THEMIS
Magnetics Contamination Control Plan*

THM-SYS-002 Rev D
April 17, 2004

**Design guidelines adapted by the THEMIS team from material prepared by R. C. Snare and C. T. Russell for the POLAR Spacecraft.*

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Document Revision Record

Rev.	Date	Description of Change	Approved By
-	7/15/03	Preliminary Draft	-
A	10/25/03	Added THEMIS specific requirements and discussion Added Preliminary Magnetics Budget Added THEMIS Main Offenders List Added Test and Verification Section	ERT
B	11/03/03	Added VA comments - AC magnetic noise level figure - Clarified AC requirement - Budget table update - Additional discussion, table on Power system DC magnetic moment to meet AC requirements	ERT
C	1/20/04	Added UCLA comments (e-mail "follow-up questions and answers", 11/18/2003) Clarified to require stability over 12 hrs only Budget stated as estimate, not required	ERT
D	4/17/04	Changed Brushless motors to Brush Battery Testing at UCLA RF Component Testing at UCLA Revised Distribution List and Magnetics Control Board	

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TBD List

Identifier	Description
TBD	Frequency Management Plan

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1. OVERVIEW

THEMIS is a NASA Explorer mission which will launch a constellation of five micro-satellites (probes) in mid-2006. Flying in synchronous orbits within the earth's magnetosphere, the probes will measure the particle processes responsible for eruptions of the aurora. As the prime contractor for THEMIS, the University of California at Berkeley will provide the project management, systems engineering, flight instrumentation, ground-based imagers, mission operations, and Performance Assurance. Swales Aerospace will provide probe buses. Key international partners include instrument teams from Canada, France, Germany, and Austria. UCLA provides oversight for the THEMIS magnetic cleanliness program.

1.1 PURPOSE

The main purpose of this document is to assist the THEMIS team with the design of magnetically clean subsystems to ensure DC- and AC-magnetic experiments on-board the five THEMIS probes can reliably observe the magnetic field as required by primary mission objectives. Previous spacecraft projects like Helios, GEOS, ISEE, Giotto, and Ulysses have conducted thorough magnetic cleanliness programs to ensure the success of the mission. Much of the material presented here is based on this previous experience. In particular, the design guidelines consist of material first prepared for the Giotto and Cluster missions and subsequently modified for the POLAR spacecraft.

1.2 OBJECTIVES

The objective of this Magnetics Contamination Control Plan is to discuss how to achieve acceptable magnetic cleanliness levels for THEMIS and describe the means to validate such levels. The document is structured by the specific objectives as follows:

- Establish overall responsibility for executing the provisions of this plan
- State the system-level magnetic requirements
- Establish a magnetic moment budget
- List special considerations and requirements for worst offender subsystems and assemblies
- Provide generic subsystem and assembly design requirements and guidelines
- Describe magnetic test methods and procedures for performing tests on subsystems and assemblies
- Describe methods for preventing subsystems/assemblies from becoming magnetically contaminated

1.3 RESPONSIBILITIES

The central role the magnetic field investigation plays in achieving the scientific objectives of THEMIS means that magnetic cleanliness is an important requirement for the success of the mission. The approach adopted for THEMIS relies on a high level of cooperation among all parties concerned. Each organization providing flight hardware for the THEMIS mission is responsible for complying with the provisions of this plan, and the applicable detailed plans and procedures referenced herein.

A THEMIS Magnetics Control Board (members listed in pre-face) has been formally established in order to provide assistance to Cognizant Engineers regarding magnetic cleanliness matters, to identify potential threats posed to the magnetometer experiments, and to recommend solutions for such concerns. The board holds bi-weekly meetings to coordinate all relevant activities and ensure that the magnetic cleanliness design goal is met or bettered.

1.4 PROJECT DOCUMENTS

THM_SYS_001	THEMIS Mission Requirements Document
THM_PA_001A	THEMIS Performance Assurance Implementation Plan
THEMIS-IWF-SW-0001b	Magnetic cleanliness SW Description. Version V1.0, June 2003. M. Delva, IWF – Graz
TBD	THEMIS Frequency Management Plan

1.5 REFERENCE DOCUMENTS

Mario H. Acuña Laboratory for Extraterrestrial Physics Goddard Space Flight Center	The Design, Construction and Test of Magnetically Clean Spacecraft – A Practical Guide. Rev 1.1, April 1994, Revised June 2000
R. C. Snare and C. T. Russell	Guidelines for Magnetic Cleanliness for Use on the Polar Spacecraft. Revised June 1990
Cluster Magnetometer Team (Cluster PI A. Balogh)	Guidelines for Magnetic Cleanliness on the Cluster Spacecraft
FAST-SPEC-012	SMEX-FAST Magnetics Contamination and EMI/EMC Control and Implementation Plan. Rev A, September 17, 1993
FAST-SPEC-023 Dave Everett	SMEX-FAST I&T Magnetic Cleanliness Requirements. June 15, 1993
P. Narvaaz	JPL D-7726 CRAF/CASSINI Magnetics Control Plan. April 1991
M. Delva IWF – Graz	THEMIS-IWF-SW-0001b Magnetic cleanliness SW Description. Version V1.0, June 2003
B. J. Anderson and H. Korth	MESSENGER Propulsion Latching Valve Magnetic Moment Measurements. June 2002
NASA SP-8037	Assessment and Control of Spacecraft Magnetic Fields. Sept. 1970
P. Narvaaz	JPL D-7726 CRAF/CASSINI Magnetics Control Plan. April 1991

2. REQUIREMENTS

The magnetic cleanliness requirements of the THEMIS mission are driven by the two magnetometer experiments aboard the probes: (1) a Search Coil Magnetometer (SCM) on a 1 meter deployable boom; and (2) a Fluxgate Magnetometer (FGM) on a 2m deployable boom. No mission level requirements are invoked uniquely by this document. The requirements of this document evolve from those stated in the THM-SYS-001 Mission Requirements Document (MRD), specifically:

M-30: AC magnetic noise radiated by the Probe and other instruments shall not exceed the following levels at 1 meter from the Probe.

Requirement: noise <30pT/sqrt(Hz) at 1Hz
Desire: noise < 10pT/sqrt(Hz) at 1Hz

Requirement: noise < 1pT/sqrt(Hz) at 10Hz
Desire: noise < 0.08pT/sqrt(Hz) at 10Hz

Requirement: noise < 0.1pT/sqrt(Hz) at 1kHz
Desire: noise < 0.01pT/sqrt(Hz) at 0.5kHz

Requirement : noise <0.1pT/sqrt(Hz) in range 1kHz-10kHz
Desire : noise <0.01pT/sqrt(Hz) in range 0.5kHz-10kHz

At frequencies between DC and AC, i.e., in the range of 0.01Hz to 1Hz, the noise level should be lower than the noise prescribed by the (typical) 1/sqrt(f) noise spectrum of FGM instruments.

Figure 2-1 illustrates the rationale behind the AC magnetic noise requirements (M-30) and desirements, showing the predicted FGM and SCM sensitivity compared to typical spectrum. For frequencies 1-10kHz, flat noise <0.1pT/sqrt(Hz) is required and the desire remains <0.01pT/sqrt(Hz) in the range 0.5kHz-10kHz.

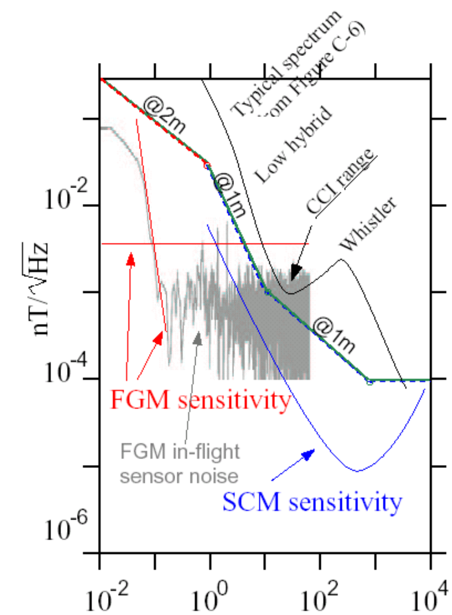

Figure 2-1: FGM and SCM sensitivity at the sensor location (1m and 2m respectively). Ordinate is frequency measured in Hz. Abscissa is amplitude spectral density in nanoTeslas per root Hz.

Additionally, Figure 2-2 shows pictorially the aforementioned required and desired AC noise levels at a distance of 1m from the spacecraft.

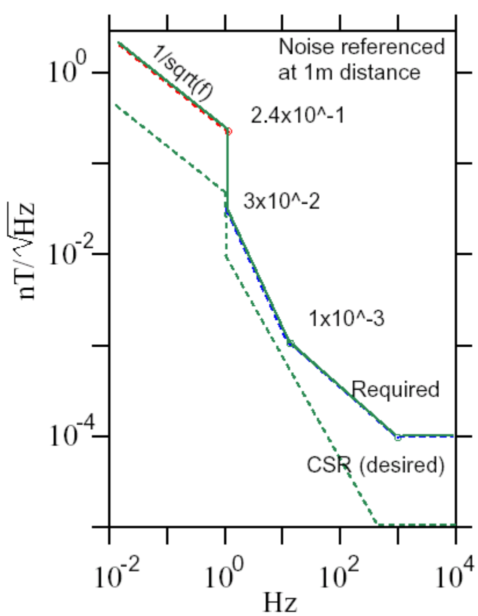

Figure 2-2: *AC magnetic noise level requirement (solid curves) and goal (dashed curves) at 1m from the spacecraft. Ordinate is frequency in Hz. Abscissa is amplitude spectral density in nanoTeslas per root Hz.*

M-31a: DC magnetic field generated by the Probe and other instruments shall not exceed 5nT at 2 meters from the Probe (location of FGM sensor).

M-31b: DC magnetic field generated by the Probe subsystems and other instruments shall be stable to <0.1nT over 12hrs at 2m from the Probe (location of FGM sensor) over the operational temperature range of these subsystems and instruments.

The DC magnetic noise requirement (M-31a) was relaxed from 1nT as stated at the System Requirements Review to 5nT with the understanding that the offset can be measured on the ground and on-orbit in the solar wind. Therefore, the 5nT DC field at the FGM sensor must be verified by a combination of measurement, analysis and modeling. The 5nT level is commensurate with ACS requirements (1deg at 300nT provides a good orbit arc for modeling) and, if measured at 2m distance to better than 1nT (or inferred by measurements closer to the spacecraft) it meets the Level 1 science requirements.

In addition to the absolute DC offset, THEMIS mission objectives are also concerned with DC drifts (from Level 1 requirements, 1nT absolute knowledge and stability of 0.2nT over 12 hours is required). Therefore, the contribution to the Z-axis FGM offset, which is difficult to measure more than once per year, should be a small fraction of the total (1nT) absolute knowledge budget. Additionally the DC spacecraft offset should not drift over typical subsystem temperature variations within the 12hrs centered around apogee in science mode (excluding shadows).

Therefore, the DC magnetic stability requirement (M-31b) must be met during science mode only, over the mission-life in operational temperature ranges and shall be verified by analysis. This dictates less than +/-1% drift of DC magnet strength over operational temperature range.

3. DESIGN GUIDELINES

To meet the mission requirements, considerations of magnetic cleanliness must have a high priority during the design phase, when the design, selection and positioning of flight components and hardware needs to be carefully evaluated for possible magnetic contamination. The design guidelines contained in this section considers the effects of hard and soft magnetic parts and materials, and those of stray fields, resulting from currents in the probe and instrument electrical systems.

Permanent fields can be controlled to some extent by careful positioning of magnetic components. However, it is not always possible to optimally position some of the major contributing sources which have known or predictable magnetic characteristics. Therefore, parts and materials to be used in the probes must be selected so as to minimize their contribution to the background magnetic field.

In considering perm fields it is important to recognize the difference between hard and soft magnetic materials. Whereas the contribution of hard magnetic perm fields can be expected to be quite stable, the magnetic field of soft materials may very appreciably, particularly during launch and in response to varying electrical activity in the spacecraft or in response to varying magnetic activity of the ambient field. The hard perm field background due to permanent magnets for instance, if not large, can be determined by a combination of ground testing, modeling and in-flight determination, and is therefore often of lesser concern. The strongly varying contribution of soft magnetic materials, on the other hand, must be kept low by strictly limiting their use.

Stray fields are due to uncompensated DC or AC current loops or stray currents. These may result in permanent or variable magnetic moments. Control of stray fields must be considered during the design phase to minimize their effects. As with the permanent fields, positioning is important and must be considered, along with harness layout, shielding, etc.

3.1 APPROACH TO MINIMIZING PERM FIELDS

For the reduction and control of perm field contamination levels, the major areas of consideration shall be as follows:

a) Component and piece-part evaluation; selection of components that balance cost and risk.
b) Parts layout for circuit boards and power routing
c) Component or assembly orientation for mutual compensation.
d) Provisions for the safe performance of components during deperming operations.

3.2 APPROACH TO MINIMIZING STRAY FIELDS

To comply with the requirements of the experimenters for minimizing stray fields, the following areas shall be considered (noting that all stray fields are also considered in the realm of EMI/EMC):

a) Design of the probe wiring and power distribution system, with special attention to bonding, shielding and grounding.
b) The use of paired, twisted leads wherever possible.
c) Equipment location within the probe.
d) Elimination of current loops throughout the probe by the careful control of grounds and current return paths.

3.3 APPROACH TO MAGNETIC MOMENT MANAGEMENT

The Magnetics Control Board will continually evaluate the list of acceptable magnetic moments for individual subsystems. As preliminary tests occur and materials selected, estimates will be re-evaluated and re-adjusted as necessary. Detection of too large magnetic contents will start a collaborative effort, where the Magnetic Review Board, along with the magnetometer teams, will analyze the problem and suggest possible solutions. Subsystem re-allocations within the overall science-driven magnetic moment budget are possible as confidence in the design and analysis matures.

The driving THEMIS DC magnetic cleanliness requirements (<5nT magnetic field and <0.1nT magnetic field stability/12 hours at 2 meters) are apportioned to the principal offending subsystems as shown in Table 3-1. All flight hardware will be designed so that the static maximum magnetic field when extrapolated as the inverse cube of the distance at two-meter distances from the center of the hardware does not exceed the values given (unless otherwise noted). These tables provide an approximate delineation and budget of magnetic offenders given current knowledge. All offenders will be actively tracked in a separate spreadsheet and the budget will be updated accordingly as preliminary tests and more detailed estimates are available.

Table 3-1: *THEMIS Maximum allowable DC magnetic field*

Item	**Requirement**	***Notes***
EFI Magnets (Boom Motors)	<0.75nT @ 2m, DC	*Indeterminate field*
SST Broom Magnets	<0.75nT @ 2m, DC	*Drops off as quadrapole*
Other instrument sources:	<0.5nT @ 2m, DC	
Probe System Total	<3nT @ 2m, DC	
…….Latch Valve	<2nT @ 2m, DC	*Antiparallel matching. 0.075%/deg stability.*
…….Thruster Valves	<0.25nT @ 2m, DC	
…….Tanks	<0.2nT @ 2m, DC	
…….Other bus sources:	<0.55nT @ 2m,DC	

The THEMIS AC magnetic cleanliness requirements are principally challenged by variable currents generated by the power system. On a spinning spacecraft such currents vary on the spin frequency and its harmonics. With four panels as the main source of power, the main contribution will be at 2-4 times the spin frequency, i.e., ~1Hz. Assuming a spectral width of f=1/T_spin=0.333Hz, and the requirement of 30pT/sqrt(Hz) at 1Hz [desirement of 10pT/sqrt(Hz) at 1Hz], we obtain a signal <17pT @ 1m [<5.7pT @ 1m], due to solar illumination of consecutive panels. This corresponds to a signal of 17nT @ 10cm from the probe skin [desirement: 5.7nT @ 10cm]. To attain that, all current loops in the power system (i.e., solar cells strings and battery charging circuitry) must have an overall magnetic moment < 8.5×10^{-5} Am^2 [desirement <2.8×10^{-5} Am^2]. If the spectral width of the noise due to spacecraft rotation is larger, then the cleanliness requirement can be further relaxed. Table 3-2 tabulates the guidelines on the power system magnetic moment contribution at DC levels from a non-spinning probe (e.g., computation, or measurement) to ensure compliance from the THEMIS probes in a spinning environment.

Table 3-2: *Power system DC magnetic moment guidelines (for a non-spinning probe) in order to meet AC requirements from a spinning probe with a period of T_spin=3sec. (Assumes Δf=0.333Hz FWHM)*

Item	**Requirement**	**Desire**	***Notes***
Power system	8.5×10^{-5} A-m2	2.8×10^{-5} A-m2	
….Solar Panels	6×10^{-5} A-m2	2×10^{-5} A-m2	
….Battery	1×10^{-5} A-m2	3×10^{-6} A-m2	
….Power system loops	1.5×10^{-5} A-m2	5×10^{-6} A-m2	

3.3.1 THEMIS Main Offenders

Budgeting was based on a survey of THEMIS components and identifying (based on prior experience) the main offenders listed below in decreasing order for each group:

- Hard Perm Fields: Latch valves, Thruster valves, Tanks, Motors, SST magnets
- Soft Perm Fields: Mu metal shielding, Welding
- Stray Fields: Solar panels, Current loops (and power cables), Battery, RF components
- AC Fields: Solar panels, Power converters

Special considerations and activities taken or to be taken for each of these major offenders are described in the sections below.

3.3.1.1 Latch Valves

The THEMIS latch valves shall be geometrically compensated per analysis to minimize their field at 2 meters. The valves shall have moments matched as close as possible and aligned in anti-parallel directions as close together as possible. Anti-parallel matching of the moments for an open position ideally produces a 0nT field at 2m, allowing a budget for uncertainty in temperature fluctuations and geometrical offsets. Measurements shall indicate valve DC field and demonstrate typical variations of magnet field within the same family. Analysis shall demonstrate a constant DC offset in accordance with Table 3-1 above. Alternatively (should such measurements not be available), the valves will be measured at UCLA as a combined system in the geometry selected.

3.3.1.2 Thruster Valves

The THEMIS thruster valves shall be procured in accordance with Table 3-1 above. Repeatability with temperature and operation shall also be considered.

3.3.1.3 Tanks

Inconel 718 propulsion tanks have been approved for use on the THEMIS mission based on the analytical calculations and preliminary testing as described below:

For a sphere, the induced magnetic moment can be calculated as follows: $m = H * S / (1+S/3) * V$
For small S, the equation can be reduced to: $m = H * S * V$
Where: *S=susceptibility, H=external field, V= volume of the sphere*

The stated susceptibility of Inconel 718 is 1.1×10^{-3} to 1.3×10^{-3}. Therefore, assuming a susceptibility of 0.001, a volume of 1000cm3, and an external field corresponding to 0.5Gauss (50.000nT), the following magnetic moments can be calculated:

Gauss system: m_gauss = B (in Gauss) / 4 / Pi * S * V (in cm3) = 0.04Gcm3
SI system: m_ampere = B (in nT) / my0 * S * V (in m3) = 0.04mAm2

1Gcm3 or 1mAm2 generates a field of 0.2nT in a distance of 1m, well below the noise of the magnetometer experiments (FGM and SCM).

To ensure the Inconel properties were as expected, a test was performed on a prototype tank to show <10nT signature in 35,000nT external field at 0.5 inches away from tank (or <0.02pT at 1m). The test was performed at UCLA, where the tank was suspended with a rope from an overhead pipe. The total field was about 35000nT. Only the N-S horizontal component was measured. The horizontal component was 17960nT with the LSB on the meter at 10nT. There was no change in the field reading when moving the tank to within 0.5 inch (12.7mm), confirming less than 10nT at 0.5 inch induced field.

The Inconel tanks were approved with the understanding that cold-form processing will be guaranteed, the first tank will be tested after welding, and magnetic cleanliness will be tested after Probe I&T. In addition, it was determined that geometry is not of importance for small susceptibilities and the rotation of the tank should have no influence.

3.3.1.4 Motors

Motors are used to deploy 4 radial booms for the electric field experiment on THEMIS. A brush motor design has been selected. The motor will have mu metal shielding and has been tested at UCLA.

3.3.1.5 SST Magnets

The SST magnets consist of 4 permanent magnets and 2 yokes, oriented with two oppositely oriented dipoles. Stray fields are estimated at <10nT at a 1-meter distance. The SST has a quadropole, so it is expected to drop off faster that r^3 (more like r^4). Assuming the quadropole contribution starts at 1m then the value at 2m will be 0.625nT. If the quadropole contribution starts earlier, more margin exists. The SST magnets shall be tested early in configuration to ensure that they meet the allocation indicated in Table 3-1. Although not expected or desired, compensating magnets can be used if necessary.

3.3.1.6 Mu Metal Shielding

Normally, if there are experiments on board that are sensitive to ambient magnetic fields, magnetic shielding, using more or less "soft" magnetic materials (as opposed to permanent magnets) are used to shield to some extent DC, and more often AC magnetic fields. However, for the spacecraft carrying magnetometers there are strong objections to the use of shielding materials for DC or AC magnetic fields. The reason for this is that for perm fields produced by permanent magnets, the residual field is fairly stable and can be calibrated or, in some, but not all cases, compensated using highly stable permanent magnets, whereas the soft magnetic shielding material itself can easily be magnetized during handling, vibration, launch, etc. This will produce an unknown, variable field which cannot be calibrated or subtracted during flight. Therefore it is preferable to accept a known (but still small) perm field background which is stable instead of having a lower, but variable field produced by soft magnetic shielding material. Thus, any use of soft magnetic material for shielding must be cleared with the Magnetics Review Board.

3.3.1.7 Welding

For THEMIS, structural welding on components such as the battery or propulsion system are done in accordance with mil standards and fill material selection is based on fracture toughness and other mechanical properties, not driven by magnetic requirements. The propulsion system pipes are non-magnetic 304L stainless steel. It is expected that sample welds will be tested by UCLA.

3.3.1.8 Solar Panels

The Solar Array can be the most significant source of stray magnetic fields in the spacecraft due to the large currents circulating there when illuminated. Because THEMIS is a spinning spacecraft, spurious noise generated by changes in currents collected by batteries, as the square-shaped probe rotates, is a serious issue. On the other hand, its linear geometry makes it straightforward to compensate or cancel out by correct placement of forward and return interconnections. The stray fields can be minimized by the technique of "backwiring". In backwiring, the return wire (or wires, if more than one) from each string of solar cell modules is (are) returned behind the modules of that particular string and carefully routed along a line just behind the center-line of the modules. Separate wiring of multiple parallel wires is preferential for reducing fringe fields than a single wire carrying the total current.

The advantages of backwiring are obvious. Each string and module of the string is self-canceling and does not depend on the magnetic field of an adjacent module or string for cancellation. Thus, if a module fails during flight, the current in both the string and the return drops to zero simultaneously, leaving no uncompensated currents in the array. Similarly, if the current level is reduced in a string through the loss of cells, the current in the return wire (which is the same current) is reduced so that there is no imbalance.

The net dipole moment of the THEMIS solar array panels shall be minimized by alternating the current direction of solar cell strings, twisting wire pairs of opposite polarity, using a symmetrical panel layout, retracing on the backside the same circuit paths, and orienting wire runs appropriately. Given the thickness of the THEMIS panels, no cell should be left uncancelled and all cells should be nulled with opposite loops as close as possible. The Magnetics Control Board shall review the Solar Array vendor specifications to ensure compliance.

A significant advantage of array geometries is that they can be easily modeled. Based on the geometry of the solar array interconnects, UCLA will model the resultant magnetic fields when the array is illuminated. In addition, modeling will be used to evaluate the magnetic signature for differing cells sizes and layouts including horizontal and vertical string configurations and backwiring schemes.

3.3.1.9 Current Loops and Power Cables

To ensure problems from current loops and power cables are minimized to the greatest extent possible the following guidelines shall be followed on THEMIS:

- (1) Leads carrying appreciable current (greater than 1 mA) must be twisted with the return lead, such that the net current in the twisted wires is as near zero as possible. Even if it is not possible to achieve a null net current, partial cancellation is still desirable.
- (2) In wiring through connectors all leads should be kept as close as possible to their return to obtain the best possible self-cancellation through the connector (i.e. adjacent pins).
- (3) All connectors should be placed in one particular area of the assembly, this area being as small as possible.
- (4) All power wiring throughout the spacecraft requires twisted cabling.
- (5) Extreme caution must be exercised to avoid circulating ground loops through the structure (single point ground).

Precautions 1, 2 and 3 aim to reduce the possible area of the current loops in the assemblies and probe harness. A large magnetic moment can be built up by summing many relatively small moments. Thus, the basic approach is to minimize even the smallest loops within the assemblies and harness.

Precautions 1 and 2 are especially necessary when dealing with assemblies in Power Supplies. The current carrying leads internal to the converter assemblies must be carefully routed and twisted wherever possible to provide cancellation of stray fields.

All wiring in the probe harness carrying more than 1 mA should be twisted with the return, with the number of twists per unit length determined by the gauge of the wire used. The twisting must be tight enough to prevent "birdcaging" of the wires but not so tight that the wires will be twisted into solenoids. Typically, the number of twists ranges from 1 to 0.3 turns per cm. Precaution 4 is a restatement of 1, specifically dealing with the power distribution leads.

Precaution 5 suggests a single-point power grounding system to avoid uncontrolled, circulating ground loops in the equipment platform. The prime danger is that the ground loops cannot be accurately calculated in that they may not be completely controlled. In addition, they are very hard to determine experimentally prior to the magnetic testing of the completed, integrated spacecraft.

In addition to these guidelines, shunt resistors must be selected with the DC field specifications in mind. Current loops can be minimized by careful placing of shunt capacitors.

3.3.1.10 Battery

Batteries can be a major source of background field. However, careful design and compensation techniques have been developed to cancel the external field, for instance on the FAST, Ulysses and Giotto missions. The Magnetics Control Board shall review the Battery Specification and provide suggestions on how such techniques can be easily and cost-effectively implemented. In addition, the Battery shall be tested at UCLA as early as possible.

3.3.1.11 RF Components

Antenna/RF components often use magnetically hard material (springs, magnets, gyrators, circulators). RF components shall be inspected and sniffed very carefully, and degaussed if necessary. Care shall be taken to ensure that degaussing will not affect the transponder performance. Early testing at UCLA will provide an indication of any adverse effects from degaussing.

3.3.1.12 AC Fields

As discussed above, the main concern for the THEMIS AC-magnetic experiment is the level of noise produced by the changes in the collected current from the solar cells as the probe rotates. Effort will be made to accurately model this effect early in the program.

In addition to this concern, beat frequencies of power converters must be avoided so as not to interfere with ambient AC (SCM and FGM) field measurements. To alleviate this concern, THEMIS shall develop a Frequency Management Plan to examine the frequencies of available power converters early in the development stage and avoid nearby frequencies. The plan shall ensure that beating frequency between power supplies is beyond 4kHz for SCM measurements and away from 16kHz for FGM measurements.

To a lesser extent, AC magnetic fields generated by the switching transformers, by current loops, and in the case of some PWMs, the switched series inductor, can be of some concern. The transformers and inductors should be well-built, with tight evenly-spaced windings and be of core material well adapted to the operating frequency. Furthermore, overall shielding of the transformers is highly desirable. This usually consists of both a magnetic shield and an electro-static copper shield.

3.4 GENERAL METHODS TO ACHIEVING MAGNETIC CLEANLINESS

As stated earlier, there are two sources of magnetic fields: materials that can be, or have been magnetized (permanent fields), and currents in the spacecraft electrical subsystems that produce magnetic fields (stray fields). This section provides general methods to be implemented by the THEMIS team in addition to the special considerations described above for the THEMIS main offenders.

3.4.1 Permanent Fields

3.4.1.1 Materials

General. Aluminum, fiberglass, magnesium and titanium are all non-magnetic. These are among the most desirable materials for use in structures. Highly magnetic steel or other magnetic materials use should be limited in the structure or mechanical hardware where practical. A286 steel is an acceptable material. Use of titanium fasteners is encouraged both due to their nonmagnetic material and low mass, especially for those applications with larger sizes and greater numbers. Material lists will be provided to the Magnetics Control Board for their review. All materials, if not known to be satisfactory, must be carefully tested prior to their use.

Welding Wire. Ordinary nickel welding wire used for inter-connections between components in welded modules is highly magnetic. As such, its use should be limited. A nickel-copper alloy should be considered for welding. This alloy is composed of 78% copper and 22% nickel. Although a significant fraction of the alloy is nickel, the alloy remains non-magnetic through welding, heat treatment, vibration and all environmental testing. This alloy is easily welded and considered as reliable as nickel.

Plastics and Epoxies. Plastics and epoxies are not magnetic in themselves, but some fillers used are magnetic. Care should be exercised in the use of red and black fillers especially, since these may contain iron in various oxide or metallic forms as colouring agents. Problems are not expected when other fillers are used, such as white or green.

3.4.1.2 Electronic Parts

Resistors. Non-magnetic metal film and carbon composition resistors can easily be obtained if non-magnetic lead materials are specified. Care should be taken in the choice of metal film resistors to avoid the use of those having a spiral or helical pattern in which passing currents will produce large stray magnetic fields.

Capacitors. Tantalum Capacitors: Non-magnetic tantalum capacitors are difficult to find (the use of MINITAN* caps is recommended). The source of magnetic field is in the glass to metal seal and the magnetic lead material commonly employed. However, non-magnetic sintered tantalum, electrolytic slug capacitors and electrolytic tantalum foil capacitors are available with non-magnetic lead material.

The magnetic fields of other types of tantalum capacitors can be reduced somewhat by using the non-magnetic nickel-copper alloy leads in place of the highly magnetic kovar leads with the glass-to-metal seal.

The following types of capacitors are available in non-magnetic forms:

- Fixed Silver Mica Dielectric Dipped Coating
- Fixed Ceramic, Dielectric, Filter, Feedthrough
- Fixed, Glass Dielectric
- Fixed, Ceramic, Dielectric (general purpose)
- Fixed, Mica Dielectric
- Variable, Piston
- Variable

Crystals. *MINITAN capacitors are made by AVX. The standard capacitors in this catalogue have solid Nickel leads which are highly magnetic. These parts should be purchased to the GSFC specification S-311-P-17(01)A which specifies non-magnetic lead material.

Packaging of crystals in titanium or plated brass cans is desirable since this type of packaging is non-magnetic.

Latching Relays. Since the more reliable relay mechanisms depend on magnetic actuation for switching and permanent magnets for latching, the use of relays should be limited to only the most critical functions which cannot be handled by solid state switching.

The magnetic field of the permanent magnet in a latching relay can be minimized through the choice of the smallest, least magnetic relay adequate for the task. Further reduction can be accomplished by the addition of a small permanent compensating magnet, sized and positioned on the relay case so that its magnetic field partially cancels the magnetic field of the magnet internal to the relay.

In the case of banks of (at least two) relays, these should be arranged to achieve maximum mutual compensation.

Wire and Cable. The following precautions are necessary to ensure that non-magnetic wire and coaxial cable are used:

1) No wire with plated steel conductors should be used.
2) No shielded wire with braided steel mesh shielding should be used.

Connectors. It is necessary to specify non-magnetic connectors like Cannon-NMB and AMP Series 109 where practical. Care must be taken when ordering connectors containing springs and bayonet type locking mechanisms. A number of R/F connectors contain kovar glass-to-metal seals. Connector crimp pins may be magnetically clean but exhibit field after crimping. While this field may be low, i.e., several nT at a cm, it can cause problems if the connector is in close proximity to the magnetometer sensor.

Transistors. When using single transistors, non-magnetic packages should be given preference. Heat wires made of Kovar should be trimmed as short as possible.

Diodes. Although the majority of diodes are commonly available in glass packaging employing large, highly magnetic glass-to-metal seals and lead materials, several types of acceptable packages are available. Among them are the "DO-7" package and the "Adam" package. At times it may be necessary to use diodes which are available only with the highly magnetic lead materials. Kovar lead wires should be trimmed as short as possible.

Integrated Circuits. By minimizing the lead length to the smallest practical value, the magnetic field of integrated circuits can be reduced. Careful layout, avoiding the addition of small magnetic contributions, should be used. Back-to-back mounting of electronic boards can also minimize the resultant field of assemblies.

Ferrite Cores and Pulse Transformers. Generally, ferrite cores exhibit less magnetic field after magnetizing than powdered iron cores of similar size. The size appears to be the only factor in determining the magnetic moment retained by the core. Since the powdered iron cores retain higher magnetic moments after exposure to a magnetic field, the use of powdered iron cores should be avoided wherever possible.

Many small pulse transformers are acceptable for use. The size of the core or bobbin determines the magnetic field retained after exposure to a magnetizing field. Small cores or bobbins wound with non-magnetic copper wire are preferred.

Power Transformers, Chokes and Inductors. All magnetic components must be carefully wound on toroidal cores with nonmagnetic copper wire (using bifilar winding techniques when possible and appropriate). In this manner, the permanent and stray fields of the magnetic components are minimized.

3.4.2 Stray Fields

Many techniques have been identified for minimizing the stray fields produced by currents within the spacecraft and solar array, both of which were discussed in detail in the THEMIS Main Offenders Section.

Parts with Magnetic Cores. In general, the construction of magnetically acceptable power transformers, chokes and inductors is a problem. As previously discussed, these parts can be constructed with very low permanent fields. However, the stray fields associated with them can be quite large and care must be taken to reduce them to an acceptable level. Although most currents in the transformers and inductors are high frequency, DC offsets are usually present in at least one set of windings and large DC currents are always present in the chokes. Studies have been made to determine the factors which significantly affect the stray magnetic fields of the parts when direct current is applied. The results of these studies may be summarized as follows:

1) Only ring cores with toroidal windings should be used for transformers and inductors.
2) The windings, whether they be few or many, must be uniformly spaced around the toroid.
3) The windings must be wound very tightly to the core to reduce air gaps. The use of multifilar magnet wire is recommended.

4. MAGNETICS TESTING AND VERIFICATION

This section contains the testing and verification requirements for the THEMIS magnetic control program, including the following specific categories:

- Magnetic assessments of subsystem components and assemblies
- Development testing of components and assemblies
- Formal subsystem/assembly testing

- Demagnetization of flight hardware and post-demagnetization control of flight hardware
- Integration and Test requirements
- Formal system-level testing

The THEMIS magnetic verification program is an effort to ensure that the probe subsystems/assemblies and ultimately the system as a whole are within their respective allocated magnetic field requirements. In order to achieve these goals, it is necessary to test and evaluate hardware to verify compliance with the design requirements. The easiest way to implement this is to have a simple way of detecting magnetic parts and to test candidate parts for magnetism as early in the design process as possible.

4.1 MAGNETIC ASSESMENT

To provide assurance that subsystems will be able to satisfy their respective requirements after their fabrication and assembly, the Magnetics Control Board will address the adequacy of the magnetic design of subsystems based on descriptions and/or heritage of the hardware. The Board will recommend components that should undergo informal developmental magnetic testing and proceed to obtain samples of these components.

There are no pass/fail criteria for developmental tests, as these tests are for informational purposes only. Developmental test results will be reported to the Magnetics Control Board, which will determine whether there may be a potential problem in satisfying the subsystem/assembly requirements.

4.2 COMPONENT, SUBSYSTEM and ASSEMBLY VERIFICATION

The most important factor in the verification process is to identify magnetic problems early while they can still be corrected. It is recommended that every supplier of hardware have a simple way of checking flight hardware components for magnetism, thus allowing easy identification of magnetic parts at a very early stage of instrument and probe design and construction. This will enable designers to select nonmagnetic alternatives where possible, and to keep track of the magnetic budget of their assembly and hold it within their allocation. If magnetic testing equipment does not exist, UCLA can perform the tests. Information from the tests can also be used to further increase the fidelity and accuracy of the magnetic modeling.

Complete assemblies for which a magnetic specification and allocated magnetic moments are issued will be subjected to acceptance testing to demonstrate that the specification and allocation are met (see Table 3-1 and main offenders list above). Magnetic acceptance testing is performed early in the design process and again just prior to delivery of the subsystem/assembly. Test consists of demagnetizing the subsystem/assembly (if necessary) and then measuring its residual magnetic field. Demagnetization of components with magnetic parts prior to installation is a very cost effective technique since good demagnetizers are available at very low cost. (Latching relays are inherently magnetic and cannot be demagnetized but, as discussed above, they will be arranged in opposing pairs to cancel out their magnetic moment). Subsequent to flight hardware demagnetization, any hardware removed from the probe assembly area shall be re-measured and may be demagnetized again if the residual magnetic field has changed by more than 10 percent. This control is continued through transport to the launch site (ETR) to ensure that the probe was never subjected to high perm conditions.

4.3 PROBE INTEGRATION AND TEST (I&T) REQUIREMENTS

This section describes the requirements necessary to maintain the magnetic cleanliness of the THEMIS probes during integration and test (I&T). Actual step-by-step procedures will be described as part of the general I&T procedures. In most cases, the requirements should be relatively easy to implement. In general, the best protection for the probe is an awareness of its sensitivity to magnetic fields.

Since THEMIS will be measuring faint variations in the magnetic field around the earth, it is very sensitive to any magnetic fields generated internally. Prior to I&T, great care will have been taken to minimize magnetic materials and current loops which generate magnetic fields. In order to maintain magnetic cleanliness, extra precautions must be taken to not magnetically charge any of the material on the probe (such as the battery) with a tool or fixture that is magnetized. Generally, ambient fields will not be a problem except when the source is close (a foot or two) to the probe (such as the vibration table). DC magnetic fields are much more of a problem than AC fields.

- All externally applied fields shall not exceed 2 Gauss at probe location. This level is low enough to prevent magnetization of any materials on the probe. Ambient fields in most areas where the probe will be are well below this level. Potential problem areas, which must be tested, are the vibration table and the thermal vacuum chamber.
- The magnetic field of all fixtures used to support or move the probe shall be measured. The field shall not exceed 2 Gauss at fixture surface. A hall meter should be used to verify and any fixture above 2 Guass should be degaussed.
- The maximum magnetic field on the surface of any tool in the clean tent area shall not exceed 2 Gauss. Tools shall be screened anytime they are brought into the clean tent. Any tools exceeding the specification shall be degaussed and retested. Since tools come in direct contact with the probe, a surface field greater than 2 Gauss could easily magnetically charge something on the probe. This specification does not necessarily require tools made of a non-magnetic material.
- Keys and watches shall not be brought into the clean tent. In addition, jewelry, belt buckles, and other personal metal objects shall be screened. These items can have a substantial magnetic field.
- No DC powered soldering irons shall be used near the probe. The DC magnetic fields from these irons are substantial. If necessary, an AC iron is acceptable, as long as it is powered off away from the probe. If a strong AC field is interrupted suddenly, it will leave some residual magnetism; moving the iron away allows the field to drop off.
- No magnets shall be brought anywhere close to the probe or anything that gets near the spacecraft. If a tool or fixture is exposed to a magnet, it must be tested and probably degaussed prior to it being used with the probe again.

To degauss in the lab, one should use and alternating field, slowly collapse to zero. A stationary coil with 60 Hz current in and equipped with a rheostat can be provided for this purpose. The current should be turned up, then slowly turned down (within 20 seconds). Effectively, one should go around the B-H curve, slowly collapsing the curve area in the Earth's field, leaving 0.3 Gauss (30,000nT) as the remnant field exposure. Assuming a permeability fo 4 gives a field of 1.2G. Then measure surface field with a Hall field device. This device can be used to measure remnant fields as the spacecraft is transferred between facilities.

4.4 PROBE SYSTEM-LEVEL VERIFICATION

System-level testing can be performed with little impact by taking advantage of the normal Integration and Test activities. A magnetically "quiet" period should be selected (usually centered around midnight) and the immediate vicinity of the probe instrumented with magnetometers, which monitor the ambient field. The probe subsystems are commanded through modes that result in significant power changes (already identified from subsystem level testing) and their magnetic signatures recorded. If harnessing and power distribution have been built following the guidelines laid out in this document, these signatures should match those already established individually. On the other hand if secondary current loops and unknown current return paths exist, they will be detected immediately by the test instrumentation allowing corrective action where required.

In addition to these test measurements, measurements of the effect of current loop fields and other dynamic effects at the science magnetometer sensors caused by the operation of the probe in various modes are to be made by the magnetometer instrument teams or representatives.

Due to the fast schedule, and the number of probes, testing at a Magnetic Test Facility to map the probes magnetic field or make system-level measurements of the magnetic field at the magnetometers is not planned. In lieu of this, subsystem/assembly measurements will be used to determine the approximate magnetic field at the sensor by analysis and modeling. However, if schedule permits and subsystem/assembly testing is determined not to be sufficient by the Magnetics Control Board, testing of at least one probe (or two probes to verify variance between builds) may be considered.