Multi-Mission Scheduling Operations at UC Berkeley

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Abstract

The University of California, Berkeley conducts mission operations for eight spacecraft at present. Communications with the orbiting spacecraft are established via a multitude of network resources, including all NASA networks, plus assets provided by foreign space agencies and commercial companies. Mission planning is based on the science requirements as well as accessibility to communications network resources. The integrated scheduling process is complex and is supported by partly automated software tools. Challenges encountered and lessons learned are described.

Introduction

The University of California, Berkeley (UCB) currently conducts operations for eight spacecraft from its Multi-mission Operations Center (MOC) at Space Sciences Laboratory (SSL). Science goals and observations fall into the solar/heliophysics and astronomy categories:

- The *Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI)* – a NASA Small Explorer (SMEX), launched in February 2002 – is a solar observatory (Lin, Dennis, and Benz 2002).
- *Time History of Events and Macroscale Interactions during Substorms (THEMIS)* – a NASA Medium Explorer (MIDEX), launched in February 2007 – is a magnetospheric constellation of originally five spacecraft, called *probes* (Angelopoulos 2008). Three of these probes (P3, P4, P5) are currently still operating in Earth orbit while the other two probes (P1, P2) have been transferred into lunar orbits.
- *Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS)* – two of the original five THEMIS probes – is a new mission that started after THEMIS completed its primary two-year mission phase (Angelopoulos 2013). The low-energy lunar transfer trajectory was completed in 2011 when both probes were inserted into stable lunar orbits (Cosgrove et al. 2012, Bester et al. 2013).
- The *Nuclear Spectroscopic Telescope Array (NuSTAR)* – a NASA SMEX mission launched in June 2012 – is a high-energy X-ray observatory carrying twin telescopes with focusing optics (Kim et al. 2013).
- The *CubeSat for Ion, Neutral, Electron, and MAgnetic fields (CINEMA)* – the first CubeSat built in-house at SSL – launched in September 2012. The project home page can be found at http://sprg.ssl.berkeley.edu/cinema.

A summary of these missions and their characteristics is provided in Table A1 in the Appendix. In addition to those five missions, the UCB MOC also operated the *Fast Auroral SnapshoT Explorer (FAST)* – a NASA SMEX mission launched in August 1996 – and the *Cosmic Hot Interstellar Plasma Spectrometer (CHIPS)* – a NASA University-class Explorer (UNEX), launched in January 2003. After many years of successful operations, these two missions came to a termination in 2009 and 2008, respectively.

Mission requirements for the currently operating missions are levied onto planning and scheduling, and are explained in more detail further below. Mission orbits include the low-Earth orbit (LEO), as well as highly elliptical orbit (HEO) regimes around the Earth and the Moon, and with a wide range of inclinations. Scheduling tasks are rather complex, as they involve arranging for communications opportunities via a large number of ground stations across multiple, dissimilar networks to allow for spacecraft command and control, as well as science data return.

Mission planning is interrelated with scheduling to ensure science data are acquired onboard and returned to the ground. In addition, special operations events such as thrust maneuvers need to be covered. THEMIS and ARTEMIS also require tracking passes to be scheduled to collect radiometric tracking data for accurate orbit determination in both Earth and lunar environments.

Communications Networks

Currently the following communications networks are in operational use at the Berkeley MOC to support RHESSI, THEMIS, ARTEMIS, NuSTAR and CINEMA:

1. NASA Near Earth Network (NEN) ground stations at Wallops Island, VA, White Sands, NM and Santiago, Chile (WLP 11M, LEOT; WHS 18M1; AGO 9M, 13M)
2. NASA Space Network (SN) ground stations at White Sands, NM and Guam plus five operational Tracking and Data Relay Satellites (TDRS 5, 6, 7, 9, 10)
3. NASA Deep Space Network (DSN) ground stations at three complexes at Goldstone, CA; Madrid, Spain; and Canberra, Australia (DSS-14, 15, 24, 27, 34, 43, 45, 54, 63, 65)
4. German Aerospace Center (DLR) ground station at Weilheim, Germany (WHM 9M, 15M1, 15M2)
5. Italian Space Agency (ASI) ground station at Malindi, Kenya (MLD 10M1, 10M2)
6. Universal Space Network (USN) ground stations at South Point, Hawaii and Dongara, Australia (USNHI 13M1, 13M2; USNAU 13M1)
7. Kongsberg Satellite Services (KSAT) ground station at Singapore, Singapore (SNG 9M1)
8. University of California, Berkeley (UCB) ground station at Berkeley, California (BGS 11M)

The architecture of the ground data system at the MOC integrates all of these networks elements. Transmission Control Protocol/Internet Protocol (TCP/IP) based socket interfaces are utilized across secure mission networks to establish connectivity for real-time spacecraft command and control functions. The MOC is responsible for delivery of acquisition data to all supporting networks to allow for communications antenna configuration and pointing.

The level of work required for planning observations and science data acquisition varies greatly between the five supported missions.

Mission Planning for Single Spacecraft

This section covers the mission planning activities for the single spacecraft missions operated at UCB, namely RHESSI, NuSTAR, and CINEMA.

RHESSI

The RHESSI observatory carries only one instrument, a spectroscopic imager to measure solar flares at hard X-ray and gamma-ray wavelengths. The instrument consists of a rotating grid collimator and cooled germanium detectors to achieve high spatial as well as high spectral resolution.

Mission planning for RHESSI is relatively straightforward, as the observatory is pointed at the Sun most of the time. RHESSI is pointed off the Sun once or twice per year for seasonal observations of astronomical targets passing near the Sun.

However, collected on-board data volumes are dependent on solar activity and are therefore difficult to predict. On-board data decimation and generation of ancillary instrument data can be adjusted to accommodate times when the Sun is active. During times of high solar activity the operations team arranges for additional downlink bandwidth by scheduling passes at the Weilheim, Germany ground station.

NuSTAR

The NuSTAR observatory is a three-axis stabilized instrument platform carrying two co-aligned hard X-ray telescopes with grazing-incidence, nested mirrors with a 10-m focal length (Kim et al. 2013).

The concept of operations includes long, pointed observations of survey fields or of specific science targets, such as supermassive black holes. In addition, the operations team may be alerted by the Principal Investigator to support observations of targets of opportunity on short notice.

Planning of observations for NuSTAR is carried out at the Science Operations Center (SOC) at the California Institute of Technology (Caltech), Pasadena. The SOC delivers to the MOC observatory pointing requests via an electronic messaging interface. The information includes time-tagged target slew coordinates, as well as expected photon count rates and a criticality/priority classification code.

The MOC in turn processes the observatory pointing requests, and assesses how many ground station passes are required to recover the expected science data volume. Further details of the mission planning and mission operations processes will be described elsewhere.

CINEMA

The CINEMA CubeSat carries a three-axis magnetometer mounted on a boom, and a solid-state detector to measure auroral ion and electron precipitations. Due to limited on-board power resources, passes can be afforded only a few times per day. Passes are scheduled only at the Berkeley Ground Station, using a S-band downlink and a UHF uplink.

At present CINEMA is still in an experimental phase to improve the concept of operations.

Mission Planning for Constellations

Mission planning for the THEMIS constellation, and since 2009 for THEMIS and ARTEMIS, includes activities to determine, based on inputs from the science team, where and when along the orbits science instruments are configured and science data are acquired, and how science data are transmitted to the ground to achieve mission goals.

Activities related to mission trajectory design, execution of thrust maneuvers, and navigation operations that have an influence on mission planning as well, are described elsewhere.

THEMIS and ARTEMIS Science Instruments

The THEMIS and ARTEMIS probes carry identical suites of five science instruments, designed to initially investigate the physics of magnetospheric substorms during the THEMIS primary mission phase (Angelopoulos 2008):

1. Fluxgate Magnetometer (FGM) to measure ambient low-frequency (DC−64 Hz) magnetic fields in 3D
2. Search Coil Magnetometer (SCM) to measure ambient high-frequency (1 Hz − 4 kHz) magnetic fields in 3D
3. Electrostatic Analyzer (ESA) to measure 5−30 keV thermal ions and electrons
4. Solid State Telescope (SST) to measure the angular distribution of super-thermal (30−300 keV) ions and electrons
5. Electric Field Instrument (EFI) to measure the ambient (DC−8 kHz, 100−400 kHz) electric field in 3D

THEMIS and ARTEMIS Science Data Collection

Configurations of science instrument modes and on-board data acquisition cadencies for so-called *survey* and *burst* data sets are selected based on predicted crossing times of scientific regions of interest (ROIs). In addition, burst data collection is also triggered by real-time detection of significant events. The four primary modes of data collection are summarized in Table 1. Quoted data collection rates represent a combination of all science instruments, and can be tuned to address different science goals.

Table 1. THEMIS Data Collection Modes.

Mode	Utilization	Data Rate
Slow Survey (SS)	Low cadency routine data capture	~0.5 kbps
Fast Survey (FS)	High cadency routine data capture	~12 kbps
Particle Burst (PB)	High resolution capture of particle energy distributions and low frequency waveforms	~43 kbps
Wave Burst (WB)	High resolution capture of electric and magnetic field waveforms	~470 kbps

Regions of interest were originally implemented for the THEMIS multiprobe mission to define time intervals, such as crossing times of specific regions in space that sequencing of on-board activities can be queued of off. In total, THEMIS and ARTEMIS use 26 ROIs for mission planning purposes. Some of these regions are defined to indicate times when the THEMIS probes form conjunctions, or when THEMIS and ARTEMIS form joint conjunctions to allow for simultaneous science data collection. Such opportunities arise during the magnetospheric tail observing season (see Figure 1 below), and to a lesser extent once per month when the Moon carries the two ARTEMIS probes through the Earth's deep magnetospheric tail at a distance of about 60 R_E. This new geometry allows valuable observations to be made twice as far from the Earth as feasible during the THEMIS prime mission. The complete list of ROI crossing indicators include the following:

- Earth and lunar shadows
- South Atlantic anomaly
- High magnetic field
- Northern and southern auroral zones
- Periapsis passage
- Orbit inbound and outbound
- Radial distance region
- Inner and outer radiation belts
- Magnetotail and magnetosheath
- Magnetopause and bow shock
- Average plasma sheet
- Deep plasma sphere
- Foreshock solar wind
- Solar wind beam
- 2-day and 4-day conjunctions (THEMIS prime mission)
- Time based conjunctions (between individual probes)
- Ground based observatories (alignment with probes)

For the ARTEMIS mission, two newly defined ROIs were added:

- Low periselene science
- Lunar wake

An illustration of how the alignment of the magnetospheric regions of interest change with the orientation of the spacecraft orbits over the course of a year is shown in Figure 1 (Bester et al. 2009).

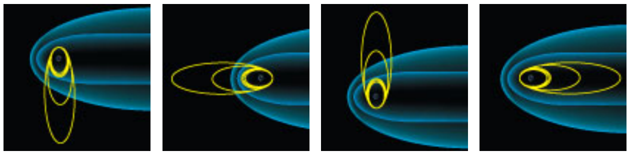

Figure 1. Orbit alignment with respect to the magnetosphere for different observing seasons, from left to right: dusk (spring), dayside (summer), dawn (fall) and tail (winter).

THEMIS and ARTEMIS Mission Ephemeris

The mission design and planning process begins with generating a predictive end-to-end mission ephemeris for each probe, using the Mission Design Tool (MDT), a software package developed in-house at SSL (Frey, Angelopoulos, and Bester 2009). MDT is based on high-level Interactive Data Language (IDL) code that calls the Goddard Trajectory Determination System (GTDS) for orbit propagation with high-fidelity force modeling (Bester et al. 2008). Finite thrust maneuvers are included where applicable.

The mission ephemeris contains columns of time (in 5-s increments), Cartesian position, velocity and attitude components, current spacecraft and fuel mass, accumulated ΔV, thrust status flags, and a 32-bit word to define the status of each of the ROI crossings.

Mission ephemeris files are routinely updated once per week or more frequently, if necessary, during maneuver seasons, and typically cover 4-6 weeks into the future. Longer duration runs to plan one year into the future are typically generated once per month. Definitive ephemerides for science data analysis are generated in the same file format.

Constellation Science Observations

All regions of interest are analyzed for each probe independently. Very specific for THEMIS and ARTEMIS is the simultaneous FS data collection. The total FS duration per orbit is limited by the on-board memory and downlink capacities, but is otherwise designed to be very flexible. It can be defined by one probe crossing one or more specific regions of interest, or by a composition of multiple probes and regions of interest. It can also be one or more intervals per orbit. Even non-coordinated or partly coordinated FS collections are possible and have been scheduled.

Definition of the FS data collection intervals has been parameterized to be able to easily adapt to changing orbital geometries, new science target specifications, or an increase/decrease in FS capacity. Typical parameters are durations or radial distances. It is also relatively easy to modify or add new regions of interest, if necessary.

Examples of Complex Planning Problems

The following two examples, one each for THEMIS and ARTEMIS, illustrate how complex the process of determining optimal times for science data capture can become, and how vital it is to have a streamlined, automated process in place to support planning activities.

Secondary THEMIS science, conducted during three months in the dayside season (see Figure 1), was focused on observing two magnetospheric boundaries with the solar wind – the magnetopause and the bow shock regions. Depending upon details in orbit alignment with the magnetosphere, each of the three THEMIS probes could cross the magnetopause region and/or the bow shock region once or twice per orbit. Therefore, FS allocation per orbit was split into 40% for the magnetopause and 60% for the bow shock. FS data collection intervals were set individually for each probe, centered at the crossing time and with a duration depending on the total number of crossings of that region on any given orbit to maximize the science data volume without overflowing on-board memory.

With ARTEMIS, the two primary regions to address the science goals are the low periselene passes and the lunar wake region crossings. For magnetospheric observations and specific instrument modes, the space plasma environment was subdivided into the solar wind beam region, the magnetotail region, and the magnetosheath region.

The challenge for planning maximum FS collection during the journey to the Moon and in the early lunar orbit phase was set by the different space plasma regimes requiring different instrument modes. FS data were to be collected on both probes simultaneously whenever one probe was within the periapsis region or crossing the lunar wake region. However, the selected instrument mode for both probes depended on the space plasma environment of the probe that happened to cross one of these regions. By orbit design, one probe (P1) is in a retrograde and the other (P2) in a prograde, low-inclination lunar orbit. Thus, the probes are often passing through opposite plasma regimes. Furthermore, periselene passes and lunar wake crossings often overlap. If not properly accounted for, this would result in less than maximum allowed FS collection per orbit.

The FS data collection capacity for ARTEMIS varies significantly over time, and sometimes even between the two probes. Therefore, parameterization of the region definitions was implemented and proven beneficial, as adjustments can be made very easily. The formula for determining FS collection times T(FS) on the two ARTEMIS probes (P1, P2) can be expressed as

$$\begin{aligned} T(FS,P1) \; = \; & n1 \times \mathrm{periselene1} + m1 \times \mathrm{lunarwake1} \\ & + n1 \times \mathrm{perislene2} + m1 \times \mathrm{lunarwake2} \end{aligned} \tag{1}$$

and

$$\begin{aligned} T(FS,P2) \; = \; & n2 \times \mathrm{periselene1} + m2 \times \mathrm{lunarwake1} \\ & + n2 \times \mathrm{perislene2} + m2 \times \mathrm{lunarwake2} \end{aligned} \tag{2}$$

where n1, m1 , n2, m2 are scale factors, and periselene1/2 and lunarwake1/2 are the durations of the respective region crossings. The scale factors are equal to 100% for maximum FS data volume, and are otherwise adjusted to lower the FS data volume, depending upon available downlink bandwidths and pass durations.

Once the science planning process is completed, the next steps are to arrange for communications opportunities to recover the collected science data, and to build sequence tables that are uploaded in order to control instrument configuration and science data collection on the probes.

Mission Planning Products

This section covers the generation of data products that are essential to support pass scheduling and building of sequence tables.

Scheduling Products

Mission ephemeris files described earlier are ingested into the product generation process by SatTrack that in turn integrates all of the information into operational timelines for further processing by the SatTrack Scheduling Tool and the sequencing process.

SatTrack calculates view periods and dynamic link access periods for each spacecraft and each operational telemetry data rate at any of the supporting ground stations. Calculation of link access periods is based on knowledge of the spacecraft transmit power, attitude dependent spacecraft antenna gain, free-space path loss, ground station figure of merit (G/T), and low-elevation terrain effects. Over time, the models have been adjusted to operate reliably with the smallest possible, positive link margin in order to maximize the science yield.

Sequencing Support

SatTrack also calculates other derived products, such as so-called duration event files containing the region of interest crossing times in a format that the sequencing software can readily ingest and utilize to queue on-board instrument configuration and science data collection per pre-defined sets of activities. Other SatTrack products contain the operational pass schedule, including configuration information for space-to-ground communications for each pass.

Network Acquisition Data

The UCB MOC is responsible for providing acquisition data files to all networks elements for antenna pointing. Different networks require data to be delivered in different formats, such as Orbit Ephemeris Message (OEM) files (NASA/DSN), Improved Interrange Vector (IIRV) files, (NASA/NEN and SN), Internet Predict Version 2 (INP2) files (NASA/NEN, USN), and two-line element (TLE) sets (NASA/NEN, DLR, ASI, USN).

Scheduling and Data Recovery Strategies

This section describes the strategies for scheduling passes and data recovery that are employed with different supported missions.

RHESSI

With RHESSI, the data recovery strategy is fairly straightforward. The primary ground station is the Berkeley Ground Station, supporting 5-6 passes per day, while Wallops and Santiago provide secondary support with up to 4-6 daily passes combined. The Weilheim Ground Station is scheduled in *blind dump mode* (telemetry only) during times of increased solar activity.

NuSTAR

NuSTAR is primarily supported by the Malindi Ground Station while Singapore and USN Hawaii provide secondary support. For this mission, the decision was made to configure the on-board recorders for cyclic overwrite. A sufficient number of passes – typically at least 4 per day – are scheduled, to avoid data losses.

Gaps in the recovered telemetry data are detected on the ground and are filled very effectively by sending automated commands to retransmit the missing sections.

THEMIS and ARTEMIS

Mission support requirements for THEMIS and ARTEMIS have changed significantly over time. During the prime mission phase, the five spacecraft were maneuvered into synchronized orbits with multiples of sidereal periods, so that the perigees were always located over the American longitude sector. This scheme allowed primary telemetry recovery at the highest data rate to occur at the Berkeley Ground Station, and with secondary support by other NASA/NEN ground stations (Bester et al. 2010).

During the extended mission phase, two of the five spacecraft were transferred from Earth to lunar orbits, requiring the DSN to be brought online for science telemetry recovery from much larger distances, and for radiometric tracking support (Roberts et al. 2010).

In early 2012, the three Earth orbiting THEMIS probes were maneuvered into non-sidereal orbits with lower perigees to initiate a rate of orbital precession that is intended to eventually align the lines of apsides of the THEMIS orbits with those of the *Van Allen Probes*, launched in 2012, to allow for collaborative observations. Future alignments with the *Magnetospheric Multiscale Mission (MMS)*, presently scheduled for launch in 2014, are included in the mission design also.

The orbital periods of the three THEMIS probes are now approximately 22.9 h long, resulting in a shift of the longitude of perigee in Earth-centered Earth-fixed coordinates by about 15° per day. This means that in this coordinate frame the perigee revolves around the Earth approximately once every 24 days, leading to situations where none of the ground stations in the American longitude sector have a view period for certain orbits.

To facilitate optimal science return for collaborative observations with the *Van Allen Probes*, THEMIS now requires expansion of the FS data collection periods from approximately 10-12 h per day to ideally as much as 24 h per day, meaning that high-cadency science data are to be captured on a quasi-continuous basis. This latest increase in daily data volume is a factor of 4-5 higher than originally planned for the THEMIS prime mission. Originally, the THEMIS on-board memory had been sized for data recovery at high telemetry rates once per orbit near perigee, and with sufficient margin for storing two orbits worth of science data, in case a data recovery pass is missed. With the new scheme, there is little room for errors.

To meet this new requirement, the THEMIS Project obtained permission from NASA to certify the White Sands 18-m ground station (a.k.a. WS1) that primarily supports the *Lunar Reconnaissance Orbiter (LRO)* to also support THEMIS science data recovery. With this ground station, telemetry links are closed with data rates up to 262.144 kbps from apogee at a range of about 70,000 km. This way the on-board recorder can be downloaded after half an orbit already, thus avoiding saturation. However, since LRO has higher priority on WS1, THEMIS passes need to be broken up into 20-min segments to fit in between LRO passes when the Moon is above the station mask.

Additional complications arose with DSN support for ARTEMIS after the lunar *Gravity Recovery and Interior Laboratory (GRAIL)* twin-spacecraft mission launched. DSN was not able to meet the nominal ARTEMIS support requirements of one 3.5-h long pass per day with a 34-m subnet station. However, DSN offered usage of the 70-m stations to mitigate resource contention. With the significantly larger G/T, ARTEMIS in turn was able to increase the telemetry data rates to 524.288 kbps, limiting the required downlink time to 45 min. This re-allocation of resources helped to reduce overall loading. On the downside, the 70-m stations do not provide S-band uplinks, so commanding and radiometric tracking data are unavailable. To mitigate these issues, additional passes were scheduled at low telemetry rates (4.096 kbps) with WS1 and the USN 13-m stations in Hawaii and Australia. The Berkeley 11-m antenna provides continuous wave (CW) tracks several times per day for each ARTEMIS probe to supplement the sparse two-way Doppler tracking data sets.

Given all of these changes, the operations team needed to push the envelope in network communications to meet the multitude and complexity of the new requirements. Dynamic link models were adjusted and optimized to successfully recover data with only little telemetry link margin for all five THEMIS and ARTEMIS probes combined.

Scheduling Process

The complex multi-mission scheduling process that includes interaction with several different networks is described in the following subsections.

Scheduling Cycles

Pass scheduling activities cover one week at a time, from Monday, 00:00:00 UTC to Sunday, 23:59:59 UTC, and are developed in three stages:

- Forecast stage (2+ weeks ahead of the real-time week)
- Planning stage (1 week ahead of the real-time week)
- Operational stage (real-time week)

Operational schedules can be updated in real-time, if needed. Planning schedules are typically built and released on Wednesdays-Fridays for the upcoming week to allow flight controllers to build sequence tables for upload to each spacecraft. Output products include operational timelines that drive the automated process control system within the multi-mission operations center.

Scheduling Interfaces

Electronic interfaces exist with all scheduling offices to submit specific schedule requests and/or to receive committed schedules. Of course, all of these networks have their own list of users with different support requirements and assigned priorities.

The process of pass scheduling varies significantly between networks. DSN typically encourages the network user community to resolve scheduling conflicts in a collaborative effort, and pass supports are scheduled up to several months in advance. Other networks are typically scheduled on shorter notice.

Scheduling Software

A block diagram of the multi-mission schedule processing flow with the SatTrack Suite of software tools consists of several branches and loops, as illustrated in Figure 2. Details of this process are described elsewhere (Bester 2009).

The core of the SatTrack Scheduling Tool (SatSchedule) is a rule-based engine that is configured via several input data files. Rules and constraints are applied sequentially to generate forecast, planning and operational schedules.

Output products from the scheduling process simultaneously feed both the ground system and the spacecraft side, so that timelines for executing pass operations match identically.

Humans in the Loop

A scheduling environment that includes many different missions plus a number of networks with dissimilar requirements and overlapping conflicts is very difficult to automate. Therefore, human interaction is unavoidable.

The scheduling team at the UCB MOC interacts with external scheduling offices via voice communications and electronic mail exchanges on a daily basis. Participation in DSN schedule meetings to negotiate mid-term schedules

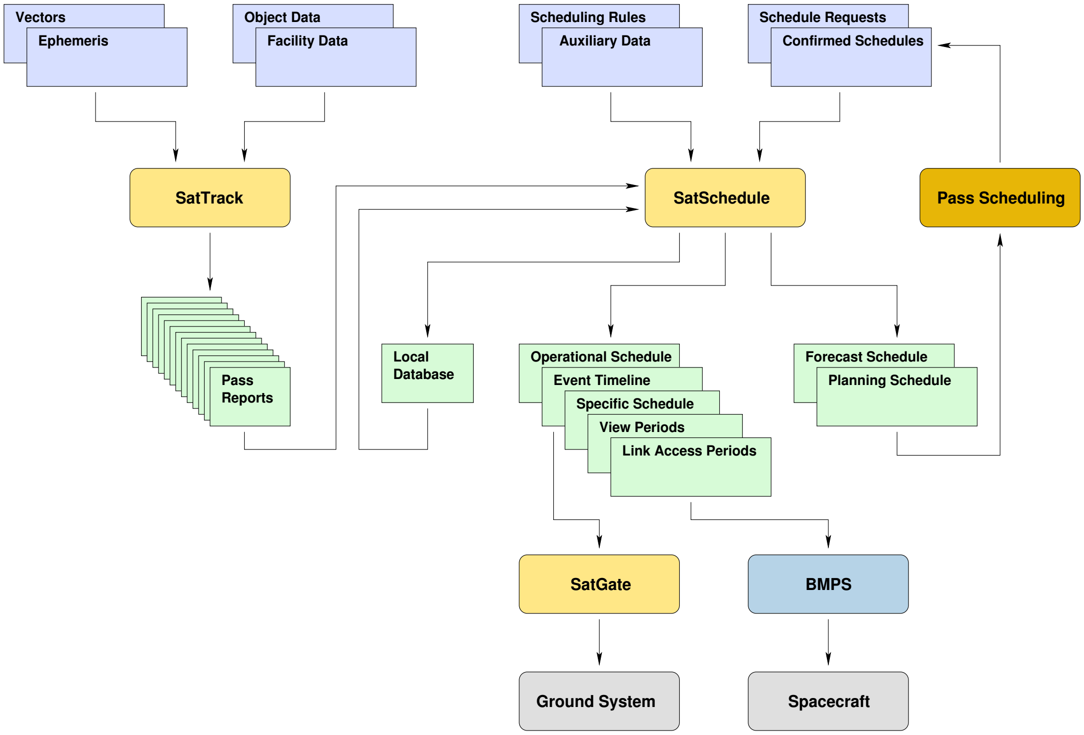

Figure 2. Block diagram of the multi-mission pass scheduling process.

several weeks to months into the future is essential to resolve conflicts efficiently.

Schedule Execution

Once the weekly mission planning and scheduling process cycle is completed, all data products are released and the schedules are executed in the real-time week.

Master Schedule

The master schedule is maintained in a flat file format. Each run of the SatTrack Scheduling Tool rebuilds the master schedule from individual, committed schedules provided by the different networks. Inconsistencies, errors and constraint violations are detected.

The SatTrack Scheduling Tool also generates all secondary products needed to build sequence tables and to feed the centralized automation system in the MOC. A variety of software tools are available to display current operational schedules. An example of a multi-mission schedule is shown in Figure 3.

Sequencing

Absolute Time Sequence (ATS) tables are built with the Berkeley Mission Planning System (BMPS). BMPS ingests the pass schedules for the real-time or planning week along with other planning products to generate ATS tables for each spacecraft.

With the special requirements for THEMIS and ARTEMIS to maximize FS data collection, BMPS performs additional checks to ensure the on-board solid-state recorders are not saturated. This assessment is based on inputs from the mission design, as described above, and the committed pass schedule. If memory saturation is predicted, then the FS data collection is trimmed back accordingly. Corresponding flight software commands are adjusted in the sequence table, as it is built.

Special care is given to activities that cross week boundaries. Once reviewed and approved, ATS tables are uploaded to the respective spacecraft.

Control Center Automation

Real-time schedules are also processed by the SatTrack Gateway Server (SGS) that serves as the centralized backbone for the entire MOC automation. SGS maintains the operational pass schedule in form of an event timeline.

SGS also maintains continuous TCP/IP network socket connections with all spacecraft command and control workstations running the Integrated Test and Operations System (ITOS) software (the Hammers Company 2009). Other clients connected to SGS are frame routing systems that establish end-to-end network socket connections

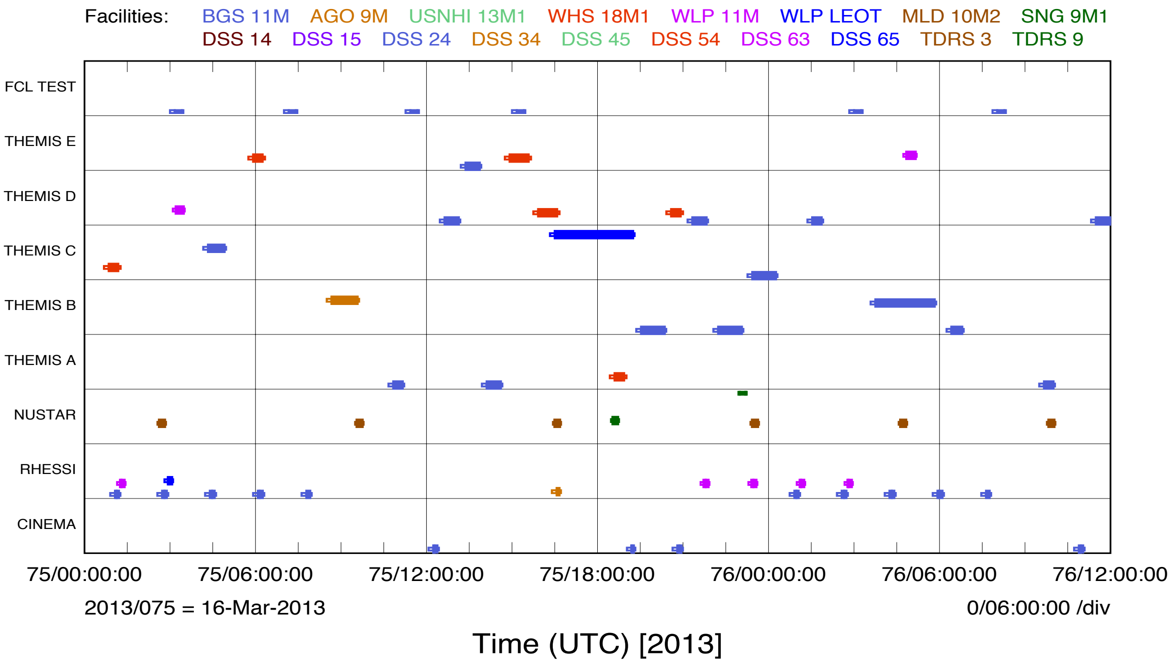

Figure 3. Illustration of an operational, deconflicted multi-mission pass schedule for a typical 36-h period. Periodic facility self-tests (FCL TEST) in loopback mode are automatically inserted into gaps in the tracking schedule of the Berkeley Ground Station.

between the supporting ground station and the ITOS workstation for a given pass support, as well as the Monitor and Control System (MCS) of the local Berkeley Ground Station.

Based on time tagged events, such as start of pre-pass configuration, begin of track, end of track, and end of post-pass deconfiguration, the client systems receive messages from SGS to initiate automated pass support activities. Connected clients provide extensive status information back to SGS that is used in turn for logging and error messaging purposes (Bester et al. 2010).

Science Data Recovery and Processing

Once a pass is completed, the telemetry files are transferred to the MOC for processing by the Berkeley Data Processing System (BDPS). BDPS performs additional error correction functions, and verifies the file content against the operational schedule.

Once the telemetry files pass the initial verification checks, the CCSDS source packets are extracted and stored in a MySQL database. If data gaps are detected, then the operations team is notified, and in some cases, automated replays from the spacecraft are queued up. Data gaps in the database may be filled in when the telemetry files from the next pass are ingested.

Once all received packets are stored in the database, they are automatically time ordered, and duplicates are discarded. These benefits are provided by nature of the database algorithms. It is in turn very easy to extract Level-0 data products, typically spanning 24 h. Those products are then delivered to the respective SOC for each mission.

Experiences and Lessons Learned

A number of lessons were learned over time with operating multiple missions and interacting with many different scheduling offices in an environment where support requirements keep changing.

1. Scheduling involves direct human interaction with many individuals, both within the local team and at remote scheduling offices, often on a daily basis. Communications skills and an excellent team spirit are very important. Interacting with networks in different time zones can be challenging when schedule changes need to be made on short notice.
2. A good understanding of the scheduling environments in which different networks operate, as well as knowing their limitations, procedures and ways to communicate, is important.
3. Making concessions when possible and understanding requirements of other missions competing for the same resources will result in successful cooperation in the long run, and will benefit all parties involved towards achieving their mission goals. The community based

DSN scheduling model is an excellent example for this approach.

4. It is very useful to have options to meet network support requirements. If a network element becomes unavailable and alternate options exist, then mission requirements may be met. Otherwise, science data losses have to be expected. Flexibility is key to success, but limitations and boundaries must be known.
5. Having the Berkeley Ground Station co-located with the MOC is very valuable, as passes can be scheduled on short notice to support anomaly recovery, or as a backup to playback telemetry data from a pass missed elsewhere.

Future Work

Improvements to further streamline the mission planning and scheduling process include a number of short-term software upgrades, such as implementation of new scheduling rules, or additional constraint checking.

In the mid-term, the interface to NASA's Space Network Access System (SNAS) for electronic exchange of committed SN schedules and upload of pass requests will be implemented.

Long-term upgrades of the scheduling system may include architecture changes to store all scheduling products such as view and link access periods in a MySQL database. Likewise, forecast, planning and real-time pass schedules may also be stored in the same database. Additional software tools to populate the database and to extract operational schedules in support of control center automation and sequence table generation will have to be developed.

Time frames for these upgrades will depend upon new mission requirements and available resources within the operations team at UCB.

Summary

Operating multiple space missions with very different and changing support requirements, and across eight different networks can be rather challenging. Over time the operations team at UCB streamlined its internal software tools and procedures, and collaborated with external networks to find ways to meet complex mission requirements.

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Appendix

Table A1. Overview of missions presently supported by the Multi-mission Operations Center at UCB/SSL.

	RHESSI	THEMIS *	ARTEMIS *	NuSTAR	CINEMA
Mission Class	NASA SMEX	NASA MIDEX	NASA MIDEX	NASA SMEX	NSF CubeSat
Launch Date	Feb. 5, 2002	Feb. 17, 2007	Feb. 17, 2007	June 13, 2012	Sep. 13, 2012
Mission Phase	Extended Mission	Extended Mission	New Lunar Mission Started in 2009	Prime Mission	Prime Mission
Science Objectives	Solar Flares, Heliophysics	Magnetospheric / Heliophysics	Magnetospheric / Heliophysics	X-ray Astronomy, Black Holes	Magnetospheric / Space Physics
Science Instruments	X-ray / Gamma Ray Rotating Grid Collimator	Particle and Fields Detectors	Particle and Fields Detectors	Hard X-ray Focusing Telescope	Particle and Fields Detectors
Instrument Platform	Spin Stabilized 15 rpm	Spin Stabilized 15 - 21 rpm	Spin Stabilized 14 - 15 rpm	Three-axis Stabilized	Spin Stabilized < 1 rpm
Mission Orbit Geometry	553 × 534 km 38.0 deg	3 Synchronized, Highly Elliptical, Low Inclination Earth Orbits	2 Synchronized Highly Elliptical, Low Inclination Lunar Orbits	637 × 618 km 6.0 deg	776 × 477 km 64.7 deg
Network Support **	BGS, WGS, AGO, WHM	BGS, WGS, WHS, AGO, USNAU, USNHI, TDRSS	BGS, WHS, USNAU, USNHI, DSN	MLD, SNG, USNHI, TDRSS	BGS
Passes / Day	6 - 10	3 - 15	2 - 8	4 - 8	3 - 5
Communications Links	S-Band	S-Band Coherent	S-Band Coherent	S-Band	S-Band (downlink) UHF (uplink)
Telemetry Data Rates	4000 kbps	4.096, 65.536, 131.072, 262.144, 524.288, 1048.576 kbps	4.096, 32.768, 65.536, 131.072, 262.144, 524.288, kbps	2000 kbps	1048.576 kbps
Required Average Downlink Time	75 min / day	90 min / day Each Spacecraft	105 min / day Each Spacecraft	40 min / day	30 min / day
Average Telemetry Volume	18 Gbits / day	1.8 Gbits / day Each Spacecraft	0.4 Gbits / day Each Spacecraft	4.8 Gbits / day	1.8 Gbits / day

* For the extended mission phase, THEMIS was bifurcated into THEMIS-Low and ARTEMIS, a new lunar mission.
** Acronyms are explained in the Communications Networks section.