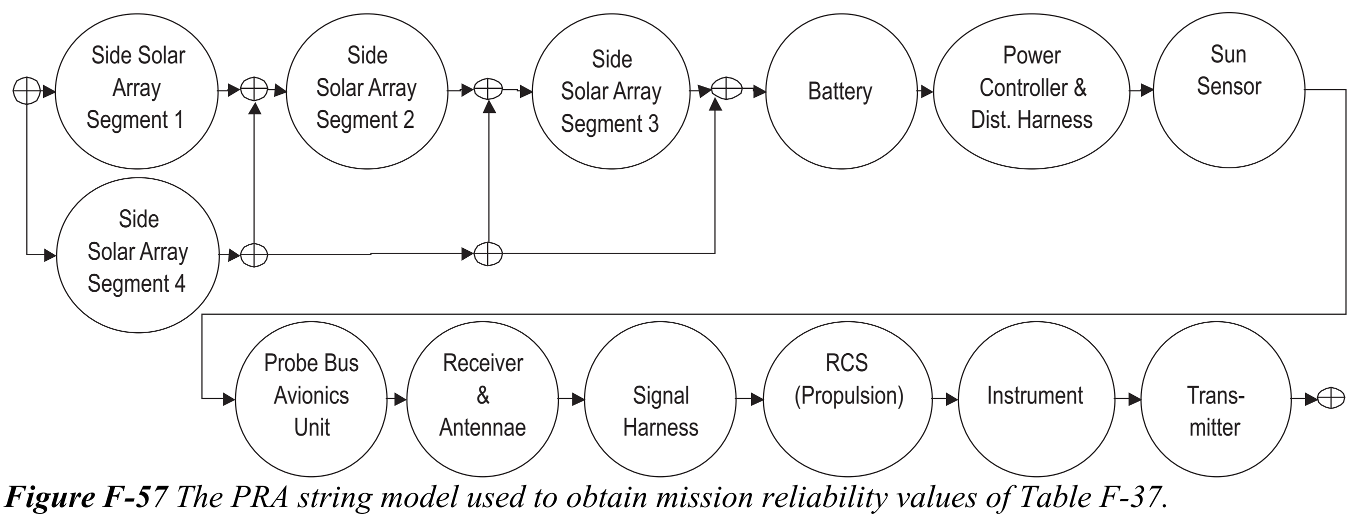


Figure F-57 *The PRA string model used to obtain mission reliability values of Table F-37.*

ture decisions and subsequently as a validation of the mission (constellation) reliability relative to minimum and nominal mission lifetime requirements. The "string" model is used in this analysis to compute the probe success probability, P_S (Figure F-57**).** Conservative component reliability data from vendors and from Swales's internal (EO-1 and prior industry survey) electronics database have been integrated to generate individual failure rates and resultant probabilities. Mission reliability P_S is then computed (Table F-37). The ability of either probe #3 or #4 to replace any other (hypothetically) failed probe results in excellent mission reliability with mission P_S=93% for 1 year (minimum mission duration) and P_S=80% for 2 year (nominal mission duration). This preliminary fault tolerance and risk assessment gives us high confidence that the mission architecture produces the best balance of number of probes, simplicity of probe and PC, launch injection strategy, and operational simplicity.

THEMIS 1 year mission life probability	
Item	P_S
Any single probe	0.91
Constellation mission probability (4 of 5)	0.93

THEMIS 2 year mission life probability	
Item	P_S
Any single probe	0.83
Constellation mission probability (4 of 5)	0.80

Table F-37 *THEMIS mission reliability values.*

o. Software IV&V.

UCB and Swales have three areas of critical software suitable for evaluation by IV&V during the concept study: Probe, Instrument and Ground Data System (GDS). As shown in Table F-38, the Likelihood of Failure (LOF) for all products was low due to the small size of the software team, a negotiable schedule, known objectives and small code size. IDPU software controls boom deployment and high voltages. Despite the long history of successes in this area, we have conservatively rated the consequence of failure at marginal. GDS envisions a number of small modifications to software programs similar to what was done for HESSI. Some of these programs have the potential for causing probe loss through miscalculation of attitude, or misrepresentation of telemetry to controllers.

In the highly unlikely situation of IDPU or GDS software failures leading to the loss of a probe, ensuing probe replacement and data analyses would still recover the minimum performance science for the mission (1yr) or a significant fraction of the baseline science (in 2 years). Thus, the consequence is rated as a loss of greater than \$2M, and less than \$20M.

THEMIS shall continue to work closely with the IV&V office in accordance with MIDEX program guidelines.

Product	LOF	COF
Probe Software	30	Insignificant
Instrument Software	30	Marginal
GDS (Max)	29	Marginal

Table F-38 *IV&V summary*

G. MANAGEMENT PLAN

G1. TEAM MEMBER RESPONSIBILITIES

The THEMIS mission is implemented by an experienced space hardware development team from the University of California at Berkeley (UCB), the University of California at Los Angeles (UCLA), University of Colorado (LASP), Goddard Space Flight Center (GSFC), and Swales Aerospace. In addition, THEMIS brings together a group of scientists to provide world-class theory, ground- and space-based context observations, mission and science operations, data analysis, and educational and public outreach.

Organi-zation	Responsibility	Recent Experience
UCB	Project Management	HESSI
	Electric Field Instruments	POLAR, ClusterII
	Electrostatic Analyzers	FAST, ClusterII
	Solid State Telescopes	ISEE, WIND,
	Magnetometer Booms	FAST, LP
	Instrument Data Processor	FAST, HESSI
	Mission Ops Center	FAST, HESSI
	Science Ops Center	FAST, HESSI
	Msn Ops & Data Analysis	FAST, HESSI
	Ground All Sky Imagers	AGOs
	EPO Lead	HESSI, IMAGE
UCLA	GMAGs, Magnetic Cleanliness	Measure, FAST
CU	Fields Processing	FAST
TUBS	Fluxgate Sensors	Equator-S, MIR, Rosetta
IWF	Fluxgate Electronics	
CETP	Search Coil Sensors	ClusterII
UC	ASI deploy, data recover, relay	NORSTAR
ESTEC	SST Counters	Wind, ClusterII
GSFC/ GNCD	GN&C advise (flight dynamics, ACS, RCS, CelNav)	Small Explorers
Swales	Probes Busses Probe Carrier Mission I&T System Safety Launch Operations Mission Ops Support	FUSE, EO-1 SCONCE, Triana FUSE, EO-1 FUSE, EO-1 FUSE, EO-1

Table G-1 *Organizational roles in THEMIS mission implementation.*

Capitalizing on its successful HESSI experience UCB manages the project and provides mission systems engineering and quality assurance. UCB coordinates instrumentation efforts, producing the Electric Field Instrument (EFI), the Electrostatic Analyzers (ESA), the Solid State Telescopes (SST), magnetometer booms, Instrument Data Processor Unit (IDPU) software and I&T of the entire instrument complement prior to delivery to Swales.

Swales is responsible for the probe busses and integration of the instrument complements. Swales also provides the probe carrier, integration of the probes to the carrier, environmental tests, launch vehicle integration, launch and operations support.

Institute/Person		Role	Recent Experience
UCB	Harvey	PM	HESSI, FAST, Cluster
	Jackson	MAM	HESSI
	Pankow	LME	HESSI, FAST
	Taylor	MSE	CHIPS
	Bester	MOM	FAST, HESSI, IMAGE
	Sterling	I&T Mngr	HESSI
	Berg	Instr. Mngr	HESSI
	Curtis	IDPU	LP, HESSI STEREO
	Abiad	Processor	FAST, HESSI
	Turin	ESA, SST	FAST, ClusterII
	Pankow	EFI	Polar, ClusterII
	Besuner	Mag.Booms	FAST
	Mende	GBOs, ASIs	AGOs/Antarctic
	Craig	EPO officer	HESSI, IMAGE
UCLA	Russell	GMAGs, EMC	Measure, FAST, ST-5
CU	Ergun	DFB	FAST
TUBS	Auster	FGS	Equator-S, Rosetta
IWF	Schwingen-schuh	FGE	Rosetta, MIR
CETP	delaPorte	SCM Sensor	Galileo, ClusterII
ESTEC	Escoubet	SST FPGA	Wind, ClusterII
GSFC	Richon	GN&C advisory team lead	Explorers (e.g., FAST)
Swales	Cully	Swales PM	EO-1
	Ajluni	System Engr	MAP, FUSE
	McMeekin	I&T mngr	GLAST

Table G-2 *Key members, roles and experience*

UCB extends the usage of the FAST and HESSI Mission Operations Center and Science Operations Center to meet THEMIS space and ground requirements. UCB leads the EPO effort and collaborates with UCLA, Lawrence Hall of Science and other partners. The EPO officer manages the daily EPO activities, coordinates magnetometer school-site selection and the UCLA production, shipment and installation of the ground magnetometers at selected schools. The lead EPO officer reports to the PI.

TUBS and IWF produce fluxgate magnetometer sensors and circuit designs to which UCB manufactures engineering test units (ETUs) and flight boards. Extensive testing and calibration of sensor/ electronics boards occur prior to instrument integration, at the co-Is' magnetic calibration facilities.

CETP provides the search coil sensors; UCB purchases the preamplifiers to CETP's design specification. CETP provides testing of the system prior to delivery to UCB for instrument integration.

ESTEC provides counter chips for the SST from the same production run as STEREO, and be-

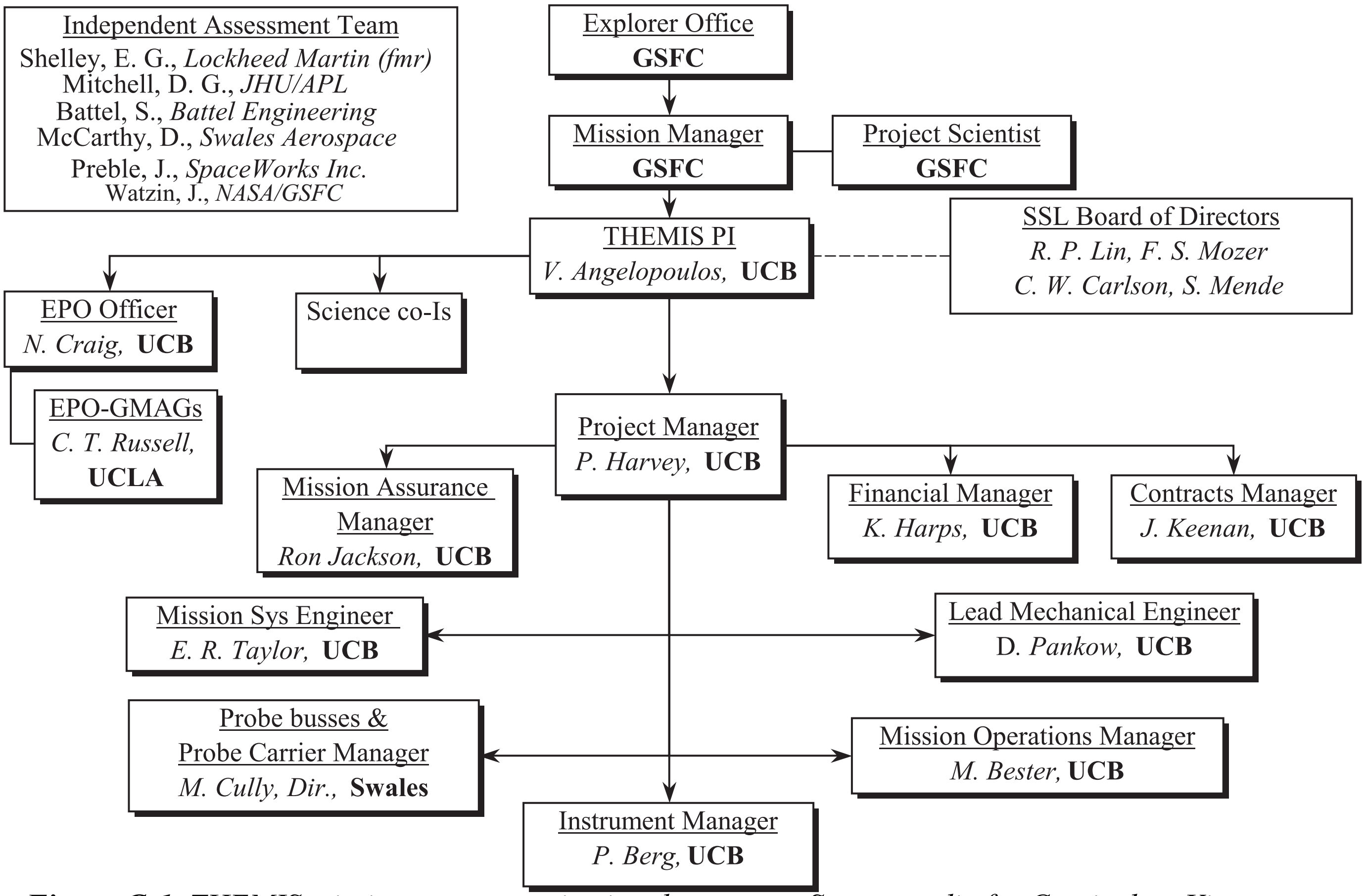


Figure G-1. *THEMIS mission team organizational structure. See appendix for Curriculum Vitae.*

ing ahead of the THEMIS timeline, has afforded the opportunity to begin working with ESTEC to assess the performance and radiation tolerance of these devices for the THEMIS environment.

Funding of all US team partners is executed by a single contract from GSFC to UCB, and subcontracts implemented by UCB to team members. As performed for prior Explorers, funding for GSFC's involvement is managed internally by GSFC and coordinated with UCB. Reporting directly to the PI is the Project Manager (PM), Mr. Peter Harvey, who coordinates the overall program implementation including space and ground segment developments and operations preparations at UCB. Following a successful launch campaign, the Mission Operations Manager will direct the Operations at UCB with program management responsibility transition to the MOM for phase E.The PM is aided in his day-to-day responsibilities by the Mission Assurance Manager (MAM), the Financial Manager (FM), the Contracts Manager (CM), the Mission Systems Engineer (MSE), the Lead Mechanical Engineer (LME), the Mission Operations Manager (MOM), the Instrument Manager, and the Probe Busses/Probe Carrier Manager. This core team of individuals is responsible for informing the PM on the daily evolution of financial, technical and schedule progress and resource status, and is also responsible for transmitting the program's requests for action to the teams.

a. Organizational structure

The THEMIS PI, Dr. Vassilis Angelopoulos, is the single point of contact at UCB that the Explorer's Office interacts with for the overall responsibility of the THEMIS investigation. The PI is supported by co-Investigators and the Education/ Public Outreach Coordinator (Figure G-1). The PI is responsible for ensuring that the science goals of the mission are met and in doing so initiates and oversees science impacts and benefits from trade studies (e.g. science-yield from optimized orbit strategies), ensures accurate representation of Level 1 and Level 2 requirements, is responsible for the final decisions relating to trade studies, conducts science working team meetings, maximizes the inclusion of the US and international communities in the THEMIS data analysis, and oversees (and participates in) the EPO effort. The PI has access to the institutional experience at SSL through the SSL board of directors.

Reporting directly to the PI is the Project Manager (PM), Mr. Peter Harvey, who coordinates the

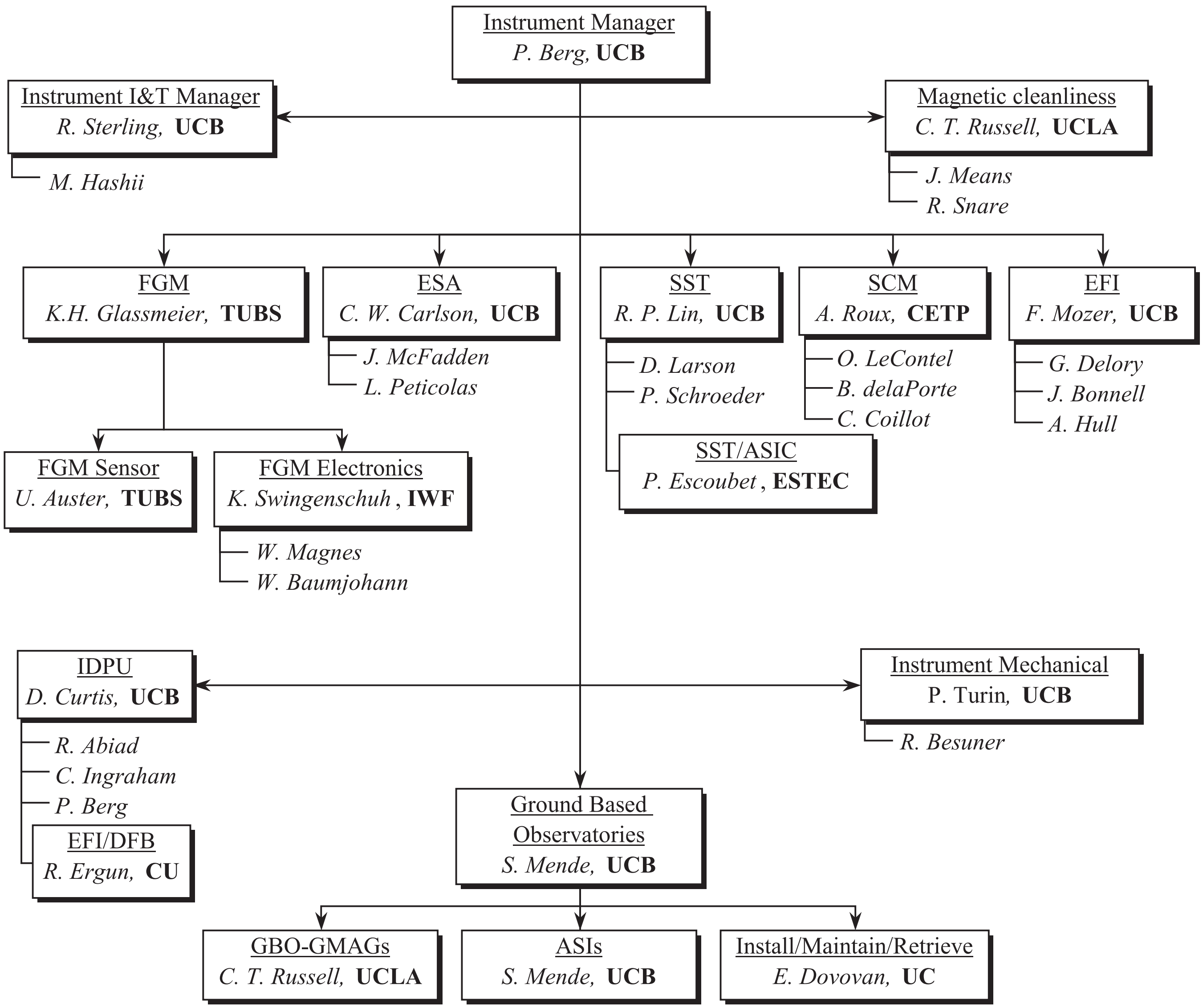


Figure G-2. *THEMIS instrument team organizational structure. See appendix for Curriculum Vitae.*

overall program implementation including space and ground segment developments and operations preparations at UCB. Following a successful launch campaign, the Mission Operations Manager (MOM) directs the mission operations at UCB. Program management responsibility transitions to the MOM in phase E. The PM is aided in his day-to-day responsibilities by the Mission Assurance Manager (MAM), the Financial Manager (FM), the Contracts Manager (CM), the Mission Systems Engineer (MSE), the Lead Mechanical Engineer (LME), the Mission Operations Manager (MOM), the Instrument Manager, and the Probe Busses/ Probe Carrier Manager. This core team of individuals is responsible for informing the PM on the daily evolution of financial, technical and schedule resources, and is also responsible for transmitting the program's requests for action to the teams.

The instrument manager in particular (Figure G-2) is responsible for overseeing the development, integration and test of the THEMIS space and ground instrumentation, in accordance with programmatic requirements of the five THEMIS instruments, the IDPU, the ground based observatories, GSE development, instrument I&T procedures, and the magnetic cleanliness program. The instrument manager is a single integrated voice representing the instrument subsystems status to the PM. The instrument manager facilitates the effective distribution of engineering resources and technicians amongst the various instruments and ensures efficient utilization of calibration and test facilities. In this function he is aided by the lead instrument mechanical engineer, the lead IDPU engineer and the instrument I&T manager.

The Instrument Data Processing Unit (IDPU), containing low power analog signal processing electronics, data system and bus interface, is built

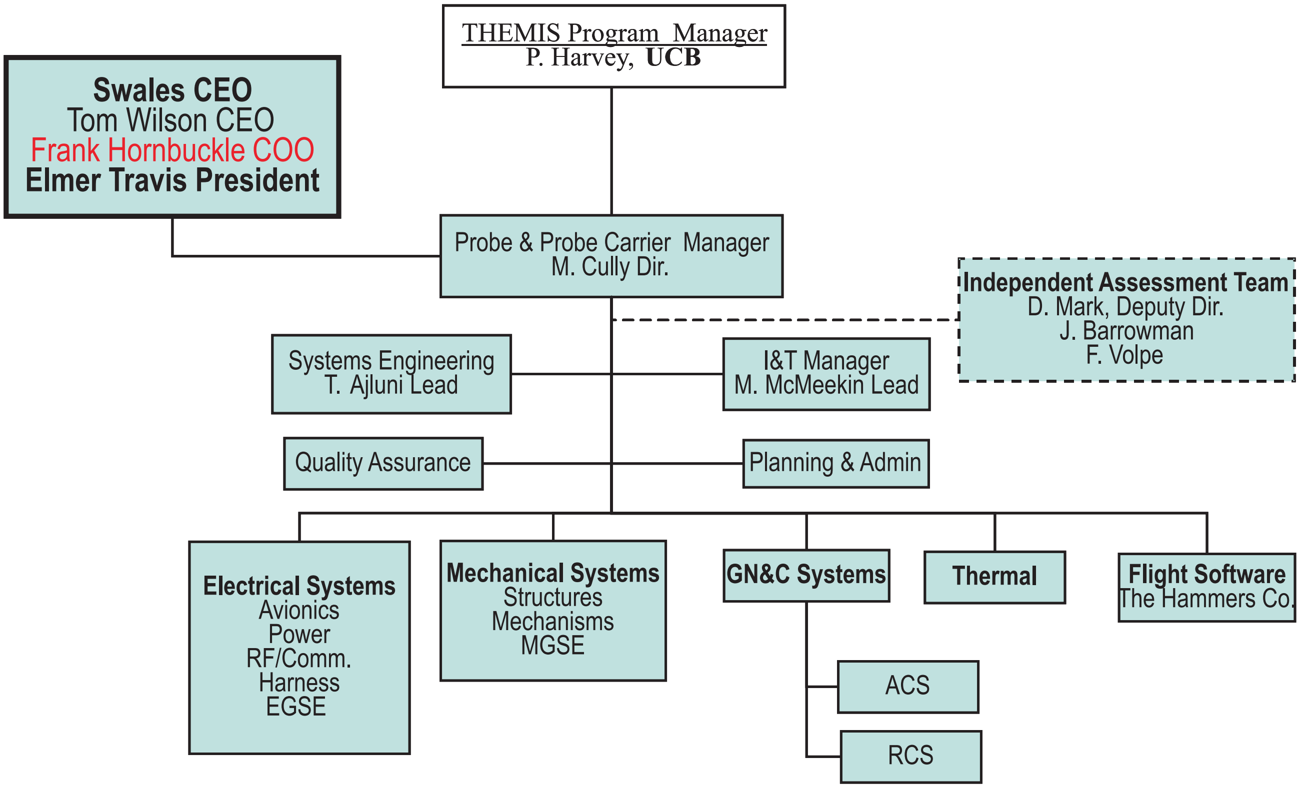


Figure G-3. *Swales THEMIS organizational structure.*

by the same UCB group that developed these systems for FAST, WIND, POLAR, MGS, Lunar Prospector, and many others.

UCB will duplicate the HESSI/FAST SOC for data processing and CDROM production. Ground-based observatories (GBOs) are selected to provide key context measurements to maximize the scientific return from THEMIS space observations.

The probe bus, probe carrier, mission I&T, and launch operations are provided by Swales.

a1. Swales organizational structure

The Swales Aerospace organization is specifically structured to meet customer needs through Strategic Business Units (SBUs) that are supported by a fully functional matrix organization. Each SBU reports to the Chief Executive Officer (CEO), Tom Wilson, and his senior staff including the Chief Operations Officer and the President.

The THEMIS program is managed through the Civil and Commercial Program (CCP) SBU, that has managed the successful FUSE and EO-1 programs. Swales' key ingredient to successful program management, taken from our approach on EO-1 and FUSE, dedicates a Core Team to the program, from the initiation of the program through launch and early orbit checkout, providing continuity for the program essential to maximize quality, efficiency and accountability on the program.

THEMIS has the highest visibility within the Swales Organization as illustrated in the program organizational chart Figure G-3. The single program manager for the THEMIS program at Swales, Mr. Michael Cully, manages all aspects of the probe busses, probe carrier (PC), mission integration, launch vehicle and early orbit operations. Within the Swales organization, Mr. Cully reports directly to the Chief Executive Officer (CEO). Within the THEMIS organizational structure, Mr. Cully is responsible for all Swales THEMIS activities and reports to the THEMIS PM, Mr. Peter Harvey. Directly supporting the Swales program manager is the Probe and Probe Carrier Lead Systems Engineer, Mr. Thomas Ajluni, who leads the systems engineering effort of bus and probe carrier development, and the Integration & Test (I&T) Manager, Mr. Michael McMeekin, who leads the bus I&T, probe I&T, probe carrier I&T and mission I&T efforts at Swales. An independent assessment team, led by Mr. Dan Mark, is responsible for senior in-house reviews and advice to the Swales THEMIS team and reports, through an independent path, to the Swales CEO. The team supports Swales internal reviews and, at the request of the UCB PM, also supports mission level reviews.

Swales has identified several experienced candidates for the remaining subsystem lead engineering core team with finalization by Phase B startup. These leads are drawn from the Phase A personnel each of whom has more than 18 years of satellite

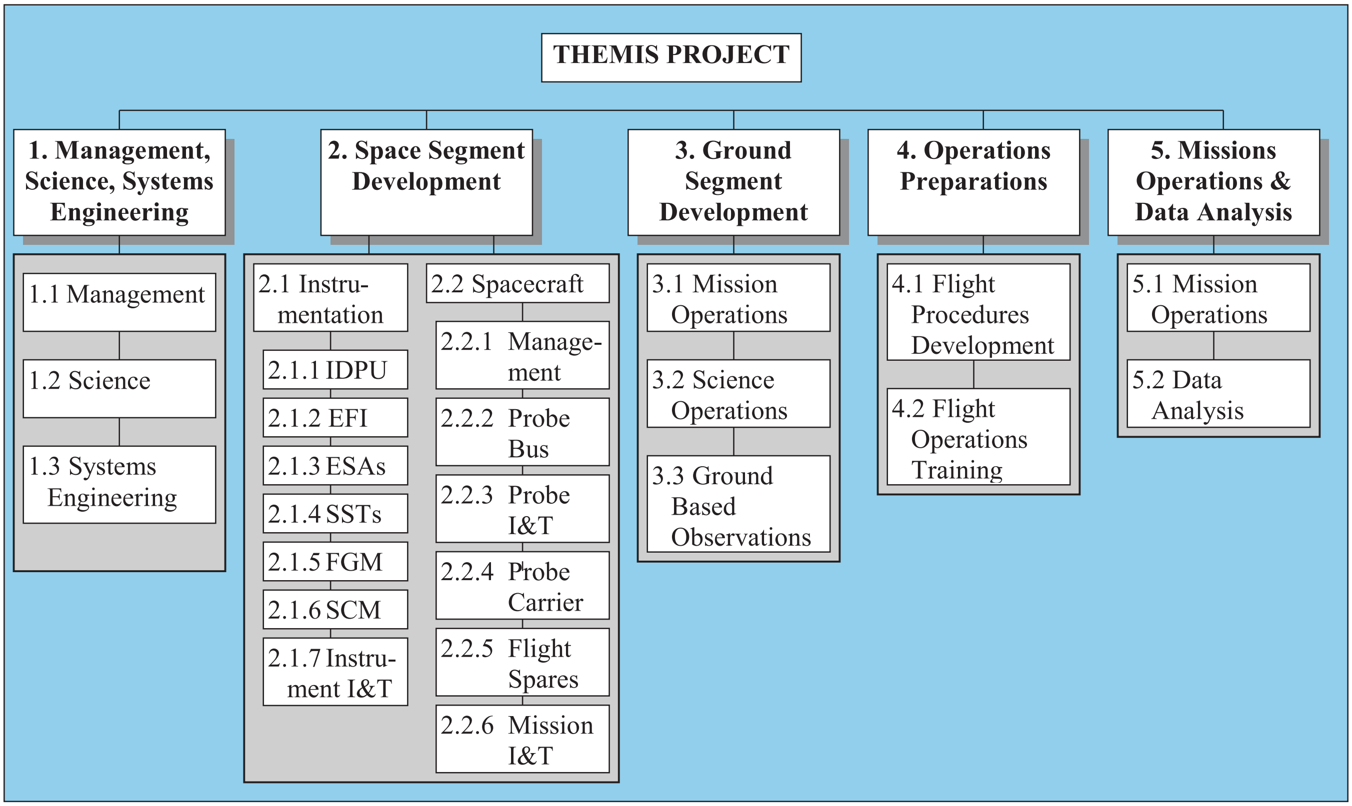


Figure G-4. *THEMIS top-level work breakdown structure elements.*

experience. Swales has integrated personnel from the Hammers Co., Swales' software team partner, who have worked previously with Swales in this same manner on EO-1, Triana and SMEX-Lite commercialization programs. All core team lead engineers and program support staff report directly to the Swales Program Manager. Changes in Core Team personnel are coordinated with and receive the concurrence of the UCB Program Manager.

The continued success of our organization results from open and frequent communication between all team members, as demonstrated in the Phase A study. All of the major UCB team members have direct access to the Swales core team. All members participated in weekly telephone conferences and bi-monthly site visits to discuss technical aspects and program status of the THEMIS program. Proposed changes to the bus and probe carrier were brought up, were captured by, and were evolved by the lead Swales systems engineer and were communicated to the THEMIS program manager in a formal "tablet of change" that was built up prior to final review and disposition by UCB. Electronic file transfer systems have been established that control single source location and transmit relevant documentation between UCB and Swales.

a3. THEMIS work breakdown structure (WBS)

The THEMIS top-level work breakdown structure elements capture the deliverable end items and functions and is depicted in Figure G-4.

b. Experience and commitment of key personnel

UCB is implementing the THEMIS program with a lean, highly experienced and highly committed team of engineers and scientists. Their experience is outlined below and points of reference are summarized in Table G-3.

i. Principal Investigator. The Principal Investigator, Dr. Vassilis Angelopoulos, has primary responsibility for the THEMIS mission. He has worked on space physics simulations, theory and data analysis since 1988, and his scientific contributions have been recognized by the American Geophysical Union's Macelwane medal (2001) and Fred Scarf award (1994), and the Russian Academy of Sciences' Zeldovich medal (2000). Since 1998 Angelopoulos has been an active member of various NASA mission science and technology definition teams, has authored multiple technical papers on Constellation-class microsatellites and edited a book on this topic. He has been leading science and technical definition studies on microsatellite missions at the Space Science Laboratory science since 1996. Angelopoulos devotes 100% of his time on THEMIS-related activities: This includes THEMIS-related data analysis using Cluster data on substorm events, assisting in science planning and preparation for THEMIS data analysis while maintaining a strong connection between THEMIS and the international scientific community.

ii. Project Manager. The PM has responsibility and decision-making authority for day-to-day management of the spacecraft, instrument and ground segment developments. He maintains the cost and schedule database, analyzes project performance against targets, and reports budget and schedule analyses to the PI and the Explorer's project office. The PM leads trade studies and provides cost and schedule impact data for PI decisions. The PM also directs personnel changes and redirects project resources as needed to keep THEMIS on schedule and below cost.

The THEMIS PM, Peter R. Harvey, is an experienced spaceflight developer and manager with nearly 30 years in space projects. He holds BA and MA degrees in Computer Science from the University of California. Most recently, he was the Project Manager for the NASA HESSI project, which was successfully launched in February 2002. Prior to that, he was both project manager for, and designer of, the EFI instruments on the CRRES, Polar, and Cluster satellites, and led the flight software development for the FAST IDPU. Other flight software efforts include the ISEE-1 Quasi-DC Electric Field Instrument, the Firewheel spacecraft, and the HIREX long-duration balloon systems. He developed ground support software for ISEE-3 Particles, ISEE-3 X-Ray. Firewheel, and HIREGS instruments, and developed both GSE hardware and software for CRRES 701-14, Polar EFI, Cluster EFW. and the FAST IDPU. Mr. Harvey's time is 100% dedicated to THEMIS.

iii. Other THEMIS key personnel at UCB. The **MSE**, Dr. Ellen R. Taylor, has a Ph. D in Aerospace Engineering from the University of Colorado, Boulder. She currently is the MSE for the NASA CHIPS spacecraft, due to be launched in December 2002. Her experience includes systems engineering of the ISS LTMPF and multiple rocket payloads. She will be responsible for flow-down and verification of mission requirements; defining and documenting technical interfaces; allocating and tracking system resource budgets; and developing system test plans and procedures. Ms Taylor will be 100% time on THEMIS.

The **LME**, Dr. David Pankow, oversees the development of the space probes and probe carrier and reports to the PM at UCB. He has an M.S. and a Doctor of Eng. from UCB. His experience includes lead mechanical engineering for HESSI, FAST instrumentation, Polar EFI, Cluster EFW, Wind 3DP, CRRES Electric Field booms, Firewheel satellite, ISEE and S3-3 Electric Field Instruments. He worked on the Keck Telescope, and leads the efforts in SSL's rocket and balloon programs. He has consulted on spacecraft design to the Air Force Geophysics Lab, Naval Research Lab, Globesat, University of Surrey (UOSAT), Ball Aerospace Systems Division, and Martin Marietta Astro Space Division. He is a member of the Mechanical Engineering faculty at UCB. Dr. Pankow maintains a teaching career at UCB, so will be available 60% to THEMIS.

The **MAM**, Mr. Ron Jackson is responsible for the THEMIS quality assurance program. He has over 20 years of experience in quality assurance and parts procurement. His experience stems from many years of similar work in the industry and at UCB on the EUVE, HESSI and, currently, the ISUAL and STEREO programs.

The **MOM**, Dr. Manfred Bester, is responsible for the design and implementation of the THEMIS Operations functions, described in Section F7. He has a Ph.D. in Experimental Physics from Cologne, Germany, and has worked at UCB for >15 years. He has been responsible for the design and implementation of the HESSI/FAST Mission Operations Center and the Berkeley Ground Station, which also support IMAGE and CHIPS. Dr. Bester's time is 100% dedicated to THEMIS.

Person	Reference
Angelopoulos, PI	Dr. C. F. Kennel, Scripps Institution of Oceanography, 8602 La Jolla Shores Drive, La Jolla, CA 92037-0210, ckennel@ucsd.edu, (619) 453-0167.
Harvey, PM	Frank Snow, GSFC, Code 410.0, Greenbelt MD, 20771, Francis.E.Snow.1@gsfc.nasa.gov, 301, 301 286-7494.
Taylor, MSE	Dave Pierce, Wallops Flight Facility Mailstop 850.0 Wallops Island, VA 23337, David.L.Pierce.1@gsfc.nasa.gov, 757 824-1749.
Pankow, LME	Frank Snow, GSFC, Code 410.0, Greenbelt MD, 20771, Francis.E.Snow.1@gsfc.nasa.gov, 301 286-7494.
Jackson, MAM	Richard D. Claffy, GSFC, 303.0, Greenbelt MD, 20771, Richard.D.Claffy.1@gsfc.nasa.gov, 301 286-7866.

Table G-3 *References for key THEMIS personnel*

iv. Other THEMIS key personnel at Swales. The Swales THEMIS-program manager, Mr. Michael Cully, is the Civil and Commercial Program Director. He has >23 years of industry experience, and has been involved in numerous commercial and NASA satellite programs with his most recent assignment as the program manager for the EO-1 Swales Prime contract and Spacecraft.

The probe and probe carrier lead systems engineer, Mr. Thomas Ajluni, brings >20 years of Aerospace experience from his major systems engineering and launch vehicle interface roles on the COMET, FUSE and MAP programs. The Swales THEMIS I&T manager, Mr. Michael Mc-

Meekin has >20 years experience on many NASA missions, and is currently managing I&T on the GLAST Instrument.

Mr. Daniel Mark, a Swales Deputy Director, leads the Swales independent assessment team. Mr. Mark is responsible for all Mission Architecture at Swales, has played a key role on THEMIS from its inception more than 4 years ago, and managed the FUSE Instrument development and Mission I&T. This team draws from internal senior personnel such as Mr. Jim Barrowman and Mr. Frank Volpe, both of whom have extensive program management and engineering experience on a multitude of NASA and Explorer missions. Mr. Dennis McCarthy, a Swales Director (also the FUSE program manager), is a standing member of UCB's Independent Assessment Team.

G2. MANAGEMENT PROCESSES AND PLANS

UCB manages the THEMIS program based on its exemplary record on HESSI and previous large NASA programs. The THEMIS management process is designed to provide clear lines of authority and accountability as shown in Figure G-1 (THEMIS program), Figure G-2 (THEMIS instrumentation) and Figure G-3 (THEMIS busses and probe carrier). The THEMIS management ensures frequent and accurate communications along the lines of responsibility and across the lead developers at UCB and Swales. The detailed program management process and plans for UCB is described in Section G2.a, below. The detailed Swales program management is described in Section G2.b, also below.

Individual instrument development at UCB is overseen by a responsible senior scientist with >20 years of experience who is in charge of a core instrument team. The team includes at least one less senior but experienced scientist who is aided by associate scientists and draws from the experienced UCB senior electrical and mechanical engineers and technicians. Fabrication and board assembly at peak times takes place through heritage local vendors with whom UCB has many years of experience. Core team scientists are involved in reviewing the instrument design, participateing in calibration and tests, and ensuring, by their own vested-interest in analyzing the data, the highest-quality data return from the instrument. This approach, derived from the FAST and HESSI models, optimizes engineering talent and institute resources, ensures skillful science analysis in Phase E, and levels personnel fluctuations. The instrument manager coordinates activities between UCB and foreign-provided instruments, arranges for and facilitates usage of calibration test equipment, clean rooms and chambers, and aids the PM and the I&T manager in the coordination of individual instrument deliveries into the full instrument-complement I&T.

Foreign instrument providers (TUBS/IWF, CETP) perform sensor calibration, qualification and delivery, and participate in I&T in the US in a similar fashion; with core instrument teams composed of a senior responsible scientist, a less senior but experienced scientist aided by at least one senior instrument engineer. This management structure is evident in Figure G-2 and supported by the CVs of the participating individuals.

a. UCB

a1. Systems Engineering and Integration

The MSE is responsible for coordinating the development of, and then maintaining, the complete set of mission requirements and specifications. Using those requirements, the MSE develops system and subsystem block diagrams, coordinates with the probe systems engineer, instrument engineers, and ground station engineer in creating a coherent high-level design that meets those requirements. This design is defined in a set of internal and external specifications and ICDs between the subsystems, which the MSE then maintains under configuration control.

The MSE is the chief technical resource for the Project Manager and the focus of technical evaluations for the trade studies. The MSE also represents the maintenance of the scientific merits of the baseline design in discussions with the PM regarding cost and/or schedule trades. The MSE coordinates the development of subsystem acceptance test plans, instrument I&T plans, and develops mission I&T plans. By careful planning, test procedures and equipment the MSE ensures a smooth transition from the instrument functional test environment to the mission level.

a2. Requirements Development

The mission concept is built upon the set of requirements stated in the proposal and refined during Phase A. Level 1 mission requirements, developed by the PI in consultation with the science co-Is, are refined into the derived set of requirements (Level 2) with the participation of spaceborne and ground-based instrumenters, orbit analysts, mission operations engineers, system engineers, and subsystem leads. Upon selection the MSE formalizes the mission requirements and reviews them with the team in a Requirements Review. As the project develops, the MSE maintains traceability of the requirements back to the prime science and forward into the system definition an verification.

a3. Configuration Management

THEMIS's plan for configuration management (CM) stems from the successful HESSI practices. Probe and Probe Carrier CM is handled by Swales; all other CM is handled by UCB. Instrument-probe interfaces are held by the MSE at UCB. Probe design changes which effect form, fit or function are subject to review and approval by the MSE.

The THEMIS Performance Assurance Implementation Plan shall include a CM Plan which incorporates instrument, spacecraft and ground segment documentation.

a4. Schedule Management

Stemming from the successful schedule management practices of HESSI, schedules are constructed by subsystem developers in their preferred software and formatted with a small number of agreed-upon links to an integrated master THEMIS schedule. The PM holds all contingencies at the end of each major milestone, and developers provide electronic schedule updates supported by status reports, including any perceived risks to meeting target dates. The combined schedule is updated regularly and made available via the THEMIS web page.

During Phase A, UCB has coordinated the development of a detailed schedule for each instrument and linked them all to the THEMIS master schedule using Microsoft Project. These schedules were used to cost the THEMIS project, calculate manpower loading and identify critical facility usage. The EFI, ESA, SST, FGM, SCM, IDPU, GBO and GDS development schedules are thus shown in Section J, next to (and in support of) the cost estimation. Probe, Probe Carrier and I&T schedules, maintained by Swales, are based on Primavera. Key points of this schedule have been linked to and are being tracked on the master schedule.

Maintaining current schedules is essential for cost projections and for pacing development in a rational and efficient fashion. By communicating this accurate schedule information the designers can maximize usable design and verification time, knowing how much time is available for fabrication and test, etc. The schedule also shows the likely problem areas and allows managers to try workarounds of the schedule through automation.

These experiences from HESSI are particularly important on THEMIS because of the multiple copies of instruments and probe busses being built. As was done in HESSI, the UCB management budget includes a full time scheduler who works on the schedules continuously through one-on-one interactions with lead subsystem engineers and subcontractors. The results of these interactions are discussed weekly with the PM.

a5. Team Coordination and Communication

The THEMIS team uses a combination of in-place conference call facilities for weekly telecons, coordinated email broadcasts for announcements, and an FTP site for large data file exchange. Weekly meetings are held at the instrument and probe level, and focus attention on design details. Monthly meetings have a more comprehensive approach, and have a wider audience. Probe and instrument monthly meetings are attended by the PM, MSE, MAM and other engineering personnel as needed to facilitate the project.

a6. Performance Measurement

Performance management entails the developers' self-assessment and measure of how complete the effort is, and a comparison of the amount completed against the cost at that point. Experience suggests that designers are occasionally optimistic as to how far along the design really is. In response, and in accordance with HESSI practices, THEMIS shall focus on completed tasks rather than partially completed tasks when discussing design efforts. Thus, management activities in the design phase include evaluating the performance of the design against real milestones (e.g., delivery of a final drawing, a working breadboard, or completing a functional test). As on HESSI, UCB shall identify and track major milestones, analyze variances, and shall report on their program-wide effects.

a7. Resource Management

The PM maintains for the PI and makes available to the Mission Manager upon request, detailed cost plots, cost risk and reserve projections. These allow the Mission Manager at GSFC to participate in the planning process.

a8. Mission Ops & Data Analysis Phase

Following the successful launch and early orbit campaign that gets the THEMIS probes into their final orbits, the management structure is simplified, as the majority of the engineering support moves on to other projects, and the scientific support is fully functional. The effort is managed by the Mission Operations Manager who oversees data gathering, and approves configuration changes to the probes, such as instrument mode changes. This follows successful HESSI practices.

Probe and instrument operation is automated and normally requires no ground intervention, except turning on the transmitter. Routine ground operations are limited to dumping data from THEMIS memory, monitoring currents and temperatures, and occasionally sending UCB-generated binary command loads. All of these operations are performed automatically by the current MOC computers and ground antenna. Downlinked data is automatically forwarded to the SOC where quick-look science plots are generated and put on the website and CD-ROMs are produced for shipment to co-investigators.

A few limited-period, orbit-adjust operations for 3 of the probes require engineering support. Each of these orbit adjust times occur, in accordance with the general operations philosophy on THEMIS, with rehearsed and previously uplinked ground commands. They are of short-duration and in contact with the ground (near-real time). Support from Swales for the spacecraft probe bus and flight software during those periods are implemented by a cost-reimbursement support contract.

b. Swales

b1. Program planning

The Swales management process first establishes a clear set of technical requirements, cost limits, and schedule objectives. Phase A activities exemplify this process. During Phase A the preliminary technical requirements (Level 1 and Level 2) from UCB were further deconstructed by Swales' THEMIS systems engineer and subsystem leads to identify driving requirements on the probe bus and PC and to assess them, relative to the AO proposal design, to determine trade study content and optimization opportunities, so as to maximize margins within the cost and schedule objectives.

A comprehensive work plan, organized by a detailed Work Breakdown Structure (WBS) framework emanated from this optimized design. Component specifications and Statements of Work (SOW's) were developed to define the basis for each major procurement and to support our Phase A industry Request for Quotations (RFQ) for these components. The integrated THEMIS program WBS was generated early in Phase A collaboratively with all team members, and included Non-Recurring and Recurring work elements. In conjunction with the WBS a detailed program schedule, using the Primavera scheduling tool, was developed at the ~250 task resolution level, encompassing all major tasks and interdependencies from the start of Phase B through on-orbit checkout. The detailed WBS, coupled with the schedule, provided the top-level work plan for THEMIS at Swales. The Swales process of management and planning, as exemplified by Phase A activities, is shown in Figure G-5.

Hardware and Software acquisition was assessed and multiple vendor sources were confirmed for all major components (via formal RFQ responses). Component technical performance, qualification status, lead times and costs were thus assembled. Refinement of this plan during Phase B includes design updates, further workaround and contingency planning, and refinement of subsystem and component work packages, SOW's, and specifications. Thus, the probe busses, probe carrier and mission I&T detailed program is based on a well established and validated plan ensuring that the work is accomplished within schedule and cost.

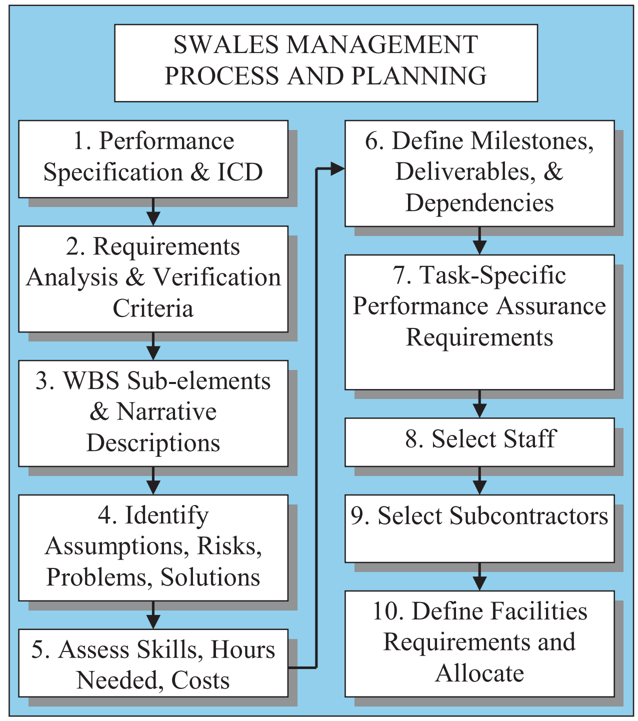


Figure G-5. *Swales' management process and planning.*

b2. Performance measurement system

During the implementation phases of THEMIS, Swales ensures conformance of technical, cost, and schedule performance by careful assessment of accrued hours and cost at each level of the WBS. Experienced cost accounting personnel utilize Swales' Costpoint system, to track expenditures against the work plan, typically at the fourth or fifth level. Swales uses Primavera, Microsoft Project/Excel, and in-house database and analysis tools (including web-enabled database systems) to perform scheduling, resource estimation, and tracking. Each work package is broken down to a manageable level, commensurate in value and duration, with clearly defined deliverables at interim milestones. This plan forms the basis for technical, cost, and schedule performance.

Performance is measured at Swales by the Performance Measurement System (PMS) and by incorporating Earned Value analysis, where appropriate. The PMS enables control of cost and schedule by gaining insight into forecast trends via communication with subsystem lead engineers regarding actual schedule progress, labor utilization/efficiency, and technical progress. Labor charges are reviewed for accuracy, ODC commitments are compared with approved purchase orders, and facility charges are verified with the planned usage. Cost data is gathered routinely by the Swales accounting department using weekly time cards, subcontract vouchers, labor reports, and travel/materials/Other Direct Charges (ODC) input to produce cost summaries for each task. Swales controls cost and schedule by review and approval of expenditures before they occur, by monitoring actual expenses to ensure they are properly allocated, and verifying that positive trends exist.

Each subsystem lead is responsible for maintaining their task plan and associated expenditures. In addition to the formal tracking methods, project engineers alert the program management to potential deviations that may occur to provide "look-ahead" awareness. Project engineers summarize and communicate this information at the monthly Program Status Reviews (PSR's). The Swales' Program Manager interacts continuously with the project engineers and evaluates updated performance information.

Review and approval of expenditures begins with the subsystem lead with any proposed exceedances of established thresholds requiring formal approval by the Swales Program Manager, as this can affect contingency levels. Swales' functional managers, subsystem leads, and the program manager have secure access to cost and labor financial management data (current to prior week). The results of the PMS correlation are reported to the PM. Deviations from the plan are examined, explained, and corrective risk recovery actions are identified and implemented. In addition, Swales senior management independently reviews this data, and the resultant PMS outputs, during the PSR's. The Swales senior management at PSR's includes the Chief Operating Officer, engineering, manufacturing, product assurance, business, and SBU Directors and are conducted by the Swales THEMIS Program Manager, supported by the lead program planner and the appropriate subsystem leads. Status of cross-unit issues, such as critical skill and staffing needs, is discussed with Engineering Group managers to ensure that the THEMIS program visibility occurs at the highest level of management planning and major procurements and subcontractor status discussions ensure proper attention and prioritization within business and logistics support groups.

b3. Configuration management and documentation systems

Configuration Control (CC) is another vital element of Swales' effective management. It entails continuous capture and control of the information associated with the design, fabrication, testing and integration of hardware and software. Swales' internal, on-line, centralized configuration management system (CCMS, ISO 9001 certified) provides a systematic approach for controlling documents, drawings, performance and verification data, and implementation procedures. CCMS was successfully applied on Swales' EO-1, FUSE, HST/WFPC, SWIFT, Triana, SSPP, Spartan, ULDB, ISIS, and SMEX-Lite commercialization programs.

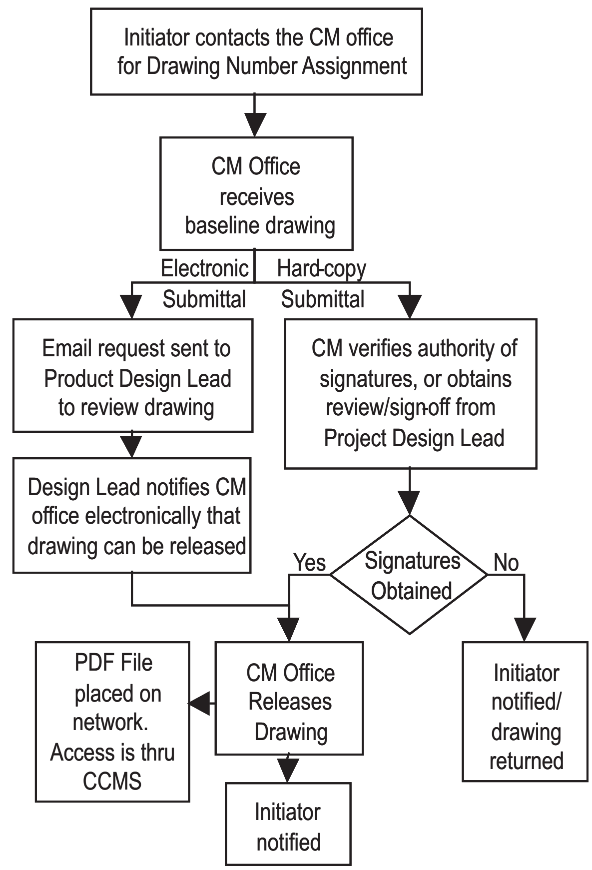


Figure G-6. *Typical document control process at Swales using the centralized configuration management system (CCMS).*

CCMS is an electronic submittal and approval process for drawings/documents (Figure G-6). All system-level Interface and Control Documents (ICDs) require release and change approval from UCB and are placed under CC upon first release. I&T procedures are also under CC with changes captured via redlines, a problem report generated for the needed change and with formal changes incorporated prior to next usage. UCB participates in the mission integration problem report resolution process and has total visibility to any proposed change. The Command and Telemetry (C&T) data base and the I&T EGSE software are maintained in a configured work area on the I&T system, managed by the I&T manager and implemented by the C&T database programmer with change approval by the Swales system engineer, Flight Software lead, and the affected subsystem or systems leads. Daily I&T shift meetings allow for configuration changes in test to be formally and verbally communicated to test personnel. Controlled versions of the C&T database are delivered, at coordinated points, to the MOT at UCB. Intermediate change information is delineated via the UCB involvement in the problem reporting/resolution process.

G3. SCHEDULE

a. THEMIS Master Schedule

The overall schedule to design, build, test and integrate five probes on its carrier by the first MIDEX launch opportunity takes advantage of the excellent working relationships between the THEMIS experienced team partners, the UCB heritage in working with the Explorers Office on two previous missions (FAST and HESSI) and seasoned independent assessment teams. The schedule assumes a Phase B start in March 2003, a 27 month design, development and probe integration phase (up to probe PER), and 13 months for Mission I&T plus launch site operations. Included in this are 6 months of distributed and costed schedule contingency. These have been developed based on subsystem development estimates (bottom-up) and the duration of each task is based upon experience from recent practices. The master schedule is presented in Figure G-7. Detailed subsystem schedules are available next to the basis of estimates in Section J.

b. Instrument schedules

This includes design, development calibration, integration and test of flight instrumentation, up to delivery to Swales for instrument-on-probe I&T and mission I&T. It includes the period of instrument integration and test as an “instrument-complement” with the flight IDPU and flight cables at UCB, using a probe simulator and probe GSEs delivered to UCB from Swales. The THEMIS proposed instrument development and instrument I&T schedule has 3 months of costed contingency up to delivery at Swales for probe I&T, and 3 additional months of contingency in support of instrument I&T and MOC personnel participation up to launch.

b1. FGM

This involves small modifications to the Rosetta electronics (actel) design to adhere for the THEMIS IDPU interface requirements, building 2 Engineering and 6 flight models of the interface card and testing the cards with the sensors in Europe. Since IWF and TUBS have been working on the design modifications using internal funding during Phase A, these designs are expected to complete before the project begins. Thus, the Engineering models should complete about the same time as the 6 sensors are ready for qualification in Europe. Fabrication of the 6 flight interface cards parallels the sensor qualification.

b2. ESA

The schedule includes natural changes to the FAST electrical (actels, microchannel plate arrangement, interfaces) and mechanical (from four-packaged ESAs on FAST to two-packaged ESAs on THEMIS) design to adhere to the THEMIS IDPU and bus interfaces. It includes the addition of an existing-design WIND-type ESA attenuator for improving the solar wind performance of the unit. It entails building and testing five flight, one engineering and one fully tested spare unit. TV chamber upgrades, manipulator upgrades and ordering start shortly after selection, so as to not hold up the development schedule of a mature design.

b3. SST

This schedule includes an engineering model and 6 flight models. The effort includes electrical design work that incorporates the ESTEC chip into a UCB-heritage mechanical design, and building up a functional unit. Assuming a standard flow wherein the flight build waits for these tests to complete before starting flight fabrication, the 6 flight units are assembled and tested in a pipeline with F1 having 8 weeks slack and F5 having 5 weeks slack.

b4. SCM

This schedule involves fabrication of 6 sensors and 6 preamplifiers, plus one engineering model of each. The driver is the preamplifier fabrication, with flight parts procurement of 6 months and assembly/test of 7 months (all units). To facilitate this schedule, UCB directly funds the preamplifier.

b5. EFI

The fabrication schedule of the EFI spin-plane booms (SPB) and axial booms (AXB), in all 35 units including engineering models and spares for each, represents a 3-to-1 compression of the Cluster II schedule. The THEMIS provides for staffing three teams of engineer and technicians to build the units. Particular emphasis is placed in early training of these teams, which we believe to be the key to this schedule performance. Numerical milling machines are highly valuable in turning out machined parts for the units. The sensor wire design has been simplified, eliminating much of the complex fabrication steps that caused us problems in the past.

b6. IDPU

This schedule contains the Digital Fields

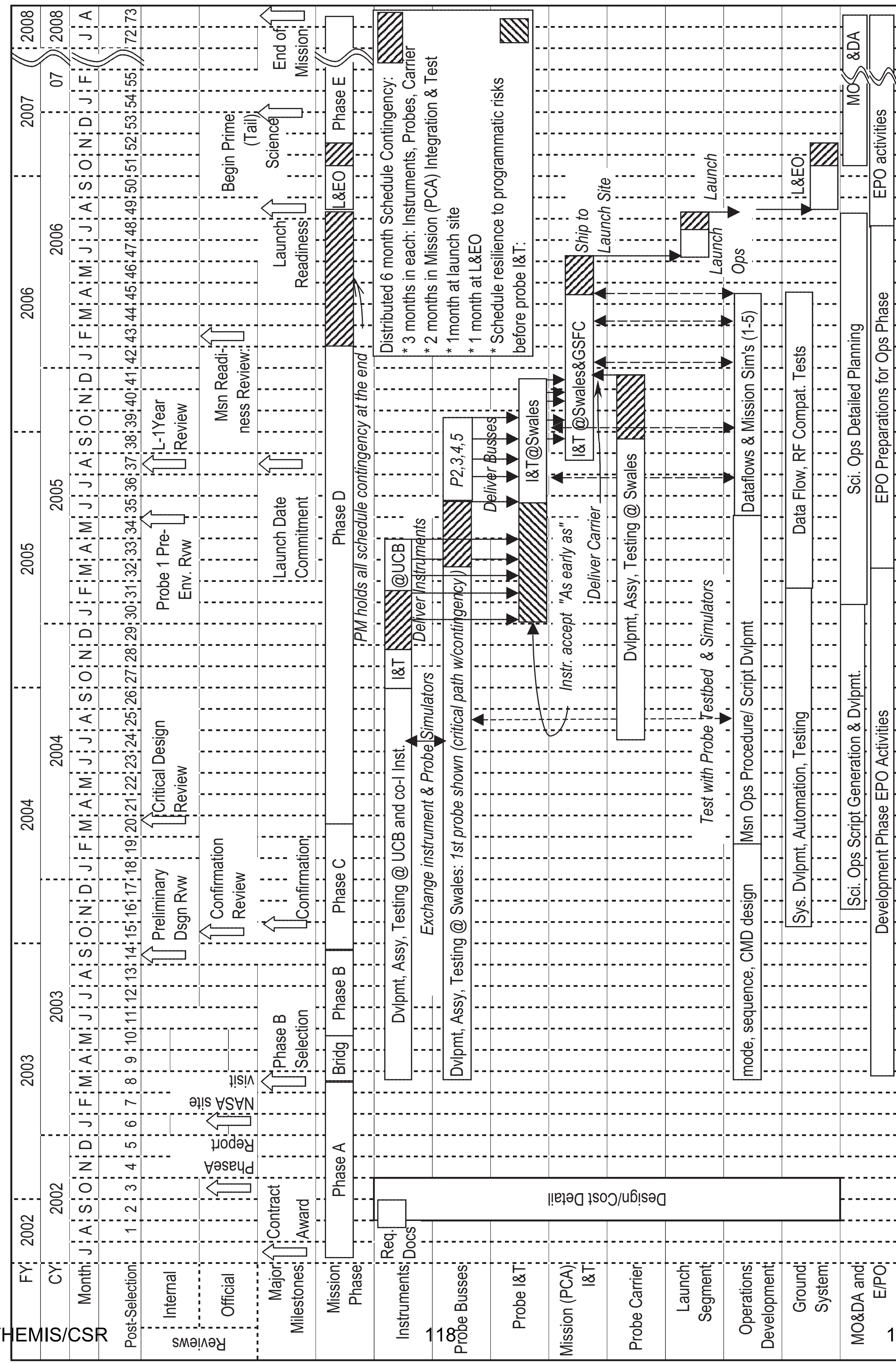


***Figure G-7** THEMIS master schedule*

Board (DFB), the Boom Electronics Board (BEB), the FGM, SST and ESA interface circuit board, a processor and solid state memory card, and DC Power Converter. It includes plans for an Engineering Model and 6 Flight models to be built. The critical path for the IDPU is the DFB board. As a high performance, precision analog board, the DFB is our single most difficult design; however it represents a simplification relative to the FAST DFB design and is not expected to pose schedule or cost risks. The THEMIS team member responsible for the design and testing of this board is designer of the FAST Fields board who is now at CU/LASP. As on FAST, fabrication, and testing of the DFB with the EFI, SCM and IDPU takes place at UCB.

b7. MAG Booms

The FGM and SCM boom schedules have been generated assuming a single mechanical engineer for design, assembly and test, a very generous machining period of 13 weeks, long lead composite parts procurement of 26 weeks and a single set of qualification equipment. Even with these restrictions, the schedule has 26 weeks of slack for F1 and 8 weeks of slack for F5.

b8. Instrument Complement I&T

Integrating each of the five instrument complements together, and then carefully and comprehensively testing them with the spacecraft simulator at UCB has been given significant time in the schedule. This schedule was presented in Section F6.b and is repeated for completeness next to the basis of estimate in Section J. Considerable attention is placed on detailed, advance planning and appropriate facilities and equipment. The HESSI and CHIPS integration clean room at UCB is used. In accordance with the general THEMIS philosophy of I&T, integration of the first instrument complement is lengthier and is used to build experience with the unit; integration of subsequent pairs of instruments proceeds in pairs. UCB plans separate thermal vacuum facilities for instrument-level testing and for instrument complement testing. This is so that the flows of upcoming sensors into the instrument-complement test flow are not impacted by the instrument-level tests.

c. Ground Data System schedule

The ground system schedule involves setting up another Mission Operations system in parallel to HESSI's and FAST's and extending the existing Science Operations system for THEMIS. This is similar to what UCB performed in the HESSI program. New technology items for UCB are formally validating and placing under configuration control the CelNav software products obtained from GSFC and fully developing the new technology ranging technique software. Neither task represents a challenge for the team.

c1. Ground Based Observatories

The ground based observatories are an essential element of the THEMIS project and, as such, warrants considerable attention from the dedicated Ground Based Observatory Manager in order to make sure we have a working network of highly reliable ground stations ready for the first winter season in 2007. The current plan involves operating as many as 5 units in the field in winter of 2005 and the entire network of 20 in the winter of 2006. This allows a small fabrication and test staff to meet the assembly and test needs of this quantity, while gaining valuable information about how to use the systems, what the environmental conditions will be, as well as provides scientific background data.

d. Probe busses, probe carrier and mission I&T

This schedule includes the Swales main activities: production and qualification of the probe busses, the production and qualification of the probe carrier, the probe I&T (with the instrument complement), the mission I&T and the launch site activities. An experienced Swales production planner works closely with the Swales PM and subsystem leads, to update the detailed schedule status on a weekly basis. The Swales planner also works closely with the THEMIS mission scheduler at UCB to ensure interactions with the instrument delivery and program schedules and, if necessary, develop joint schedule mitigation plans. Schedule variances are reported to UCB during weekly telephone conferences, allowing for frequent communication of schedule status. They are also formally reported on a monthly basis. In a similar fashion, major subcontractors are required to report schedule variances, at a minimum, on a monthly basis with weekly conference calls to communicate interim progress.

The schedule durations derived during Phase A have been based on similar tasks performed by Swales on other programs and integrate subcontractor and vendor-quoted lead times. Swales assumes a standard 5 day workweek and no work on government holidays, except during major test events such as thermal vacuum and thermal cycling which, by nature, are planned as around-the-clock operations (24 hrs, 7 days/week). Discrete contingency blocks have been distributed prior to key deliverable points such as the deliveries of the first probe and the PC to I&T (60 workdays each), subsequent probe deliveries to mission I&T (20 workdays each), post-environment test (before PCA delivery to launch site: 20 workdays), and pre-launch contingency (20 workdays). The total schedule contingency equates to 6 months for an August 2006 launch. Table G-4 provides a summary of the total activity and contingency time for each major item starting after completion of the engineering test unit (ETU) and the mission CDR.

The critical path item is probe 1 (first unit) driven by the lead-time on the reaction control system (RCS), i.e., the propulsion system. In addition to the discrete contingency time blocks allocated, we have identified an extra float time available in the schedule of 32 days (which is equivalent to >6 weeks added contingency) assuming a Phase B start in March 2003. There is comfortable lag between the completion of Probe 1 bus integration and the start of Probes 2 through 5 bus integration. This lag time is used to update procedures and work-flow and to apply lessons learned from the Probe 1 integration. The Probe Carrier is not on the critical path and has adequate contingency prior to mission integration. The schedule has been rigorously reviewed by the system and subsystem leads to ensure fidelity, logical sequence, and interdependencies of key items. Swales experience managing the EO-1, FUSE, and MAP launch site activities with the Delta II launch vehicle was used as the basis for the launch site schedule.

Phase C/D activity (after CDR & ETU's complete)	Base Time (work weeks)	Contingency (work weeks)	% Contingency	Comment
Probe Bus 1Build & Delivery	71	12	17%	First Bus (qual)
Probe Bus 2-5 Build & Delivery	30	8	26%	Subsequent Bus
Probe 1 I&T of Instruments	15	4	26%	First Instr. Suite
Probe 2-5 I&T of Instruments	8	4	50%	For Each Probe
Probe Carrier Build & Deliver	57	12	21%	Parallel w/Probes
Mission I&T	12	4	33%	PCA configuration
Launch Site Operations	10	4	40%	

Table G-4: *Individual schedule contingencies for probe bus, probe I&T, PC, & mission I&T paths.*

G4. RISK MANAGEMENT

The PM coordinates with the MSE and critical system developers to assess and maintain schedule and cost, schedule and cost reserves and technical risks and participate with the Explorers office to assess programmatic risks. Development risks and their possible resolution are discussed in informal reviews at the subsystem level.

The risk management process began in Phase A with the establishment of proper reserves and margins for technical, schedule, and cost parameters as is evident throughout this CSR. Proper science and mission acceptance criteria provided the basis for minimum and nominal acceptable lifetime, performance and operations thus defining the fault tolerance space.

As exemplified in Section F9.m, THEMIS is a fault tolerant mission and has descope options, outlined in Section F9.l, that make it resilient to unforeseen cost and schedule reserve reductions. THEMIS's design strategy is that single-point failure can result only from failure of one high-heritage item, namely the D2925-10. Since Delta II has had a 98% success rate from its inception in 1989 and 100% success rate during the last 4 years, THEMIS is by design a low risk mission.

The fault tolerance analysis produced an assessment of flight robustness and also, in most cases, defined items that could be descoped, at changing risk levels, during the implementation phase. We also identified spare units and rework plans (typically at vendor site) for components. A variety of "what if" scenarios were discussed relative to the production build of the 5 probes and alternative paths were identified depending on the nature of a circumstance (delivery, anomaly, facility conflict, etc). We funded critical items that need to be in place to support these alternate branching paths such as the EGSE #3 suite of equipment and associated mechanical fixtures at Swales to support a third probe bus and probe I&T production line. THEMIS has also ensured that its base cost funds labor through discrete periods of reserve, thereby ensuring that no "liens" exist regarding the program cost margin (i.e., cost margins and schedule reserves are totally decoupled).

a. Risk assessment and mitigation process

Based on HESSI successful practices this process entails identifying and characterizing risks, determining their likelihood, estimating their scientific, cost, and schedule impacts, and developing *early* mitigation plans and schedules in parallel to the nominal built program. At all times the combination of likelihood-of-non-delivery, cost and schedule impact forms a lien held by the PM and charged against the contingency budget and/or schedule contingency for the project. As the project develops and risks are identified, the PM tracks the total cost of the liens against the contingency budget and their likely effect on the total schedule. If the liens exceed the contingency, the PI and PM, in consultation with the Science Team and the Explorers project, commence application of descopes.

A key activity of the PM is to remove or retire risks, particularly those defined as medium and high level; i.e., those having probabilities of failure above the 10% level. Working with the instrument and mission teams, the PM is responsible for scheduling decision milestones for each risk and implementing the course of action selected at those milestones. Risk mitigation trades made in a timely fashion prevent major descoping efforts.

The Swales internal risk assessment and mitigation process begins with a survey of the program requirements developed by UCB and the design and implementation plans. Risk assessments are captured and prioritized on Risk Worksheets. The result of the process is a risk watchlist which is discussed continuously within the THEMIS PM, with management at program status reviews (PSRs), and with review teams prior to major program milestones. When the "trigger" decision points of a given risk item are reached, program management decides whether to formally implement the associated mitigation plan. The Swales Program Manager leads the Swales risk management process by development of appropriate orientation and training of the core team members.

b. Technical Risk

To lower the technical risk of the THEMIS project, THEMIS has selected heritage instrumentation with very experienced teams. The single instrument-bus-interface approach has been very successful on FAST and HESSI at simplifying the spacecraft interfaces and lowering the probabilities for technical problems after delivery. Combined with a vigorous instrument test program this approach has resulted in a FAST fully functional instrument complement lifetime of 7 years in orbit (still in operation) though it was designed for a 2 year lifetime. Similar practices of thorough purview and control of the entire mission design and development, which is afforded to the experienced UCB team by the PI-mission-mode, have resulted in the flawless on-orbit operation on HESSI, even after a vibration facility anomaly resulted in refabrication of a considerable part of the spacecraft structure. The THEMIS instrument weight and power estimates have been carefully scrutinized and include recommended margins depending upon subsystem heritage and maturity. All THEMIS electronics are designed to meet the derating guidelines of PPL 21 Appendix B, thus providing a level of performance margin.

	Technical Concern	Phase A resolution
Major	I&T flow specificity.	Instrument pre-I&T flow: see F5.f, F6.b, bus and msn I&T: see F6.c levels described in environmental test matrix in Section F6.a
	System design of probe bus missing	Described in detail in Section F3
	Probe power margin 6.6% is low	Power margin is now 42%, higher EOL power (Table F-4).
Minor	Launch margin low at 10%	Launch margin now 40%; more capable L/V
	Little discussion of PCA.	See Section F3; PCA simplified extensively.
	Effects from simultaneous release?	Nominal release is top probe first + remaining 4 probes, 4s later. Ample clearances in all worst cases. Details in Section F3.
	Separation ΔV, tip-off rates?	All addressed in Section F3. Worst case release clearances still ample.
	Battery peak DOD would be 40%	Peak DOD (50%) includes reserve pwr and conservatively adl. heater pwr. Presents no issue for limited # of cycles for LiIon battery, as verified by life-test data (see F3).
	Propellant rqnts will increase	De-orbit and tuning maneuvers accounted for with slightly larger tank. Bigger tank accommodates them. The lowest probe fuel margin is 43%.
	Flight software maturity	Discussed in Section F3.
	Redundancy	N+1 redundancy in memory blocks, selective ACS (gyros/mag) redundancy, see F9.
	I&T feed-forward/backward	Addressed in Section G4.d
	Can any replace any other?	Any of P3, P4 can replace P1, P2, P5 (Section F2).

Table G-5. *Major and minor technical risks identified in the step-1 proposal, and their retirement.*

Technical risks are identified by developers, the MSE, MAM or review teams. Technical risk items and possible resolutions are presented to the PM. The PM is responsible for maintaining a risk list and the potential effects across the entire program, including financial, schedule, cost and, with the help of the PI and the science team, science impact.

This process on THEMIS is exemplified by the retirement of technical risk in Phase A. For example, risk assessment by the Swales team revealed key risk-generating items associated with the probe carrier electronics and solid booster. Upon presentation to the PM and after thorough consideration of orbit and science effects by the PI and the science team, it was recognized that a replacement of the above these items by the lower-risk, more capable launch vehicle would benefit THEMIS at a small incremental cost increase to the program.

Another technical item identified by the Swales developing team was the importance of maximizing clearance of the probes upon release from the probe carrier to ensure mission success even under failure mode conditions. Modification of the mechanical packaging was proposed by the Swales team. After the concurrence by the UCB LME, the Swales team performed detailed deployment analysis under numerous nominal and hypothetical off-nominal operational conditions with conservative assumptions on the new mechanical packaging. The analyses resulted in ample positive dispense under all conditions with ample clearance margins (Section F3). The proposed risk mitigation was discussed on the phone and through email data exchange between the THEMIS LME, Swales SE, and the PC and probe mechanical and dynamics engineers. The PM and the PI were involved once full information exchange had occurred amongst the technical experts and were briefed about the pros and cons of the approach. The decision to go ahead with the design modification to improve clearances was then approved by the PI after the positive recommendation by the PM.

In a similar fashion the THEMIS team has addressed and retired all the technical risks (and provided clarifications to items) raised by the step-1 proposal reviewers as outlined in Table G-5. In addition, a number of trade studies have revealed minor risk items that were also addressed and were summarized in Table F-6.

c. Cost Risk

To lower the cost risks to THEMIS, we have selected an experienced aerospace partner, Swales Aerospace, with a strong business outlook and history of stable labor and overhead rates. We have arranged to use existing MOC software, SOC software, and GSFC-provided maneuver software. In addition to a very detailed costing effort in Phase A, we have included a development reserve for Phase B/C/D consistent with the level of maturity of the effort (see cost volume). While THEMIS has confidence in the instrument and spacecraft bus teams to keep to their budgets, THEMIS has sufficient reserves to address unforeseen problems, to take advantage of logistical opportunities and workarounds to maintain schedule, and is managed by an experienced UCB team with a record of making timely decisions to change the organization chart when necessary.

d. Schedule Risk

The THEMIS team believes that managing schedule risk is the most important element to the success of the program. Schedule risk can arise from mis-happenings during the I&T process, unforeseen component failures, supplier timeliness, in-process disruptions of work flow, changes in staffing/attrition or logistic inefficiencies. The adequacy of the original program time-reserve versus the adequacy of the original schedule estimates is evaluated and re-allocated as events trigger an out-of-tolerance condition. Since schedule delays can be costly to the team and threaten launch delays and because of the multiple-probes being integrated, THEMIS component failures on one probe during I&T can have significant repercussions, especially when feeding backward or forward in the I&T schedule.

In recognition of the above risk, and in accordance with the step-1 reviewer recommendations THEMIS places significant emphasis on this issue.

First, instrument or bus subsystem generic malfunctions are undesirable, and steps are taken to ensure that design flaws are eliminated (Table G4-4).

Heritage instruments are easily manufacturable and testable
Heritage, COTS subsystems from highly qualified vendors
Instrument complement I&T with the flight IDPU and cables and a Swales-provided bus simulator at UCB, prior to probe integration and test at Swales.
Bus I&T at Swales prior to probe integration and test, with IDPU/instrument simulator from UCB.

Table G-6. *First line of THEMIS defense against schedule risk: heritage components and pre-I&T eliminate design flaws.*

Second, a six month schedule contingency has been built into Phases C/D (see details in Section G3 and Figure G-7), with an additional six weeks of float on the critical path and a 6 month instrument delivery float that can mitigate programmatic slips.

Third, additional schedule risk reduction comes from early procurement of long lead items (Section G4.d1, below).

Fourth, a robust sparing policy (see Section G4.d1, below), allows for direct replacement of a malfuctioned unit or critical item in the event of a non-generic malfunction or accident.

Fifth, during I&T at Swales the strategies outlined in Table G-7 permit robust recovery from problems of several varieties. Swales history of implementing schedule mitigations was demonstrated on the FUSE and EO-1 programs. In addition, Swales can draw from a large and talented engineering services pool as required to address peak work periods, thereby further reducing schedule risk.

Sixth, if more than one instrument of one type fails, THEMIS has a fall-back position, since all instruments are not necessary to fulfill the minimum or the baseline mission, as discussed in Section F9. In the event of a malfunction of a non-critical instrument (i.e. one not necessary on all 5 probes for the baseline mission) on a second probe for which a spare is not available and replacement/re-fabrication stresses resources, that probe will be assigned to an orbit where that particular instrument is not crucial for achieving the overall mission objectives. A decision will be made, in this case, whether to fly the problematic instrument or its mass model based on the problem diagnosis.

Finally, the probe bus design is modular (one or two solar panels are easily removable) and the mating of all of the non-descopable instruments is easily accomplished. This allows for limited refurbishment locally, i.e., at Swales' clean facilities, without invalidating the previously completed structural tests. This option, though available, is unlikely to be reached since critical instruments have more than one spare (G4.d2).

Probe and PC I&T items for mitigating schedule risk
Single shift (8-5) operations baselined for I&T, allowing for addition of shifts during implementation if necessary.
Sufficient time between Probe 1 and subsequent Probe builds allows for the insertion of lessons learned reducing cycle times
Baseline serial flow of thermal vacuum testing for Probes 2 thru 5. This allows for the potential of parallel processing as a workaround to mitigate problems.
An extra EGSE (#3) as a backup to the two primary EGSE production lines; also usable as a workaround solution and as a re-test station to ensure continuous production line flow.

Table G-7. *The fifth line of THEMIS defense against schedule risk: an I&T process with built-it workaround potential for unforeseen emergencies.*

UCB has a long history of instrument and IDPU system on-time delivery and in-flight performance (e.g., FAST, WIND, HESSI). The Swales THEMIS team consists of individual developers with >20 years of experience in subsystem design, bus and mission I&T (e.g., FUSE, EO-1). Therefore, the first and second lines of THEMIS defense, namely design flaw elimination and a generous schedule contingency, are sufficient to mitigate the threat of schedule slips during I&T.

d1. Long lead items

Critical paths in the THEMIS instrument schedule are outlined in Table G-8. THEMIS places orders for these well-known lead items immediately upon selection. In particular DFB actels are bought outside of the THEMIS common parts-buy program. Regarding NTIA, THEMIS probes all use the same frequency which limits the licensing requirements with NTIA. Based on HESSI, it is possible that the NTIA licensing process can be slow but our scheduling of the license application beginning early in phase A mitigates this risk.

Analysis of the probe bus and probe carrier schedules and Swales interaction with subcontractors and vendors during Phase A has identified the key long lead items which require the placement of procurements prior to Phase B completion. These are also listed in Table G-8. The THEMIS probe, probe carrier and mission I&T schedule fully support these item procurement strategies in its integrated master schedule.

	Item	Remedy
Instruments	ESA Actels/MCPs	Orders placed prior to end of Phase B.
	SST detectors	
	IDPU DFB Actels	
	SCM pre-amps	
NTIA	S-band NTIA licence	Use same frequency
Probe bus	probe #1 propulsion tank	Orders completed with authorization to proceed prior to Phase B completion.
	probe #1 transponder	
	EEE parts for ETU of BAU	

Table G-8. *THEMIS long lead items*

d2. Spares

Development of multiple, identical probes necessitates a careful selection of spares of items that (i) are characterized by long development times, (ii) are developed away from the I&T site, or (ii) are sensitive during I&T. Such are the instruments, the IDPU and selected bus subsystems. Instrument spares of FGM, SCM, ESA and SST will be built and qualified. Two FGM spares and two separate SST heads (composing the "F6" complement) are planned, in accordance with a "two spares of critical instruments" philosophy. At least one spare of non-critical instruments is also planned. An EFI boom pair and an EFI stacer pair constitute the EFI instrument spares. Spares for the IDPU consist of individual flight boards. For the probe bus, spare parts are typically retained at the manufacturers location, with spare units delivered and ready to be used. Probe bus spares include battery, spare solar panel (side), RF cable, spare processor board, propulsion tank, and spare top/bottom solar panel. Bus spares are functionally tested and may be environmentally qualified as a risk-reduction step. Instrument spares and bus subsystem spares have been budgeted in the THEMIS base costs. The End Items List (in Section F6.a) shows the expected number of completed engineering models (EM), flight-ready components (FLT) and spares (SPR).

e. Programmatic Risk

From recent experience, schedule and cost risk exists where NASA may be unable to provide a launch commitment due to unforeseen launch vehicle failures. This can translate into a substantial cost risk if it occurs when the entire program is near launch and manpower load is high.

THEMIS does not have a science quality impact for this type of scenario, since launch can occur any day of the year. Since launch penalties would not apply in this case, program cost risk can be mitigated by a hurry-up-and-wait approach, whereby the probes can be integrated, delivered for storage, and a good fraction of the THEMIS technical personnel can move-on to other projects, especially at Swales where a significant volume of engineering service contracting work provides a flexible stop-gap measure for team members.

Programmatic risks associated with international involvement were outlined by the step-1 reviewers. During Phase A THEMIS addressed the recommendations of the review team regarding foreign government approvals of foreign instrumentation. The THEMIS baseline approach is now to directly procure the industry parts necessary for foreign participation from IWF and CETP and has secured institute commitments to participate in THEMIS from their own internal funding. The ESTEC chips will be procured before Phase B start. TUBS has already obtained government approval to proceed with their planned participation on THEMIS. Thus all foreign instrument team participation commitments are completed. Additionally, the Canadian Space Agency has provided THEMIS with a strong support letter for the Canadian participation on the THEMIS ground based observatory plans.

Swales is avoiding single-source suppliers for key components and has identified at least 2 vendors with high heritage bases for each key component (and more than 2 in many cases). The Swales baseline cost uses only domestic suppliers and the highest price quotes.

g. Supportability Risk

Supportability risk is attributable to items such as operability, data flow, operational support and overall system reliability. THEMIS has low supportability risk due to the experience of the mission operations team, the robust operational concept and the simplicity of the resultant THEMIS probe bus system design. System reliability has been fully addressed in section F9. It clearly shows that the THEMIS constellation design is extremely robust. With regards to operability, the THEMIS program employs the ITOS system for subsystem test, instrument/probe test, mission I&T, and operations. Personnel from the MOC team support I&T activities, providing early training of the operations team and reducing the overall risk to the program.

G5. GFE

The following items have been identified and budgeted in our baseline life cycle cost: Kennedy Space Center launch facilities; GSFC Spectrum Management for NTIA licensing using government frequencies; GSFC compatibility test van usage for determining probe-to-ground RF compatibility through the NASA ground network; GSFC Flight Dynamics Facility for early orbit tracking of the probes; DSN support during launch and early orbit and maneuvers on a contingency basis; and TDRSS facilities for L&EO support.

Swales' baseline plan uses the GSFC test facilities for probe, PC and PCA testing using a commercial cost reimbursable contract with the GSFC facility contractor (ManTech). Swales has used this approach on previous programs and has received cost estimates from the facility contractor. These costs have been accounted for in Swales' Cost Proposal and, therefore, Swales does not require any Government Furnished Property or Facilities.

THEMIS Reviews	Level
Systems Requirements Review (SRR)	Semiformal
-Concept Review	
Preliminary Design Peer Reviews	Informal
- Instrument	
- Probe Bus Subsystems	
Mission Preliminary Design Review (PDR)	Formal
Subsystem Critical Design Reviews	Informal
- Instruments	
- Probe Bus Subsystems	
Mission Critical Design Review (CDR)	Formal
Pre-Integration Readiness Reviews	Informal
- Instruments	
- Probe 1	
Pre Environmental Review (PER)	Formal
- Instruments	
- Probe 1	
Mission Pre-Environmental Review (PER)	Formal
- Probe Carrier Assembly	
Pre-ship Review (PSR)	
Operations Readiness Review (ORR)	
Flight Operations Readiness Review (FOR)	

Table G-9. *THEMIS reviews*

G6. REVIEWS

THEMIS uses a combination of subsystem and system reviews to evaluate the design to ensure that a robust, fully detailed and testable mission meets the mission requirements. Formal and informal THEMIS reviews are outlined in Table G-9. The GSFC Systems Review Office (SRO) chairs the formal reviews. Additionally internal reviews with the participation of the THEMIS independent assessment team (IAT) and peer reviews occur prior to formal mission reviews.

Swales supports all major mission reviews at the direction of the UCB PM. Swales conducts Internal Preliminary and Critical Design (IPDR/ICDR) reviews for both the probe bus and probe carrier. Additionally, informal subsystem peer reviews are held prior to PDR and CDR. Swales' review process is detailed in Section F9.

G7. REPORTING

The PM assembles and documents composite cost and performance data and provides those to the PI and the Mission Manager on a monthly basis. This communication is in the form of a THEMIS monthly status report. As was done in HESSI, team members and subcontractors provide inputs to this monthly report as a way of providing a comprehensive document on the state of the project. The monthly status report also contains mission assurance activities, mass and power charts, problems encountered and actions taken.

THEMIS reporting also includes quarterly presentations to the Goddard Program Management Council, and a weekly summary to NASA OSS. Questions regarding the cost reports are addressed at weekly telecons between GSFC and UCB.

Cost reports are prepared by UCB in 533 format as required, and these include subcontractor actuals. Subcontractors who have 533 reporting requirements shall have their cost reports forwarded through UCB to NASA.

Swales' internal reporting process also supports monthly financial reports to UCB in 533 forms, detailing expenditures for labor, material, other direct charges, etc. on both monthly and cumulative basis. These monthly reports to UCB also summarize technical issues, cost and schedule variances, personnel changes, problem report status, quality assurance status, risk tracking status, and quality audit reports (as applicable with impacts and corrective actions status). Updated schedules and a discussion of upcoming plans are also provided with weekly status meetings held via telephone with the UCB PM in order to provide interim communications between formal reports. This is an extension of the exact process utilized between Swales and UCB during Phase A.

G8. SOFTWARE IV&V

Independent verification and validation is an integral part of THEMIS' flight and ground system software build process. The process applies to the THEMIS Mission Operations Center at UC, Instrument, IDPU and associated GSE software builds at UCB and the probe bus and associated GSE software builds by Hammers Co., the responsible Swales subcontractor.

During Phase A, the software products required for flight and critical ground operations were identified and their risks evaluated as Marginal (<30 rating, see Figure G-8). The NASA IV&V center was furnished with the self-assessment survey of mission software. The IV&V cost estimates for review participation are included in the THEMIS budget.

THEMIS has also scheduled and costed both at UCB and at Swales interaction with and support of project-defined IV&V activities. Instrument and MOC code walkthroughs at UCB occur as part of peer reviews during instrument reviews. Probe bus code walkthroughs at Swales occur as part of a module level peer review, many times executing real-time on our testbed with a line-by-line debugger display stepping through each major functional section of the module code. These THEMIS practices allow for visibility of the peer reviewers while having the appropriate testbed simulation environment and external data responses occurring at proper branching points in the code to ensure that the IV&V team gains proper insight.

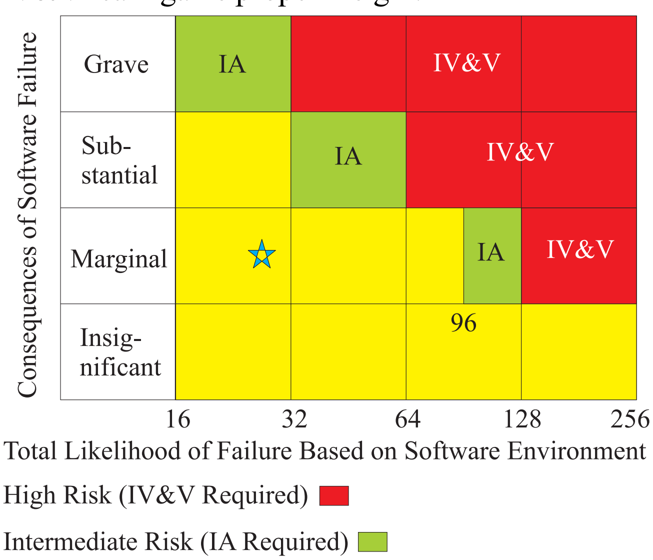


Figure G-8. *IV&V self-assessment results.*

In summary, THEMIS plans to integrate the NASA IV&V staff into existing review processes with full visibility into code development and testing. Coupled with our significant flight heritage, this practice allows for the IV&V tasks to occur in a very straightforward manner. Although we do not anticipate significant additional action items, there does remain some uncertainty with the additional work as a result of those reviews, due to the lack of extensive history with this process.

H. EPO, NEW TECHNOLOGY & SDB PLAN

H1. EDUCATION AND PUBLIC OUTREACH

a. Abstract

The THEMIS mission will determine the onset time and location of magnetic substorms in Earth's space environment, a prerequisite to understanding space weather. THEMIS will also determine how substorms power the aurora. The THEMIS team, recognizing our country's need for improved mathematics, science, and technology education (TIMSS 2000 www.timss.org), proposes a nationwide partnership with science centers, K-12 educators, professional science organizations, and mission scientists to implement a comprehensive education and public outreach program. The THEMIS EPO plan benefits from UCB's successful EPO models on HESSI, STEREO/IMPACT, and CHIPS. This plan embodies proven EPO practices of diversification and efficient strategies in reaching underserved populations, in direct confluence with the guidelines of NASA OSS "*Partners in Education* and *Implementation Strategy*". The project devotes 1.5-2% of its budget (excluding launch) to EPO and EPO-related activities over 5 years. This support allows a mature EPO team to engage remote and diverse educational and general public communities, target and engage underserved populations, and develop products and programs to be disseminated through existing national education networks, professional development workshops and Space Grant Consortia already in place.

b. The THEMIS EPO team and national partnerships

The THEMIS EPO team builds upon an existing UCB network of national partners. The THEMIS teaming arrangements are tabulated in Table H-1. The Center for Science Education @ Space Sciences Laboratory (CSE@SSL) shall lead the THEMIS EPO effort. The program builds on the infrastructure of several national leaders in education and public outreach in coordination with Lawrence Hall of Science (LHS) with collaboration of Carson City School District, NV and Space Grant Consortia of AK, MT, MI, ND, OR, PA, SD, WI. All SGC states are coordinated by MT Space Grant Consortium (see EPO letters of support in Appendix M). IMAGE EPO director Dr. Sten Odenwald joins the partnership with his well-established MagNet program based on Walter Payton School in Chicago, Ill. Table H-1 summarizes our proposed partnership. Our EPO philosophy is: avoid duplication of effort and tap existing dissemination networks; coordinate with key players within NASA Space Science, NASA Education, and with institutions outside of NASA interested in our resources; involve mission scientists throughout the EPO activities spanning all phases of the mission; reach out to underserved communities; and evaluate for impact on the intended audiences.

Partner	Role, Products and Programs
SEGway@SSL	Leadership and coordination. Formal Education. Development of SEGway web-module. Use of SECEF resources for use in K-4 (auroras) and 6-12.
Astronomy Café-GEONS	Development of GEONS resources and teacher training. Formal Education
OSS Support Network	Coordination. Dissemination through National Conferences and other existing networks.
IMAGE and FAST EPOs	Coordination. Dissemination. Formal Education. Identification of Professional Development Workshops for educators. Using existing resources
LHS -UCB	GEMS Distr. & Training Center PD Program. Formal Education
LHS -UCB	*Northern Lights Planetarium* traveling exhibit . Updated with THEMIS discoveries. Informal Education
SACNAS and other PD workshops	Teacher workshops with Native American Tribes. Formal Education
Space Grant Consortia (8 States) Coordinator: MT	Selection of School Sites- Dissemination Workshops. Formal Education
Carson City Sch. Dist –NV and Walter Payton School in Ill.	Committed schools, teachers and school district administration for the Magnetometer sites for NV and Il. Formal Education
Cornerstone Evaluation	Formative and Summative Evaluation.

***Table H-1** EPO partners in THEMIS*

c. Formal (K-12) education activities

c1. Geomagnetic Event Observation Network by Students (GEONS)

The nature of the THEMIS mission, and in particular the correlations of ground observatory measurements with storm activity measured from THEMIS probes, holds tremendous potential for inquiry-based instruction of pre-college students and teachers. In recognition of this, the THEMIS EPO proposal calls for establishing ten ground-based magnetometer stations each located in the proximity of a rural school in traditionally under-served, under-represented communities. This unique component of the project provides stu-dents and teachers project-based activities that support inquiry and promote access to real scientific data. This is one of the key targets of the National Science Education Standards (NSES) that is not routinely supported by traditional science curricular materials. The National Research Council called for theme-based instruction that is engaging students in projects that foster scientific inquiry and model the practices of science research. THEMIS utilizes *precisely* this approach to introduce to K-12 students themes of fundamental importance (space weather and effects habitability of near-Earth environment; satellite communications; electrical power distribution).

Dr. Sten Odenwald shall develop with the advice of the THEMIS PI, EPO lead and THEMIS scientists and existing technical magnetometer user manuals: (1) a ground magnetometer user manual appropriate for a school setting, (2) classroom guides and (3) learning materials on how to utilize the magnetometer data to enhance classroom instruction in space science concepts. The classroom guides include topics such as: Forces and Motion, Magnetic Induction, The Geomagnetic Field, Solar Storms and Space Weather and data analysis as appropriate. The guides also include student activities suitable for middle and high school students. Dr. Odenwald coordinates the GEONS program with the MagNet Program, a network of student-built magnetometer stations developed as part of the IMAGE EPO at Walter Payton College Preparatory School in Chicago. He conducts the first magnetometer workshop with participants from both networks. The workshops include venues at the National Science Teachers Association regional and national conventions. After magnetometers have been operating for a year he conducts a teacher workshop for the purpose of comparing classroom experiences and revising the classroom resources as needed. The results of this research are then formally presented in articles to The Science Teacher or similar professional educator's journals.

c2. Site Selection and Space Grant partners

In an effort to best utilize existing infrastructure and reach out to a larger sector of the K-12 community and the public, the THEMIS EPO partners with the following (8) Space Grant Consortia coordinated by Montana State; Alaska, Idaho, Montana, North Dakota, South Dakota, Oregon, Pennsylvania and Wisconsin for selecting the schools that will become the host-sites of the ground magnetometers. For this purpose, this consortium of Space Grant partners conducts a statewide competition in each state. The selection criteria are (i) commitment of the school/teacher and availability of local infrastructure, (ii) demostrable advancements to the education process at the particular school with particular consideration towards reaching underserved students (iii) the potential for reaching a large community of students and teachers and (iv) the site's potential for science discoveries, based on its geographic location within the state, that may result in stronger interactions with the THEMIS research team. The selection takes place in Fall '03 or Winter '04 in order to be coordinated with magnetometer installation schedule of the mission. The Space Grant Consortium has strong ties with underserved, under-represented communities at rural areas. Tribal Colleges, which maintain a strong local community presence, are affiliates of their state Space Grant program and would also be excellent target sites for a THEMIS EPO data collection stations. These networks serve as effective venues for teacher professional development workshops focusing on data-centered classroom activities.

c3. Module development by SEGway

SEGway is a mature program at the CSE@SSL, with more than seven years' experience and an established national consortium of science museum partners. SEGway has established a robust process for producing effective, inquiry-based classroom resources tied to the NSES. SEGway shall create for THEMIS several nationally-tested lesson plans or units of study for grades 6-12. The specific formal education modules and products to be developed by THEMIS are guided by analysis of identified gaps in the 6-12 grade curriculum and alignment with the NSES. Additionally, the THEMIS EPO team taps the K-4 education resources at CSE, to develop aurora-related activities within age-appropriate language arts and art classes. The modules are classroom tested in paper form and online at Internet-equipped GEONS schools in ten states, and latter are disseminated at the NCTM and NSTA conferences. The THEMIS EPO K-12 module development leverages CSE resources and avoids duplication of products by coordinating with the existing IMAGE and FAST EP/O resources.

c4. Teacher professional development

THEMIS EPO provides content, training, and materials for use in existing professional development teacher workshops at our partnering informal education institutions and school districts. These workshops familiarize both pre-service and in-service teachers with the best science of THEMIS science topics. All workshops are inquiry-based in both practice and theory and include strong emphasis on both scientific content and effective pedagogical approaches. Professional development workshops are presented at national and regional education meetings as well. The GEMS program at LHS and the national GEMS network described previously offer a wide spectrum of nationwide professional development opportunities. The GEONS program incorporates training on the THEMIS specific activities as part of their ongoing workshops for master teachers, explaining the usage of THEMIS data techniques. THEMIS also contributes to the planned SECEF offerings for pre-service and in-service teachers.

d. Informal (public) education activities

d1. Creating a new, THEMIS GEMS site.

The THEMIS EPO team shall create a new *GEMS* Network site at the Carson City School District in Carson City, Nevada. *GEMS,* the Great Explorations in Math and Science teacher's guide series, is a proven resource for excellence in inquiry-based mathematics and science. Developed at UC Berkeley's Lawrence Hall of Science (LHS), *GEMS* guides are used nationwide from preschool through eighth grade. To support the growing number of teachers using *GEMS* materials, LHS *GEMS* maintains an international network of over 55 sites offering professional development and other services for teachers. The proposed Carson City GEMS Network Site serves teachers in northern Nevada, many of them in very remote and underserved school districts. Gail Bushey, a committed and active Associate of the *GEMS* Program takes the lead at the new site, with the strong support of District Assistant Superintendent Mike Watty. The Nevada State Science Coordinator and the Director of the new Planetarium at nearby Western Nevada Community College also lends their support. Lawrence Hall of Science staff would launch the site with a 2-day leadership workshop, emphasizing space science, earth science and physical science. The site team, together with LHS staff and the THEMIS/EPO lead, plan how the site will provide long-term science professional development in the region. Carson City was selected as a *GEMS* site because it satisfies the conditions for being a prime candidate for EPO magnetometer installation and the because of its strong ties with the *GEMS* effort.

d2. *Northern Lights* Show Update

The THEMIS EPO team builds on its experience adapting Sun-Earth Connection discoveries from NASA missions such as FAST and IMAGE to excite the general public. THEMIS, with its science themes centered around the aurora fits nicely in LHS's continuing efforts to evolve and update its existing products in collaboration with CSE@SSL.

The *Northern Lights* is a planetarium show, the 13th Volume in the series known as Planetarium Activities for Student Success (PASS) produced by LHS. Northern Lights became a product of the Sun-Earth Connection Education Forum and release of that program in the Spring of 2002 resulted in approximately 100 planetariums receiving free show kits for express use in school and public shows around the country. The program has been scrupulously reviewed by SEC scientists. As part of the THEMIS EPO LHS shall: (i) Update the Northern Lights program, replacing images, adding animations, and revising the script to reflect THEMIS mission science discoveries related to auroras, (ii) Field test the revised show in four planetariums, (iii) Distribute the updated show to all existing planetarium users (about 100 planetariums) and (iv) Announce the availability of the updated program and distribute it though planetarium conferences and through the world-wide planetarium listserv, dome-I.

e. Under-served, under-utilized and minority communities

To maximize our impact on the Native American community through the selection of magnetometer installed schools THEMIS shall reach out to economically disadvantaged school districts with large populations of Native American youth. Through the South Dakota and Montana Space Grant Consortia (already supported by NASA to train teachers and students in space science) the GEONS project creates lesson plans and experiments used in classrooms. Next, the EPO team expands its services to other Native American students and tribal schools by offering teacher workshops in southeastern Idaho and Utah. To achieve maximum effectiveness with Native American audiences, THEMIS includes other members of the school administration, parents, and tribal elders. Due to the states and geographic preferences it is quite likely that at least 3 GEONS schools will be Tribal Colleges. We are also collaborating with the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS) and have the support of one of the directors, Dr. Ramon Lopez, to work with THEMIS EPO to facilitate the inclusion of THEMIS teacher workshops into the SACNAS K-12 workshop program. The annual meetings of SACNAS provide a professional development program for approximately 140 teachers who serve Hispanic and Native American students. This venue would provide an excellent opportunity to reach SACNAS teachers. Dr. Lopez, an internationally renowned researcher in substorm research, has offered consultations on the design of the workshops to ensure that they are well aligned with the theme of the meeting.

f. Dissemination and National Impact

To disseminate resources nationally and prevent duplication of effort our EPO program shall be coordinated with the Sun-Earth Connection Education Forum, a UC Berkeley/GSFC collaboration, and with the OSS-sponsored Broker/Facilitators nation-wide, as well as networks supported by NASA Education, e.g. the Educator Resource Center Network, NASA CORE, Aerospace Education Specialists Network, and Spacelink. THEMIS mission resources will be accessible through the OSS Resource Directory, which is compatible and linked to the U.S. Department of Education Eisenhower Clearinghouse and Gateway to Educational Materials resource directories. THEMIS links to NOAA centers via our NOAA co-Investigator Dr. H. Singer. THEMIS reports on auroras, solar storms and geomagnetic activity contributes to Spaceweather.com, a member of the popular Science@NASA family popular website. National distribution of THEMIS resources takes advantage of the many already existing web-based and physical dissemination networks available through SEGway museum partnerships, at the National Air and Space Museum, Lawrence Hall of Science, Science Museum of Virginia, the Exploratorium. Working within the SEGway structure thus provides our program with an efficient and high-leverage way of serving the needs of both the formal and informal education communities. EPO staff also routinely publishes articles in the San Francisco Mercury News; the Universe in the Classroom (ASP); Insight magazine (NASA); Science Teacher and National Science Teachers Association newspapers; Working Group on Astronomy Education Newsletter (AAS) and also in the on-line refereed journal, Astronomy Education Review, AER.

g. Evaluating EPO Effectiveness and Impact

The THEMIS EPO partnerships, methods, activities, and visibility is monitored and evaluated by Cornerstone Evaluation Associates, an established independent evaluation group with experience in evaluating the development of science learning resources and the use of technology in science education. Cornerstone assesses the effectiveness of the EPO effort, evaluating: multiplier effect, scope of dissemination, and effectiveness of tapping high-leverage opportunities made available through the partnership with LHS, and Space Grant Consortium. CEA collects formative information from partners about communication, cooperation, goals, and the use of resources, in order to make any necessary mid-course corrections. CEA works alongside with the LHS and its internal evaluation groups on the effectiveness of the establishment of the new GEMS site and the Northern Lights Planetarium update. All products are submitted to the content evaluation process of NASA OSS.

For evaluating the effectiveness of its public outreach component, THEMIS relies on log analysis of the SEGway and other partner websites, audience attendance metrics, and surveys. Suggestions and improvements as part of the formative evaluation and analysis are made available as part of summative evaluation of this program.

h. PI and Science Team Involvement

The PI, Dr. Angelopoulos, and the scientific and technical teams at UCB, UCLA and NASA-funded co-I institutions are committed to provide input on the scientific accuracy of the materials developed, to collaborate and communicate with EPO partners, and to participate in the science center/ museum presentations. The PI oversees the EPO Program. The EPO Lead, Dr. Nahide Craig, provides direction to the THEMIS EPO effort and ensure the coordination of the proposed activities with the help of key EPO personnel at the partner institutions. Dr. N. Craig is uniquely qualified to lead the EPO effort, having coordinated numerous successful UCB mission EPO components, including the UCB/HESSI, STEREO/ IMPACT, CHIPS and the newly selected SPIDR mission. To support the EPO efforts at Berkeley, she supervises a team composed of an EPO scientist/specialist, an illustrator, summer teacher interns, and a grant administrator. Dr. N. Craig is responsible for all written EPO reports, including the contributions for mission reviews, and reports directly to the PI.

THEMIS team members Delory, Bester and Ergun, participate in the EPO functions as guest speakers and contribute THEMIS stories to popular science magazines. The above members have been active in UCB's EPO program in similar roles in the past. For example, Dr Bester, the Mission Operations Manager, has conducted mission operation center tours and delivered public lectures on SSL activities. Drs. Delory, Craig and the PI participate in the LHS planetarium show update development, and dissemination. The co-I team at UCLA is personally committed to the EPO effort led by Dr. C. T. Russell who is also the Director of the UCLA branch of the California Space Grant Consortium and coordinates GMAG-related EPO activities.

EPO-GMAG technical specifications and development are explained in Section F7.e3. EPO-GMAG analysis is discussed in Section F7.e6. UCLA is responsible for GMAG development and deployment and for coordination of GMAG operation and data retrieval by local personnel.

By building on successful EPO efforts, such as those of FAST, HESSI, CHIPS and STEREO/IMPACT, and by securing strong and meaningful partnerships the experienced THEMIS EPO team leads a sustained, well-evaluated program that supports the involvement of scientists and their research in education for the benefit of broad audiences.

i. Project timeline, budget explanation and EPO implementation plan

Please see Section J4 for a detailed budget explanation, including project timeline.

H2. SDB AND MINORITY INSTITUTIONS

The Space Sciences Laboratory utilizes the UCB Office of Small Business Development (OSBD) and all of their resources, including their Small Business Directory, which will be available online in December 2002. SSL maintains a strong relationship with a number of small, disadvantaged businesses (SDBs). For example, M-B Systems, a contractor who participated in our FAST project, developed circuit board assembly capability to NASA standards, including ESD control and NHB5300.4 certification. UCLA is an Accredited US Postsecondary Minority Institution, and will receive approximately $2.5M for THEMIS work, through a campus subaward. This award and our existing relationships with several SDBs, along with our commitment to coordinate with OSBD, will enable us to produce an SDB subcontracting plan that will be readily acceptable to NASA.

H3. NEW TECHNOLOGY

No new technologies are required for the THEMIS mission. However, in recognition of its pathfinding role for STP mission Magnetospheric Constellation (MagCon), and future Explorers THEMIS has carefully evaluated four candidate new technologies proposed in the step-1 proposal for consideration during Phase A. Of those, two are deemed practical and can have a profound effect on future SEC missions. They will be applied at or after the end of the prime mission and have minimal cost, and no weight, power or risk impact.

a. Low cost ranging.

This technique[155] employs an algorithm to obtain ranging information without the need for an expensive (~$0.3M) and heavy (~3kg) 2-way-Doppler-capable transponder. The method permits the use of a receiver/transmitter complement at <50% of the weight and cost and achieves ranging-like accuracies. The difference from other ranging methods is that the ranging algorithm is applied on encoded data, rather than on the subcarrier signal. The idea comes from the first application of this method by the AMSAT community on Oscar 10, 13 and 20 satellites [Miller]. The technique has also been proposed for use on NASA's ST-5 satellite. However, while ST-5 does not have an on-board ranging-capable transpoder, whereas THEMIS does. Thus THEMIS can validate much more accurately the efficacy of this method for obtaining rapid, high quality ranging data, which can lead quickly to convergence of orbit determination algorithms. This is particularly important for the high altitude orbits of THEMIS and other constellations that are affected by lunar perturbations.

In this technique a unique signal (e.g., time-stamp) is uplinked using the encoded 1kbps signal. The signal is received with a unique APID by the THEMIS probe com-card and is listened-to through a command serial interface by the IDPU. The IDPU time-stamps the signal again and sends it back through the com-card to the ground ("burst" downlink mode). Known on-bard processing and cable loss times are subtracted on the ground station leading to direct information on the round-travel time of the signal. Clock stability and iospheric delay contributions are similar to standard 2-way ranging. Detailed error analysis has been published elsewhere. The method is entirely within the baseline THEMIS probe capabilities. A ground interface card near the antenna feed (to reduce ground cable losses) implements a phase-locked loop and time-differencing. Range data obtained are processed by the SatTrack Orbit Determination Tool.

b. Celestial navigation (CelNav)[156]

This GSFC/GNCD technique processes on-board Sun sensor, gyro and (optionally) one-way Doppler data for orbit determination and RCS command generation. The code will be run on the probe avionics processor in C after the end of the prime mission. Commands generated by celestial navigation are downloaded for analysis, validation and are fed into ground spacecraft simulators but are not actually run autonomously on THEMIS because all THEMIS probe RCS functions are ground-commanded. Thus there is no impact on the probe RCS.

CelNav code simulations show position and velocity rms error convergence to <1.2 km and 0.036m/s respectively within four orbits (w/o Doppler data). Near-steady state accuracy is achieved in one orbit. This technology is enhancing for both MMS (MMS requires <10km position knowledge but can afford the weight and power of an on-board two-way ranging system which is already planned). It is enhancing also for MagCon (MagCon requires only 100 km position knowledge) as it eliminates the need for ground orbit determination from ground station angles for the several dozens of MagCon micro-satallites.

The GSFC-developped code since its early use on Apollo has seen several levels of on-board validation (LS4/5, SSTI-Lewis, COBE, EUVE, EO-1). Previous codes have relied heavily on GPS on low altitude missions. The proposed usage on THEMIS would be the first demostration of on-board orbit determination using attitude sensor data, and is entirely within the processing and memory capabilities of the bus avionics processor card.

I. PHASE B PLAN

I1. Phase B Plan: Overview

In Phase B THEMIS refines the CSR baseline design by further detailing the Level 2 and 3 requirements and finalizing the instrument and subsystem interfaces, including ICD generation. These products become the baseline for generation of all data required for the Confirmation Review and subsequent entry into Phase C/D. Swales updates existing component specifications to support flight and ground software plans and mission operations concept, and commences the BAU ETU detailed design. Because of the maturity of the Phase A design no major trades are necessary; minor trade studies are carried out to further optimize mission design and improve margins in known areas. THEMIS continues its aggressive pursuit of retiring risk and maximizing margin in the design and program planning in response to the NASA CSR review.

I2. Phase B key mission trades

These are all non mission-critical (Table I-1).

Item	Who	Trade study
Launch	KSC/ Boeing	Further D2925 performance optimization to improve margin (no science effect).
Ascend	MSE	Optimize fuel by raising apogee after lowering perigee. Check fire stability (operations) under off-nominal conditions.
ACS	MSE	Assess performing attitude precession maneuvers in concert with orbit trimming; increases propellant margin.
Orbits	MSE	Optimize orbit perigee and P1,P2 ascend time to minimize differential RAP with P3.
Ground system	MOC	Finalize trade of SOMO cost estimate versus commercial support
Ground System	MOC	Finalize uplink power/downlink rate to optimize link and bandwidth.
Probe RCS	MSE, LME, Swales	Optimize thruster placement to improve efficiency and RCS functional redundancy, while ensuring compatibility with instrument molecular sensitivities.
PC design	Swales	PC structure manufacture simplicity (honeycomb panel vs. Iso-grid machining)
Probe release	Swales	Increased fidelity model for separation system strain energy, separation spring (plungers) and probe attach, and detailed fuel dynamics.

Table I-1. *Phase B trade studies.*

Other trade studies may emerge from our continuous fault tree analysis and PRAs. As evidenced in Phase A the efficient interaction between the key team members at UCB and Swales permits rapid exploration of the trade space available to the mission and design for optimization. The overarching philosophy of those trade studies (as shown in Phase A) is to improve mission reliability, increase margins, and to develop risk recovery schemes. These provide further methods to manage mission implementation within cost and schedule.

I3. Long-lead procurements

A detailed discussion appears in Section G4.d1 (see Table G-8). Orders are placed prior to the completion of Phase B. Fixed price quotes for the baseline tank (as well as backup candidates) and the transponder are valid through May 2003 based on responses to formal Requests for Quote (RFQ).

I4. Phase B trade study decision points critical to mission success.

Trade studies specified in Table I-1 improve mission performance and margin but are not mission-critical. Their results are provided as part of the confirmation review package. Long lead procurements outlined commence during phase B as discussed in section G4.d1.

I5. Phase B Plans

Finalization and formalization of the Level 1 and the Level 2 requirements with NASA (drafts of both are in place) are a key responsibility of the PI. The MSE and the Swales LSE lead generation of these requirements, with the PM managing the effort and evaluating effects on schedule and cost. Communications are accomplished via site travel and maintained via use of web based tools, email, and teleconferencing. Interface Control Documents (ICDs) are formalized early and are placed under configuration control, after joint signatures, at the responsible institution. They are placed under THEMIS Project change control after the PDR. Key efforts leading to detailed ICD generation are: (1) EMC/ESC cleanliness detailed requirements generation and verification; (2) Thermal analysis with detailed instrument thermal models and interfaces; (3) ESA/SST contamination detailed requirements generation and verification.

Emphasis at Swales is placed on systems engineering, based on the Swales Systems Engineering Control Plan. Swales utilizes a small, highly experienced, focused team; direct lines of communication and rapid decision-making capability and authority. The THEMIS MSE coordinates and manages system requirements and interfaces and leads the overall system engineering process with support in probe bus and PC systems engineering by the Swales Lead System Engineer. The MSE provides the guiding force for well-defined and documented requirements, simplified interfaces, verifiable requirements, integrated performance and resource summaries and budgets, fault tolerance assessments and risk management recommendations.

I6. Phase B products and delivery schedule

Value-added products with appropriately minimized paper reporting allow UCB, Swales and other team partners to satisfy NASA Program and Project Management Processes and Requirements (NPG: 7120.5A). The Phase B products and their timeline are outlined in Table I-2.

Product		Delivery
	NTIA application for S-band, Phase 1	April 1, 2003
	Level 1 Requirements Draft	April 1, 2003
	Level 2 Requirements Draft	
	Instrument Requirements & Draft ICDs	
	Preliminary Mission-Level ICD	
	Project requirements document	
	Product Assurance Implementation Plan	April 15, 2003
	Mission Assurance and Safety Plan	
	Mission Verification Plan	
	Contamination Control Plan	
	I&T Plan	
	System Requirements Review	May 02, 2003
	Materials and Processes Program	May 12, 2003
	Long Lead Procurement List	May 12, 2003
Preliminary ICDs	L/V Interface & Payload Questionnaire	Aug. 18, 2003
	Instrument ICDs	
	Probe Bus and Probe Carrier ICDs	
	Probes to Ground Station ICD	
	Ground Based Observatories ICDs	
	Subsystem PDRs	Aug. 25, 2003
	Mission PDR Package	Sep. 19, 2003
	Mission PDR	Sep. 26, 2003
	Confirmation Review	Oct., 24, 2003

Table I-2. *THEMIS Phase B deliverables*

I7. Reviews

The review process is detailed in Section F9. Phase B-specific review activities are discussed herein. Emphasis is placed in minimizing risks by communicating freely amongst team members and catching errors or deficiencies early in the process.

a. System Requirements Review

UCB leads the System Requirements Review (SRR) with the core THEMIS team. The SRR documents all Level 1 and 2 requirements (Down to Segment and System). Preliminary subsystem or component key requirements are discussed during the SRR to ensure there are no inconsistencies in interpretation, flowdown, or content. Outstanding items are formally documented as action items for resolution. The process ensures that all team members are aware of the driving requirements. The SRR also functions as a System Concept Review to provide the core team members with a system architecture and design overview of the mission baseline, in the context of the requirements, and allows finalization and prioritization of Phase B activities.

b. Peer reviews

These are hosted by instrument or subsystem lead engineers prior to the Preliminary Design Review (PDR) to validate designs and to identify and address any open issues prior to PDR. The design team demonstrates clear requirements traceability and clear interfaces. It provides a design overview, estimates performance characteristics and margin and discusses fault tolerance, test plans and manufacturing logistics. The panel is comprised of independent technical experts from within host institutions and across the team.

c. Mission Preliminary Design Review (PDR)

This is held near the end of Phase B, formally reviews all mission designs and summarizes key changes to the Phase A baseline. All mission system elements are re-examined for technical feasibility relative to the mission requirements and the margin, risk, and fault tolerance assessments are updated to evaluate the state of the entire system.

d. Confirmation Review

The Conformation Review combines the technical status of the PDR into the basis for the programmatic and risk evaluation of the mission implementation plan. It confirms that the mission is technically and programmatically ready to proceed with minimal risk. The status of schedule, manufacturing approach, subcontracts, procurements, risk mitigation items/strategies and costs are reviewed.

I8. Staffing

Phase B-activities involve the key members of the THEMIS program, instrument and IDPU teams, already identified in Section G (see THEMIS organizational charts). Swales has identified members of the Phase A study team as subsystem leads to transition onto the program in the first few weeks of Phase B. Following SRR key engineers are placed on the THEMIS's mechanical and avionics designs (probe design, BAU ETU).

I9. Subcontracting

UCB has identified, and plans to bring onboard as subcontractors during Phase B, local industry personnel who have worked previously at UCB in similar roles.

Key subcontracting at Swales includes flight software engineering (the Hammers Company) and selection of the propulsion subsystem integrator.

K. CHANGES IF SECOND MIDEX

K1. SCIENCE CHANGES

There are no direct implications to the science investigation if this mission is selected as the second MIDEX. However here there are repercussions to the SEC program:

i) If THEMIS is the second MIDEX the lessons learned from the THEMIS practices will propagate to MagCon and other proposed (Magnetospheric, Heliospheric, Astrophysics) constellations a lot slower. THEMIS represents an opportunity for the SEC to demonstrate that multi-spacecraft missions are possible within the Explorer budget, and explain not only why this is so in the planning phase, but in actual practice. Lessons learned from THEMIS will be effective in generating confidence in SEC's ability to construct such missions, and release scientists' inhibition about the feasibility of creative new experiments.

ii) MMS is currently planned with a summer of 2008 launch. THEMIS's development, I&T, orbit strategy practices can only be of benefit to MMS's science planners and engineers if THEMIS is the first MIDEX.

iii) Significant gains for the US SEC community can be obtained from conjunctions between Cluster and THEMIS. THEMIS/Cluster conjunctions for the winter of 06/07 are shown in Figure K-1. It is evident that Cluster represents an ionospheric and a solar wind monitor for THEMIS's tail science. Six months later Cluster represents an ideal tail monitor for THEMIS's dayside investigation. Cluster is currently funded through 2005, but even with (possibly) reduced capability (fuel, number of probes, instruments) it still has tremendous potential for augmenting THEMIS's science in 2006 and 2007. Conversely benefits to the US Cluster community can be obtained from the natural Cluster/THEMIS conjunctions. If THEMIS is the second launch these benefits will undoubtedly be reduced as Cluster will be further away from its design lifetime.

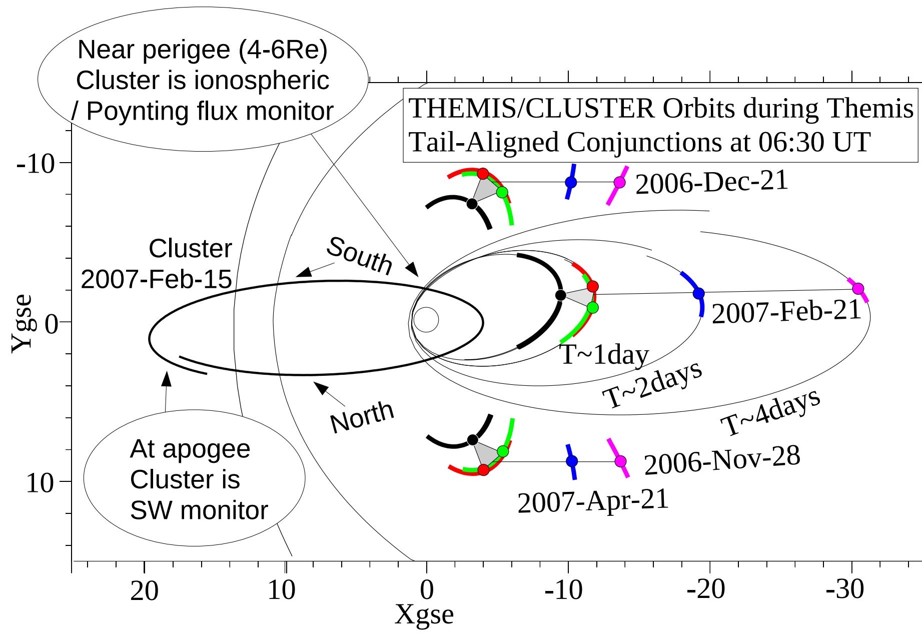


Figure K-1. *Cluster's orbits are ideally placed relative to THEMIS's for significant potential in exploring simultaneously the Solar Wind energy inflow (Cluster) and the response of the magnetosphere (THEMIS). Cluster's polar orbits (projections on equatorial plane shown here) bring the Cluster spacecraft at perigee over the auroral ionosphere. At those times with THEMIS in the tail, Cluster will study the ionospheric response of the substorm tail energy release right over THEMIS's deployed ground-based observatories.*

K2. IMPLEMENTATION PLAN CHANGES

The basic team strategy if THEMIS is selected as the second MIDEX is to fund the "core team" system engineers together with the science support and management. These elements would develop and document the mission requirements and further detail the implementation of the concept, and get started on the long lead item procurements. Naturally, the long lead item procurements would be tailored to the availability of NASA funds.

The second launch option would provide an important benefit to the UCB in its ability to meet the staffing requirements. Instead of having to ramp up quickly, staffing increases and training could be implemented in a more straightforward fashion.

Foreign involvement in FGM and SCM will be able to continue ahead of the US funded efforts, lowering those risks to the program.

NTIA licensing is also an important activity which can be a long process. A second launch scenario would benefit the ability of GSFC and UCB to obtain the S-band license at a time consistent with long-lead procurement of the probe transmitters and receivers.

During the extended period, system engineering will be able to continue mission design trades as itemized in the following table.

Item	Who	Trade study
Launch	KSC/ Boeing	Further D2925 performance optimization to improve margin (no science effect).
Ascend	MSE	Optimize fuel by raising apogee after lowering perigee. Check fire stability (operations) under off-nominal conditions.
ACS	MSE	Assess performing attitude precession maneuvers in concert with orbit trimming; increases propellant margin.
Orbits	MSE	Optimize orbit perigee and P1,P2 ascend time to minimize differential RAP with P3.
Ground system	MOC	Finalize trade of SOMO cost estimate versus commercial support
Ground System	MOC	Finalize uplink power/downlink rate to optimize link and bandwidth.
Probe RCS	MSE, LME, Swales	Optimize thruster placement to improve efficiency and RCS functional redundancy, while ensuring compatibility with instrument molecular sensitivities.
PC design	Swales	PC structure manufacture simplicity (honeycomb panel vs. Iso-grid machining)
probe release	Swales	Increased fidelity model for separation system strain energy, separation spring (plungers) and probe attach, and detailed fuel dynamics.

Table K-1. *Key trade studies to be performed in Phase B (none mission-critical).*

Based upon funding to the system engineering, the expected products of the extended period would be outlined in Table K-2.

Product
NTIA application for S-band, Phase 1
Level 1 Requirements Draft
Level 2 Requirements Draft
Instrument Requirements & Draft ICDs
Preliminary Mission-Level ICD
Project requirements document
Product Assurance Implementation Plan
Mission Assurance and Safety Plan
Mission Verification Plan
Contamination Control Plan
I&T Plan
System Requirements Review
Materials and Processes Program
Long Lead Procurement List

Table K-2 *Deliverables in an extended Phase B, provided NASA resources suffice.*

K3. COST PLAN CHANGES

The cost impact in FY02 dollars for an extended phase B with management, science support and systems engineering at UCB and Swales (WBS 1 and 2.2 for one year) would be as listed in Table K-3. Tables K-4, K-5 and K-6 detail the Real Year budgetary calculations for the extended Phase B option.

Organization	Cost ($M)

Table K-3 *Cost impact if second MIDEX*

L PHASE F ACTIVITIES

These activities, in the case of THEMIS, consist of a Guest Investigator program and the THEMIS Extended Mission. The THEMIS Extended Mission is a two year period of operations and data analysis beyond Phase E. Its objective is to take advantage of the THEMIS unique orbit alignments that form due to the natural progression of the orbits, and the possible overlap with the first two years of MMS (MMS's inner magnetosphere, magnetopause and reconnection observatory phases).

L1. PHASE F: GI PROGRAM

a. Plan

It is recognized that while (i) the baseline THEMIS science investigation covers a timely and exciting scientific goal; and (ii) the THEMIS team of co-Is is well equipped to carry out the data analysis and provide answers to the primary, secondary and tertiary scientific questions that are the target of the mission; the value added to both the THEMIS program and the SEC program by duly incorporating the talent of the entire scientific community as a planned and rational fashion within the THEMIS program. For this reason a GI program is proposed, and is distributed in 4 years spanning both the primary and the THEMIS extended mission period i.e. the period (10/2006-08/2010).

Although data and software dissemination is part of the THEMIS baseline plan, it is in SEC's benefit that the US scientific community's usage of the THEMIS data is duly supported at a level deserving of the new discovery opportunities that the THEMIS dataset opens. The Guest Investigator program is to be run in parallel to the THEMIS program to ensure full immersion of the science community in the primary THEMIS goals as well as full feedback on the software capabilities (and science analyses) of THEMIS.

Following HESSI practices we anticipate the GI program to be run by NASA HQ. We recommend that 2-year proposals are selected in 3 years following successful launch and early orbit operations.

b. Cost plan

Based on the above plan, assuming a yearly THEMIS GI grant of $90K (in accordance with SR&T typical grants) for the duration of 2 years and funding 6 new GI grant starts in 3 consecutive years since launch, the value of the total GI program to be $3.6M, in FY02 dollars. Additional funding for running the program (HQ) is required. UCB science operations can consider a request from HQ for a limited funding for (i) programming and (ii) data analysis in direct support of GI scientists. This will be done if support over and above the nominal operations of THEMIS data and software dissemination and support (nominally covered under the THEMIS baseline budget for Phase E and THEMIS Extended Mission) is deemed necessary. A recommendation to that effect will be made to HQ during mid-phase E and once the GI program is in full operation.

L2. PHASE F: EXTENDED MISSION

a. Plan

The unique THEMIS orbit evolution during the 3rd and 4th year after launch while continues to augment an already large dataset of tail and dayside magnetopause conjunctions.

Moreover the THEMIS constellation progression is ideal for investigations of the bow shock and low latitude boundary layer. Figure L-1 shows the THEMIS probes at L+3.5 years (nominal August launch; nominal orbit parameters). It is evident that natural progression of the orbits due to the differential precession starts to impart a significant difference in the apoapsis location, which in turn is beneficial for studies of the magnetopause and bow shock. Under nominal solar wind conditions (as shown in Figure L-1) P1 and P2 study the evolution of the bow shock and magnetopause properties. Under extreme conditions (enhanced dynamic pressure) probes P3,4 and 5 will also encounter the magnetopause and bow shock simultaneously.

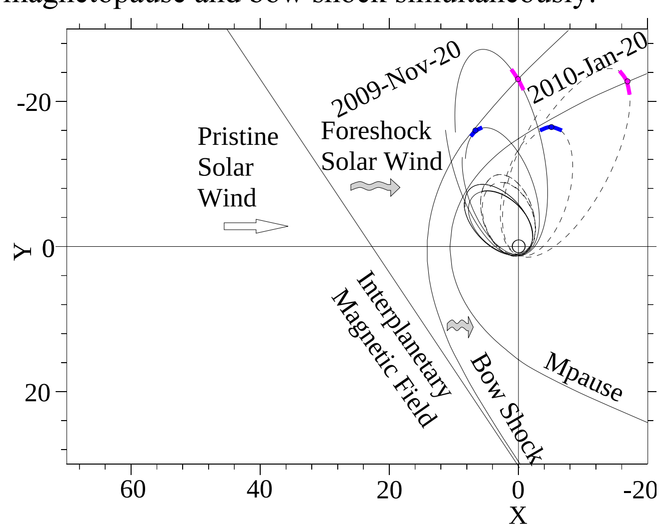


Figure L-1. *Natural progression of THEMIS orbits with only minimal fuel for orbit period tweaks ensures high quality Bow Shock and Magnetopause alignments which permit understanding of those boundaries' evolution under the same external solar wind conditions.*

Moreover, MMS is planned for launch in 2008. The conjunctions with MMS in the dayside and nightside part of the THEMIS are shown in Figures L-2 and L-3 respectively.

At the dayside, THEMIS is ideally suited for probing the large scale structure of the solar-wind magnetosheath/magnetopause interaction over scales from 0.5-20 R_E, while MMS studies local magnetopause structures at scales 0.1-2 R_E. The synergy between the two missions is evidently quite powerful.

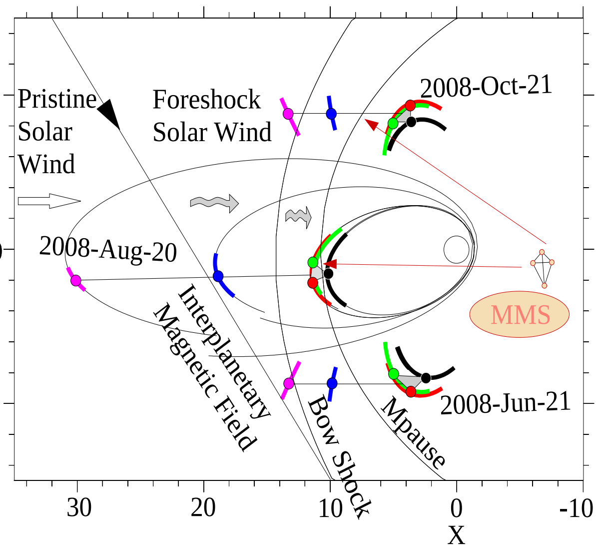


Figure L-2. *THEMIS and MMS at the dayside explore simultaneously the large scale solar-wind magnetosphere interaction (THEMIS) and the local magnetopause boundary layer response (MMS).*

At the nightside, THEMIS is ideally suited for providing the global context in which MMS will perform its mission to understand the boundary layer acceleration and heating processes at the inner edge of the plasma sheet and the reconnection region.

b. Cost Plan

We propose an extension of the THEMIS mission for 2 years in order to carry out the above plans. In the case that MMS launch plans continue to remain ideally overlapping with the extended THEMIS period we propose that a standing member from the THEMIS team participate in the MMS science definition team in order to maximize the potential of the THEMIS-MMS collaboration. Since MMS stands to benefit from the ground observatory deployment of THEMIS and the selection of the late winter season as a tail season, and since THEMIS has sufficient fuel reserves to accommodate possible orbit adjustments unique to the MMS-THEMIS conjunctions we expect that there is no reason why this synergy cannot be exploited scientifically to its fullest.

The THEMIS extended mission cost plan is to continue the Phase E mission operations and data analysis effort for two more years. MMS-specific MOC functions, if they arise, shall be covered under the baseline THEMIS MOC operations.

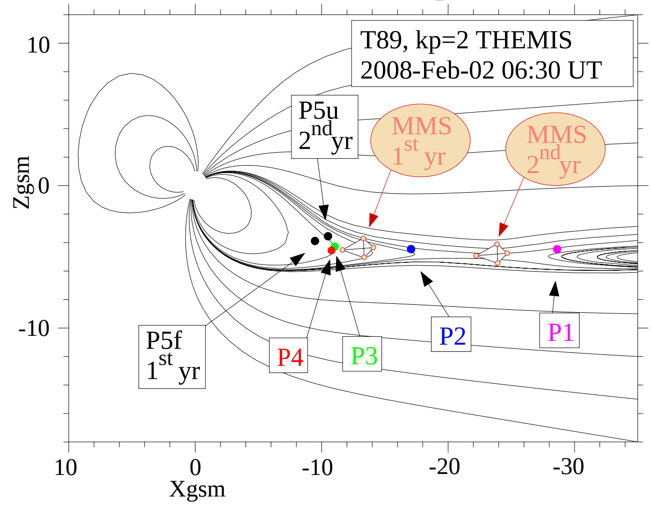


Figure L-3. *THEMIS and MMS at the nightside explore simultaneously the large scale substorm and storm evolution of the magnetosphere (THEMIS) and the local particle acceleration and heating phenomena at the inner edge of the plasma sheet and the reconnection region (MMS).*

M12. ACRONYMS LIST

3DP	3 Dimensional Plasma instrument on the WIND spacecraft
A/D	Analog-to-Digital Converter
AA/OSS	Associate Administrator for the Office of Space Sciences
AC	Alternatic Current
ACE	Advanced Composition Explorer
ACS	Attitude Control System
ADC	Analog to Digital Converter
AEC-ABLE	A company name
AFRL	Airforce Research Laboratories
AGI	Analytical Graphics Inc.
AGO	Automated Geophysical Observatory
AGS	Alaska Ground Station at Poker Flat
AKM	Apogee Kick Motor
AKR	Auroral Kilometric Radiation
AMPTE	US/European Mission consisting of 3 satellite: CCE, IRM and UKS
AMSAT	Amateur Radio Operator Satellite
AO	Announcement of Opportunity
APER	Argument of Perigee
APID	Application Process Identifier
ASA	Austrian Space Agency
ASI	All Sky Imager
ASIC	Application Specific Integrated Circuit
ASCII	American Standard Code for Information Interchange
ATS	Absolute Time Sequence
AXB	Axial Booms
BAU	Bus Avionics Unit
BEB	Boom Electronics Board
BGS	Berkeley Ground Station (used for satellite tracking of FAST, HESSI, IMAGE and other spacecraft)
BPSK	Binary Phase Shift Keying
BTE	Bench Test Equipment
BTS	Bester Tracking Systems software
C&DH	Command & Data Handling
C&T	Command & Telemetry
CAD	Computer Aided Design
CANOPUS	A network of ground observatories (magnetometers, all sky cameras and meridional scanning photometers) in Canada
Cassini	European Spacecraft to Saturn
CC	Configuration Control
CCAS	Cape Canaveral Air Station
CCD	Charge-Coupled Device
CCE	A US / European Scientific Satellite
CCI	Cross Field Current Instability
CCP	Civil and Commercial Program
CCSDS	A signal encoding procedure outlined by NASA's Consultative Committee for Space Data Systems
CD	Current Disruption
CDAW	Community Data Analysis Workshop A substorm event-based forum
CDHS	Command & Data Handling Subsystems
CDI	Command-Data Interface
CDF	Common Data Format
CDROM	A data archival medium
CESR	Centre d'Etude Spatiale des Rayonnements
CEI	Contract End Item
CEO	Chief-Executive Officer
CETP	Centre d'etude des Environnements Terrestres et Planetaires, Velizy, France
CGM	Canadian Geospace Monitoring
CG	Center of Gravity
CGS	Canadian Geospace System
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer (A NASA UNEX mission).
CITU	Carrier Initiator and Telemetry Unit
CLCW	Command Link Control Word
CLTU	Command Link Transmission Unit
CLUSTER	A European / US Scientific Satellite that was destroyed at launch
CLUSTERII	A repeat of CLUSTER
CM	Contracts Managers
CMD	Command
CMS	Command Management System
CNES	Centre National d'Etudes Spatiales
CNR	Carrier-to-noise Ratio
COP	Command Operation Procedure
CPMN	Circum Pacific Magnetometer Network
CPT	Comprehensive Performance Testing
CPU	Central Processing Unit
CQ	Calendar Quarter
CRRES	An Airforce Mission (Combined Release and Radiation Effects Satellite) with Scientific Instruments
CSA	Canadian Space Agency
CSR	Concept Study Report
CU	Colorado University
CY	Calendar Year
DAC	Digital-to-Analog Converter

M12. ACRONYMS LIST

DAS Debris Assessment Software
DC Direct Current
DC MUX Direct Current Multiplexer
DET Direct Energy Transfer
DFB Digital Fields Board in the Instrument Data Processing Unit (IDPU)
DLR German Aerospace Center
DMA Direct Memory Access
DMI Danish Meterological Institute
DOD Depth of Discharge
DPMB Data Processor & Memory Board
DPU Data Processing Unit
DSN Deep Space Network (A NASA tracking antenna network)
DSP Data Signal Processor
Dst A Geomagnetic Activity Index
E&B Electric and Magnetic (Fields)
EDAC Error Detection and Correction circuit
EECO Electronic Engineering Change Order
EFI Electric Field Instrument
EFW Electric Field and Wave experiment on CLUSTER, and CLUSTERII
EGSE Electrical Ground Support Equipment
EM Engineering Models
EMC/EMI Electromagnetic Cleanliness/Electromagnetic Interference
EO-1 Earth-Observing Satellite-1, a NASA mission
EPO Education and Public Outreach
Equator-S A German Scientific Satellite
ESA Electrostatic Analyzer
ESC Electrostatic Cleanliness
ESTEC European Space Research and Technology Center
ETU Engineering and Testing Unit
EUVE Extreme Ultra-Violet Explorer
FAST Fast Auroral SnapshoT Explorer, a SMEX mission
FDAB Flight Dynamics Analysis Branch
FDC Flight Dynamics Center
FDF Flight Dynamics Facility
FEM Finite Element Model
FFT Fast Fourier Transfer
FGM Fluxgate Magnetometer
FGS Fluxgate Sensor
FLT Flight-ready components
FMEA Failure modes, and effects analyses
FOT Flight Operations Team
FOV Field of View
FPGA Field Programmable Gate Array
Freja Swedish Satellite
FSW Flight Software
FTE Flux Transfer Events
FTP File Transfer Protocol
FUSE Far UltraViolet Spectroscopic Explorer
FUV Far UltraViolet (experiment on IMAGE mission)
FY Fiscal Year
Galileo NASA Satellite to Jupiter
GBOs Ground Based Observatories
GDS Ground Data System
GEM Geospace Environmetal Modelling
GEO Geostationary Orbit
GEONS Geomagnetic Event Observation Network by Students
GEOS European Geostationary Scientific Satellite
GEOTAIL Japanese-US Satellite
GI Guest-Investigator program
GMAG Ground Magnetometer
GMAN General Maneuver Program (GSFC software)
GN Ground Network
GN&C Guidance Navigation and Control
GNCC Guidance Navigation and Controls Center, at GSFC
GOES NOAA's Geostationary Operational Environmental Satellite
GOTS&COTS Government and Commercial Off-The-Shelf
GSE Ground Support Equipment
GSFC Goddard Space Flight Center
GTDS Goddard Trajectory Determination System (GSFC software)
HCI Horizon Crossing Indicator
HEO High Earth Orbit (>20,000 km)
HESSI High Energy Solar Spectroscopic Imager
HFA Hot Flow Anomaly (in the Solar Wind)
HQ Headquarters
HSKP Housekeeping
HST Hubble Space Telescope
HV High Voltage
I&T Integration and Testing
IAT Independent Assessment Team
ICD Interface Control Documents
IDL Interactive Data Language (a data analysis commercial program)

IDPU Instrument Data Processing Unit
IGRF International Geophysical Reference Model
IIRV Improved Interrange Vector
IMAGE Imager for Magnetopause-to Aurora Global Exploration (MIDEX Mission)
IMPACT The In-situ Measurements of Particles and CME Transients investigation on STEREO. This is a consortium of seven instruments: The Solar Wind/ SW, Magnetometer/MAG, Solar Energetic Particle package/SEP composed of 4 smaller instruments. The IMPACT data processing unit accomodates these 7 instruments and additionally the Plasma and Supra-Thermal Ions and Composition/PLASTIC investigation on STEREO.
IMU Inertial Measurement Unit (a commercial gyroscope)
IMF Interplanetary Magnetic Field
Interball A Russian scientific satellite
I/O Input/Output
IOC In Orbit Checkout
IONet Internet Protocol Operational Network
IPDR/ICDR Internal Preliminary and Critical Design Reviews
IRM Spacecraft part of the AMPTE mission (also see AMPTE)
IRT Independent Review Team
ISDN Integrated Service Digital Network
ISEE A NASA scientific satellite
ISIS A US Polar Orbiting Satellite
IT Information Technology
ISTP International Solar-Terrestrial Program
ISUAL Instrument built by UCB for a Taiwanese satellite
ITAR International Traffic in Arms Regulations
ITOS Integrated Test and Operation System
IV&V Independent Verification and Validation
IWF Institut für Weltraumforschung (Space Research Institute, Graz)
IWS Integration Work Station
JPL Jet Propulsion Laboratory
KH Kelvin-Helmholtz
KSC Kennedy Space Center
L&EO Launch and Early Orbit
LANL Los Alamos National Laboratory
Landsat US Remote Sensing Satelllite
LET Linear Energy Transfer (1 MeV cm^2/g)
LEO Low Earth Orbit
LHS Lawrence Hall of Science
LHCP Left Hand Circular Polarization
LME Lead Mechanical Engineer
LOF Likelihood of Failure
LPT Limited Performance Testing
LV Launch Vehicle
L/V also Launch Vehicle
LVPS Low-Voltage Power Supply
LWS Living With a Star program of NASA
MACCS A Ground Magnetometer Network
MAG MAGnetometers
MagCon Magnetospheric Constellation a NASA mission under study, in the Solar Terrestrial Probes category
MAM Mission Assurance Manager
MCM-V Multi Chips Module Vertical
MCP Micro-channel Plate
MEASURE A ground magnetometer array along the Eastern United States
MER Mars Exploration Rover
MeV Mega (10^6) electron Volts
MGS McMurdo Ground Station
MHD Magnetohydrodynamics
MIDEX Middle Explorer program of NASA
MIR The Russian Space Station
MI Magnetosphere-Ionosphere
MLI Multi-layer Insulation
MLT Magnetic Local Time
MMS Magnetospheric Multiscale mission
MO&DA Mission Operation and Data Analysis
MOC Mission Operations Center
MOM Mission Operations ManagerS
MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor
MOT Mission Operations Team
MPS Mission Planning System
MSASS Multimission Spin Axis Stabilized Spacecraft (MatLab-based GSFC code)
MSE Mission Systems Engineer
MSI&T Mission Integration and Testing (and Preparation for Operations as defined in this AO)
N_2H_4 Monopropellant Hydrazine

M12. ACRONYMS LIST

NASA	National Aeronautics and Space Administration
NENL	Near-Earth Neutral Line model of sub-storms
NIPR	National Institute of Polar Research, Tokyo, Japan
NLS	NASA Launch Services
NORAD	North American Aerospace Defense Command
NORSTAR	A Canadian program to instrument with filtered all sky imagers 6 ground stations
NPD	NASA Policy Directive
NPG	NASA Procedures and Guidelines
NRC	National Research Council
NRE	Non-Recurring Engineering
NSES	National Science Education Standards
NSPAR	Non-Standard Parts Approval Request
NSSDC	National Space Science Data Center
NTIA	National Telecommunications and Information Administration
ODC	Other Direct Changes
OSS	Office of Space Sciences
PA	Product Assurance
PAF	Probe separation system
PAIP	Performance Assurance Implementation Plan
PC	Probe Carrier
PCA	Probe Carrier Assembly
PESA-H	PESA-High (an instrument on the WIND satellite)
PFR	Problem/Failure Reporting system
Phobos	A Russian Scientific Mission
PI	Principal Investigator
Pi2	Pulsation irregular of type 2
PiB	Pulsation irregular of type B
PIL	Parts Identification List
PM	Project Manager
PM	Phase Modulation
PMC	Program Management Council
PMS	Performance Measurement System
POLAR	A US Scientific Mission
PPL	Preferred Parts List
PRA	Probabilistic Risk Assessment
PRIMAVERA	Scheduling Software Package
PROM	Programmable Memory
PSAT	Predicted Site Acquisition Table
PSR	Program Status Reviews
PTPNT	Programmable Telemetry Processor for Windows NT
QA	Quality Assurance
QUATRO	QUantitative Assessment of Magnetospheric TRanspOrt
RAID	Redundant Array of Independent Disks
RAP	Right Ascension of Perigee
RAAN	Right Ascension of the Ascending Node
R_E	Mean Radius of Earth
RHESSI	Ramaty High Energy Solar Spectroscopic Imager
RCS	Reaction Control System
RF	Radio Frequency
RFA	Request for Action
RFCS	RF Comminations Subsystem
RFQ	Request for Quotations
RHCP	Right Hand Circular Polarization
RID	DSN station in MadRIT, Spain
ROMAP	A particle and field instrument on the European Rosetta Mission
ROSETTA	European Satellite
RTS	Relative Time Sequence
Rx	Reconnection site
S3-3	An Airforce mission with scientific instruments to study the aurora
SAC-C	Brazilian satellite to be launched by NASA
SACNAS	Society for the Advancement of Chicanos and Native Americans in Science
SAMBA	A Ground Magnetometer Network
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer, A NASA Small Explorer mission
SB	Small Business
SBUs	Strategic Business Units
SC	Spacecraft
SCa	Search Coil antennae
SCpa	Search Coil preamplifier unit
SCAT	Spacecraft Command and Telemetry
SCAMA	Switching, Conferencing and Monitoring Arrangement
SCM	Search Coil Magnetometer
SCONCE	A dispenser structure built for AFRL by Swales
SDB	Small Disadvantaged Business
SDRAM	Static/Dynamic Random Access Memory

M12. ACRONYMS LIST

SDT Science Data Tool
SEC Sun-Earth Connections
SEGway Science Education Gateway, a UCB-led education and public outreach program
SEI-CMM Software Engineering Institute's Capability Maturity Model.
SEPT Solar Electron and Proton Telescope
SERS Spacecraft Emergency Response System
SEU Sudden Event Upset
SMALL Sino-Magnetic Array at Low Latitudes (an NSF-funded effort)
SMEX Small Explorer Program
SMRB Swales Materials Review Board
SN Space Network
SOC Science Operations Center
SOHO A US / European Scientific Satellite
SOW Statement of Work
SPB Spin-Plane Booms
SPCB Swales Parts Control Board
SPR Spare units
SR&T Space Research and Technology program of NASA
SSD Space Sciences Division
SSL Space Sciences Laboratory at UCB
SSPA Solid State Power Amplifier
SSS Swales Structure Systems
SST Solid State Telescope
SR System Reliability
SRAM Static Random Access Memory
SRO Systems Review Office
STAFF A French experiment on the European satellite, CLUSTER
STDN Spaceflight Tracking and Data Network
STEM A production line of carbon epoxy tubular sensors
STEREO A NASA Solar Terrestrial Probes mission to study the Sun from two spacecraft providing stereoscopic view of flares and coronal mass ejections
ST5 A NASA technology demonstration mission
STK Satellite Tool Kit
STP Solar Terrestrial Probes
STS/SHELS Shuttle Payload
SWIFT US Mission
TCP/IP Transmission Control Protocol/Internet Protocol
TDRSS Tracking and Data Relay Satellite System, includes 6 spacecraft and ground centers for satellite communications
TDRSS/MATDRSS Multiple Access mode
THEMIS Time History of Events and Macroscale Interactions during Substorms
TIMED A NASA Scientific Satellite
TLM Telemetry
TRIANA NASA Mission to the L-1 Point
TUBS Technical University, Braunschweig
T/V Thermal Vacuum
UA University of Alberta, Canada
UC University of Calgary
UCB University of California at Berkeley
UCLA University of California at Los Angeles
UC-LANL A Ground Magnetometer Network
ULDB Ultra Long Duration Balloon
ULF Ultra-low Frequency
UNEX University Explorer
UOSAT University of Surrey
USAF US AirForce
USN Universal Space Net, a commercial satellite tracking network.
USN-AU Universal Space Network Australia
USP University of Saint-Petersburg, Russia
USGS U.S. Geological Survey
UT Universal Time
UTC Universal Coordinated TimeS
UTDF Universal Tracking Data Format
UV Ultra-Violet
VSat Virtual Satellite
VSAT A satellite internet connection
Viking A Swedish Satellite
VLSI Very Large Scale Integrated
VME Virtual Memory Extension
VRTX A Real Time Operating System commercial program for microcontrollers
WBS Work Breakdown Structure
WGN Wallops Ground Network
WGS Wallops Ground Station
WGST White Sands Ground Terminal
WIND An ISTP spacecraft to study the solar wind
WOA Work Order Authorization
WWW World-Wide Web

M13. REFERENCES LIST

[1]A Science Strategy for Space Physics, National Research Council report, 1995; Page 41, line 36.

[2]Lui, A. T. Y., A multiscale model for substorms, Space Sci. Rev., 95, 325, 2001.

[3] Akasofu, S. -I., Physics of magnetospheric substorms, Dordrecht, Netherlands: Reidel, 1976.

[4]Spence, H. E., The what, where, when and why of magnetospheric substorm triggers, EOS, 77, 81, 1996.

[5]Daglis, I. A., et al., "Fine structure" of the storm-substorm relationship: ion injections during Dst decrease. Adv. Space Res., 25, 2369, 2000.

[6] Siscoe, G. L. and H. E. Petschek, On storm weakening during substorm expansion phase, Ann. Geophys. 15, 211, 1997.

[7]Sergeev, V. A., et al., Steady magnetospheric convection: a review of recent results, Space Science Reviews, 75, 551, 1996.

[8] Aikio, A. T. et al., Characteristics of pseudo-breakups and substorms observed in the ionosphere, at the geosynchronous orbit, and in the midtail, J. Geophys. Res., 104, 12263, 1999.

[9] Shinohara, I., et al., Rapid large-scale magnetic field dissipation in a collisionless current sheet via coupling between Kelvin-Helmholtz and lower-hybrid instabilities, Phys. Rev. Lett., 87, 095001, 2001.

[10] Voronkov, I., et al., Shear flow instability in the dipolar magnetosphere, J. Geophys. Res., 104, 17323, 1999.

[11]The Space Science Enterprise Strategic Plan, November 2000; Page 14

[12]See above document; Page 15.

[13]Sun-Earth Connection Roadmap, Strategic Planning for the years 2000-2025 (Final Distribution); Page 62.

[14]See above document; Page 98.

[15] Friedrich, E., et al., Ground-based observations and plasma instabilities in auroral substorms, Phys. of Plasmas, 8, 1104, 2001.

[16]Lui, A. T. Y., Current disruption in the Earth's magnetosphere: Observations and models, J. Geophys. Res., 101, 13067, 1996.

[17]Mitchell, D. G., et al., Current carriers in the near-Earth cross-tail current sheet during substorm growth phase, Geophys. Res. Lett., 17, 583, 1990.

[18]Atkinson, G., The current system of geomagnetic bays, J. Geophys. Res., 23, 6063, 1967.

[19]McPherron R. et al., Satellite studies of magnetospheric substorms on Aug 15th, 1968, J. Geophys. Res., 78, 3131, 1973.

[20]Lui A. T. Y. et al., A case study of magnetotail current sheet disruption and diversion, Geophys. Res. Lett., 7, 721, 1988.

[21] Ohtani, S. -I., et al., Tail current disruption in the geosynchronous region, in Magnetospheric Substorms, AGU Mongr. Ser., 64, 131, 1991.

[22]Nagai, T., Observed magnetic substorm signatures at synchronous altitudes, J. Geophys. Res., 87, 4405, 1982.

[23]Jacquey, C., et al., Location and propagation of the magnetotail current disruption during substorm expansion: analysis and simulation of an ISEE multi-onset event, Geophys. Res. Lett., 3, 389, 1991.

[24]Ohtani, S., et al., Radial expansion of the tail current disruption during substorms: A new approach to the substorm onset region, J. Geophys. Res., 97, 3129, 1992.

[25]Nagai, T., et al., Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations, J. Geophys. Res., 103, 4419, 1998.

[26]Hones, E. W., Jr., The magnetotail: its generation and dissipation. In Physics of Solar Planetary Environments, ed. D. J. Williams, AGU, 558, 1976.

[27]Nagai, T., er al., Substorm, tail flows, and plasmoids, Adv. in Space Res., 20, 961, 1997.

[28]Fairfield et al., Geotail observtions of substorm onset in the inner magnetotail, J. of Geophys. Res., 103, 103, 1998.

[29]Angelopoulos, V., et al., On the relationship between bursty flows, current disruption and substorms, Geophys. Res. Lett., 26, 2841, 1999.

[30] Sergeev, V. A., et al., Detection of localized, plasma-depleted flux tubes or bubbles in the mid-tail plasma sheet, J. Geophys. Res., 101, 10817, 1996.

[31] Angelopoulos, V., et al., Multipoint analysis of a bursty bulk flow event on April 11, 1985, J. Geophys. Res., 101, 4967, 1996; also see correction: J. Geophys. Res., 102, 211, 1997.

[32] Angelopoulos, V., et al., Magnetotail flow bursts: association to global magnetospheric circulation, relationship to ionospheric activity and direct evidence for localization, Geophys. Res. Lett., 24, 2271, 1997.

[33] Angelopoulos V. et al., Statistical characteristics of bursty bulk flow events, J. Geophys. Res., 99, 21257, 1994.

[34] Kennel, 1992, The Kiruna conjecture: The strong version, in ICS-1 proceedings, ESA SP-335, 599, 1992.

[35] Fairfield, D. H., Advances in magnetospheric storm and substorm research: 1989-1991, J. Geophys. Res., 97, 10865, 1992. [See abstract].

[36] Lui, A. T. Y., and J. R. Burrows, On the location of auroral arcs near substorm onsets, J. Geophys. Res., 83, 3342, 1978.

[37] Elphinstone R. D., et al., Observations in the vicinity of substorm onset: implications for the substorm process, J. Geophys. Res., 100, 7937, 1995.

[38] Frank, L. A., et al., in Proceedings of the International Conference on Substorms - 4 (ICS-4), Terra Scientific, Tokyo, 1998, p. 3.

[39] Frank, L. A., and J. B. Sigwarth, Findings concerning the positions of substorm onsets with auroral images from the Polar spacecraft, J. Geophys. Res., 105, 12,747, 2000.

[40] Samson, J. C., Proton aurora and substorm intensifications, Geophys. Res. Lett., 19, 2171, 1992.

[41] Voronkov, I., et al., Dynamics of the substorm growth phase as observed using CANOPUS and SuperDARN instruments, J. Geophys. Res., 104, 28491, 1999.

[42] Kaufmann, R. L., Substorm currents: growth phase and onset, J. Geophys. Res., 92, 7471, 1987.

[43] Ohtani, S.-I., et al., Initial signatures of magnetic field and energetic particle fluxes at tail reconfiguration: explosive growth phase, J. Geophys. Res., 97, 19311, 1992.

[44] Lui, A. T. Y., Extended consideration of a synthesis model for magnetospheric substorms, in AGU Mon. Ser., 64, 43, 1991.

[45] Ohtani, S.-I., Earthward expansion of tail current disruption: dual-satellite study, J. Geophys. Res., 103, 6815, 1998.

[46] Hones, E. W., Jr., The magnetotail: its generation and dissipation. In Physics of Solar Planetary Environments, ed. D. J. Williams, AGU, 558, 1976.

[47] Baker, D., et al., Neutral line model of substorms: Past results and present view, J. Geophys. Res., 101, 12975, 1996.

[48] Baumjohann, W., et al., Substorm dipolarization and recovery, J. Geophys. Res., 104, 24995, 1999.

[49] Hones, E. W. Jr., et al., Detailed examination of a plasmoid in the distant magnetotail with ISEE 3, Geophys. Res. Lett., 11, 1046, 1984.

[50] Slavin, J. A., et al., CDAW 8 observations of plasmoid signatures in the geomagnetic tail: An assessment, J. Geophys. Res., 97, 8495, 1992.

[51] Shiokawa, K., et al., High-speed ion flow, substorm current wedge, and multiple Pi2 pulsations, J. Geophys. Res., 103, 4491, 1998.

[52] Hesse, M. and J. Birn, On dipolarization and its relation to the substorm current wedge, J. Geophys. Res., 96, 19417, 1991.

[53] Shiokawa, K., et al., Azimuthal pressure gradient as driving force of substorm currents, Geophys. Res. Lett., 25, 959, 1998.

[54] Birn, J., et al., Flow braking and the substorm current wedge, J. Geophys. Res., 104, 19895, 1999.

[55] Sergeev, V. A., et al., In situ observations of magnetic reconnection prior to the onset of a small substorm, J. Geophys. Res., 100, 19121, 1995.

[56] Petrukovich, A. A., et al., Two spacecraft observations of a reconnection pulse during an auroral breakup, J. Geophys. Res., 103, 47, 1998.

[57]Yamade, Y., et al., Field-aligned currents generated in magnetotail reconnection: 3D Hall-MHD simulations, J. Geophys. Res., 27, 1091, 2000.

[58] Henderson, M. G., et al., Are north-south aligned auroral structures an ionospheric manifestation of bursty bulk flows? Geophys. Res. Lett., 25, 3737, 1998.

[59] Sergeev, V. A., et al., Multiple-spacecraft observation of a narrow transient plasma jet in the Earth's plasma sheet, Geophys. Res. Lett., 27, 851, 2000.

[60]Nakamura, R., et al., Earthward flow bursts, auroral streamers, and small expansions, J. Geophys. Res., 106, 10791, 2001.

[61] Nakamura, R. et al., Flow bursts and auroral activations: Onset timing and foot point location, J. Geophys. Res., 106, 10777, 2001.

[62] Ohtani, S. -I., Substorm trigger processes in the magnetotail: recent observations and outstanding issues, Space Sci. Rev., 95, 347, 2001.

[63] Schodel, R., et al., Rapid flux transport in the central plasma sheet, J. Geophys. Res., 106, 301, 2001.

[64] Wygant, J. R., et al., Polar spacecraft based comparisons of intense electric fields and Poynting flux near and within the plasma sheet-tail lobe boundary to UVI images: an energy source for the aurora, J. Geophys. Res., 105, 18675, 2000.

[65] Zesta, E., The auroral signature of earthward flow bursts observed in the magnetotail, 27, 3241, 2000.

[66] Angelopoulos, V., et al., Plasma sheet electromagnetic power generation and its dissipation along auroral field lines, J. Geophys. Res., in press, 2001.

[67]Kan, J. R., A globally integrated substorm model: tail reconnection and magnetosphere-ionosphere coupling, J. Geophys. Res., 103, 11787, 1998.

[68]Henderson, M. G., et al., Observations of magnetospheric substorms occurring with no apparent solar wind/IMF trigger, J. Geophys. res., 101, 10773, 1996.

[69]McPherron, R. L., et al., Solar wind triggering of substorm onset, J. Geomagn. Geoelectr., 38, 1089, 1986.

[70]Lyons, L. R., Substorms: Fundamental observational features, distiction from other disturbances, and external triggering, J. Geophys. Res., 101, 13011, 1996.

[71]Sergeev, V. A., et al., Triggering of substorm expansion by the IMF directional discontinuities: Time delay analysis, Planet. Space Sci., 38, 231, 1990.

[72] Lyons, L. R., A new theory for magnetospheric substorms, J. Geophys. Res., 100, 19069, 1995.

[73] Borobsky, J. E., et al., The occurrence rate of magnetospheric-substorm onsets: random and periodic substorms, J. Geophys. Res., 98, 3807, 1993.

[74] Daly, P. W., et al., Sounding of the plasma sheet in the deep geomagnetic tail using energetic particles, Geoph. Res. Lett., 11, 1070, 1984.

[75] Kettmann, G., and P. W. Daly, Detailed determination of the orientation and motion of the plasma sheet boundary layer using energetic protons on ISEE 1 and 2: waves, curves, and flapping, J. Geophys. Res., 93, 7376, 1988.

[76] Sarris, E. T., et al., Location of the source of magnetospheric energetic particle bursts by multispacecraft observations, Geophys. Res. Lett., 3, 437, 1976.

[77] Sarris, E. T., et al., Detailed observations of a burst of energetic particles in the deep magnetotail by Geotail, J. Geomagn. Geoelectr., 48, 649, 1996.

[78] Richardson, I. G., et al., Plasmoid-associated energetic ion bursts in the deep geomagnetic tail: properties of plasmoids and the postplasmoid plasma sheet, J. Geophys. Res., 92, 9997, 1987.

[79] Richardson, I. G., and S. W. H. Cowley, Plasmoid-associated energetic ion bursts in the deep geomagnetic tail: properties of the boundary layer, J. Geophys. Res., 90, 12133, 1985.

[80]Olson, J. V., Pi 2 pulsations and substorm onsets: a review, J. Geophys. Rev., 104, 17499, 1999.

[81]Liou, E., et al., Evaluation of low-latitude Pi2 pulsations as indicators of substorm onset using Polar ultraviolet imagery, J. Geophys. Res., 105, 2495, 2000.

[82] Heacock, R. R., Two types of Pi micropulsations, J. Geophys. Res., 72, 3905, 1967.

[83] Troitskaya, V. A., Pulsations of the Earth's electromagnetic field with periods of 1 to 15 seconds and their connection with phenomena in the high atmosphere, J. Geophys. Res., 66, 5, 1961.

[84] Bosinger, T., et al., Correlations between Pi B type magnetic micropulsations, auroras and equivalent current structures during two isolated substorms. J. Atmos. Terr. Phys., 43, 933, 1981.

[85] Clauer, C. R., and R. L. McPherron, Mapping the local universal time development of magnetospheric substorms using mid-latitude magnetic observations, J. Geophys. Res., 79, 2811, 1974.

[86] Vagina, L. I., et al., On the relationship between parameters of substorm current wedge and westward electrojet, Adv. Space Res., 20, 477, 1997.

[87] Vagina, L. I., et al., Use of mid-latitude magnetic data for modelling and diagnostics of magnetospheric substorms, Adv. Space Res., 18, 229, 1996.

[88] Kubyshkina, M. V., et al., Hybrid Input Algorithm: An event-oriented magnetospheric model, J. Geophys. Res., 104, 24977, 1999.

[89] Sergeev, V. A., et al., Comparison of UV optical signatures with the Substorm Current Wedge predicted by an inversion algorithm, J. Geophys. Res., 101, 2615, 1996.

[90] Chao, J. K., et al., A model for thinning of the plasma sheet, Planet. Space Sci., 25, 703, 1977.

[91] Bamjohann, W., et al., Characteristics of high-speed ion flows in the plasma sheet, 95, 3801, 1990.

[92] Raeder, J., et al., Global simulation of the Geospace Environment Modeling substorm challenge event, J. Geophys. Res., 106, 381, 2001.

[93] Xinlin Li, et al., Multiple discrete-energy ion features in the inner magnetosphere: observations and simulations, Geophys. Res., Lett., 27, 1447, 2000.

[94] Sergeev, V. et al., Current measurements within a flapping plasma sheet, J. Geophys. Res., 103, 9177, 1998.

[95] Lopez, R. E., The position of the magnetotail in the near-Earth region, Geophys. Res. Lett., 17, 1671, 1990.

[96] Jacquey, et al., Substorm associated tail current changes inferred from lobe magnetic field observations, in Magnetospheric Currents, AGU monograph series, in press.

[97] Haerendel, G., Disruption, ballooning or auroral avalanche - on the cause of substorms, in Proceedings of the first International Conference on Substorms, ESA SP-335, 417, 1992.

[98] Roux et al., Plasma sheet instability related to the westward traveling surge, J. Geophys. Res., 96, 17697, 1991.

[99] Ohtani, S. -I., et al., A multi-satellite study of a pseudo-substorm onset in the near-Earth magnetotail, J. Geophys. Res., 98, 19355, 1993.

[100] Lee, D.-Y., and R. A. Wolf, Is the Earth's magnetotail balloon unstable? J. Geophys. Res., 97, 19251, 1992.

[101] Hurricane, O. A., MHD ballooning stability of a sheared plasma sheet, J. Geophys. Res., 102, 19903, 1997.

[102] Samson, J. C., et al., Substorm intensifications and resistive shear flow-ballooning instabilitys in the near-Earth magnetotail, in ICS-3 proceedings, ESA SP-389, 399, 1996.

[103] Hurricane, O. A., et al., Substorm detonation, J. Geophys. Res., 104, 10221, 1999.

[104] Voronkov, I., et al., Large-scale vortex dynamics in the evening and midnight auroral zone: observations and simulations, J. Geophys. Res., 105, 18505, 2000.

[105] Fenrich, F. R. and J. C. Samson, Growth and decay of field line resonances, J. Geophys. Res., 102, 20031, 1997.

[106] Maynard, N. C., et al., Dynamics of the inner magnetosphere near times of substorm onsets, J. Geophys. Res., 101, 7705, 1996.

[107] Erickson, G. M., et al., Electromagnetics of substorm onsets in the near-geosynchronous plasma sheet, J. Geophys. Res., 105, 26265, 2000.

[108] Motschmann, U., et al., Multi-spcecraft filtering: Plasma mode recognition, in Analysis methods for multi-spacecraft data, International Space Science Institute report, SR-001, ESA publica-

tions, p. 79, 1998.

[109]Buechner, J., et al., Three-dimensional reconnection in the Earth's magnetotail: Simulations and observations, in Geospace Mass and Energy Flow: Results from the ISTP program, AGU Geophys. Monograph Series, 104, p. 313, 1998.

[110] Goertz, C. K. and W. Baumjohann, On the thermodynamics of the plasma sheet, J. Geophys. Res., 96, 20991, 1991.

[111] Erickson, G. M., and R. A. Wolf, Is steady convection possible in the Earth's magnetotail? Geophys. Res. Lett., 7, 897, 1980.

[112] Pontius, D. H. and R. A. Wolf, Transient flux tubes in the terrestrial magnetosphere, Geophys. Res. Lett., 17, 49, 1990.

[113] Chen, C. X., and R. A. Wolf, Interpretation of high-speed flows in the plasma sheet, J. Geophys. Res., 98, 21409, 1993.

[114]Perraut, S. A., et al., Evidence for a substorm trigger, in ICS-4 proceedings, Kluwer Acedemic, p. 349, 1998.

[115]Shinohara, I., et al., Low-frequency electromagnetic turbulence observed near the substorm onset site, 103, 20365, 1998.

[116]Sugiyama, T., et al., Highly collimated electron beams observed during quiet times, Geophys. Res. Lett., 24, 1651, 1997.

[117]Le Contel, O., et al., Self-consistent magnetospheric convection during the growth phase, in ICS-4 proceedings, Kluwer Acedemic, p. 425, 1998.

[118]Li et al., Multisatellite observations of the outer zone electron variation during the November 3-4, 1993, magnetic storm, J. Geophys. Res., 102, 14123, 1997.

[119]Ingraham et al, in AIP Conference proceedings 383 of Workshop on the Earth's Trapped Particle Environment, edited by G. D. Reeves, p.103, AIP, New York 1996.

[120] Li, X. et al., Long Term Measurements of Radiation Belts by SAMPEX and Their Variations, Geophys. Res. Lett., in press, 2001.

[121] Li, X., et al., Quantitative Prediction of Radiation Belt Electrons at Geostationary Orbit Based on Solar Wind Measurements, Geophys. Res. Lett., 28, 1887, 2001.

[122] Brautigam, D. H., and J. M. Albert, Radial diffusion analysis of outer radiation belt electrons during the 9 October 1990 magnetic storm, J. Geophys. Res., 105, 291, 2000.

[123]Baker, D. N., The role of magnetospheric substorms in high-energy particle production within the Earth's magnetosphere, ICS5, St. Petersburg, Russia, ESA SP-443, p. 419, July 2000.

[124]Paschmann et al., Plasma acceleration at the magnetopause: evidence for reconnection, Nature, 282, 243, 1979.

[125]Russell, C. T., and R. C. Elphic, Initial ISEE magnetometer results: magnetopause observations, Space Sci. Rev., 22, 681, 1978.

[126] Lockwood, M. and M. N. Wild, On the quasi-periodic nature of magnetopause flux transfer events, J. Geophys. Res., 98, 5935, 1993.

[127] Le, G., C. T. Russell, and H. Kuo, Flux transfer events - Spontaneous or driven?, Geophys. Res. Lett., 20, 791, 1993.

[128] Crooker, N. U., et al., Factors controlling degree of correlation between ISEE 1 and ISEE 3 interplanetary magnetic field measurements, J. Geophys. Res., 87, 2224, 1982.

[129] Paularena, K. I., et al., Solar wind plasma correlations between IMP 8, INTERBALL-1, and WIND, J. Geophys. Res., 103, 14601, 1998.

[130] Collier, M. R., et al., Timing accuracy for the simple planar propagation of magnetic field structures in the solar wind, Geophys. Res. Lett., 25, 2509, 1998.

[131]Fairfield, D. H., et al., Upstream pressure variations associated with the bow shock and their effects on the magnetosphere, *J. Geophys. Res., 95*, 3773-3786, 1990.

[132] Thomas, V. A. and S. H. Brecht, Evolution of diamagnetic cavities in the solar wind, *J. Geophys. Res., 93*, 11341-11353, 1988.

[133] Völk, H. J. and R.-D. Auer, Motions of the bow shock induced by interplanetary disturbances, J. Geophys. Res., 40-48, 1974.

[134] Lin Y., D. W. Swift, and L. C. Lee, Simulation of pressure pulses in the bow shock and magnetosheath driven by variations in interplanetary

magnetic field direction, J, Geophys. Res., 101, 27251, 1996.

[135] Paschmann, G., G. Haerendel, N. Sckopke, E. Möbius, H. Lühr, and C. W. Carlson, Three-dimensional plasma structures with anomalous flow direction near the Earth's bow shock, J. Geophys. Res., 93, 11279, 1988.

[136] Sibeck, D. G., K. Takahashi, S. Kokubun, T. Mukai, K. W. Ogilvie, and A. Szabo, A case study of oppositely propagating Alfvén fluctuations in the solar wind and magnetosheath, Geophys. Res. Lett., 24, 3133, 1997.

[137] Song, P., C. T. Russell, and M. F. Thomsen, Slow mode transition in the frontside magnetosheath, J. Geophys. Res., 97, 8295, 1992.

[138] Southwood, D. J. and M. G. Kivelson, Magnetosheath flow near the subsolar magnetopause: Zwan-Wolf and Southwood-Kivelson theories reconciled, Geophys. Res. Lett., 22, 3275, 1995.

[139]Phan, T. D. and G. Paschmann, The magnetosheath region adjacent to the dayside magnetopause, in Physics of the Magnetopause, AGU Monograph 90, 1995.

[140] Sibeck, D. G., et al., The magnetospheric response to 8-minute-period strong-amplitude upstream pressure variations, J. Geophys. Res., 94, 2505, 1989.

[141] Farrugia, C. J., F. T. Gratton, and R. B. Torbert, Viscous-type processes in the solar wind-magnetosphere interaction, Space Sci. Rev., 95, 443, 2001.

[142]Walthour, D. W., et al., Remote sensing of 2-dimensional magnetopause structures, J. Geophys. Res., 98, 1489, 1993.

[143]Nakamura, R., et al., Substorm observations in the early morning sector with Equator-S and Geotail, Ann. Geophysicae, 17, 1602, 1999.

[144]Table 2.3 of: MMS: Resolving fundamental processes in space plasmas, a Report of the NASA Science and Technology Definition Team for the Magnetospheric Multiscale (MMS) Mission, published by NASA-GSFC, NASA/TM-2000-209883, page 19, 1999.

[145]Santolik, O., et al., Complete wave-vector directions of electromagnetic emissions: Application to INTERBALL-2 measurements in the nightside auroral zone, J. Geophys. Res., 106, 13191, 2001.

[146]Fornacon, K.-H., et al., The magnetic field experiment onboard Equator-S and its scientific possibilities, Ann. Geophysicae, 17, 1513, 1999.

[147]Auster, H. U., et al., Concept and first results of a digital fluxgate magnetometer, Measurement Sci. and Tech., 6, 477, 1995.

[148]Kepko, E. L., et al, Accurate determination of magnetic field gradients from four point vector measurements: 1. Use of natural constraints on vector data obtained from a single spinning spacecraft, IEEE Trans. Magnetics, 32, pp. 377-385, 1996.

[149]Khurana, K. K., et al., Accurate determination of magnetic field gradients from four point vector measurements: 2. Use of natural constraints on vector data obtained from four spinning spacecraft, IEEE Trans. Magnetics, 32, 5193, 1996.

[150]Lin, R. P., et al., A three-dimensional plasma and energetic particle investigation for the WIND spacecraft, Space Sci. Rev., 71, 125, 1995.

[151]Delory, G. T., et al., A high science return, low cost constellation pathfinder, in Science Closure and Enabling Technologies for Constellation Class Missions, UC Berkeley, p. 22, 1998.

[152]Lee G.-Y., et al., Mechanical considerations of Release and Spin-up of Constellation Microspacecraft, in Science Closure and Enabling Technologies for Constellation Class Missions, UC Berkeley, p. 107, 1998.

[153]Battle, R., and Hawkins, I., A study of emerging teacher practices in internet-based lesson plan development, J. Sci. Educ. Tech., 5, 321, 1996.

[154]Doctor, A., and R. Burton, Self powered body mounted horizon crossing indicator for small satellites, paper in: Proceedings of the AAS Guidance and Control Conference, Keystone, CO, AAS-95-035, 1995.

[155]Angelopoulos, V., et al., Tracking and operations of constellation microspacecraft, in Science Closure and Enabling Technologies for Constellation Class Missions, UC Berkeley, p. 91, 1998.

[156]Folta, D. C., et al., Autonomous navigation using celestial objects, paper in: Proceedings of the AAS Astrodynamics Specialists Confer-

ence,Girdwood, AK, AAS 99-439, 1999.

[157]Harvey, P. R., et al., The FAST Spacecraft Instrument Data Processing Unit, Space Sci. Rev., 98, 113, 2001.