The Revised Concept of the THEMIS and MMS Coordination

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Abstract: *Advances in our understanding of the changing space environment surrounding the Earth, commonly known as space weather, increasingly rely on prolonged simultaneous observations of the time varying conditions within the Sun-Earth system from various vintage points in space and from the ground. Since launch in February 2007 the NASA THEMIS mission has been tracking the flow of energy from the Earth's midtail to the inner magnetosphere as a pathfinder for multi-mission coordination within the HSO. With the implementation of NASA's second magnetospheric constellation, the MMS mission, launched in March 2015 to study the conversion of magnetic energy into particle energy through magnetic reconnection, the opportunity arose for a truly multi-mission system-wide approach involving the HSO fleet and ground assets to provide the global context. In particular, the coordination of the alignment of the THEMIS and MMS orbits allows prolonged simultaneous observations at key regions much needed to enhance our understanding of the space environment of the Earth and its dynamical response to external and internal influences. In this paper, we will give an overview over the next six years and outline our new coordination strategy with MMS. We describe how we utilize our very different remaining fuel reserves on the three Earth orbiting probes while frequently synchronizing THEMIS apogee passes with those of MMS and at the same time enacting separations on various scales between the THEMIS probes in order to quantify local processes.*

Keywords: *Mission design, THEMIS, multi-mission constellation, maneuver planning, HSO.*

1. Introduction

Advances in our understanding of the changing space environment surrounding the Earth, commonly known as space weather, increasingly rely on prolonged simultaneous observations of the time varying conditions within the Sun-Earth system from various vintage points in space and from the ground. With nineteen operating solar, heliospheric, geospace, and planetary missions the Heliophysics System Observatory (HSO) monitors key processes across the Solar System. Results from fortuitous conjunct observations have revealed coupling processes on multiple scales and demonstrated the potential of coordinated cross-scale multi-missions to quantify the driving mechanisms of the vast flows of energy and particles.

Since launch in February 2007 the NASA mission *Time History of Events and Macroscale Interactions during Substorms (THEMIS*) has been tracking the flow of energy from the Earth's midtail to the inner magnetosphere as a pathfinder for multi-mission coordination within the HSO. With the extended mission in 2010 we formed the combined missions THEMIS and

ARTEMIS (*Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun*) [1] utilizing our experience with the macro-scale constellation of the five THEMIS probes and their coordination with the Ground Based Observatories [2, 3]. At the same time we have integrated synchronized observations with other missions such as CLUSTER, GOES, and GEOTAIL in our science planning [4]. Starting in 2012 we have been coordinating the separations between the Earth orbiting THEMIS probes with the Van Allen Probes, NASA's mission dedicated to study the radiation belts. The resulting continuous complementary observations are aiding the development of empirical models of the geoelectric field [5]. With the implementation of NASA's second magnetospheric constellation, the *Magnetospheric Multiscale (MMS)* mission, launched in March 2015 [6] to study the conversion of magnetic energy into particle energy through magnetic reconnection, the opportunity arose for a truly multi-mission system-wide approach involving the HSO fleet and ground assets. In particular, the coordination of the orbit alignment of THEMIS and MMS allows prolonged simultaneous observations at key regions much needed to enhance our understanding of the space environment of the Earth and its dynamical response to external and internal influences.

Although coordinating these two missions seems natural it came with unprecedented challenges. The THEMIS mission, already in orbit, has very limited resources for orbit re-design whereas the MMS mission came with various launch related uncertainties. In fact, the final launch day shift proved to be the most demanding. Just short of its late 2014 launch window, MMS experienced a launch delay that required a significant change in orientation of the launch trajectory with dramatic impact on the first cross-scale multi-mission alignment.

As previously reported [7] THEMIS has committed its long-term active orbit design during its extended mission phases to the coordination with existing and future HSO assets. In this paper we outline the new concept of alignment with MMS and our planning process covering the years 2015 to 2020. The strategy of the apogee altitudes is described with emphasis on the probe specific fuel reserves. We also address the new requirement to stay above 650 km altitude, re-entry commitment at end of mission, and fuel efficiency. The planning of the upcoming first year of coordinated THEMIS-MMS mission is described in detail.

2. Multi-Mission Coordination

2.1 The revised THEMIS-MMS Alignment

The THEMIS mission is dedicated to study the energy and particle flow in the Sun-Earth system. The nominal mission focused on the time line of macroscale interactions during substorm onsets while the extended mission phases seek further understanding of our new findings. After zooming in on inner magnetosphere processes we now look at energy release mechanisms that occur beyond 10 Re and after substorm onset. The ARTEMIS probes either monitor solar wind input at lunar distances sunward of Earth or provide observations of plasma structures when crossing through the Earth magnetotail at lunar distances once per lunar cycle. The Ground

Based Observatories (GBOs), high time resolution imagers and magnetometer across the northern American sector (Greenland, Canada, Alaska) will be fully utilized during the next two winter seasons when the THEMIS apogees line up in the tail and coincide with long polar nights.

The MMS mission aims at the microphysics of magnetic reconnection in two magnetospheric regions by placing a small-scale tetrahedron inside the narrow layer from where the magnetic energy is released. This divides the mission into two phases. In phase 1 the MMS apogees are at 12 Re to maximize encounters with the dayside magnetopause. In phase 2 apogee altitudes will be at 25 Re to cross the midtail plasma sheet on the night side [8].

Both missions have the optimal instrumentation to measure electric and magnetic fields and to characterize the plasma at the electron and ion kinetic scales in Earth's space environment. Also equipped with onboard propulsion systems they are capable to alter the orbits. The original proposal [5] combined the total of seven spacecraft into a cross-scale formation by placing the THEMIS probes at three vertices of a tetrahedron at medium scales and the MMS tetrahedral formation at small scales at the fourth vertex. Such a configuration would have allowed looking at electron and ion kinetics simultaneously at the reconnection side. The concept required aligning the lines of apsides of both missions. We adjusted the rotation rate of the THEMIS lines of apsides by reducing perigee altitude. Mitigating our fuel capacities and the launch uncertainties of MMS we started adjusting our rotation rate years ahead of the MMS launch and steadily fine-tuned it for an optimized alignment as we approached the nominal MMS launch. For a launch in fall of 2014 THEMIS would have been within a few degrees of the MMS line of apsides in both phases. The shift of the MMS launch into spring 2015 resulted in opposing apogees and the THEMIS fuel reserves became insufficient to overcome that much offset by reversing the drift of the THEMIS orbits alone. For a comprehensive analysis of the changes needed on both missions and in order to still facilitate the tetrahedral formation the remaining time was not sufficient and we had to give up to study magnetic reconnection on multiple scales.

The spring 2015 launch of MMS resulted in opposing apogees. Leaving the apogees of both missions about 180 degrees apart provides the opportunity of prolonged simultaneous observations on the day and night sides with shifting emphasis on the coupling between plasma processes across the entire system. Additional aurora observations at very high time resolution in northern and southern polar regions are crucial in correlating local and global processes. Gaining this inside will greatly improve our capacity to predict space weather.

Figures 1 and 2 summarize the evolution of the revised alignment of the THEMIS and MMS orbits where the lines of apsides precess counter clockwise at a rate primarily defined by apogee and perigee altitudes as well as inclination [4]. Starting at 180 degrees separation and with MMS on the dayside and THEMIS in the tail both missions will drift and alternate into MMS on the nightside and THEMIS on the dayside. By keeping both missions at similar altitudes we maintain this alignment throughout phase 1 of MMS. In phase 2 the MMS orbits will pass through the nightside at the higher apogee altitudes. THEMIS will continue to observe beyond

10 Re and progressively raise its apogees based on fuel reserves resulting in significantly different drift rates of the lines of apsides. By 2020 both missions will have moved out of the opposing apogee alignment as shown in Fig. 2. This roughly 90 degree alignment is well suited to investigate important drivers of magnetic reconnection when THEMIS apogees are magnetically connected to the northern and southern polar regions.

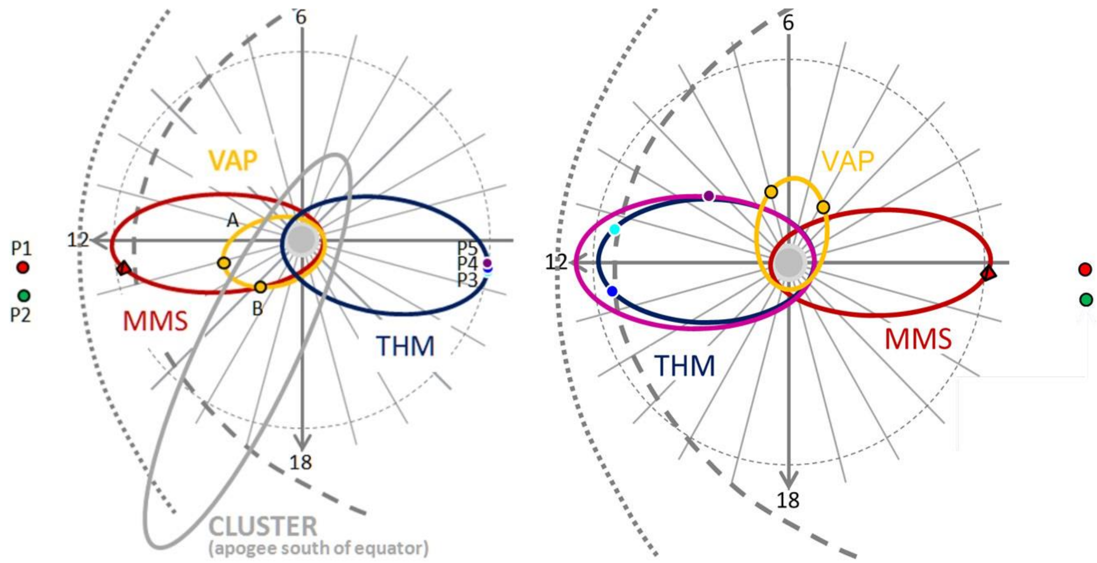


Figure 1: **Snapshots of constellations with MMS on the dayside (Dec. 2015, phase 1a, left) and on the nightside (Jun. 2016, phase 1x, right) shown in the ecliptic plane looking from north. The sun direction is to the left. The dashed and dotted lines are the outer bounderies of the magnetosphere against the solar wind. CLUSTER, the Van Allen Probes (VAP), and ARTEMIS (P1, P2) are shown in addition to MMS and THEMIS (THM).**

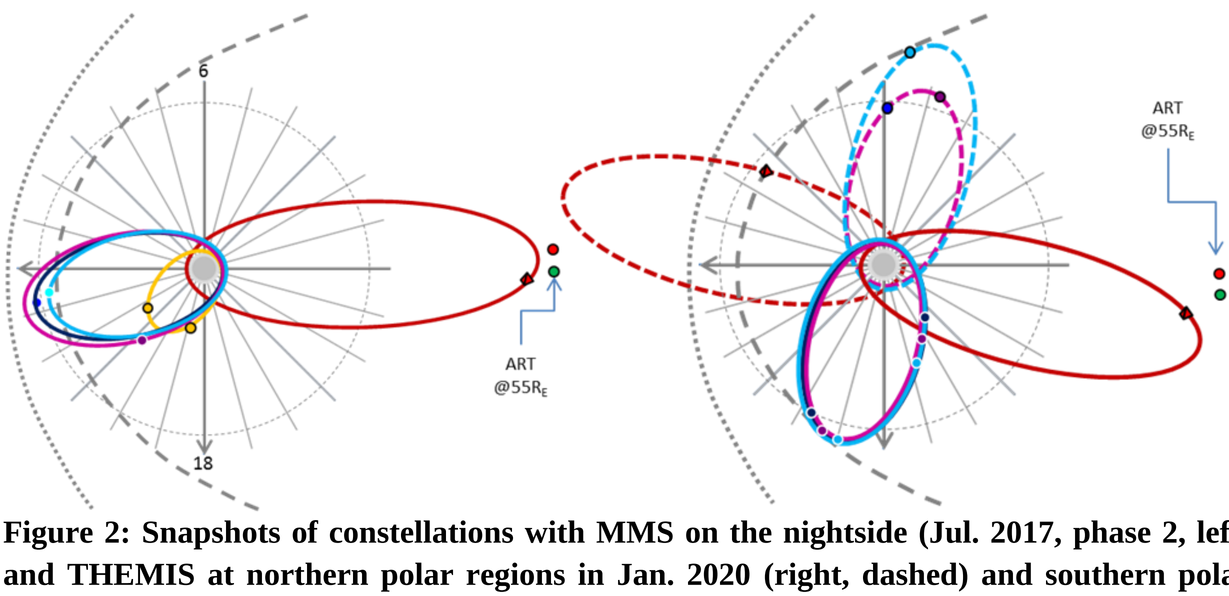


Figure 2: Snapshots of constellations with MMS on the nightside (Jul. 2017, phase 2, left) and THEMIS at northern polar regions in Jan. 2020 (right, dashed) and southern polar region in Sep. 2020 (right, solid), in the same geometry as Fig.1. Shown are VAP (yellow), and ARTEMIS (ART) in addition to MMS (red) and THEMIS (blue, cyan, purple).

The THEMIS science goal for the years 2015 to 2020 is to improve our understanding of the coupling mechanism across the entire magnetospheric system such that quantifying the effect global processes impart onto local phenomena will be possible. In order to provide the crucial comprehensive coverage of the key regions on both sides of the Earth with regard to the sun at all kinetic scales, orbits are specifically designed with geocentric apogee altitudes from 10 to 16 Re. Inter-probe separations will vary from a few hundred over multiple thousand kilometers up to one or two Earth radii. Based on our most recent findings the consensus of the science community is that probe separations in the order of a few hundred kilometers in the xy-plane of the sun referenced frame, will be best suited to explore the microphysics of substorms. Taking advantage of the closely aligned THEMIS lines of apsides in 2015 we start with a clustered formation, and then facilitate probe specific apogee raises which will impart an intermittent increase of differential precession, and reassemble probes on a string-of-pearl formation in 2020. The latter will allow observations of particle and energy flow into the inner magnetosphere.

2.2. Planning Process

Each mission must pursue its own science goals in order to stay competitive in the NASA review process. The success of coordinating multiple missions and ground assets depends on how well the individual science objectives can be strengthened by prolonged simultaneous observations. Well defined primary science targets are essential and willingness to cooperate early on is necessary. Even though the science goals of THEMIS and MMS are strongly related they are different and put different constraints on the orbit design and strategy of each mission. THEMIS has a strong time constraint on the tail observations by season and time of apogee passes in order to maximize conjunctions with its GBOs. The in situ reconnection observations of MMS are time independent but require the tetrahedron being nested inside the reconnection layer. Location and size of this highly variable target are hard to predict. Therefore spacecraft separations are kept flexible and the optimal fit is frequently redefined and established through maneuvers. Therefore timing coordinated orbit events has become the most demanding planning task in this endeavor.

In order to make the best use of our fuel reserves we utilize time through long term planning. Assuming good health for all instruments on both missions and successful nominal MMS phases we outline a science strategy through 2020, as illustrated in Figures 1 and 2. Our orbit planning cycles go through a sequence of five steps:

1. Define overall alignment of lines of apsides; targeting parameter is the clock angle (or Local Time) in the sun referenced frame as shown in Figures 1 and 2 at the season center epoch, long term planning through 2020
2. Define THEMIS science with the safety constraints, including probe separation to address science, differential precession, minimum perigee altitude, eclipse durations, and fuel budget; targeting parameter is apogee altitude, long term planning through 2020
3. Synchronize THEMIS and MMS apogee passes; targeting parameter is time of apogee passes at center epoch, near term planning 2015-2017

4. Optimize coordination with HSO missions and ground assets; targeting parameter is event time, near term planning 2015-2017
5. Ensure close encounters of the neutral sheet during tail seasons when on sidereal orbits; targeting parameter is distance to that plasma sheet, short term 2015-2017

The final orbit design is the result of multiple iterations to verify fuel consumption and long term drift by high fidelity orbit propagation using the Goddard Trajectory Determination System [9]. Since 2014 we limit the perigee altitude to 650 km as a safety measure for the electric field instrument. In chapter 3.1 we analyze the evolution of the perigee altitudes and describe how this new constraint is integrated in the maneuver planning. Details of the apogee strategy are outlined in chapter 3.2.

For near term planning, we tune THEMIS separation and orbit-phase according to the positions of MMS, Van Allen Probes, and GBOs for optimal utilization of all HSO assets. Defining the time of the apogee passes has become the most challenging part, particularly for the first shared season. Our fuel efficiency is maximized by combining the small maneuvers needed to synchronize the apogee passes for the winter season in 2015 with those aiming at our seasonal probe separation target for summer 2015. Due to the nature of the MMS maneuvers their apogee times were only known with certainty a few weeks after launch. To overcome the arising time conflict we planned our maneuvers based on the best estimated range of MMS apogee times. Details of our spring-summer maneuvers are described in Chapter 3.4. Knowing the apogee times we start coordinating observations with the HSO fleet and ground assets (step 4). However, exploring all the options cannot start early enough. As a matter of fact reaching out to the HSO community as soon as the THEMIS-MMS coordination became a possibility has greatly enhanced the anticipated science results. The final step is to look for conjunctions with the neutral sheet (NS) in the magnetotail. For the upcoming tail season in December 2015 we had the orbits already locked around the neutral sheet when we reset our orbital periods to sidereal periods by a method described in [10]. The THEMIS apogee times are defined for the upcoming two seasons to provide a maximum overlap between MMS magnetopause coverage, THEMIS crossings with the neutral sheet, GBO conjunctions as well as HSO observations.

3. Implementation

3.1 Minimum Perigee Altitude Constraint

Below 1000 km, satellites encounter the neutral atmosphere where high densities of atomic oxygen can cause surface erosion and oxidization. In particular, we are concerned about our electric field instrument. Its measurements of the geoelectric field can be altered by surface conversions of the spheres. After lowering the perigee altitudes in 2014 we experienced such effects during prolonged periods with perigee altitudes below 600 km and decided to avoid permanent degradation of our instruments by raising perigee. Common knowledge about the dynamics of the neutral atmosphere in response to solar as well as geomagnetic activities is still very basic which makes it difficult to predict altitude dependent atomic oxygen concentrations [11]. Based on our years-long in orbit experience we chose 650 km as the lower limit on the perigee altitude and watch carefully whether further adjustments are needed. However, increasing perigee altitudes goes against our end-of-life commitment to re-enter for which we need to preserve sufficient fuel for de-orbit maneuvers. We estimate the necessary fuel by simulating a perigee reduction maneuver that forces the probes to re-enter. Lunisolar perturbations cause perigee altitudes to fluctuate dramatically and complicate precise predictions. Using high fidelity orbit propagation we first analyzed the perigee evolution to identify occurrences below the critical altitude and then repeat frequently with new updates of the long term orbit design including the re-entry maneuvers.

Figures 3-5 show that THEMIS perigee altitudes fluctuate by about 900 km between 2015 and 2020, and all three probes need maneuvers in order to stay above 650 km. Each increase in perigee altitude counts twice in terms of fuel consumption because of the re-entry commitment. Integrating necessary perigee raises into the maneuvers needed for the coordinated orbit design rather than raising perigees at once to be safely above the threshold we can minimize fuel consumption. In this strategy time and size of perigee maneuvers are dictated by the local minima of the perigee altitudes that fall below 650 km. Our analysis revealed critical local minima in spring (P5) and fall (all) 2015, summer and fall 2016, and in late 2019 (all). Local maxima occur in 2018 and 2023. For verification of the re-entry capability we define a de-orbit maneuver by the difference between the local minima at the end of 2024 and 150 km. Due to the lunisolar perturbation this estimate of perigee reduction can be applied any time. In Figure 6 we compare pre- post maneuver perigee altitudes for all three probes for a maneuver done just after the peak at end of 2023.

- P5
    - 50 km perigee raise in spring, 80 km before fall 2015 as part of apogee time synchronization
    - 175 km perigee raise in summer 2016 together with apogee raise of 1.2 Re
- P4
    - 90 km perigee raise before fall 2015 as part of apogee time synchronization
    - 180 km perigee raise before fall 2016 as part of apogee time synchronization
    - 50 km perigee raise (touch up) with apogee raise of 1.2Re in late 2018
- P3
    - 90 km perigee raise before fall 2015 as part of apogee time synchronization
    - 180 km perigee raise before fall 2016 as part of apogee time synchronization
    - 50 km perigee raise (touch up) with apogee raise of 0.6 Re early fall 2019

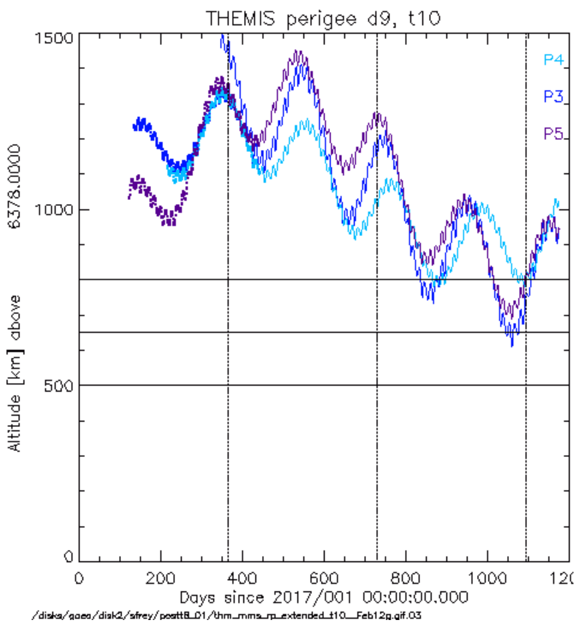


Figure 3: THEMIS Perigee altitudes over 3 years starting January 2017 with P3 maneuver sequence in December 2017.

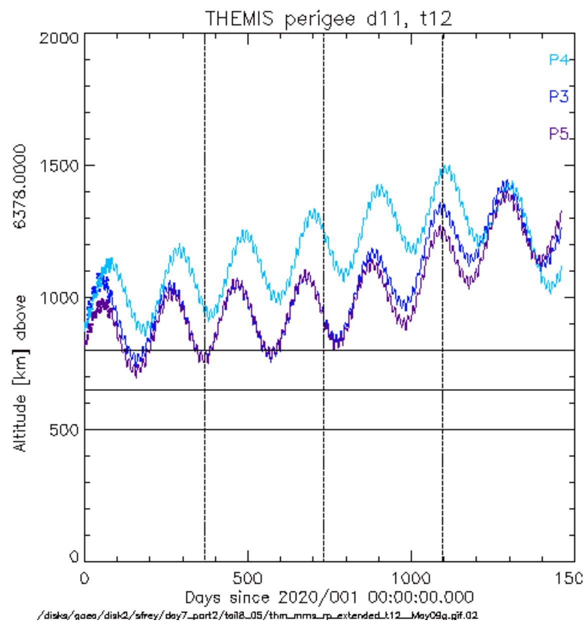


Figure 4: THEMIS Perigee altitudes over 4 years starting January 2020.

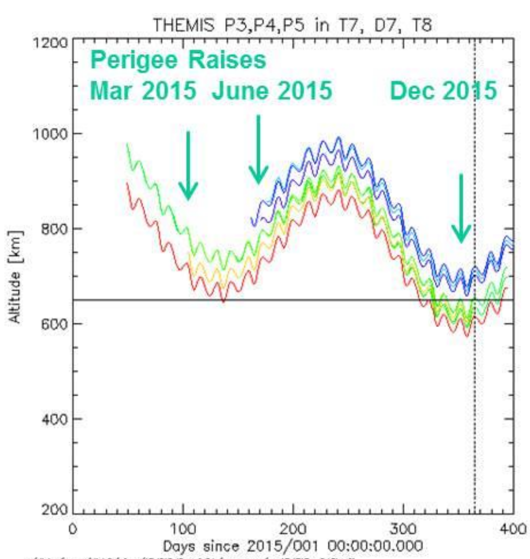


Figure 5: THEMIS Perigee altitudes in 2015 before and after perigee raises in March (P5) and June (P3, P4, P5). Red, yellow, purple for P5, green, blue for P3, cyan for P4, final post maneuvers states in blue, cyan, purple.

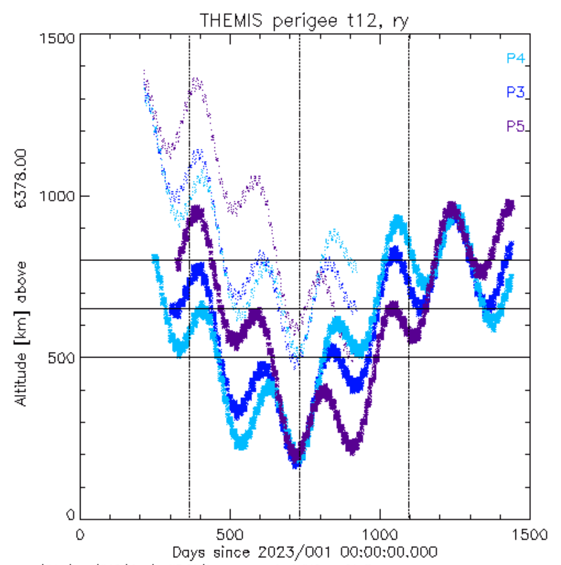


Figure 6: THEMIS Perigee altitudes starting in January 2023 comparing states before and after (thick lines) perigee was reduced by 400 km in 2023 to target a minimum perigee at 160 km.

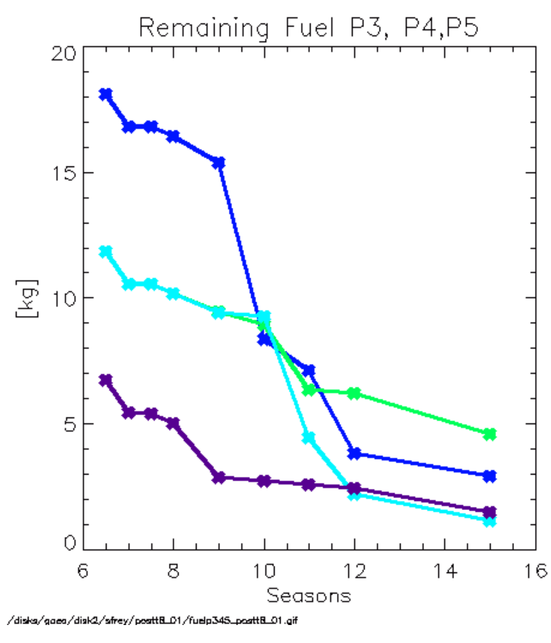
3.2 Apogee Altitude Strategy

The particular apogee altitudes are defined by the probe specific fuel reserves after accounting for re-entry maneuvers and in order to minimize differential precession among THEMIS probes and with MMS as well as to optimize conjunctions with MMS and the GBOs by resonant orbit periods. The two probes with the most (P3) and the least (P5) remaining fuel define the feasible altitude range between 13.5 and 16 Re and feasible resonant periods at $8/7*T_s$, $1/2*T_{MMS}$, and $4/3*T_s$, where T_s stands for sidereal period and T_{MMS} refers to the MMS period. The discrete resonant periods lead to the corresponding geocentric apogee altitudes of 13.2 Re, 14.8 Re, and 15.5 Re, respectively. P5 has sufficient fuel left to lift its apogee to 13.2 Re and to reach a period of $8/7*T_s$.

Table 1: Apogee altitudes in Re for THEMIS probes and for THEMIS seasons 2015 to 2017.

MMS	1a	1x	1b	2b					
THEMIS	T8	D8	T9	D9	T10	D10	T11	D11	T12
P3	12	12	12	11.5	14.8	15.5	14.8	15.5	13.2
P4-base	12	12	12	12	13.2	13.2	13.2	13.2	13.2
P4-science						14.8	14.8	14.8	14.8
P5	12	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2

Figure 7: Fuel reserves for THEMIS probes P3 (blue), P4 (cyan, green), P5 (purple) vs THEMIS seasons. For dayside 6 through tail season 8 post maneuver data, predictions thereafter, season 15 accounts for de-orbit maneuver.



Apart from a de-orbit maneuver and the occasional adjustments of the apogee pass time there will not be any major orbit changes. Consequently, this defines the altitude for the THEMIS string-of-pearls formation in 2020. On these orbits P5 will scan a wide radial range every 8 days. Due to the discrete altitudes P3 can spend some fuel on enhancing science by swapping between

GBO and MMS resonant orbits at geocentric apogee altitudes of 14.8 Re and 15.5 Re and lower apogee altitude to 11.5 Re to optimize differential precession. The lines of apsides of P3 and P5 will only be a few degrees apart towards 2019/2020. P4 will either stay with P5 or join P3 and use a good part of its fuel to minimize its precession offset to P3 and P5. The fuel conservative approach is to stay on the low orbit at 12 Re for some time then raise apogee to 13.2 Re and continue on this orbit. However, the P4 line of apsides will be 25 degrees away from those of P3 and P5 which is still within the 30 degree offset seemed feasible based on our experience from the nominal mission. The alternative option raises apogee first to 13.2 Re then further to 14.8 Re, and reduces to 13.2 Re in 2020. The duration on the highest orbit can be adjusted in order to improve differential precession on the final orbits in 2020.

Perigee raises are kept to a minimum while still requiring to stay above 650 km. Science in regions above 13.2 Re can greatly be enhanced while the differential precession is reduced to 18º. However, the discrete apogee target of 14.8 Re constraints the feasibility. The analysis of the fuel usage relies on well predicted maneuver estimates and perigee altitudes. Since apogee passes at the higher altitudes last for many hours relaxing the resonance criteria on the high orbit can be explored as an option to ensure sufficient fuel for reducing apogee altitude to 13.2 Re in 2020. As in the past the conservative approach is implemented in the baseline plan. Table 1 gives an overview of the apogee targets and Figure 7 illustrates fuel consumption for the THEMIS probes.

3.3 Synchronization of Apogee Pass Time

Prolonged simultaneous observations in the magnetosphere on the day and nightside require synchronized apogee pass times of both missions. Through selection of the apogee pass time, we optimize the conjunctions between THEMIS and MMS, with the neutral sheet and the GBOs and utilize the HSO capacities to provide global context. Coordinating with neutral sheet encounters and the ground observatories is vital for quantitatively investigating the linkage between the processes in the mid tail to the modulating processes on the dayside. Apogee pass times will be frequently adjusted to bias conjunctions towards seasonal specific science goals and to counter small offsets in period and precession rate of the lines of apsides.

The apogee pass time is targeted on the epoch when both missions have reached the opposing Local Times near the Sun-Earth line. The precession of the orbits with respect to the sun divides a year into two main seasons, when the apogees are centered either on the day or the night side. The epoch when the apogee lies on the Sun-Earth line is referred to as the center epoch of the season. For each season the suitable geometries between orbits and the targeted magnetospheric regions along the Sun-Earth line last about 120 days and are nearly perfect for 60 days around the center epoch. This provides at least 120 days for transitions per year and even more at apogee altitudes beyond 12 Re. As explained in chapter 2 final apogee times are frequently coordinated with the MMS mission team who provide orbit updates for an upcoming season rapidly.

If synchronizing the apogee pass time coincides with a significant orbit change we time the orbit change maneuver such that the targeted apogee pass time is achieved. In those cases the average size of maneuvers is chosen to minimize losses due to finite maneuver arcs and number of maneuvers. If necessary one or two maneuvers are modified to achieve the targeted apogee pass time. This concept has served us well ever since we moved the probes from the insertion orbit into their distinct science orbits in the nominal mission. Otherwise, the apogee pass time is adjusted by two small maneuvers. The first one increases or decreases the orbital period. Once the apogee pass time is achieved a second maneuver resets the orbital period. The size of these maneuvers depends on the time shift at apogee and the time available to drift into the target time. For optimizing fuel consumption we keep the orbit changes as small as possible and trade drift time vs. fuel. However the limited time to transition into the next season ultimately dictates how much temporary change in orbital period has to be applied.

On the sidereal orbits apogee pass times change by about -4 min with each revolution but the geographic longitude is time independent and thus better suited for maneuver planning. We determine the maneuver size by the required change of geographic longitude and the available drift time according to Equation 1:

$$dt_{drift} = \Delta apolon/\delta apo_{probe} \qquad (1)$$

where dt_{drift} is the time between maneuvers, Δapolon is the required change in geographic longitude, and δapo_{probe} is the probe specific change in geographic longitude per orbit due to the period offset from sidereal period and depends on the change of the semi-major axis. The least fuel is consumed by utilizing apogee changes only. If perigee raises are unavoidable we can minimize fuel consumption by replacing one apogee change. Depending whether a shorter or longer intermediate period achieves the target faster the first maneuver is either a perigee or apogee change according to equations:

$$dT>0 \text{ then } dT_1=f(drp) \text{ and } dT_2=f(dra) \text{ with } drp>0,\ dra<0 \qquad (2)$$

$$dT<0 \text{ then } dT_1=f(drp) \text{ and } dT_2=f(dra) \text{ with } drp>0,\ dra<0 \qquad (3)$$

3.4 Implementation of the First Year of Coordinated THEMIS-MMS Conjunctions

With the MMS launch in March 2015 the center epochs for the first two seasons fall into December 2015 for the first dayside magnetopause crossings by MMS (phase 1a) and its first nightside season (phase 1x) in July 2016. THEMIS will have its 8th tail and 8th dayside seasons. Synchronizing the first two shared seasons is the most challenging part for various reasons. First of all prolonged high quality conjunctions are critical to maintain the support of this multi-mission approach. The tolerances at the apogee pass time targets are most stringent on the lower orbits at 12 Re and become more relaxed once apogee altitudes have been raised. Planning had to start before the MMS launch and account for launch delays and dispersion. Each THEMIS season is set up by its own maneuver sequences. The setup of this tail season was unique as it was combined with the setup of the preceding dayside. These maneuvers have been successfully executed between March 10 and June 24 in 2015. The setup of the following dayside in spring 2016 is less complex but not without challenges.

The setup of THEMIS tail season T8 aimed at two objectives, the small cluster by summer 2015 as explained in chapter 2 and synchronizing apogee passes for MMS phase 1a in December 2015. In order to be fuel efficient we wanted to:

- Start early changing probe separations from the equally separated probes in spring of 2015 to the clustered formation in summer, that is changing from 8h-8h-8h to minutes of separations
- Include raise of P5 perigee before the spring minimum below 650 km into separation change maneuvers
- Utilize the maneuvers for synchronizing apogee pass times with MMS for perigee raises of all three probes before the fall 2015 minima below 650 km

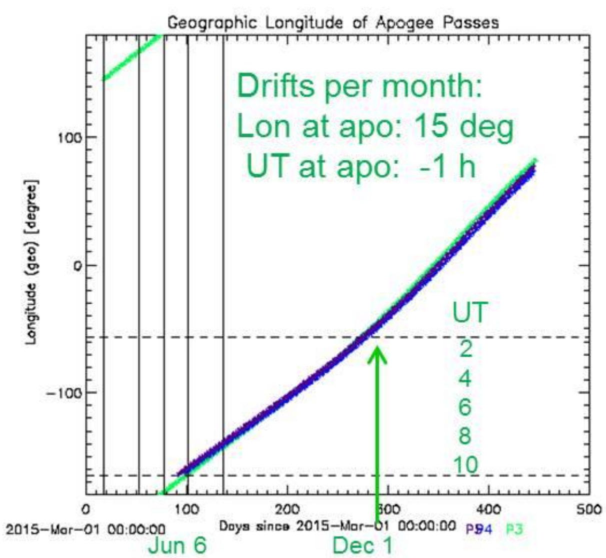


Figure 8: Geographic longitude of apogee passes for small cluster of THEMIS probes P3,P4,P5 in 2015, probes drift through target range of UT at apogee in Dec from June through November.2015. Maneuvers at end of Jun. targeted the 09 UT at apogee on Dec 23.

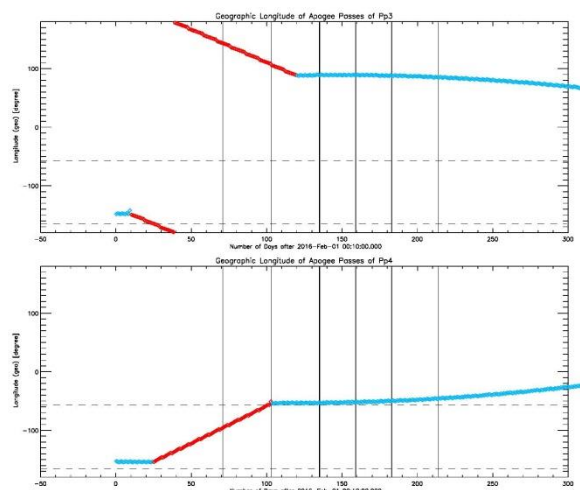


Figure 9: Geographic longitude of apogee passes for THEMIS probes P3 (top) and P4 (bottom) during setup of THEMIS dayside 8 in 2016, in red drift phase into target apogee time, dashed lines indicate geographic range of GBOs, the 3 thick solid lines mark 120 days around the season center.

The selection of the optimal apogee pass time based on post launch definitive MMS orbit data conflicted with our early start of maneuvers for the small clustered formation. Based on the March launch window and the three-sigma launch dispersion we estimated the apogee pass times between 2 and 10 UTC. This knowledge allowed us to target the western most geographic longitude associated with the UTC range with the maneuvers that initiated the drift into the small cluster. Once the targeted separation was achieved in May the small cluster was frozen at an orbital period that moved the apogee passes eastward in geographic longitude across the estimated range in time for the winter season and to raise the perigee altitudes above the critical local minima in December. When the target longitude is reached a final maneuver establishes sidereal period again and freezes the geographic longitude. Since in this maneuver scenario maneuver sizes only depend on the change of orbital period and are independent of maneuver time we were able to plan the entire maneuver sequence with place holder maneuvers. Once the apogee pass time target was determined in May 2015, all we had to do was defining the time of the second set of maneuvers and schedule pass coverage. Figure 5 provides the time line for the local perigee minima and Fig. 8 illustrates the drift of the geographic longitude of the apogee passes and its relation to the UTC range.

During the first MMS nightside season (phase 1x) in summer 2016 THEMIS will be on the dayside (dayside 8). For the vital comprehensive polar observations we take advantage of the HSO ground based assets in the southern hemisphere which will experience the long winter nights favorable for auroral imaging. Unlike the THEMIS GBOs the southern observatories are not deployed to specifically align with THEMIS orbits. In order to optimize the science return we separately target conjunctions with MMS and the southern observatories and maximize their overlap. This is accomplished by different apogee pass times for the two THEMIS probes on the lower orbit with apogee altitudes at 12 Re and sidereal period. In particular, the P3 apogee pass time at the center epoch will be around 06 UTC and that for P4 around 15 UTC. P5 will increase its apogee to 13.2 Re and due to the $8/7*T_s$ period align with P3 or P4 once in 8 days. For both probes the change in apogee pass time from 09 UTC at the center of the preceding tail season is significant and goes in opposite direction. In terms of geographic longitude P3 has to change by about -120º and P4 by about +100º as shown in Fig. 9. In order to accomplish this in time for the dayside season the apogee passes have to drift at least by one degree in geographic longitude per orbit (Eq. 1). It takes about 200 km change in apogee or perigee altitude which matches about the change in perigee altitude needed to keep the local minima of 2016 above the 650 km. For the setup of the THEMIS Dayside D8 the individual maneuver goals are:

- P3: 06 UTC, 180 km perigee raise before mid of June 2016, δapo_{probe}=1.2 deg/day
- P4: 15 UTC, 175 km perigee raise before mid of June 2016, δapo_{probe}=1.2 deg/day
- P5: raise apogee by 1.2 Re, 175 km perigee raise before end of April 2016

In order to use fuel optimally, P3 and P4 will change apogee pass times by utilizing the perigee raise either to start (P4) or stop (P3) the drift according to Eqs. 2 and 3. P5 has the perigee raise included in the increase of its period from Ts to 8/7*Ts. With drift times of 110 (P3) and 80 (P4) days maneuvers have to start early in 2016.

The development of such an ambitious science plan is only possible with strong confidence in the green state of health of the flight and ground systems as well as the reliable ground operations gained over eight years in orbit through 650 thrust operations, 47,000 passes and over 1,100 well managed shadow cycles. Much facilitated through the high degree of automation of mission operations and maneuver planning at UC Berkeley [12-15] it has become characteristic for the THEMIS/ARTEMIS extended mission that the latest science discoveries are nearly instantaneously adopted in the frequent orbit reconfiguration. The challenging time conflicts in coordinating the first shared seasons of THEMIS and MMS could not be resolved without significant automation of the scheduling process [16] and the cooperation of the team.

4. Summary

The THEMIS mission has always been committed to align itself with current and future Heliophysics missions to advance our understanding of the dynamic interaction of the Earth's magnetosphere with its space environment. For many years THEMIS has progressively utilized its resources to optimize conjunctions between all HSO assets culminating in the coordination of prolonged simultaneous multi-scale observations of reconnection processes with the new MMS mission. Challenges due to uncertainties related to launch have been overcome through relentless efforts in revising the science strategy for the first ever coordinated multi-mission constellation. As a result, the coming years will provide the most comprehensive opportunity to study the coupling processes system wide across multiple scales. For that we have outlined the long term strategy through 2020 and the near term planning processes we have put into place. We are looking forward to realizing these ideas through the productive cooperation with the HSO community and the MMS team in particular.

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