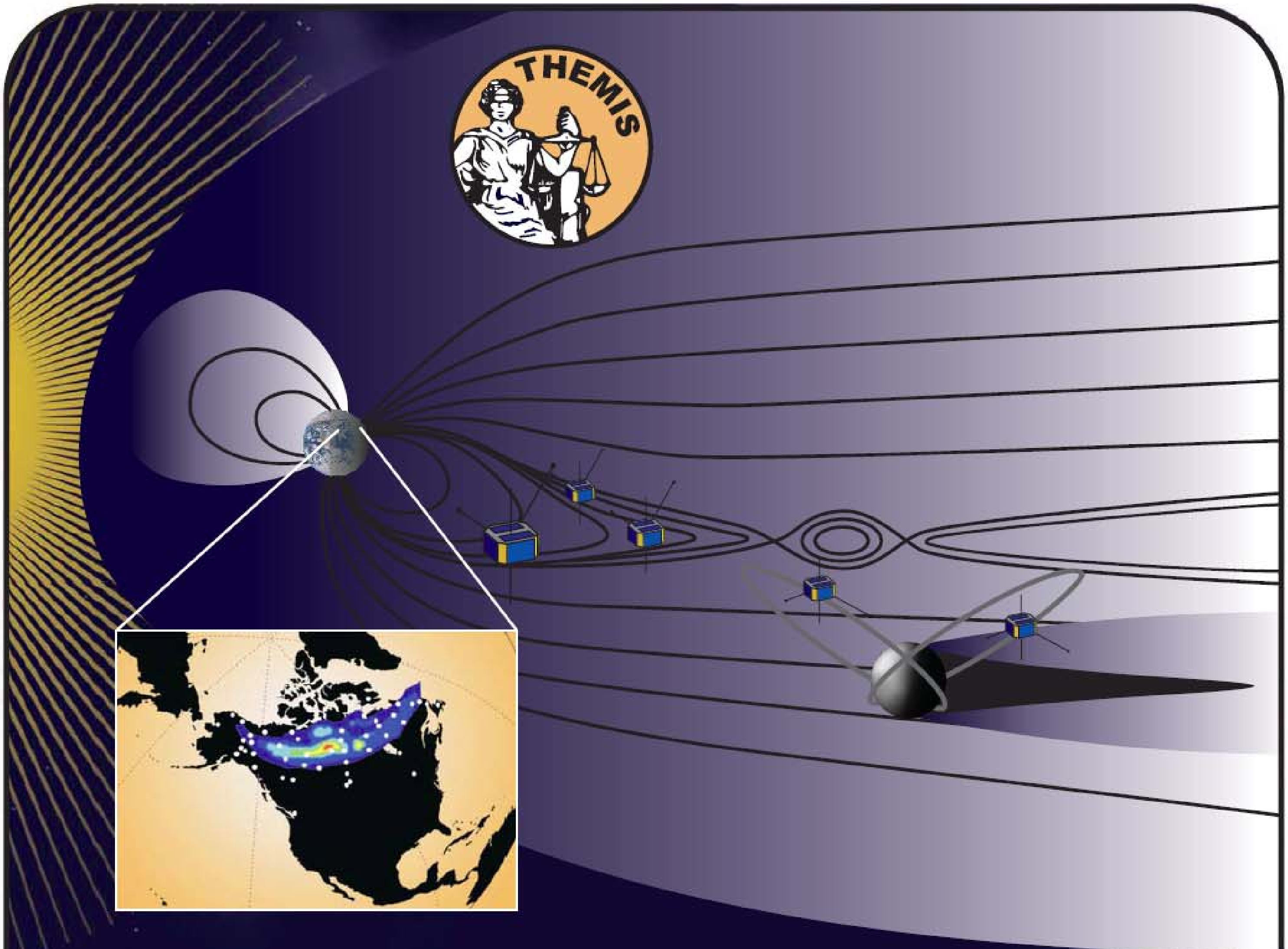

TIME HISTORY OF EVENTS AND MACROSCALE INTERACTIONS DURING SUBSTORMS: THEMIS

PROPOSAL SUBMITTED FOR:
SENIOR REVIEW 2015 OF THE MISSION OPERATIONS AND DATA ANALYSIS PROGRAM
FOR THE
HELIOPHYSICS OPERATING MISSIONS
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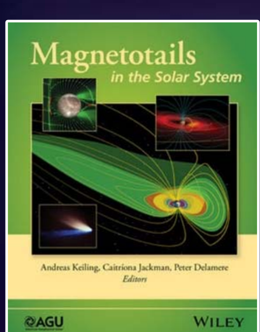
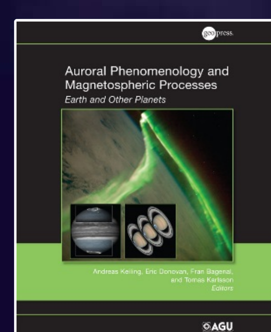
V. Angelopoulos
THEMIS Principal Investigator
University of California

D. G. Sibeck
THEMIS Project Scientist
NASA/GSFC





THEMIS

2015 SENIOR REVIEW PROPOSAL

Submitted: March 6, 2015

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1. Executive Summary

THEMIS, an efficiently developed and implemented five satellite constellation mission, was launched on February 17, 2007 as NASA's 5th MIDEX under $200M, a small fraction of the cost of missions with equivalent scope. After successfully completing its prime mission in 2010, THEMIS proposed and implemented a split into three Earth-orbiting (THEMIS "low") and two lunar orbiting (ARTEMIS) spacecraft groups to optimize its scientific return (Fig. 1A). Both missions have achieved many firsts, reshaping space science, answering longstanding questions regarding the origin of discrete and pulsating aurora, electromagnetic energy conversion in the magnetosphere, magnetic reconnection, upstream transients, the elusive origin of plasmaspheric hiss, the propagation and effects of morning chorus, the lunar wake and exosphere and many others. Science productivity is at an all-time high, with >150 refereed publications in 2014 alone (see http://themis.ssl.berkeley.edu/publications.shtml), and continues to rise thanks to: (i) the missions' unique, critical, and comprehensive multi-point dataset (ii) a pro-active strategy to develop and distribute high-quality, high-resolution data products; (iii) the development, maintenance, and free dissemination of all-purpose analysis tools that enable optimal cross-mission Heliophysics System Observatory (HSO) data analysis; and (iv) strong THEMIS software and science team support for the research community. While 33% of the aforementioned papers were led by THEMIS team members and their partially-funded affiliates, the remaining 67% were led by non-THEMIS community members, demonstrating heavy data use by the community at large. Moreover, 64% of all papers include THEMIS coIs or affiliates, showing the important in-kind support of the community by the THEMIS funded team. Finally, the analysis tools being developed by THEMIS can ingest data from dozens of other space and ground assets. "Plug-ins" for instruments on the Van Allen Probes and GOES spacecraft, >100 ground-based observatories, all SuperDarn sites, and the entire ERG mission exist, and plug-ins for MMS are under development. They represent a grass-roots science-community software developers' platform (herein referred to as: "SPace Environment Data System" or SPEDAS), that promises to become a space physics standard (like "solarsoft" for Solar Physics) and thus further optimize return from Heliophysics assets.

Today, THEMIS "low" and ARTEMIS (henceforth referred to jointly herein by their original name, THEMIS) boast a flawless operation, unscathed by space radiation and with all instruments effectively as good as new. With comprehensive, well-calibrated and -characterized space instrument suites in mint condition located at key equatorial vantage points at ~60R_E and inside ~15R_E, THEMIS herein proposes to use its significant remaining fuel resources and reconfigure, yet again, its orbits to: (i) perform unique cutting edge science that will revolutionize the field in its own right while simultaneously (ii) aligning itself optimally with current and upcoming Heliophysics missions to usher in an era of unprecedented Heliophysics system science return per dollar.

The first incarnation of this plan for utilizing the THEMIS available fuel resources towards an HSO optimization was proposed in 2013 (SR13 PSG#1) and was highly ranked and approved. The idea is to ensure that optimal HSO science can be obtained from the coordination of two high-altitude missions: THEMIS and MMS by forming a network of scales (from electron, to ion/MHD to large scale, to global) and provide the main context for all HSO assets (space and ground) to tie into. The 2013 version of this plan, consistent with an October 2014 MMS launch, called for THEMIS's ion/MHD scale exploration to be co-located with MMS's electron scale exploration and was focused on kinetic physics across electron, ion and MHD scales. The MMS launch delay, however, from September 2014 to March 2015 rendered the original plan increasingly less workable (primarily due to a communications breakdown within NASA, affecting the ability of the MMS launch vehicle team to respond, in due time, with orbit analysis results). Additionally, new science results emerging in 2013 and early 2014 suggested that localized, reconnection-driven dayside activations couple efficiently across the magnetosphere readily affecting global circulation. The THEMIS team seized the opportunity to make "lemonade out of lemons" by redirecting its observation strategy to observe reconnection on kinetic scales and its interaction with the surrounding medium simultaneously at multiple locations (day *and* night) while maintaining the essential spirit of the MMS-THEMIS coordination as the basis for an optimized HSO network. This improved strategy engages the ground-based community whose remote sensing and imaging provide a global perspective in what promises to be the most comprehensive cross-scale coupling campaign in the history of space science. The proposed plan is akin to the multi-billion dollar "International Solar-Terrestrial Program" (ISTP) of the 80's and 90's. However it is far more rewarding given the multi-point, high-time resolution measurements obtained on kinetic scales by THEMIS (ion/MHD/regional scales) and by MMS (electron/ion); the presence of significant space-based (VAP, ERG, GOES, POES…) and ground-based (AMISR, PFISR, StormDARN, red-line imagers,...) assets; and the ability of the THEMIS mission to utilize its fuel and optimize the conjunctions between all HSO assets. By informing the HSO community of the optimal operation times for "HSO campaigns", and by continuing to facilitate data and information exchange through SPEDAS, THEMIS plans to lead the field in this exciting new period.

Specifically, in light of new, exciting results that show that regional dayside and magnetotail activations have global consequences, and in particular that polar cap flows (evidenced by red-line day-glow patches or next to polar cap arcs) provide a link between small scale dayside and nightside reconnection bursts, THEMIS seeks to understand the global connections between kinetic phenomena. To do so requires that THEMIS be at the neutral sheet or plasma sheet boundary near apogee and in view of the GBOs while MMS observes the dayside reconnection phenomena that result in polar cap flow enhancements. **As its "Optimal HSO" Prioritized Science Goal (PSG#1), THEMIS will:**

(i) Change the orbit period and phase (mean-anomaly) of P3-P5 (Figure 1A) to match that of MMS in FY16/17 in order to be near apogee in the magnetotail, near the neutral sheet and in view of the ground based observatories (GBOs and North American observing assets) when MMS is near apogee crossing the magnetopause. While THEMIS measures the ion inertial to MHD scale-lengths of reconnection jets and fronts with P3-P4, MMS will study the electron scale physics of dayside reconnection. Although it is anticipated that ground based viewing conditions will be ideal for those intervals and the data will be routinely available, the optimal conjunction times will be communicated to the ground based community in advance for planning campaign modes with radars and red-line imagers. From opposition, the two missions will be able to study the global link of dayside reconnection impulses, nightside reconnection, dipolarization fronts, and the origin and effects of particle injections in the inner magnetosphere. ARTEMIS will provide pristine, high-fidelity solar wind data on the dayside or magnetotail flux content and reconnection locations on the nightside. When MMS increases its apogee to 23R_E in FY17 up to FY18, THEMIS will also increase the apogees of P3-P5 to 13.2R_E and enter into a resonant orbit strategy with MMS, preserving the frequent alignment of the two missions along the magnetotail axis. In FY17 MMS will be on the nightside and THEMIS on the dayside. In FY18-FY20 THEMIS will raise its apogee to explore comprehensively (for the first time in its history) the intermediate altitude region from 13-16 R_E that recent findings show plays a critically important role in magnetospheric energy dissipation. The scientific justification for the orbit raise strategy is the same as in PSG#3. Under PSG#1 the resonant orbit strategy with MMS and the HSO-optimized yield of kinetic scale conjunctions with MMS across global and regional scales will also occur, with the added synoptic views afforded from other HSO missions and from its own and other ground based assets.

(ii) Increase the duration and cadence of its Fast Survey (FS) captures. Note that increased duration FS captures were proposed in Senior Review 2013 (SR13). Although not funded, they are implemented at no extra cost and on a best-effort basis (goal: 20hrs/day), using the 18m diameter White Sands WS1 antenna. This strategy will continue. Recent observations of nightside dipolarization fronts and dayside in-vivo flux-transfer events suggest that it is also important to capture reconnection and turbulence at electron temporal scales not by means of on-board triggers but through using continuous waveform captures over timescales of 10s of minutes. This is important to avoid the selection bias from apriori trigger quantities and settings, as well as to bridge MMS's cadence in waves, even if not in particles. We thus seek to improve the duration of high resolution waveform captures by THEMIS to continuous 8k samples/s using DSN. Test runs of the so called:

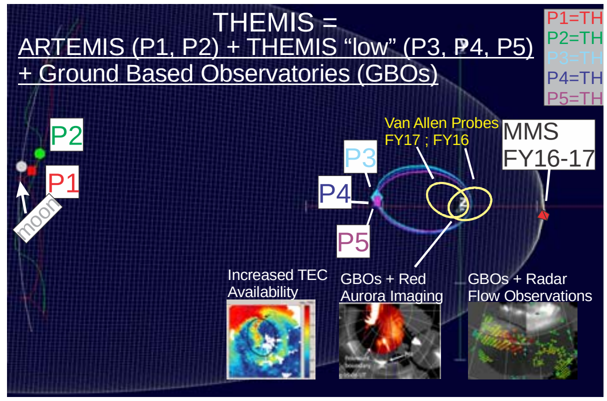

Figure 1A. THEMIS mission with its constituents: THEMIS "low" P3-P5 and ARTEMIS P1 and P2, shown for the fall/winter months of FY16/17 along with MMS. While MMS measures dayside reconnection and THEMIS the results of nightside reconnection, ARTEMIS measures global lobe flux release and reconnection sites when in the tail (or the pristine solar wind when at the upstream regions) and Van Allen Probes studies their effects for the inner magnetosphere. THEMIS also entails 20 ground based observatories (all-sky imagers + magnetometers) which will be observing under optimal conditions in fall/winter when THEMIS apogees will be at the nightside. Combined with increasingly available and powerful TEC monitors, red-auroral imagers and radars, these will provide a synoptic, global view of the causes and consequences of the reconnection phenomena measured by MMS at the magnetopause and THEMIS/ARTEMIS in the tail. To achieve this, THEMIS uses its fuel to adjust its orbit period and phase to that of MMS in order to be (optimally) located at apogee, near the neutral sheet and in view by the GBOs when MMS is near apogee. Beyond that, in FY17-18 THEMIS apogees will be raised further (13-16R_E) to create resonant orbits with MMS (not shown). THEMIS's proposed alignment with MMS unites HPS assets into a powerful system-observatory.

"Ultra-Fast Survey" (UFS) mode have successfully taken place for up to 7 min per spacecraft (this amount fills up the entire memory). The goal is to obtain ~1hr long captures simultaneously on all 3 spacecraft once per orbit by matching recording and downlink rates with appropriate buffer and requesting 3hrs/day of additional DNS 34m dish support. If approved, further testing will take place in the upcoming dayside season of THEMIS prior to MMS dayside season.

(iii) Provide, disseminate and maintain SPEDAS plug-ins for MMS, VAP, GOES/POES, SuperDARN, Incoherent Scatter, Red-aurora and other concurrent HSO mission data to facilitate optimal analysis of these data within one software platform during this unique period in our research field's history.

As its "Baseline HSO" Prioritized Science Goal (PSG#2) THEMIS will simply execute the THEMIS-MMS coordination plan approved in response to its 2013 proposal. Under this plan, item (i) will occur fully; item (ii) will retain its best-effort extended FS captures and frugal execution of simultaneous 5min UFS captures on all 3 spacecraft; and item (iii) is not covered. This status quo represents the agreed-upon plan by HQ as of summer 2013, reported upon in THEMIS's quarterly updates to HQ and amended by the MMS launch delay but also optimized for best science yield per dollar.

In the event that THEMIS does not receive HQ approval to proceed with MMS coordination for HSO optimization, its goals are more modest. As its "Going-it-alone" Prioritized Science Goal (PSG#3) THEMIS would perform no active phasing between its satellites and MMS, nor would it assume an active role in coordinating the ground observatory communities. HSO-style conjunctions with MMS and radar or red-aurora camera data acquisitions might still occur but will be fortuitous and thus un-optimized. In FY16-20, PSG#3 executes the scientific investigation that would otherwise occur in FY18-20 under PSG#1 and PSG#2, namely to progressively extend the observational range of THEMIS out to 16 R_E. The plan is motivated by recent findings regarding the efficacy of reconnection fronts (a.k.a. "dipolarization fronts") in converting 1-5x10^{15}J of lobe magnetic energy into plasma energy during their inward collapse from the reconnection X-point [Angelopoulos et al., T2013; Yamada et al., 2014; Oieroset et al., 2014]. The fronts carry ~0.3MA of cross-tail current [Liu et al., T2012; T2013; T2015] and divert it into the aurora. After collapsing into the inner magnetosphere during substorm expansion or storm recovery the dipolar region expands tailward. THEMIS has shown that the interface between that dipole and tail-like region is the site of both the quiet time arc [Sergeev et al., T2011; Jiang et al., T2012], and the active time arc [Chu et al., T2014] as it expands poleward and as the dipole region expands outward beyond 12R_E. Global energy input and tail reconnection rate will be assessed by the ARTEMIS spacecraft upstream or in the magnetotail. Since the most intense energy release during a substorm occurs during substorm recovery phase, it is important to understand how energy flows from lobe reconnection to the aurora through studies of this critical area. Moreover, it is important to understand how and why only some (~20%) of the fronts result in geoeffective injections (inside geosynchronous altitude) while many do not. One such geoeffective event rendered Galaxy 15 a "zombie" satellite for about one year on Apr. 5, 2010. It serves as a stark reminder that mid-tail phenomena play a vital role in space weather and storm geoeffectiveness.

Towards PSG#3 THEMIS will use the true-and-tried strategy of resonant orbits (as it we did during the prime mission), namely 1-2 R_E XY, XZ and YZ separations once each 4 or 8 orbits so that it will progressively explore the near-Earth region out to 16R_E over the course of FY16-20. This is the region of the strongest cross-tail current diversion into the ionosphere, during the time of the largest substorm energy release, namely the recovery phase. On the dayside, it has now become clear that transient foreshock phenomena (Hietala and Plaschke, T2013; Turner et al., T2013b) and plume-sheath interactions (Walsh et al., T2014) are important modifiers, if not drivers, of magnetospheric activity. Therefore, on the dayside THEMIS will explore the recently discovered foreshock bubbles (forming well beyond the bow shock), the process of hot flow anomaly and foreshock wave propagation through the magnetosheath and magnetosphere (in particular as a mechanism for driving ULF pulsations), the azimuthal evolution of boundary waves and the efficacy of Kelvin-Helmholtz waves at the flanks. In continued collaboration with the Van Allen Probes THEMIS will study how dayside and flank transients and magnetopause shadowing affect the sudden loss and acceleration of radiation belt and ring current particles. THEMIS does not depend on the Van Allen Probes as it can simultaneously measure both the inner magnetospheric phase space density and the solar wind/sheath/magnetopause drivers as well as nightside drivers (during 3 out 4, or 7 out of 8 orbits). However, it contributes to the synergy between all Heliophysics missions such as Van Allen Probes, GOES/POES and ERG by providing uniquely important information regarding the radial profiles of the equatorial phase space density out to large L-shells. Recent THEMIS discoveries [Turner et al., T2013a] suggest that a combination of processes, including wave-acceleration, magnetopause shadowing, diffusion, and wave-scattering is responsible for storm geoeffectiveness; these processes can only be understood from multiple distributed HSO space and ground platforms. THEMIS will play a key role in this arsenal by providing not only 5 additional data points but the global magnetotail flux content and pristine energy input (ARTEMIS) and the source population for the radiation belts at large L-shells.

THEMIS notes with pain that the current guide was inadvertently reduced in 2013 by ~$670K/year due to a clerical error that NASA/HQ confirmed (see Section 7) and additionally does not reflect the post SR13 decision to perform the THEMIS-MMS coordination. As a result, while THEMIS's contract extension option for FY16, already negotiated, is supposed to reflect the proposed "baseline" plan (including an allocation of $300K towards the coordination), it has an inadequate guide. Therefore the "Baseline HSO" plan is underfunded by 500K in FY16 and by 900K in the ensuing years. Should the guide be implemented, the funding loss would represent a severe toll to the scientific productivity of the field: a >50% reduction in community-wide THEMIS-related science; a >60% decrease in THEMIS-led science, significant attrition of students and young researchers and a dramatic loss of potential for HSO science.

THEMIS's results related to the discovery of energy conversion sites in the magnetosphere (Angelopoulos et al., Science, T2013) and the plume interactions with the dayside reconnection (Walsh et al., Science, T2014) were featured on NBC news and other popular media programs; 5 JGR/GRL Editor's highlights; 2 AGU monographs (one on auroral phenomenology and magnetospheric processes and another on magnetotails in the solar system) and several NASA press releases generating media attention with audiences of millions. The above discoveries highlighted the forthcoming goals of the mission which are directly aligned with the objectives and focus areas of the 2014 SMD Science plan. We seek to understand the fundamental processes that occur in the space environment; to determine how planetary habitability is affected by solar variability and to provide the knowledge needed to improve space weather forecasting. For example THEMIS targets understanding energy transformation, energy partitioning and transport at reconnection fronts, particle acceleration upstream at foreshock bubbles, and phase space density evolution in the inner magnetosphere due to wave-particle interactions, all of which are ubiquitous across planetary space environments and at the Sun, yet have tremendous importance for space weather understanding and prediction. Finally, THEMIS is completely aligned with the recommendation of the Heliophysics Decadal Survey to enable and optimize a powerful HSO. In fact, THEMIS lies at the heart of such a Heliophysics Division response to this recommendation. *It applies state-of-the-art technologies (mission design) to optimize the cost-effectiveness of its mission complement, including international partnerships (e.g., ERG synergy through SPEDAS, Canadian Red-Auroral imaging and GBO operations) by optimizing (augmenting) the scope of its planned mission (MMS) at miniscule cost to the MO&DA program.* This is, almost verbatim, the self-assessed charge for NASA per the 2014 Science Plan (p. 28). THEMIS allows NASA/HQ to pro-actively implement an efficiently executed, optimal HSO in response to the Decadal Survey recommendation and Roadmap plan. By maneuvering to optimize its current and future assets it provides the most comprehensive coordinated study of our space environment that Heliophysics has ever seen, a cross-scale investigation of the field's most pressing questions.

2. Recent discoveries shaping the future

Over the last four years THEMIS "low" and ARTEMIS made significant discoveries that have illuminated and, in some cases, changed our understanding of how the magnetosphere couples to the solar wind and ionosphere. These studies provide strong motivation not only for revising our own mission's future plans, but will also play a key role in designing observational strategies for NASA's HSO (including both MMS and other magnetospheric missions) and its partnerships with the NSF, NOAA, and international space agencies. They reinforce the view expressed in the HPS Decadal Survey that implementation of an HSO is the best way forward for Heliophysics. This section describes the findings that affect THEMIS's proposed science planning.

2.1 Magnetotail

By 2011 it had been realized that transient magnetotail activations like flow bursts and busty bulk flows (BBFs) that are associated with dipolarization fronts in the magnetotail and north-south arcs, or streamers, in the ionosphere move from the reconnection site all the way to the inner magnetosphere. These harbingers of tail reconnection occur during all phases of substorms (where they initiate the expansion and recovery phases), storms like those encountered during the recent solar maximum, and the pseudo-breakups that abounded during the prior solar minimum. Over the past two years a new paradigm for magnetotail activity has emerged, whereby modes of magnetospheric convection are increasingly being viewed as the superposition of individual reconnection impulses. The intensities and recurrence rates of these impulses affect both global convection (evidenced by AE) and storm-related activity (evidenced by Dst and radiation belt fluxes). In fact, it is now understood that the AE index itself is a poor measure of global convection during relatively quiet times, because classical, substorm-like auroral brightenings can appear in the absence of a significant magnetic response [Sergeev et al., T2014b]: unless plasma sheet electrons are heated enough by the collective action of reconnection impulses to produce sufficient energetic electron precipitation and affect E-region (Hall) conductance the ground response is weak. Moreover, we now know that storms with significant electron injections as monitored by AE result in higher radiation belt fluxes than storms with low AE [Turner et al., 2014b], a fact directly attributed to whistler-mode chorus driven acceleration of injected (seed) electrons. The inferred significance of reconnection-driven injections in the inner magnetosphere during storms is mounting from both THEMIS and Van Allen Probes proton and electron analyses [Gkioulidou et al., 2014; Turner et al. T2015], as will be further discussed in Section 2.3. Here we discuss the drivers, magnetotail reconnection, and global connections.

It has become evident over the last two years (e.g., Gabrielse et al. [T2014]) that ion and electron injections (superthermal flux increases) accompany dipolarizing flux bundles and fast flows at all distances from Earth (Fig. 2A). At geosynchronous altitude THEMIS injection statistics match the occurrence rates and local time distributions from early LANL observations [Birn et al., 1997] very well, whereas at greater distances (6 - 30R_E) THEMIS occurrences and spectra are consistent with early observations of tail acceleration [Sarris et al., 1979] and plasma heating [Christon et al., 1988]. Coincident dispersionless ion and electron injections are rare and consistent with head-on encounter of the 1-3 R_E cross-tail scale size of the electric pulse responsible for the acceleration. Most injections are, however, solely ion or electron injections due to the fact that the accelerated particles drift azimuthally away from the pulse and mix quickly with the ambient plasma. Particle heating (spectral hardening) results from the cumulative action of consecutive impulses – not a single pulse. Significant magnetic flux transport accompanies each 1-2 min electric field pulse [Liu et al., T2014]. Each pulse is associated with a substantial (0.3 MA) current system [Liu et al., T2012] in which a significant portion flows along the magnetic field (a stronger Region-1 type and a lesser Region-2 type) very reminiscent of the substorm current wedge space [Sergeev et al., T2013] and evident also on the ground [Lyons et al., T2013] except that its scale size and total intensity are factors of ~3 smaller.

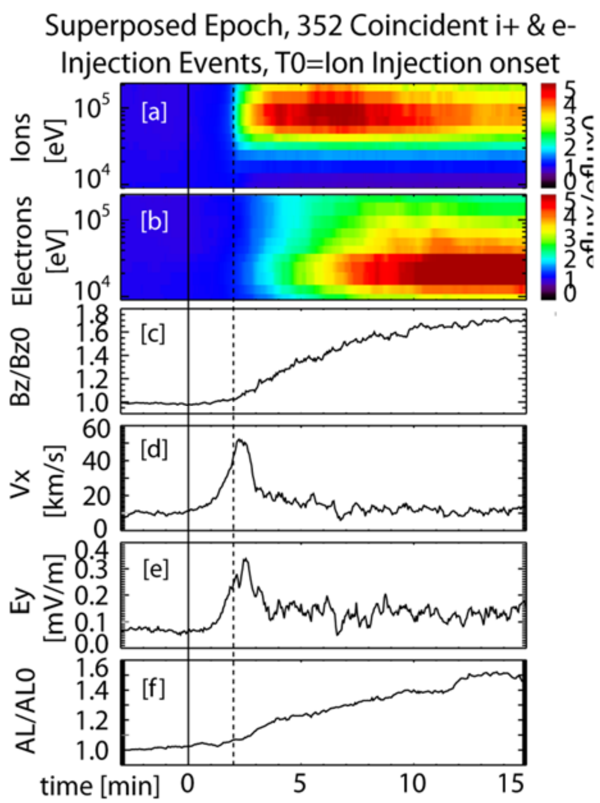

Figure 2A: Simultaneous ion and electron injections in the 6-30R$_E$ region have the hallmarks of reconnection impulses, including plasma jets, flux transport and progressive heating of the plasma sheet [JGR highlight: Gabrielse et al., T2014].

Auroral-plasma sheet mapping had also remained an open question until recently. Do the arcs map close to Earth, near the radiation belts, or do the severe distortions associated with strong currents cause them to map to mid-tail regions? How is the mapping distorted during the course of a substorm and what does this tell us about the source of energy conversion from magnetic to kinetic in the plasma sheet? Thanks to the THEMIS space and ground observatories tremendous progress has been made on these topics during the last two years, informing the questions for the emerging HSO. By the conclusion of the THEMIS-dominated Substorm Focus Group of the Geospace Environmental Modeling meeting in 2012 it was realized that the quiet arcs map to the interface between the dipole and tail-like field lines, near the inner edge of the electron plasma sheet [Sergeev et al., T2011; Jiang et al., T2012]. Since then, modeling has revealed that what was traditionally dubbed the poleward expansion (or poleward leap) of the auroras is well-explained by the distortion of the mapping associated with the substorm current wedge (SCW) as seen in Fig. 2B [Chu et al., T2014] even if the fast tail flows (related to the flow shears or pressure gradients feeding the arcs) were to experience little or no tailward motion. This is not to say that tailward motion of the

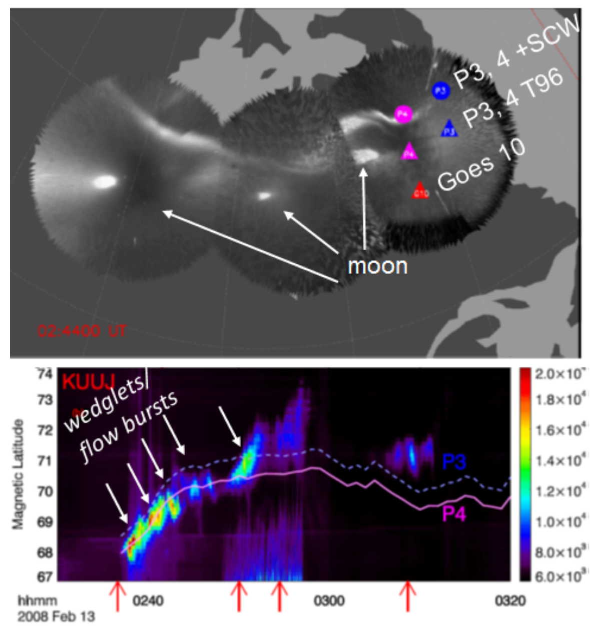

Figure 2B: Chu et al., [T2014] modeled the aurora-to-plasma sheet mapping distortion due to the substorm current wedge, determined (as a function of time) from mid-latitude stations. The revised mapping of THEMIS spacecraft P3 and P4 (top, denoted P3, 4 +SCW) places them onto the active arc. P3 and P4 were observing wedgelets and flow bursts in the tail, each corresponding to an auroral intensification at their footprint, as seen in the keogram (bottom).

dipolarized region or of the reconnection X-points does not occur (in fact we know they both do), but that the flux encompassed in the dipolarized region of the plasma sheet at late recovery phase becomes progressively less. As the newly reconnected plasma piles up new magnetic flux against the strong magnetic field of the inner magnetosphere the dipolar plasma sheet expands and engulfs the satellite, quenching the flow locally (a spatial aliasing effect). The poleward and azimuthal expansion of the aurora is mainly due to the field-aligned currents emanating on both sides of the dipolar region. The key, therefore, is to understand the origin of the field aligned currents driven by plasma sheet pressure gradients and flow shears at the interaction region between flow-bursts and the dipolarized plasma sheet as it gradually expands tailward.

This shows that the region tailward of $10R_E$ is a prime

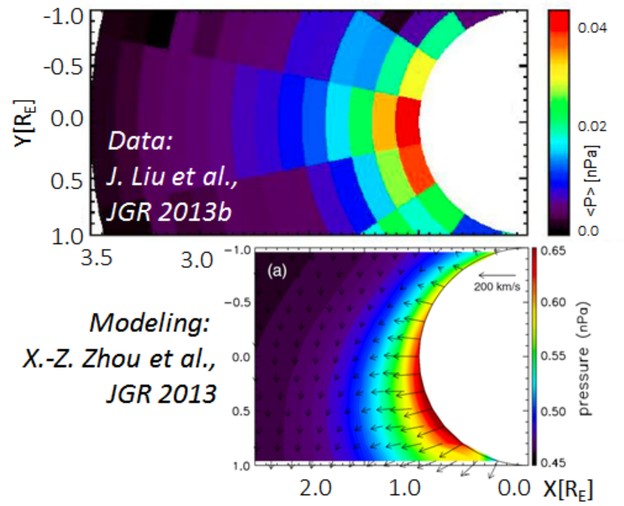

Figure 2C: Top: superposed epoch analysis of pressure from hundreds of dipolarization fronts showing the increased pressure buildup ahead and near the center of the front. Bottom: Modeling results are consistent with this pressure buildup, ion flows and related secondary electrical currents [Zhou et al., T2013]. How does this pressure contribute to the large scale SCW? What drives the large scale magnetospheric energy dissipation?

candidate for studies of current diversion and energy dissipation/conversion. Since the late expansion and early recovery phase of substorms is also when most energy is deposited in the aurora and inner magnetosphere, we must also extend our studies of the dipolarized boundary evolution beyond the current THEMIS low apogee of $12R_E$ to determine global energy transfer from magnetic reconnection to the auroral ionosphere.

But what process interacts with and stops the incoming bursts at the dipolarized plasma sheet? Per Sergeev et al., [T2012a, b] this involves a combination of inner magnetospheric Maxwell stresses and plasma pressures as well as the density (more accurately the entropy) of the newly reconnected flux tube. This picture is simplistic because plasma sheet flux tube plasma content recirculates and this picture obscures the force balance dynamics. Ions are reflected [Eastwood et al., T2014] and energized at the incoming front, building up plasma pressure (Fig. 2C) that decelerates the front and accelerates the ambient plasma both earthward and out of the way. Recent modeling [Artemyev et al., 2015] indicates that the fronts efficiently accelerate ions up to 100s of keV at their stopping points. The pressure buildup and flows merge with the global pressure system at the edge of the dipolarized plasma sheet. This pressure system takes 10s of minutes to subside, consistent with SCW lifetimes. What is responsible for lobe flux transport and energy conversion at that time?

Answers to such long-standing space physics questions are both far reaching (as they pertain to energy conversion at the Sun, at accretion disks and tokamaks) and within reach assuming a concerted effort involving the entire panoply of tools available to the THEMIS team and the Heliophysics community in the next few years.

First, from the ground perspective, the potential is tremendous and the pace of progress accelerating: The combination of imagers and ground-based radars (SuperDARN, StormDARN, PFISR) is revolutionizing our

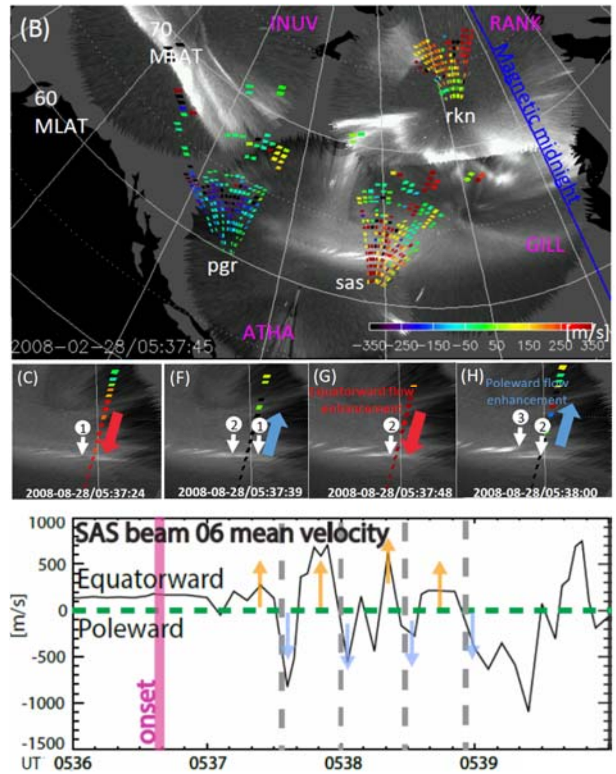

Figure 2D: Gallardo et al. [T2014] used the SuperDARN radar's special "THEMIS mode" to demonstrate the presence of high speed flow shears and strong field-aligned current pair systems in the near-Earth plasma sheet feeding beaded arcs. Following recent observations of beaded arc conjugacy [Motoba et al., T2012] these methods represent a major breakthrough in our understanding of magnetosphere-ionosphere coupling and a powerful tool for further exploration of energy conversion in conjunction with THEMIS satellites in the upcoming few years.

capabilities to explore small scale structures at high time resolution while simultaneously understanding the global context. For example, radars reveal that at the flow-burst – dipolar plasma sheet interaction region auroral beading is associated with up-down field-aligned current filaments. As these filaments pass through the radar field of view (Fig. 2D) they result in away-toward-away flows that are consistent with a flow vortex. Up to 1000 m/s ionospheric flows have been captured by the special single-beam, 6s resolution "THEMIS" radar acquisition mode. These small scale

(10km), fast, periodic flows map to 100s of km structures moving at 100s of km/s in the plasma sheet, where they have recently been detected by THEMIS [Panov et al., 2015], opening a new opportunity to understand the generation mechanism for auroral beads in the plasma sheet and their potentially crucial role in substorm dynamics.

Second, kinetic modeling can help us understand non-periodic, larger scale undulations. A highlighted JGR paper [Pritchett et al., T2014] described the breakup of 1-3R_E scale-size dipolarizing flux bundles approaching the inner magnetosphere via interchange motion. Such a breakup may be the equatorial counterpart of the north-south arcs (streamers) observed in the THEMIS all-sky imagers (Fig. 2E). In-situ investigations of flux conservation and statistical studies of flux content as a function of distance confirm that flux bundles must break up into smaller pieces [Liu et al., T2015a,b]. The question is whether this filamentation is inherent to the magnetic to kinetic energy conversion, or merely an intellectual curiosity? The dipolarizing bundles are a site of intense particle acceleration that provides a seed population to the ring current and radiation belts. As the plasma collides with and is diverted sideways from the strong field, high pressure region the flows become turbulent. The potential for re-reconnection increases [Vogiatzis et al., T2014], as does the potential for magnetic misalignment resulting in conditions similar to storms of nanoflares at the Sun [Parker, 1983; Klimchuk et al., 2006]. Particle scattering and heating at such turbulent centers [Hoshino, 2013] could result in even more efficient acceleration than at single propagating fronts. Kinetic effects must be considered over a range of electron and ion scales, as well as on MHD scales.

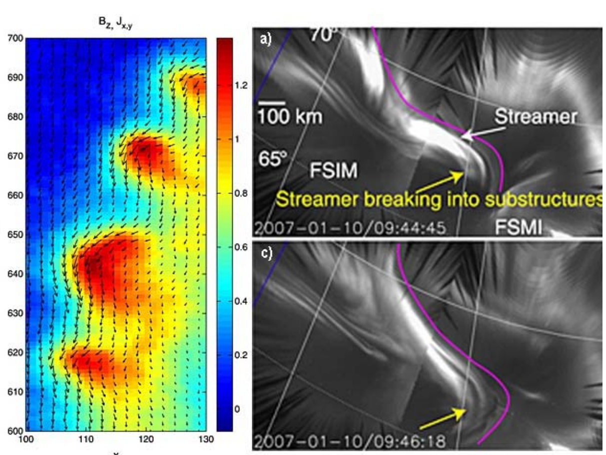

Figure 2E: In this JGR Editor's highlight, Pritchett et al. [T2014] show how interchange motions cause incoming flows to break up into pieces with scale sizes consistent with those of observed streamers. Liu et al., T2014a,b showed evidence for such breakups in the tail; the resultant turbulence may enhance the efficiency of particle acceleration at the dipole-tail interface.

In the mid-tail plasma sheet, it has been amply demonstrated that reconnection participates during the early stages of substorm onset. The ARTEMIS spacecraft provides significant new information on this topic. When aligned with THEMIS (low) they can determine the location and downtail evolution of active X-points and dipolarized plasma sheet plasma. ARTEMIS has already observed hundreds of plasmoids. Comprehensive case and statistical studies [Li et al., T2013; T2014a] show that plasmoids are localized to ~ a few R_E, except during large substorms, when they coalesce earthward of lunar distance. This localization may explain why plasmoids appear to emerge and grow out of X-point reconnection in the plasma sheet prior to lobe reconnection. It is also consistent with lobe reconnection in the late substorm expansion phase and less often at substorm onset: localization allows plasmoids to grow and slip through the plasma sheet field lines to be detected in the distant tail, in good timing agreement with substorm onset and consistent with older ISEE-3 and Geotail distant tail observations. This would mean that (substorm timing aside) significant energy release during substorms does not really take place in earnest until one or more plasmoids have been released, during the late expansion and early recovery phases of substorms, when lobe reconnection has commenced.

The availability of ARTEMIS at lunar vantage points in the tail, from where we can evaluate the total magnetotail flux content, the magnetotail energy conversion rate, and the locations of active X-points in conjunction with a solar wind monitor is a powerful Heliophysics asset. Angelopoulos et al. [T2013] used such observations to publish a case study in Science (Fig. 2F, panel A) that showed that the tail reconnection rate was zero for the first 20 min after onset, steady and equal to the dayside reconnection rate for 40 minutes thereafter, and increased rapidly at the late substorm recovery and for 30min, thereby reducing the lobe flux to its pre-substorm value. During that interval, the X-points determined by ion beams or flows moved from the near-Earth tail, to the mid-tail and back, with the main intensification associated with a near-Earth onset and lobe reconnection. During that time the ARTEMIS estimates for the energy conversion rate by matched that from the near-Earth THEMIS spacecraft. The regions of peak energy conversion, dubbed generically "reconnection fronts", are sites of high flux transport (Panel C), large integrated value of J*E (Panel D), turbulence and flows. Energy conversion at THEMIS, near 11R_E took place in electron-scale regions within earthward dipolarization fronts and (at a much reduced rate) in tailward-moving anti-dipolarization fronts of negative Bz, as illustrated in Panels D-G. Numerous tailward moving reconnection fronts have since been identified in ARTEMIS observations (Li et al., T2014b), suggesting that plasmoids are not fully formed at lunar distance but are still emerging/evolving following near-Earth tail reconnection. However, it is understood that earthward moving fronts, especially those near Earth, are the dominant sites of energy conversion (by a factor of 10, Fig. 2F, Panel D) even though flux transport at THEMIS and

ARTEMIS (on the two sides of the X-points) is equivalent (Panel E).

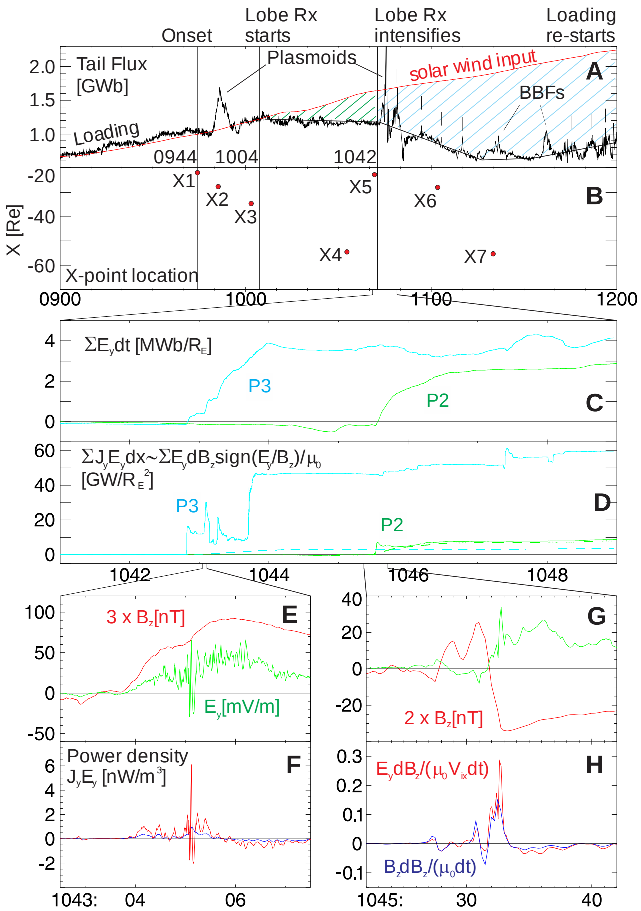

*Figure 2F: Panel A: red curve is flux transport into the tail estimated by the cumulative integration of the merging electric field from OMNI solar wind data; black is the tail lobe flux, estimated by determining the tail flaring angle and tail radius from pressure balance at ARTEMIS P2. The difference, highlighted, is the amount of flux the tail has lost to nightside reconnection. Tail reconnection is most intense for 30 min after 10:41UT. Panel B: the location of the X-point determined from time-of-flight ion measurements and/or flow reversals. Panel C: cumulative integrated flux transport during an 8 min period. It is most intense during bursty flows accompanied by "reconnection fronts" at P3. Panel D: cumulative integrated J*E, the power conversion density, in units of GW/R_E^3. Panels E and G: magnetic and electric field during a few seconds of a reconnection front at P3 and P2. Panels F and H: Conversion power density from direct electric field measurements (red), different from that computed from the MHD approximation (blue) and revealing the kinetic nature of the conversion process. Adapted from Angelopoulos et al., [T2013]*

When power conversion at reconnection fronts was integrated over temporal and spatial scales commensurate with the observed flux transport duration and extent it sufficed to account for the total energy conversion expected from the lobe magnetic energy reduction (3×10^{15}J) during this substorm. This means that reconnection fronts can be very significant on global scales. They represent the sites where lobe magnetic energy is converted to particle kinetic energy or waves as flux tubes shrink, moving away from the reconnection point. They are even more important than the reconnection X-point itself, since they are responsible for the first step in the conversion of lobe magnetic energy to eventual ionospheric heating and Van Allen belt ion and electron heating, or plasmoids. Consequently, understanding the means of electron and ion energization and wave radiation away from these sites has become topic of great interest [e.g., Eastwood et al., 2013; Yamada et al., 2014]. Further multipoint studies are needed at the locations where the fronts form and evolve: between 10 to 12 RE from Earth but also further away at locations where energy conversion occurs unhindered by any interaction with the inner magnetosphere. The challenge of understanding magnetotail dynamics over the next few years calls us to employ multipoint THEMIS observations to quantify the power conversion into kinetic, thermal, and translational plasma energy and/or waves; to incorporate ground-based and ionospheric observations to define the coupling of that energy to the inner magnetosphere and ionosphere; and to work with HSO spacecraft ARTEMIS, Geotail, Cluster, and MMS to establish the global connection of that energy conversion to the global configuration, including magnetopause flaring.

In summary, we know from recent observations that the region between 10-16R_E harbors intense electric fields, flows and currents that couple to the auroral ionosphere and inner magnetosphere. This region is under-explored because THEMIS has not used its full multipoint observational capability outside of 12R_E and Cluster has not spend much time in this region (being polar-orbiting and high-apogee). *THEMIS's planned apogee increase of P3-P5 and separations (from kinetic to MHD scales) in the next 5 years will provide the much needed data, tools and personnel to study the intense power conversion region in the nightside equatorial magnetosphere. Moreover, it is critically important to understand the coupling of that region to the global forcing (magnetopause flaring angle and current system) and reconnection sites (with the help of ARTEMIS, Geotail, Cluster and allied MMS measurements), to the inner magnetosphere (with the help of inter-THEMIS correlations, GOES, and Van Allen Probes) and to the aurora (with the help of THEMIS ground based assets, and allied observatories, such as magnetometer arrays, SuperDARN and other radars).*

2.2 Dayside

By 2011 it was clear that transient dayside phenomena (hot flow anomalies, or HFAs, upstream waves, pressure

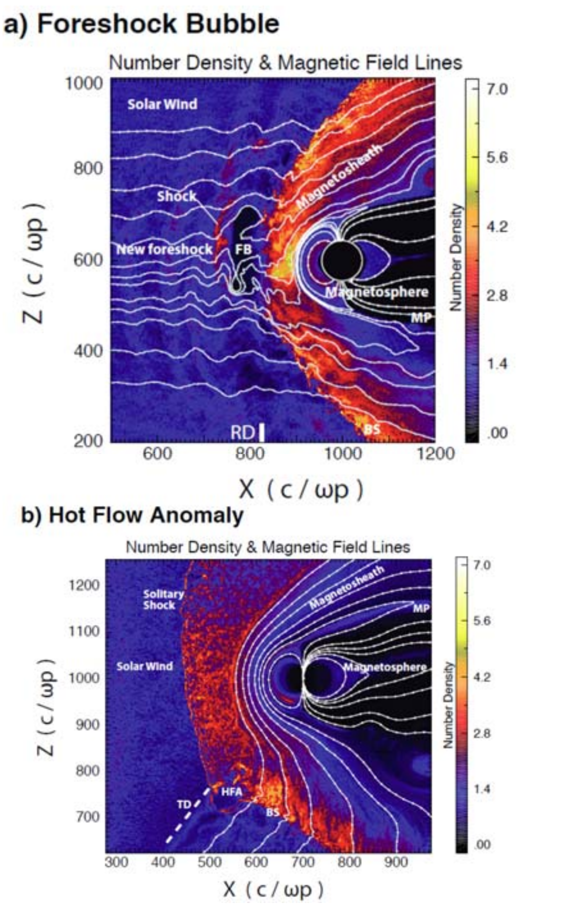

Figure 2G: Foreshock bubbles in hybrid simulations (top) contrasted with the more traditional (and smaller) hot flow anomalies (bottom). Note that HFAs form close to the shock and are convected past it, whereas foreshock bubbles form in the solar wind upstream of the shock and are convected into the shock by the solar wind. Equatorial measurements from beyond the shock distance (as planned by the extended THEMIS phase) are needed to study these kinetic phenomena in their birthplace, but ARTEMIS, THEMIS and allied HSO measurements in the pristine solar wind, the inner magnetosphere and on the ground will also be essential. [Turner et al., T2013b].

pulses and transient reconnection) apply significant pressure variations to the dayside magnetosphere and have global consequences. Today, the observational discovery of the foreshock bubbles predicted by hybrid simulations, we seek to further examine these and similar transient phenomena in-situ, in conjunction with other spacecraft and ground measurements, and hand-in-hand with simulations, to assess their relative importances and global consequences. THEMIS has revealed how localized plasmaspheric plumes protruding towards the magnetopause modulate the dayside reconnection rate even under steady solar wind conditions in ways not previously anticipated or appreciated. We will expand upon such findings to understand how dense plumes

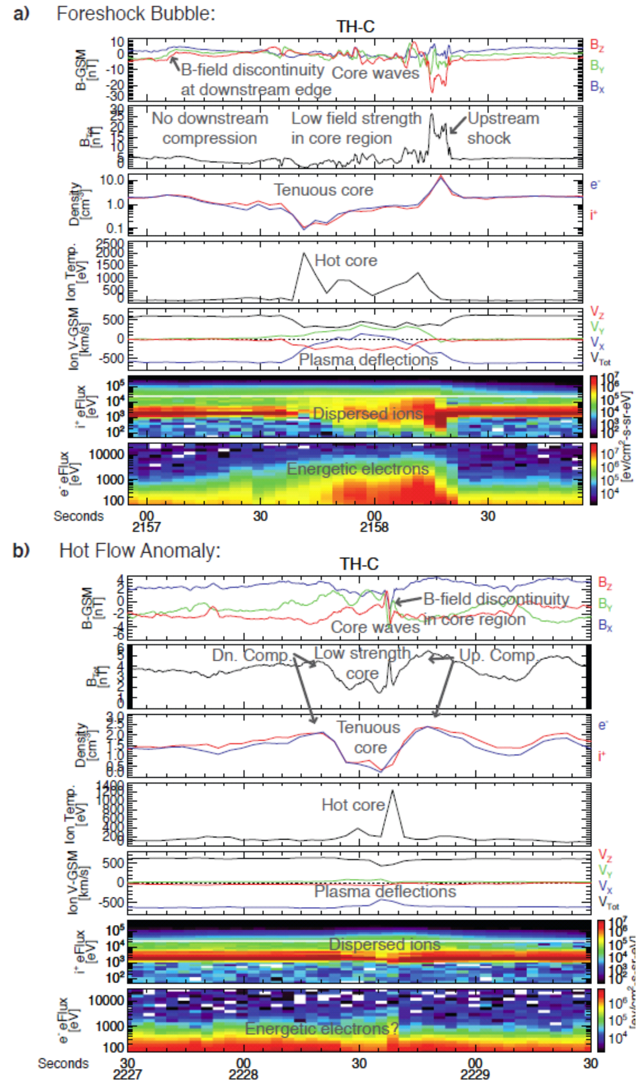

Figure 2H: Foreshock bubble at ARTEMIS P2 (TH-C) (top) contrasted with the more traditional HFA seen at another time by the same spacecraft (bottom). From Turner et al., [T2013b].

and upflowing ions interact with the magnetopause to affect local and global energy input. Finally, studies of in-vivo FTEs generated by multiple X-points reveal how waves and kinetic magnetic structures result in electron heating. The formation, evolution and energy partitioning during reconnection inside such structures are critical to understand the effects of reconnection on particle heating. Because the phenomena occur on scales ranging from ion kinetic, through MHD, to regional scales, THEMIS observations will complement those by MMS on electron scales. In conjunction with MMS, timely observations from the planned 12-16R_E THEMIS apogee will complement HSO's goals to understand how solar wind energy is processed and enters geospace.

Foreshock bubbles occur whenever rotational discontinuities enter low cone angle foreshocks. Figures 2G and 2H contrast their properties with those of hot flow anomalies in simulations and observations. Reflected and Fermi-accelerated particles become trapped in the region upstream from the discontinuity, resulting in extremely large high pressure cavities that grow as they approach the shock. THEMIS and ARTEMIS have not only confirmed that the existence of the bubbles first seen in hybrid simulations [Omidi et al., 2010], but have also shown that they are very common [Turner et al., T2013b]. Previously observed foreshock bubbles may have gone unrecognized as HFAs because the two share similar characteristics.

These upstream features have global magnetospheric consequences. In addition to generating pressure pulses, they routinely drive global magnetospheric Pc5 ULF waves

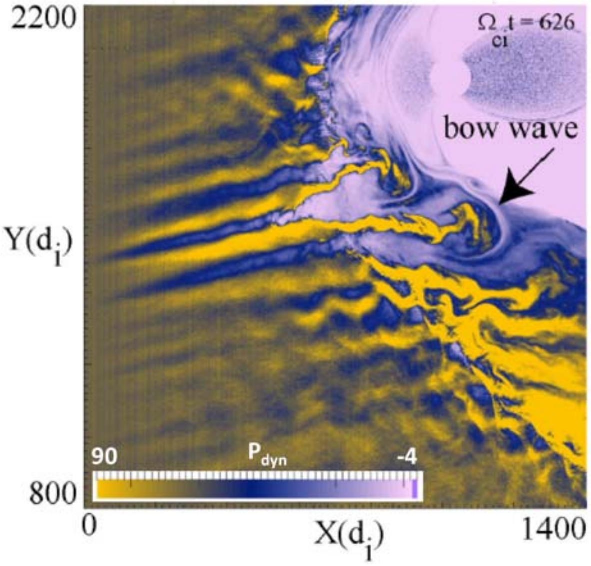

Figure 2I: Hybrid simulations show pressure pulses launching magnetosheath jets that buffet the magnetosphere. Generated by shock undulations, the jets drive magnetopause reconnection and generate flux transfer events [Karimabadi et al.,T2014].

with E and B field amplitudes up to 10mV/m and 10nT near geosynchronous orbit (Fig 2I). The peak magnetospheric response at pre-noon local times correlates well with the location of the ion foreshock. Similar behavior is seen when HFAs and other transients impact the magnetosphere, but FBs elicit the largest response.

Foreshock bubbles are not the only feature generating large scale magnetopause undulations. High-speed jets emanating from corrugated shocks are also a new and important phenomenon, first discovered in the data [Hietala et al., 2009; Hietala and Plaschke, T2013; Archer et al., T2014] and then shown by means of simulations (Fig. 2I) to be extremely effective in generating magnetopause transients. Other transients, well studied in the past in data but only now becoming equally well explored by global hybrid simulations [Karimabadi et al., T2014] are shocklets, SLAMS (short, large amplitude magnetic structures), and upstream turbulence, that are convected downstream and have significant effects on the magnetosheath interaction with the bow shock.

Case and statistical studies, simulations and theory now suggest that transient foreshock phenomena play an important role in driving ultra-low frequency (ULF) waves in the magnetosphere (Fig. 2J). These waves couple to field line resonances that dissipate energy into the ionosphere and accelerate radiation belt particles in the aftermath of corotating interaction regions.

Understanding the processes that generate these foreshock kinetic phenomena and their coupling to the magnetosphere requires the appropriately equipped, positioned, and spaced spacecraft that THEMIS plans to have in place during the next 5 years. This is particularly important during the forthcoming declining phase of the solar cycle, when corotating interaction regions are most prevalent in the solar wind.

Global convection changes within the magnetosphere can detach plasmaspheric plumes. Plumes may be quite localized azimuthally [Walsh et al., T2013a,b] but deliver high density plasma to the magnetopause interface and can then spread out over long distances carried by the low latitude boundary layer flows. As a result, high density plasma is quite common on the magnetospheric side of the magnetopause, significantly affecting the dayside reconnection rate. This is true not only during solar minimum conditions when the plasmasphere can extend out to $8R_E$ or beyond, but also during solar maximum in response to dynamic solar wind drivers. After prolonged periods of quiescence, enhanced solar wind electric field drivers can generates plumes that in turn actively moderate magnetopause reconnection [Walsh et al., T2014]. What remains unclear is whether the local suppression of the reconnection rate results in a global suppression of the dayside energy coupling or whether it is compensated by a corresponding increase in the reconnection rate at nearby local times [Lopez et al., 2010]. Simultaneous observations of upstream quantities, reconnection on ion kinetic scales, and but regional boundary conditions and context (over several R_E scale) are absolutely critical in determining the reconnection drivers, rate and evolution of dayside reconnection.

THEMIS kinetic scale studies near the subsolar magnetopause provide important new information. There magnetic reconnection is often transient, with repetition cycles on the order of 5-10 minutes, but can also continue steadily for hours, under low plasma beta (β) conditions. Until recently what controlled the rate and stability of reconnection upstream has been a puzzle.

Recent simulations [Swisdak et al. 2010] have revealed that reconnection is suppressed when the jump in β across the magnetopause, $\Delta\beta$, exceeds $2\,(L/\lambda_i)\tan(\theta/2)$, where θ is the magnetic shear, L the gradient scale, and λ_i ion Debye length across/inside the current layer. THEMIS set out to check this prediction. A recent statistical study of THEMIS magnetopause crossings, shown in the lower panel of Fig. 2L, indicates that non-reconnection crossings occur for low shears and large jumps in β across the magnetopause. Furthermore, the upper panel indicates that reconnection occurs over a larger range of shears for lower as opposed to higher Δβ. Thus our recent results provide striking confirmation of the Swisdak et al., [2010] model.

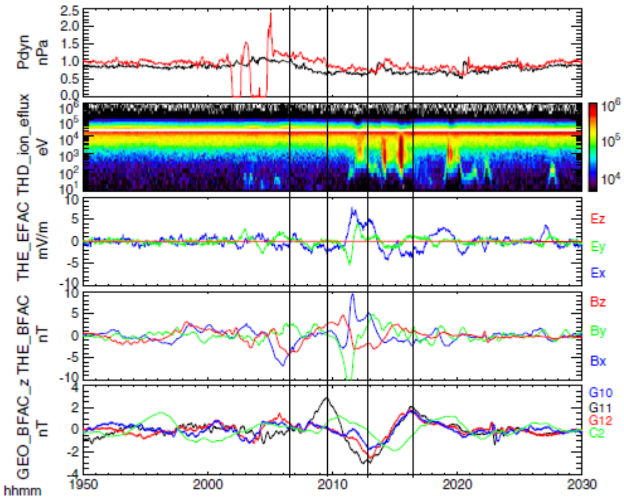

Figure 2J: Transient foreshock phenomena drive significant ULF activity in the inner magnetosphere. Top panel shows data from TH-B (in the solar wind, black) and THC (in the ion foreshock, red) during the passage of a foreshock bubble. The response in the inner magnetosphere (bottom 4 panels) is prolonged and dramatic, with significant power in Pc5 waves [Hartinger et al., T2012]. The ULF waves can accelerate radiation belt particles during stream-stream interactions regions and storms in general. From careful and systematic global studies of these kinetic transient phenomena we stand to gain significant knowledge regarding solar wind-magnetosphere coupling. Such studies require the presence of spacecraft directly upstream of the shock (THEMIS extended phase) and pristine, high-fidelity solar wind monitors (such as ARTEMIS).

The suppression of low-shear reconnection at high Δβ (and therefore high magnetosheath β) has generals consequences for the occurrence of reconnection in space and laboratory plasmas. It is very likely that this effect explains why most prolonged magnetopause reconnection events have been observed for low magnetosheath β. Under such conditions the magnetosheath plasma is stable to the mirror-mode, allowing relatively steady β conditions in the sheath, and permitting magnetopause reconnection to be steady. Similarly, bursty reconnection is expected when the underlying magnetosheath β is high and mirror waves are present, producing fluctuating intervals of low and high-β. At the magnetopause flanks, however, the data are far more complex and do not follow the aforementioned simple β–shear relation. It seems likely that flow shear also affects the rate and duration of reconnection. Moreover, as Kelvin-Helmholtz waves are expected to form in that region, reconnection sites may start to form within rolled up vortices at the terminator and further downstream. Further testing requires multi-spacecraft observations to simultaneously examine β in the magnetosheath and flow shears across the boundary while observing the onset and rate of reconnection at the magnetopause.

Additionally, it has been unclear how much of the

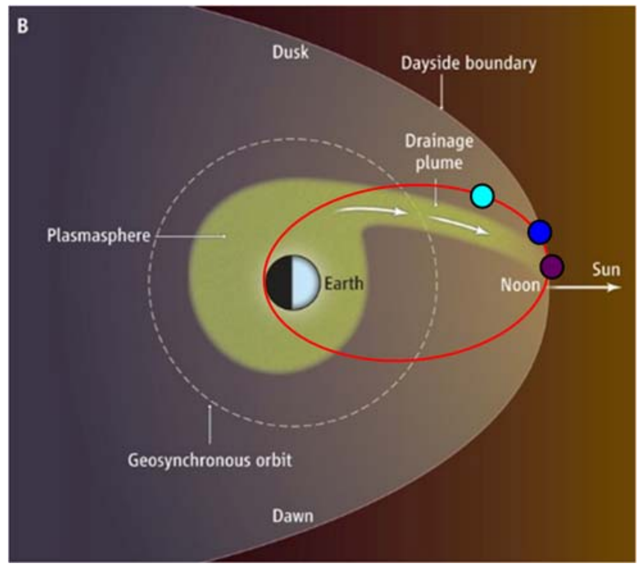

Figure 2K: Pictorial representation of the THEMIS configuration that measured a suppression of the dayside reconnection rate due to the interaction of plasmaspheric plumes (dispatched sunward under strong solar wind drive) with the magnetopause. "Magnetospheric physics is evolving toward a system-science approach… [where] the behavior of the entire interacting system is considered when studying any aspect of the system... [This] effect is indicative of a new level of sophistication in the understanding of how the magnetospheric system operates. The effect can be particularly important … during geomagnetic storms. Instead of unchallenged… the magnetosphere, with the help of the ionosphere, fights back." [Borovsky, 2014 on Walsh et al., T2014].

energy in the reconnection process is deposited to electrons, ions and how much is released as Poynting flux and how/where particle heating occurs under different upstream conditions. Recent THEMIS results show that ion heating is ~20% of the available magnetic energy per particle and a factor of 8 larger than the electron heating within reconnection exhausts [Phan et al., T2013, T2014], consistent with recent simulations [Shay et al., 2014] and laboratory measurements [Yamada et al., 2014]. This is far less than the electron heating observed in the Sun, where a very significant fraction of the energy is deposited in electrons. The open outflow boundary, typical of dayside reconnection, may have a significant role to play in this result. This hypothesis can be tested by careful studies of

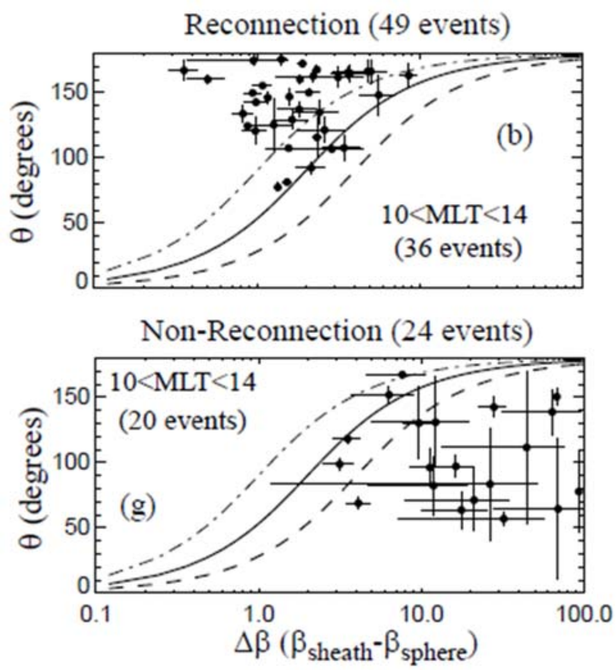

Figure 2L: Testing the Δβ-shear relation of Swisdak et al [2010] with THEMIS observations, Phan et al. [T2012] showed that reconnection is suppressed for high Δβ. It is unclear if this conclusion is valid in the presence of flow shears near the flank magnetopause. Multipoint THEMIS observations in FY17-20 will test this relation at the magnetopause and the conditions for reconnection on the flanks.

multiple reconnection inside in-vivo FTEs [Zhang et al., T2012] and at magnetic islands in the solar wind [Eriksson et al., T2014] emerging through the action of multiple X-lines on the two sides of a growing island. Such "closed" outflow boundary conditions may be more favorable to reconnection in the solar context, while nonetheless quite pertinent in a geophysical context. As Oieroset et al. [T2014] pointed out, low-frequency kinetic Alfvén waves are enhanced at the colliding jet region between two active reconnection lines, suggesting a possible link with the observed ion heating. Determining how electrons are heated to suprathermal energies will require further case studies, statistics and modeling. In particular the role and relative importance of electron holes, whistlers, and the front-like structures observed within the colliding jets (reminiscent of magnetotail reconnection fronts) remain to be explored. By obtaining a significant number of in-vivo FTE events from ion-scale separations and with sufficient waveform captures to resolve the nature and role of kinetic phenomena within these active sites, THEMIS plans to lead the way in understanding energy conversion at the outflow jets at dayside reconnection sites and thus complement MMS's electron diffusion region investigations.

THEMIS's plans to make observations from ion-scale separations, with a significant increase in the duration of high-frequency waveform captures, to test the leading hypotheses for magnetopause reconnection and extend such studies to cases of flow shear near the terminator and the magnetopause flanks. Following its recent discoveries and new directions in our studies of dayside reconnection, it will examine the role of energy partitioning under open-boundary and colliding-jet reconnection conditions.

2.3 Inner magnetosphere

THEMIS has advanced our understanding of wave generation, properties, and wave-particle interactions in the inner magnetosphere. With the recent increase in solar activity, THEMIS has now captured more than 60 storms from a multipoint perspective. Consistent with reports from previous solar cycles and more spatially-constrained databases, THEMIS finds that 58% of geomagnetic storms result in enhanced peaks in electron radial phase space density (PSD), 19% resulted in depleted peaks, and 23% resulted in no significant change in PSD peaks [Turner et al., T2013]. This extends previous results from geosynchronous altitudes out to $12R_E$, and confirms the maxim that "not all storms are created equal" at least in terms of their geoeffectiveness. Moreover, by studying individual storms that epitomize such disparate electron PSD behaviors during otherwise similar Dst and Auroral Electrojet (AE) profiles, THEMIS has been able to show that: 1) growing peaks in PSD were co-located with chorus waves observed outside the plasmapause during active periods of the electron PSD-enhancing storms, but not during the PSD-reducing storms, providing good evidence for the critical role of the wave acceleration mechanism during PSD-enhancing storms; 2) outer belt dropouts due to magnetopause shadowing and subsequent outward radial transport were a key loss process during all storms; 3) slow decay in PSD is often associated with hiss; 4) precipitation loss caused by wave-particle interactions with EMIC waves was critically important during the PSD-depleting storms but not the PSD-enhancing storms; and 5) ULF-wave driven radial diffusion away from peaks in PSD was evident during the recovery phase of the PSD-enhancing storms and therefore enhanced ULF wave power is critical in the redistribution of the PSD after local acceleration.

Recent joint THEMIS and Van Allen Probes studies showcase the importance of nightside injections in creating the whistlers and EMIC waves that partake in storm time PSD enhancements and losses, and also pre-accelerate electrons to significant intermediate energies (100keV) prior to injection into the inner magnetosphere, enabling wave-particle interactions there to further accelerate them to relativistic energies [Turner et al., T2015]. Joint THEMIS – ground based studies also reveal how ion injections, followed by EMIC wave generation, are critical for proton aurora enhancements and sub-auroral polarization streams [Nishimura et al., T2014c] while electron injections [Nishimura et al., T2012c; Li et al., T2012a,b] are responsible for electron acceleration and pulsating aurora precipitation.

It is evident that a variety of waves, and particle acceleration/loss processes that had been studied individually in the past conspire to accelerate particles during some storms, but flux depletion in others, depending on the external drivers. These results strongly suggest that a system-observatory approach is required to make progress in inner magnetospheric research. THEMIS's planned large inter-spacecraft separations in FY17-20 are ideal to sample storms from a maximal spread in positions when combined with Van Allen Probes (FY17/18) or ERG (at or beyond FY18) and GOES data. This is true especially with data analysis tools such as SPEDAS that enable multi-spacecraft analysis (Fig. 2M).

During the last three years, the THEMIS team has vetted and released its characterization of the solid state telescope response to energetic particle fluxes. Thanks to the full use of anticoindicence detectors, penetrating electrons no longer affect the calibrated data up to 1MeV and penetrating ions remain a problem only in the inner belt. GEANT modeling and inter-anode and inter-spacecraft calibration of detectors have also improved our understanding of the final energy calibration and dead-layer response. Clean particle fluxes are now available routinely throughout the entire mission including in the outer radiation belt.

Very significant progress has also been made in understanding the wave generation, properties, and propagation needed for global diffusion models and reanalysis tools. For example, Li et al. [T2013] recently reported the azimuthal propagation properties of chorus in the inner magnetosphere. On the other hand, hiss waves are a major loss mechanism for relativistic electrons. Following earlier successes in tracing the origin of hiss in morning chorus patches [Bortnik et al., T2011; Chen et al., T2012], the THEMIS team discovered new hiss waves at high L-shells (L~9-10) in the outer magnetosphere fed by extended dayside chorus patches [Li et al., T2015]. Additionally, in a JGR Editor's highlight, Kim et al., [T2015] (Fig. 2N) showed how hiss intensity during storms is independent of whether a storm is CIR or CME driven, but primarily depends on the IMF B_z orientation during the storm. Again this signifies the importance of chorus-generating substorm-type injection processes for promoting and maintaining hiss wave amplitudes. Such studies promise a future in which we can model hiss amplitudes as a function of chorus amplitude, or as a function of nightside injection rate and plasma properties, or as function of solar wind drivers. Motivated by THEMIS analysis of loss-cone flux profiles and occurrence statistics, a global hiss-wave model has been developed based on data from the polar-orbiting POES fleet [Li et al., 2013] to aid global studies of wave amplitudes in the upcoming optimal HSO era.

With an increased physical understanding provided by these and future studies and methods, assimilative models

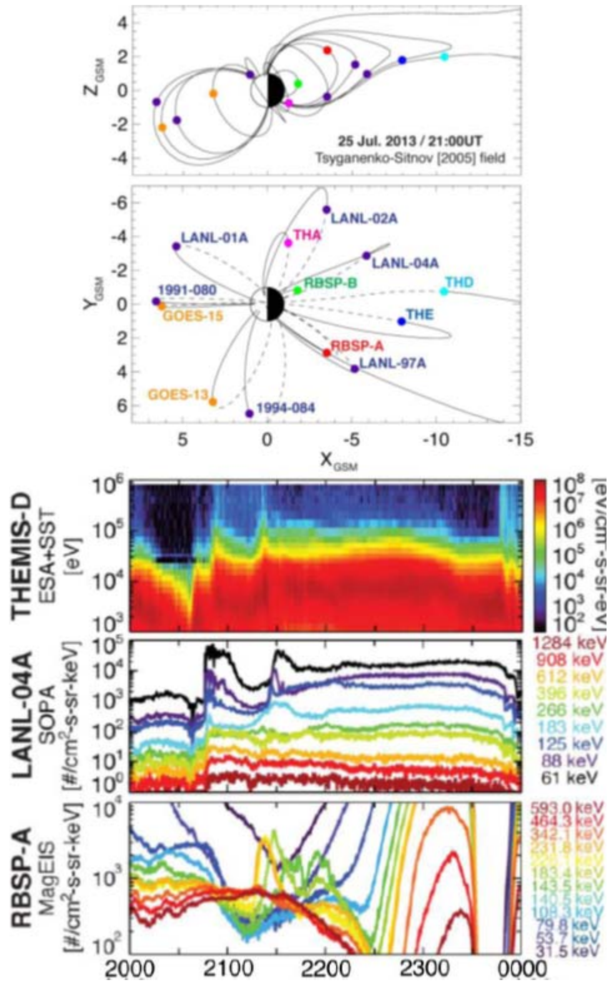

Figure 2M: THEMIS is the only mission that can provide both the plasma sheet inputs to the inner magnetosphere and the evolution of radial phase space densities from passes through the radiation belts (once/12hrs when clustered, faster when separated along-track). Here the source of electron injections seen by RBSP-A at 21:30 (L~4) is traced through LANL-04A to TH-D, but is not seen at TH-E, showing the localized nature of injection fronts [Turner et al., T2015]. This confirms the current paradigm that the rate, intensity and extent of multiple localized reconnection fronts are responsible for space weather phenomena. Thus, a system-wide approach is needed to understand and characterize geospace – making the HSO concept not just a programmatic imperative but a necessity for the field's advancement. In conjunction with the Van Allen Probes, GOES, ground based assets and upstream monitors, THEMIS provides the precise observations that our field needs to tackle the complex problem of storm geoeffectiveness. THEMIS observations of high L-shell sources, PSDs, losses and waves represent a once-in-a-lifetime opportunity for an advanced, optimized HSO. Tools developed by THEMIS but adapted for joint analysis (SPEDAS, used for plotting the bottom panels and for analysis) make scientific collaborations far more efficient and powerful.

can be built to use all the above observables, emphasizing either increased fidelity or advance forecast time depending on the monitor available. In combination with other HSO assets, THEMIS correlative studies from multiple vantage points (out to and beyond L~12) will advance our understanding of inner magnetosphere particle acceleration, transport and losses. Specifically, *THEMIS is unique amongst all HSO assets in providing radial space density information out to large distances in the current peak and upcoming declining phase of the solar cycle. On the nightside, THEMIS will measure the injections that drive chorus, EMIC, and hiss wave growth in situ, while on the dayside it will measure the ion foreshock transients and upstream waves that power electron flux-enhancing ULF waves and the sudden dynamic pressure enhancements that compress the magnetosphere and thereby enable rapid magnetopause shadowing of inner magnetosphere fluxes.*

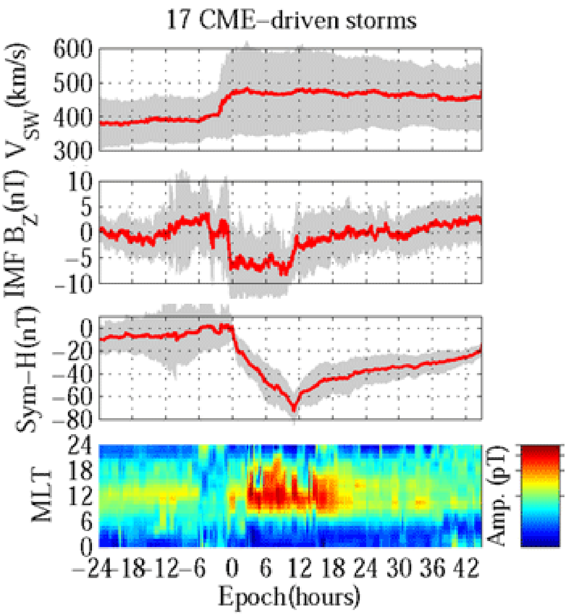

Figure 2N: CME storms (shown above) and CIR storms (not shown) are equally responsible for hiss waves because such waves correlate best with the IMF Bz over the last 3 hrs, regardless of the type of storm. Adapted from Kim et al. [T2015; JGR Editor's highlight].

2.4 Global connections

With the increased availability of TEC monitors SuperDARN radars, and red-line imagers in combination with THEMIS ground-based observatories, a new perspective on the inter-connected processes of the coupled magnetospheric system has emerged. This new paradigm suggests that regional activations (reconnection driven but also potentially dayside transient or dynamic pressure pulse driven) on the dayside have direct counterparts on the nightside. While this may disagree with our pre-conceived notion of connection times through high latitude convection there is mounting evidence that connections are faster than anticipated and such a direct link may, after all, be possible. Such is the exploratory nature of research that we are compelled to follow this lead by coordinating existing capabilities and anticipate that even if this lead ultimately proves incorrect, it surely opens up a new window into global connections, the timescales and physical processes involved.

Walsh et al., [T2014] recognized that plumes entering dayside reconnection regions result in enhanced density ionospheric patches moving into the polar cap (Fig. 2O). Since then more TEC studies have revealed the critical role of dayside reconnection and have followed subauroral polarization streams from the pre-midnight/dusk sector back to dayside plumes entering the high latitude cusp and polar cap [S. S. Zou et al., 2015]. Pulsed reconnection is also evident in broken up patches entering the polar cap. These observations reveal global magnetospheric dynamics at play, and are invaluable tools for addressing global forcing of local instabilities, and effects of kinetic phenomena back into the global circulation.

Around the same time, it was recognized that the nightside polar cap is also replete with airglow patches moving anti-sunward at high speeds (500-1000m/s). These patches (Fig. 2P) emanated from the dayside cusp airglow and had some intriguing association with poleward boundary intensifications (PBIs) suggesting participation in the nightside reconnection process. The patches, whose speeds were confirmed by radar measurements, are simply evidence (tracers) of fast ionospheric flows amidst slow polar cap convection, as the re-excitation timescale of the red line permits the airglow to continue over the tens of minutes' time it takes the patch to traverse the polar cap.

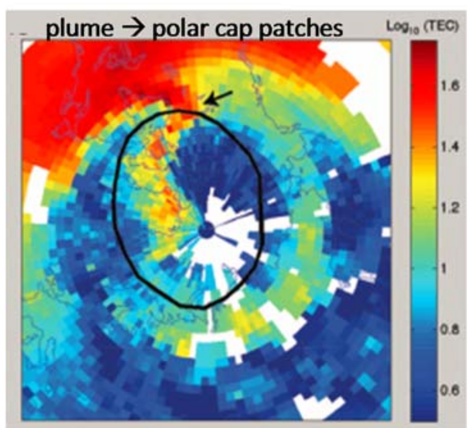

Figure 2O: Enhanced density ionospheric patches move into the polar cap in the aftermath of plume-magnetosheath reconnection measured by THEMIS at the dayside magnetopause. Such patches can be traced ("imaged") through the polar cap [Walsh et al., T2014] by increasingly available TEC map methods, potentially connecting phenomena on both sides of the magnetosphere.

PBIs initiated by polar cap patches are often the source of streamers that initiate substorm onsets in the (now) "classical" sequence of streamer-initiated substorm onset [Nishimura et al., T2011]. The interaction of these dayside airglow patches with the poleward boundary, and the nightside oval motivate a novel picture of global magnetospheric connections. They suggest that regional *magnetospheric* dayside fast flows created by regional magnetopause reconnection rate enhancements protrude into the polar cap and are accelerated to high speeds and are immersed into the lobe plasma. Reaching the nightside plasma sheet, they then induce nightside reconnection. But how does this happen? Do the fast lobe flux tubes sink into the plasma sheet due to their inertia from the slingshot accelerated dayside reconnection? Do they simply radiate fast mode waves that induce nightside reconnection that sucks the plasma inward towards the neutral sheet?

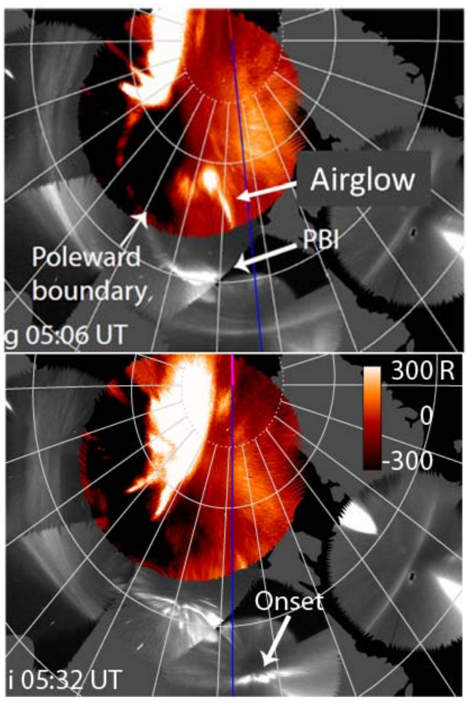

Figure 2P: Dayside airglow has a de-excitation time of several minutes. Fast ionospheric flows produced by dayside reconnection transport bright airglow from the dayside cusps into the dark polar cap. Red-line imagers at Svaalbard, Resolute Bay (shown above) and other sites [Shiokawa, website] monitor fast flows into the polar cap. These airglow patches cause auroral intensifications (top), streamers and eventually (bottom) substorm onset when they interact with the nightside polar cap boundary [Nishimura et al., T2014b].

To make matters more interesting, previous researchers had already suggested a connection between another polar cap phenomenon and PBIs based on global (space-based) imaging: Murphree et al., [1989] pointed out that polar cap arcs are occasionally linked with such intensifications. Indeed THEMIS researchers have explored this connection as well, using imagers, radars and low altitude satellites (Y. Zou et al., 2015, Fig. 2Q). They found that 89% of polar cap arcs are associated with PBIs, and of those a small fraction (13%, all related to thick ovals) lead to substorm onset, whereas the others (thin ovals) result in simple PBI latitudinal expansion but no classical (low latitude) substorm. Such polar cap arcs are typically exhibit soft precipitation on one side, i.e., are bounding closed plasma sheet field lines. The precise connection of the plasma sheet boundary with the nightside plasma sheet location and process that is activated during a substorm remains to be determined. However, the arcs again clearly connect dayside phenomena to nightside activations, and provide an important context within which to place concurrent dayside and nightside observations. Future space-based activations at the dayside/MMS or THEMIS and nightside/THEMIS or MMS must be understood within this context, in particular with the increased availability of these datasets both in the northern and in the southern hemisphere.

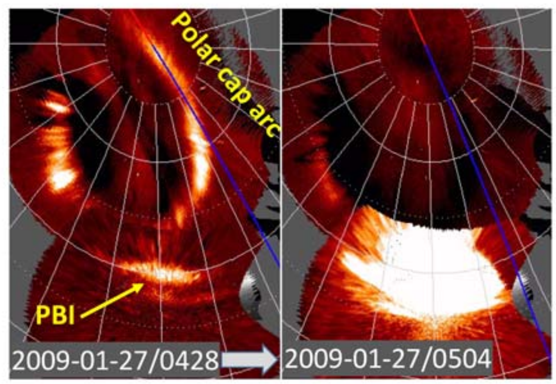

Figure 2Q: Airglow patches are not unique in causing PBIs. Murphree et al. [1987] reported that polar cap arcs induce night-side plasma sheet activations. These have been recently studied more extensively [Y. Zou et al., 2015] but their relation to dayside reconnection and the plasma sheet processes leading to nightside activations remains unclear. Concerted ground-space correlations from disparate parts of the systems (dayside/MMS, nightside/THEMIS; or both MMS and THEMIS at the magnetopause flanks at different X_{GSM} locations) are needed to address such questions. (Data courtesy: Y. Zou, K. Shiokawa, K. Hosokawa).

In summary, new information from both ground and space suggests that the two primary drivers of magnetospheric activity (dayside and nightside reconnection) are intimately interconnected. Regional flows on one side move across the system to impact flux and energy via regional flows at the other. Complete circulation of the flux can now be followed by radars and TEC measurements enabling an advanced understanding of both local, kinetic processes and how they are driven by and, in turn, affect the global system. An optimized HSO is required whereby MMS and THEMIS on the dayside and nightside magnetosphere explore how kinetic processes take place in combination with other HSO space-based and ground based assets. Without careful orbit design and implementation, a strategy that optimizes the THEMIS residence in the plasma sheet, near apogee and in view of the ground based observatories at the nightside when MMS is at the dayside magnetopause, such coordinated measurements would be impossible. Once the optimal conjunction times are identified and maneuvers planned, care must be taken such that the ground based community is notified of optimal HSO times to collect high-cadence, high-quality data. The THEMIS team is fully committed to advance the field to its next level of discoveries and meet the challenges laid upon us by recent findings. A coordinated approach amongst the disparate assets is the only way for the field to proceed forward, else the Heliophysics resources would remain un-optimized and the opportunity for a golden era in space research will be missed. Heliophysics gets only one chance to do this right for the benefit of a generation of space scientists. The THEMIS team is prepared to do its part, as is explained in the next section.

3. Science plan

Recent THEMIS/ARTEMIS discoveries reinforce the view expressed in the HPS Decadal Survey and NASA's Science Plan that implementation of an Optimized HSO is imperative for the field of Heliophysics. Here we describe the optimal plan for addressing this critical need (PSG#1). We also describe the sub-optimal plan "Baseline HSO" (PSG#2), the "Go-it-Alone" plan (PSG#3) that relies on fortuitious, hence unoptimized conjunctions between HSO elements, and finally the scientifically decimated THEMIS implementation that is consistent with the present guide.

As spelled out in the aforementioned NASA documents, the primary goals of the Heliophysics (HPS) Division are to understand the fundamental space environment processes that determine planetary habitability and the space weather effects that result from solar variability. Space physics lies at a crossroads: First, we now understood that kinetic processes in the magnetotail, on the dayside, and in the inner magnetosphere have global (system-wide) consequences for energy coupling and dissipation. Second, an unparalleled opportunity to coordinate current and upcoming multi-spacecraft missions during the active and most interesting phase of a solar cycle is emerging. Going beyond the ISTP era, which employed single, isolated probes to establish global connections on long time-scales, the nascent HSO composed of multiprobe missions THEMIS, MMS, Van Allen Probes, and many missions, builds upon an emerging scientific paradigm of global coupling through transient, regional flows and targets an even deeper understanding of how kinetic microphysics and regional plasma physics like vortices and gradients are affect and in turn are affected by global connections. We now have an opportunity to conduct true cross-scale science for the first time, and it is an opportunity that will not arise again for decades. The ability of THEMIS to adjust its orbits and optimally link HPS's assets can lie at the heart of the HPS Division's response to the call by the HPS Decadal Survey to optimize its network of missions to address system science. The potential for an HSO from the proposed THEMIS orbit adjustments and the concurrent availability of ARTEMIS lies beyond simple alignments and datasets. The grass-roots and mature SPEDAS software provides a comprehensive data integration solution. The software plug-ins already developed for many space and ground-based datasets beyond THEMIS serve as a model for upcoming missions and have already been underwritten by the MMS and Van Allen Probe PI teams. By enabling efficient data tool exchanges (far beyond data and plot sharing), SPEDAS enables high-level scientific interactions and therefore community integration.

The overarching scientific questions are driven by the fact that we presently do not know the details of how global forcing drives local processes. For example global flux transport in the Earth's lobes over 10s of R_E in the mid-tail is related to electron-scale conversion at reconnection fronts over 10s of km in the near-Earth region, yet only now can we begin to piece together this relationship from simultaneous measurements at disparate locations. Similarly, seemingly uninteresting intervals of pristine solar wind can drive dramatic variations in the pressure applied to the magnetosphere and recurrent large amplitude ULF waves at geosynchronous altitude. In the inner magnetosphere, hiss waves directly powered by chorus leakage into the plasmasphere work against chorus and nightside localized injections to establish the geoeffectiveness of a given global solar wind input. Key to the generation of these waves is the rate and intensity of localized injections from the nightside. Yet the injections themselves may be driven by dayside reconnection rate enhancements - if we are to take our ground-based imaging of airglow patches driving PBIs at face value. So simultanous kinetic measurements are needed at key magnetospheric locations (dayside-nightside-inner magnetosphere), together with ground observations to establish context and reveal the global connections. The availability of ARTEMIS as a high-fidelity global flux monitor when in the tail and a pristine solar wind monitor (unaffected by the transients that are themselves the point of further study) presents a critical asset for the space physics discipline, beyond ARTEMIS's in situ contribution to kinetic studies of reconnection fronts, upstream particles and plasmoids.

3.1 Implementation strategy

The considerations above suggest that only a coordinated observational strategy bringing together multipoint missions with a well-choreographed strategy can provide high-quality results that take full advantage of the developing

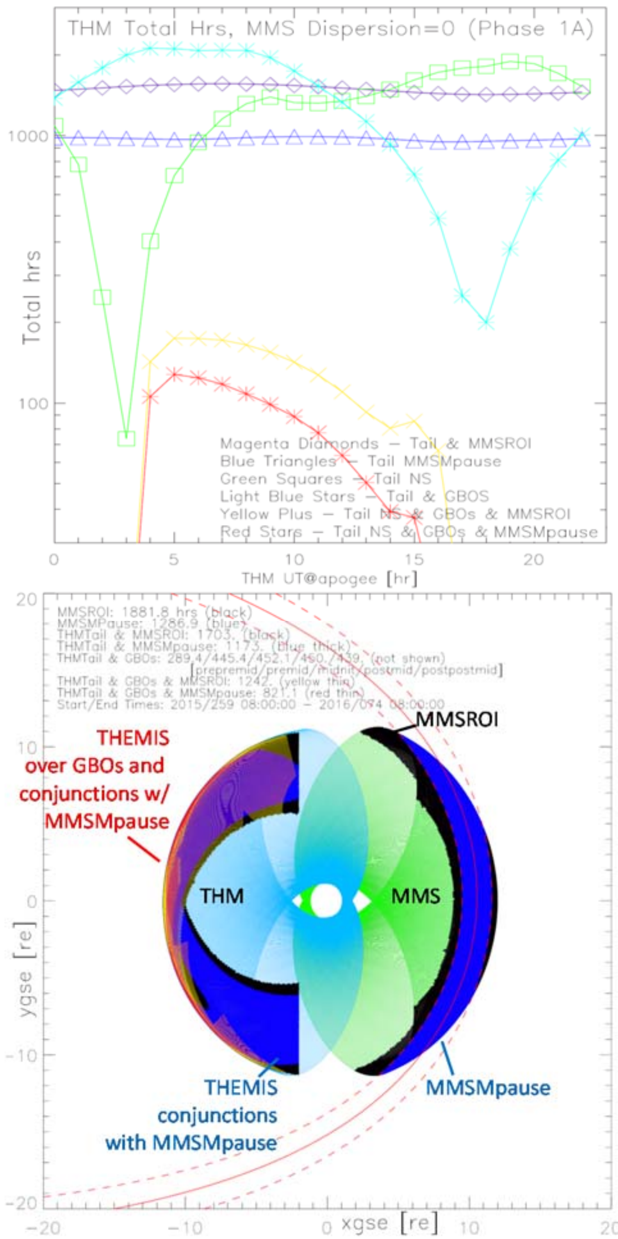

Figure 3A: Top: For nominal MMS launch the THEMIS mean anomaly (parametrized as UT@apogee for reference time when apogee is at 23LT) can be adjusted to optimize THEMIS in the tail (Tail) conjunctions with MMS regions of interest (MMSROI) or magnetopause crossings (MMSMpause). Yellow and red stars mark THEMIS tail neutral sheet and GBO conjunctions simultaneous with MMSROI and MMSMpause, respectively. Conjunctions peak for THEMIS phases when THEMIS is at apogee between 4UT and 8UT. Based on these conjunction locations we chose 8UT for THEMIS at apogee as the optimal mission design solution. Bottom: For the optimal THEMIS design the locations of the GBO conjunctions with MMSMpause crossings are the red/magenta colors on the left and last >800hrs (>100hrs when THEMIS is near the neutral sheet). Dispersion does not affect yields.

Heliophysics System Observatory. As explained below, THEMIS's approach is to help the discipline do just that.

First, THEMIS on the opposite side of the magnetosphere from MMS, will use its fuel to change its orbit period and phase (a.k.a. "mean anomaly") to be near apogee routinely when MMS is also near apogee, thus optimizing nightside near-neutral sheet observations of reconnection fronts and jets when MMS simultaneously observes magnetopause crossings. Maneuvers have been planned to optimize THEMIS conjunctions with the nominal MMS orbit. Our orbit predicts show (Fig. 3A, for MMS Phase 1A on the dayside in FY16) that high quality conjunctions are possible with MMS for a wide range of THEMIS orbit designs (MMS dayside/THEMIS tail). Placeholder maneuvers have been planned to change THEMIS orbit periods and mean anomalies to match those of MMS in the event launch vehicle dispersions shift MMS away from its current orbit plan: our phasing plan is robust to three-sigma MMS launch dispersions and such dispersions have been accounted for in the THEMIS maneuver plan. Our good coordination with the MMS mission design team allows rapid delivery of definitive MMS orbit elements (~3 weeks after MMS launch) in time to definitize these maneuvers.

Second, THEMIS plans to work with the ground based community to take advantage of the imminent, unprecedented space-ground conjunction opportunities (Fig. 3B). A mini-GEM session at the 2014 AGU meeting was attended by more than two dozen ground observatory leads or affiliates. THEMIS plans an HSO coordination and ground assets optimization session at the upcoming GEM meeting to finalize the plans and coordinate campaigns. Stronger ties with CEDAR are envisioned in light of these developments, given the importance of TEC, radars, and optical observations. The THEMIS/NASA side need only supply in-kind support (data sharing and coordination).

Third, THEMIS will employ a two-pronged approach to obtain the high-time resolution observations needed to study kinetic phenomena. On the one hand, THEMIS will continue its increased Fast-Survey captures using the extra time available from the White Sands antenna WS1. Due to lack of funding from SR13 this has been a best-case-effort with a target of 20hrs/day of FS collections (up from the nominal 12hrs/day). Nonetheless it has resulted in a marked increase in data quality and will be further improved in the future as team experience with WS1 scheduling matures and as new NASA ground assets (Singapore and South Africa) are certified with THEMIS team help at no additional costs. On the other hand, THEMIS proposes to use DSN to capture continuous high-cadence, 8-16kS/s waveforms ("Ultra-Fast Survey", or UFS) simultaneously on all three Earth-orbiting spacecraft. The rationale here is that higher time resolution phenomena (solitary waves) require high frequency wave captures; until recently THEMIS has been relying on limited, 6-12sec duration, wave burst collections. The problem with such on-board trigger based collections is that the results are predicted on a specified trigger and cannot provide an unbiased set of observations. This is particularly true for solitary waves that are spiky and broadband in Fourier space. These defy automated recognition as they are assigned lower significance by nominal burst schemes.

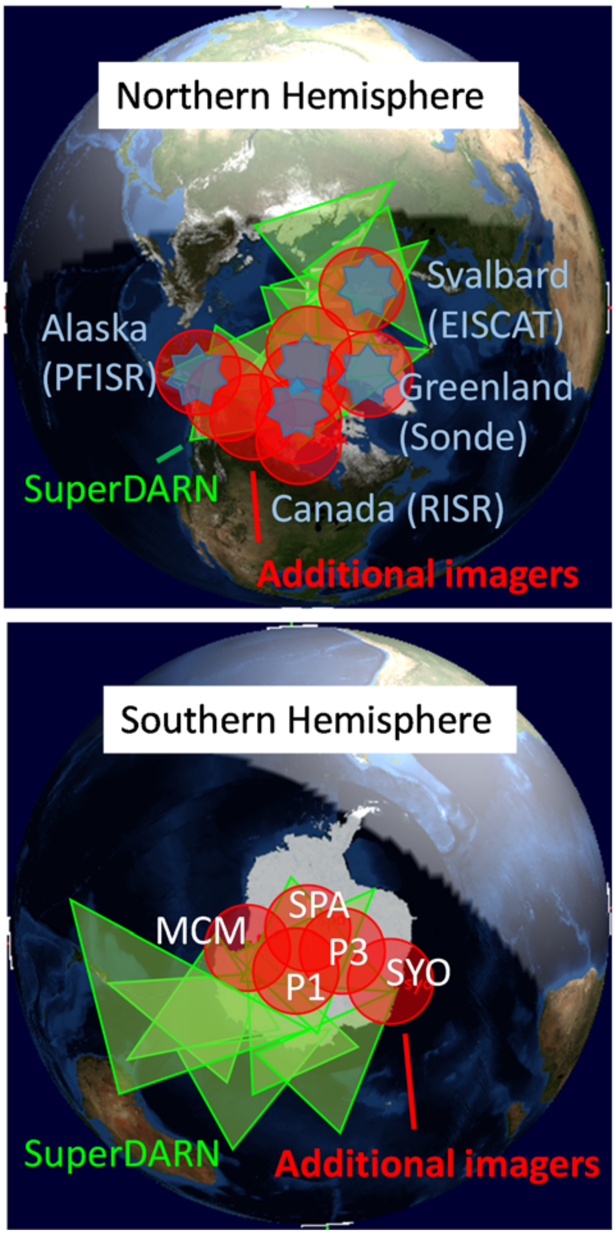

Figure 3B: Assets available to the coordinated Optimal HSO plan. Beyond the THEMIS ground-based observatories (a network of 20 white-light cameras in Alaska and Canada that are fully functional and ideally positioned to image during the next 5 winters when THEMIS is in the tail), the "additional imagers" represent red-line (Svalbard, Resolute Bay, SPA, …) and white light imagers that can monitor the cusp and polar cap during northern or southern winter. SuperDARN and other Incoherent Scatter Radars are well positioned to support NASA's HSO investigations, if optimally coordinated.

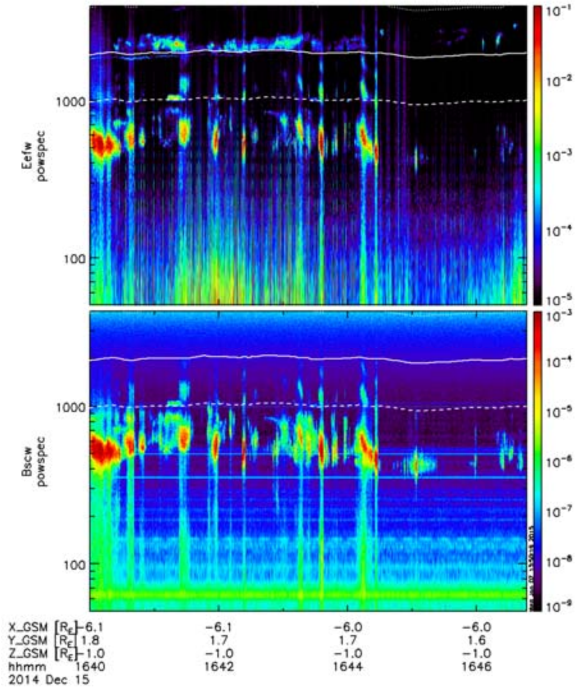

Figure 3C: Spectra from continuous (7min-long) waveforms (E & B) captured on THEMIS in preparation for Optimal HSO operations (solid line = f_{ce}; dotted line = $0.5*f_{ce}$). ECH, lower and upper band chorus bursts, solitary waves (appearing as broadbanded "spikes") are evident. Continuous waveforms free us from preconceived notions of the relative importance of various modes, reflected in our trigger choices for nominal waveburst captures. THEMIS will capture waveforms for 1hr/day simultaneously on all 3 inner spacecraft using DSN, in all critical regions (nominal magnetopause, tail and inner magnetosphere).

Therefore the THEMIS team has started to experiment with dedicated use of the entire on-board memory for UFS captures (7min at a time, Fig. 3C). Downlink through the WS1 antenna once per orbit is sufficient to achieve this result – this has already been tried on two dozen passes, including multiple spacecraft. Further increase of UFS waveform collections to up to 1hr per spacecraft will require DSN time (an additional 3 hrs per day) and will be tested at the dayside magnetopause if approved by this Senior Review. The implementation will match on-board collection and DSN downlink rates to avoid on-board memory saturation. UFS waveform collections promise to revolutionize our understanding of kinetic processes, in light of recent discoveries of the role of kinetic phenomena on electron acceleration and scattering [Angelopoulos et al., T2013; Oieroset et al., T2014; Mozer et al., 2014] even when studied from THEMIS's ion-scale separations.

3.2 The Optimal HSO (PSG#1)

The overall five year plan for the Optimal HSO is shown in Figures 3D (for FY16/17), 3E (for FY18/19) and 3F (for FY20). Unique, high-quality science that addresses the critical needs of the discipline and the aforementioned objectives is possible during this 5-year period. The overall idea is to coordinate the THEMIS positions such that when MMS is at low apogee (MMS Phases 1A, 1B, i.e., MMS dayside observations in FY16 and FY17 respectively) one or more THEMIS (low) probes (P3, P4, P5) will be locked to the same period or will be resonant with the MMS period such that conjunctions of the two fleets near apogee will occur frequently. Additionally, when THEMIS (low) probes are in the tail they need to be in view of the highly-instrumented North American sector and optimize conjunctions with the neutral sheet. Finally, THEMIS will need to be brought to higher apogees to study the critically important but under-explored tail and dayside region between 12-16R_E. When MMS apogee is raised to 23R_E (Phase 1B and beyond) the THEMIS plan is raise its apogees but maintain resonant orbits with the GBOs on the nightside, as those provide global context. However, the remainder of the time (when MMS is at the nightside or when both missions are at dawn or dusk) the plan is for the THEMIS orbits to be MMS-resonant. During the entire period ARTEMIS will transit the magnetotail for four days/lunar month and spend at least 2 weeks/month in the upstream solar wind. ARTEMIS is thus depicted as the 2 spacecraft on the right (tail) or on the left (dayside) and will be available in all configurations. The figures also show Van Allen Probes (VAP) up to their end-of-mission and Geotail and Cluster for the first 6 months.

Fig. 3D shows the plan in FY16. During MMS Phase 1A (dayside), shown at the top left, the THEMIS spacecraft will be clustered in the tail at ion scales with 100 – 5000km separations, nominally crossing the neutral sheet near apogee at ~8UT in excellent view of the ground based observatories. Since this happens in mid-winter, THEMIS GBOs will have optimal viewing (dark night) conditions. The same is true for red-line cameras at Svalbard and Resolute Bay. From these vantage points, MMS will study electron kinetic phenomena, THEMIS ion kinetic phenomena, and VAP ion and electron injections. Svalbard red-line cameras imaging the dayside cusp (optimally around 5-8UT) and SuperDARN radars will monitor dayside regional activations. Red-line imager Resolute Bay and SuperDARN or other radars and THEMIS GBO (white light) cameras will observe the polar cap ionospheric flows that link dayside and nightside regional activations.

When THEMIS is at dusk (Fig. 3D top, middle panel) the spacecraft separations will increase to several hours along-track to enable simultaneous string of pearl mode sampling of the inner magnetosphere with MMS on either side. P5's apogee will be raised to 13.2R_E where it becomes MMS-resonant but also builds differential precession with P3,4. The intent from the variable separations is to explore the global connections of chorus, EMIC, hiss and other waves as well as injections (evident in dispersed particle flux enhancements) and determine how they conspire to control storm geoeffectiveness. When THEMIS is on the dayside the same orbit strategy ensures frequent alignments with MMS. South Pole station will be ideally positioned to observe dayside activations corresponding to THEMIS events. Those MMS instruments that operate in the mission's tail Phase 1x can explore the boundary layer activations that occur in response to dayside reconnection measured by THEMIS.

In FY17, shown at the bottom of Fig. 3D, the tail phase of THEMIS (bottom left, MMS dayside, Phase 1B) now has the spacecraft exploring a wide range of separations, from a few thousand km (between P3 and P4) up to several R_E (P5 and the others). P3, 4 being period-locked to MMS guarantee residences near magnetotail apogee that lie in view of ground observatories, similar to FY16. Additionally P5 is also MMS resonant, such that once per 5 orbits P5 is also near apogee along with P3,4 when MMS is crossing the magnetopause. This guarantees exploration of wider spatial scales in the magnetotail, enables THEMIS to follow the evolution of phase space density of injected plasmas and ensures that at least one spacecraft is at high L-shells all the time, providing observations of the plasma sheet sources for VAP, thus enhancing the capabilities of an Optimized HSO.

When THEMIS apogee lies in the dusk sector in 2017 (Fig. 3D, bottom, center) MMS will be increasing its apogee to 23R_E in the dawn sector and busy with complex maneuvers. THEMIS will then center its observational campaign on understanding inner magnetosphere processes, particularly those pertaining to electron losses, by either magnetopause shadowing or EMIC waves and microbursts. Conjunctions with VAP will be particularly opportune at the same longitude, especially if they are accompanied by continuous waveform captures on all 5 spacecraft and coordinated with observations from ground VLF stations and ionospheric monitors of precipitation (POES, ELFIN).

When MMS has raised its apogee to 23R_E and is in the tail (MMS Phase 2B), THEMIS will create resonant orbits with MMS so that its magnetopause reconnection observation coincide with MMS tail reconnection observations. Because the residence time of MMS near apogee is long (~24 hours) the UT@apogee of THEMIS waveform collections and magnetopause crossings will be planned to optimize concurrent ground based observations.

In FY18-19 (Fig. 3E) THEMIS will increase its apogee to ~16R_E to address questions concerning the magnetotail energy conversion during substorms and the emergence, evolution, and effects of dayside transients, both in conjunction with ARTEMIS when on the same side of the Earth, and in conjunction with MMS on opposite side. In particular THEMIS will acquire periods resonant with the GBOs on the nightside (left panels).

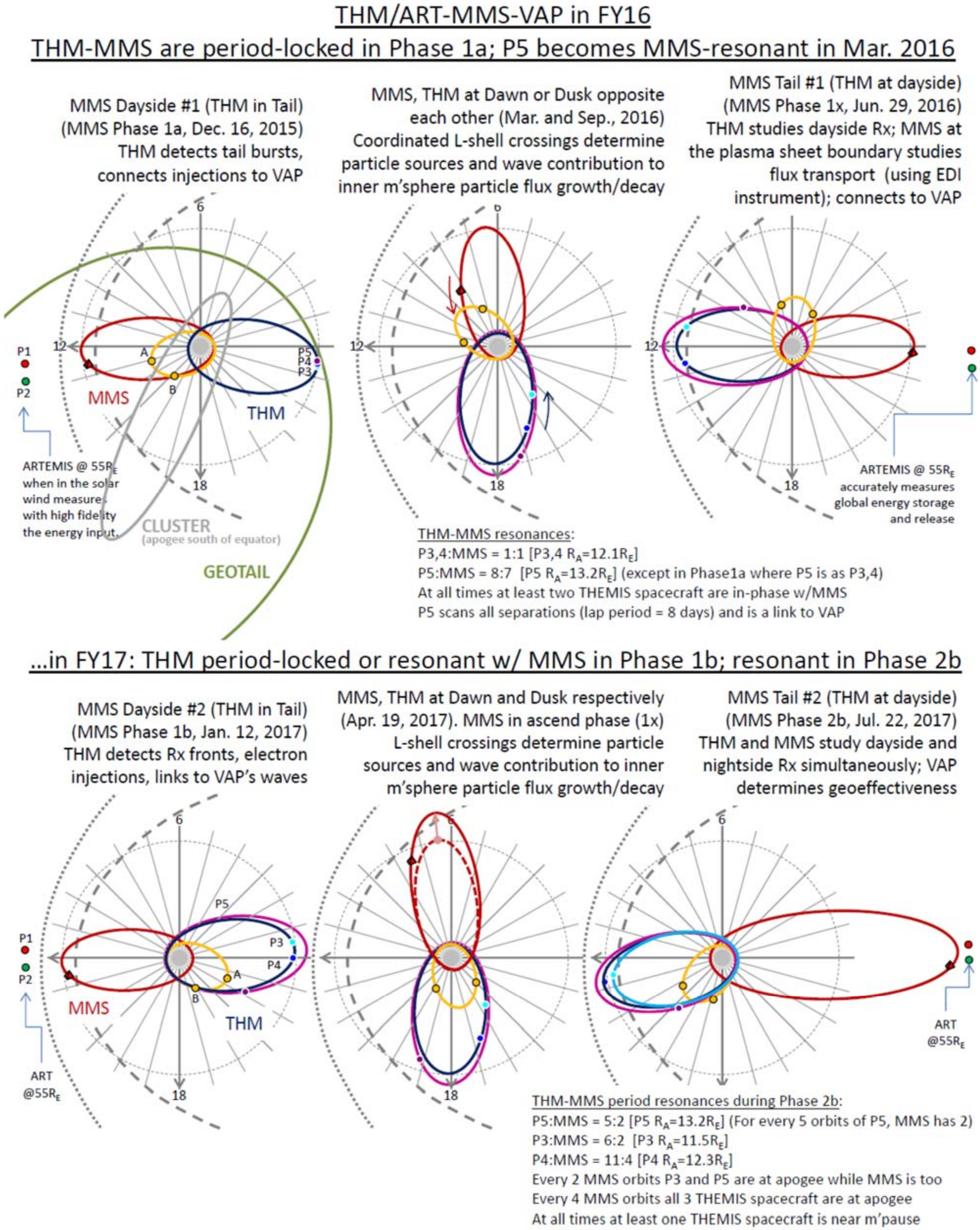

Figure 3D: Optimal HSO (PSG#1) constellation for FY16/17. THEMIS uses its fuel resources to permit studies of reconnection-related kinetic phenomena at electron (MMS), ion and MHD (THEMIS) scales simultaneously with their global drivers/consequences.

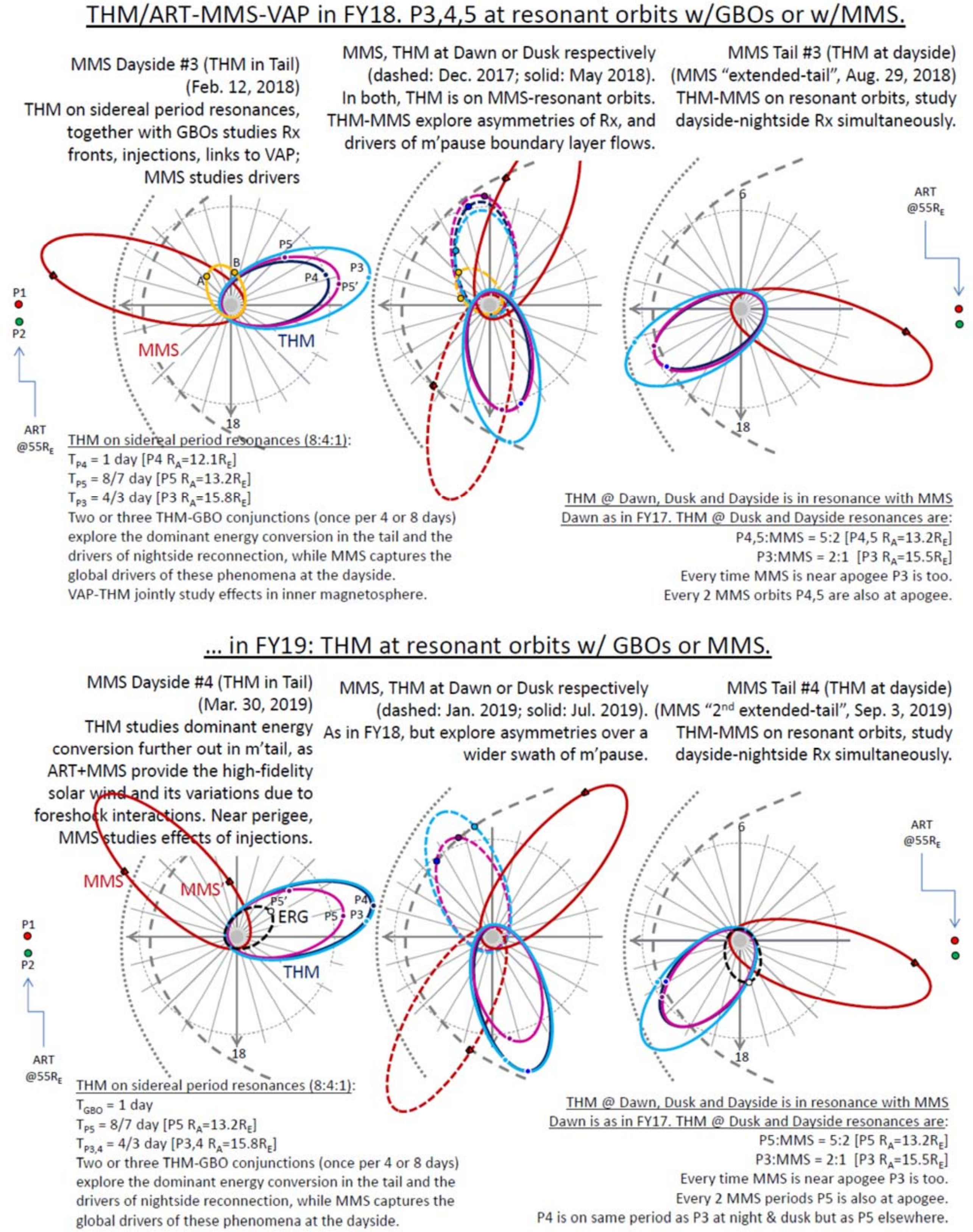

Figure 3E: Optimal HSO (PSG#1) constellation for FY18/19. From 12-16 R_E apogee THEMIS studies jointly w/ MMS the dominant energy release in the magnetotail, and the relation of dayside transients to magnetospheric energy coupling and tail reconnection.

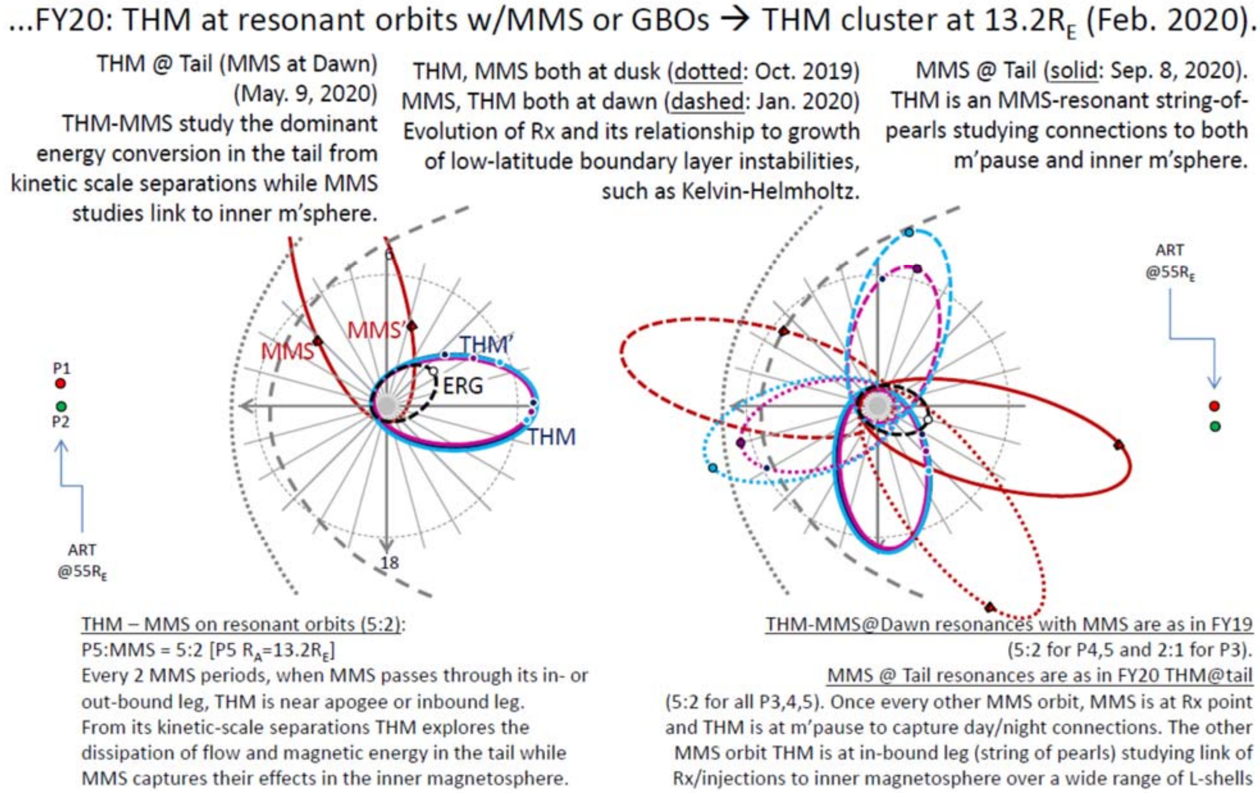

Figure 3F: Optimal HSO (PSG#1) constellation for FY20. THEMIS uses its fuel resources to permit studies of reconnection-related kinetic phenomena at electron (MMS), ion and MHD (THEMIS) scales simultaneously with their global connections. In particular THEMIS studies the kinetic aspects of particle heating by injections and their effects at electron scales at the inner magnetosphere; additionally both missions study the growth and evolution of reconnection phenomena pertaining to Kelvin-Helmholtz waves as function of down-tail distance at the flanks.

When on the dayside THEMIS will acquire periods resonant with MMS but with appropriate planning for GBO conjunction optimizations to reveal the effects of dayside and magnetopause activations on nightside reconnection and global energy circulation. Although the VAP mission will end by FY19, the Japanese mission ERG (dashed black orbit) will be in-position to complement THEMIS's measurements deep in the inner magnetosphere. ERG uses SPEDAS tools for analysis and scientific collaboration has already begun. The same MMS-resonant strategy as in the tail will be employed by THEMIS on its dawn and dusk magnetopause crossings (middle panels, top and bottom in Fig. 3E), when THEMIS and MMS will have (assuming proper coordination enabled by THEMIS's fuel reserves) the unique opportunity to explore the dawn-dusk asymmetries of magnetopause reconnection, particle and momentum transport and contributions of the low-latitude boundary layer to global flux circulation.

During the first 6 months of FY20 (Fig. 3F), THEMIS will study the evolution of magnetopause reconnection as a function of distance on the *same* side of the magnetosphere as MMS (Fig. F, right panel, dotted lines = dusk flank; dashed lines = dawn flank). This coordination is possible due to the resonant orbits and the mean anomaly control afforded by the THEMIS fuel reserves and the capable and efficient THEMIS mission design team. After the first 6 months, THEMIS will change its apogees to a common, 13.2R$_E$ apogee between its inner probes and acquire a string-of-pearls configuration to explore the energization and transport of particles into the inner magnetosphere from a range of ion kinetic-to-MHD scales, either from the source side (left panel) or from the local acceleration side (right panel) in close collaboration with MMS. THEMIS's mission design strategy and the anticipated availability of the ERG mission will ensure, for the first time in the summer/fall of 2020, a direct exploration of the connection between tail reconnection (MMS) to injections in the outer magnetosphere (THEMIS) to the inner magnetosphere (ERG), an exploration that was not possible even during the prime THEMIS mission.

3.2.1 On the nightside. From their unique vantage points in the equatorial magnetosphere (left panels in Figures 3D, E, F) THEMIS and ARTEMIS, will address how kinetic processes in the magnetotail related to tail reconnection (injections, reconnection fronts, near-Earth turbulence, heating, flow-shear and pressure increases) operate and how they interact with the global system. These measurements will be accompanied by optical and ground radar measurements revealing the ionospheric precipitation (diffuse, discrete, pulsating or proton aurora) and electric fields (by means of SuperDARN flows) that provide both the dissipation rate and the geophysical context.

In FY16 THEMIS's kinetic scale separations and high-quality waveform captures will determine how electromagnetic energy from collapsing flux tubes is transformed into particle kinetic, thermal energy, Poynting flux and waves. Particle acceleration by local waves (whistlers, kinetic Alfvén waves) will be studied in a regional context. Local cross-tail current density measurements will be compared with pressure gradients and flow shears at the three nearby spacecraft to determine how field aligned currents are driven and how the cross-tail current is diverted into the auroral ionosphere. The relationship of that current diversion, and ionospheric dissipation to the magnetopause flaring angle and total energy content will be revealed.

In FY17 as larger spatial scales are achieved, THEMIS will explore particle acceleration at the turbulent sites created by the breakup of individual flux bundles or by the accumulation of multiple bundles. During this period and in conjunction with VAP, GOES and LANL data, ideally operating ground imagers, THEMIS will address what dictates the innnermost propagation of flux bundles, how bundles break up, and how they drive space weather phenomena in the inner magnetosphere. As THEMIS extends its observations to higher apogees it will readily explore the evolution of the active aurorae and their drivers in the magnetosphere, as measured by pressure gradients, flow shears, and kinetic or MHD scale waves. These will be compared to global energy release as measured by ARTEMIS (when in the tail).

Using THEMIS observations in the magnetotail plasma sheet or boundary layer when MMS is at the magnetopause, and the unprecedented capability available to the Heliophysics HSO to monitor dayside reconnection and its global effects via ground imaging (polar cap red-line aurora, SuperDARN stations) the THEMIS team will determine how dayside activations drive nightside reconnection phenomena. For over 800hrs (Fig. 3A) of THEMIS – MMS conjunctions THEMIS will be in the boundary layer and for >100hrs near the neutral sheet directly measuring the regional activations (PBIs or reconnection fronts) driven by global forcing, and affecting the inner magnetosphere.

Global correlations are crucial for progress. For example, the inability of flux tubes to convect inward past THEMIS due to enhanced entropy may quench the global tail reconnection rate observed by ARTEMIS. On the other hand, the tailward progression of dipolarization past THEMIS and ARTEMIS may initiate a new reconnection site between them when prompted by a new dayside reconnection enhancement causing the remaining stored magnetic flux (monitored by ARTEMIS) to be expelled from the system. Such key questions could never be posed without the simultaneous availability of all HSO assets.

This simultaneous kinetic-global picture will be an unprecedented capability afforded by the Optimized HSO. It will resolve outstanding questions related to system-wide connections and will inform plasma physics, modeling, and future scientific and operational missions.

3.2.2 On the dayside. THEMIS "low" together with ARTEMIS and ground assets (cusp imagers, TEC measurements and ground radars) will progressively and comprehensively address how kinetic processes at the magnetopause and upstream partake in global forcing and energy transportation (Figures 3D, E, F, right panels). In FY16 and 17 these phenomena will be explored from a few 1000km to several R_E azimuthal separations, revealing how localized plumes, evolving HFAs and emergent high-speed magnetosheath jets control the dayside reconnection rate. In FY18-19 THEMIS's observations will expand to encompass the under-studied upstream region. There THEMIS will explore shock-ripples, shocklets, foreshock bubbles and upstream waves and the effect they have on energy coupling in the magnetosphere. For example, it is currently thought that foreshock bubbles are not only ubiquitous but also the most dynamic variations under even steady solar wind velocity and dynamic pressure [Turner et al. T2013; Hartinger et al. T2012]. These features extend far upstream, grow and pick up energy as they approach the shock. The combination of ARTEMIS, THEMIS "low" at 16-12R_E and VAP or ERG lined up along the Sun-Earth line provide a unique opportunity to study both particle acceleration and the spatial evolution of these kinetic phenomena, with applications to fundamental processes across all Heliophysics systems. In particular, these phenomena drive ULF waves and subsequent relativistic flux increases within the magnetosphere, but similar pressure variations in the aftermath of CIRs drive dayside chorus waves that may also play a role in electron energization. Fermi acceleration within foreshock bubbles may be the origin of galactic cosmic rays at stellar and interplanetary shocks. Such phenomena can be studied in situ upstream of Earth's magnetosphere thanks to THEMIS's high time resolution waveform captures in conjunction with ARTEMIS and VAP/ERG. These particles may also contribute to local upstream pressure variations, as well as to enhanced ~10 keV ion fluxes that may seed the production of relativistic particles inside the magnetosphere in the presence of southward interplanetary fields. We will use VAP and ERG measurements to assess whether these particles are "geoeffective" from the vantage point of the inner magnetosphere whether upstream phenomena affect particle acceleration in that environment.

But beyond these objectives, the simultaneous availability of MMS in the magnetotail provides an unparalleled opportunity to study the drivers of nightside reconnection by dayside impulses (including dayside reconnection impulses) in exquisite detail on ion and electron scales simultaneously. The South Pole imagers (SPA) and radars will enable synopic views of cusp and polar cap flows while THEMIS and MMS measure the local kinetic aspects of magnetic reconnection.

Finally, during FY18 and FY19 (Fig. E, middle panels) THEMIS will be on the magnetopause flanks where it will have the opportunity to study dawn-dusk asymmetries of magnetic reconnection with together with MMS on the opposite side, as well as put to the test current theories (e.g., Swisdak et al., [2010]) regarding the rate of reconnection in the presence of significant flow shear. In FY20 (Fig. F, right panel) THEMIS will be on the same magnetopause flank as MMS. From this vantage point it will study the evolution of Kelvin-Helmholtz waves and reconnection as function of distance from the subsolar point. THEMIS's remaining fuel resources will permit nearly co-incident observations of responses to the same solar wind driver along the magnetopause boundary .

The availability of ARTEMIS providing high-fidelity pristine solar wind information when upstream and measuring total flux content and tail reconnection rates when in the magnetotail, and VAP or ERG data providing information on the effects of dayside and nightside processes in the inner magnetosphere creates a system observatory of unparalleled power. For example, while THEMIS is testing reconnection theories on the dayside, the Van Allen Probes will measure the effects of reconnection and pressure or foreshock wave related boundary variations on ULF wave generation and related acceleration of energetic particles in the aftermath of the CIRs that will abound during the upcoming declining solar cycle phase.

3.2.3 In the inner magnetosphere. Going beyond the goals of studying correlations amongst its own P3-P5 spacecraft and fortuitous conjunctions with other assets, THEMIS proposes to be at the forefront of a concerted effort to optimally unite current and upcoming platforms into a common data analysis environment with unprecedented capability. By nearly doubling its highest quality data recovery in Fast Survey, THEMIS will ensure optimal data return (20hrs per day of Fast Survey on P3-P5) such that only rarely, if ever, will low cadences hamper the analysis of interesting events. THEMIS's proposed continuous waveform captures (in addition to its standard burst captures) promises unbiased detection of solitary waves, chorus and other high frequency waveforms that are thought to partake in particle energization or loss during storms. Finally, by matching its orbital period to that of MMS, THEMIS unifies the two high altitude missions into a powerful baseline for an Optimized HSO. For example, the 3 THEMIS spacecraft will cross the radiation belts at dusk as MMS crosses at dawn in FY16 and FY17 (Fig. 3D, middle panels), as well as in FY20 (Fig. 3F, left panel). Moreover, THEMIS's GBOs and ancillary ground based measurements will be optimally situated to observe the pulsating aurorae related to chorus, the subauroral polarization streams and the enhanced ionospheric flow shears associated with THEMIS ion injections and the streamers associated with inner magnetospheric flux enhancements.

THEMIS promises to study drivers of chorus, EMIC waves, hiss and ULF waves that affect radiation belt and ring current growth from its unique vantage points straddling the outer magnetosphere at all local times. For example, the Van Allen Probes can use THEMIS observations to determine if hiss or EMIC waves can be explained as a result of chorus waves and particle injections outside of $7R_E$. Thus the THEMIS team can determine the effects of external drivers on the inner magnetosphere, while the Van Allen Probes team can determine the importance of various drivers for local growth.

This combined "system" approach in which the HSO that is greater than the sum of its parts, represent the key factor that will lead to progress [Turner et al., T2013; T2015]. As Gabrielse et al., [T2012; T2014] point out, transient electric field pulses moving toward the inner magnetosphere from the nightside have the potential to explain not only wave generation and subsequent particle acceleration, but also the seeding of the initial inner magnetospheric flux with 10s of keV "pre-accelerated" electrons that can then be further enhanced to relativistic energies. THEMIS "low" and ARTEMIS plan to be at the center of NASA's systematic attempt to take advantage of the line-up of the field's assets, enabling system-wide studies of inner magnetospheric processes.

3.3 The Baseline HSO (PSG#2)

If the Heliophysics Divison cannot afford the modest funding of continuous ("Ultra-Fast Survey") waveform captures or of the efficiently constructed and disseminated tools for cross-platform analysis of Heliophysics data (a.k.a. Space Environment Data Analysis System, SPEDAS), THEMIS proposes the Baseline HSO, as its PSG#2. This entails all the aforementioned optimized conjunctions with MMS and best-effort attempt to improve FS collection with a target of 20hrs/day, and assumes that the funding level of THEMIS continues as approved by the SR13 decision level-funded through 2020. This enables THEMIS and the Heliophysics community to explore the generation, evolution, global drivers and consequences of kinetic processes at the nightside and dayside. While performing truly cross-scale, system-wide science this plan also retains THEMIS's apogee raise to $16R_E$ to explore this important under-explored region of the equatorial magnetosphere with multi-point observations. THEMIS will be on the nightside in Fall and Winter in the upcoming few years, which brings into play its powerful ground based array of auroral optical imagers in addition to a growing list of ground magnetometer networks from across the world under one analysis system. THEMIS will take advantage of fortuitous conjunctions with Van Allen Probes and GOES, but does not rely on these to complete its goals. Despite the loss of the quality UFS dataset, THEMIS will continue to play a leading role in the coordination of Heliophysics assets towards a well-executed HSO.

3.4 The Go-it-alone plan (PSG#3)

As explained in the executive section, if the coordinated mission design between THEMIS and MMS cannot be funded THEMIS proposes to execute the more modest plan of addressing the critical questions related to global energy conversion by kinetic processes on the nightside and dayside at regions progressively outward from $12R_E$ to $16R_E$, a very important but under-explored region of the equatorial magnetosphere. Only THEMIS probe phasing with each other will be planned and executed in FY16-20, without regard to MMS phasing. Fortuitous conjunctions with MMS may be possible but they are not be guaranteed, implying that simultaneous dayside-nightside, or dawn-dusk observations of the magnetosphere will not be possible. The proposed plan still takes advantage of THEMIS's ground based assets, and by means of planning the appropriate times for GBO conjunctions, it invokes the polar cap imaging and radar capabilities that are possible in the baseline plan. Thus questions pertaining to energy conversion in the magnetotail or magnetopause reconnection sites, and relative importance of upstream phenomena for magnetopause energy coupling will still be addressed. The disadvantage of this plan, however, is that the available fuel is not utilized for coordinating across the entire constellation and therefore does not promote system-wide science or an effective HSO. Therefore questions related to global effects of dayside reconnection, or the global drivers of nightside reconnection, will not be addressed.

3.5 If the guide remains (PSG#4)

As explained earlier, the toll from performing such a drastic (and we believe inadvertent) cut to the mission will be a dramatic decrease in science funding, although THEMIS orbits, mission, and science operations will remain intact. The science toll will cause a decrease in researchers, including a >50% loss of community-wide science, a 60% decrease in THEMIS-led science, significant reduction in student and young researcher participation and a dramatic loss of potential for HSO science.

4. Technical

4.1 Technical

4.1.1 Observatory and instrument status overview As of this writing, the entire THEMIS/ARTEMIS constellation is in outstanding health and performing nominally. Specifically, all subsystems are as good as new. The added knowledge that the operations team and scientists have of their specific characteristics makes data use much more powerful than that for a newly launched mission. The minor technical issues (see below) that have appeared since the last senior review have been resolved with workarounds and without any science degradation.

THEMIS "low" probes P3-P5 are currently in orbits with 23hr periods and inter-spacecraft separations decreasing from 2 and 4 hrs to zero, aiming at 100-1000km separations in the summer of 2015 and for a year thereafter. ARTEMIS probes P1, P2 are in nominal ~18hr period, equatorial, stable lunar orbits (retro- and pro-grade respectively), performing nominal operations for optimal Heliophysics research as per plan. Ground-based observatories (all-sky white-light imagers and magnetometers) continue to operate nominally: in the absence of a Heliophysics remote sensing auroral platform from space they will be increasingly important during the northern winters of 2015-2019 when they will provide global context for the THEMIS and MMS missions. This is becoming possible again because THEMIS apogees will drift back into the magnetotail during winter months in the upcoming years, as they were in the first 3 years after THEMIS launch. By arranging for the THEMIS UT at apogee to range from 2 to 10UT the imagers can be optimally operating in darkness for auroral observations.

After >650 individual thrust operations, >1100 shadow cycles, and approximately 8 years in orbit traversing the radiation belts there are still no signs of any significant degradation in the performance of any spacecraft or instrument subsystem, including the solar array power and battery charge retention. Probe and instrument status is updated in real-time during pass-supports. The last recorded status is seen at: http://soleil.ssl.berkeley.edu/ground_systems/themis_constellation_status.html.

During the last 5 years there have been only three new hardware issues. All have been resolved satisfactorily without any science degradation: 1) A micrometeroid severed one of P1's EFI wire boom spheres on October 14, 2010. Spin-period science can be recovered using the other (unaffected) boom pair and high-time resolution science can still be obtained from potential differences between the remaining 3 spin plane probes; 2) a Helium bubble developed inside one of the tanks on P4 (THEMIS-E) that can be controlled by a few back-and-forth actuations of the latch valves (over the remaining fuel lifetime) when fuel in the two tanks isotropizes again. This operation may need to happen once or twice over the next 5 years of THEMIS operations; 3) The EFI spheres on P5 (THEMIS-A) developed reduced photoemission ability when the perigee of THEMIS-A fell below 600km for a prolonged period, resulting in atomic oxygen oxidizing the sphere surfaces. The spheres recorded increased noise and reduced absolute DC electric field values. Following recalibration and resetting of the bias voltages, instrument performance has recovered. By maintaining the spacecraft's perigee above

600km, we will ensure that the THEMIS-A spheres either anneal due to UV radiation or at least suffer no further oxidation (which means that current settings are adequate).

Instruments nominally operate in Slow Survey (SS) mode most of the orbit and in Fast Survey (FS) mode during conjunctions (~12 hrs/orbit). Horizontal bars indicate fast and slow survey mode intervals in overview plots at: **http://themis.ssl.berkeley.edu/summary.php**. Particle or low frequency field events (e.g. north/south magnetic field turnings in the magnetotail) trigger 8-12 min Particle Bursts (PB), while high frequency wave power events trigger 3-6s Wave Bursts (WB). As of 2 years ago the operations team has gained access to the White Sands WS1 antenna, while the science-team has obtained extended FS durations of up to 20 hrs/day on a best-effort basis for better collaborations with the Van Allen Probes. The scheduling and operations teams have increased their proficiency with the use of the new station and data volumes have increased markedly.

Automated operations support routine passes. Approximately 47000 passes have been completed to date. As of the fall of 2014 the operations team has been acquiring some additional Ultra-Fast Survey (UFS) data whereby almost the entire memory is dedicated to waveform captures up to 16kSamples/s for a duration of ~7min. The data is then downlinked from higher altitude than typical using the 18m WS1 antenna. The over two dozen test operations of this mode have been very successful. If THEMIS receives approval to implement UFS coverage for optimal use of Heliophysics System Observatory assets (as called for by PSG#1) then THEMIS will conduct further tests of this mode during the summer using the DSN 34m dishes to increase the UFS duration to ~1hr per spacecraft. This mode will then be implemented with DSN during the upcoming years for an additional 3.5hrs/day which would double the current THEMIS DSN allocation.

ARTEMIS operations continue with DSN support at a rate of one 3.5hr contact per day. Nominally, ARTEMIS spacecraft collect one time-based periapsis burst and one onboard trigger-based apoapsis burst per FS interval, each FS interval being ~8hrs/orbit per probe.

4.1.2 Status of ground systems All data processing and software continue to function reliably. All flight dynamics systems are nominal. Mission design runs with the latest orbit solutions occur months in advance for nominal planned maneuvers with a quick turnaround reaffirming conjunctions, shadows, and fuel budget. Product generation based on updated ephemerides is fully automated. GSFC flight dynamics provide backup orbit solutions for each probe. Telemetry files are transferred post-pass from the ground stations to UCB, checked and archived. Level 0, 1 and 2 data processing is automated. Instrument scientists ("tohbans") review survey plots ~1 day after receipt of data on the ground. See http://sprg.ssl.berkeley.edu/~themistohban/ for tohban functions. The Berkeley ground station continues to function well. NASA Ground Network stations continue to support THEMIS nominally, including WS1, and certified USN station supports THEMIS contacts when needed after other NASA station contact opportunities have been exhausted. WS1 is used in good part for altitude contacts to obtain FS data beyond 12hrs for Optimal HSO support currently on a best-effort basis.

As mentioned earlier, DSN has been supporting ARTEMIS with its 34m antennas, and scheduling and tracking is proceeding nominally. Limited DSN coverage in 2013-2014 due to resource conflicts (LADEE, LRO, MSL, Maven) resulted in the following successful workarounds: Use of the 70m stations (DSS-14, 43, 63) for receive-only support with rates up to 1024K; Use of the WS1 18m antenna; Commanding and tracking support from alternate stations (AGO, USN, BGS for Doppler tracking only). As a result the ARTEMIS data recovery has been >99%. The NTR T-1 line from GSFC to the MOC over the Open IONet and 3 voice loops continue to function nominally.

In terms of future plans: the BGS 11m antenna control system upgrades are planned for 2015. A 9-m ground station in Singapore and the HBK station in South Africa are slated for certification and are expected to come into operation within 2015. Thus although the UFS coverage and ARTEMIS resource contentions have been challenging, the new assets create opportunities to relax schedule conflicts.

4.1.3 Mission operations. Thanks to the increased familiarity of the operations team with the propulsion and thermal systems of the probes in both Earth and lunar orbits it is now possible to control a maneuver down to a fraction of a single side-thrust pulse, or 10cm/s, which is important for clustered configuration orbits in FY16 planned to achieve kinetic science in coordination with MMS. Similar very fine maneuvers have already been performed in FY11/12 for a few 100km separations on a best effort basis. No issues are expected for the upcoming (significant) orbit changes requested under PSG#1. If approved, THEMIS will execute an observation strategy and ascend profile similar to that for the prime THEMIS mission, except that orbit periods will be resonant to those of MMS. If PSG#3 is executed throughout FY16-20, the planned resonant orbits of satellite pair P4 and P5 (with similar periods) with satellite P3 (with a period resonant to those of P4, P5) will occur at progressively larger apogees from the current $11R_E$ out to $16R_E$. These orbits will be easier to achieve than those for PSG#1 due to the greater (20%) tolerance in the separations and the larger ($1\text{-}2R_E$) inter-spacecraft separations desired. All probes retain healthy fuel reserves after accounting for de-orbit, thereby permitting exciting possibilities for joint work with MMS in FY16-FY20.

Instrument operations. Under the PSG#1 plan, FS intervals for P3, 4 and P5 will be commanded at 20hrs/day (leaving 4hrs of SS operations near perigee) plus 1hr/orbit/spacecraft of UFS collection. The UFS interval will be scheduled near the magnetopause, inner-edge of the plasma sheet or the inner magnetosphere depending on season. ARTEMIS P1 and P2 operations will be coordinated with THEMIS or MMS apogees when in the magnetotail or on the dayside to enhance the science return under a system-observatory approach. In that plan the FS intervals will be centered on times of optimal joint HSO science, even though FS durations will remain the same.

Under the PSG#2 plan (Baseline) the UFS collections will not be executed but everything else in PSG#1 remains.

Under the PSG#3 plan (Go-it-alone), THEMIS operations requirements will continue as they are today, i.e., 12hrs/orbit of FS with 1.2hrs/orbit of PB collection. Under the same plan, ARTEMIS P1 and P2 operations will remain nominal, i.e., 8hrs of FS out of which 1hr brackets periselene; and simultaneous FS intervals on both ARTEMIS spacecraft. When in the magnetotail, FS time assignments nominally prioritize the pre-midnight sector to capture plasmoids and tailward/Earthward fast flows; those result in tens of hours of continuous coverage, in exchange for lower coverage near the flanks and in the magnetosheath. These are coordinated by a scientist interested in the tail science and with appropriate expertise. Instrument operation staffing levels are assumed as required to execute the PSG#3 baseline plan in FY13/14. Significant savings from operational simplicity, automation and familiarity of the team with instrument operations have already significantly reduced the mission and science operations personnel in FY14/15 (relative to that in FY11/12) and no further reductions are possible. As a result PSG#4 (Guide) assumes no mission operations personnel reductions below PSG#3.

4.1.4 Science operations and community support. Thanks to continuous data analysis, calibrations of the instruments have evolved and L2 data have been re-generated a few times and have been updated at SPDF. The primary updates are noted here, in order of importance:

1. FGM magnetometer observations are now routinely despun during shadows (despite the lack of a sun-pulse the moments of inertia of all spacecraft have been modeled and a spin-phase good to ~1° has been released with the nominal despinning software). This is very important near the lunar wake and pre-midnight when shadows would otherwise prevent analysis in the midnight sector where substorms often occur. The modeled phase is then used to despin particle and EFI data (including the velocity and pressure tensor). Available since 2012.
2. EFI electric field observations have seen phase corrections of the 16kS/s data. Its data now match the phases expected for chorus waves, allowing Li et al. (2013) to calculate Poynting fluxes at the highest possible resolution. Available since 2011.
3. SST energetic particle fluxes have now been fully calibrated by modeling: i) the energies using GEANT4 simulations, ii) the dead layer evolution with time by comparison with ESA spectra, and iii) the response as a function of detector for isotropic flux conditions to determine relative anode efficiencies. Software enables recomputation of the flux at pre-set energies for partial moment generation and for spectral plots. Clean fluxes from the anti-coincidence channels are now available routinely. All the above changes are implemented with a single keyword, on the fly, by publicly available software. Available since 2013.

Additional instrument calibrations are recorded online at the THEMIS web site (themis.ssl.berkeley.edu) under: "software→enhancements" or directly at: http://themis.ssl.berkeley.edu/themisftp/SCI/Soft/Progress/.

In addition, software plug-ins have been developed for multiple ancillary data and are discussed further in the MAP. Here we only mention that ground magnetometer networks from Alaska, Canada, Greenland, Scandinavia, Iceland, Russia and the North-South American chain McMac have been incorporated (http://themis.igpp.ucla.edu/instrument_gmags.shtml), and additionally GOES and SuperDARN load and analysis routines have also been implemented. Instrument and software training sessions for the community and routine community support on instrument specifics and software for calibration and analysis are implemented through a "Help Request" line on the THEMIS Web page (under software → Themis Science Support Team). The THEMIS MAP provides more discussion along these lines.

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