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Multi-mission Flight Operations at UC Berkeley – Experiences and Lessons Learned

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The University of California, Berkeley has conducted flight operations for multiple NASA-funded spacecraft from its multi-mission operations center at Space Sciences Laboratory for more than a decade. All ground systems were designed and implemented by members of the multi-mission operations team who are involved in all phases of mission life cycles from the early proposal stages through mission design and development, integration, launch and on-orbit operations. Operational task areas include mission and science operations, mission design and navigation, ground station operations, and hardware and software systems support. Team members are trained across missions and across support disciplines to provide a breadth of knowledge and redundancy within the team. This paper describes the ground system design and summarizes experiences, challenges, and lessons learned with conducting complex multi-mission spacecraft operations in an academic environment.

I. Introduction

THE University of California, Berkeley (UCB) has carried out active flight operations for NASA-funded astronomy and space science missions since the mid 1990s. The first mission was the *Extreme Ultraviolet Explorer (EUVE)*, launched on June 7, 1992. Mission operations for EUVE were initially conducted at NASA Goddard Space Flight Center (GSFC), and science operations at UCB. Outsourcing of full flight operations from GSFC to UCB began during the extended mission phase in April 1996, and was completed in March 1997. EUVE was successfully operated from its dedicated mission control center at the Center for Extreme Ultraviolet Astrophysics (CEA) for nearly four years until mission termination on January 31, 2001.[1]

Figure 1. Artist's rendering of RHESSI observing solar flares. *Credit: NASA.*

Meanwhile, science operations were also carried out at the Space Sciences Laboratory (SSL) for the *Fast Auroral SnapshoT Explorer (FAST)*, a NASA Small Explorer (SMEX) mission launched in August 1996.[2] One year later, SSL won the proposal for a second SMEX mission – the *Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)*, shown in Fig. 1. This proposal included all flight operations to be conducted by UCB from the moment of payload separation at launch.[3] It also included the establishment of a local ground station to allow for communications and science data recovery. Additionally, UCB proposed to NASA to transition flight operations for the extended mission phase of FAST from GSFC to SSL. For this purpose, a new Multi-mission Operations Center (MOC) was

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then established at SSL in 1998 to provide full flight operations support for both FAST and RHESSI. RHESSI eventually launched in February 2002. The next mission supported by the MOC was the *Cosmic Hot Interstellar Plasma Spectrometer (CHIPS)* – a NASA University-class Explorer (UNEX), launched in January 2003.[4]

A very significant step-up in expansion of the MOC and its capabilities, and in challenges for the operations team came in February 2007 with the launch of the *Time History of Events and Macroscale Interactions during Substorms (THEMIS)* mission – a NASA Medium-class Explorer (MIDEX) involving five spacecraft called *probes* that were launched on a single Delta II rocket. The probes were subsequently maneuvered into synchronized, highly elliptical, nearly equatorial Earth orbits with periods of 1, 2, and 4 days to form conjunctions inside the Earth's magnetospheric tail.[5] For the extended mission phase of THEMIS, beginning in fall of 2009, the Project was split into two parts. THEMIS-Low is a continuation of the THEMIS mission with three of the five probes (THEMIS A, D and E) on the 1-day period orbits, but in a closer formation. The other two probes (THEMIS B and C) are transferred from Earth to lunar orbits via low-energy transfer trajectories to start a new mission, called *Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS)*.[6]

Currently, UCB is also involved in the implementation of a third SMEX mission, the *Nuclear Spectroscopic Telescope Array (NuSTAR)*, presently scheduled for launch in February 2012.[7] A summary of all missions supported by the MOC at UCB/SSL is given in Table 1.

Table 1. Overview of missions supported by the Multi-mission Operations Center at UCB/SSL.

	FAST	**RHESSI**	**CHIPS**	**THEMIS** *	**NuSTAR**
Mission Class	NASA SMEX	NASA SMEX	NASA UNEX	NASA MIDEX	NASA SMEX
Launch Date	Aug. 21, 1996	Feb. 5, 2002	Jan. 13, 2003	Feb. 17, 2007	Feb. 3, 2012 (Planned)
Mission Status	Decommissioned in 2009	Active in Extended Phase	Decommissioned in 2008	Prime Mission Ended in 2009	Development Phase
Science Objectives	Auroral and Space Physics	Solar Flares, Solar Physics	EUV Emission, Interstellar Medium	Magnetospheric Physics	X-ray Astronomy, Black Holes
Science Instruments	Particle and Fields Detectors	X-ray / Gamma Ray Rotating Grid Collimator	Extreme Ultraviolet Spectrometer	Particle and Fields Detectors	Hard X-ray Focusing Telescope
Instrument Platform	Spin Stabilized 12 rpm	Spin Stabilized 15 rpm	Three-axis Stabilized	Spin Stabilized 20 rpm	Three-axis Stabilized
Mission Orbit Geometry	3706 x 347 km 83.0 deg (End of Mission)	573 x 552 km 38.0 deg (Current)	580 x 565 km 94.0 deg (End of Mission)	5 Synchronized Constellation Orbits	600 x 550 km 6.0 deg (Planned)
Ground Network Support **	AGS, MGS, WGS, ASF, PF1, BGS, USNAK, USNAU	BGS, WGS, MILA, AGO, WHM	BGS, WGS, ADE	BGS, WGS, MILA, AGO, HBK, USNAU, USNHI	MLD, USNHI, BNG
Passes / Day	8 - 10	6 - 10	2 - 4	5 - 20	3 - 5
Primary Telemetry Rate(s)	2250 kbps	4000 kbps	115 kbps	1048.576 kbps 4.096 kbps	1990.4 kbps
Average Downlink Time	185 min / day	75 min / day	35 min / day	25 min / Orbit / Spacecraft (Prime Mission)	40 min / day (Planned)
Average Telemetry Capacity	25 Gbits / day	18 Gbits / day	240 Mbits / day	1.6 Gbits / Orbit / Spacecraft (Prime Mission)	4.8 Gbits / day (Planned)

* Data in this table refer to the THEMIS prime mission phase. For the extended mission phase, THEMIS was bifurcated into THEMIS-Low and ARTEMIS.

** Acronyms are explained in the Mission Support Networks section.

II. Ground Systems Architecture

A. Ground Systems Design Approach

The ground system that was implemented at the MOC is the result of a careful systems engineering approach and was envisioned from the beginning as a true multi-mission system, capable of supporting multiple spacecraft simultaneously, and covering a wide spectrum of concepts of operations. The modular architecture allows flexibility for growth with a high degree of built-in automation, using a blend of commercial off-the-shelf (COTS), government off-the-shelf (GOTS) and in-house developed tools, and has not fundamentally changed in more than a decade.[8,9] However, all software tools were upgraded and some of the original components were meanwhile replaced with more modern, in-house developed tools. Other tools were added as the system was gradually expanded to meet the requirements of new missions. In many cases, upgrades were driven by a particular mission, but were implemented in such a way that all supported missions would benefit.

All ground systems elements were designed, integrated, and tested by members of the operations team, i.e. the end user rather than subcontractors to ensure that tools meet both operations requirements and expectations for usage during on-orbit operations. This approach has many advantages, such as selecting software tools and tailoring the system to the usage in the particular operations environment at an academic institution, as well as reducing costs. It also establishes the foundation for a deep understanding of systems functionality and performance within the team, and allows for planning refinements to be made at a later stage to further increase reliability.

B. Spacecraft Command and Control Systems

The spacecraft command and control system in operation at the Berkeley MOC is the Integrated Test and Operations System (ITOS) that was originally developed at NASA GSFC.[10] The decision to adopt this system was primarily based on heritage that came with the transition of FAST operations from GSFC to UCB. ITOS is used for telemetry displays and spacecraft commanding, and allows scripting in the Spacecraft Test and Operations Language (STOL). ITOS was also selected as the spacecraft command and control system for RHESSI, THEMIS and NuSTAR mission integration and testing, as well as on-orbit operations.

Over the last decade, the Berkeley team invested a large amount of effort in developing so-called *workspaces* for each mission that allow configuration management of telemetry (TLM) and command (CMD) databases, scripts, telemetry display pages, flight parameter tables, and a support environment for reliable lights-out operations. An appreciable step-up was the implementation of the THEMIS workspace to allow for a common configuration for all five probes across the constellation, and for handling probe specific resources.

C. Centralized Architecture for Systems Automation

To support control center-wide automation, a centralized architecture was implemented to integrate process control for all spacecraft operations at the MOC. A fully automated, centralized control system needs to perform at minimum the following functions:

1) Execute tasks such as automatically regenerating multi-mission event schedules
2) Distribute event messages such as expected times of acquisition of signal (AOS) and loss of signal (LOS)
3) Respond to specific client requests for information such as schedule queries

These capabilities are provided by the SatTrack Gateway Server (SGS), as is described further below.[11] All systems requiring real-time automation support connect to the Gateway Server via Transmission Control Protocol / Internet Protocol (TCP/IP) network sockets that are typically established only once, and then remain connected indefinitely. A corresponding block diagram of this scheme is shown in Fig. 2. Upon establishing a connection to the server on a predefined network port, each connecting client identifies itself as a particular client type. A subset of all implemented client types and their functions are summarized in Table 2. To communicate with a given spacecraft, three ground

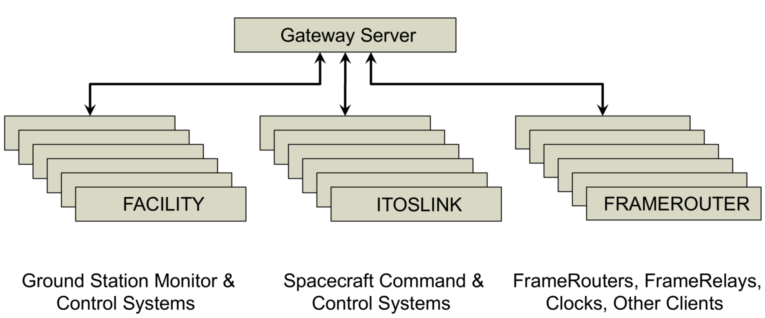

Figure 2. Gateway Server connections.

system elements are required at minimum: a ground station, a spacecraft command and control system, and a network connecting these together to allow telemetry and command data streams to be transferred end-to-end between the spacecraft and the command and control system. Client types corresponding to these three ground system elements are *FACILITY*, *ITOSLINK,* and *FRAMEROUTER*. The core of the system automation is to instruct each of these three elements in real-time as to when a pass support occurs, and which specific configuration to use, based on a master event schedule.

Table 2. Gateway Server client types and functions.

Client Type	Client Function
FACILITY	Ground station monitor and control system
ITOSLINK	Spacecraft command and control system
FRAMEROUTER	FrameRouter software for TLM/CMD routing
FRAMERELAY	FrameRelay software for TLM/CMD relaying
TRACK	Query of current state vector for specified object
DATABASE	Query of pass schedule for data processing system
SCHEDULER	Remote control of scheduling functions
CLOCK	Remote event countdown clocks for AOS and LOS
MESSAGE	Submission of status, warning or error messages
WATCHDOG	Remote monitoring of Gateway Server functions
HTTP	Schedule and status access via web browser
CONFIG	System administrator controls

The local Berkeley Ground Station (BGS), described further below, signs onto the Gateway Server as a *FACILITY* client to receive all pass support request messages for this facility. *ITOSLINK* clients are the primary ITOS command and control systems for each of the spacecraft. *FRAMEROUTER* clients enable the telemetry and command data flows between individual ground stations and spacecraft command and control systems.

At program start, the Gateway Server reads a comprehensive configuration file and then enters an indefinite processing loop, as indicated by the simplified flow chart in Fig. 3. Tasks are typically UNIX C shell scripts that are executed once or twice per day to initiate regeneration of all mission-planning products, and of multi-mission event schedules. Input data to this process are the latest orbital elements, as well as committed pass support schedules obtained from all supporting networks, covering at minimum two weeks and including the current operational week plus the following week. The last step in this process is the generation of an operational event timeline that is in turn read by the Gateway Server itself. The processing loop then checks for the expiration of event times, such as pre-pass set-up times, and then sends corresponding messages to all connected clients, thus initiating an automated pass support sequence.

An example for a client request submitted to the Gateway Server is the query by an instance of ITOS for real-time ephemeris information for a given spacecraft, such as the range from the currently supporting ground station to allow for on-board clock correlation.

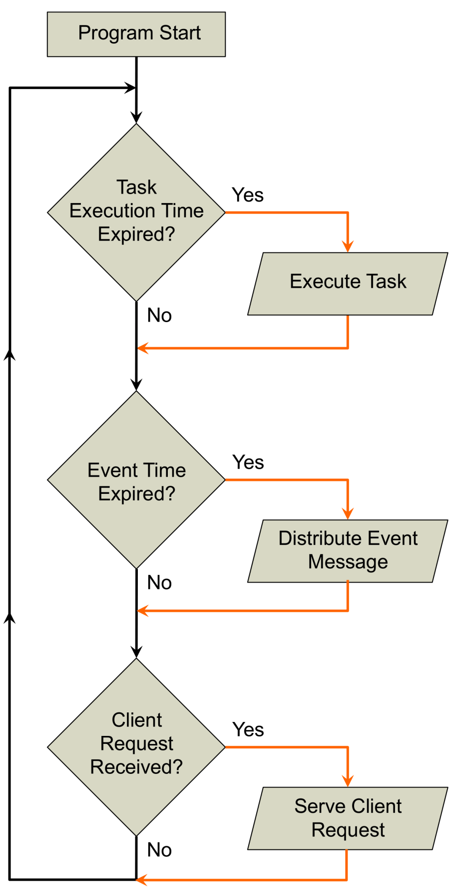

Figure 3. Gateway Server flow chart.

D. Telemetry and Command Flows

The THEMIS constellation is by far the most advanced user of the integrated MOC at SSL. Telemetry and command flows need to be established with several different networks, including NASA's Ground Network (GN), Space Network (SN) and Deep Space Network (DSN), and allowing passes to occur simultaneously with any of the five probes (THEMIS A-E) while involving different protocols for telemetry and command transfer.[12,13] The overall network topology is shown in Fig. 4. Network connectivity is managed via remote control of multiple instances of the FrameRouter application that acts as the TCP/IP equivalent of a matrix switch, allowing ground stations to connect to dedicated network ports for each spacecraft on one side, and ITOS command and control systems to connect to another set of dedicated network ports on the other side, and then flowing telemetry and command data back and forth between these elements. Telemetry streams are also forwarded in real-time to a secondary instance of FrameRouter to allow for further dissemination, processing, detection of spacecraft limit violations, and storage in the telemetry database. The latter is part of the Berkeley Trending Analysis and Plotting System (BTAPS) – one of the advanced software tools developed in-house at SSL to allow for data trending of all spacecraft engineering data collected across the entire THEMIS constellation since launch.[14] BTAPS forwards detected error conditions to another in-house developed tool – the Berkeley Emergency and Anomaly Response System (BEARS) that in turn sends paging messages to operations personnel, as required.[15]

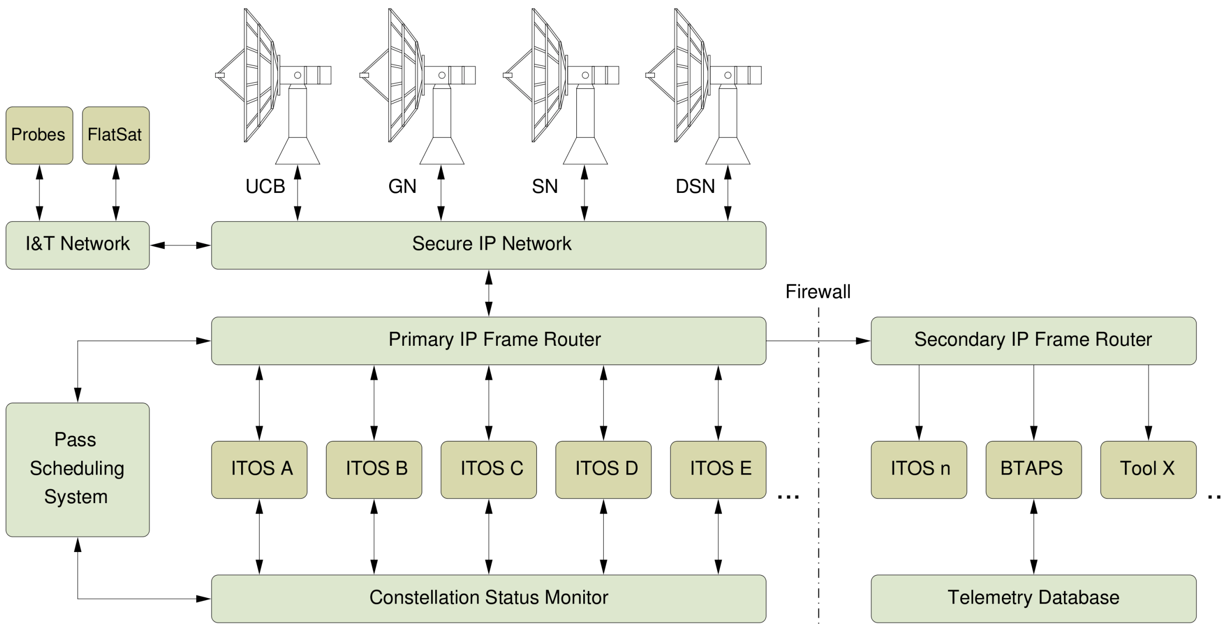

Figure 4. THEMIS mission network topology.

III. Mission Support Networks

The missions described in this paper have been utilizing a large number of government, commercial, and academic assets for communications, science data recovery, and tracking. Each of these networks has its own customers, and often with higher support priorities. Having direct access to a local ground station was particularly valuable during the complex THEMIS instrument deployment operations, as well as for supporting numerous maneuver operations.

A. Berkeley Ground Station

Figure 5. MOC and Berkeley Ground Station 11-m antenna, co-located at UCB/SSL.

The Berkeley Ground Station (BGS), shown in Fig. 5, was installed at SSL in October 1999, and is co-located with the MOC. The system currently serves as the primary ground station for RHESSI with nearly 16,000 supported passes to date, and for THEMIS with almost 13,000 passes across the constellation supported to date. The 11-m parabolic reflector is mounted on a three-axis azimuth/elevation/cross-elevation pedestal. Key features include S-band transmit and receiving equipment, dual baseband processors, and two-way Doppler tracking capabilities. All subsystems are monitored and configured for each pass support via a redundant, Linux-based Monitor and Control System (MCS) that is also part of the SatTrack Suite, and interfaces directly to the SatTrack Gateway Server to allow for fully automated pass operations.[11] Long-loopback self-tests are automatically inserted into gaps in the tracking schedule approximately every six hours. These self-tests exercise the entire receive chain in order to detect any system degradation or malfunction early, and helps to further reduce the risk of losing telemetry data.

B. Scheduling Passes Across Multiple Networks

Ground station antennas that were previously used, or are currently still used to support FAST, RHESSI, CHIPS, THEMIS, and eventually NuSTAR are listed in Table 3. These shared assets belong to the NASA GN, the German Aerospace Center (DLR), the Italian Space Agency (ASI), the Indian Space Research Organization (ISRO), the Center for Scientific and Industrial Research (CSIR) in South Africa, the Universal Space Network (USN), and academic institutions such the University of South Australia, Adelaide, and UCB. In addition, NASA SN assets, namely the Tracking and Data Relay Satellites (TDRS) F3-F7 and F10 supported THEMIS maneuver operations near perigee of the highly elliptical orbits. Integration of the DSN 34-m subnet (Deep Space Stations DSS-15, 24, 27, 34, 45, 54, 65) into the mission network was recently completed, allowing for communications with the two ARTEMIS probes (THEMIS B and C) during the trans-lunar transfer phase and eventually in their Lissajous and lunar orbits.[13]

Table 3. Ground stations supporting UCB missions.

Acronym	Ground Station Antennas
ADE	Adelaide 3-m, Australia
AGO	Santiago 9-m, Chile
AGS	Poker Flat 5-m, 8-m, 11-m, Alaska
ASF	Alaska Satellite Facility 11-m, Fairbanks, Alaska
BGS	Berkeley 11-m, California
BNG	Bangalore 10-m, India
HBK	Hartebeesthoek 6-m, 10-m, 12-m, South Africa
MCM	McMurdo Base 10-m, Antarctica
MILA	Merritt Island 9-m (2), Florida
MLD	Malindi 10-m, 13-m, Kenya
PF1	Poker Flat 11-m, Alaska
USNAK	North Pole 13-m, Alaska
USNAU	Dongara 13-m, Australia
USNHI	South Point 13-m, Hawaii
WGS	Wallops Flight Facility 5-m, 8-m, 9-m, 11-m, Virginia
WHM	Weilheim 9-m, 15-m (2), Germany
Note: Some of the antennas listed in this table have been decommissioned.	

Scheduling of pass supports across multiple networks requires interaction with several different scheduling offices. Software at the MOC predicts available link access periods for each spacecraft and ground station combination at any of the operational data rates, based on a dynamically modeled telemetry link margin that takes into account view periods, attitude dependent spacecraft antenna gains, the ground station figure of merit (G/T), degradation of the link performance due to thermal background radiation from the Sun and the Moon, plus a number of network and mission specific constraints.[16]

Already committed schedules from external networks are included in the local planning process to minimize iteration cycles with conflict resolution.

To schedule DSN passes, members of the multi-mission operations team at SSL participate in the complex DSN resource allocation process. Operational DSN schedules are then downloaded and integrated with those from other networks to form the operational multi-mission schedule for the MOC.

A typical operational schedule, including passes at multiple networks for CHIPS, FAST, RHESSI and the five THEMIS probes is presented in Fig. 6.

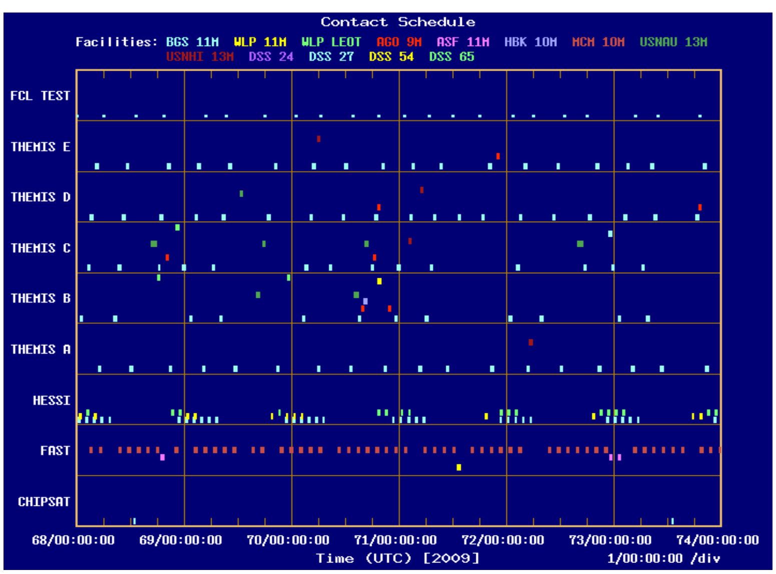

Figure 6. Typical 6-day operational multi-mission schedule.

Committed operational schedules are incorporated into on-board sequence tables that are generated with the Berkeley Mission Planning System (BMPS) – a third in-house developed tool.[8]

IV. Multi-mission Flight Operations

Multi-mission flight operations at UCB involve spacecraft command and control, instrument configuration, flight dynamics and navigation, data processing and ground systems engineering functions, and are carried out by an integrated multi-mission team.

A. Spacecraft Command and Control

Routine spacecraft pass supports are conducted in a fully automated, lights-out fashion. An autopilot system developed for THEMIS operations handles scheduled passes as well as blind acquisitions with all networks. Automated passes are monitored by flight controllers during normal work hours. Operations team members carry iPhones during off-hours to receive paging messages, in case an anomaly with any of the spacecraft or ground systems is detected. Required response times are 60 minutes or less.

All passes that require sending commands, except for standard state-of-health checks and initiation of data playback, are usually staffed. Flight controllers perform table loads, clock correlation, and instrument configuration.

Passes involving maneuver operations require at minimum the presence of the Operations Manager, one of the flight controllers, the Mission Design Lead and the Navigation Lead, or their designates. Earlier in the mission, maneuver operations were also supported on console by systems and propulsion engineers, but these functions have since been taken over by members of the operations team. Propulsion systems operations always follow a standard procedure that includes sign-off on required maneuver design paperwork, testing the maneuver execution on the flight simulator, loading the sequence table to the spacecraft, performing a standardized spacecraft pre-maneuver check-out, and conducting a go/no-go poll prior to burn start.

B. Payload Operations

All payload operations for the currently supported missions are conducted by members of the operations team who are cross-trained as instrument engineers. Those team members work with the respective science teams to develop instrument configuration changes that are then first tested on the flight simulator prior to upload to a spacecraft. On the science team side, a *Scientist-on-duty* is designated for typically one or two weeks to be the point of contact for the operations team. Approval by the Scientist-on-duty is required for any on-orbit instrument configuration change, along with the approval by at minimum the Principal Investigator, the respective Instrument Lead, and the Operations Manager. The Scientist-on-duty is also responsible for monitoring the quality and completeness of the recovered science telemetry data, and for checking the performance of the science instruments themselves, and reports his/her findings at the weekly mission operations meetings, or notifies the operations team earlier, if necessary.

V. Mission Design and Navigation

By far the most complex tasks carried out by the multi-mission operations team were the mission design and navigation for THEMIS and ARTEMIS. To date nearly 400 individual thrust operations were executed to place the five THEMIS spacecraft into their initial, synchronized prime mission orbits, and to continue on with the extended mission phase. An artist's rendering of the fully deployed THEMIS constellation is shown in Fig. 7.

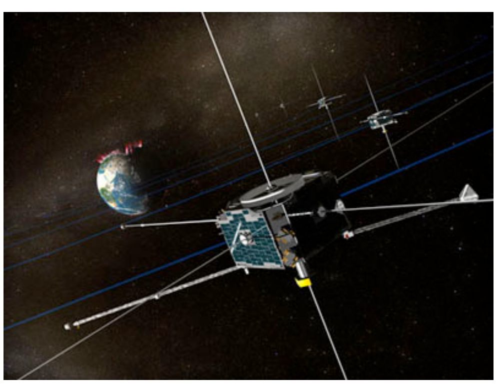

Figure 7. Artist's rendering of the deployed THEMIS constellation, observing magnetospheric substorms. *Credit: NASA.*

A. THEMIS Mission Design and Navigation

The complex mission design for the THEMIS constellation was developed in-house at SSL, and is described in much detail elsewhere.[17,18] All navigation tasks including maneuver preparation and ground simulations, on-orbit execution, post-maneuver calibration, fuel bookkeeping, as well as orbit and attitude determination are handled by the operations team also.[19,20]

B. ARTEMIS Mission Design and Navigation

The complete trajectories of ARTEMIS P1 (THEMIS B) and P2 (THEMIS C) are illustrated in Figs. 8 and 9.[21] Key features

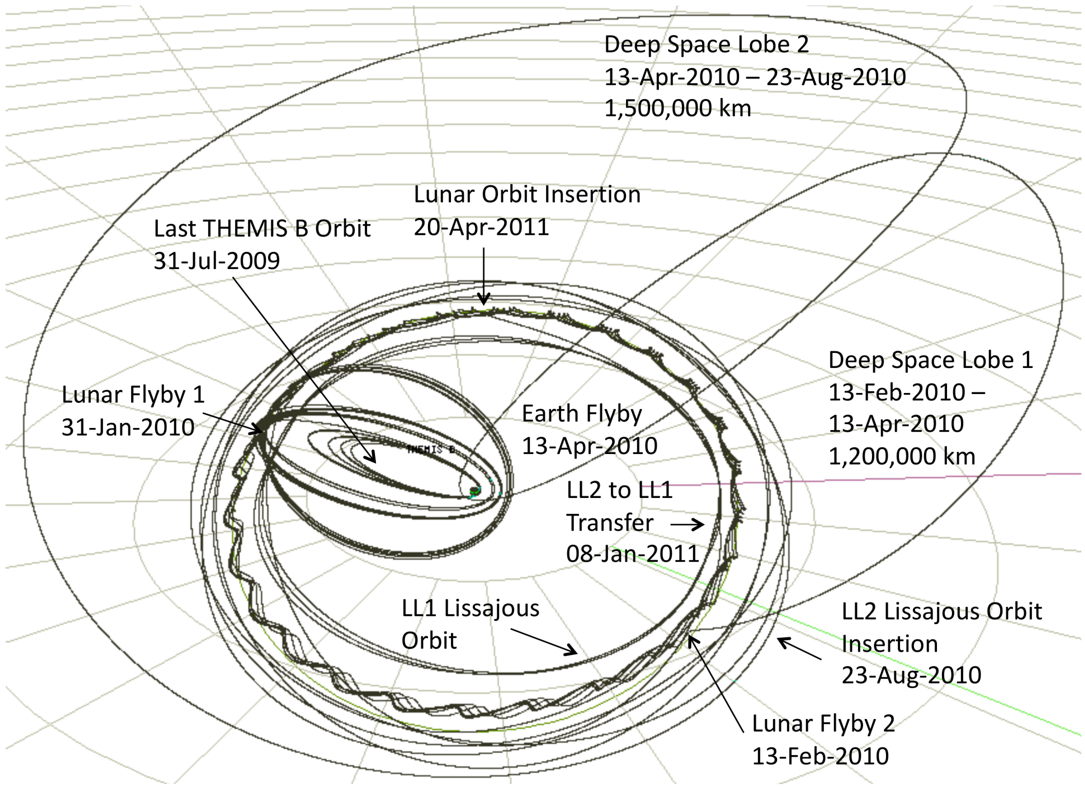

Figure 8. ARTEMIS P1 (THEMIS B) mission trajectory. *Earth departure began on July 31, 2009 with gradually raising the apogee of the last THEMIS B orbit until lunar gravity assists led to the trans-lunar transfer.*

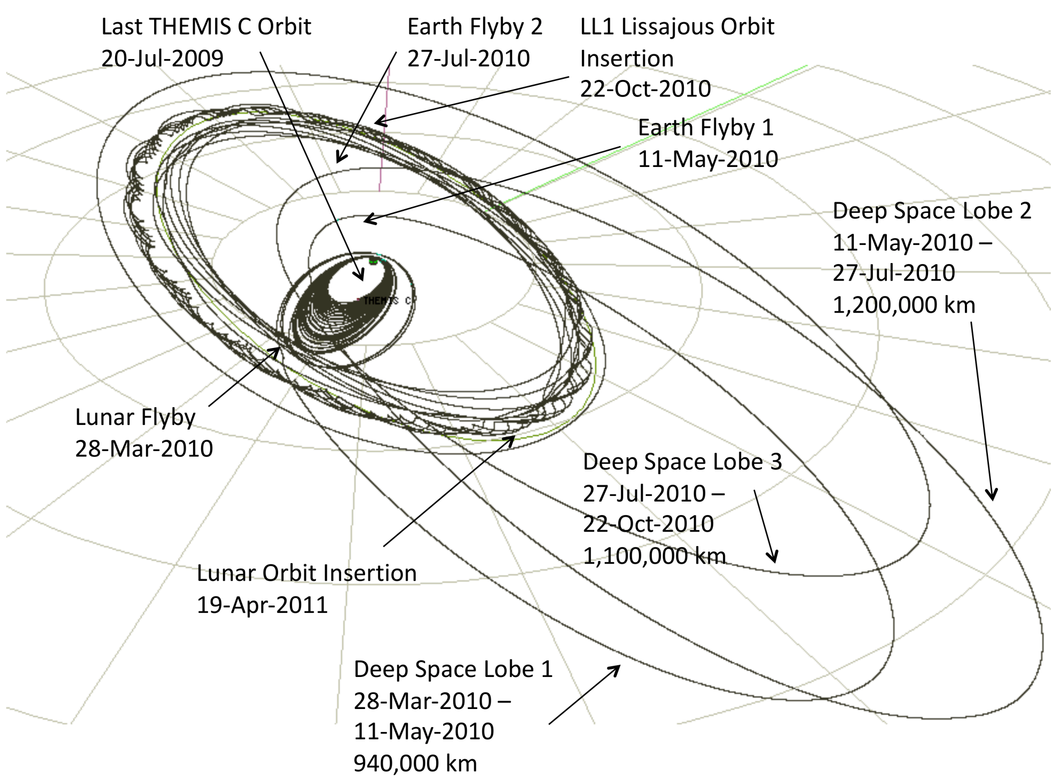

Figure 9. ARTEMIS P2 (THEMIS C) mission trajectory. *Earth departure began on July 21, 2009 with gradually raising the apogee of the last THEMIS C orbit until lunar gravity assists led to the trans-lunar transfer.*

and events are marked in these figures. The overall concept includes raising the apogees of both probes until lunar perturbations and gravity assists lead to a transfer from highly elliptical Earth orbits to low-energy trans-lunar trajectories that target LL1 and LL2 Lissajous orbits as way points.[22] After spending 6-8 months in these Lissajous orbits, the two ARTEMIS probes are then inserted into lunar orbits in mid-April 2011 for the remainder of the extended mission phase. Details of the trajectory design and execution of the navigation plans will be described in future publications.

The ARTEMIS lunar transfer trajectories were developed by the mission design team at Jet Propulsion Laboratory (JPL) at the California Institute of Technology.[21] The Navigation and Mission Design Branch (NMDB) at NASA/GSFC performed critical navigation error analyses.[22] All maneuver operations, including simulations, generation of spacecraft command loads, burn execution, and post-processing were conducted by the UCB operations team.[23] However, this complex team effort will still continue for several years to come. The ARTEMIS navigation tasks are clearly the most advanced spacecraft operations the UCB team has been involved in to date.

VI. Experiences and Lessons Learned

Operating up to eight spacecraft simultaneously with a wide variety of complex tasks can be handled by a relatively small team, provided that the environment is set up efficiently. The overall approach of designing and implementing a robust ground system, as well the assignment of roles and responsibilities needs to be carefully planned, and team members need to be trained across many disciplines to ensure mission success for all missions supported at SSL. A number of experiences and lessons learned are described in the following subsections.

A. Ground Systems

1. Systems Design, Implementation and Support

The overall ground systems design has worked out very well to support all missions so far. Some of the tools inherited from NASA/GSFC when FAST operations transitioned to UCB were replaced in the meantime with more modern, in-house developed software. Changes to operational ground systems are carefully planned and implemented in an incremental approach. New software is validated and tested during a period of parallel processing with already operational systems, before being relied upon operationally. All software and hardware changes are configuration managed. External contractors and vendors are only called upon for maintenance of commercial software such as ITOS, and for various aspects of information technology and operating systems support.

2. Ground Systems Automation

An automated ground system works only as well as the weakest element. Therefore, an appreciable effort was invested over the years in refining software and interfaces to make the overall system as robust as possible. The level of redundancy was also increased over time, as more missions depended on the control center to function with as little downtime as possible. With each new mission proposal, funds are included to add more redundancy, and to gradually replace obsolete hardware and software.

3. Berkeley Ground Station

The Berkeley Ground Station has been instrumental in conducting efficient operations. For THEMIS in particular, passes could be added on a very short notice when needed. Operations and communications procedures could be tested locally first before implementing these with other network assets, which saved cost and reduced risk. In some cases other ground stations were not able to establish communications with FAST, CHIPS, RHESSI, or THEMIS. In many of these cases, a BGS pass was quickly scheduled to assess and verify spacecraft health and safety, and in some cases to initiate recovery from a spacecraft anomaly.

Being able to work with a ground station locally also helps operations team members to better understand how other ground stations at remote sites work, which then allows for more efficient troubleshooting when network communications problems are encountered.

4. Multi-mission Risks and Benefits

Operating multiple spacecraft out of a common facility bears the risk that a system failure could affect multiple missions at the same time. This risk is mitigated by providing redundancy with data processing systems, and by enhancing the reliability of the supporting infrastructure, such as air conditioning systems and back-up power generation. The overall benefits of using integrated tools and cross-trained personnel were found to save overall costs and outweigh the associated risks. A compact clone of the multi-mission operations center, termed the *mini-MOC*, is currently installed at NASA/GSFC as a back-up control center for all UCB-operated missions.

5. Operations Team Involvement

Involving the operations team in the mission life cycle from the earliest stages has the large benefits that proposed concepts of operations can be made compatible with the existing ground systems, or allow operations management to be aware of and plan for implementation of new requirements early on. Having an experienced multi-mission operations team involved in designing and integrating the required ground systems almost guarantees that there are no large disconnects in understanding interfaces, end-to-end functionality, and data flows. This approach reduces costs and risk for transitioning from mission integration and testing to on-orbit operations, and ultimately leads to a higher probability for mission success, and a higher quality of science data. Working with a small team also reduces management overhead and allows a more rapid response with respect to implementing and certifying necessary system changes or upgrades.

B. Mission Readiness Testing

1. General Test Approach

In preparation for THEMIS on-orbit operations, a comprehensive mission readiness test program was designed and meticulously executed, verifying and validating all aspects of operations from box level to full-up mission level in a *test-like-you-fly* configuration where practical.[24] This approach paid off after launch, as it allowed the operations team to concentrate on operating the five-spacecraft constellation instead of debugging ground systems issues. The test program for NuSTAR will follow along the same path.

2. Test Plan Logistics and Execution

The test plan was implemented as a large Excel spreadsheet, which allowed the team to track progress and report status to Project Management. The test program was executed relatively late in the schedule, but all required tests were completed prior to launch.

3. Utilization of a Flight Simulator

For THEMIS pre-launch simulations it was very valuable to have a flight simulator (*FlatSat*) that could stand in for any of the five probes, allowing thread testing of realistic scenarios, also including contingencies. The FlatSat was also used extensively for simulation of every targeted ΔV and attitude precession maneuver during on-orbit operations. In some cases, problems were detected and rectified prior to on-orbit maneuver execution, thus preventing the waste of fuel.

C. Flight Operations

1. General Multi-mission Operations

Overall, multi-mission operations as conducted at UCB have been very successful. The integrated ground systems have been supporting flight operations very well. Automated functions to initiate playback of engineering and science telemetry data are very reliable, and data losses occur only very infrequently.

2. Instrument Operations

Members of the operations team also handle science instrument operations for all missions as double duty. Requests for configuration changes are discussed in weekly operations meetings for each mission.

3. Multi-mission Anomalies

Over the past decade there were no serious cases where problems or anomalies occurring on one spacecraft caused an adverse impact to another spacecraft supported at the MOC. In general, the benefits of an efficiently run multi-mission facility clearly dominated over the potential risks. However, various scenarios of cascading problems were simulated during pre-launch readiness testing to prepare the operations team. In some cases, ground system problems caused data losses on multiple spacecraft. Procedures, software, and hardware were subsequently improved to prevent recurrences of similar problems in the future.

4. Navigation

The steepest growth in required knowledge and skill levels within the operations team was seen in the navigation area. For THEMIS and ARTEMIS, new software was implemented to support these tasks. Maneuver operations were prepared and executed following established and well-tested procedures. Maneuver operations procedures were refined to lower the risk of missing a maneuver due to problems with real-time passes or thrust aborts due to unforeseen limit monitor trips aboard the probes.

D. Operations Team

1. Team Composition

All members of the operations team are full-time UC Berkeley employees, many for more than ten years, with an educational background in various science and engineering disciplines, such as physics, astronomy, mathematics, aerospace engineering, electrical and mechanical engineering, and computer science. There has been relatively little turnover within the team.

2. Involvement in Ground Systems Design

The involvement of all operations team members in the ground systems design and implementation is an excellent way to ensure that ground systems not only meet technical requirements, but are also easy to use in day-to-day operations. This approach allowed lessons learned from the earlier missions, namely FAST and RHESSI, to be applied to the more advanced ground systems for THEMIS. With NuSTAR this approach is carried further still, as the operations team provides the command and control system in almost a turnkey fashion to the spacecraft contractor for flight software development, spacecraft bus and instrument integration, and testing.[25]

3. Involvement in Mission Integration and Testing

All flight controllers participate in mission integration and testing as console operators. This approach began with RHESSI, and was followed with CHIPS and THEMIS, and is also planned for NuSTAR.[25] The familiarity with all flight systems gained during this final phase of the mission development is a very valuable training tool and allows for a low-risk transition to on-orbit operations. Flight controllers are also involved in development and fine tuning of telemetry pages and scripts for spacecraft command and control.[26]

4. Response to Anomalies

All flight controllers are trained as first responders to handle anomalies discovered during real-time pass supports, and are authorized to perform safing operations or turn off instruments if red limit violations are present. The Mission Operations Manager forms a tiger team and leads subsequent recovery steps after consultation with cognizant systems and subsystems engineers. Sustaining engineering support contracts are in place with spacecraft contractors.

5. Cross Training

In a small team it is important that flight controllers are cross-trained on multiple missions and in multiple disciplines and subsystems. Furthermore, team members are encouraged to take on more responsibilities and become proficient with multiple aspects of operations, including duties as flight controllers, instrument engineers, flight dynamics analysts, schedulers, and programmers. This approach provides redundancy within the operations team and allows individual team members to understand concepts of operations, and to gain in-depth knowledge of flight-to-ground systems interaction. The academic environment lends itself to continued education, required to conduct successful flight operations.

VII. Conclusion

The multi-mission approach that UC Berkeley has taken over the last decade appears to be very successful. Starting with two Small Explorer missions without propulsion systems, the operations environment evolved and currently supports a five-spacecraft constellation with a very complex trajectory design and ambitious mission extensions. It is believed that the large overall success can be traced back in part to a cleanly designed ground system, allowing safe on-orbit operations and a high quality and quantity of returned science data. Preparation for on-orbit operations includes extensive pre-mission verification and validation of all ground systems, utilization of flight simulators, and operations team involvement early in the mission life cycle. The operations team took on more complex tasks with each new mission, delivered the science data, and lived up to the expectations outlined in the ambitious mission proposals.

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