THEMIS OPERATIONS


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Abstract. THEMIS – a five-spacecraft constellation to study magnetospheric events leading to auroral outbursts – launched on February 17, 2007. All aspects of operations are conducted at the Mission Operations Center at the University of California at Berkeley. Activities of the multi-mission operations team include mission and science operations, flight dynamics and ground station operations. Communications with the constellation are primarily established via the Berkeley Ground Station, while NASA’s Ground Network provides secondary pass coverage. In addition, NASA’s Space Network supports maneuver operations near perigee. Following a successful launch campaign, the operations team performed on-orbit probe bus and instrument check-out and commissioning tasks, and placed the constellation initially into a coast phase orbit configuration to control orbit dispersion and conduct initial science operations during the summer of 2007. Mission orbit placement was completed in the fall of 2007, in time for the first winter observing season in the Earth’s magnetospheric tail. Over the course of the first 18 months of on-orbit constellation operations, procedures for instrument configuration, science data acquisition, and navigation were refined, and software systems were enhanced. Overall, the implemented ground systems at the Mission Operations Center proved to be very successful and completely adequate to support reliable and efficient constellation operations. A high degree of systems automation is employed to support lights-out operations during off-hours.

Keywords: THEMIS; satellite constellation; satellite ground systems; mission operations; flight operations.
1. Introduction

The *Time History of Events and Macroscale Interactions during Substorms* (THEMIS) mission is a National Aeronautics and Space Administration (NASA) Medium-class Explorer (MIDEX) mission to study magnetospheric events leading to auroral outbursts (Angelopoulos, 2008). The space segment consists of five small, identical spacecraft called *probes*, each carrying a suite of five science instruments. The probes were launched on February 17, 2007 on a single Delta II launch vehicle from Cape Canaveral Air Force Station (CCAFS) into a highly elliptical insertion orbit with an orbital period of 31.4 hours at an inclination of 16 deg. Significant magnetospheric science observations were already made in March 2007, only little more than one month after launch. Following an initial 30-day on-orbit check-out and science instrument commissioning period, the probes were placed into nearly identical, temporary coast phase orbits to control orbital dispersions. Mission orbit placement in preparation for the first winter observing season commenced in early September 2007, and the constellation was fully deployed by mid January 2008.

THEMIS is NASA’s first scientific constellation mission. This paper describes aspects of mission operations conducted by the University of California at Berkeley’s Space Sciences Laboratory (UCB/SSL), and covers ground systems, operational software tools, navigation, planning of science observations and data recovery.

1.1 Concept of Operations

The THEMIS probes are robust, spin-stabilized instrument platforms with nominal operational spin rates of 20 rpm. During normal science operations, the probes are oriented such that their spin axes point towards either the ecliptic north or south pole, providing a stable and safe power and thermal environment. Monopropellant hydrazine propulsion systems are used for orbit and attitude control. Each probe carries an identical suite of five science instruments comprising two magnetometers, two particle detectors to measure the energy distribution of electrons and ions, and an electric field instrument.

For communications at S-band, ten telemetry data rates allow for high-rate data recovery near perigee and closing of the telemetry and command links with 11-m
class ground antennas out to the farthest apogee at a range of 200,000 km. All probes share the same radio frequencies, but have unique spacecraft identifiers that are hard-coded in each probe bus. Telemetry and command frame formats are compatible with the Consultative Committee for Space Data Systems (CCSDS) Version 1 standard. Telemetry links employ concatenated Reed-Solomon and rate-1/2 convolutional coding with Viterbi decoding for error correction. In addition to seven ground stations, special operations near perigee are also supported by NASA’s Tracking and Data Relay Satellite System (TDRSS), a.k.a. the Space Network (SN). Orbit determination is based on two-way Doppler tracking, and attitude determination on Sun sensor and three-axis magnetometer data.

The THEMIS constellation operates in store-and-forward mode. Science and engineering data are recorded in on-board solid-state memory and are recovered primarily near perigee at the highest data rate compatible with the predicted link margin for any given pass. Instrument configuration for science data acquisition is based on modeled crossing times of magnetospheric regions of interest in combination with various on-board trigger algorithms (Harvey et al., 2008).

All aspects of THEMIS constellation management and operations are performed at the Mission Operations Center (MOC) at UCB/SSL and include mission and science operations, flight dynamics and ground station operations. A high degree of automation and autonomy is achieved using a number of novel tools that are integrated into a coherent ground system to perform all required operations functions, particularly in the areas of routine task execution, flight dynamics products generation, pass support and ground station operations, networking, telemetry processing and archiving, and spacecraft limit monitoring with error detection and operator notification. Virtually all state-of-health monitoring, tracking and data recovery passes are conducted in lights-out mode.

1.2 MISSION TIMELINE

An overview of the THEMIS mission timeline, beginning with launch on February 17, 2007, is shown in Figure 1. Since all five probes were launched with an identical configuration and identical fuel loads, any probe could in principle assume any role in the constellation. Following on-orbit check-out and detailed characterization of all probe buses and science instruments, the probe placement decision had to be made to determine which probe would be maneuvered into which
of the five mission orbits. This decision would be based on knowledge gained from pre-launch testing and on-orbit performance during the first 38 days. Once the probe placement decision was made, it would be clear as to which probes could deploy their Electric Field Instruments and which ones had to keep their wire booms stowed to maintain a low moment of inertia required to perform a series of attitude and ΔV maneuvers for efficient mission orbit placement.

As a result of several launch slips from August 2006 to February 2007, a coast phase was inserted into the timeline in order to control orbital dispersion prior to the mission orbit placement in the fall of 2007 (Frey et al., 2008). The coast phase would also allow for two months of additional science observations with the five probes arranged in a string-of-pearls configuration. Next would be the mission orbit placement campaign, followed by the first tail season (T1), the first dayside season (D1), the second tail season (T2) and a nominal mission termination.

![Figure 1. THEMIS mission timeline from launch to nominal mission termination.](image)

**Figure 1.** THEMIS mission timeline from launch to nominal mission termination.

### 2. Ground Systems

Ground systems supporting the THEMIS constellation include the Mission and Science Operations Centers (MOC/SOC), the Flight Dynamics Center (FDC) and the primary Berkeley Ground Station (BGS), all co-located at UCB/SSL, plus a
number of external elements, such as the secondary Ground Network (GN) stations and the Space Network (SN) with their interconnecting network links.

2.1 GROUND SYSTEM ELEMENTS

From the earliest stage of development, THEMIS flight operations were able to take advantage of much of the existing ground system architecture already developed to operate three other NASA missions, the Fast Auroral Snapshot Explorer (FAST), the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) (Bester et al., 2003). Nevertheless, the simultaneous launch of five new spacecraft would more than double the number of active satellites managed by the operations group at UCB/SSL, which drove requirements towards a high degree of reliability, autonomy and integration of all components into one coherent, multi-mission ground system. Additionally, THEMIS presented a number of new challenges that had to be managed by an efficient but relatively small flight operations team. Among these were:

- A complex constellation mission design
- Orbit and attitude maneuver planning, execution, reconstruction and calibration for several hundred maneuvers over the life of the mission.
- Ground-based orbit and attitude determination
- Pass support planning for five separate spacecraft using seven ground stations spread around the globe, as well as five different Tracking and Data Relay Satellites (TDRS).
- Sufficient pass coverage to play back science data and collect Doppler tracking data, amounting to no fewer than 15-20 pass supports every day of the year.

To accomplish these complex tasks, the existing multi-mission environment at UCB/SSL was expanded to meet the new requirements. All of the already integrated tools were reused, while a number of new tools were added. The latter include primarily flight dynamics and navigation software to perform the mission design and navigation functions, described in more detail in the following sections. A block diagram of the functional elements of the THEMIS ground system is shown in Figure 2. The spacecraft command and control system for THEMIS is the Integrated Test and Operations System (ITOS) (Pfarr et al., 2008), which is also used for FAST and
RHESSI mission operations. Other tools within Mission Operations support functions such as pass scheduling, mission planning, data trending and anomaly resolution. Details of the science data processing and archiving systems are covered elsewhere (Phan et al., 2008).

Figure 2. THEMIS ground system functions and operational interfaces.
2.2 COMMUNICATIONS NETWORK

Stored data playback must occur when each probe is near perigee, and since the probes’ on-board solid-state memory is not large enough to store more than one orbit’s worth of data, the communications network requires a sufficient selection of ground stations so at least one will be available to cover every perigee pass of every probe. The coordinated nature of the probes’ orbits often causes several probes to approach perigee at nearly the same time, requiring separate ground stations to support simultaneous data playback passes. In addition to data recovery, accurate Doppler-based orbit determination requires that several measurement arcs be taken from different ground stations on every orbit. The communications links were designed to be closed with 11-meter class ground stations at the lowest telemetry rates out to the farthest apogee at a 200,000 km range, allowing execution of maneuvers as well as recording two-way Doppler data and monitoring state-of-health telemetry in real-time anywhere along mission orbits. The seven ground stations currently used by THEMIS are:

1. Berkeley, California (BGS) – 11-m antenna
2. Wallops Island, Virginia (WGS) – 11-m antenna
3. Merritt Island, Florida (MILA) – two 9-m antennas
4. Santiago, Chile (AGO) – 9 and 12-m antennas
5. Hartebeesthoek, South Africa (HBK) – 10 and 12-m antennas
6. Dongara, Australia (USNAU) – 13-m antenna
7. South Point, Hawaii (USNHI) – 13-m antenna

An overview of the THEMIS mission control network is shown in Figure 3. Network connectivity is achieved via a frame routing and relay system that can be envisioned as the Transmission Control Protocol / Internet Protocol (TCP/IP) equivalent of a matrix switch which is configured remotely by the centralized, automated pass and network scheduling system to facilitate secure command and telemetry data flows for any scheduled pass (Bester and Stroozas, 2007).
Figure 3. The THEMIS communications network includes seven ground stations and the Tracking and Data Relay Satellite System (TDRSS).

### 2.3 MULTI-MISSION CONTROL CENTER

Established in 1998 to support the RHESSI and FAST missions, the Multi-Mission Operations Center (MOC) at UCB/SSL was designed from the onset to function as a truly multi-mission environment, and is now the nerve center for THEMIS flight operations, as well as ongoing operation of the FAST, RHESSI and CHIPS satellites (Bester et al., 2003). All computer systems in the MOC are supported by a secure, isolated operations network with centralized, redundant file servers. Critical computers and electronics are backed up by uninterruptible power supplies (UPS) as well as a diesel generator, guaranteeing that the MOC and the Berkeley Ground Station can operate through an extended power outage.

The bulk of the 850 square foot facility, shown in the floor plan in Figure 4, is taken up by equipment racks needed to operate the Berkeley Ground Station (BGS), and by THEMIS ITOS workstations. Each THEMIS probe has a dedicated ITOS workstation for command and control (OPS 1-5) to allow for simultaneous communication pass supports with all five probes. A second row of five telemetry-only ITOS workstations (OPS 6-10) accommodates instrument and spacecraft engineering and flight dynamics staff during critical operations and maneuvers. Though not used for spacecraft commanding, these workstations can nevertheless be
reconfigured as command consoles in the event one of the primary ITOS systems fails.

The Flight Dynamics Center (FDC) is co-located with the MOC and is responsible for timely mission design, maneuver planning and reconstruction, as well as orbit and attitude determination. Servers for science data processing and storage are located in the adjacent building.

![Figure 4. Floor plan of the multi-mission operations center at UCB/SSL.](image)

### 2.4 SOFTWARE TOOLS

The software needed to operate the THEMIS mission is a blend of government off-the-shelf (GOTS) and commercial-off-the-shelf (COTS) products, heritage software that had already been developed in-house for other missions, and software written specifically for the THEMIS mission.

1. **ITOS** – the Integrated Test and Operations System, a NASA/GSFC-developed system already in use for the FAST and RHESSI missions, is used for THEMIS real-time telemetry monitoring and command and control as well as
limit-level-based health and safety monitoring (Pfarr et al., 2008). In-house development extends ITOS and integrates it with other components of the ground system allowing pass supports, including recovery of stored science and engineering telemetry data, to be conducted in a hands-off and lights-out manner with a high degree of reliability.

2. SatTrack – a comprehensive software suite that controls, monitors, coordinates and automates most aspects of the ground system, such as the completely automated operation of the Berkeley Ground Station, scheduling, maintaining and disseminating the operational pass schedule for all active satellites, routing command and telemetry streams between ground stations and command and telemetry workstations, and autonomously configuring ITOS and other software clients prior to each pass support (Bester et al., 2008).

3. BFDS – the Berkeley Flight Dynamics System is based on the SatTrack Suite and generates and distributes daily-updated orbital data products necessary for science planning, pass support, and maneuver execution.

4. MDT – the Mission Design Tool is an in-house developed suite of Interactive Data Language (IDL) programs that was purposely written for overall THEMIS mission orbit design as well as fast, iterative maneuver re-planning (Frey et al., 2008).

5. GTDS – the Goddard Trajectory Determination System is a NASA/GSFC GOTS software package used for THEMIS orbit determination and orbit propagation with a high-fidelity force model.

6. GMAN – the General Maneuver Program, another NASA/GSFC GOTS software package, is invoked by the MDT to perform high-accuracy, finite maneuver targeting.

7. MSASS – the Multi-mission Spin Axis Stabilized Spacecraft attitude determination system is a suite of MATLAB-based tools used to perform batch and real-time ground-based attitude determination. MSASS was inherited from NASA/GSFC and extended in-house.

8. BTAPS – the Berkeley Trending and Plotting System is another in-house developed software suite that decommutates and converts all real-time and post-pass engineering telemetry data and stores these in a MySQL database,
allowing both real-time strip charting as well as archival plotting, trending and anomaly detection (Cruce et al., 2007). BTAPS also provides maneuver and attitude related engineering telemetry data for attitude determination and maneuver reconstruction.

9. BMPS – the Berkeley Mission Planning System incorporates orbital data products generated by the MDT and BFDS, and builds Absolute Time Sequence (ATS) command tables that autonomously control science data collection and spacecraft operation outside of real-time passes.

10. BEARS – the Berkeley Emergency and Anomaly Response System detects spacecraft and ground system anomalies and broadcasts messages to the Flight Operations Team (FOT) members by way of electronic mail and two-way pager messages, until the problem is resolved.

11. SWSI – the Space Network Web Services Interface allows scheduling and remote monitoring of performance of the White Sands Ground Terminal (WSGT) during pass supports via the Tracking and Data Relay Satellite System (TDRSS).

3. Mission Operations

THEMIS mission operations include all aspects and activities related to managing the constellation on orbit. Members of the operations team participated in all phases of the mission life cycle, beginning with the earliest stages of proposal writing throughout the mission development and integration phases to prepare and plan for on-orbit operations.

3.1 PRE-LAUNCH TESTING

In preparation for on-orbit operations, the THEMIS team developed and executed an extensive Mission Readiness Test (MRT) program. Individual test catalog items were designed to exercise all aspects of on-orbit operations as close as possible – where practical – to a Test-like-you-fly configuration, and were categorized in the following scheme:

0xx - Ground Systems
1xx - Flight Systems
2xx - Interfaces and Data Flows
3xx - Ground Operations
4xx - Launch Operations
5xx - Special Operations
6xx - Maneuver Operations
7xx - Normal Science Operations
8xx - Contingency Operations
9xx - Operational Readiness Tests

All of the nearly 300 individual tests with an increased level of complexity and involvement of different systems elements were executed successfully at least once to obtain a pass mark. Many tests, such as end-to-end data flows between the ground stations and the MOC, were repeated multiple times to shake out any remaining issues and to allow the operations team to gain a high level of proficiency and confidence. This comprehensive and meticulous test approach paid off many times over after launch, as it allowed the operations team to focus on operating the constellation rather than being forced to spend precious time with debugging ground systems issues.

Since final integration of the probes occurred in the same building at UCB/SSL in which the MOC and BGS are located, the operations team had a unique opportunity to perform radio frequency (RF) and data compatibility tests with full end-to-end data flows in a way that most missions do not have. Communications were established via a low-power RF path by pointing the 11-m antenna at the integration facility and commanding the five probes from the MOC as if they were on orbit already. A full cycle of round-robin state-of-health checks with all five probes could be simulated in the same way it would occur during the first acquisition after orbit insertion.

Leading up to launch, a series of formal mission simulations and dress rehearsals were conducted (Harvey et al., 2008). These involved the MOC, the THEMIS probes and personnel at CCAFS, United Launch Alliance (ULA), the NASA Ground and Space Networks (GN/SN), NASA’s Integrated Services Network (NISN), and the Flight Dynamics Facility (FDF) at GSFC. Simulations were conducted six times for Launch Day (LD) and twice for Launch Day + 1 (LD+1).
3.2 LAUNCH AND EARLY OPERATIONS PHASE

The THEMIS launch was originally scheduled for Thursday, February 15th, but was moved to Friday, February 16th because lightning storms near the launch pad delayed the fueling operations at L−2 days. On February 16th, the countdown was in the 4-minute built-in hold just prior to the opening of the launch window at 23:05:00 UTC when excessive high-altitude wind speeds forced the launch to be scrubbed with a 24-hour turn-around. THEMIS finally launched aboard a Delta II 7925-10 from Space Launch Complex (SLC) 17B at CCAFS on Saturday, February 17, 2007 at 23:01:00.384 UTC, right at the opening of the 19-minute launch window.

Following burn-out of the STAR48 third stage solid rocket motor, the five probes separated from the Probe Carrier, beginning with THEMIS A, mounted at the top of the stack, and followed 3 seconds later by the simultaneous release of THEMIS B-E into a 435 × 91,958 km predictive, post-launch insertion orbit at an inclination of 16.0 deg. The Delta II launch sequence is depicted in Figure 5.

To monitor the separation event, a communications link with THEMIS A was established via TDRS West three minutes prior to the scheduled time of separation. As launch occurred on time at the opening of the launch window, vector rotation was not required and the nominal pre-launch state vector was used for acquisition. The spacecraft transmitter was successfully commanded on via blind acquisition 70 min

Figure 5. THEMIS Delta II flight profile on February 17, 2007.
after lift-off at 00:11:00 UTC, and the return link came up nominally at a telemetry rate of 1K (1.024 kbps). Separation occurred right on time at 00:14:00 UTC. Even though separation of only one probe was confirmed in real-time telemetry, there was a high level of confidence that separation of the other four probes had occurred as well.

Shortly after the initial acquisition of THEMIS A and verification of its release, all five probes were contacted via BGS to verify the release of THEMIS B-E, to check their state of health and to record two-way Doppler data in order to obtain an early orbit solution. Insertion attitude parameters are summarized in Table 1. Despite an insertion attitude that was very challenging from a communications perspective, a sufficient number of telemetry frames were received to verify probe separation, attitude and spin rate, and to establish good state of health across the constellation. Figure 6 shows photographs of the post-launch activities at the MOC.

Figure 6: THEMIS launch team at the Mission Operations Center at UCB/SSL.
Table 1: Insertion Orbital Elements and Attitudes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>THEMIS A</th>
<th>THEMIS B</th>
<th>THEMIS C</th>
<th>THEMIS D</th>
<th>THEMIS E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perigee Height ([\text{km}])</td>
<td>466.9</td>
<td>466.8</td>
<td>465.4</td>
<td>466.3</td>
<td>469.5</td>
</tr>
<tr>
<td>Apogee Height ([\text{km}])</td>
<td>87349.9</td>
<td>87329.7</td>
<td>87089.3</td>
<td>87310.6</td>
<td>87548.9</td>
</tr>
<tr>
<td>Inclination ([\text{deg}])</td>
<td>15.9</td>
<td>15.9</td>
<td>15.9</td>
<td>15.9</td>
<td>16.0</td>
</tr>
<tr>
<td>RAAN ([\text{deg}])</td>
<td>329.1</td>
<td>329.1</td>
<td>329.1</td>
<td>329.1</td>
<td>328.9</td>
</tr>
<tr>
<td>ARG. of Perigee ([\text{deg}])</td>
<td>319.8</td>
<td>319.8</td>
<td>319.8</td>
<td>319.8</td>
<td>320.0</td>
</tr>
<tr>
<td>Anomalistc Period ([\text{h}])</td>
<td>31.174</td>
<td>31.164</td>
<td>31.052</td>
<td>31.155</td>
<td>31.267</td>
</tr>
<tr>
<td>Predicted Spin Rate ([\text{rpm}])</td>
<td>16.0 ± 2.0</td>
<td>16.0 ± 2.0</td>
<td>16.0 ± 2.0</td>
<td>16.0 ± 2.0</td>
<td>16.0 ± 2.0</td>
</tr>
<tr>
<td>Observed Spin Rate ([\text{rpm}])</td>
<td>17.1</td>
<td>16.1</td>
<td>16.1</td>
<td>16.1</td>
<td>16.1</td>
</tr>
<tr>
<td>Predicted Sun Aspect Angle ([\text{deg}])</td>
<td>47.0 ± 5.0</td>
<td>47.0 ± 5.0</td>
<td>47.0 ± 5.0</td>
<td>47.0 ± 5.0</td>
<td>47.0 ± 5.0</td>
</tr>
<tr>
<td>Observed Sun Aspect Angle ([\text{deg}])</td>
<td>45.6</td>
<td>47.3</td>
<td>46.2</td>
<td>41.8</td>
<td>43.4</td>
</tr>
</tbody>
</table>

Note: Orbital elements are given in Earth Centered Inertial (ECI) True-of-date (TOD) coordinates and correspond to the first orbit solution for each probe with epochs on February 20, 2007. Uncertainties in the predicted sun aspect angle include launch vehicle dispersions, characteristics of the probe release mechanisms and post-separation nutation.

3.3 INSTRUMENT COMMISSIONING

Flight operations procedures and Spacecraft Test and Operations Language (STOL) scripts for on-orbit instrument commissioning, control and configuration were developed during the mission integration and test phase. Changes were validated on a flight simulator called FlatSat, connected to a complete and fully functional instrument suite that was built as a flight spare.

Instrument commissioning started on LD+5 with powering the Instrument Data Processing Units (IDPUs) and Fluxgate Magnetometers (FGMs) on (Ludlam et al., 2008; Ludlam et al., 2008; Auster et al., 2008). The strategy was to keep all five probes in a similar state and to perform corresponding operations on back-to-back passes, where practical. In this case, all five IDPUs and FGMs were powered on and checked out during five consecutive passes, spanning 6 hours total. This approach worked very well as on-console staffing could be optimized and the operations and engineering support teams concentrated on one set of procedures at a time. The remaining instruments, namely the Search Coil Magnetometers (SCMs) (Roux et al., 2008), Electric Field Instruments (EFIs) (Bonnell et al., 2008), Electrostatic Analyzers (ESAs) (Carlson et al., 2008), and Solid State Telescopes (SSTs) (Larson et al., 2008), were powered on and checked out in a similar assembly-line fashion. The magnetometer booms were deployed on all probes between LD+7 and LD+9 (Pankow et al., 2008).
The first probe that had its EFI spin-plane and axial booms deployed was THEMIS C, beginning on LD+81 (Bonnell et al., 2008). Detailed analyses showed that reeling out a section of the wire booms followed by a pulsed spin-up maneuver with two short pulses per spin revolution would not compromise dynamic stability (Pankow et al., 2008). Nevertheless, a great deal of care was used to gradually deploy the booms. Once initiated by ground command, the X and Y wire boom pairs were deployed autonomously by on-board software in the IDPU, controlling the deploy motors in such a way that a symmetrical deploy state was maintained at any time. Once the wire booms were fully deployed to their end-to-end lengths of 50 m in ±X and 40 m in ±Y, the ±Z axial stacer booms were released. No issues with excitation of wire boom bending modes and/or fuel slosh oscillations were encountered – the amplitudes were small, as predicted. The entire EFI deployment sequence of the first probe, involving 13 steps of alternating deploy, spin-up and sensor diagnostic tests, was completed by LD+88, with 7 working days.

Once the EFI deployment procedures were successfully executed on the first probe, the next two probes, THEMIS D and E, were deployed in back-to-back operations that started on LD+103 and completed on LD+110, involving only 5 working days. Again, it turned out to be very efficient to group deployment activities on the two spacecraft in such a way that the number of shift changes for on-console support of instrument and maneuver operations was minimized, allowing the overall operations schedule to be accelerated. The EFI booms on THEMIS A and B were deployed after their mission orbit placement had been completed, so that the low moments of inertia allowed attitude precession maneuvers and ΔV maneuvers in axial firing mode to be used efficiently.

3.4 SPECIAL AND ROUTINE OPERATIONS

Special operations include table loads, probe bus and instrument configuration changes, all operations of the propulsion system, and recovery from probe bus or instrument anomalies. Passes involving special operations are always supported by flight controllers at the console.

Operations that are repeated at least weekly are considered routine operations, and include monitoring state-of-health and progression of automated data recovery of the constellation during normal working hours, and uploading Absolute Time Sequence (ATS) tables. Clock correlation is also performed manually, using a special
software tool that measures the probe clock offset by comparing time tags inserted into transfer frames on the spacecraft and on the ground station side, also taking into account a range dependent propagation delay. The on-board clock offset is then adjusted accordingly. The requirement for each probe’s clock is to always match UTC within 0.5 s.

4. Navigation

Navigation tasks for the THEMIS constellation include executing ΔV and attitude maneuver plans, performing post-maneuver processing, calibrating thruster performance, determining and archiving the probe states, and maintaining accurate knowledge of the on-board fuel loads.

4.1 MANEUVER PLANNING AND OPERATIONS

Spacecraft trajectories, maneuver plans and thruster command sheets for finite thrust maneuvers are generated by the Mission Design Tool (MDT) (Frey et al., 2008). Command sheets are included in ATS loads and are verified on a flight simulator prior to on-orbit execution. There are five maneuver types that can be executed on the spacecraft, using a combination of thrusters in different firing modes, as summarized in Table 2.

<table>
<thead>
<tr>
<th>Maneuver Type</th>
<th>Typical Maneuver Goal</th>
<th>Thrusters Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial thrust</td>
<td>ΔV maneuver with stowed EFI spin-plane booms or with deployed EFI booms when no large attitude precession is required</td>
<td>A1 and A2 continuous firing</td>
</tr>
<tr>
<td>Side thrust</td>
<td>ΔV maneuver with deployed EFI spin-plane booms or with small ΔV goals</td>
<td>T1 and T2 sun synchronous pulsed firing</td>
</tr>
<tr>
<td>Beta thrust</td>
<td>ΔV maneuver deployed EFI spin-plane booms</td>
<td>A1 and A2 continuous firing alternating with T1 and T2 sun synchronous pulsed firing</td>
</tr>
<tr>
<td>Attitude precession</td>
<td>Attitude change</td>
<td>A1 or A2 sun synchronous pulsed firing</td>
</tr>
<tr>
<td>Spin-up / spin-down</td>
<td>Spin rate adjustment</td>
<td>T1 or T2 continuous or pulsed firing</td>
</tr>
</tbody>
</table>

Note: Beta thrust maneuvers are executed as a segmented sequence of alternating axial and side-thrust maneuvers.
Spin rate adjustments are performed by firing one of the two tangential thrusters in a pulsed firing mode with pulses phased 180 degrees from each other to minimize the torque on the EFI wire booms. The direction of spin rate change, up or down, is controlled by whichever tangential thruster is activated. Targeted attitude precession maneuvers are performed by phased firing of one of the two axial thrusters, with pulse widths selected to avoid oscillatory resonances of fuel motions and wire boom bending modes.

ΔV maneuvers use either an axial thrust or a side-thrust mode. Axial thrusts are used when the probe’s spin-axis is aligned in the direction of the desired velocity change. This mode fires both axial thrusters (A1 and A2) in a continuous burn to achieve large velocity changes in a short time. Axial thrusts were utilized for large ΔV maneuvers on all probes while their EFI booms were still undeployed, as these maneuvers usually required attitude maneuvers into and out of the axial firing attitude that would become expensive in fuel once the EFI booms were deployed. ΔV maneuvers in side-thrust mode utilize both tangential thrusters (T1 and T2) in a phased pulsed firing mode. The direction of velocity change in the spin plane of the spacecraft can be controlled by adjusting the phase of the thruster firing, allowing orbit changes to be executed without expensive attitude precessions.

The first maneuvers executed during the THEMIS mission, and also the first maneuver on each spacecraft, were attitude maneuvers to precess the inertial attitude in such a way that the sun aspect angle changed from 49.0 to 15.0 deg, providing a more stable power and thermal environment, and better communications. These maneuvers were executed as so-called Attitude Recovery Maneuver to Sun Normal, using an ITOS STOL script that specifies all thrust parameters via ground command. This type of maneuver procedure does not require extensive planning and FlatSat simulations, as it fires one axial thruster, A1 or A2, at a fixed angle of 90 or 270 deg from the sun pulse with a pre-determined number of pulses.

Maneuver operations were typically supported by the Mission Systems Engineer and at least one of the propulsion subsystems engineers from UCB or Alliant Techsystems (ATK) on console. Eventually, the operations and navigation team gained a high level of proficiency so that system engineering support was no longer required. Progression of maneuvers was closely followed using real-time trend plots of critical subsystems parameters, such as the plot shown in Figure 7.
Figure 7. The first maneuver of the mission was a THEMIS C attitude precession maneuver towards sun normal. The top panel shows the targeted change in sun aspect angle from 49.0 to 15.0 deg, the center panel the undesired, but unavoidable small change in spin rate from 16.15 to 16.118 rpm, and the bottom panel the accelerations in X and Y probe body coordinates, as measured by the Inertial Reference Units (IRUs), indicating an onset of nutation caused by fuel slosh at the beginning and more so at the end of the thrust maneuver, and decaying significantly after 40 min.
Maneuver reconstruction involves analysis of recorded engineering and thrust history telemetry data that are downloaded from the probes once a maneuver is completed. The primary quantities taken into account are tank temperatures and pressures, and the exact thruster firing times.

Undesired but unavoidable changes in spin rate and orbital elements are experienced with attitude precession maneuvers. These changes are caused by small differences in thrust efficiencies up to 4% and vary from one maneuver to another. The mass models of the probes were continually refined based on dynamic data obtained during the maneuvers. Once the spin-plane booms were deployed, the moments of inertia were much larger, and the probes became less sensitive to these effects. The maneuver calibration procedure includes models for the tank stretch as a function of pressure and temperature, and appears to work very well.

4.2 COAST PHASE

After completing the first two months of on-orbit operations, the THEMIS constellation continued to function in a very good state of health. All five spacecraft were in stable orbits and attitudes with solid power and thermal conditions. All science instruments were operational and collected data, although the EFI spin-plane and axial booms were not yet deployed.

The probe placement decision that would relate the probe bus names to the constellation orbit identifiers was made on March 27, 2007 in the following way:

\[
\begin{align*}
\text{THEMIS A} & \rightarrow \text{P5 Orbit} \\
\text{THEMIS B} & \rightarrow \text{P1 Orbit} \\
\text{THEMIS C} & \rightarrow \text{P2 Orbit} \\
\text{THEMIS D} & \rightarrow \text{P3 Orbit} \\
\text{THEMIS E} & \rightarrow \text{P4 Orbit}
\end{align*}
\]

This decision was primarily based on the performance characteristics of the telecommunications subsystems, since the five probes were otherwise essentially equivalent.

The mission orbit placement in preparation of the first tail observing season was planned to commence in late August 2007 and be completed in early November 2007 when the probe orbits would align with their lines of apsides with the Earth's magnetospheric tail. Meanwhile all five probes were maintained in temporary coast-
phase orbits. These orbits were adjusted periodically to prevent differential drifts of the arguments of perigee during the coast phase while providing opportunities to collect interesting science data. The relatively small orbit and attitude maneuvers required to arrange the orbits for the coast phase counted towards the mission orbit placement and were included in the fuel budget.

Figure 8: THEMIS orbit views from north (top panel) and apogee (bottom panel) on April 22, 2007, prior to rearranging the constellation for the coast phase. Equatorial grid circle spacing is 2 Re.

The separation from the launch vehicle placed the five probes into nearly identical orbits in a string-of-pearls configuration with C leading and E trailing the group B–D–A with differential orbital periods of ±5 min, respectively:

\[ \text{--} \quad C \quad \text{--} \quad B \quad D \quad A \quad \text{--} \quad E \quad \text{--} \]
A snapshot of the probe orbits in April 2007 is shown in Figure 8. As probes C, D and E had their EFI booms deployed by then, the desired orbit configuration for the coast phase was as follows:

<—— B ———— C – E – D ———— A ———

The THEMIS E orbit served as the reference for the coast phase orbit placement. To achieve this coast phase configuration, several small orbit maneuvers were performed to initiate a drift into the desired orbit positions. These drifts were stopped between late May and early June 2007 to maintain the coast phase configuration during the 2007 summer observing season.

4.3 MISSION ORBIT PLACEMENT

The mission orbit placement phase involved maneuvering the five probes from their nearly identical coast phase orbits with a period of approximately 32 hours into their final mission orbits, and was easily as complex as the launch campaign from an operations perspective, if not more demanding in many ways. Up to the end of the coast phase, 68 individual thrust maneuvers had been executed. For the mission orbit placement and remaining EFI deployments, another 108 thrust operations had to be performed. Some of the required orbit maneuvers applied a ΔV of more than 10% of a probe’s total fuel budget. The achieved THEMIS orbit configuration at the center of the first observing season in the magnetospheric tail in early February 2008 is shown in Figure 9, and corresponding orbital elements of the constellation on this day are summarized in Table 3.

Early maneuvers in the orbit placement sequence were very difficult to plan in terms of magnitude and timing, as the mission design team had to work with a rather narrow window of opportunity in the blow-down pressure profile for fuel tank repressurization (Frey et al., 2008; Sholl, Leeds and Holbrook, 2007). This repressurization had to be interleaved with the maneuver sequence on each probe in such a way that a pyrotechnic valve would be fired at a time when the ullage volume determining the fuel tank pressure was still small enough to not violate the minimum thruster inlet pressure prior to repressurization, but already large enough to not exceed the maximum-allowed fuel tank pressure after repressurization at all expected temperatures. Working around these critical constraints, fuel tank repressurization was successfully accomplished on all probes by LD+227.
Figure 9. Depiction of the maneuver sequence for placement of THEMIS B (P1) into its mission orbit (top panel), and the achieved orbit constellation of THEMIS B-E (P1-P4) on February 2, 2008, the Wedding Day of the first tail observing season (bottom panel).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>THEMIS A P5</th>
<th>THEMIS B P1</th>
<th>THEMIS C P2</th>
<th>THEMIS D P3</th>
<th>THEMIS E P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perigee Height [km]</td>
<td>2873.0</td>
<td>1281.8</td>
<td>1935.6</td>
<td>2678.0</td>
<td>2713.9</td>
</tr>
<tr>
<td>Apogee Height [km]</td>
<td>57063.5</td>
<td>191226.7</td>
<td>117971.1</td>
<td>68897.8</td>
<td>68862.5</td>
</tr>
<tr>
<td>Inclination [deg]</td>
<td>11.2</td>
<td>0.7</td>
<td>5.6</td>
<td>6.2</td>
<td>6.8</td>
</tr>
<tr>
<td>RAAN [deg]</td>
<td>304.4</td>
<td>54.9</td>
<td>310.4</td>
<td>303.2</td>
<td>302.1</td>
</tr>
<tr>
<td>Arg. of Perigee [deg]</td>
<td>13.7</td>
<td>257.1</td>
<td>3.5</td>
<td>18.6</td>
<td>19.8</td>
</tr>
<tr>
<td>Anomalistic Period [h]</td>
<td>19.2</td>
<td>90.9</td>
<td>47.2</td>
<td>23.9</td>
<td>23.9</td>
</tr>
<tr>
<td>Spin Axis RA [deg]</td>
<td>281.0</td>
<td>103.6</td>
<td>103.7</td>
<td>276.8</td>
<td>277.5</td>
</tr>
<tr>
<td>Spin Axis Dec [deg]</td>
<td>60.2</td>
<td>-60.0</td>
<td>-60.8</td>
<td>60.1</td>
<td>60.1</td>
</tr>
<tr>
<td>Spin Rate [rpm]</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Note: Orbital elements and attitudes are given in Earth Centered Inertial (ECI) True-of-date (TOD) coordinates.
Additional maneuvers were required to maintain orbital conjunctions during the first tail season, to prepare the constellation for the first dayside season, and then to maintain conjunctions during the first dayside season. Overall maneuver statistics for 212 individual thrust operations and the fuel budget for the first 18 months of on-orbit operations are summarized in Table 4.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>THEMIS A P5</td>
</tr>
<tr>
<td>Total ΔV [m/s]</td>
<td>396.331</td>
</tr>
<tr>
<td>Attitude Precession Maneuvers</td>
<td>18</td>
</tr>
<tr>
<td>Spin Rate Change Maneuvers</td>
<td>14</td>
</tr>
<tr>
<td>ΔV Maneuvers</td>
<td>16</td>
</tr>
<tr>
<td>Total Number of Maneuvers</td>
<td>48</td>
</tr>
</tbody>
</table>

Note: Total ΔV includes targeted ΔV maneuvers plus contributions imparted by attitude precession and spin rate change maneuvers.

4.4 ORBIT DETERMINATION

Orbit determination (OD) for the constellation is based on two-way Doppler tracking data, obtained from all ground stations supporting THEMIS. These data are processed by the Goddard Trajectory Determination System (GTDS). Arc lengths are typically 7 days long, but shorter arcs are usually selected to obtain a quick orbit solution following a ΔV maneuver. For a single-station solution, based on BGS tracking data only, the required number of passes is typically three times higher than for a multi-station solution to achieve convergence and comparable accuracy. For operational purposes, the quality of THEMIS orbit solutions is characterized by comparing the differences in orbit periods from one orbit solution to the next. Orbit solutions are routinely generated three times per week, and more frequently during maneuver campaigns. An OD summary is provided in Table 5.
TABLE 5: Orbit Determination Summary  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>THEMIS A P5</th>
<th>THEMIS B P1</th>
<th>THEMIS C P2</th>
<th>THEMIS D P3</th>
<th>THEMIS E P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Arc Length [d]</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Typical Number of Passes per Arc</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Typical Pass Duration [min]</td>
<td>20 – 30</td>
<td>20 – 30</td>
<td>20 – 30</td>
<td>20 – 30</td>
<td>20 – 30</td>
</tr>
<tr>
<td>Typical Achieved Accuracy in Orbit Period [s]</td>
<td>0.05</td>
<td>0.8</td>
<td>0.2</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Total Number of Orbit Solutions</td>
<td>256</td>
<td>270</td>
<td>269</td>
<td>256</td>
<td>260</td>
</tr>
</tbody>
</table>

4.5 ATTITUDE DETERMINATION

Attitude determination for THEMIS is based on data from the Miniature Spinning Sun Sensor (MSSS) and the three-axis Fluxgate Magnetometer (FGM) – one of the science instruments. The FGM provides data suitable for attitude determination when the magnetic field strength is greater than 5 mG. Since the vector components of the magnetic field vary rapidly with spacecraft position in the near-Earth region, accurate orbit knowledge is essential. Therefore, attitude determination requires orbit determination as a prerequisite.

Attitude sensor data are processed by the Multi-mission Single-Axis Stabilized Spacecraft (MSASS) software developed at NASA/GSFC, and utilizes its Kalman filter attitude determination estimator. Attitude solutions are typically generated once per week using a single 20-min data arc centered on the probe’s perigee transit where the magnetic field strength is at its maximum.

TABLE 6: Attitude Determination Summary  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>THEMIS A P5</th>
<th>THEMIS B P1</th>
<th>THEMIS C P2</th>
<th>THEMIS D P3</th>
<th>THEMIS E P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Arc Length [min]</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Typical Achieved Accuracy [deg]</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total Number of Attitude Solutions</td>
<td>76</td>
<td>78</td>
<td>76</td>
<td>74</td>
<td>72</td>
</tr>
</tbody>
</table>
5. Science Operations

Science operations include all operational activities related to the planning of observations, science instrument configuration, data acquisition, data recovery and subsequent ground processing. Most of these tasks are carried out by operations team members in collaboration with and under the guidance of the science team.

5.1 SCIENCE PLANNING

Due to the complex nature of the scientific observations made with five instruments aboard five identical probes, each in a different orbit, and thus sampling different regions of the magnetosphere, the instrument configuration differs from probe to probe, and has also changed with the different mission phases. The Instrument Systems Engineers (ISE) have coordinated with the science and operations teams to support the necessary instrument configurations as the THEMIS mission has progressed. Instrument configuration has evolved since the first deployments after launch, through the final EFI deployments after the last major orbital placement maneuvers, and has continued to be refined as science data are processed and interpreted. As the probes pass through different regions of the magnetosphere on each orbit, on-board timed commands configure the instruments for data acquisition, including Fast Survey and Burst data collection, Slow Survey and data compression, as well as autonomous actuations of the SST attenuators. Each week, the operations team loads a new ATS table aboard each probe. The ATS table also supports maneuver and calibration configurations, such as the pre-maneuver ramp down of instrument high-voltage power supplies, or monthly gain toggle tests for the ESA instrument, that are executed during certain parts of the orbit for calibrations and confirmation of configuration changes.

Members of the science team coordinate with the ISE by passing on desired configuration changes that are documented in Instrument Configuration Change Requests (ICCRs). The ISE devises the necessary command sequences and tests these on the FlatSat and VirtualSat instrument and flight dynamics simulators. Once the commands are tested, following approval by the science team and the operations manager, the real-time commanding is executed during subsequent ground station contacts with the probe or probes in question. Permanent or temporary changes are executed by the operations team via ground commands and are sometimes integrated
into the regular ATS loads. Changes are also reflected in updates of mission operations procedures and on-board patches to the instrument flight software and flight parameter tables.

5.2 TELEMETRY REQUIREMENTS

The THEMIS constellation captures data by a store-and-forward operation. Science and engineering data are recorded in on-board solid-state memory and are played back to the ground segment primarily near perigee, where the highest downlink data rates are achieved. The required science data volume is 750 Mbits per orbit for each probe, and periods of data acquisition at different cadencies are selected such that one complete orbit of data can be downlinked during each perigee passage. Prior to transmission, science data are compressed by about a factor of two using a lossless algorithm (Ludlam et al., 2008).

State-of-health telemetry from the instruments is part of the normal telemetry stream acquired during each ground station contact. Instrument configuration and status changes are typically monitored via specific IDPU mnemonics in the real-time, or by plotting a corresponding data history via BTAPS. Analysis of the configuration changes, however, is best achieved in the science data that are normally evaluated by the science team after downlink and subsequent processing of the instrument science telemetry.

5.3 SCIENCE DATA ACQUISITION

The baseline for on-orbit science data acquisition is Slow Survey mode. Special data acquisition schemes such as Fast Survey or Burst data collection are selected based on predicted passages through magnetospheric regions of interest, and also by configurable on-board trigger logic that takes input from different science instruments to autonomously detect and record interesting events. Burst data are sampled at a higher cadence and stored in dedicated memory segments.

Regular changes in instrument configuration are part of the normal daily operation of the probes as they acquire data in various scientifically distinct regions of their orbits. Also, on a larger time scale, there are instrument configurations that correspond to the long-term scientific periods of the THEMIS mission, namely post-launch coast phase, first tail season, dawn/dusk and dayside science.
Daily or per-orbit changes are made via ATS commands stored aboard the probes. The ATS also contains commands for probe bus operations, such as transmitter cycling for ground station contacts, and thruster commands for maneuvers. The instrument commands select data acquisition modes and periods of data compression. The transition from Slow Survey into and out of Fast Survey and Particle Burst collection, for example, is achieved by ATS activation of on-board relative time sequences (RTS), which include commands for the transition and execution of IDPU programs called scripts that properly configure instruments for that particular period of data acquisition (Ludlam et al., 2008). Once configured, internal triggering mechanisms that are programmed per science team requirements via memory settings in the IDPU autonomously trigger specific data acquisition routines.

ATS tables are built with BMPS, incorporating data products from the mission planners and flight dynamics group. These products are used to determine orbital periods of interest for differing instrument configurations such as passage through the radiation belts, magnetopause crossings, and apogee and perigee passages. These regions of interest are different for each of the probes in their different orbits, but also are coordinated such that conjunctions between multiple probes and orbital geometries allow for a wide variety of magnetosphere data sampling. The system is versatile and responds quickly to most configuration changes requested by the science team, usually within days and sometimes within a single day.

5.4 PASS SCHEDULING AND DATA RECOVERY

Ground station pass scheduling is based on the predictions of dynamic link margins, taking into account probe range, attitude, antenna pattern, and ground station figure of merit (G/T) to optimally select the highest available data rate – up to 1,024 kbps – for each pass. The pass scheduling software applies a number of rules and constraints to generate a strawman schedule. Confirmed passes are ingested by the SatTrack Gateway Server that drives the entire operations center (Bester et al., 2003). This includes the configuration of frame routers to enable telemetry and command data flows via secure network connections between the MOC and any supporting ground station, and to initiate pass supports from the Berkeley Ground Station.

As mentioned earlier, the THEMIS instrument telemetry stream containing Survey and Burst data comprises approximately 750 Mbits per orbit (differing
depending on duration of each probe’s orbit, currently between 0.8 and 4 days). The two probes in larger orbits, and thus with less frequent perigee passages, have smaller margin for data storage and are usually scheduled with backup data dump contacts on each orbit. Much of the data downlink procedure was automated by the first anniversary of the THEMIS launch, with redundancies built in, and has proven very reliable.

5.5 GROUND DATA PROCESSING AND ARCHIVING

Once compressed and downloaded to the ground, a science data processing pipeline first matches the arriving files against the pass schedule to detect missed passes and perform quality checking for data gaps. If an error condition occurs, the operations team is automatically notified and data replay is requested. Science data are then passed into an automated processing pipeline to generate Level 0, 1, and 2 data sets.

The science data processing system utilizes several MySQL databases to track the data recovery and processing status. These database systems also provide critical feedback to the operations team regarding completeness and quality of telemetry data sets downloaded from the constellation. At the current time, virtually all state-of-health and tracking passes, as well as most data recovery passes near perigee, are conducted successfully via an autonomous autopilot system.

6. Summary

Generally, all aspects of THEMIS on-orbit operations have been very successful. By mid-January 2008, all five probes were completely commissioned and the constellation was fully deployed in its mission orbits for science data acquisition in the first tail observing season. There were no on-orbit failures, and all 5 probe buses and 25 science instruments functioned very well. All critical operations such as deployment of 10 magnetometer booms, 20 spin-plane and 10 axial booms, 5 releases of the ESA instrument covers and the firing of 5 pyrotechnic valves for fuel tank repressurization were performed flawlessly.

The flight dynamics and flight operations teams planned and executed 212 thrust operations across the constellation within the first 18 months of the mission. As many as 4 ΔV maneuvers were performed on different probes within a single 24-hour
period. Mission orbit placement and fuel consumption are close to projections, and no planning or operational mistakes were made that could have led to reducing fuel reserves or delaying the commissioning schedule. Towards the end of the mission orbit placement phase, most of the flight dynamics operations had turned into routine activities.

All of the ground systems and operational software worked as expected, and all functional elements of the multi-mission operations facility at UCB/SSL worked essentially flawlessly. During the first 18 months of on-orbit operations, the THEMIS ground systems supported more than 7,500 passes. By the end of the first tail season, all of the routine operations had transitioned to a fully automated lights-out mode.

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