THEMIS
Sun Sensor Science Processing
(Preliminary Document)

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Jim Lewis, THEMIS Science Software Engineer

Vassilis Angelopoulos, THEMIS Principal Investigator

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Rev.	Date	Description of Change	Revised By

Distribution List

Name	Email
Jim Lewis, U.C. Berkeley	jwl@ssl.berkeley.edu
Dr. Tai Phan, U.C. Berkeley	phan@ssl.berkeley.edu
Dr. Forrest Mozer, U. C. Berkeley	fmozer@ssl.berkeley.edu
Dr. Robert Ergun, LASP	ree@fast.colorado.edu
Dr. Chris Cully, LASP	cully@colorado.edu
Dr. Manfred Bester	Manfred@ssl.berkeley.edu
Dr. Ellen Taylor, U.C. Berkeley	ertaylor@ssl.berkeley.edu
Dr. Krishan Khurana, UCLA	kkhurana@igpp.ucla.edu
Dr. Dave Sibeck, NASA GSFC	david.g.sibeck@nasa.gov
Dr. Davin Larson, U. C. Berkeley	davin@ssl.berkeley.edu
Dr. James McFadden, U.C. Berkeley	mcfadden@ssl.berkeley.edu
Peter Harvey, U.C. Berkeley	prh@ssl.berkeley.edu
Mark Lewis, U. C. Berkeley	markl@ssl.berkeley.edu
Dan Cosgrove, U.C. Berkeley	cosgrove@ssl.berkeley.edu

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1. Onboard Sun Pulse Processing and Available Telemetry

Each THEMIS probe is equipped with a MSSS (Miniature Spinning Sun Sensor) which detects the times at which the sun crosses the MSSS field of view. The ACS module of the BAU flight software uses the sun crossing times and a filtering algorithm to determine the probe's spin rate.

Each time the BAU detects that a MSSS sun crossing has occurred, its flight software produces an apid 0x305 packet containing the MET (Mission Elapsed Time: count of seconds and 16-bit subseconds since BAU boot) of the sun crossing, and the result of the onboard spin rate calculation. During ground processing, the BAU UTC Offset (telemetered in apid 0x30c) is added to MET to yield time in seconds since the THEMIS epoch 2001-01-01 00:00:00 UTC.

The electrical interface between the BAU and IDPU contains a line dedicated to the BAU sun pulse. The BAU emits a signal over this line whenever a MSSS sun crossing is detected. The IDPU FSW has its own ACS module which performs its own independent spin period determination. The IDPU is also responsible for providing the sectoring clock (32 hardware pulses per spin) to the particle instruments.

The IDPU housekeeping telemetry includes several items pertaining to the sun pulse processing. The spin period and phase error (expected vs. received sun pulse time) are stored in the apid 0x404 IDPU housekeeping packets, which are produced every 2 to 4 seconds, but are often decimated to a rate of one 404 packet per minute. The IDPU also produces a diagnostic quantity called "ISUNTIME" representing the sun pulse time, but ISUNTIME does not contain the full 48-bit timestamp, only 8 bits of seconds and 16 bits of subseconds. It is referenced to the IDPU startup time. Unfortunately, no IDPU UTC offset is telemetered, so this quantity is not useful for ground processing. However, the IDPU spin period may turn out to be very useful for interpreting data acquired during shadows, since it is the basis of the sectoring algorithm which drives the data acquisition of the particle instruments.

2. Ground Processing: Spin Model Calculation from BAU Telemetry

The ground processing of sun sensor data is performed during the L0 packet to L1 CDF processing. This processing takes place one UTC day at a time. The sun pulse times from the BAU telemetry are used to create a "spin model", which at this writing is not a full-fledged L1 product, but is used to populate the spin period and spin phase variables in the L1 state CDFs.

In the current software, the sun pulse data is modeled by a piecewise constant spin period. Each 24-hour time interval is covered by a set of multi-spin segments, such that the spin period is essentially constant within each segment. By constraining the segment start and end times to line up with sun pulse times, phase interpolation between segments is guaranteed not to contain any discontinuities at the segment boundaries.

By averaging the spin period over a multi-spin segment whenever possible, the uncertainty in individual crossing times is mitigated, and the mission requirement (knowledge of instantaneous probe orientation to within 0.1 deg) can be achieved.

The spin model is created using a "greedy" algorithm, where as many crossing times as possible are included in each segment until the phase error threshold (4 msec at this writing) is violated for some crossing time in the segment.

The following (considerably simplified!) pseudo code illustrates the important points of the spin modeling algorithm:

```
Create initial segment using first crossing time and ACS spin period.

WHILE more crossing times remain to be processed:

  Determine how many spins have elapsed between end of segment
  and current crossing times

  Update spin period using start time of current segment, current
  crossing time, and segment spin count

  Test each crossing time within current segment to see if phase
  error threshold (4 msec at this writing) is exceeded

  IF phase error threshold violated anywhere
  THEN finalize current segment without including current crossing
       start new segment with current crossing and ACS spin period
  ELSE include current crossing time in current segment
END crossing time processing loop
```

The final result of this process is a file named "spinmodel.txt" in the working directory of the L0 to L1 processing. Each line in spinmodel.txt represents one constant-spin-period segment and contains the following information:

start time, end time of segment
The modeled spin phase is assumed to be 0.0 degrees at the start and end times, which are currently referenced to the THEMIS epoch 2001-01-01.

start spin number, end spin number
The first crossing time of the data set is arbitrarily assigned spin number 0. Spin number 1 would be one spin later, whether or not that crossing was telemetered.

spin period
The average spin period over this segment: (end time - start time) / spincount

maxerr
The maximum phase error (absolute value in seconds, actual crossing time vs. modeled crossing time) of all the crossing events that were included in this segment.

Here is an excerpt from spinmodel.txt from probe A, 2007-03-23:

```
196300799.608795 196304027.783447 0 1044 3.092121314186 0.003995
196304027.783447 196310972.662979 1044 3290 3.092110210156 0.003999
196310972.662979 196315938.568787 3290 4896 3.092095770860 0.003997
196315938.568787 196331649.482330 4896 9977 3.092090837037 0.003996
196331649.482330 196338312.960953 9977 12132 3.092101449189 0.003548
196338312.960953 196338316.055115 12132 12133 3.094162017107 0.000000
196338316.055115 196344296.204269 12133 14067 3.092114350557 0.004000
```

3. Spin Model Usage

The L1 processing code includes some library routines for loading and working with spin model data as described above. The two most important operations are:

Given a time: return the spin number, spin phase, and spin period

Given a spin number: return the crossing time and spin period

Each operation is implemented by scanning the list of segments until one containing the desired time or spin number is found. With the matching segment in hand, the desired outputs are easily calculated from the segment data.

4. STATE File Processing for Spin Period and Spin Phase

The THEMIS MOC periodically generates predictive and definitive ephemeredes for each of the probes, which constitute the bulk of the data in the L1 state CDFs. The MOC products do not include spin period or spin phase information, so these must be added during the L0 packet to L1 CDF processing using sun sensor data from the probes.

The probe state data is sampled at one minute intervals. The process of adding the spin period and spin phase data is very simple, once the spin model is produced: at each sample time, the spin model library is called to obtain the spin number, spin phase, and spin period at that instant. The spin phase and spin period data is written into the state CDF, yielding the V01 (predictive) or V02 (definitive) L1 state file.

5. Calculating Time Tags for Particle Distributions

The calculation of crossing time given a spin number is useful for time tagging the particle distributions. A distribution packet has a header time which represents (approximately) the time at which the first data was written into that packet. Depending on the instrument configuration, subsequent samples may be produced each spin, or every N spins after the initial sample, where N can be as large as 192 spins between samples.

Since the spin period is subject to variation over such timescales, the simplest approach of adding N*current_spinper to the current sample time to obtain the next sample time may not perform as well as desired. It is more accurate to tag the next sample with the N-th crossing time after the current sample, and this is easy to accomplish with the spin model library:

Calculate initial spin number from the header time, then subtract one spin to obtain the crossing time at which data acquisition began for that sample. Assuming each sample is a one-spin snapshot, the initial time tag is the spin midpoint (crossing time plus half the spin period).

Subsequent samples are time tagged by adding the appropriate increment to the current spin number, then calling the spin model library to obtain the crossing time of that spin. The midpoint of the preceding spin is the next sample time.

6. Known Problems with BAU Sun Pulse Timing

There are a few known issues with the BAU flight software that can affect the sun pulse processing. There are FSW patches that may correct these problems, but due to the inherent risk of changing the BAU software, the patches have not been applied to the probes as of this writing.

From time to time, the MSSS crossing times reported by the BAU are off by about 2 milliseconds. The phase error introduced by these 2 msec glitches can be interpreted by the spin modeling algorithm as a brief change in spin period. The effects are generally limited to the immediate neighborhood of the glitch.

A somewhat more troubling problem is that the BAU can occasionally fail to register a MSSS crossing at all. When this occurs, the BAU ACS module assumes that the spin period has changed, and the next several telemetry samples will have incorrect spin rates until the ACS filter algorithm converges back to the true spin period. Even though the spin modeling algorithm is robust enough to cope with an occasional missed sample (due to a dropped packet, for example), the incorrect ACS spin rate reports can result in a spin model that is missing a spin, and contains a segment with a grossly incorrect spin period at the point of the missed MSSS crossing.

Since the IDPU sectoring algorithm remains relatively undisturbed by these events, the missing spin in the spin model can result in a mismatch between the modeled behavior and the true data acquisition times. Any particle distribution packet in progress during one of these missed sun pulses will most likely contain some off-by-one-spin errors in the sample time tags.

Workarounds for both BAU FSW problems have been proposed, and should be implemented in a future release of the ground processing software.

7. IDPU and Particle Instrument Performance at Unusual Spin Rates

The IDPU spin sectoring algorithm (which generates a hardware 32 sector per spin signal to drive the particle instruments) only operates properly at spin rates of 5.0 sec/spin and faster. If the spin rate exceeds 5.0 sec/spin (e.g. during EFI boom deployments), both the onboard spin fit processing and the hardware sectoring clock operate as if the spin period is 5.0 sec/spin exactly.

The spin fits are rendered useless by this limitation, so the ground software rejects spin fit samples acquired during these periods. The particle distributions may still contain some useful information, so they are written into the L1 CDFs, but the mismatch between the spin model and the IDPU sectoring clock under these conditions can result in non-monotonic sample times. This is because the packets fill faster than one would expect from the spin model, so the time tags assigned to the last few samples in the packet may be later than the first few time tags in the next packet.

If the probe spins too fast (approximately 2.5 sec/spin or faster),a different problem arises. The IDPU sectoring clock works as expected, but the ETC board produces more data in one of these fast spins than can be sent to the IDPU during the time available. The DMA data transfer from ETC to IDPU becomes erratic, and the required synchronization between data flow and packet header time stamping is lost. This causes both gaps and non-monotonicities in the sample time tags.

Both these conditions are expected to occur only during EFI boom deployments, so the vast majority of THEMIS probe data will be unaffected.

8. Known Issues and Proposed Enhancements to Sun Pulse Processing

The current spin modeling algorithm works quite well in practice, but there is still room for improvement.

The piecewise constant spin rate model cannot account for slow drifts in spin rate over time. Such drifts have been observed in THEMIS data, most likely due to thermal expansion and contraction of the spacecraft body. The current algorithm interprets such drifts as a slowly increasing phase error, and starts a new constant-spin-period segment when the phase error exceeds the current threshold of 4 msec. If one were to plot modeled spin period against time, the plot would show large discrete jumps instead of a slow drift.

By adding a spin rate drift term to the spin model, these effects can be accounted for, yielding a smoother and more realistic picture of the spin rate behavior over time, and increasing the accuracy of the instantaneous spacecraft attitude determination.

Some of the previously mentioned BAU sun pulse processing issues can affect the spin model with varying degrees of severity, and even if the problems are rectified by future FSW patches, it would be desirable to clean up the data already collected.

Many of the 2 msec glitches in the MSSS crossing times can be removed by modifying the modeling algorithm to look at the next sample, before committing to processing the current sample. If the current sample is 2 msec early, but the next sample is back on time, it may be better to discard the current sample. Such an algorithm may also mitigate the effects of the missed MSSS crossings and accompanying ACS spin rate upsets.

The spin model data is not currently released in any of the L1 CDF data products (except, somewhat indirectly, in the state CDF spin period and spin phase data). In a future release of the L0 to L1 processing tools, the spin model data will be released in CDF format. At that point, it may be advantageous for processing that requires spin phase or spin timing to work directly with the spin model, rather than indirectly via the state CDF at one minute time resolution.

Although there is no science requirement to calculate accurate sample times and spacecraft orientation during shadows (when sun sensor data is not available) such capabilities would be nice to have. As things stand now, spin data during shadows is extrapolated from the last constant-spin-period segment before the eclipse. The particle sample timing, however, is derived from the IDPU sectoring algorithm, which flywheels through shadows at whatever spin period was last calculated by the IDPU ACS filtering algorithm. The slight difference in spin period between the spin model and the fly wheeling IDPU sector clock will accumulate over time, with accumulating errors in the particle data and spin fit sample times. Sample times calculated using the IDPU ACS spin period will probably be more accurate than those calculated using the extrapolated spin model.

For attitude determination through shadows, a slightly different approach is needed, since in this case we are more concerned with the actual spin behavior, as opposed to simulating the IDPU sectoring algorithm. It may be possible to model the spin period changes by comparing the spin period just before and just after the penumbral phase of the shadow period. (Data acquired during penumbral passage, when the solar disk is partially eclipsed by the Earth or Moon, is subject to timing errors due to the asymmetry introduced by the eclipse). Spin tone analysis of FGM data may also be useful in characterizing the spin behavior through shadows, if the ambient magnetic field is strong and stable enough to show usable spin tones.