THEMIS: IMPLEMENTATION OF A CHALLENGING MISSION DESIGN

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ABSTRACT

Launched on February 17, 2007 on a DELTA II rocket, NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) is a Medium-class Explorer Mission and the first space mission to study the sequence of magnetospheric events that trigger gigantic auroral displays in the polar regions using a macro-scale constellation of spacecraft. THEMIS is composed of a space segment of 5 identical probes equipped with particle and field instruments and a ground segment of twenty Ground Based Observatories (GBOs) with all-sky cameras and magnetometers. The probes utilized their own propulsion systems to reach their final, near equatorial orbits with periods of one, two, and four days, respectively. Operated by a small team at the University of California in Berkeley, THEMIS just finished its nominal mission with all science goals fulfilled and all instruments operating flawlessly. As part of the extended mission phase, two of the five spacecraft are transferred to orbits around the moon, while the three remaining probes continue magnetospheric observations in Earth orbit. The orbit design strategy is primarily driven by the scientific goals of the mission, but it also represents a compromise between the probes' thermal constraints and fuel capabilities. Mission specific software tools, integrating NASA-provided software for high-fidelity orbit prediction and maneuver simulation as well as common magnetospheric models, were developed with the capability to gracefully recover from missed maneuvers or maneuver execution errors and to progressively increase the final placement fidelity. The same tools are used for long-term as well as operational planning and near-real time maneuver preparation. In this paper we focus on the implementation of the mission design, describe our low-risk strategy and summarize our experiences on what contributed to the successful performance.

1. INTRODUCTION

NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission is the first constellation to study the coupling of space plasma processes on large and disparate scales in the Earth's magnetosphere. Magnetic substorms are energy storage and release phenomena of the Earth's magnetosphere – a large-scale instability in the Sun-Earth's energy coupling process. The sudden outbreaks of intense and dynamic auroras in the polar regions are counterparts of energy releases in Earth's space environment that can expand over more than 30 R_E away, on the night side. The THEMIS mission was designed to simultaneously observe substorm related processes in the equatorial magnetotail with the auroral breakups in the polar regions. A space segment of five identical, small spacecraft called *probes* is deployed over key magnetospheric regions on highly elliptical orbits with periods ranging from one to four days, and is coordinated in time with a set of twenty Ground Based Observatories (GBOs) located along the average auroral oval in North America (Fig. 1). Crucial for mission success is that all measurements be taken inside of or near the neutral sheet. This thin plasma layer is formed around the magnetic equator inside 10 R_E but stretches parallel to the ecliptic in the magnetotail, following the diurnal motion of Earth's magnetic dipole and moving in and out of the ecliptic over the course of a year.

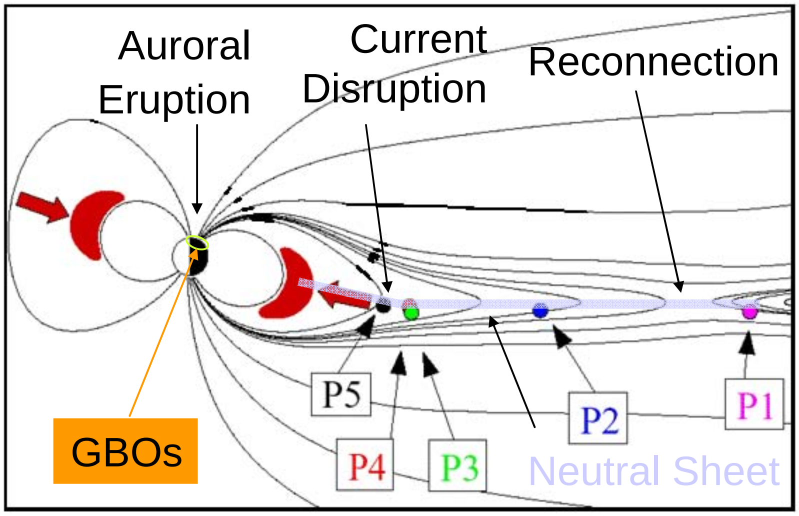

Fig. 1: Overview of probe constellation projected into the midnight meridian (XZ-plane) near the neutral sheet and of the GBOs near the auroral oval. The thin curved lines represent magnetic field lines and illustrate how the locations of P2, P3, P4 and P5 are magnetically coupled to the auroral regions. The three probes P3, P4 and P5 are placed where current disruption takes place and the dipole-shaped field gets stretched into the tail, while probes P2 and P1 are placed down in the tail on either side of the reconnection zone.

The challenges to capture the complex dynamic of the magnetospheric processes by the orbit design have been threefold:

- Aligning the relatively fixed orbital planes with the magnetospheric key regions of primary science interest in the anti-sunward directed magnetotail.

- Accounting for eclipses and orbital precession due to Earth and Lunar perturbations, and counteracting some of them over at least two years of nominal mission lifetime.
- Ensuring this alignment in space at the times these tail regions are magnetically connected to the polar regions observed by the ground segment for any launch day of the year.

Each of the identical spinning probes is equipped with five scientific instruments. Instruments and data collection are designed to provide the field and particle measurements at a time resolution and over a dynamic range corresponding to the temporal and spatial scales of the plasma environment. For initial placement, station-keeping and attitude control, each probe carries its own monopropellant hydrazine propulsion system with two axial and two tangential thrusters, all capable of independent continuous or pulsed thrusting, sun synchronized or time-synchronized. Each GBO operates an all-sky camera and a magnetometer at time resolution and sensitivity required to determine onset times. For a comprehensive description of the THEMIS mission including all subsystems, instrumentation and first science results, the reader is referred to [1] and references therein. After four years in Phase B-D development, the mission was launched with all five probes on a Delta-II rocket from Cape Canaveral on February 17th, 2007. Since launch we have performed 297 maneuvers of which 114 changed orbits, at times significantly, while the others maintained spin axis orientation and spin rate. The science data return has been excellent. Over 20 substorm events, more than twice the number required for the baseline mission, have been observed during perfect alignments between the probes and the GBOs. The number of multi-point measurements across the magnetopause and bow shock is countless. Managed by the Space Sciences Laboratory of the University of California at Berkeley (UCB/SSL), THEMIS has just finished its nominal mission with all science goals fulfilled and all engineering systems operating flawlessly, thus proving a mission and operations concept that can act as a model for future multi-spacecraft missions. The mission has also proven its role as a pathfinder for future constellations [2] and accomplished data collection that meets the stated science goals set forth for the prime mission [3]. Furthermore, the successful execution of the THEMIS mission has allowed us to move on to two extended missions until 2012. Two probes have already started their ambitious journey to the moon – the Acceleration Reconnection and Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission. The remaining three probes will continue to study the mass, energy, and magnetic flux transfer through the magnetopause and radiation belt processes in a close triangular formation. This paper emphasizes the implementation of our orbit strategy with a computerized approach to orbit design, probe deployment and constellation maintenance, and summarizes our experiences gained from long-term mission planning through in-flight implementation. An in-depth description of the orbit design is given in [4].

2. THEMIS MISSION OVERVIEW

In order to time and localize substorm onsets, THEMIS utilizes conjunctions between 10 and 30 R_E on low inclination orbits with a lateral separation of less than 2 R_E. As shown in Fig. 1, these nightside conjunctions occur near the substorm meridian at times of local midnight of the ground observatories. Three inner probes (~1day period) monitor current disruption at 8-10 R_E and two outer probes (~2 and ~4 day periods) monitor lobe plasma flux dissipation and magnetic field reconfigurations during reconnection at 20-30 R_E. Inclinations and arguments of perigee have been chosen such that the apogee passes are closest to the neutral sheet [3]. This orbit configuration also provides radial profiles of highly energetic particles through the radiation belts year-around, and on the dayside coverage of magnetopause and bow shock crossings with upstream monitoring. Overall, THEMIS addresses three science objectives as described in [3] and summarized here:

- Evolution of substorm onsets (primary tail science)
- Generation of storm-time high-energetic particles (radiation belt science)
- Control of the interaction of the magnetosphere with the solar wind by upstream processes (dayside science)

Due to the annual rotation of the magnetosphere in inertial space the time for the primary science is limited to the relatively short time (~2 month interval) when the outer probes can provide the necessary coverage of the reconnection zone. Equally limited in time is the alignment required for the dayside science. According to the rotation in the Sun-Earth system, the mission can be divided into two main seasons: the tail season where apogees cross the Sun-Earth line in the tail for primary science; and about six months later the dayside season where apogees cross upstream in the solar wind. Fig. 2 shows the orbits every three months in the XY-plane in a Sun-Earth aligned coordinate system (X towards the Sun).

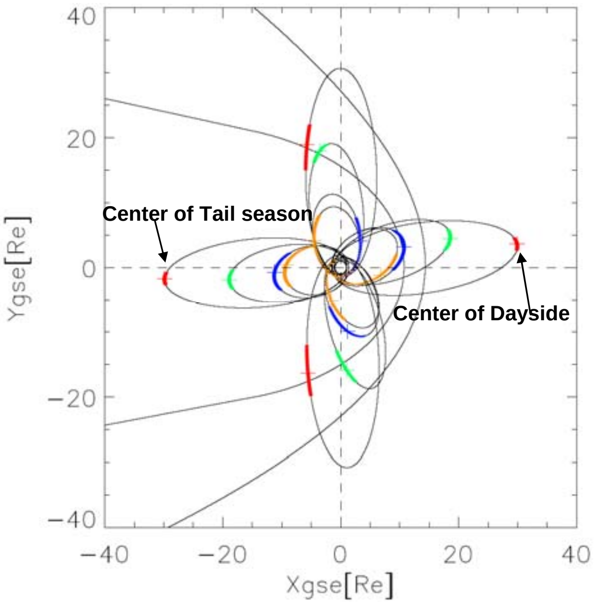

Fig. 2: Orbit evolution over the first year, projections onto XY-plane in geocentric solar ecliptic coordinates (GSE) are taken every three months starting with the tail season. The colored tracks mark simultaneous 3 hour intervals. Also shown are magnetopause and bow shock (from [4]).

The primary science season was chosen from January to March so that the apogees of all probes align crossing the Sun-Earth line in early February. This center epoch for the primary science season is a compromise between eclipse durations and recurrence rate of substorms, and takes advantage of long winter nights in North America for optical observations with the GBOs [5]. Once chosen, this center epoch determines the orientation of the launch trajectory and drives the mission timeline. Since the inertial position of the line of apsides is determined by science criteria, a launch date can be accommodated by adjusting the Universal Time of the launch to result in placement into the desired inertial position in the sky. This position has to be tuned to the specific day of launch such that Earth and Moon perturbations accumulating over the time elapsed from launch until the start of the prime science collection will bring all probes into the desired inertial locations of the line of apsides and desired inclinations. Due to launch vehicle delays, a coast phase was inserted between the actual launch date and the prime science season, whose function was simply to provide a smooth transition from the launch elements into the prime season elements. The coast phase therefore ensured the mission design remained intact regardless of launch date, thereby reducing risk from a continuous mission redesign to accommodate a changing launch date. This variable-duration coast phase mission design entailed five probes in a string-of-pearls configuration to ensure minimal differential precession of the probes' orbits while science would benefit from instrument cross-calibration and a unique view of the magnetosphere from small-scale separations. Table 1 gives an overview of all mission phases. Probes are referenced in their order within the constellation: P1, P2, P3, P4, P5.

Table 1: Overview of Mission Phases, probes are referenced as P1, P2, P3, P4, P5

Mission Phase	Orbit Period	Time Frame	Purpose
Launch	31h	Feb. 17, 2007	
Early Orbit		Spring 2007	Post launch check out, Power and thermal save attitude Magnetometer boom deploy, Stabilizing perigees Assignment of position in constellation (1,2,3,4,5)
Coast phase	31h	Summer 2007	Boom deploy on three probes, Instrument commissioning, Additional dayside science
Placement Phase	Variable	Sept.-Nov 2007	Placing all probes in their science orbits Complete boom deploy and instrument commissioning Science attitude, spin rate
Tail Season 1	4/5d,1d,1d,2d,4d	Winter 2007/2008	Primary and radiation belts science observation Conjunction maintenance
Dayside 1	8/9d,1d,1d,2d,4d	Summer 2008	Dayside and radiation belts science observation Conjunction maintenance
Tail season 2	1d,1d,1d,2d,4d	Winter 2008/2009	Primary and radiation belts science observation Conjunction maintenance
Dayside 2	8/7d,1d,1d,2d,4d	Summer 2009	Dayside and radiation belts science observation Conjunction maintenance

3. IMPLEMENTATION

Strategy to Implement a Robust Mission Plan

The key to mission design success was a robust and reliable set of mission planning tools, which is a prerequisite also to reliable operations and highly automated implementation. Given the large number of maneuvers our strategy was to keep the orbit design as simple as possible by breaking down the complexity of the THEMIS constellation concept in terms of design goals. The cumulative effect of Earth and lunar perturbations on the orbital environment could only be sufficiently assessed with a complete trajectory over the entire mission. Mostly due to the requested flexibility in launch day we decided early on to develop a mission-specific software tool to generate a baseline end-to-end trajectory to:

- Quickly reconfigure the orbit design as desired
- Progressively increase the final placement fidelity
- Gracefully recover from missed maneuvers or maneuver execution errors

Computerizing the orbit design and maneuver planning was of great benefit to our strategy. Rather than handling each probe and maneuver on a case-by-case basis, we integrated orbit design, maneuver planning, and evaluation of requirements into one well-structured process for the entire mission. We formalized the planning process by identifying the similarities and differences between the probes. Breaking up the mission requirements and defining tolerances was not only essential for automated data processing but also crucial for effective contingency planning and for consistency in evaluating mission design success. Through the analysis of isolated exceptions to the generalized design rules we were able to eliminate potentially critical events. By reducing error sources and by integrating a wide range of contingency responses, we achieved a high degree of flexibility that made orbit design and maneuver planning very robust and efficient. This in turn allowed us to evaluate optimization strategies, sensitivity to input parameters (e.g., probe inclinations, apogees, periods) and to ensure robustness of the mission implementation plan. Structuring the mission in phases with repetitive maneuver schedules not only enabled effective long term planning but also a fast transition into routine operations and the ability to redesign portions of the mission without affecting the follow-on mission phases.

Mission Success Parameters and Design Drivers

Of the three science goals only the primary science goal was important for mission success. In other words, secondary and tertiary science goals did not drive mission design. Mission planning was also designed to be compliant with the guidelines for operations of instruments and for the data collection scheme [1]. For a quantitative evaluation of the design success, the science requirements were reduced to three parameters:

- The conjunction hours per season
- The maximum eclipse duration
- The total impulsive Delta-V

Furthermore, the requirements to obtain the measurements needed to answer the substorm question were simplified to just three conjunction criteria, the inter-probe separation in the XY-plane in geocentric solar magnetic coordinates (GSM), the distance to the neutral sheet distinguishing inner and outer probes, and the twelve hours the GBOs covered local magnetic midnight. Based on these three parameters, the center epoch of the first tail season and the orbital parameters at that time were pre-selected from an extensive parameter study. However, from early-on the final selection and maneuver fine targeting for the end-to-end trajectories always took into account all operational constraints to achieve a robust design with a high degree of fault tolerance. The complete list of design drivers that are considered by each design run and in-flight maneuver planning consists of:

- Primary science:
    - Tail conjunctions along Sun-Earth line near neutral sheet
    - Conjunctions with GBOs at local midnight
    - Center epoch of first tail season
    - Tolerances are more relaxed for inclination, perigee and apogee distances than for orbital period
- Orbital debris requirements
    - Compliance required for launch trajectory
    - Account for end of mission compliance in fuel budget
- Engineering constraints:
    - Maximum eclipse duration
    - No maneuver during eclipse, automated shifting out of shadow
    - Pressure limits for repressurization of fuel tank
- Operational constraints:
    - Maneuver execution in real-time
    - Minimum time for orbit and attitude updates before short-term planning of the next maneuver
    - Minimum time between maneuvers on different probes
- Fuel efficiency:
    - Limit arc losses by shorter burn times near perigee
    - Avoid axial thrust with deployed booms of the Electric Field Instrument (EFI)
    - Limit attitude changes during intensive placement phase
    - Set size of maneuvers in terms of burn time according to the blow-down pressure curve of the propulsion system
- Robustness:
    - Limit number of placement maneuvers
    - Include placeholder for final target maneuvers
    - Keep placement and maintenance for probes independent until final alignment
    - Add margins to each phase
- Fast re-planning capability:
    - Inherent flexible data derived maneuver targeting and rescheduling
    - Very limited manual data entry required to start
    - Combine post maneuver update with short-term maneuver planning
- Fault tolerance:
    - Inherently re-target maneuvers
    - Keep maneuver times non-critical
    - Reduce maneuver size towards the end of the placement sequence

- High degree of automation through data derived default settings
- Avoid mission critical events
- High rate of redundancy

Partitioning of mission design into placement and science phases.

In time:

For breaking the complex orbit design into well defined tasks we take advantage of the relative repetitiveness of the science seasons (tail, dawn, dusk, dayside seasons for each year) that follows the rotation of the line of apsides around Earth in a Sun-Earth aligned system (Fig 1). Each science season has a setup phase of 60 days and an observational phase of 120 days. Within each season we distinguish between the inner and outer probes according to their specifics of their placement and the maintenance of their final science orbits, making it easy to apply mission constraints and science targets with simple logic.

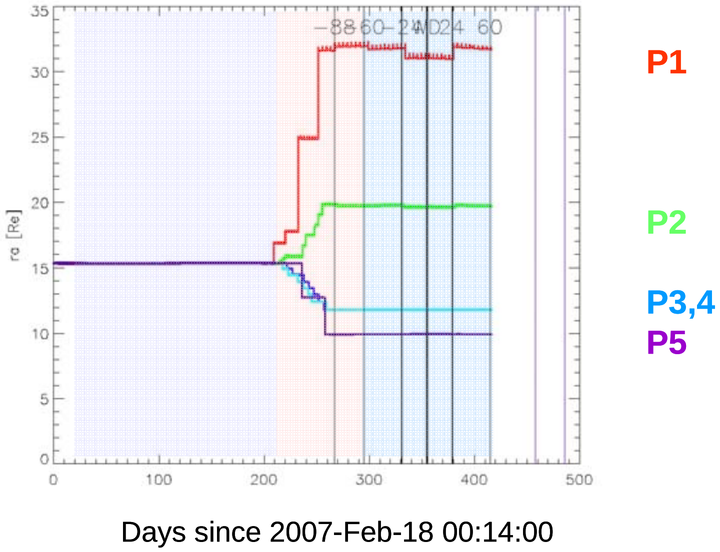

Fig. 3: Apogee distances for all probes from launch through first tail season. Colored areas mark coast phase, placement phase, and 1st tail season. Vertical lines mark tweak maneuver schedule. The thick line refers to the center epoch also nick named wedding day (WD). The thin black lines mark the four tweak maneuvers of the tail season. The purple lines already point to the first two tweaks of the dayside.

During setup for the first tail season, the placement phase, the inner probes descended (Fig. 3) from their launch apogee height. All maneuvers leading into the science orbits are determined and re-targeted in such a way that the probes arrive in their constellation position in time and with an orbital period close to what is required to maintain conjunctions. In order to account for the differential precession, the outer probes are frequently re-aligned with the inner probes during the observational phase. These relatively small maneuvers (tweaks) to adjust apogees were referenced in time with the center epoch of the season and in space with the apogee passes of the inner probes P3 and P4. The tweak schedule splits an observational season into three intervals indicated by the vertical lines in Fig. 3. According to its position in the constellation, each probe was assigned a target in space and time defining the total orbital change required for placement or seasonal setup and the available time. This total change was then split into a series of maneuvers by applying the set of constraints keeping maneuver time, number and size variable. Decreasing the last maneuvers in combination with a placeholder maneuver that was included for each targeted orbital element allowed to inherently adjust to contingencies like thrust variations or a postponed maneuver and made the re-planning process very capable.

Inner probes P3, P4 monitoring current disruption processes:
The space and time targets for the inner probes are final apogee distances near 12 R_E, aligned over the geographic center of the GBOs prior to the final placement of the outer probes. The separation of about 1 R_E between the probes at apogee is achieved by modifying the geographic targets around the center of the GBOs. The sidereal period required to lock the apogee passes throughout a season can be settled by only one small maneuver.
Size, number and time of placement/setup maneuvers are determined by the amount of offset to the geographic center of the GBOs, the drift rate of the apogee passes, the available time, and maximum burn time. Fig. 4 shows how placing the probes over the GBOs is controlled by number of orbits and the drift rate of the apogee passes which is a function of period.

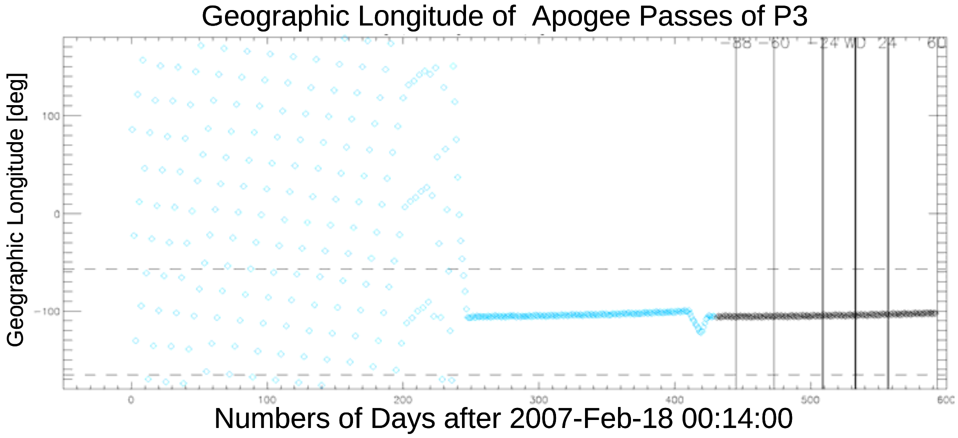

Fig. 4: Geographic longitudes of each apogee pass of P3 are shown from launch through first year tail and dayside seasons. Vertical lines indicate the dayside tweak schedule. Changes in apogee drift rates are due to intentional changes in period by maneuvers. Horizontal dashed lines frame the longitude range of the GBOs. Prior to the dayside there were a few maneuvers to raise perigee and reset sidereal period by adjusting apogee (from [4]).

Third inner probe P5 monitoring current disruption processes:
The third inner probe (P5) is the designated replacement spare for the probe going into the outermost orbit. Its deployment into the science orbit is delayed until P1 is fully commissioned in order to have the necessary fuel reserves. After the first tail season P5 undergoes larger period changes by apogee raises from about 9 to 13 R_E in order to form a triangular formation with P3 and P4. Size, number, and time of placement/setup maneuvers are determined similar to probes P3, P4. However, its final period is modified by aligning its apogee pass at center epoch with the apogee passes of P3 and P4 requiring P3 and P4 being in place.

Outer probes P1, P2 monitoring reconnection processes:

The space targets for the outer probes are final apogee distances near 20 R_E (P2) and 30 R_E (P1) at center epoch of the first tail season. The aim of the placement phase of these probes is to arrive close in time for the first conjunction tweak maneuver with the two and four-day orbital periods. Number and size of maneuvers are driven by the total change in apogee distance, available placement time, and maximum burn time. Only the tweak maneuvers are coupled with the inner probes. After the first tail season, the tweak maneuvers are repeated for each season to maintain lateral conjunctions. Prior to the second tail season a few setup maneuvers are necessary in order to reduce eclipse durations according to requirements and to bring the apogee passes closer to the neutral sheet in the tail.

Orbit re-design automation

The underlying concept for mission operations at UCB/SSL is to minimize the human interface by automating the data flow and evaluation, and keeping manual input simple. The THEMIS-specific mission design software, the Mission Design Tool (MDT) followed the same principle. It was developed for pre-launch mission design as well as for in-flight maneuver planning and operations. Written in the Interactive Data Language (IDL), a high level programming language, it is integrated into the set of software tools used by the mission operations center to support THEMIS [6]. The MDT integrates the mission goals, requirements and constraints into an impulsive maneuver plan, calls the Goddard Trajectory Determination System (GTDS) for high fidelity orbit propagation and uses the General Maneuver Program (GMAN) for finite maneuver targeting. Since launch it has been reading orbit and spacecraft states from an archive that is frequently updated with orbit and attitude solutions as well as maneuver reconstructions, and provides the ephemerides needed to generate the standard products for generating forecast pass schedules and onboard operations. In more detail, MDT functions include:

- Calculation of exact maneuver times
- Shadow and conjunction analysis
- Generation of maneuver command loads
- Determination of regions of interest for instrument operations
- Generation of operational ephemerides

And specifically to support verification and visualization:

- Generation of graphics to visualize orbital evolution and mission requirements
- Generation of maneuver overviews with headers listing the mission success criteria (Table 2) and listing of time, size, delta-V, fuel, burn time, and thrust mode for each maneuver per probe but also one probe interleaved schedule
- Generation of extensive log files as diagnostics

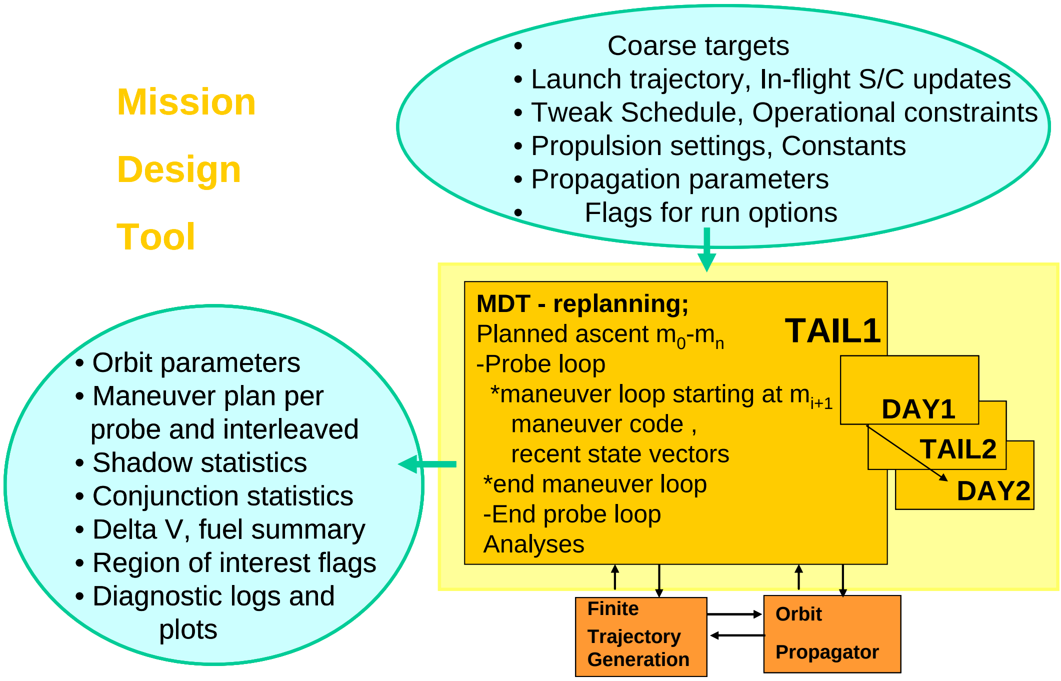

Fig. 5 Mission Design Tool flow chart

Fig. 5 shows the MDT flow chart which is organized to run one season at a time, fully automated for all probes. Based on a pre-determined parameter set, probes are processed consecutively starting with the inner probes generating the actual maneuver plan. Iterating through the maneuvers per probe makes it easy to change the number and even order of maneuvers. At the end of the maneuver series, probe-specific analysis (shadow, hours of conjunctions within regions of interest) are performed. After all probes have been processed, the conjunction analysis using a common model of the neutral sheet is performed to evaluate the science criteria and at the same time overview logs and plots are generated. While maneuver sizes and times are internally reassessed (optimized) for fuel efficiency and time constraints, finite maneuvers are automatically shifted out of eclipses and other parameters such as the center epoch and tweak schedule, the coarse space targets, and tolerances can vary from season run to season, thus balancing automation with user control. The extensive set of parameters was determined during the pre-launch long term mission planning by generating thousands of full mission end-to-end finite trajectories. The number of parameters needed to generate all five end-to-end finite trajectories in such an automated fashion is so large that we sorted them into subsets according their purposes:

- Orbit parameter targets and tolerances
- Finite targeting and propulsion parameters
- Tweak schedule, GBO longitudes
- GTDS parameters for high fidelity propagation
- Scheduling constraints
- Conjunction criteria
- Parameters for magnetospheric regions of interest
- Spacecraft specific parameters and properties

- Miscellaneous constants and out put parameters
- Flags for run options

For all parameters a default set is organized in two input files. One file holds all mission specific parameters needed to generate the mission trajectory based on impulsive maneuvers while the other file provides all spacecraft specific parameters to obtain finite trajectories. For user control a copy of the default input file is made to update or change individual parameters thus keeping a hard copy of each input.

Table 2: Standard Header List of Mission requirements (from [4]).

Season	**Center Epoch WD**	**Conjunctions [h] (4 probes)**	**Maximum eclipse [min]**	**dV [m/s]**
			P1 P2 P3 P4 P5	P1 P2 P3 P4 P5
Tail1	02-02-2008	72+ 77+102=251	166 113 109 114 79	373 287 307 300 345
Day1	08-03-2008	80+120+ 95=304	63 97 108 106 80	392 299 389 378 396
Tail2	02-07-2009	57+ 96+ 85=238	159 130 180 180 168	705 552 390 377 448
Day2	08-09-2009	33+ 99+ 93=225	129 137 164 165 158	731 568 394 381 498

From one season to the next only one filename is passed on referencing a binary file holding all end-states of a season. Only the finite trajectories of each maneuver are collected in an ASCII-file from which ephemerides can be generated at any time invoking high fidelity propagation. This two-step process saves runtime in planning and evaluating the entire season or mission in a sufficient time resolution. At the same time it allows to generate one or more sets of ephemerides at any time resolution and for any given time period. Once maneuver execution has begun, orbit states are picked from the archive by time reference while maneuvers are associated with a maneuver code. By comparing the last maneuver code in the archive prior to the time reference with the entire maneuver list of a probe, the process finds automatically where to jump into the maneuver sequence. No knowledge of actual maneuver times is required. For maneuver planning the typically required input is the time reference (usually the end of the current day) and latest updates of tank temperatures.

Flexible Mission Planning/Re-planning

Keeping the center epoch of the first tail season fixed with no restrictions on the launch was resolved by varying perigee altitude and argument of perigee of the launch trajectory and using the margins allocated at various steps through the placement phase. However, once the launch is too close to the center epoch the mission time lines had to be re-planned with significant changes. Fig. 6 illustrates the two extreme mission profiles we were able to design with feasible maneuvers while fulfilling all mission success criteria. At first, launch day delays could be resolved by cutting into early observations of the first tail season until the required hours of conjunctions could only be achieved by a delayed tail season. The original concept with the immediate placement of all probes into their science orbits took advantage of the lower moment of inertia while the EFI booms were still stowed, which allowed for the planning of most maneuvers in continuous axial thrust mode. This concept changed with the additional coast phase during which electric field measurements had been very desirable. However, having the booms deployed during the placement phase changes the maneuver dynamic and fuel consumption. Strictly preserving the resources for the primary science allowed to deploy booms only on three probes. Maintaining redundancy for placement into the outer most orbit, the EFI booms were kept undeployed on two probes (P1, P5) due to their high fuel demand. For probes with deployed EFI booms, all in-plane changes had to be done in side thrust mode which increased the number of maneuvers dramatically (in Fig. 3 compare the many little steps to increase apogee for P2, P3 and P4 with those for P1). Within a few weeks the delayed maneuver plan was finished without compromising the primary science fuel resources. The decision on the position of each probe within the constellation was done after launch, based on in-flight operations to best support primary science. The outcome required a re-arrangement of the probes to put those with deployed EFI booms at the center of the string-of-pearls formation for the additional dayside science. In very short time we were able to implement the desired formation with probe separations between 0.1 to 3 R_E for the coast phase [4].

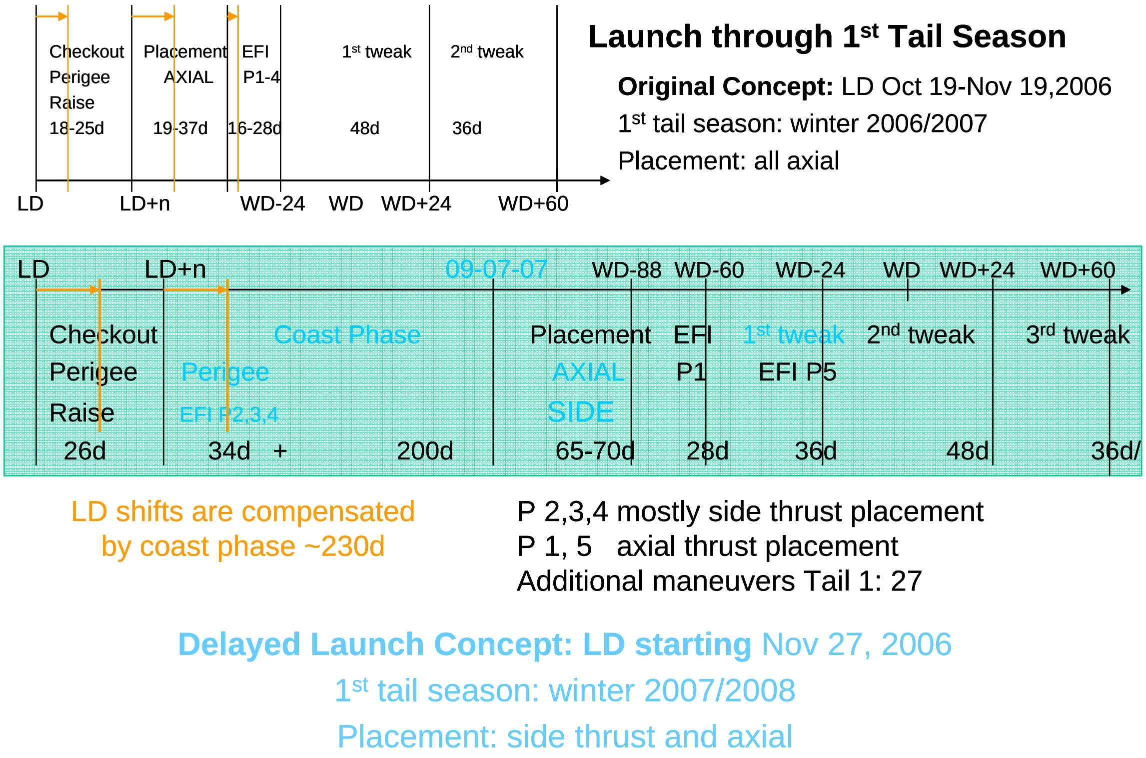

Fig. 6: Mission timeline from launch through first tail season, above without delay of first tail season, below with delayed tail season and added coast phase. Margins are indicated in orange, the arrows indicate how delays were absorbed without changing the schedule.

4. SCIENCE OPTIMIZATION

THEMIS science findings have made the news more than once. The first analysis on whether substorms are triggered by current disruption processes or by reconnection processes was selected the cover story of the science magazine in August 2008, a major feat based on the revolutionizing contributions of the mission and the excellent quality of the conjunctions [7]. This could only be achieved by instantaneous snapshots of the magnetospheric processes that are complementary to previous statistical analyses. The quantity and quality of the collected THEMIS science data have exceeded the promise and expectations mainly because of:

- Well defined feasible mission objectives
- Continuous operation of all instruments as designed
- High data retrieval at an average rate exceeding requirements
- Deployment of the constellation at required science targets
- Open data policy allowing scrutiny of our results

The strengths of our orbit design are our focus on the primary science, assessing end-to-end feasibility and mission success with increasing fidelity, and building up the mission design tool with and the ability to quickly re-generate a full-mission end-to-end trajectory with the highest possible fidelity and with operational capability. The flexible long-term mission planning and fast in-flight maneuver re-planning capability freed up our resources to enhance the quality of the science data. The highly automated mission design product generation, ensuring compliance with requirements, enabled the mission designers to work on further optimizing the orbit and maneuver design in the following ways: First, the team could respond quickly to launch vehicle changes by adjusting a flexible coast phase. Second, we were able to adjust the coast-phase probe positions ideally to study the structure and dynamics of magnetopause and bow shock [3]. Third, we could enhance the quality of our primary science data by implementing what we learned from the first tail season. The first tail season suggested that the magnetotail was much thinner than previously envisioned during substorms, necessitating tighter constraint on the location of the probes relative to the current sheet. In time for the second tail season the team had the maneuvers needed to avoid long eclipses while ensuring probes P1 and P2 were as close to the neutral sheet as the tighter science requirement stipulated.

This success was partly due to the fact that only six months between data collection and analysis of the first tail season, the team reassessed the probe thermal properties based on in-flight data and developed a mitigating on-board heater operation that allowed the probes to sustain even longer eclipses that the spacecraft design permitted. This study allowed us to bring the outer probes closer to the neutral sheet during their conjunctions while relaxing the engineering constraint on maximum shadow duration from 3 to 4 hours, without compromising the fuel budget for the proposed ARTEMIS mission.

Having an end-to-end mission trajectory early in mission development was crucial for long-term mission planning and strategic decisions on data collection modes. It allowed the science team to constantly evaluate the mission design by taking advantage of existing sophisticated web-based 4D visualization tools, such as [8] that combine spacecraft trajectories with magnetospheric models. Also possible became the coordination with ongoing as well future mission and ground networks which significantly contributes to the science return. Thanks to the open data policy, these data and tools have been available to the entire international science community initiating a broad and invaluable input essentially in real time.

5. CONCLUSIONS

Since THEMIS launch, all instruments have been functioning nominally and the ground operations were flawless. Commissioning of all instruments and the full deployment of the constellation were accomplished in time and science operations have been continuous thereafter. By the end of second tail season in March 2009, THEMIS has fully accomplished its baseline mission objectives with minimum fuel usage. Despite the extended solar minimum, THEMIS science data are magnificent and data retrieval is twice what was initially proposed. Throughout the mission the team was able to greatly enhance the science return. Our careful and diligent on-target execution of all operations has provided the resources for the equally ambitious extended THEMIS and ARTEMIS missions. The analysis of the THEMIS data, together with data from other magnetospheric missions such as STEREO, CLUSTER, Double Star, GOES and future missions such as RBSP, MMS, and the introduction of the ARTEMIS mission into the Heliophysics fleet will bring our understanding of the space plasma processes to a new level and revolutionize modeling and predictive capabilities of space environmental processes. By focusing on the primary science objectives, accounting for contingencies in planning and operations, and aiming for a high degree of automation, the THEMIS team was able to significantly optimize the science yield from this NASA investment.

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