INNOVATIVE THEMIS EXTENDED MISSION DESIGN AND IMPLEMENTATION TO ACHIEVE CROSS-SCALE MAGNETOSPHERIC CONSTELLATION

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Abstract: *The Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission (5 identically-instrumented probes) was launched in February 2007 with the goal of unravelling the sequence of events during magnetospheric substorms. In 2010 two of these probes were transferred to lunar orbits, forming the Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission. The combined THEMIS/ARTEMIS mission is an important component of the Heliophysics System Observatory (HSO), which studies the interaction between the solar wind and the magnetosphere in a large-scale system-level approach. Substantial fuel reserves on the remaining three THEMIS probes allowed for redesigning and implementing new orbit strategies to align THEMIS with other HSO components to address new scientific objectives. In the past two years, THEMIS orbits have been modified to complement the Van Allen Probes in the study of the response of the inner magnetosphere, especially the radiation belts, to inner magnetospheric boundary conditions. In the near future, the Magnetospheric Multiscale (MMS) mission will join in, studying the microphysics of magnetic reconnection. We describe science drivers, mission design strategies, and implementation of THEMIS orbit changes to produce an optimal THEMIS-MMS tetrahedral alignment even under the constraints of an uncertain MMS launch date, minimum fuel consumption, and fulfillments of the end-of-mission requirement of a controlled de-orbit.*

Keywords: *Mission design, THEMIS, magnetospheric constellation, maneuver planning.*

1. Introduction

Time History of Events and Macroscale Interactions during Substorms (THEMIS), a NASA Medium Explorer (MIDEX) mission launched into Earth orbit in February 2007, began as a magnetospheric constellation of five spacecraft (probes P1, P2, P3, P4, and P5). Three of these probes (P3, P4, and P5) are still operating in Earth orbit as the extended THEMIS mission. In 2010 the other two probes (P1, P2) were transferred into lunar orbits, forming the new Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission.The combined THEMIS/ARTEMIS mission is an important component of the Heliophysics System Observatory (HSO), a global constellation of multiple international missions that studies the Earth's space environment and its dynamical interaction with the solar wind and the ionosphere. This interaction is comprised of various plasma processes at key regions spread across the vast expanse of the magnetosphere. Driven by three fundamental kinetic components, the plasma processes take place over three characteristic scales, 10 km (electron kinetics), 100-2000 km (ion kinetics), and 3000-15000 km(fluid dynamics) [http://www.nasa.gov/mission_pages/sunearth/missions/#.U1XDaFeGdow]. In order to put local processes inside the magnetosphere into a global context, the approaching solar wind and the plasma of the distant Earth magnetotail (30 to 100 Re) must also be monitored.

Simultaneous measurements of electric and magnetic field and plasma parameters are now being made by the three well-spaced THEMIS probes; the four CLUSTER satellites, a European magnetospheric mission [http://sci.esa.int/cluster/]; and the two Van Allen Probes, NASA/s mission to explore the Earth's radiation belts [http://www.nasa.gov/mission_pages/rbsp/main/#.U1XDzFeGdow]. The goal of these measurements is to develop empirical models of the geoelectric field and the radiation belts in particular. Simultaneous measurements of the solar wind by WIND, ACE, and ARTEMIS characterize the geomagnetic impact of solar activity on a global scale.

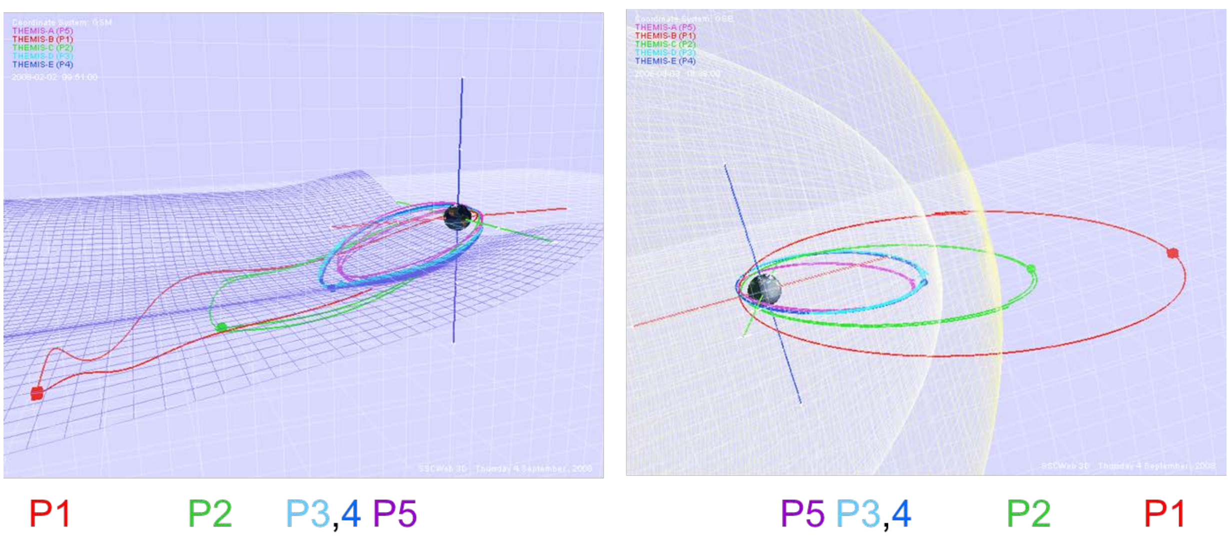

Figure 1: 3D visualization with TIPSOD [http://sscweb.gsfc.nasa.gov/tipsod/] of the five THEMIS probes during the nominal mission. (a) 02-02-2008 tail configuration with neutral sheet shown as the blue wire mesh and the GBOs near the Polar Regions in the north. (b) 08-03-2008 dayside configuration and the magnetosphere overlaid by the yellow wire mesh with its inner (MP) and outer (BS) boundary to the solar wind (SW).

The Magnetospheric Multiscale (MMS) NASA mission, which is expected to be launched in early 2015, will join in soon. The MMS mission is a Solar Terrestrial Probes mission comprising four identically-instrumented, closely-separated spacecraft that will use Earth's magnetosphere as a laboratory to study the microphysics of fundamental plasma processes [http://mms.gsfc.nasa.gov/]. Combining these spacecraft with the THEMIS probes in a tetrahedral formation at small to medium-scale separations will create an unprecedented constellation with which to conduct magnetospheric studies.

The THEMIS and ARTEMIS probes are equipped with onboard propulsion systems to perform orbital changes and maintain attitude as well as spin rate within the science requirements [1]. With THEMIS in its eighth year, fuel reserve and exciting science opportunities have become a greater challenge to the orbit design as re-entry at end-of-mission must be ensured. Future plans call for large orbit raises in the order of multiple Earth radii, and maneuvers must be planned carefully.

In this paper we report on our efforts to contribute to the Heliophysics System Observatory. We start with an overview of how the evolution of science goals from nominal into extended THEMIS missions drives orbit design. We next describe variations in the relative positioning of the three THEMIS probes to support measurements coordinated with those of the Van Allen Probes to study radiation belt physics. We also outline our long-term strategy to optimize the unique opportunity provided by cross-scale THEMIS-MMS conjunctions. The challenge here is to leave room for THEMIS orbit adjustments to support good quality lineups with the upcoming MMS mission. We then outline orbit and maneuver design strategies to address the ambitious science goals optimally and at very low cost. We conclude with a short summary.

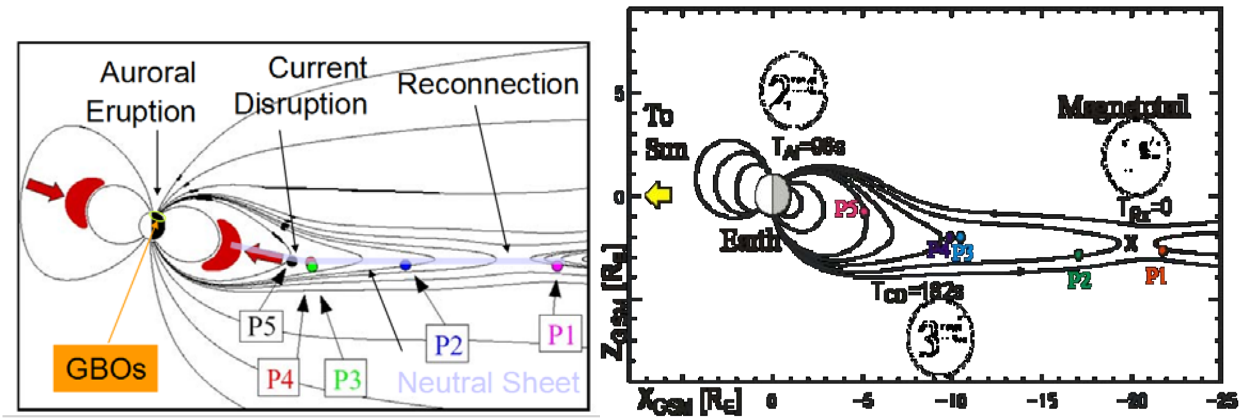

Figure 2: THEMIS probes at their proposed (left) macro scale configuration and during the 2nd tail season (right) at the moment of making simultaneous observations of plasma structures while in conjunction with the GBOs. The high time resolution of these conjunct measurements turned out to be crucial for the discovery of the actual timeline of substorm onset. Although considered the final event of substorm onset in the pre-THEMIS models, auroral breakup had to be revisited, as it was found to occur after reconnection in the tail and before current disruption in the equatorial magnetosphere.

2. Science Goals Drive Orbit Design

2.1 THEMIS Nominal Mission 2007-2009

THEMIS is a science mission dedicated to studying the Sun-Earth connection [2]. When the THEMIS mission was developed, geomagnetic substorms had been established as the magnetospheric mechanism for transferring energy and particles from the solar wind into the inner magnetosphere. In an attempt to put together the vast number of observations of the many substorm phenomena from the reconnection in the nightside magnetotail to current systems at the inner magnetosphere and auroral displays in the polar ionosphere, two substorm models emerged. Although both models agreed upon the three key regions involved in the substorm process, neither could fully explain the time sequence of substorm phenomena. The purpose of the THEMIS mission was to provide simultaneous multi-instrument measurements at those three regions to resolve fundamental questions about event timing.

The THEMIS baseline mission focused solely on the timeline of macroscale interactions during substorm onsets using an unprecedented coordination of a space asset of five identical satellites (probes) placed at nearly equatorial regions and an array of Ground Based Observatories (GBO) along the northern auroral oval over central Canada [3]. Each probe, one cubic meter in size, is equipped with field and particle instruments to characterize magnetic field topology, variations of plasma flows as well as electrical fields, and the structures of current systems over the required dynamical ranges at the necessary time resolution. Each GBO combines an all-sky imager and a magnetometer capable of resolving the timing of auroral brightening onsets.

A unique set of highly elliptical orbits aligned the probes at macro-scale separations along the Sun-Earth line in the nearly equatorial magnetotail. The apogees of three probes (the inner probes) were placed in the inner magnetosphere at 12 Re. Only two inner probes were required for baseline mission success; the third was initially kept as a spare. The remaining two probes (the outer probes) were placed to bracket the tail reconnection site between 20 and 30 Re. Orbital periods of multiples of sidereal day ensured prolonged conjunctions with the GBOs at apogee. Initial inclination and argument of perigee were selected to ensure prolonged conjunctions with the equatorial region of the magnetotail plasma (neutral sheet) [4].

Table 1. Orbit parameters for THEMIS probes during the nominal mission. Column dra is apogee, drp is perigee distance, dinc is inclination, and dV shows total DeltaV

S/C	Period	Apogee	dra	drp	dinc	dV	Fuel used	
	[d]	[Re]	[Re]	[km]	[deg]	[m/s]	[kg]	%
P1	4	30	25, 17	4600	3	712	34.4	70.5
P2	2	20	8, 5	930	14	552	27.8	57.0
P3	1	12	3.5	3300	4	419	21.5	44.0
P4	1	12	3.3	3300	4	406	21.2	43.6
P5	4/5,8/9,1,8/7	10,11,12,13	6.6	2200	1	514	26.3	53.9

In the Sun-referenced frame, the orbits rotate around once per year. Apogees cross the Sun-Earth line twice per year, once in the magnetotail at midnight and once in the solar wind at noon, as shown in Fig. 1. These crossings divide each year into two 120-day observational seasons, the tail and the dayside seasons centered at the apogee crossings of the Sun-Earth line, and two transitional phases crossing dusk and dawn when the orbits move from tail to dayside and back. Regardless of launch date, THEMIS mission design called for tail crossings to be during northern winter when the probability of observing substorms is higher and the conjunctions with the GBO take advantage of the longer operational hours of the all–sky imagers because of long winter nights.

Although the primary science observations in the magnetotail were the drivers of orbit design, THEMIS orbits cover a wide radial range through the radiation belts when going through dusk and dawn. On the dayside, the probes are again separated at macro scales across the inner (magnetopause) and outer (bow shock) boundaries of the magnetosphere with the solar wind. These separations allowed THEMIS to dedicate secondary and tertiary science goals to additional magnetospheric phenomena and to return valuable data from new vantage points year round.

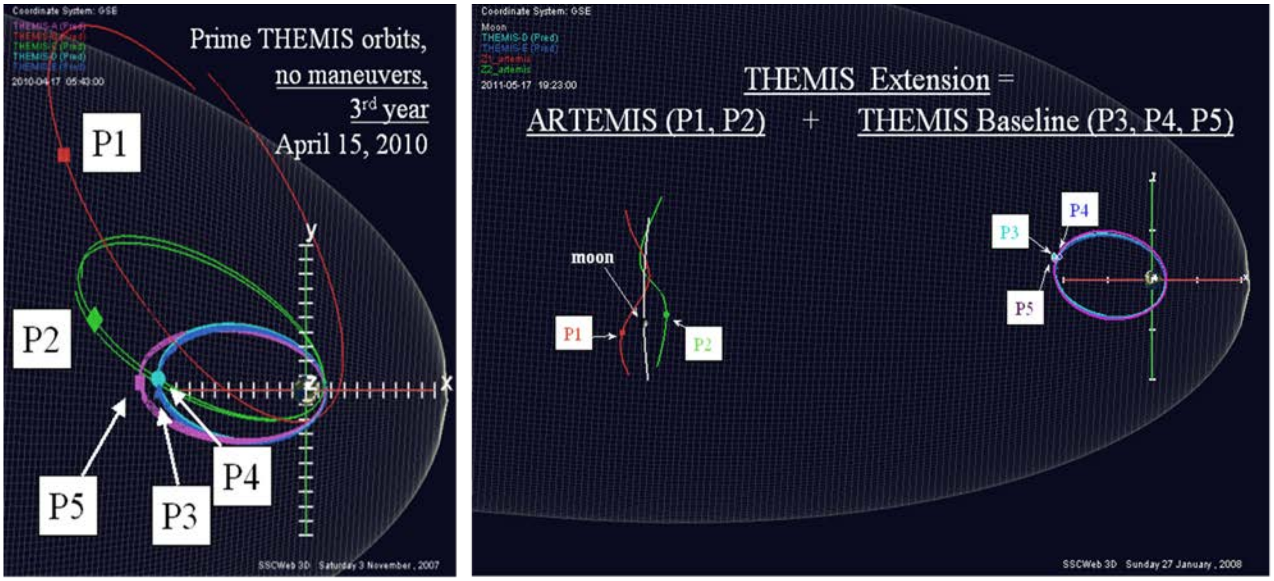

Figure 3: Division of the THEMIS mission into the extended THEMIS and ARTEMIS missions in 2010. Left panel shows the primary orbits approaching dusk with P1 crossing the MP twice. It illustrates the critical range of radial distances provided to characterize generation of high energetic particles (secondary science). Right panel shows the ARTEMIS (P1, P2) and the extended THEMIS mission (P3, P4, P5) after the two year journey of P1, P2 through libration orbits. Shown here is a 2 day arc of the Moon's orbit with two P1, P2 orbits illustrating the range of separations while crossing the center tail. Once per lunar cycle the ARTEMIS probes pass through the center tail, providing observations of the distant tail needed to unfold the energy release mechanism during substorm events. When on the opposite side of Earth, the ARTEMIS probes measure the incoming solar wind, thus providing global input.

Obviously, such a mission must be able to move its space assets via onboard propulsion. Each THEMIS probe has a monopropellant hydrazine propulsion system with two axial and two tangential thrusters that allow continuous or pulsed thrusting. The fuel budget had to accommodate probe placement into science orbits, setting up macro-scale separations near the equatorial plasma (neutral sheet) in the tail, maintenance of those conjunctions, end-of-mission maneuver to ensure re-entry, deployment of booms holding the field instruments, shadow avoidance maneuvers, and attitude and spin rate maintenance. The probes were launched together and released into a parking orbit almost simultaneously. Regardless of the magnitude of maneuvers needed to position the probes in their science orbits, all probes had the same fuel loads. One probe was designated as spare until all four l probes critical to minimum mission objectives were in place and functioning. Since all probes were identical, post-launch selection of the outermost probes based on in-flight performance, especially that of the communications system, was possible. The probes' fuel budgets for placement into science orbits and constellation maintenance differed according to their positions within the macro-scale constellation. The inner probes' apogees had to descend by about 2 Re, whereas the outer probe apogees had to rise by several Earth's radii. The outer probes had to be realigned with the inner probes frequently to account for differential precession due to the very different apogee heights.

Figure 9 illustrates the ratios of DeltaV utilized for placement to constellation maintenance. An overview of the final science orbits, the accumulated changes of perigee and apogee altitudes from release through the nominal mission, the DeltaV, and the expended fuel is given in Tab. 1. More orbit design and maneuver strategy details are provided in [4].

With at least 24 unprecedented THEMIS tail conjunctions such as those shown in Fig. 2 and more than 100 substorms studied, THEMIS observations enabled determination of the trigger mechanism of substorms and established the revised sequence of events leading to substorms. This not only provided closure on the mission's prime science objectives by the end of the nominal mission but also revealed the complexity of the mid-tail (<20 Re)-inner magnetosphere interaction [5]. This discovery underlines the importance of neutral sheet observations (requiring low-inclination orbits) to our understanding of Sun-Earth coupling and energy transfer.

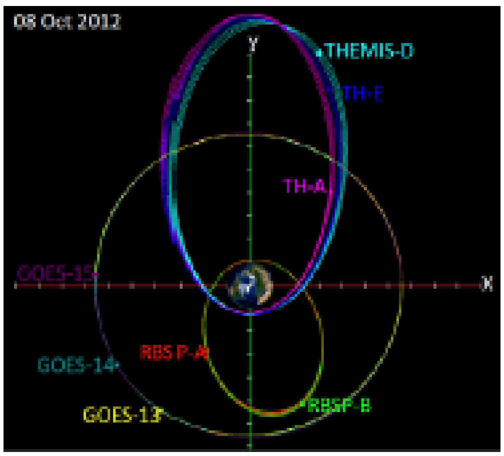

Figure 4: Snapshot of positions of the THEMIS, Van Allen Probes, and GOES missions at the time of a powerful magnetic storm on Oct. 10th, 2012. The three missions are ideally spread across the inner magnetosphere with the THEMIS probes at dusk on the dayside, the Van Allen probes crossing the radiation belts at the dayside as well as nightside and both GOES satellites are at 6 Re on the nightside.

2.2. THEMIS Extended Mission 2010-2014

After the nominal mission with all probes and ground systems working well and holding remarkable fuel reserves, THEMIS was ready to reposition the inner probes into orbits optimized for routine observations needed to track the flow of energy from the mid-tail reconnection site to the inner equatorial magnetosphere. For the outermost probes, the need to avoid shadows far exceeding the design limit was turned into an opportunity for two-point observations with comprehensive instrumentation in the distant magnetotail and the solar wind at separations between hundreds of kilometers and tens of Earth's radii, shown in Fig. 3. In the ARTEMIS mission, both probes were sent into stable lunar orbits on a novel journey of its own [http://www.nasa.gov/mission_pages/artemis/#.U1XEy1eGdow]. The plan for the extended mission takes full advantage of the low inclination of the inner probes and incorporates synchronized observations from other missions (GOES, Van Allen probes) positioned at complementary key regions closer to Earth, as shown in Fig. 4.

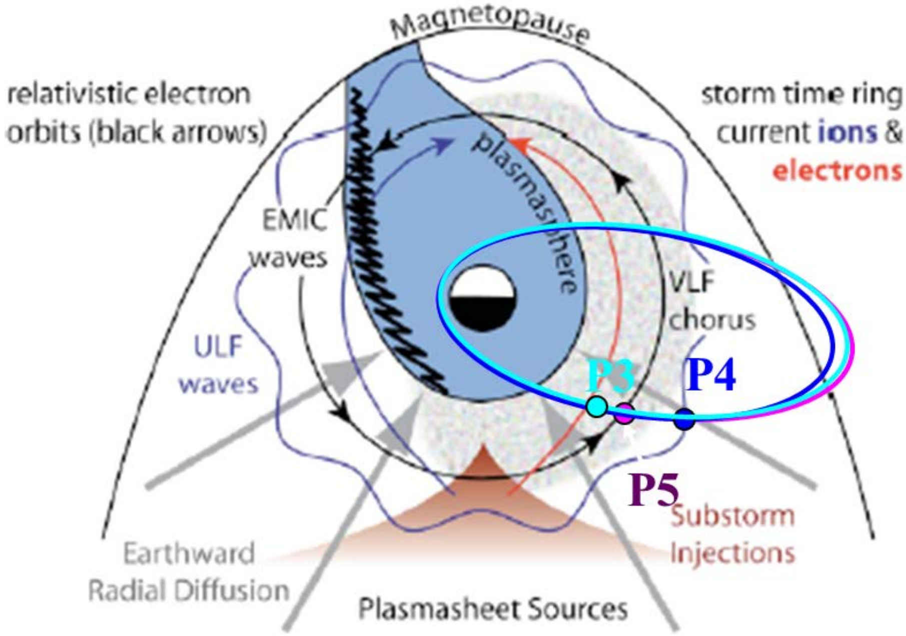

Figure 5: View of the equatorial magnetosphere bound by the magneto pause and with main wave-particle interaction and particle transport phenomena at approximate scales. Overlain are THEMIS orbits of the first stage of the extended mission. The snapshot at dawn shows how the string-of-pearls configuration has the separations that straddle different wave structures. The clustered configuration is near or inside the plasma sheet in the mid-tail and skimming the MP on the dayside (orbits not shown).

Key kinetic processes in the inner magnetosphere (7 to 12 Re) are explored in two stages of probe separations. The first two years were dedicated to smaller scales decreasing from 6000 to 100 km in a novel clustered configuration in the tail and on the dayside, and as a string-of-pearls configuration when traversing dawn and dusk, as shown in Fig. 5. In the clustered configuration, two probes were vertically and two probes radially separated; thus they lay in the meridional plane in the sun-referenced frame as shown in Fig. 6. In the tail, radial separations of 500 km and vertical separations of 1000-5000 km were set to optimally study the nature and evolution of magnetic field topology and current structures. On the dayside, those separations are needed to determine the efficiency and extent of magnetopause reconnection, the process that controls transfer of solar wind energy into the magnetosphere. With these observations THEMIS advanced from the macro-scale characterization of modulation of the solar wind approaching the bow shock during the nominal mission. In dawn and dusk the probe separations varied from hundreds to thousands of kilometers in order to determine the role of electromagnetic waves and electric fields in radiation belts and inner equatorial current systems (Fig. 5). By zooming in on the wave structures, we can further test the local acceleration hypothesis established in the nominal mission.

The second two years were dedicated to understanding the response of the inner magnetosphere to its boundary conditions using large along-track separations of 4-8-12 h one year and 8-8-8 h (current) the other year. Of particular interest are processes involving radiation belt particles. Although these observations were planned to greatly complement observations by the Van Allen probes, the separations also provide unique measurements in the tail and on the dayside. In the tail THEMIS was spread across the azimuthal substorm expansion at 7-10 Re where the dipole-like magnetic field is transformed into a stretched tail field.

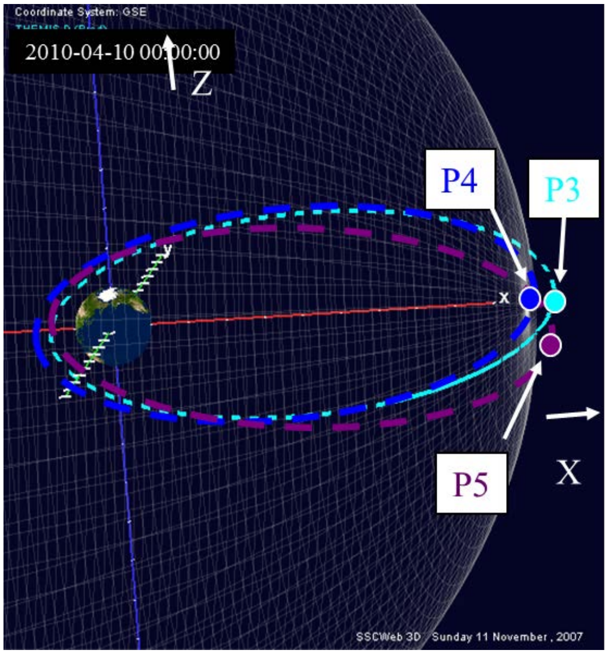

Figure 6: THEMIS clustered meridional configuration during the first stage of the extended mission in the sun-referenced frame shown at the dayside. Orbits in the tail are similar. Over two years the radial separations increase from 500 to 5000km.

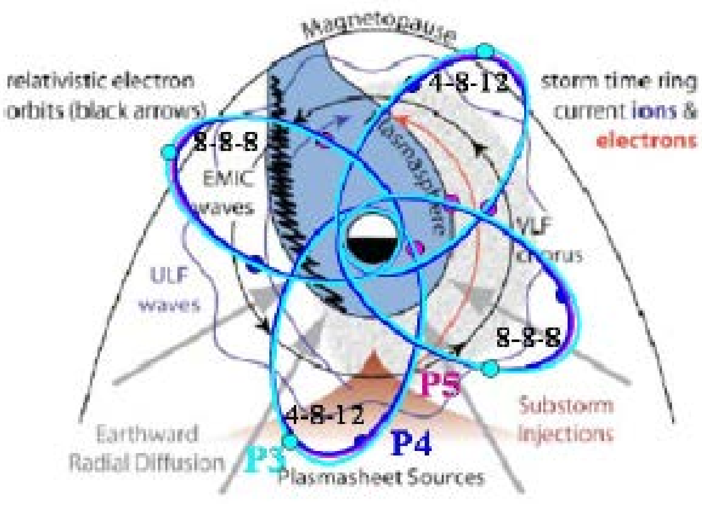

Figure 7: Same view as in Fig. 5 onto the equatorial magnetosphere illustrating how the THEMIS probes cover various local times simultaneously during the second stage of the extended mission with along-track separations that are complementary those in the first stage. The orbits crossing the magneto pause on the dayside and those passing through the

center tail have along-track separations of 4-8-12 h. Those orbits shown at dawn and dusk have equal separations of 8-8-8 h.

Early key THEMIS results on the dayside included the discovery of new phenomena predicted by simulations to have global consequences through local particle acceleration. THEMIS nightside results confirmed that quiet auroral arcs can be mapped to the interface between dipole and tail-like magnetic field in the equatorial magnetosphere and suggested that this link continues during substorm events when the dipole expands. THEMIS observations have also provided evidence that major energy release comes significantly after substorm onset. These results emphasize that further understanding of substorm events is to be found in the equatorial tail regions beyond 10 Re.

2.3. Future THEMIS Extended Mission 2015-2018

Ever since in orbit THEMIS has led or greatly contributed to observations of many substorm events by multiple space missions, such as Cluster, GOES, and Geotail. Such joint case studies, however, rely on fortuitous constellations and can only provide episodic insight into Sun-Earth interactions. Through its cooperation with the Van Allen probes, THEMIS goes beyond such constellations by providing continuous complementary observations. Because of THEMIS's large-scale separations, at least one probe is always at a key position within the inner magnetosphere.

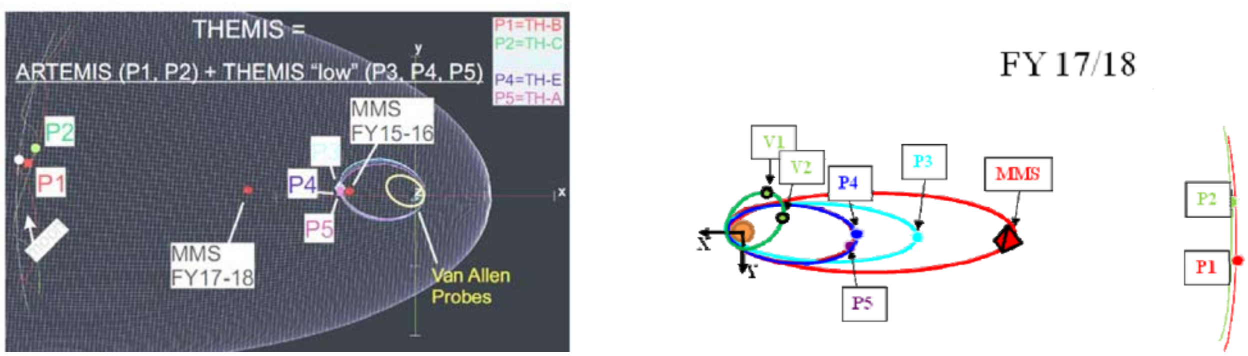

Figure 8: Snapshots of two tail-season configurations with THEMIS, MMS, and Van Allen probes inside the equatorial magnetosphere. The ARTEMIS probes P1 and P2 are shown crossing the center tail at lunar distance. Left panel shows MMS crossing the tail at two distances (~12 and 25 Re) during its phase one. THEMIS is shown with the inner probes (THEMIS low) P3, P4, and P5 at 12 Re. Right panel shows the proposed configuration during the second phase at the larger orbits of MMS at 25 Re and THEMIS P3 at ~16 Re.

Now in its eighth year, THEMIS is stepping further toward a system-wide approach by proposing to coordinate its orbits with those of MMS spacecraft. For the years 2015 through 2018, THEMIS plans to reconfigure its orbits [6] to align its line of apsides with that of MMS (see Tab. 2). In phase one of MMS, both missions will form a tetrahedron around magnetic reconnection regions on the dayside and in the mid-tail at 12 Re. In phase two, MMS will increase its apogees in order to capture reconnection in the tail at 25 Re. THEMIS will position itself in resonant orbits at tail distances between 12 to 16 Re, again forming a medium-scale three-probe configuration. At the same time the ARTEMIS probes will monitor the solar wind or observe plasma structures in the distant tail once a month as the Van Allen Probes and GOES monitor the inner magnetosphere. As shown in Fig. 8, THEMIS will link reconnection observations by MMS to inner magnetosphere observations by the Van Allen Probes. With tail seasons in northern winter, the THEMIS GBOs will again provide continuous coverage of the North American portion of the auroral oval. This configuration, which is optimal for tracking energy and particle flows through the magnetosphere, will provide an unprecedented synergy of multiple missions to study the micro and macro physics of the Sun-Earth interactions.

Our early planning of the extended THEMIS mission included the possibility of aligning THEMIS orbits with the future MMS mission. The probe with the highest fuel reserves (P3) was chosen to increase its apogee to about 16 Re during phase two of MMS. Its orbit redesign followed the highest constraint in fuel consumption. We then developed orbit plans to adjust the drift rate of the THEMIS lines of apsides so THEMIS probes would meet and stay synchronized with MMS spacecraft in phase two. We also explored the feasibility of raising the other probes' apogees in phase two in order to maximize coverage in the under-sampled region beyond 12 Re, as shown in Fig. 8, right panel. The final step was to implement maneuvers needed to set proper drift rates. An MMS launch in late summer or fall of 2014 would require an increase in THEMIS orbit drift rates, which could be done most effectively by reducing perigee altitudes. Once aligned with MMS, the apogee raises planned for phase two of MMS will decrease the drift rate. Reducing the drift rates is more effective with higher perigee. Long drift times are preferred because they require less perigee reduction. Short drift times, however, are better suited to launch-day uncertainty. In order to balance optimal perigee altitude, minimal fuel consumption, and MMS launch date uncertainty, increasing the drift rate was done in two steps.

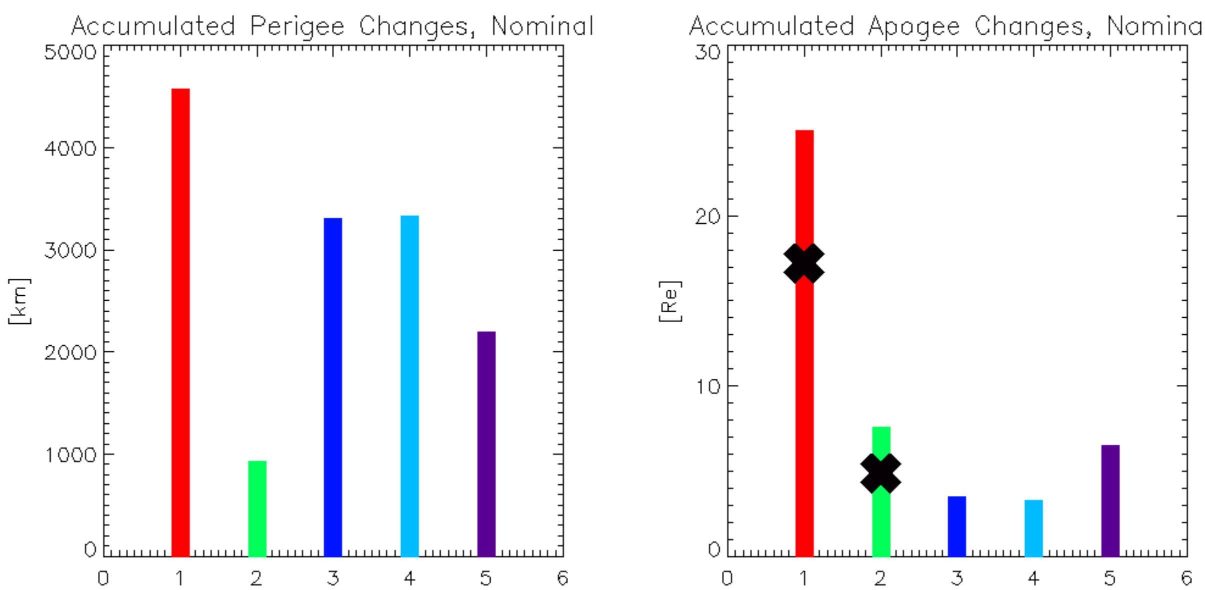

Figure 9: Accumulated changes of perigee (left) and apogee (right) altitudes applied during nominal mission for P1 (red), P2 (green), P3 (blue), P4 (cyan), and P5 (purple). The upper portions for P1and P2 are DeltaV used for constellation maintenance.

The perigee targets are bound by the re-entry commitment. Within two years of the nominal MMS launch day, we reduced perigee altitudes to meet our baseline goal, the optimal alignment in phase two. Within one year of the nominal MMS launch date, we fine-tuned the THEMIS orbit drift rate to optimize THEMIS-MMS alignment in both phases by further reducing perigee as well as apogee altitudes.

Table 2: THEMIS and MMS season timelines for an MMS launch in late 2014. T and d refer to the tail and dayside seasons; the numbers are counted each season starting with the nominal missions. In season D5, THEMIS began to increase the precession of the line of apsides. MMS mission phase 1 comprises the first three seasons D1, T1, D2, and phase 2 starts with season T2. Because MMS launch has been rescheduled to spring 2015, the actual timeline is shifting by 6 to 12 months as new options to reconfigure the THEMIS orbits are being coordinated with the MMS team.

THEMIS				MMS	
Season	3 Months	Orbit Change	RA , Period		
THM D5	11-01, 2012	P3,P4:drp=-2500 km P3,P4:dra=-1150 km P5: drp=-1000 km dra= 2000 km	11.9 Re, 22.8 h		
THM T6	07-09, 2013	drp=-100 km dra=-1400 km	11.7 Re, 22.2 h		
THM D6	02-04, 2014	phasing	11.7 Re, 22.2 h		
THM T7	09-11, 2014	phasing	11.7 Re, 22.2 h	MMS LD	
THM D7	04-06, 2015	phasing	11.7 Re, 22.2 h	MMS D1	
THM T8	11-01, 2015/16	dra≤0.5 Re	12.1 Re, 24 h	MMS T1	12 Re 24 h
THM D8	06-08, 2016		12.1 Re, 24 h	MMS D2	
THM T9	01-03, 2017	dra≥ 3 Re dra≈1.5Re (p5)	15.5Re, 33h 13.9Re, 29h	MMS T2	25 Re 67 h
THM D9	05-07, 2017	phasing	15.5Re, 33h 13.9Re, 29h	MMS D3	

In 2016 and 2017 the THEMIS orbits will again cross the magnetotail during the northern hemisphere winter while again in conjunction with the GBOs in the North American polar region as during the nominal mission. Higher apogee distances will be chosen to cover the transition region between dipole and tail-like field topology and to focus on the massive energy releases that take place here in later phases of substorm events. The optimal plan includes all three probes at higher apogees, as shown in the right panel of Fig. 8. Probes P3 and P4 will have sufficient fuel reserves to account for contingencies related to launch delays in 2014. For P5, the probe with the least remaining fuel, the contingency plan is to mitigate fuel concerns with lower apogee altitudes.

Meanwhile, MMS launch has now been moved to spring 2015, significantly changing the timeline and targets for the alignment with THEMIS probes. Under the new conditions, quality alignments require the reversal of the relative motion between both missions and that both teams work very closely together to ensure optimal alignment. While various options are being explored, it is clear that this new reconfiguration of THEMIS orbits leave insufficient fuel reserves on P4 and P5 to adjust for further MMS launch delays. In order to stay independent of further launch days, the orbit changes with the goal to align both probes will take place after MMS has been launched. THEMIS demonstrated this flexibility prior to its own launch in 2007 by accommodating launch on any day of the year with a fixed tail season center epoch. THEMIS launch resulted in a one-year delay of the first tail season; the extra onboard time during the so-called coast phase was used to collect dayside science from a unique orbit at an apogee of 14 Re [2].

3. THEMIS Extended Mission Implementation

Significant fuel reserves after the nominal mission allowed for ambitious plans to expand the mission with only two constraints: first, timely re-entry after the end of mission must be ensured, and second, minimal deferential precession between the three probes must be maintained. The extended mission for the three inner probes demanded several orbit reconfigurations. The number of inner probe orbit changes for the extended phase exceeds the number from the nominal mission. As shown in Fig. 9, the DeltaVs utilized until March 2014 vary among the probes. According to its long-term dedication to raise apogee to 16 Re during MMS phase two, P3 has spent the least amount of fuel. P4 and P5 have undergone the larger repositioning needed to move from the large-scale azimuthal triangular configuration of the nominal mission to the smaller-scaled meridional configuration during stage 1 and into large along-track separations during stage 2 of the extended mission. The transitions have been choreographed such that if necessary the P3 perigee could only be reduced. Any small adjustments must be done by apogee changes. The perigee altitudes of P4 and P5 were dictated by maintenance of differential precession. Perigee altitude raises and are used to equalize differential precession with time. Once the goal to align with MMS became realistic we started to increase the precession of our orbits and used those maneuvers to establish the along track separations at the same time. The alignment with MMS required a reduction of perigee altitude. As this is in support of the re-entry constraint we started early. In order to further increase our precession rate we did not reset the orbit period. Maintaining sidereal day period was not require by the current science goals and releasing this orbit parameter allowed us to save fuel. As outlined above, in the coming years

THEMIS proposes to raise apogee altitudes to explore the mid-tail range between 12 and 16 Re. These changes are planned to be coordinated with the MMS mission (see Tab. 2). Figure 11, which is similar to Fig. 9, shows the changes of perigee and apogee altitude during the extended mission until March 2014 and also indicates the proportions dedicated to increase the precession of the THEMIS lines of apsides.

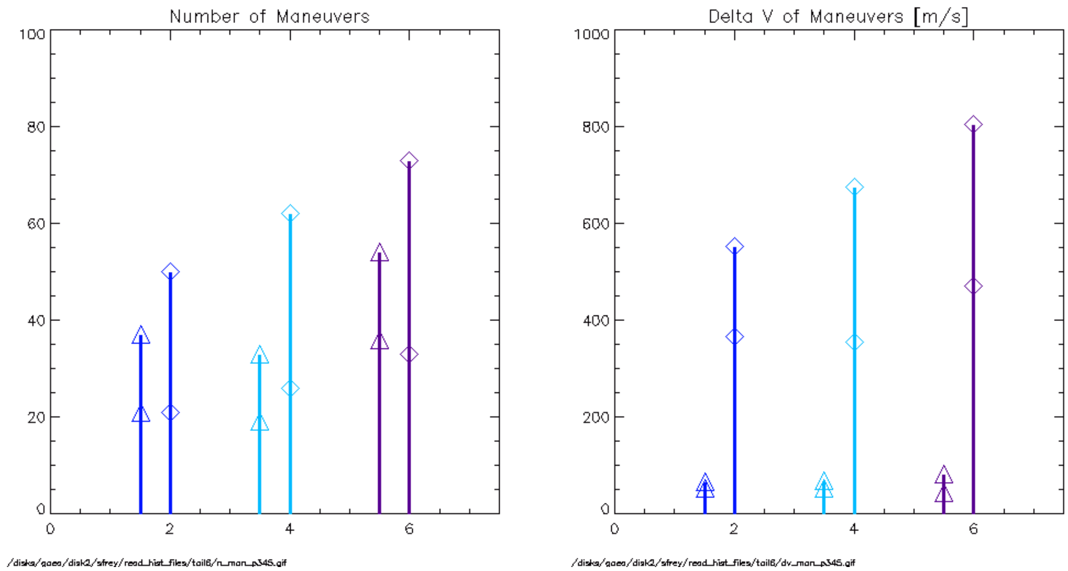

Figure 10: Numbers of maneuvers (left) and DeltaV (right) during nominal and extended mission until March 2014 for inner probes P3 (blue), P4 (cyan), P5 (purple) distinguishing ACS (triangles) and orbit change (diamonds) maneuvers.

The implementation of the extended mission is based on lessons learned during the nominal mission. Primary science is again the driver, with implications for not only orbit design but also constraints on science-specific parameters such as orbital parameters. Finite fuel reserves are addressed by prioritizing the probes within the constellation. Maneuver strategies are driven by long-term goals. Smaller reconfigurations into intermediate constellations are designed to work towards long-term goals. Exceptions are only permitted if they are necessary to achieve targeted science goals. We constrain large reconfigurations through orbit changes that work toward the re-entry goal. Fuel for maintenance of differential precession is kept to a minimum. Although the orbits must be reconfigured essentially in real time, we coordinate maneuver times among the probes so that conjunctions with the neutral sheet [7], over the GBOs, or the along track separations are achieved with the lowest DeltaV according to (Eq 1).

$$\Delta \text{Parameter} = \sum_i dparameter_i * dt_i \qquad (1)$$

As seen in Fig. 10, a substantial number of attitude and spin-rate control maneuvers require small yet substantial fuel consumption. Attitude controls on THEMIS, necessary once or twice per year to maintain a science specific attitude, impart small changes to the orbit. We account for those changes by combining attitude control maneuvers with an orbit change maneuver and adjust the finite maneuver target by (Eq 2).

Impulsive target = finite target + attitude_control_change (2)

When possible we place the attitude control maneuver so its change contributes to the orbit change. Spin-rate control maneuvers are small enough that we can neglect the orbit change they may impart.

All THEMIS and ARTEMIS maneuvers have been prepared and executed by the mission operations center at the UC Berkeley. Flawless maneuvers are a significant source of onboard fuel [8].

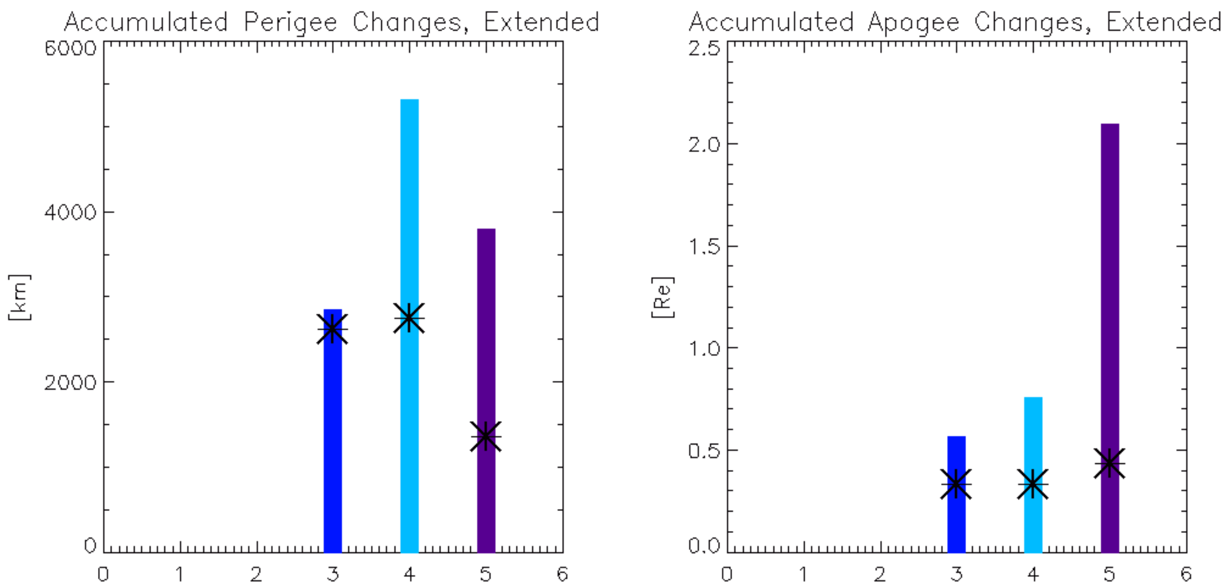

Figure 11: Accumulated changes of perigee (left) and apogee (right) altitudes applied during extended mission until March 2014 for inner probes P3 (blue), P4 (cyan), and P5 (purple). The lower portion changes are used to increase the precession of lines of apsides.

4. Summary

THEMIS has been using its capability to actively change its orbits to steadily enhance the science return [9]. Mission goals and orbit design have been adjusted to scientific lessons learned. Probe separations and focus areas have been chosen to address new questions or to rephrase old ones. THEMIS began by focusing on the timeline of substorm onset with a macro-scale equatorial constellation and is moving on to study subsequent substorm phases of expansion and recovery. Its remaining fuel reserves are being used to address new discoveries with an updated mission design. The THEMIS extended mission alternates between micro-system and system-wide studies with probe configurations tailored towards the refined science goals inside the magnetosphere, and ARTEMIS provides global context. The science return is further enhanced by coordinating THEMIS probe separations with the Van Allen Probes. The proposed THEMIS-MMS coordination will be the first cross-scale multi mission with optimal instrumentation.

HSO provides fortuitous conjunctions across multiple scales. Dedicated multi-scale missions can provide prolonged simultaneous observations needed to move from case studies to elucidation of the roles of several processes within the Sun-Earth system. THEMIS has been and will be a pathfinder for future multi-missions, not least through its innovative mission design. In addition, THEMIS has shared and is now jointly creating data analysis tools across missions.

7. Acknowledgments

The THEMIS and ARTEMIS missions are operated by the University of California, Berkeley Space Sciences Laboratory under NASA contract NAS5-02099.

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