THEMIS IN RELATION TO CLUSTER AND DOUBLE STAR

Vassilis Angelopoulos[(1)]

[(1)]*Space Sciences Laboratory, University of California, Berkeley*

ABSTRACT

The Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission is a five-satellite mission that will be launched in the Fall of 2006 to answer where and when magnetospheric substorms begin in the magnetotail. Its orbit strategy, with an apogee anti-diametric to Cluster and orthogonal to Double-Star TC1 is uniquely suited to perform correlative measurements during the course of substorms, dayside phenomena and radiation belt and ring current dynamics with high fidelity and completeness. In this paper the THEMIS observation strategy and the possibilities for joint research with Cluster and TC1 are presented.

1. THE THEMIS MISSION

The THEMIS mission, selected in 2003 as NASA's 5th MIDEX mission (http://sprg.ssl.berkeley.edu/themis) aspires primarily to elucidate which magnetotail process is responsible for substorm onset, at the region where substorm auroras map (~10R_E): (i) a local disruption of the plasma sheet current or (ii) that current's interaction with the rapid influx of plasma emanating from lobe reconnection at 25R_E. Correlative observations from long-baseline (2-25R_E) probe conjunctions will delineate the causal relationship and macroscale interaction between the substorm components. Ground based observatories (GBOs) in North America identify the time and meridian of the auroral breakup. THEMIS's identical spacecraft (termed probes) measure particles and fields on orbits which achieve tail-aligned conjunctions over the GBOs once per four days. The three inner probes monitor current disruption onset at 10R_E, while the two outer probes, at 20 and 30R_E, monitor remotely reconnection onset. In addition, THEMIS's unique alignments at the dayside will study interaction of solar wind discontinuities with the upstream particles, bow shock and magnetopause, and THEMIS's frequent traversals of the radiation belts will provide information on the radial profile of the MeV electron phase space density and study, with unprecedented cadence, electron source and transport.

1.1 THEMIS mission elements

Figure 1 shows the three main substorm components that require timing in order for their causal relationship to be resolved. These drove the mission design. The communication time between these regions (via fast mode waves down the tail, Alfvén waves down to the ionosphere, or fast flows to Earth) is shown in Table 1.

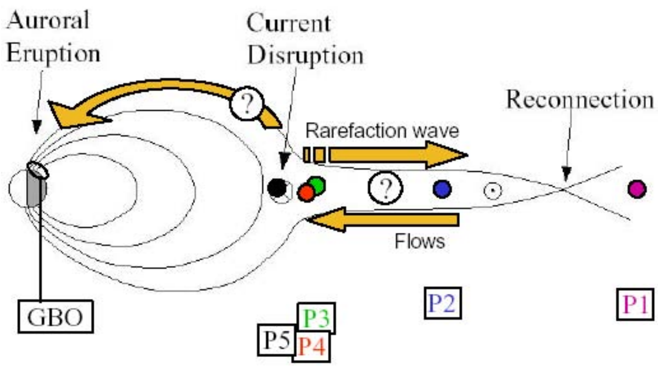

Figure 1. Three main substorm components (auroral breakup, current disruption and reconnection) and the elements of THEMIS mission (Ground based observatories and five spacecraft bracketing the current disruption and reconnection process).

The time resolution required is on the order of 30 seconds, apportioned equally to the three observation platforms: GBOs (in Canada and Alaska, <3s cadence), current disruption monitors (P3,4,5) and reconnection monitors (P2, P1). The probes have a 3s spin period. While onset can be determined by Pi2 and PiB pulsations measured at ground magnetometers with 0.5s resolution, the white-light, high sensitivity cameras can make determination of the onset meridian, latitude and extend far easier by providing both a synoptic global view of the night-time sky and a local view of the auroral eruption at sub-km resolution. Daily data transmission of all magnetometer data and thumbnail images is sufficient for primary science; disk swapping provides all ~2TB/yr high resolution images with ~1.5month latency.

Table 1: Information and energy propagation delays between main substorm elements in accordance with two main substorm models

Current Disruption Model		Reconnection Model	
time	Event	time	Event
0 sec	Current Disruption	0 sec	Reconnection
30 sec	Auroral Eruption	90 sec	Current Disruption
60 sec	Reconnection	120 sec	Auroral Eruption

Proceedings Cluster and Double Star Symposium – 5th Anniversary of Cluster in Space, Noordwijk, The Netherlands, 19 - 23 September 2005 (ESA SP-598, January 2006)

Figure 2, top, depicts the GBO stations. It is evident that with two imagers and two ground magnetometers per hour in local time a complete and dense coverage of North America is possible. Ionospheric projections for two Alaskan stations is shown for reference, and a ultraviolet image of a typical onset captured by the IMAGE satellite is superimposed on the array for reference of the auroral oval location. Additionally, ten science-grade magnetometer stations are deployed at mid-latitude schools, an important aspect of THEMIS's Education and Public Outreach program.

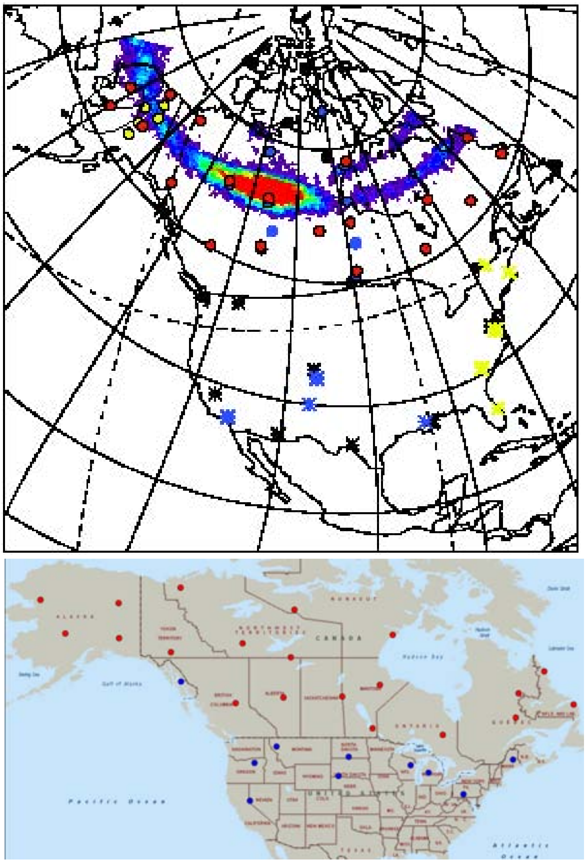

Figure 2. The GBO (red circles) and EPO (bottom only, blue dots) network of stations. 10 out of 20 GBO stations and all 10 EPO stations are operational one winter season ahead of the first THEMIS tail observations (Feb 2007). Additional dots and stars represent stations already in place by other agencies, complementing the data acquired by THEMIS.

The five identical probes carry instruments that measure in situ particles (ions and electrons) in the range from 3eV to >1MeV and electric (**E**) and magnetic (**B**) fields from DC to >4kHz (4kHz in **B**, 8kHz in **E** routinely, plus an AKR **E** band in the 100-300kHz range). The probe with instruments deployed is shown in Figure 3. The ElectroStatic Analyzer (ESA) measures ions and electrons in the range 3eV – 40keV, with nominal 22.5^{o} resolution in azimuth and elevation, except in the solar wind when near-spin plane ions are measured at 11.25^{o} resolution. The Solid State Telescope (SST) measures ions and electrons in the range 25Kev-1MeV range (1MeV electrons, 6MeV ions). The FluxGate Magnetometer (FGM) measures the DC magnetic field up to 128 S/s at the tip of a ~2m rigid boom and the SearchCoil Magnetometer (SCM) measures the magnetic field up to 8kS/s at the tip of a similar ~1m boom. The Electric Field Instrument (EFI) measures the voltage difference between spherical sensors at the tips of 20m (X) and 25m (Y) booms on the spin plane and between stacer sensors at the tips of 3.5m booms (Z) along the spin axis. The DC- and AC- coupled signals are digitized and processed by FPGAs up to 16kS/s on a special Digital Fields Board. Data are stored on a 2GByte memory and down-linked at in-bound or out-bound ground-contact opportunities. A nominal downlink session at 512kbps for 30min allows for ~100Mbytes of data transmission assuming a factor of 2 compression. Survey quantities (slow and fast survey) include partial ESA and SST ion and electron moments, DC and band-pass fields traces, reduced distribution functions and occasional full distribution functions. Burst quantities include full distribution functions and high frequency fields waveforms (up to 2kHz Nyqist).

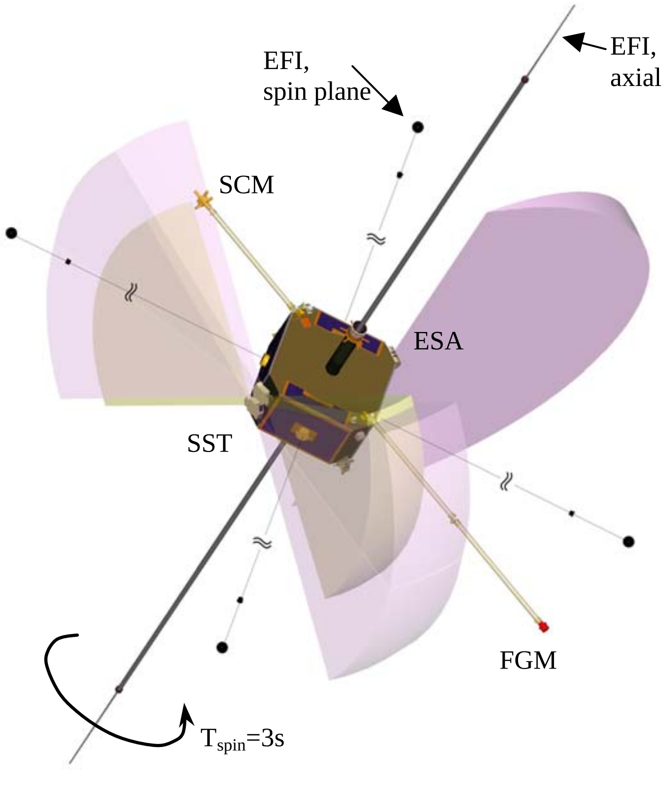

Figure 3. Deployed probe (Courtesy: Swales Aerospace Inc., THEMIS spacecraft provider)

The burst strategy is to monitor on-board trigger quantities for local magnetospheric activity (flows, heating, particle flux, dipolarization, local wave-power) and capture buffered pre-burst and acquired post-burst, high resolution data into memory. A burst quality factor is checked to determine which, if any, memory location is over-written. In addition, a band-passed signal in the AKR range at sub-second resolution provides yet another (now global) on-board trigger of activity related directly to substorm onset. Time-tagged bursts have precedence over quality factors.

High-resolution data collection (Fast Survey) is possible for ~12hrs/orbit, encompassing all conjunctions. These data can satisfy primary science objectives. Bursts within these times last a total of 1.2 hrs (split between ~4-8 bursts) and provide the highest resolution possible when local activity demands it. This strategy captures all fast flows and dipolarizations for the anticipated (10%) occurrence frequency with the highest resolution afforded by the available instrumentation.

1.2 THEMIS Observing Strategy

Observations are made near Northern winter (to ensure all sky imagers are at maximum operation). A number of considerations were made in the selection of center-tail observations to optimize overall mission performance, and are listed in Table 2. Earth-shadow duration increases near equinox, but observations there are preferable because tilt angle is minimal, plasma sheet residence is optimal and substorm recurrence is the highest. One of the salient features of high apogee orbits is the continuous torque the moon imparts on the orbital angular momentum. This results in high fuel consumption requirements to station-keep the probes near the plasma sheet (1/3 of the fuel consumption of P1). The effect is minimum for equinoctial center-tail observations, due to symmetry of the orbit plane (near equator) relative to the lunar orbit (near ecliptic). Of the two choices (vernal or autumnal) preference was given to vernal equinox. This also optimizes conjunctions with Cluster, as will become apparent in the next section.

Table 2: Considerations in selection of line of apsides (right ascension of ascending node=312^{o}) and season of center-tail observations (mid-February, 2007, 2008).

Purpose	Optimal Season	Effect magnitude
Minimize cloud cover	Feb.±2mo	+100% relative to Dec.
Maximize substorm recurrence	Vernal equinox	+50% relative to winter solstice. Pro-rated effect.
Polar night >6hrs	Dec.±4mo.	No THEMIS effect if within
B angle to spin plane >10°	Dec.±4mo.	No THEMIS effect if within
Minimize shadows	Solstice	P1, P2: <3% data loss, some fuel consump-tion if target date on Feb.-21
Relative orbit maintenance	Equinox	No effect if target date in mid- to late February

The orbit strategy calls for near-equatorial probes (inc <9^{o}) in multiple-day orbit periods such that once per 4 days all probes line-up along the Sun-Earth line for a period of ~2months in the tail, and likewise in the dayside. This is accomplished by having P1 at an apogee of ~30R_E (4day period), P2 at 20R_E (2 day period), P3 and P4 at 12R_E (1day period, separated only in time along the same orbit path) and P5 at a variable apogee near P3 and P4. All probes have a low (1.1-2R_E) perigee; conjunctions are valid when probes map over central Canada +/- 6hrs in MLT (i.e., over THEMIS GBOs). Conjunctions criteria include that any one of the probes is within δY_{GSM}<2R_E from any other, to account for the narrowness of the flow channels and substorm meridian at onset. Neutral/plasma sheet encounters are assured by a requirement of δZ_{NS}<2R_E for inner probes (P3, 4, 5) and δZ_{NS}<5R_E for outer probes (P1, P2).

Probe P5 is there to assure mission success through a constellation replacement strategy (i.e., to replace a probe that might inadvertently fail to meet minimum science objectives). It is originally placed in an orbit period of 4/5days such that it participates in 4-day conjunctions, albeit at variable distances from P3, P4 as it moves quickly in and out of conjunction. This allows the combination of P3,4,5 probes to scan distances in the range 1-10R_E in Y and 1-3 R_E in X, during the first year. In the second year, P5 is placed at the same apogee but at slightly different inclination than P3,4, such that it is at δZ_{GSM}~1-2R_E away from P3,4. This allows P3,4,5 to monitor current sheet thickness at the inner edge of the plasma sheet while P1 and P2 are observing Earthward flows and reconnection onset.

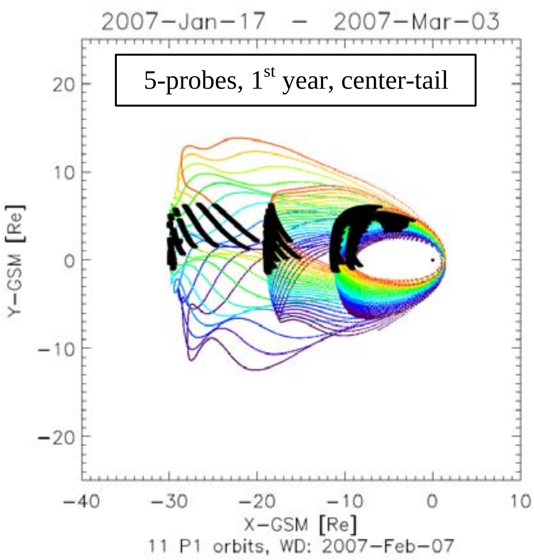

Figure 4. THEMIS conjunctions (Courtesy: S. Frey)

Figure 4 shows the THEMIS 5-probe orbits in the central portion of the 1st year tail season. Dawn and dusk sector conjunctions are also possible, with slightly different vantage points. As the substorm process recurs with a period of 3-4 hrs (3.75hrs used for mid-February season) and THEMIS alignments (spanning a $4R_E$-wide swath in the tail) have a 1:5 chance of capturing the reconnection flows (occurring over a $20R_E$-wide cross-tail region), the resultant statistics call for a requirement of 19hrs residence per substorm observation. Assuming that we need at least 5 substorms (minimum mission) observed with at least 4-probe alignments, we obtain a requirement of 94hrs (188hrs preferred) of 4-probe alignments over Canada. Orbit simulations (such as those of Figure 4) show >200hrs/yr of 4-probe alignments, and 94hrs/yr of 5-probe alignments. This satisfies minimim mission requirements with a factor of 4 margin (2 year mission). Non-perfect alignments should also provide useful knowledge on substorm flow channels, their timing and cross-tail extent. Alignments missing P1 are twice as numerous, resulting in a wealth of statistical information regarding relationship between fast flows, current disruption and energy dissipation.

2. THEMIS, CLUSTER AND DOUBLE STAR 1

In order for THEMIS probes to maintain conjunctions with each other and with GBOs in North America, maneuver locations and probe orbits are carefully prescribed for the entire mission. More than 120 maneuvers are performed for the constellation to maintain its formation. Inadvertently missed maneuvers or propulsion system under/over performance are expected to be corrected through targeting of increasing fidelity as each science season is approached. Corrective maneuvers are also planned if self-correcting targeting is not adequate. This orbital choreography leaves little room for additional mission design requirements to accommodate additional conjunctions with other missions. However, as Figure 5 shows, there is potential for building a powerful, large-scale constellation in the existing THEMIS orbital strategy, simply by taking advantage of fortuitous alignments between the THEMIS, Cluster and TC1 spacecraft.

2.1 THEMIS in tail

As shown in Figure 5, Cluster's line of apsides is Sunward and TC1's line of apsides is duskward when THEMIS alignments occur at the nightside.

Cluster in the solar wind is able to provide unique observations of upstream conditions just ahead of the bow shock, eliminating uncertainties that propagation delay and solar wind structuredness might introduce when using a conventional, L1 monitor, such as ACE.

The global effects of substorms during nominal, active and storm-time conditions depend on the amount of plasma sheet material that is injected in the partial ring current. The ring current grows, its peak asymmetry moves Eastward and the plasmaspheric material is lost through the dayside as solar wind dynamic pressure and storm-time electric fields vary. TC1 will be precisely in the path of the asymmetric ring current buildup, evolution and loss and will observe the plasma sheet and plasmaspheric motion in the course of storm-time substorm injections observed by THEMIS. Dayside reconnection has the potential of re-circulating the plasmaspheric plasma, whereas energetic particles may be accelerated at the bow shock and re-enter the magnetosphere, resulting in deep L-shell penetration. CLUSTER inbound and outbound passes will monitor the bow shock and magnetopause particles to determine leakage, acceleration, reconnection and recirculation of plasma sheet plasma. It is evident that the unique THEMIS-TC1-Cluster configuration during both quiet and active time intervals can provide complementary views of the storm-time evolution of plasma sheet and plasmaspheric plasma. This grand-constellations' in situ observations, will provide an important picture of the sources and sinks of plasma complementary to IMAGE's and offer important insights as to the geoeffectiveness of storm-time substorms.

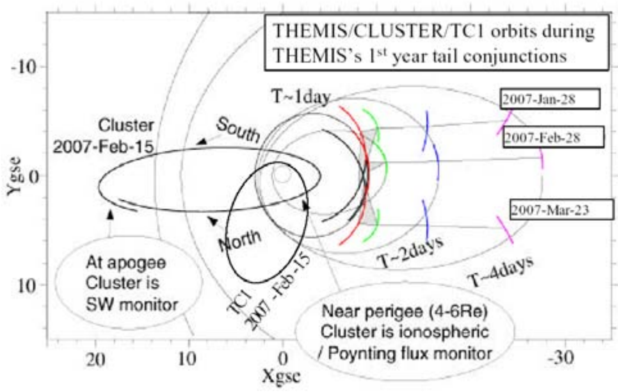

Figure 5. THEMIS – CLUSTER – TC1 constellation configuration during THEMIS's 1st year tail alignments.

Finally, at its nightside perigee, at altitudes $4\text{-}6R_E$, Cluster is typically in a string-of-pearls configuration. It is scanning in latitude, just above the auroral acceleration region, over tens of minutes duration and with spacecraft separations of several minutes. Cluster measurements will be made in the context of THEMIS's GBO measurements offering unprecedented temporal and spatial resolution below it, and with THEMIS's probe alignments above it. Cluster will afford accurate mapping between plasma sheet and ionospheric phenomena, and will separate spatial and temporal effects in the ionosphere complementing THEMIS's prolonged residence at the equatorial magnetosphere. Plasma sheet spectra will be matched from the near and mid-tail to the ionosphere to provide a direct mapping to the GBO images below. In that context, field aligned currents, flow shear and vorticity regions, Alfven wave Poynting flux, and plasma sheet pressure gradients will be mapped all the way from plasma sheet to their auroral counterparts. The numerous THEMIS P2,3,4 alignments, once per two days, and the twice-per-orbit Cluster latitudinal scans (north and south) will permit, even without pre-planned operations, sufficient fortuitous conjunctions to perform these unique observations.

2.2 THEMIS in dayside

It is evident from Figure 5 that six months after each tail season, when THEMIS is at the dayside, Cluster becomes the tail monitor, while TC1's line of apsides is pointing at dawn.

During those times THEMIS will be fulfilling its secondary goal to study the evolution of pristine solar wind plasma at $30R_E$ through the foreshock, sheath and magnetopause regions. In particular THEMIS will be studying the types of magnetopause phenomena resulting from solar wind features such as hot diamagnetic cavities, discontinuities and IMF reorientations. TC1, from its vantage point, extends the THEMIS goals: With its comprehensive instrumentation it will study the effects of the magnetopause features such as flux transfer events and Kelvin-Helmholz waves closer to Earth, quantifying their importance for transfer of mass and energy into the magnetosphere. At times when the magnetopause is compressed, TC1 will serve as the magnetopause monitor at dawn, complementing THEMIS at noon, and allowing simultaneous exploration of a wide range of local times under the same solar wind conditions monitored by THEMIS/P1.

During THEMIS's dayside observations, Cluster at perigee will be monitoring the cusp and LLBL regions from $4\text{-}6R_E$ altitude, while THEMIS GBOs will be performing ground magnetometer observations of cusp and dayside current systems with global coverage at 0.5s resolution. Phenomena such as sudden impulses, pressure pulses and FTEs will be thus monitored at multiple altitudes from their solar wind source through the high altitude magnetopause to the cusp and down to their ionospheric current systems.

Cluster will spend most of its time at apogee and will be monitoring the nightside plasma sheet and lobes, while THEMIS is observing in great detail the solar wind features and their evolution through the dayside environment. In that context, Cluster will be in a unique position to elucidate the relationship between magnetotail energy storage/release and its solar wind drivers. Observations of travelling compression regions (which Cluster discovered moving both Earthward and tailward) and flux ropes (which Cluster uniquely resolves using time-delays on multiple spacecraft) are ideal for routine tail energy content and release studies, subject to simultaneous detailed observations of solar wind phenomena afforded by THEMIS and TC1.

2.3 THEMIS in flanks

Cluster and THEMIS are on opposite flanks twice per year. Being in highly elliptical orbits the spacecraft spend most of their time near apogee, where they monitor the bow shock, sheath and magnetopause as a variable solar wind brings these regions in and out of view. Timing of these boundaries and quantitative comparisons of the particle fluxes and waves within them will create a unique and unprecedented dataset with which to study global magnetospheric response to solar wind input, and will also provide a powerful test platform for numerical models of that interaction.

At times when TC1 is at the dayside, it will provide either solar wind data from directly upstream, or a third magnetopause dataset at yet a different local time. At times when TC1 is at the nightside, it will permit a better understanding of the tail response to solar wind forcing, such as boundary layer waves and accurately timed pressure pulses, now better characterized by the synergistic analysis at both dawn at dusk.

3. CONCLUSIONS

The numerous, fortuitous conjunctions anticipated between Cluster, THEMIS and TC1 strengthen and enhance the goals of the THEMIS mission during all observation seasons. The three missions combined provide a wealth of data on the coupled solar wind - magnetospheric system over a large spatial and ground coverage. In addition to their datasets, Cluster and TC1 provide already assembled teams, established forums for exchange of ideas, and a wealth of data analysis and simulation tools. It is evident that the combined missions are well positioned to provide new science with a combined team and a dataset value that is far greater than the sum of the individual missions.

Acknowledgements

This work was supported under contract NAS5-02099. The THEMIS scientists and engineers in the US (UCB, Swales Aerospace, GSFC, UCLA, LASP, APL), Canada (U of Calgary, U. Alberta) and Europe (CETP, TUBS, IWF) are acknowledged for their diligent and conscientious efforts. They are the soul of THEMIS and the main reason for its success this far.