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Orbit Design for the THEMIS Mission

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Abstract THEMIS, NASA's fifth Medium Class Explorer (MIDEX) mission will monitor the onset and macro-scale evolution of magnetospheric substorms. It is a fleet of 5 small satellites (probes) measuring in situ the magnetospheric particles and fields while a network of 20 ground based observatories (GBOs) monitor auroral brightening over Northern America. Three inner probes (∼1 day period, 10 R_E apogee) monitor current disruption and two outer probes (∼2 day and ∼4 day period, 20 R_E and 30 R_E apogees respectively) monitor lobe flux dissipation. In order to time and localize substorm onsets, THEMIS utilizes Sun–Earth aligned conjunctions between the probes when the ground-based observatories are on the nightside. To maintain high recurrence of conjunctions the outer orbits have to be actively adjusted during each observation season. Orbit maintenance is required to rearrange the inner probes for dayside observations and also inject the probes into their science orbits after near-simultaneous release from a common launch vehicle.

We present an overview of the orbit strategy, which is primarily driven by the scientific goals of the mission but also represents a compromise between the probe thermal constraints and fuel capabilities. We outline the process of orbit design, describe the mission profile and explain how mission requirements are targeted and evaluated. Mission-specific tools, based on high-fidelity orbit prediction and common magnetospheric models, are also presented. The planning results have been verified by in-flight data from launch through the end of the first primary science seasons and have been used for mission adjustments subject to the early scientific results from the coast phase and first tail season.

Keywords THEMIS · Mission design · Orbit · Magnetosphere · Substorm · Maneuver · Neutral sheet · Aurora · Launch · Re-entry · Fuel budget · Orbital perturbation · Lunar force · Geopotential · Orbit maintenance · Magnetotail · Reconnection · Solar wind · Propulsion

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1 Introduction

THEMIS is the first mission to study the onset and evolution of the magnetospheric substorm instability in a macro-scale constellation. Substorms are considered the fundamental mechanism within the Earth's magnetic field environment that shields Earth from the impact of magnetized plasma clouds from outer space such as the solar wind. The main components of substorm instabilities are the giant auroral eruption at the ionosphere near the Earth poles, and near the equator, the disruption of plasma sheet currents where the magnetosphere undergoes the transition from the stretched tail to a dipole fieldlike shape, and even further out in the tail, the reconnection of magnetic fields in the neutral sheet, triggering plasma flows. For the first time, all three main substorm components that can expand over more than 30 R_E are monitored simultaneously with time resolutions that match the dynamics of the substorm-related processes. Twenty all-sky cameras and ground magnetometers completely covering North America determine the timing of auroral breakups within an accuracy of 3 s, while the five identical THEMIS probes equipped with field and particle instruments determine onsets of current disruption and plasma flow originating from the tail reconnection to an accuracy of 10 s. The synchronized measurements of the ground and space segments, taken where the equatorial tail region maps along the magnetic field onto the substorm auroras in the polar regions, allow one to correlate the onset of substorms with the macroscopic interaction of the substorm components. This is achieved by aligning all five probes along the Sun-Earth line in the magnetotail near the neutral sheet once per four days over North America during local night times, and maintaining these conjunctions while the orbits intersect with the magnetotail. A comprehensive outline of the THEMIS mission and its science objectives is given in Angelopoulos (2008) in this issue. Further outline on how the various segments address the science goals is provided by Sibeck et al. (2008), also in this issue. The THEMIS mission is operated by the Mission Operations Center located at the UC Berkeley Space Sciences Laboratory (SSL) and a description of mission operations is given by Bester et al. (2008) in this issue.

In this paper, we explain in more detail how the selected orbit strategy addresses mission requirements and how it is has been developed. We also describe the mission phases, how the constellation was configured, and how meeting the science requirements is evaluated. Locations and instrumentation of the ground-based observatories are provided by Mende et al. (2008), Harris et al. (2008), and Russell et al. (2008) in this issue. For specific information about flight instruments, we refer to the various articles in this issue.

2 THEMIS Orbit Parameters

2.1 Orbit Requirements and Constraints

In order to determine the sequence of events within, substorms the THEMIS orbit design has to combine the space segment of five probes with the ground segment of 20 observatories based along the auroral oval in northern America, the Ground Based Observatories or GBOs. The five probes are to line up in 1-, 2-, and 4 day orbits in the magnetotail in times of optimal night sky conditions for the GBOs. Prior to the first primary science season (tail season), all probes have to be placed in their science orbits, and orbital periods have to be adjusted periodically to optimize the amount and quality of the constellation's alignment. The inclinations of the outer probes need to be restored prior to the second year tail season to counteract drifts due to orbital perturbations.

In addition to the science-driven targets, the orbital design has to comply with NASA orbital debris guidelines of re-entry by selecting a launch trajectory from which LV stages and probe carrier will re-enter and by including end-of mission re-entry maneuvers in the nominal mission plan. Furthermore, the orbits should avoid long eclipses in order to achieve the energy balance for which the probes are designed. Also, mission redundancy is achieved by in-orbit replacement ability. Any replacement option needs to be considered in the orbit design. Finally, the orbit design must allow a feasible maneuver plan and is constrained by the finite fuel supply. Given the number of maneuvers it takes to set up and maintain the THEMIS mission, it is essential to consider fuel efficiency and fault tolerance in the implementation. Once the long antennas of the electric field instruments are deployed, large maneuvers to reorient a probe are to be avoided. Upon meeting all engineering requirements and constraints, the validity of the orbit design is measured as the accumulated times at which the probes are aligned within small stripes along the Sun-Earth line and in the vicinity of the neutral sheet (conjunctions) as defined in Table IV in Angelopoulos (2008).

2.2 Selection of Apogee Distances and Orientation in Inertial Space

The space and time targets are solely driven by the primary science goal to study the sequence of events during substorms. At the time target all apogee passes line up along the Sun–Earth line in the magnetotail, which at that time crosses the center meridian of the ground based observatories. The time target defines the center epoch of the first primary THEMIS season and was set to early February, balancing between shorter eclipse duration, visibility of the night sky, and substorm occurrence. The geocentric apogee distances and orbital periods are selected to cover current disruptions near $-10\ R_E$ as well as tail reconnection between -20 to $-30\ R_E$. To ensure mapping of substorm-related events in the tail, observed by the space segment, into the field of view of the ground-based observatories in the night sky (for exact locations see Mende et al. 2008, Fig. 4), the apogee passes of the inner probes are locked over the center of the ground segment at local midnight by sidereal-day period. In Fig. 1, the top left panel depicts the THEMIS constellation at the center epoch (WD) for the first tail season in sun-referenced GSM coordinates with the z-axis following the magnetic dipole axis and overlaid with a neutral sheet model, the predominant plasma feature on the night side. At that instance all apogees are aligned near the x-axis in the tail (see also Fig. 6). With respect to the sun the orbits drift around so that half a year later apogees align near the x-axis pointing to the Sun at the center epoch (at local noon). For that instance orbits are shown in the top right panel of Fig. 1 with sun-referenced GSE coordinates with the z-axis pointing to ecliptic north and overlaid with magnetopause and bow shock models, the predominating interfaces on the dayside. This natural evolution of the orbits in the sun-referenced system allows to address the secondary and tertiary science goals by simply following the same alignment strategy. Hence, the orbit design is solely driven by the primary science goals.

The strategic position each probe has within the constellation is reflected by the constellation IDs (CIDs). CIDs start with the outermost probe and count Earthward, whereas the flight models are referenced by letter IDs A through E. As shown in Fig. 1, P1 always points to the four day orbit, P2 always points to the two day orbit, P3 and P4 point to the two orbits with sidereal-day periods, and P5 points to the remaining fifth orbit, complementing the baseline mission. The CIDs have been assigned to the flight models after launch to best match the probe in-flight properties with the different orbit demands, such as propulsion systems and instrument ranges. Mainly based on communication systems, the assignments are P1PB, P2PC, P3PD, P4PE and P5PA.

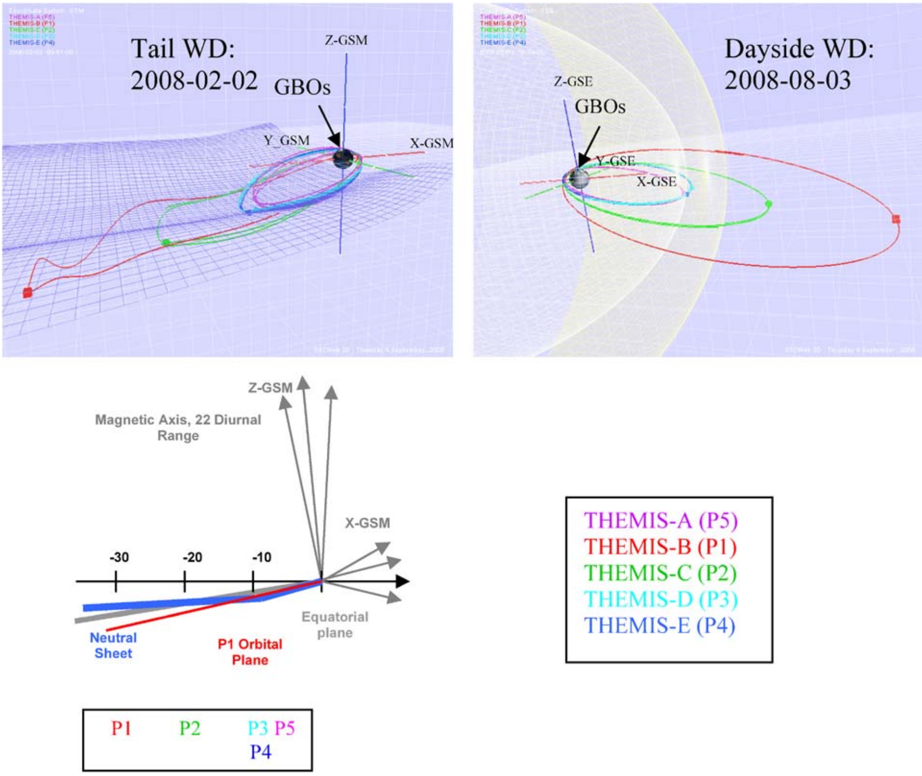

Fig. 1 *Upper two panels* show THEMIS orbits at center epochs (WD) for the first year with an axis scale of 10 Re (using SSCweb 3D orbit viewer). *Top left*: Tail season with the neutral sheet in GSM coordinates, GBO positions are indicated on the northern night side; *Top right*: Dayside with magnetopause and bow shock in GSE coordinates and GBOs indicated on the northern dayside; *Bottom left*: Sun referenced observational geometry at the center epoch of the tail season, superimposed are equatorial plane, P1 orbital plane, and a simple neutral sheet model. The CIDs (P1,P2,P3,P4,P5) are positioned to indicate the apogee distance at that moment of crossing the Sun–Earth line during the tail season

Inclination and argument of perigee are the main drivers to balance conjunctions and eclipse durations with the neutral sheet as described in Angelopoulos (2008). For the inner probes, the inclination is mainly determined to limit eclipses in the second year and to establish a z-separation between P3, P4 and P5 also for the second year. Increasing apogee distances make cutting through the daily and seasonal variations of the magnetospheric processes more difficult with the relatively fixed orbits. Figure 1, bottom left panel is a snap shot of the observational geometry in the Sun-referenced meridional planes (GSE, GSM coordinates) at the time the orbits are at the tail season center epoch. The neutral sheet starts forming along the magnetic equator but then follows the bending of the magnetotail towards the ecliptic induced by the solar wind at a geocentric distance of about 10 R_E downtail. The relative location of the neutral sheet to the ecliptic dramatically varies with the season along the Earth's orbit around the Sun, and the offset between the spin axis and the magnetic dipole axis leads to significant diurnal fluctuations relative to the orbital planes. As Fig. 1 indicates, a low inclination is key to bringing P1 close to the neutral sheet, especially around its scientifically strategic positions near apogee. However, placing the probes in the vicinity of the ecliptic in the anti-Sunward hemisphere in winter sets up the condition to encounter long Earth shadows, which are only to be avoided by larger inclinations. The choice of argument of perigee (APER) can mitigate the effect the inclination has on the relative position between apogee passes and the neutral sheet. As will be shown later, this option is rather limited as both APER and inclination drift significantly on the larger orbits. For the entire evolution of the orbital elements through the first tail season see also Fig. 13.

2.3 Selection of Perigee Distances and Orbital Perturbations

Once orbital periods and approximate apogee distances have been established, the drivers to determine perigee altitudes become orbit stability, Orbital Debris Requirements, the need to limit differential precession, and fuel consumptions. All of these aspects are heavily related to orbital perturbations caused by the additional forces beyond the Keplerian two-body problem that lead to various periodic and secular variations of orbital elements with time. Within the scope of this paper, we will focus on the specific drivers of the THEMIS orbit design and illustrate the most significant effects and refer to Vallado (1997) for a more comprehensive discussion of orbital perturbations. For the high altitude THEMIS orbits we have to consider third-body perturbations by the Sun and Moon, the non-spherical mass distribution of the Earth, and solar radiation, while atmospheric drag needs to be considered for launch trajectory and re-entry targets. Across the THEMIS constellation, these forces act with different magnitude and impact on the THEMIS orbit design in three ways (1) a drift between inner (P3, P4, P5) and outer orbits (P1, P2) over time (differential precession), (2) significant increases and fluctuations of the outer probes' perigee altitudes, and (3) dramatic change of inclination and argument of perigee of the outer probes.

Orbital precession depends strongly on semi-major axis and perigee, lesser on inclination, and to an even smaller extent on lunar perturbations. Hence, differential precession between inner and outer probes evolves over time due to the declining effect of the non-spherical mass distribution of the Earth with increasing orbital altitude. Figure 2 shows the drop in rotation rate of the line of apsides with increasing apogee distances as encountered by the THEMIS orbits. The different curves vary perigee altitudes representative for THEMIS orbits. Each such curve is repeated at two inclinations that are representative for the first tail season. In order to yield sufficient THEMIS conjunctions (see Table IV in Angelopoulos 2008) during the two-year nominal life time differential precession should ideally stay below 25 deg and not exceed 45 deg. As shown in Fig. 2, the rotation rates between inner and outer probes can be equalized by higher perigees for the inner probes and lower ones for the outer probes. Ideally, one would like to set perigee targets that substantially suppress differential precession, but other restrictions on perigee altitudes prevent complete optimization.

While perturbations by the geopotential decrease with increasing apogee heights far beyond a geosynchronous orbit, the Moon becomes an increasingly significant perturbing force. Figure 3 compares the lunar effect on APER (upper plot) and perigee altitude (lower plot) for science orbits of P1, P2 and P3 with the respective apogee distances of 30 R_E, 20 R_E, and 10 R_E. The thin lines are high-fidelity orbit propagations with full force models including Sun and Moon, whereas for the thick lines lunar perturbations were turned off. After one year, lunar perturbations are still negligible for the inner probes but become visible for the outer probes already within the first and severe after 3 (P1) and 4 (P2) lunar months. In addition to the rise of perigee, the orbital planes are swung around until equilibrium is established with an APER at roughly 180 degrees. The corresponding dramatic change in inclination can be seen in Fig. 13.

When left in their final science orbits, no probe would re-enter within 25 years as required, and re-entry must be forced by reducing perigee altitudes at the end of mission.

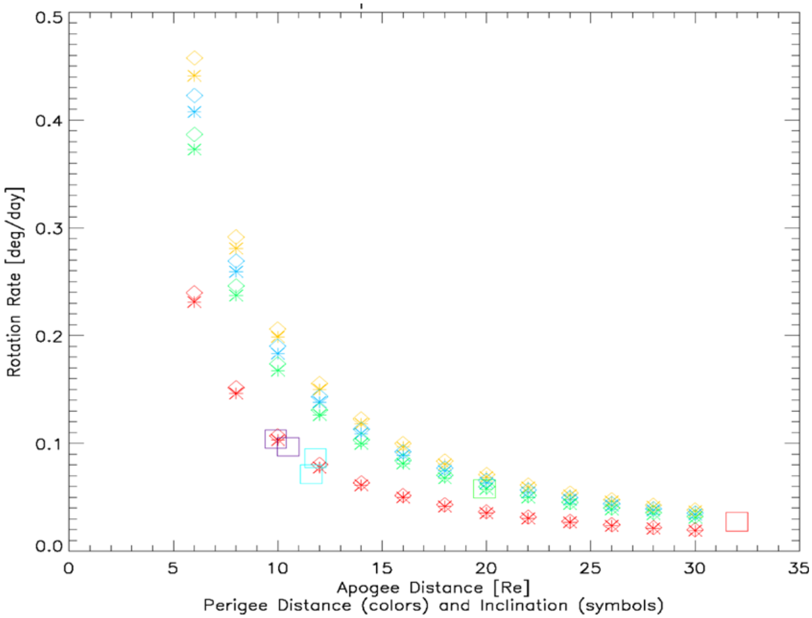

Fig. 2 Rotation of line of apsides shown as sum of argument of perigee and right ascension of node due to the oblateness of Earth as a function of apogee distances for various perigee altitudes and inclinations. Perigee altitudes are 3189 km (*red*), 1072 km (*green*), 733 km (*blue*), 446 km (*yellow*); inclinations are 7 (*) and 1 degree (◊). *Squares* mark average values for each THEMIS probe for the first year based on numbers from Table 2

Naturally, the re-entry requirement contradicts high perigees for orbital stability and the prevention of premature re-entry. Re-entry maneuvers can be significantly large and hence end-of-life maneuvers must be accounted for in the fuel budget. In particular, the perigee altitude for the outer most probe P1 must be high enough to tolerate lunar perturbations of perigee altitudes by up to 3200 km. Perigee altitudes of around 1900 and 3800 km correspond to the breakpoint between short (<5 years) and long (>20 years) P1 lifetimes (Berry 2005). A perigee altitude of 3200 km results in lifetimes of >10 years under all lunar phases. Considering differential precession and re-entry requirements, we chose 3200 km as the nominal perigee altitude for P1, about 1070 km for P2, and 730 km for P3, P4, and P5, respectively. To our advantage due to lunar perturbations, the toll in fuel spending for re-entry is much less for the outer probes than for the inner ones, thus equalizing fuel consumption between the probes. Targeting a re-entry perigee altitude of 320 km for the inner probes almost doubles their total fuel allocation. Whereas maneuvers to reach the target for the outer probes of 3000 km (P1) and 640 km (P2) take a rather small fraction of the fuel amount allocated for their ascent and conjunction maintenance.

The squares in Fig. 2 mark the targeted average rotation rate for each THEMIS probe through the first year based on the nominal perigee altitudes, which are listed in Table 1 together with apogee distance. For P5, and (P3, P4) the two sets reflect the changes in their orbits after the first tail season.

The change in apogee distance for P5 and the large difference in its inclination relative to (P3, P4) are both driven by science goals (Angelopoulos 2008). In order to keep the inner probe orbits close, the large difference in inclination could only be accommodated by a smaller perigee for (P3, P4) during the first tail season.

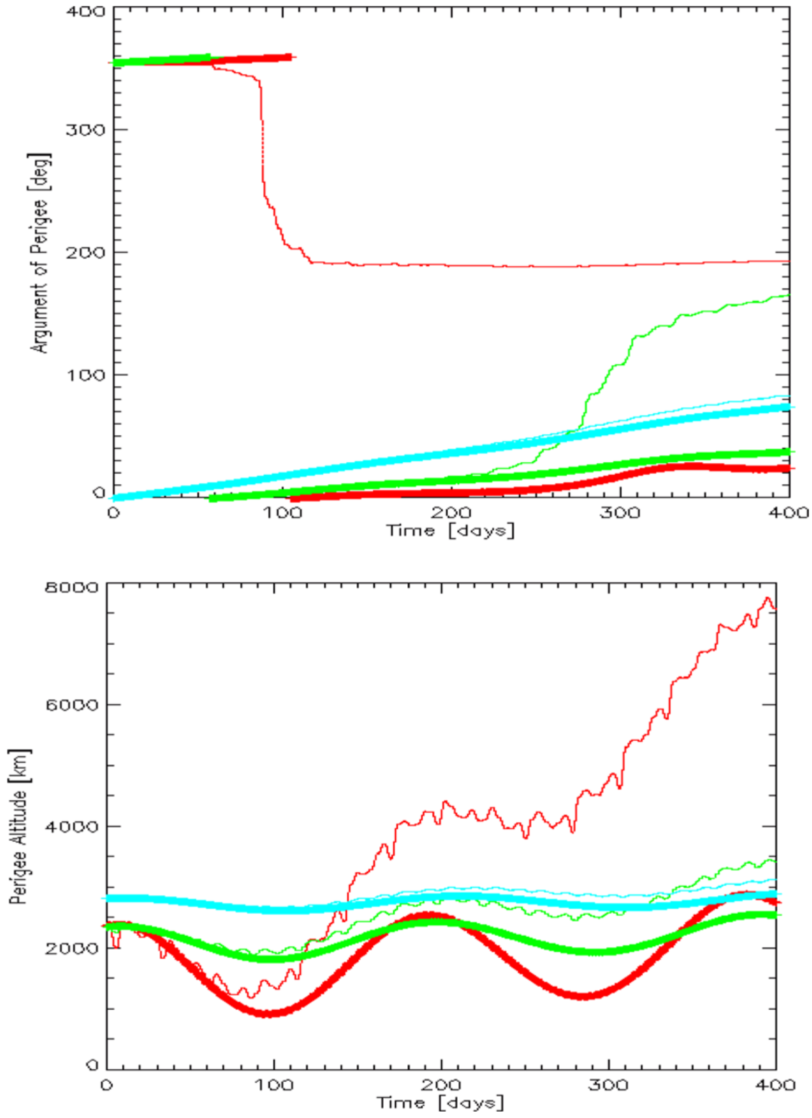

Fig. 3 Build-up of lunar perturbations in APER (*upper plot*) and perigee altitude (*lower plot*) over one year for inner and outer science orbits. Orbit propagations from high fidelity force models including (*thin lines*) and excluding (*thick lines*) the Moon. Inner orbits of P3 in light *blue*, P2 orbits in *green*, and P1 orbits in *red*

Since the perigees start low at launch, driven by an orbital debris requirement to re-enter the second and third stage, and have to be reduced at end-of-mission for re-entry, the final perigee target to minimize differential precession is ultimately dictated by the amount of fuel margin. Also, there is an additional fuel efficiency incentive to keeping the perigee low, as apogee changes and inclination changes are more efficient the lower the perigee. Shown in Fig. 3, the Moon raises the perigee for P1 and P2 significantly. Thus perigee "station keeping" is recommended to maintain a low perigee both for an efficient re-entry maneuver and for optimizing the delta V (the amount of energy needed to change the orbit is expressed

Table 1 Apogee distances, perigee altitudes, and inclination used to determine probe specific rotation rates shown by the squares in Fig. 2. The last two rows show the relative rotation rates referenced to P3, P4 during Tail 1 and afterwards. All values are average values over the first year. For P3, P4, and P5 the two sets reflect the changes after the first tail season

	P5		P3, P4		P2	P1
	Tail 1	After tail 1	Tail 1	After tail 1		
Ra [R_E]	9.9	10.5	11.8	11.6	19.9	32.0
Rp [R_E]	1.46	1.46	1.44	1.64	1.17	1.5
Rp [km]	2934	2934	2806	4082	1071	3827
In [deg]	12.0	10.5	7.0	5.0	7.5	5.0
Rel. rot. [deg/day]	0.018		0		–0.028	–0.071
Rel. rot. [deg/day]	(0.034)	0.027	(0.016)	0	–0.012	–0.054

Table 2 Perigee target constraints imposed by competing science and engineering requirements

Orbit requirements	Inner probes		Outer probes	
	P5	P3, P4	P2	P1
Re-entry of 2nd, 3rd stage	Low	Low	Low	Low
Stability	High	High	High	High
End-of mission re-entry	Low	Low	Low	Low
Differential precession	High	High	Low	Low
Fuel efficiency	Low	Low	Low	Low
Fuel consumption	Low	Low	Low	High

in total change of velocity or delta V) required for various apogee changes. Since it is done most efficiently if coupled with an inclination change, the perigee reduction for P1 and P2, needed to ensure re-entry, is scheduled immediately after the first year and combined with the reversion of the lunar pull on the inclinations that is necessary to keep eclipse durations in the second year below 3 h.

Table 2 shows how differently science requirements and fuel consumption compete in determining perigee altitudes for each probe. While the driver for (P3, P4) perigee altitudes is differential precession, the perigee altitudes of P1 and P2 are driven by lunar perturbations. For P5 to have the same average precession rate as (P3, P4), perigee selection is driven by its inclination. The difference of 7 degrees relative to the (P3, P4) inclination will naturally produce the z-separation between P5 and (P3, P4) in the second year required to achieve mission science goals.

3 Process of Orbit Design

3.1 Parameter Study

In Phase-B a large parameter study was undertaken to determine optimal orbital parameters and period tweaks necessary to meet science requirements. Conjunctions were initially simulated and selectively tabulated as a function of right ascension of perigee (RAP) which is defined as the sum of the right ascension of the ascending node (RAAN) and the argument of perigee (APER), referenced to the 1st year tail season center epoch using a high fidelity orbit propagator Goddard Trajectory Determination System (GTDS), provided by the Goddard Space Flight Center (GSFC), with an IDL-based wrapper for self-sufficient run setups and orbit post-processing. A small maneuver adjusting the period was at 36 days before and after the center epoch, and various values for APER at center epoch were used to account for any launch day of the year. From those runs, an initial determination of the RAP and launch APER was made, and the perigee and inclination drifts were tabulated for all orbits as a function of time. In the next step of runs with the selected orbit parameters, the optimal phasing schedule was derived (see Table 4). These runs were not "forward" runs from launch thereafter, but rather started at center-tail and propagated backwards and forwards from that reference time.

3.2 Design Flow

In conjunctions with that effort, ManCalc, a Microsoft Excel®-based tool, was developed to allow fast, efficient analysis of the five fuel budgets and margins as a function of launch day, launch vehicle errors, thruster inefficiencies as well as replacement strategy and trade-offs for perigee targets. It simulates the maneuvers needed to transform from insertion to the science orbits as well as the tweak maneuvers. The burns are modeled as impulsive maneuvers, using standard formulae for the J2 perturbations by the non-spherical mass distribution of the Earth (Wertz 2001), and linear drift rates for perigee and inclination as determined by the high-fidelity orbit propagations with GTDS. The main deterministic fuel inefficiency for the mission is the finite arc loss that is associated with long burns near perigee. Those were modeled separately using a GSFC-provided tool, the General Maneuver Program (GMAN), which was also made callable through IDL. After modeling maneuvers as impulsive burns, as finite fixed attitude burns, and adjustable attitude burns, we were able to include a "linearized" loss term (1–4% loss/degree in mean anomaly of the burn) to properly account for finite arc inefficiency in ManCalc.

ManCalc was thus able to simulate differential precession and RAP evolution. With reasonable assumptions on tweak maneuvers, inclination changes and re-orientation fuel requirements could be modeled for each burn. Additionally, ManCalc was able to model all realistic inefficiencies and related losses towards a computation of a true margin available for operator error at launch, and any possible extended mission science. Finally, it outlined the entire baseline mission profile as an initial guess for the higher-fidelity GTDS-based "forward" runs that were necessary in order to determine conjunction hours and shadow durations.

The mission-long end-to-end computation of the conjunctions, shadows and deltaV can only be done with "forward" runs that account accurately for the cumulative lunar perturbations and differential precession since launch. This can be done using GTDS and GMAN. The IDL-based wrapper, integrating GTDS and GMAN, that determine those quantities in a self-consistent manner, has been termed Mission Design Tool (MDT). This formed the basis of the accurate mission design, and resulted in a first order self-consistent validation of the launch elements that meet mission requirements.

By the time the mission design was almost complete and frozen, in February of 2006, the two complementary tools were both in routine use: ManCalc and MDT. ManCalc, as a Microsoft Excel®-based model of impulsive maneuvers and inclination changes, has a quick turnaround and is able to compute all deterministic inefficiencies albeit with pre-evaluated assumptions about the effects of lunar perturbations on orbit elements. ManCalc is used for quick mission redesign scenarios (e.g., if the launch month were to change, delaying first

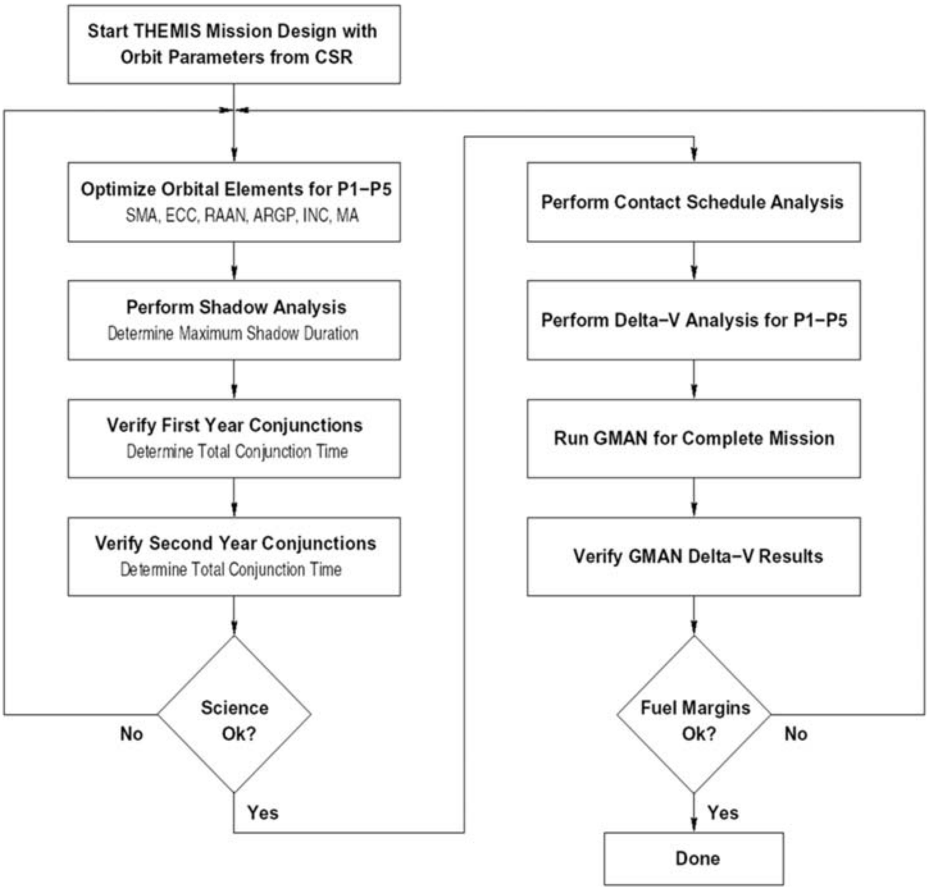

Fig. 4 Orbit design flow

prime season by one year, and extended mission concepts), for replacement scenario fuel tracking, and for accounting for deterministic inefficiencies. The input is either the mission deltaV directly from ManCalc or the input from MDT.

MDT, the GTDS and GMAN-based tool with IDL-wrappers is used for mission setup and long and short term maneuver planning. It is used for self-consistent and high-fidelity computation of conjunction hours subjected to shadow and maneuver duration limitations.

The results from the two tools are validated by frequently running identical mission profiles. Pressure, thrust, maneuver duration and deltaV curves are cross-checked and inconsistencies corrected or inconsistencies analyzed and approved as necessary. Additionally, following the Mission Critical Design Review, a mission design validation was performed over a period of 6 months by an independent team from JPL, and using JPL propagators an agreement was established. Independent validation of the P1 ascent, plane changes, and use of GTDS and GMAN, were accomplished in addition by GSFC. Finally, SatTrack (Bester et al. 2008) is used for processing mission operations-related output from MDT, i.e., for communications analysis, pass scheduling, orbit events analysis and 3D orbit visualization.

The orbit design flow is summarized in Fig. 4. Once orbital parameters set by impulsive maneuvers satisfy mission requirements, the design is reiterated with simulating finite tra-

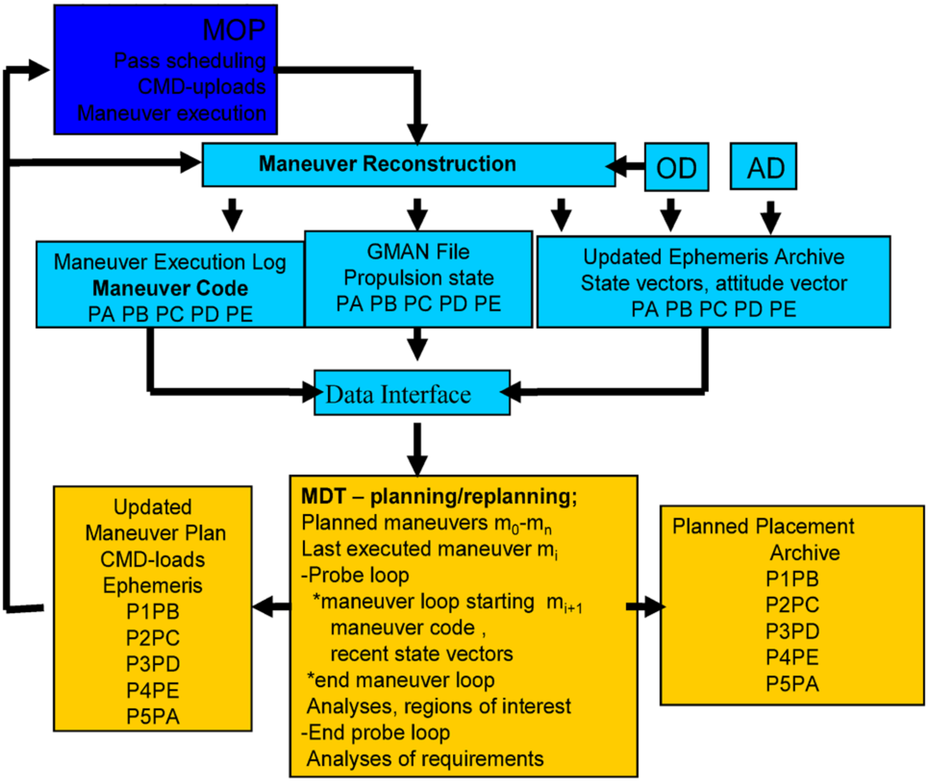

Fig. 5 Data flow between MDT, mission operations (MOP), and status updates by orbit determination (OD), as well as attitude determination (AD)

jectories, and analyzing step-by-step all operational aspects of the actual maneuvers (ground contacts, burn times, etc.). Since the MDT was developed to provide the flight-ready trajectories and maneuver command loads with finite burns end-to-end for any season, in a final step it was modified to allow maneuver re-planning as the mission is progressing. Figure 5 illustrates how the highly automated data flow is organized. Using one single interface, launch trajectories used in pre-launch mission planning are replaced by state vectors from the archive which is constantly updated after launch. The very last or any previous update is fetched by time reference. A maneuver code is the reference to properly parse the actual orbit data into the maneuver sequence (maneuver loop) for each probe. Human interference is focused on verification rather than data entry.

4 Mission Profile

4.1 Nominal Science Phases: Tail Seasons and Dayside Seasons

In a Sun reference frame (GSM or GSE coordinates) the THEMIS mission falls essentially into two observational seasons per year, the tail season with the apogee passes in the anti-Sun hemisphere, and the dayside season with apogee passes in the Sunward hemisphere (see Fig. 6). Center epochs, ideally defined as crossing the Sun–Earth line in the tail or on the

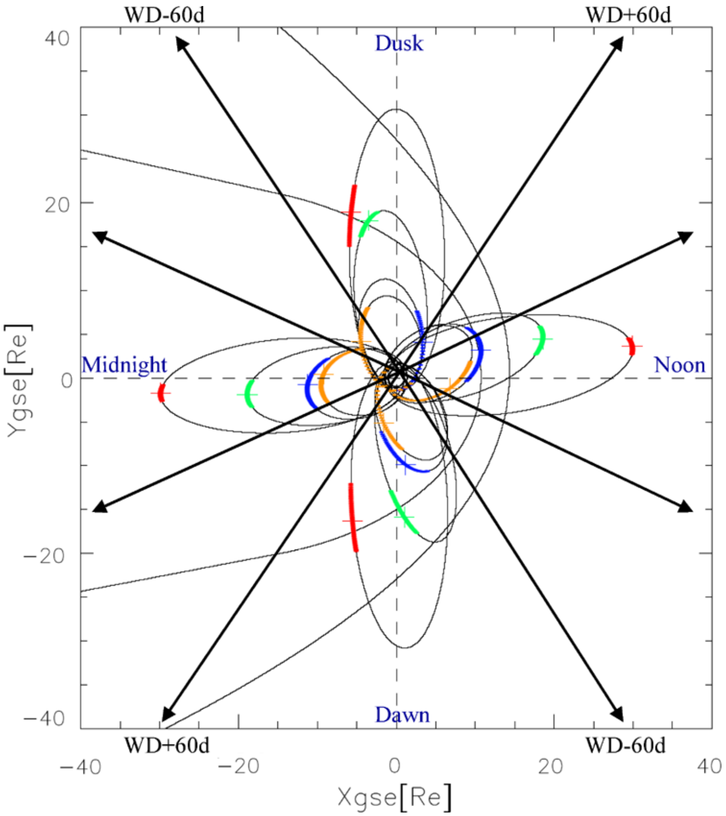

Fig. 6 The THEMIS orbits in Sun-referenced coordinates for the first year with magnetopause and bow shock. *Arrows* cut out the observational intervals according to the tweak schedule. *Colored orbit tracks* are 3-hour intervals centered at the WDs (midnight for tail season and noon for dayside) and at magnetopause crossings of P2

dayside, also referred to as Wedding Days (WD), are separated by about 6 months. Each tail season is confined to the time the orbits maintain conjunctions along the X-axis in the magnetotail. Between WD – 60 days and WD + 60 days, the outer probes will sufficiently monitor the reconnection zone while the inner probes pass through the current disruption zone. For the dayside, the 120 days centered at WD translate into a separation of the outer probes along the upstream solar wind direction from the magnetosheath, through foreshock into the pristine solar wind. In the first year, each season has about 10 to 14 WDs (about three P1 orbits) with more than 200 h of conjunctions. The actual WD is selected as the one with the highest return in the midnight interval and low deltaV. As Fig. 7 shows, once in their science orbits, the high return of conjunctions and the delta V fluctuate with the 4-day orbital period of P1.

Preparation for science operations was done during the checkout phase (early orbit operations, health and safety checks, probe constellation assignment), and the placement phase (a series of probe constellation specific maneuvers and the stepwise EFI boom deployments; for more details, see Bonnell et al. 2008 and Pankow et al. 2008). Instrument commissioning was spread over those phases at times when probes did not perform maneuvers.

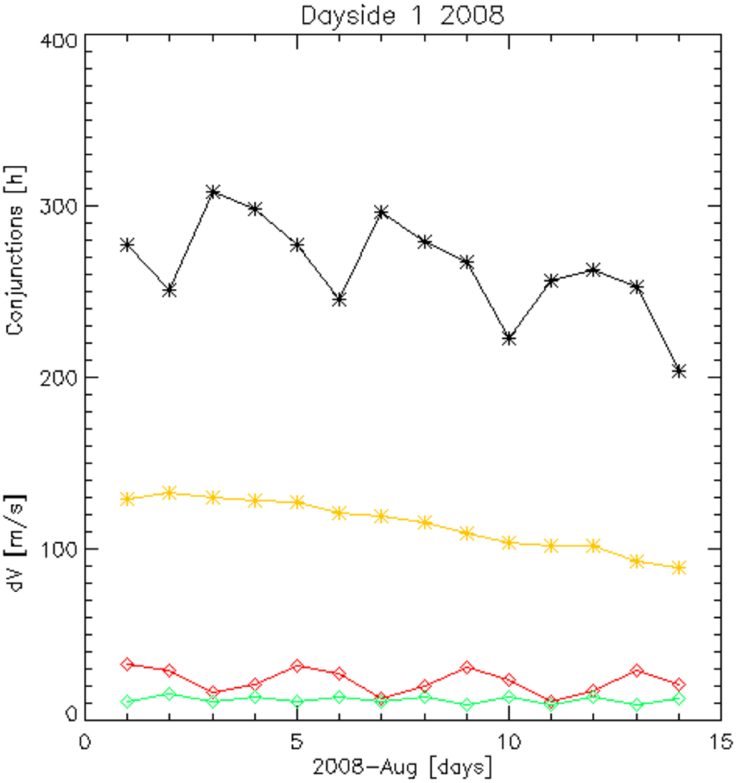

Fig. 7 Dayside 1 conjunctions (*black*) are shown for WDs August 1 to 14, in *yellow* conjunctions from the noon interval are shown. At the *bottom* the deltaV of all tweak maneuvers of this season is shown in *red* for P1 and *green* for P2

The small in-season maneuvers (tweak maneuvers) between WD – 60 days and WD + 60 days that realign the probes by small apogee adjustments to account for differential precession among inner and outer probes split each science season into three intervals (tail: dawn, midnight, dusk; dayside: dusk, noon, dawn) according to the precession in the Sun reference frame (see Fig. 6).

The schedule of the tweak maneuvers fixed relative to the WD was carefully designed to optimize conjunctions through the entire science season and minimize interruption of science data collection. This recurring timeline is:

WD – 88d, WD – 60d, WD – 24d, WD + 24d, WD + 60d. While the first one of each series is to re-align the probes after 28 days, the other three cut the entire science season into the three intervals centered around the WD, and WD + 60d marks the end of a season.

Once probes are successfully aligned for the first tail season, the tweak maneuver schedule, inner probe orbit maintenance, and P5 apogee variations are repeated for each following season. In order to comply with NASA requirements, after the nominal mission, we will be able to ensure re-entry of all probes by a series of maneuvers. Table 3 gives an overview of all phases of the entire mission.

The tweak maneuver schedule and the observational intervals for all four seasons are listed in Table 4.

Table 3 THEMIS nominal mission profile

Mission phase	Approx. time range	Periods P5->P1
Launch	Feb. 17, 2007	
Checkout	Feb., 2007–May, 2007	
Coast phase	May, 2007–Sep., 2007	String of Pearls, 31 h
Placement phase	Sep., 2007–Nov., 2007	
Tail Season1 observation	Dec., 2007–Apr., 2008	4./5d, 1d, 1d, 2d, 4d
Dayside 1 set up	Apr., 2008–May, 2008	
Dayside 1 observation	Jun., 2008–Oct.,2008	8./9.d, 1d, 1d, 2d, 4d
Tail Season 2 set up	Oct., 2008–Nov., 2008	
Tail Season 2 Observation	Dec., 2008–Apr., 2009	1d, 1d, 1d, 2d, 4d
Dayside 2 set up	Apr., 2009–May, 2009	
Dayside 2 observation	Jun., 2009–Oct., 2009	8./7.d, 1d, 1d, 2d, 4d
End of nominal mission	October, 2009	

Table 4 THEMIS tweak maneuver schedule split up into pre-season alignment and tweak intervals. First year data are based on in-flight data through the end of the inner probe setup for the dayside

Schedule	Season	Tail 1	Dayside 1	Tail 2	Dayside 2
WD –88d	Alignment	Nov. 06, 2007	May 08, 2008	Nov. 11, 2008	May 2009
WD –60d	1st Tweak	Dec. 04, 2007	Jun. 04, 2008	Dec. 09, 2008	Jun. 2009
	Observations	dawn	dusk	dawn	dusk
WD –24d	2nd Tweak	Jan. 09, 2008	Jul. 10, 2008	Jan. 14, 2009	Jul. 2009
	Observations	midnight	noon	midnight	noon
WD		Feb. 02, 2008	Aug. 03, 2008	Feb. 07, 2009	Aug. 2009
	Observations	midnight	noon	midnight	noon
WD +24d	3rd Tweak	Feb. 26, 2008	Aug. 27, 2008	Mar. 03,2009	Sep. 2009
	Observations	dusk	dawn	dusk	dawn
WD +60d	End of season	Apr. 02, 2008	Oct. 02, 2008	Apr. 08, 2009	Oct. 2009

4.2 Launch Days

Although the THEMIS mission is hinged to a fixed schedule once the tail center epoch (WD) is chosen, the design allows for launch on any day of the year. Any shift in launch day will be accommodated by an increase of RAAN to ensure proper orbit alignment in the magnetotail. However, as soon as the apogee distances of the outer orbits exceed about 20 R_E, their inclination rapidly drifts due to lunar forces. The effect is most severe for the outermost probe, with an inclination drift of about 0.1 deg/day. In order to keep the orbital plane in the required vicinity of the neutral sheet, the placement of the outer probes can only start within three month of the tail season. With the WD in early February, launches between August and October 2006 would have allowed all probes to assume their place for the first tail season in the upcoming winter of 2006/2007. For that short placement concept, the schedule for early orbit checkouts, placement maneuvers, and EFI deployment was kept flexible to ensure probe readiness for the first observational season. Launches after mid-October would have required cutting the tail season short by one tweak interval (running from WD – 24 d to WD + 60 d), but still would have provided >200 hrs of conjunctions. For any other launch day the placement of P1 and P2 needed to be delayed until early September. This in turn triggers the delay of the placement of the prospective inner probes to avoid the build-up of differential precession before the first primary season. In order to efficiently set inclinations, the launch trajectory also needed to be adjusted for APER drifts. Its inclination had to be chosen to minimize fuel consumptions for P1 and P5. Compliance with the re-entry guaranty for probe carrier also required adjustments of perigee and apogee altitudes as well as APER as a function of launch day.

Over the last 4 years milestone launch days have been the 19th of August 2006, the 19th of October 2006, the 27th of November 2006, the 20th of January 2007, and the 15th of February 2007, always meeting mission requirements within deltaV constraints. For the case of February 15, 2007, Fig. 8 shows the launch window analysis over 14 days. For each day, over the entire launch window of 20 minutes, conjunctions, and shadow durations at the end of the first tail season are well within the requirements, and the impulsive delta Vs accumulated by each probe (shown is P1 with the largest delta V account) through the first tail season remain well below the constraints by the fuel budget. Eventually, on February 17, 2007 the THEMIS probes were launched on a Delta-II 7925 from KSC and released quasi-simultaneously, setting the first primary science season for winter 2007/2008.

4.3 Coast Phase

The coast phase covers the period after early orbit check-out including constellation assignment until the start of the placement phase, during which all probes were on essentially the same orbit, with periods slightly dispersed by the release mechanism and thus drifting apart. The simultaneous launch of all probes in February, 2007 provided the opportunity to enhance the dayside science by maintaining a close formation of all five probes. While orbits drifted into the dayside, the focus was set on the consecutive magnetopause crossings by a string-of-pearls formation with three probes at small-scale inner separations and enclosed by a leading and trailing probe to provide large-scale context (Fig. 1 in Angelopoulos 2008, in this issue). The coast formation set up was primarily driven by the constraint to avoid additional fuel consumption that would compromise the primary mission. The release mechanism almost accomplished the string-of-pearls formation, except that not all inner probes would have had deployed spin plane booms of the electric field instrument. Before periods could be locked at the appropriate separations, the probes had to be rearranged from the original order of probes C <–> D, B, A <–> E to B <–> C, E, D <–> A, making small separations below 100 km over 10 to 20 orbits almost impossible under the given constraints. The reshuffle was choreographed as a sequence of maneuvers, one or more per probe, to have the coast phase formation fully in place in June, 2007 with an almost constant separation between outermost probes B and A of about 6000 km. In order to maintain the fuel budget, these maneuvers had to work towards the eventual perigee and apogee targets (Fig. 9). A common perigee target for the coast phase was needed to limit differential precession and was capped at 1.16 R_E, the final target of P2. Only for probe C, assigned to P2, which has the shortest ascent into its 2-day orbit, the fuel reserves were considered sufficient to allow for one small reversal of an apogee raise for the final phasing. Therefore, the phasing periods had to be accommodated by small apogee dispersions. Since time over which to set it up was also limited, the final coast phase periods for the inner probes were selected to allow the probes to pass each other slowly (Fig. 10). That way separations at magnetopause crossings below 500 km could be maintained for 60 to 90 days with shorter durations below 300 km and on some orbits with less than 100 km in June, 2007.

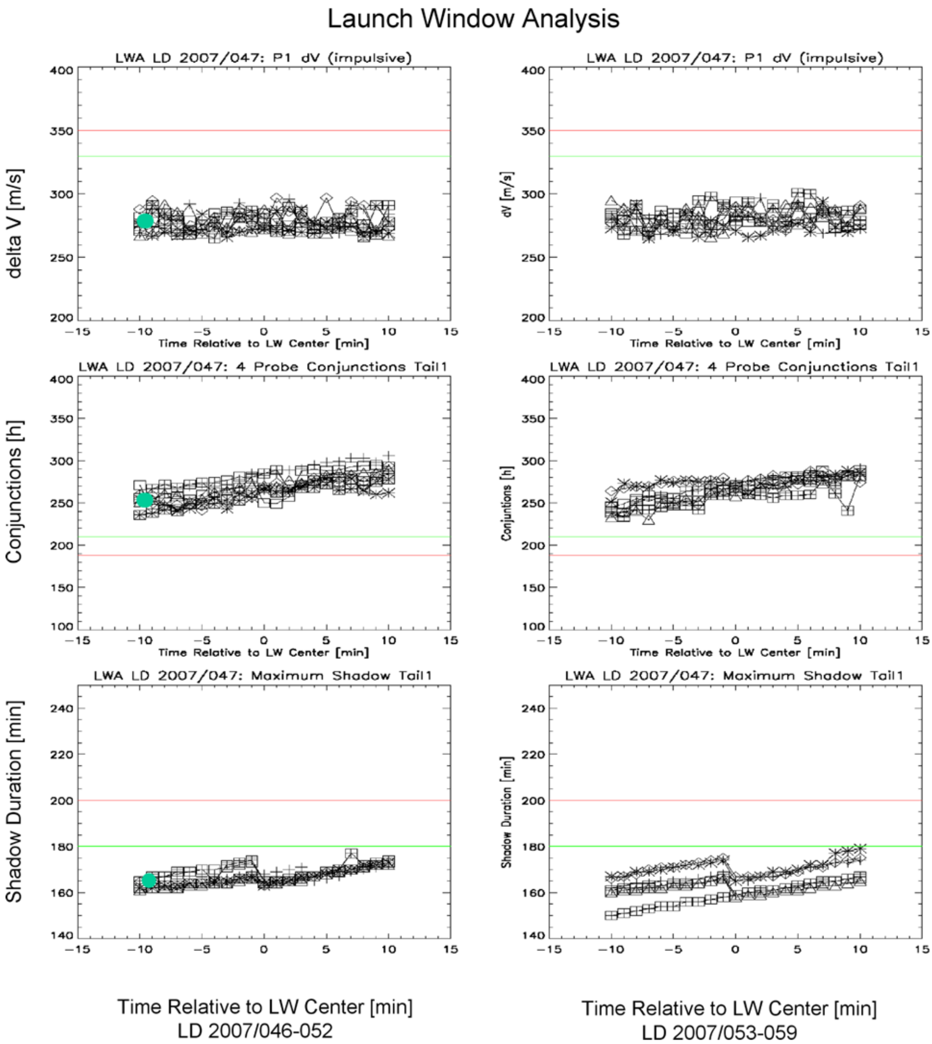

Fig. 8 THEMIS launch window analysis February 15 until 21, 2007 (*left panels*) and February 22 until 28, 2007 (*right panels*). *Upper panels* show the predicted accumulated impulsive delta V for P1 which has the largest delta V throughout the mission. Panels in the middle row show predicted accumulated conjunctions of four probes as required for the minimum mission after the first tail season. Panels at the *bottom* show predicted maximum shadow durations encountered by P1 (all other probes will experience less) during the period of peak shadows towards the end of the first tail season. Highlights are data from first season

4.4 Placement Phase

From September till November in 2007, the outer probes ascended and the inner probes descended independently into their science orbits in time for the first primary science season (tail season 1), targeting WD – 88 days for the alignment of the outer probes, with the inner probes properly locked with their apogee passes over the center of the GBOs in Central Canada (CCA). The challenge was to compromise between science targets, fuel efficiency, time constraints set by unavoidable orbital element drifts, time needed for post-maneuver

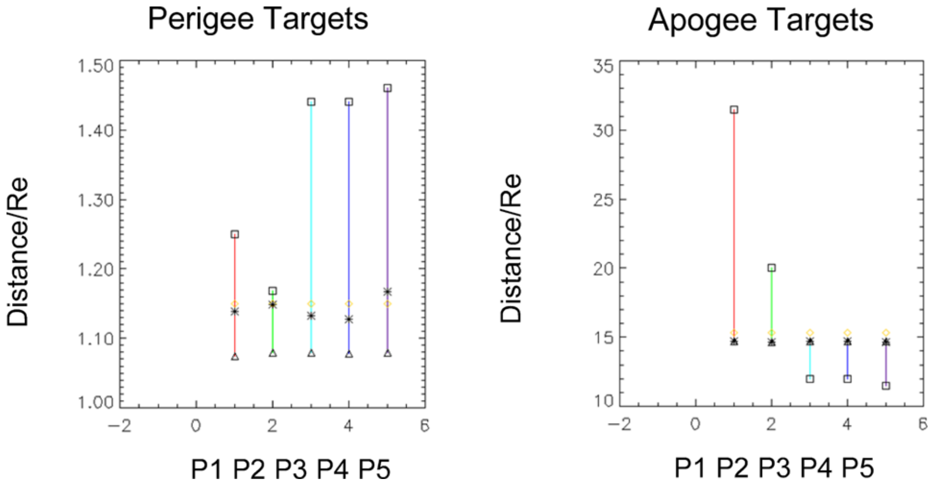

Fig. 9 Shown are perigee (*left*) and apogee (*right*) geocentric distances at probe release (△), during the coast phase (*), and at the start of science orbits (□) for all five probes

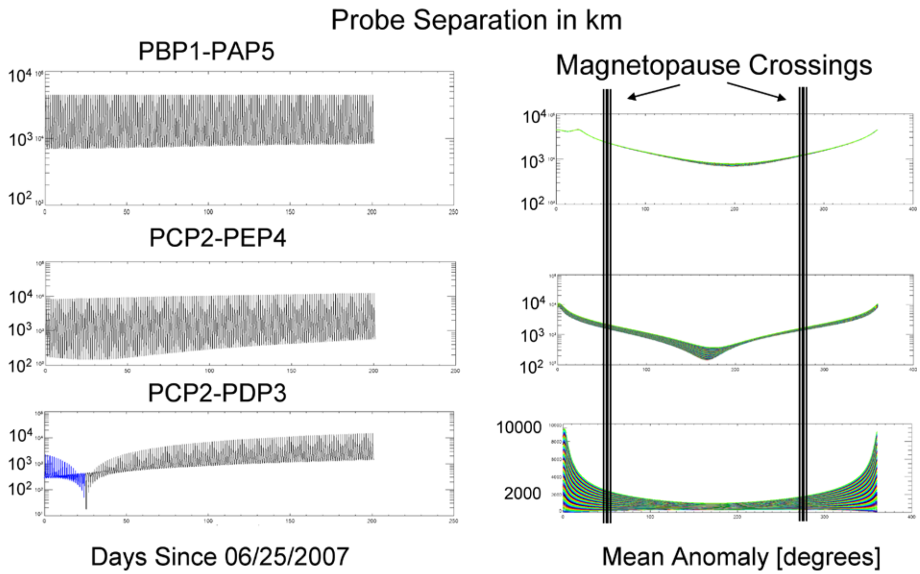

Fig. 10 Probe separation during coast phase; *left panels* show separation over time for leading to trailing probes (*top*) and pairs of inner probes (*middle*, *bottom*), *right panels* show separation over mean anomaly for same probe pairs. The change in color in the *bottom left* panel indicates passing

updates, time required for maneuver preparation, and the capability of the propulsion system with a yet flexible and robust maneuvering scenario.

The key to mission success is the center epoch (WD) of the first tail season. As it is fixed in time and space, any launch day is supported by a flexible ascent phase that leads into the fixed tweak maneuver schedule (Table 4). Based on the estimates of the orbital parameters from the ManCalc, the MDT determines the actual time and size of the ascent maneuvers for any given time span between launch day and center epoch, taking into account time slots for prescience phases and operational constraints such as orbit determination and maneuver planning. The ascent goal for the outer probes is to have their perigee passes for the 1st tweak maneuver around WD – 60 days, and at periods close to phasing period.

To reach those targets within a few weeks with a series of maneuvers per probe, the periods of the intermediate orbits determine the time of maneuvers according to (1),

$$t_{\text{final}} = t_{\text{begin}} + \sum_{i=l}^{k} n_i \cdot T_i \quad \text{with } T_k \approx T_{\text{align}} \tag{1}$$

where t_{final} is time target after k numbers of maneuvers, t_{begin} the beginning of the placement phase, and T_i periods of intermediate orbits as a result of either a perigee or apogee change. T_{align} is the period needed to maintain phasing.

The descent target for the inner probes is to place their apogee passes near the center longitude of the ground-based observatories (GBO's) at midnight. Similarly to (1), (2) relates the number of orbits with the drift of the apogee passes in geographic longitude (apogee drift),

$$lon_{\text{final}} = lon_{\text{begin}} + \sum_{j=p}^{q} m_j \cdot dlon_j \quad \text{with } dlon_q < 10 \text{ deg} \tag{2}$$

where lon_{begin} is the geographic longitude of the apogee pass at the start of placement phase and lon_{final} is the center of the GBO range. The drift rate of the last intermediate orbits determines the precision of meeting the target longitude as well as the separation between P3 and P4. The drift rate of apogee passes, $dlon_j$ is a function of period, with a value of zero for sidereal-day period. While apogee drifts of the intermediate orbits drive the time of maneuvers, the intermediate periods are constrained by the time limit for the inner probe placement,

$$t_{\text{final}}^{\text{inner}} = t_{\text{begin}} + \sum_{j=p}^{q} m_j \cdot T_j \quad \text{and } t_{\text{final}}^{\text{inner}} < t_{\text{final}}^{\text{outer}} \tag{3}$$

Figure 11 shows this for P3PD, where no apogee drift corresponds to the sidereal-day period. At about 50 days after launch it is set for the coast phase, drifting roughly 30 degrees per orbit. At the end of the placement phase, around 240 days after launch, the drift rates consecutively decrease. After tail season 1 the rise to the final perigee altitude and the reset to sidereal-day period can be seen starting around 410 days after launch. The order and times of the apogee and perigee changes have been set up to cause opposite drift rates in order to maintain alignment with CCA.

The number of maneuvers depends on the number of orbital parameters to be changed. For each such parameter, it is dictated by the size of the change of each orbital parameter between the starting point and the final target and the satellite system, as those steps usually have to be cut into pieces with feasible burn times. If a few maneuvers are necessary to reach a target, one would like to start out with big steps and continuously decrease of maneuver duration to reduce the effects of thrust variability. The feasibility of burn times depends on a variety of factors of which many are system-specific. From an operational point of view and in order to keep the placement phase as short as necessary, the fewer maneuvers, the better. For the THEMIS probes, the major burn time restrictions have been transmitter-on times since real time contacts are required during maneuvers, fuel efficiency and targeting over extended finite maneuver arcs. After launch, with in-flight evaluation, the original

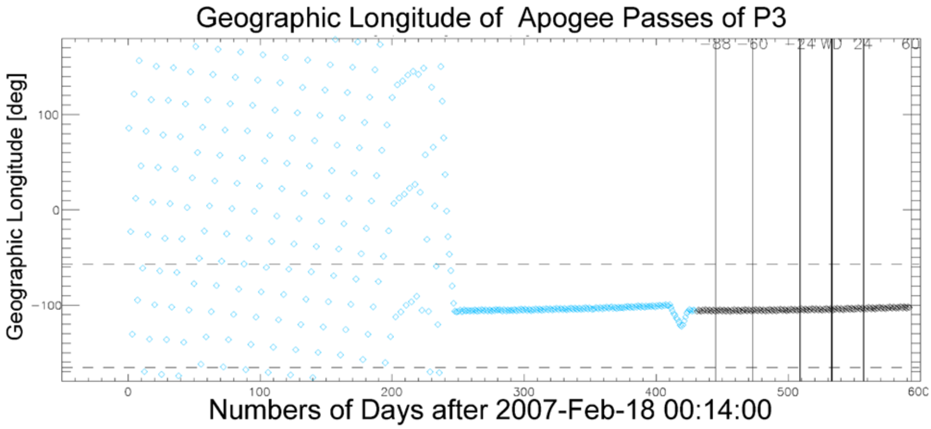

Fig. 11 Geographic longitudes of each apogee pass of P3PD is shown from launch through first year tail and dayside seasons. *Vertical lines* indicate dayside tweak schedule. Changes in apogee drift rates are due to intentional changes in period by maneuvers. *Horizontal dashed lines* frame the longitude range of the GBOs

constraint to 30-min transmitter-on time could be extended to more than 1 hour and fuel efficiency, targeting and operational aspects became the limiting factors. Once burn times have been established, the characteristics of the reaction control system (RCS) compete with constraints from (1) and (2) about maneuver size.

The THEMIS RCS (Sholl et al. 2007) is a complex design of a blow-down hydrazine system of two spherical tanks, a pyro-activated helium gas repressurization system, and four 4.5 N thrusters. Allocating 4 kg of fuel for attitude control, the fuel load at launch of 49 kg provides the equivalent of approximately 930 m/s of the total delta V capacity for each probe.

Two thrusters are located at the bottom of the probes for axial thrust, parallel to the spin axis, and the other two are located at the sides for thrusting tangentially to the spin plane (side thrust). The tangential thrusters are shown in Fig. 10 in Angelopoulos (2008). For orbit change maneuvers the axial thrusters are fired continuously, while the tangential thrusters are fired in a pulsed mode and the maneuver duration (referred to as burn time) becomes much longer than the actual thruster-on time depending on spin rate and pulse duration (for more on maneuver modes see Bester et al. 2008). Consequently, the two different sets of thrusters have a significant effect on maneuver size and thus number of maneuvers. While axial thrusts have much shorter burn times compared to same-deltaV side thrusts, they require large reorientations of the probes before and after the maneuvers. On THEMIS, those attitude changes become very costly as soon as the 40 and 50 m EFI wire booms are deployed and side thrust mode is the only feasible way to accommodate all orbit changes within the orbital plane increasing the number of maneuvers by a factor of two or even three.

In addition to thrust mode, the characteristic decrease in thrust with increasing fuel consumption of the blow-down system means significantly smaller and smaller maneuvers. Figure 12 shows how the blow-down system limits maneuver size for the side thrust mode after repressurization with a pulse width of 60 degrees. As we progress through the mission, the delta V of a 25-minute side thrust burn drops quickly from 20 m/s to 10 m/s, which is the range of the tweak maneuvers. The delta V of a continuous axial thrust of 25 minutes has dropped from 115 m/s to about 60 m/s after a total delta V of about 300 m/s (not shown). On THEMIS, the combined effect on burn time by the type of thrust and the fuel status were much larger than could be compensated by a small increase of burn time by a few

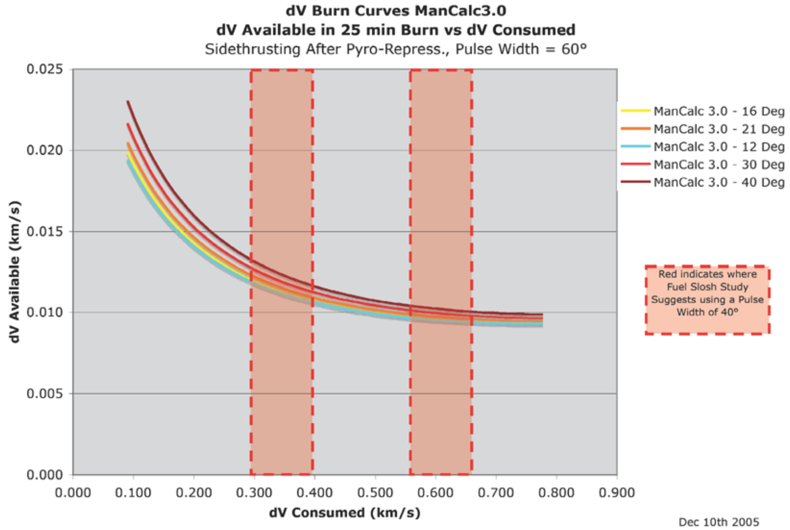

Fig. 12 Blow down curve for 25-minute side-thrust burns with a pulse width of 60 degrees for various temperatures over the THEMIS temperature range as a function of cumulative delta V. In *red* are zones where a pulse width of 40 degrees is recommended to avoid fuel sloshing

minutes. For a feasible and robust placement scenario and replanning capability, maneuvers are planned based on burn time rather than delta V using charts like Fig. 12 and a flexible number of maneuvers.

The RCS thrust performance is limited to pressures between 0.51 and 2.8 MPa. The time of the first recharge had to be chosen so that the system pressure is maintained within these limits. This added additional constraint of the size of maneuvers leading up to the first recharge. In fact, starting with large pressure drops and having to fit early maneuvers into the recharge window overwrote many of the guidelines based on orbital dynamics one typically follows to minimize the change of velocity for each maneuver.

Last but not least, the placement maneuver concept was kept very flexible and robust to ensure a high level of fault tolerance. Maneuvers have been designed smaller towards the final placement of each parameter in order to be able to account for underperformance of a previous maneuver without the penalties of very large finite arcs with the exception of P3 and P4. For them, the fully deployed EFI booms increased the number of maneuvers so much that maintaining the time target for their placement pushed burn times to the upper limit set by finite arc losses. Whenever possible, the time between maneuvers was increasing towards the final targeting, and placeholders for each final target were also part of the nominal schedule for each probe. This way, short-term rescheduling of individual maneuvers was possible without impact on the final placements.

During the placement phase, 42 orbit change maneuvers, not counting attitude and spin rate changes, have been performed to bring each of the five THEMIS probes into its science orbits well in time. For more details about THEMIS mission operations see Bester et al. (2008). After each maneuver, orbit and attitude updates as well as results from maneuver reconstruction were fed into the MDT to evaluate mission criteria and to adjust the remaining maneuver targets and maneuver times following (1) and (2). For each probe, the actual status was compared with predictions. For the outer probes, deviations in maneuver time for the next maneuver were converted in to period adjustments for intermediate orbits following all

Table 5 Numbers of executed placement maneuvers from launch through first tail season

Numbers of maneuvers	P1PB	P2PC	P3PD	P4PE	P5PA
Coast phase	3	6	2	4	4
Placement	8	10	9	9	6
Tail 1 tweaks	3	3	–	–	–
Total after tail 1	14	19	11	12	10

remaining apogee changes. For the inner probes, the number of orbits with small apogee drift rates was adjusted. Each such run always processed all five probes and quite often, while maneuvers on more than one probe were up for maneuver preparation, all previous maneuvers have been evaluated as well.

The mission-significant orbital elements since launch and through the first tail season are shown in Fig. 13. The left column characterizes the orientation of the orbital plane and the right column monitors orbit size. Changes in period can be traced as either apogee or perigee changes. Differential precession, shown as differences in RAP, starts as soon as the outer probes have started their ascent. Maneuvers are indicated by an almost instantaneous jump, though these data are based on finite burns. All inclination changes are probe-specific and are done at near-zero APER for fuel efficiency, verifying that the offset of –10 deg at launch is sufficient to account for the checkout phase.

4.5 Orbit Maintenance

The focus of orbital maintenance is to keep the constellation within science requirements. Per-probe amount and purpose differs according to the different orbits and strategic roles. Once brought into their science orbit with a sidereal-day period, the two inner probes P3, P4 need to maintain conjunction over CCA and might have to readjust for small apogee drifts and reset to sidereal-day period. Prior to each season this can be achieved by two or three small maneuvers.

The outer probes P1, P2 need to maintain their conjunctions with the inner probes P3 and P4 as well as the neutral sheet in the magnetotail. During each season, the set of four tweak maneuvers (see Table 4) will account for differential precession by small changes of the apogees. The offset in the GSM-Y-component between the center of the P3 and P4 apogees and the position of P1, P2, respectively at the end of each such interval is converted into a time offset, which is then spread over all orbits in that interval as a change to orbital period as expressed in (4)

$$T_{\text{new}}^{\text{outer}} = T_{\text{old}}^{\text{outer}} + dT \quad \text{with } dT = (t_{P3,4} - t_{P1(2)})/n \text{ and } T_{\text{old}}^{\text{outer}} \approx T_{\text{phase}} \tag{4}$$

where $t_{P3,4}$ is the time of center of apogee passes of P3 and P4 and $t_{P1(2)}$ is the time where $Y_{P1(2)} = (Y_{P3} + Y_{P4})/2$ and n is the number of orbits of P1, (P2) during that interval. Independently for P1 and P2, the correction dT is determined in an iterative process, invoking high fidelity orbit propagation until the GSM-y components of inner and outer probes are within the science criteria. Figure 14 shows the variations in period for all probes for the remaining three seasons, with the tweak schedule overlaid. The variation for the P1 period is in the order of 2 to 4 hours per tweak, and for P2 it is in the order of 20 to 30 minutes.

The distance to the neutral sheet in the tail is set by APER and inclination. Both are heavily perturbed by lunar forces as seen in Fig. 13. The flip in APER as soon as the inclination is very low (for P2 happening during the following dayside) must be reversed for the

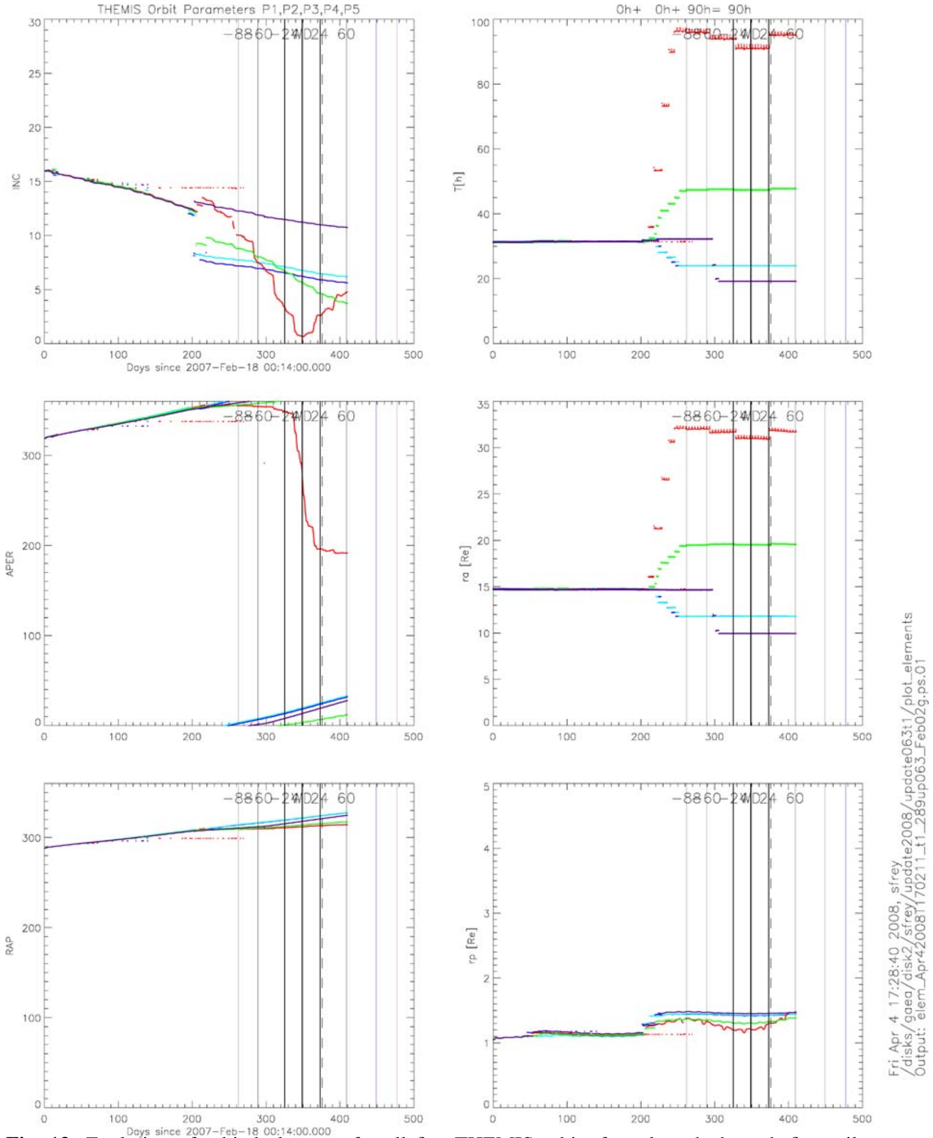

Fig. 13 Evolution of orbital elements for all five THEMIS orbits from launch through first tail season. *Left column* from top shows inclination, APER, RAP, all in degrees, *right column* from top shows period, geocentric apogee distance, geocentric perigee distance, not shown are eccentricity and RAAN. *Black vertical lines* mark the tail season schedule of WD + [−88, −60, −24, 0, 24, 60] days, the *dashed line* marks mission elapsed days and data left of it are definitive

outer probes prior to the second year tail season in order to keep probe conjunctions near the neutral sheet and also shadows below 3 hours. As discussed earlier, for fuel efficiency, this inclination change will be combined with a perigee reduction to support end-of-mission maneuvers.

The fifth probe, once relieved from its replacement role, undergoes larger changes in orbital period, aiming to greatly enhance science data in the current disruption zone as well

Table 6 Projected numbers of all maneuvers through two years of the mission

Numbers of maneuvers	P1PB	P2PC	P3PD	P4PE	P5PA
Total after tail season 1	14	19	11	12	10
Dayside 1 set up	–	–	5	5	6
Dayside 1 tweaks	4	4	–	–	–
Tail season 2 set up	2	2	3	3	6
Tail season 2 tweaks	4	4	–	–	–
Dayside 2 set up	–	–	3	3	6
Dayside 2 tweaks	4	4	–	–	–
Total after 2 years	28	23	22	23	28

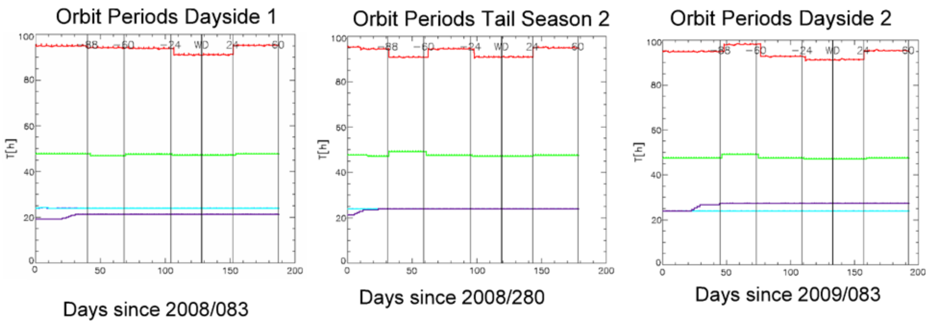

Fig. 14 Orbital periods for all five probes through seasons after first tail season. *Vertical lines* mark tweak maneuver schedule

as around magnetopause crossings in the dayside as outlined in Angelopoulos, (2008) in this issue. Figure 14 shows how P5 period goes from 4/5 of sidereal-day period in the first tail season, to 8/9 of sidereal-day period in the first dayside, to sidereal-day period in the second tail season, and is finishing off with 8/7 in the second dayside, always changing apogee.

5 Assessment of Mission Requirements

5.1 Conjunctions

The challenge of the THEMIS mission is to catch the various components of substorm events simultaneously at high time resolution with only 5 probes and a partial coverage of the auroral oval. The complexity of the tasks is broken down into a multitude of baseline science requirements in Angelopoulos (2008) in this issue and is listed in Table IV therein. For orbit design and mission planning these requirements are summarized into much simpler conjunction criteria and only probe conjunctions that fulfill those criteria are counted towards the accumulated conjunctions of four probes of at least 188 hours per season. This allows efficient, predictive evaluation of orbit solutions as an integrated part of the planning process at any stage. Likewise integrated are assessments of eclipse durations as well as the total of all velocity changes and the equivalent in fuel consumption for each probe throughout the mission.

The simplified conjunction criteria are that 1) inter probe separations of the GSM-y coordinates be within two R_E, 2) and in tail seasons only, the distance between the neutral sheet be within two R_E for the inner probes and within five R_E for the outer probes, and 3) event times during the 12 hours are centered at 6:30 UT for tail seasons and 18:30 UT for day sides. For the midnight interval of the first season, Fig. 15 shows where along the orbits conjunctions occur. The thick black markings in the left plot, showing all orbits in the GSM-XY plane, are those instances where all three criteria are met. Showing the distance to the neutral sheet along the GSM-X component for the corresponding black tracks from above, the right plot assesses where conjunctions are cut off by the neutral sheet distance criteria. Predicting the neutral sheet is rather difficult, as the transition from the magnetic equator into the bended neutral sheet varies in position and angle with dipole tilt, magnetic activity, and solar wind pressure. Current research relies on models that yet need more data-based verification and improvements. For our integrated routine analysis, we composed a neutral sheet model (THEMIS) that works for inner as well as outer probes and is focused on the magnetospheric dynamics during substorm onset in the winter season. For the outer probes where the separation becomes crucial further out in the near-tail, we apply the Hammond modification of the Fairfield model (Hammond model), Hammond et al. (1994) which is optimized for near-tail distances outside the transition region between -15 and -35 R_E. On the near-Earth side the Hammond model is not applicable and we replace it with the magnetic equator for the inner probes. A comparison with an alternative global magnetospheric data-based model optimized for the near magnetosphere inside -15 R_E (T96), Tsyganenko (1995), is shown in Fig. 16 where the upper plot shows the neutral sheet models corresponding to an inner (P3) and an outer (P1) orbit at WD. Both models agree reasonably at the tail distances, while the T96 models the inner neutral sheet fairly well by adjusting corresponding parameters to measurements of the actual magnetospheric condition. However, for our predictive analysis the lower end of the range rather than the exact position of the bend are of concern regarding the inner probes. As the lower plot indicates, for that purpose the magnetic equator is a good estimate and justifies the simpler model to avoid time-consuming computations. As conjunction instances for the outer probes are outside -10 R_E, the limits of the Hammond model through the transition region can be neglected. Furthermore, the lower plot, comparing the probe distance to either model, shows that differences between the models do not affect the evaluation of the z-criteria. Whether the chosen criteria are sufficient will be assessed by data analysis during tail season 1. Figure 17 gives an overview of the 4-probe conjunctions through the entire first tail season with time running from right to left. At WD – 60 days, orbits start to enter the magnetotail and conjunctions are happening at the outbound flank. Approaching WD conjunctions move to center around apogees. Most

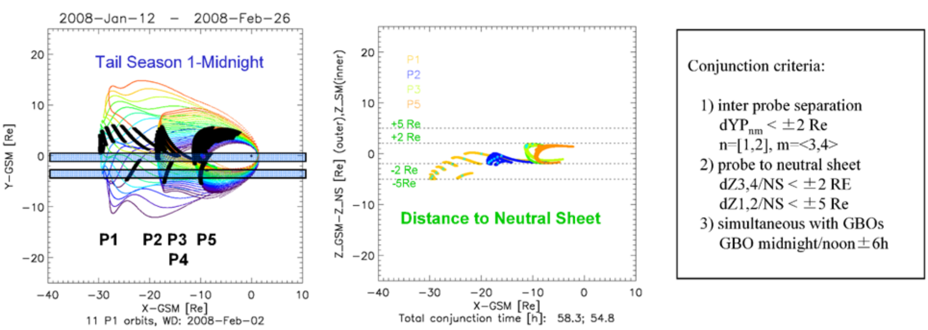

Fig. 15 Illustration of conjunction criteria for conjunctions of all five probes during the midnight interval. *Left plot* shows in *blue* the 2 R_E of inter probe separation for a given orbit parallel to the Sun–Earth line. Instances that meet all three criteria are marked in *black*

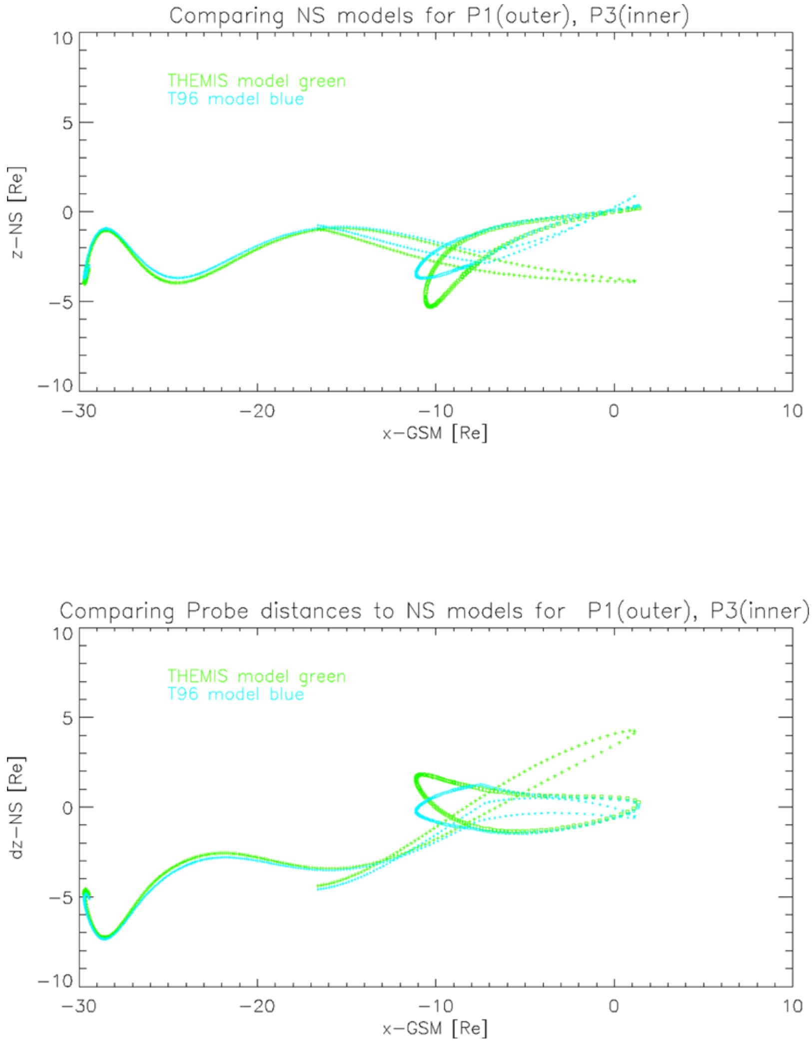

Fig. 16 *Upper plot*, neutral sheet models are compared for P1 (*crosses*) and P3 (*squares*) orbit on WD; *lower plot*, probe distances to neutral sheet models around WD

likely reconnection zones are best bracketed during the midnight interval (WD $\pm$24 days), where on the other hand, the actual waving of the neutral sheet becomes the limiting factor. Past WD conjunctions move towards the inbound flank and as the plots at the bottom show, all orbits are almost embedded in the neutral sheet near vernal equinox.

5.2 Shadow Duration

Driven by power and thermal properties, the upper limit for total shadows is three hours. Post launch experience have found this to be a rather conservative limit, thus easing maneuver target constraints. Typical eclipses encountered on the THEMIS orbits are either short umbrae near perigee or long shadows on the inbound flank in spring. Partial lunar shadows

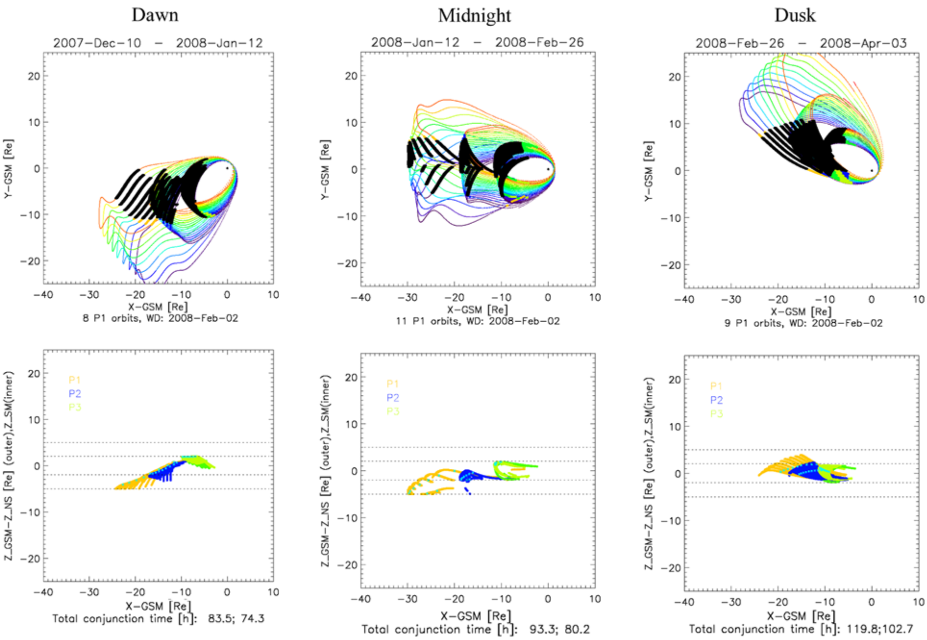

Fig. 17 Conjunctions of four probes for each interval. *Upper panels* show orbits projected into the GSM-XY plane; conjunction instances are marked in *black*, *lower panel* shows distance to the neutral sheet only for conjunction instances; *dotted lines* frame the dZ-limits

are scattered sporadically around the orbit, lasting from only a few minutes to 2 hours with varying depth. Hence, shadow analysis includes lunar and Earth shadows. For the predictive routine analysis with the MDT, which checks for upper limits of eclipse duration not to exceed 3 hours and possible overlaps with maneuver times, shadows are modeled as cones, including entry and exit of the penumbra using extended spherical objects. For applications on modeling thermal properties and for final product data generation in SatTrack, a more sophisticated shadow analysis is run that includes atmospheric effects, geoid approximation and defines entry and exit at 99% of full sunlight. This method allows determination of the depth for individual shadows and is employed for case studies such as long lunar partial shadows. The inclination is the key parameter to keep shadows below the 3-hour limit in both tail seasons and is set prior to the first tail season. In addition, the outer probes need to reverse the lunar effect on inclination and argument of perigee at the start of the second tail season. Since the inclination target of the inner probes is driven by the 2nd year, their placement maneuvers are based on verification by the shadow analysis of the 2nd year. The outer probes, P1 more than P2, derive the inclinations for each season separately to compromise between conjunctions and shadow length. Without shadow avoidance maneuvers in spring of the 3rd year, shadows would dramatically increase for the outer probes and can become of critical duration for the inner probes.

5.3 Total delta V Budget

THEMIS is a very active mission, changing orbits significantly and often during mission lifetime and constantly monitoring the delta V budget becomes essential. The largest contributors are of course the placement phase and the launch trajectory as a starting point. By

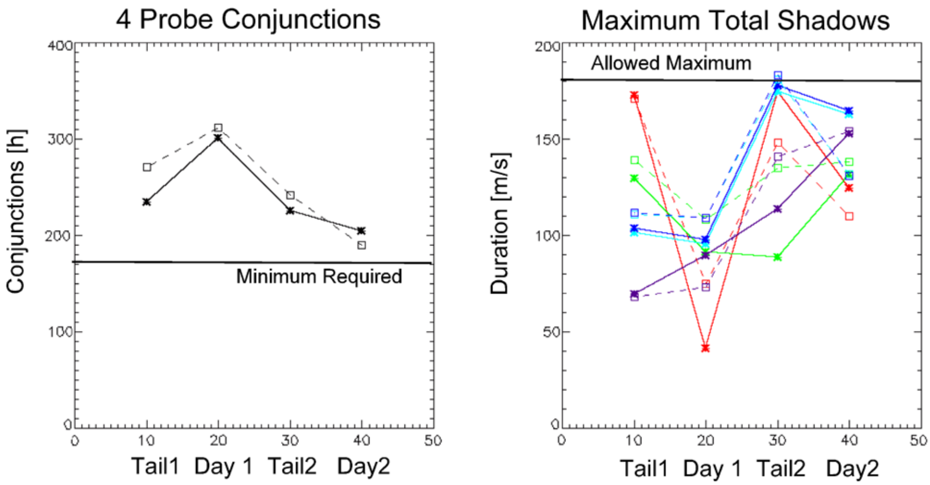

Fig. 18 Comparing evolution of mission requirements from launch through first tail season and predictions for the remaining seasons, the plot on the *left side* shows 4-probe conjunctions, the one on the *right side* shadow durations, pre-launch data (*dashed*) post-launch data with executed maneuvers until 2007-May-18 (*solid line*)

raising the launch trajectory from 12 to 14 R_E, the delta V needed for the placement is rather well equally split over inner and outer probes as inner probes lower their apogees and outer probes raise their apogees. While inner probes need more delta V for possible re-entry maneuvers, the outer probes will have to use that reserve to counter lunar perturbations. The delta V is checked in two ways as velocity change of impulsive maneuvers only and as the sum of velocity change through the finite arc maneuver and the equivalent imparted by probe reorientation and/or spin rate changes. The contributions from orbit changes, probe reorientation, and spin rate changes are also recorded separately in order to assess predictions. The total fuel allocated was based on the sum of all velocity changes from finite arc maneuver modeling, additional inefficiencies due to thruster alignments and all reorientations and spin rate changes, including those during boom deployments, plus the required 15% margin at launch.

6 Summary

Prior to launch the orbit design provided solutions for a wide range of conditions such as launch days or launch vehicle dispersion, but was centered at nominal targets, whereas ever since launch, the orbit design could be optimized for the actual launch trajectory with finalizing the maneuvers leading up to the first repressurization, based on the best WD for the first tail season. The seasons following the first tail season have frequently been updated based on in-flight data. The evaluation of the three main mission requirements, conjunctions, shadow duration, and delta V budget since launch and maneuvers through the set-up of the inner probes for the first dayside, shown in Figs. 18 and 19 and listed in Table 7, confirms the orbit design strategy.

The THEMIS orbit design and its realization is very complex and challenging in many ways and has been successfully put to test. Since launch in February 2007, we retrieved excellent science data during the coast phase and the first tail season.

Table 7 Overview of mission requirements, conjunctions are split into the three intervals. Data for the first year tail season after all maneuvers and for the first dayside after inner probe setup. Data for second year based on current estimate of WDs; delta V is adjusted to account for ACS fuel usage

Season	WD	Conjunctions [h] (4probes)	Max. shadow [min]					dV [m/s]				
			P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
Tail 1	02-02-2008	$72 + 77 + 102 = 251$	166	113	109	114	79	373	287	307	300	345
Day 1	08-03-2008	$80 + 120 + 95 = 304$	63	97	108	106	80	392	299	389	378	396
Tail 2	02-07-2009	$57 + 96 + 85 = 238$	159	130	180	180	168	705	552	390	377	448
Day 2	08-09-2009	$33 + 99 + 93 = 225$	129	137	164	165	158	731	568	394	381	498

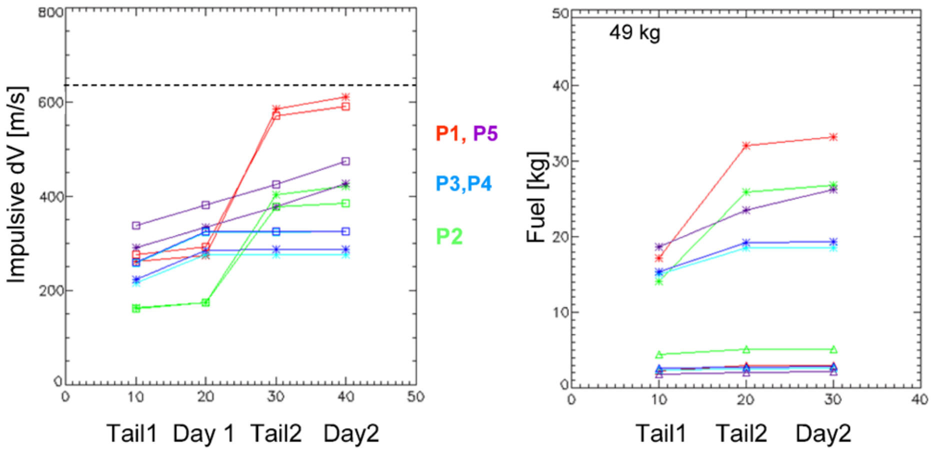

Fig. 19 Comparing the evolution of mission requirements from launch through first tail season and predictions for the remaining seasons, using post-launch data with executed maneuvers until 2007-May-18 (*). Accumulated delta V per probe is shown on the *left side*, *squares mark* pre-launch data. On the *right side* the accumulated fuel usage is shown, *triangles* are ACS fuel usage

The ambitious series of maneuvers during the placement phase went entirely according to plan, and on time. We are entering the first dayside season with all inner probes well in place.

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References

V. Angelopoulos, The THEMIS mission. Space Sci. Rev. (2008, this issue). doi:10.1007/s11214-008-9336-1
K. Berry, Orbital decay analysis for THEMIS at GSFC (2005)
M. Bester et al., Space Sci. Rev. (2008, this issue)
J. Bonnell et al., Space Sci. Rev. (2008, this issue)
C.M. Hammond et al., Imaging the effect of dipole tilt on magnetotail boundaries. J. Geophys. Res. **99**, 6079 (1994)
S.E. Harris et al., THEMIS ground based observatory system design. Space Sci. Rev. (2008, this issue)
S.B. Mende et al., The THEMIS array of ground-based observatories for the study of auroral substorms. Space Sci. Rev. (2008, this issue). doi:10.1007/s11214-008-9380-x
D. Pankow et al., Space Sci. Rev. (2008, this issue). doi:10.1007/s11214-008-9386-4
C.T. Russell et al., Space Sci. Rev. (2008, this issue). doi:10.1007/s11214-008-9337-0
D.G. Sibeck et al., Space Sci. Rev. (2008, this issue). doi:10.1007/s11214-008-9393-5
M. Sholl, M. Leeds, J. Holbrook, THEMIS reaction control System—From I&T through early orbit operations, in 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati, OH, July 8–11, 2007
N.A. Tsyganenko, Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause. J. Geophys. Res. **100**, 5599 (1995)
D.A. Vallado, *Fundamentals of Astronomics and Applications*. Space Technology Series (McGraw-Hill, New York, 1997)
J.R. Wertz, *Mission Geometry; Orbit and Constellation Design and Management, Space Technology Library*. (Microcosm Press and Kluwer Academic, Dordrecht, 2001)