Five plus four equals nine: combining the THEMIS and Cluster missions

J. A. Wild and M. A. Hapgood

Abstract: THEMIS represents the most ambitious coordinated multi-spacecraft and ground-based programme ever attempted. It is expected that this mission will dramatically increase our understanding of the substorm process. In the years leading up to the launch of the five THEMIS probes, the four-spacecraft Cluster mission has defined the state of the art in the field of multi-spacecraft/ground-based investigations of the geospace environment. Hitherto unprecedented coordination of space- and ground-based experiments have yielded multi-point (in situ and remotely sensed) measurements of magnetospheric structure and dynamics. The overlap of the Cluster and THEMIS missions presents an excellent opportunity to move the multi-point measurement technique to the next stage. Since the apogees of the Cluster and THEMIS satellites orbits are separated by nearly 12 hour of local time, the synergy of these two missions and ground-based experiments will allow the detailed observation of solar wind-magnetosphere-ionosphere on both the day and nightside of the Earth. Several experimental scenarios will be presented.

Key words: Cluster, THEMIS.

1. Introduction

Cluster is the first multi-spacecraft magnetospheric satellite mission [2, 3] to yield three-dimensional measurements of the geospace environment and allow the resolution of spatial/temporal ambiguities inherent in single-spacecraft observations. It is now operating in the extended phases of its mission and is scheduled to continue until 2010. The four identical Cluster satellites orbit the Earth in highly elliptical (4–20 R_E) polar orbits with periods $\sim$57 hours that precess through twenty four hours of local time every twelve months. Cluster is also unusual in that it was one of the first missions to include planning for coordinated ground-based measurements from an early stage in the mission's design [8, 9]. This coordination has resulted in a plethora of Cluster/ground-based studies [1].

Following launch in October 2006, the five THEMIS (Time History of Events and Macroscale Interaction during Substorms) spacecraft will be manoeuvred into equatorial orbits with apogees of $\sim$30 R_E (one spacecraft), $\sim$20 R_E (one spacecraft) and $\sim$10 R_E (three spacecraft) with orbital periods of $\sim$4 days, $\sim$2 days and $\sim$1 day, respectively.

The orbits of the THEMIS spacecraft (or "probes") have been selected such that at least three of the THEMIS probes become meridionally aligned every four days. In this arrangement, the spacecraft are in the optimum configuration to distinguish between competing substorm theories and it is estimated that over 180 hours of such alignments will occur each year [5]. Meanwhile, a network of ground-based auroral all-sky imagers (ASIs) and magnetometers in Canada and Alaska [4] will ensure that the probe alignments (at the substorm onset meridian) can be scrutinized in detail using both in situ (satellite) and remotely-sensed (ground-based) observations.

The orbits of these ground-breaking missions are such that the apogees of the THEMIS probes and the Cluster spacecraft are separated by $\sim$11 hours of magnetic local time, as indicated in Figure 1. Consequently, the space- and ground-based conjunctions arising during the coming years present unprecedented opportunities for multi-scale and multi-point measurements of solar wind-magnetosphere-ionosphere coupling. These are explored below.

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2. Methodology

2.1. Predicted satellite positions

For the purposes of this investigation, predicted THEMIS orbital information (courtesy of S. Frey, UC Berkeley) has been compared to Cluster Predicted Geometric Position (PGP) data. In advance of the launch, the THEMIS orbital information must be considered as provisional. Similarly, the Cluster orbital information is also subject to change due to spacecraft manoeuvring. Nevertheless, these data allow a preliminary investigation to be carried out looking into the various configurations of multiple satellites and ground-based instruments. Therefore, while we shall present scenarios drawn from the preliminary orbital information, we shall consider them examples of generic conjunction configurations rather than an attempt to plan for specific dates and times.

2.2. Magnetic field mapping

The Tsyganenko 1996 (T96) model [12, 13] has been employed in order to estimate the magnetic conjugacy of the Cluster and THEMIS spacecraft with ground-based experiments. In each case, fixed input parameters corresponding to "average" solar wind and interplanetary magnetic field conditions have been used (specifically P_{SW}=2 nPa, Dst=0 nT, IMF B_Y=0 nT, and IMF B_Z=0 nT). The approximate fields-of-view of the THEMIS ASIs and the international network of SuperDARN coherent-scatter radars have also been been considered.

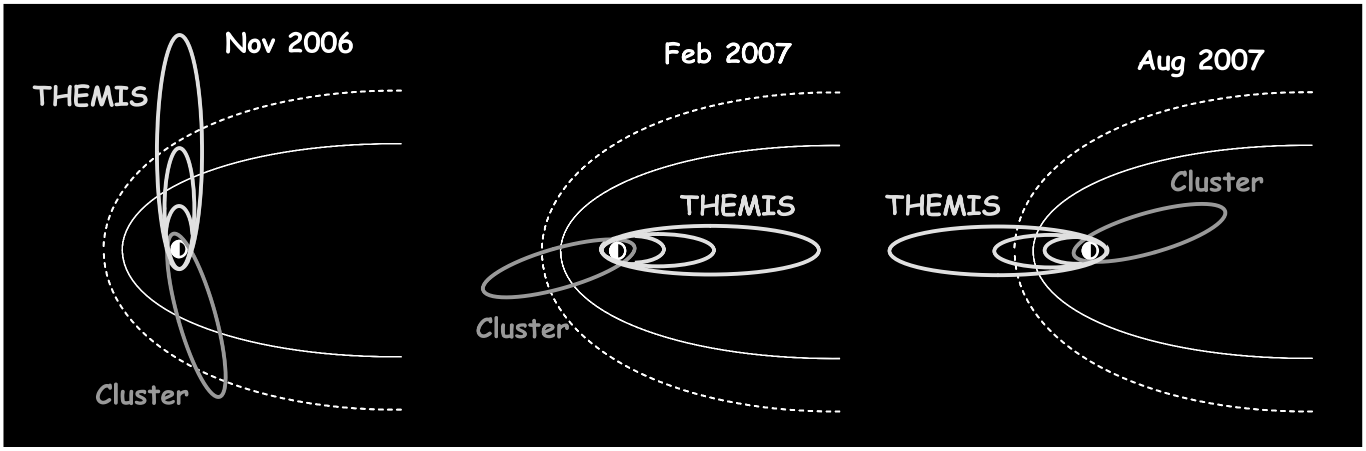

Fig. 1. The approximate configuration of the Cluster and THEMIS satellite orbits in the GSE X–Y plane during Nov 2006 (shortly after launch), Feb 2007 (during the first planned THEMIS tail observations season) and August 2007 (during the first planned THEMIS dayside observation season).

3. THEMIS conjunctions in the magnetotail

As indicated above, when the apogees of the THEMIS spacecraft are in the terrestrial magnetotail, the four Cluster spacecraft pass through apogee in the solar wind (some 11 hours earlier in magnetic local time). Figure 2 shows the location of the THEMIS and Cluster spacecraft on 6 January (left) and 3 February (right) 2007, when the THEMIS spacecraft align meridionally in the post-midnight and midnight regions.

The format of Figure 2, used throughout this paper, is as follows. For each date/time included, four sub-panels are shown. These present the location of the THEMIS probes (square symbols) and the Cluster spacecraft (circular symbols) in the GSM X–Z and X–Y planes. For comparison, field lines of the T96 model magnetic field model (in the GSM Y=0 and Z=0 planes) are also shown. The magnetic footprint of each spacecraft (square symbols for THEMIS and circular symbols for Cluster) at an altitude of 100 km are indicated in both the northern and southern hemispheres. The footprint panels are presented in magnetic latitude/magnetic local time coordinates centred upon the geomagnetic poles with midnight located at the bottom, dawn to the right, noon at the top and dusk at the left of each panel. This applies to both the northern and southern hemispheres such that the Antarctic coastline appears as if viewed from above the northern magnetic pole in order to preserved the midnight-dawn-noon-dusk position in each plot. Overlaid on the footprint panels are the approximate fields-of-view of the THEMIS ASIs (white circles) and the fields-of-view of the 10 northern hemisphere and 7 southern hemisphere SuperDARN radars [6] currently in operation (shaded grey). We note that, in general, the inter-spacecraft separation of the Cluster satellites is sufficiently small ($\sim 1\ R_E$) that the individual spacecraft cannot be resolved on the scale of the figures used in this paper. Furthermore, the preliminary THEMIS orbital data places probes 3 and 4 in close orbits such that they cannot be resolved in the figures presented here.

During both of the meridional alignments presented in Figure 2, the THEMIS probes are magnetically conjugate to the Canadian sector such that the probes' magnetic footprints lie within the fields-of-view of the THEMIS ASI array. Such configurations are the primary goal of the mission and occur approximately every four days. In the two examples shown, separated by about 1 month, the probes are aligned in the pre-midnight (6 January) and midnight (3 February) sectors. On both occasions, the four Cluster spacecraft are located upstream of the dayside magnetopause and can therefore provide detailed three-dimensional measurements of the field and plasma environment in the magnetosheath/solar wind. Such observations will remove the timing ambiguities inherent in applying propagation delays to single-point solar wind/IMF measurements traditionally made in the vicinity of the L1 position some 225 R_E upstream of the Earth and will allow the detailed investigation of the solar wind/IMF drivers and possible triggers of magnetospheric substorms.

Note also the coverage of the SuperDARN radar network during such conjunctions. In addition to the obvious (and invaluable) overlap of the THEMIS ASI array and the SuperDARN radars in the Canadian and Alaskan sectors, the CUTLASS [7] and Kurguelan SuperDARN radars provide coverage of the dayside cusp region in the northern and southern hemispheres, respectively. As such it will be possible to monitor the ionospheric signatures of dayside reconnection - the driving force behind magnetospheric substorms - while simultaneously observing the ionospheric flows within the fields-of-view of the THEMIS ASIs. Furthermore, global estimates of ionospheric convection pattern in both hemispheres derived from SuperDARN data [10, 11] will provide global context to the remotely-sensed and in situ observations of the magnetotail.

Figure 3 presents a pair of THEMIS tail conjunctions similar to those shown in Figure 2. However, in these cases, the Cluster spacecraft are passing through perigee at relatively low altitude (~2–3 R_E) on the nightside of the Earth. In the 14 January example (left hand side of Figure 3) the THEMIS and Cluster spacecraft come into close conjunction some 6 hours after the optimum THEMIS probe/ASI array alignment. Consequently, the THEMIS ASI array spans magnetic local times from midnight to noon across the dawn sector. Such conjunctions could be exploited to study morning sector auroral dynamics such as auroral Ω bands by comparing magnetotail dy-

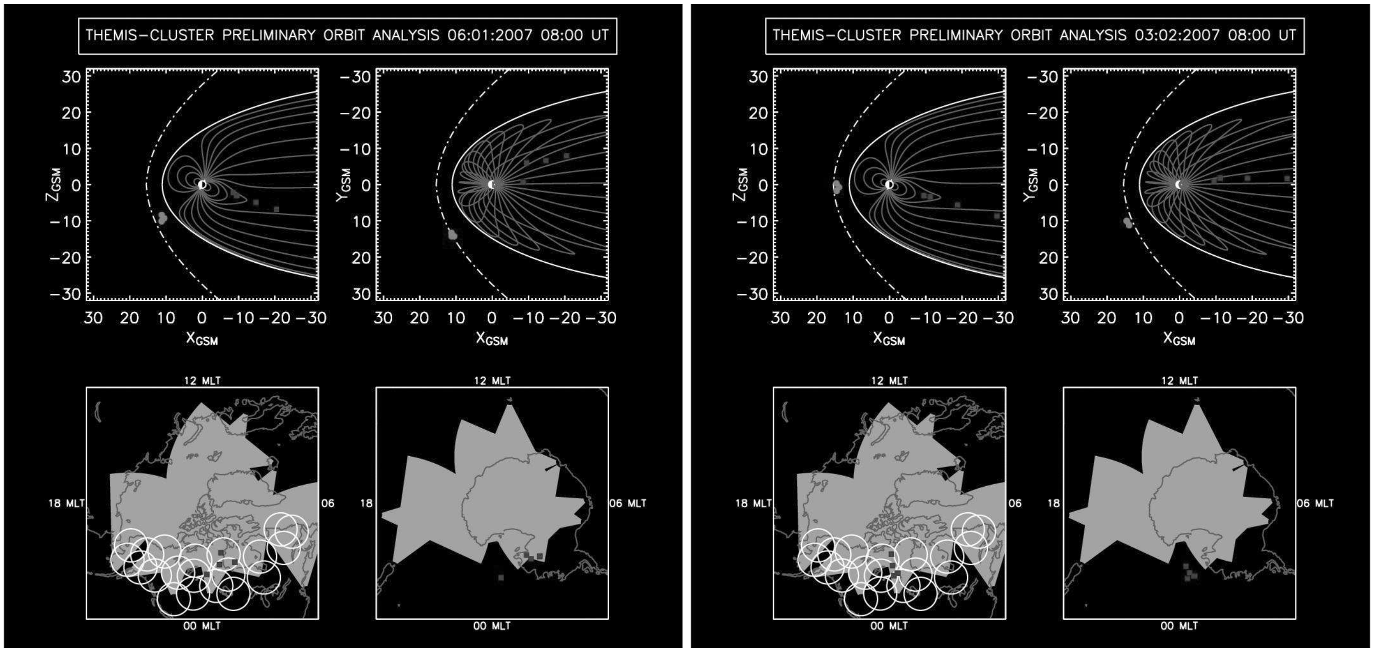

Fig. 2. THEMIS and Cluster locations and footprints on 6 January 2007 (left) and 3 February 2007 (right). In each case, the position of the THEMIS and Cluster spacecraft in the X–Z and X–Y GSM planes are indicated by square and circular plot symbols respectively. The T96 magnetospheric magnetic field configuration, is also shown in each case. The magnetic footprints of the spacecraft shown in the orbit panels are shown in both the northern and southern hemispheres. The footprint panels are presented in magnetic latitude/magnetic local time coordinates as described in the text. Overlaid on the footprint panels are the approximate fields-of-view of the THEMIS ASIs (white circles) and the fields-of-view SuperDARN radars.

namics (THEMIS), plasma dynamics in the auroral acceleration region (Cluster) and the auroral and ionospheric dynamics (THEMIS ASIs, magnetometers and SuperDARN).

The 7 February 2007 conjunction (right hand side of Figure 3) presents a similar arrangement of the THEMIS and Cluster spacecraft, save that in this example, the Cluster perigee pass has occurred during the primary midnight meridian THEMIS probe and ASI configuration. Given suitable substorm conditions, such a conjunction would result in multi-spacecraft measurements of the auroral acceleration region by Cluster at a similar magnetic local time as the radial distribution of THEMIS probes.

4. Dayside THEMIS conjunctions

4.1. Cluster in the nightside magnetosphere

Clearly, the THEMIS mission has been driven by a desire to understand the time-history of events in the magnetotail during magnetospheric substorms. However, for several months of each year, the apogees of two of the five probes will be located in the solar wind or magnetosheath. At these times, the azimuthal separation between the THEMIS and Cluster orbits is such that the Cluster spacecraft pass through apogee in the magnetic tail. In effect, when compared to the configuration presented in Figure 2, the roles of THEMIS and Cluster have been reversed; THEMIS now acts as an upstream solar wind monitor while Cluster observes the field and plasma processes and dynamics in the magnetotail.

Figure 4 shows two configurations of the THEMIS and Cluster spacecraft during the THEMIS dayside exploration season: 5 September 2007 (left) and 12 September 2007 (right). In each case, the Cluster spacecraft are passing through the plasma sheet region of the magnetotail in the vicinity of magnetic midnight. On the dayside, the THEMIS probes are distributed throughout the dayside magnetosphere, low-latitude boundary layer, magnetosheath and solar wind (depending upon the exact time selected). Once again, this will enable multi-spacecraft observations of the upstream solar wind, IMF and magnetosheath conditions that ultimately drive the substorm process without having to rely upon upstream measurements lagged to the dayside magnetopause.

While the orbits of the THEMIS probes will be arranged such that ground-based ASI array in the Canadian sector will straddle the midnight sector when the spacecraft are at apogee in the midnight sector (achieving multi-spacecraft conjunctions with various combinations of probes every 1, 2 and 4 days), the same is not true for the Cluster spacecraft. Indeed, with their 57 hour orbits, the location of the THEMIS ASI array when the Cluster satellites pass through apogee will vary from orbit to orbit. Nevertheless, interesting and potentially useful conjunctions between Cluster (in the plasma sheet) and the THEMIS ASI array occur in a significant fraction of Cluster orbits (at least half). The left hand side of Figure 4 presents an example of a "best case scenario" conjunction (which will occur 5 times per month) whereas the right hand side shows an example of partial conjunction with the THEMIS ASI array (which occur at a comparable frequency).

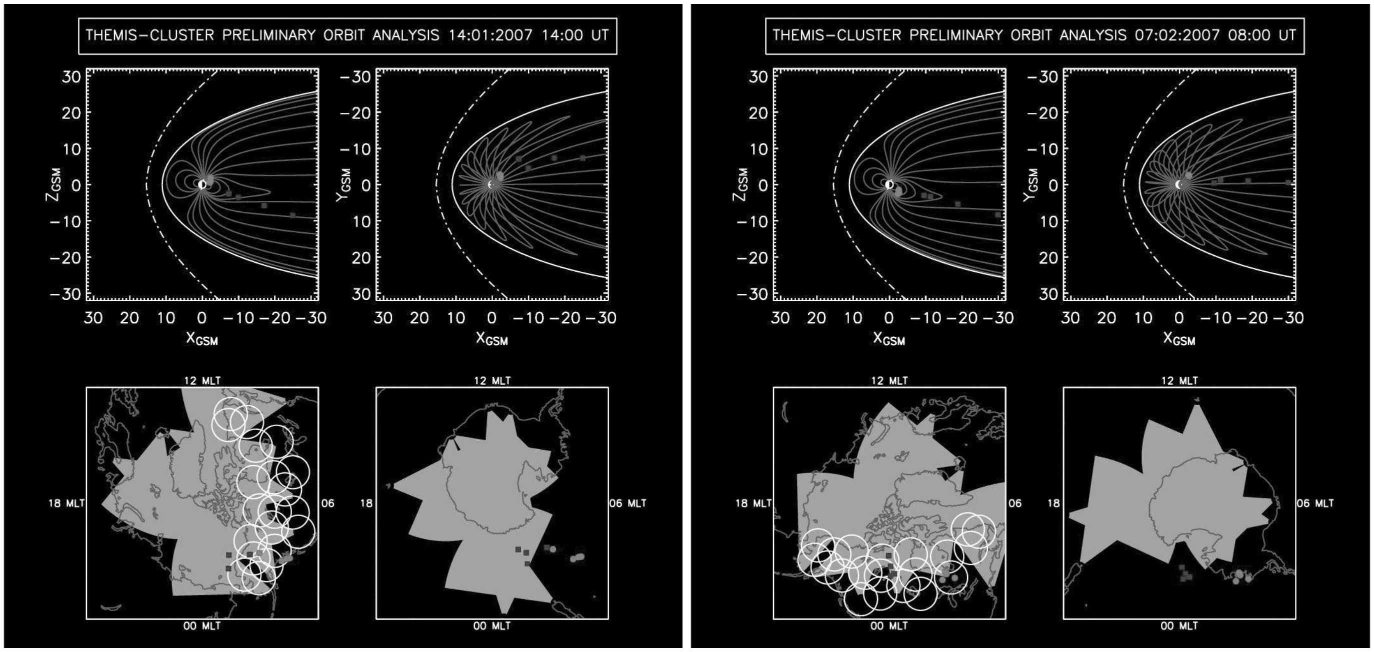

Fig. 3. Estimated THEMIS and Cluster locations and footprints on 14 January 2007 (left) and 7 February 2007 (right).

4.2. Cluster in the dayside magnetosphere

Since the Cluster and THEMIS apogees are separated by $\sim$11 hours of magnetic local time, the separation between the THEMIS apogee and the Cluster *perigee* is $\sim$1 hour. Therefore, when the THEMIS orbit takes the probes into the dayside magnetosphere, magnetosheath and solar wind, the Cluster orbits take the spacecraft through the mid-altitude magnetospheric cusps in both hemispheres as they pass through perigee. This class of Cluster-THEMIS conjunction is perfectly suited to the investigation of dayside solar wind-magnetosphere-ionosphere coupling with spacecraft ideally placed to monitor the upstream/-magnetosheath magnetic field, the low-latitude boundary later, the low-latitude dayside magnetopause and the mid-altitude magnetospheric cusps.

Two examples are presented in Figure 5. During the conjunction on 16 September 2007 (left hand side of Figure 5), two of the THEMIS probes are located in the solar wind while their companions are sampling the low-latitude boundary layer and dayside magnetopause. Meanwhile, the four Cluster spacecraft are moving from low-to-high latitudes at mid-altitudes ($\sim 2\ R_E$) through the northern hemisphere cusp (having traversed the southern hemisphere cusp as the spacecraft move inbound to perigee $\sim$1 hour earlier). At perigee, the orbital motion of the four Cluster spacecraft causes the inter-spacecraft configuration to distort from the often-cited tetrahedral geometry and adopt a “string of pearls” arrangement. While this linear distribution of spacecraft compromises the capability to perform truly three-dimensional measurements, it does result in four traversals of very nearly the same region of space over a period of time slightly shorter than one hour. As such, the mid-altitude cusp crossings by the Cluster spacecraft are spread out in time, increasing the likelihood of a Cluster spacecraft being located in the cusp when one of the innermost THEMIS probes traverse or skim the low-latitude magnetopause.

The 23 September 2007 conjunction, presented on the right hand side of Figure 5, demonstrates a further configuration of the THEMIS probes that might be exploited to investigate solar wind-magnetosphere-ionosphere coupling processes at the dayside magnetopause. In this case, the THEMIS probes make outbound traversals of the pre-noon sector low-latitude magnetopause in a “line abreast” formation. In the history of magnetospheric exploration, no other mission has offered the capability of sampling the dayside magnetopause at several local times within over a short time interval. In this case, the magnetopause crossings occur as the Cluster spacecraft traverse the southern hemisphere magnetospheric cusp.

This underlines the point that although the THEMIS mission is primarily optimized for space-ground coordination with instruments in the northern hemisphere (and the Canadian and the Alaskan sectors in particular), excellent conjunction will arise between the THEMIS probes, the Cluster spacecraft and ground-based experiments in the southern hemisphere. Clearly, since the THEMIS spacecraft probe the dayside magnetosphere, magnetosheath and solar wind during the northern hemisphere summer month, optical measurements of the cusp aurora will be not be possible using the THEMIS ASI array. However, optical instruments in the southern (winter) hemisphere will be able to make daytime measurements of the cusp aurora. Ionospheric radar observations (using both the coherent- and incoherent-scatter technique) and ground magnetometer measurements made in both hemispheres will also prove to be invaluable.

5. Summary and conclusions

Above, we have presented several examples of favorable conjunctions between Cluster, THEMIS and ground-based experiments. While the THEMIS mission is primarily intended to study the timing of substorm dynamics in the magnetotail, it

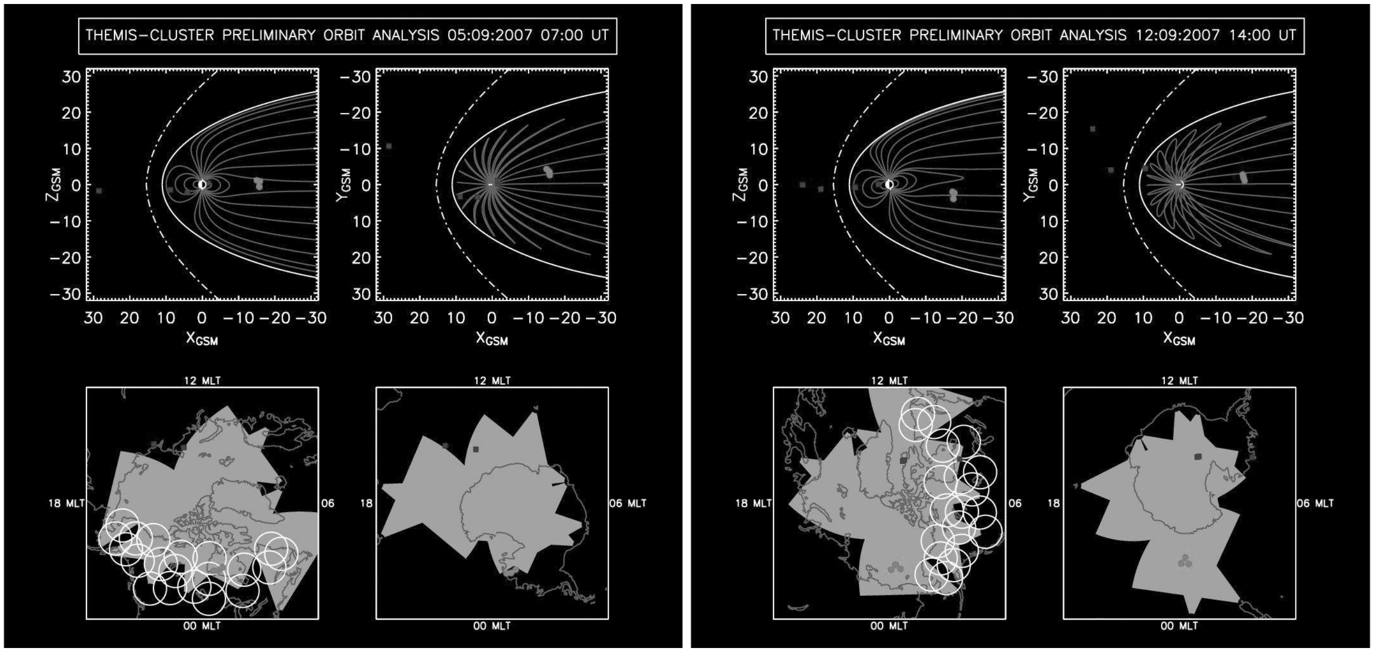

Fig. 4. Estimated THEMIS and Cluster locations and footprints on 5 September 2007 (left) and 12 September 2007 (right).

also presents a unique opportunity to investigate dayside coupling processes and the dynamics of the flank magnetopause (not shown). When combined with the multi-spacecraft Cluster mission and ground-based experiments with extended field-of-view, such as the international network of SuperDARN radars, the capabilities of this unique mission are enhanced greatly. In particular, the separation of the Cluster and THEMIS orbital apogees will allow the simultaneous observation of both dayside coupling and substorm dynamics. We note that uncertainties regarding the final orbits of the various spacecraft at the time of writing mean that specific examples may not occur at the exact dates/times indicated. However, the general arrangement of the various space- and ground-based instruments presented here will occur regularly and present unrivaled opportunities to investigate the dynamics of the terrestrial magnetosphere.

6. Acknowledgements

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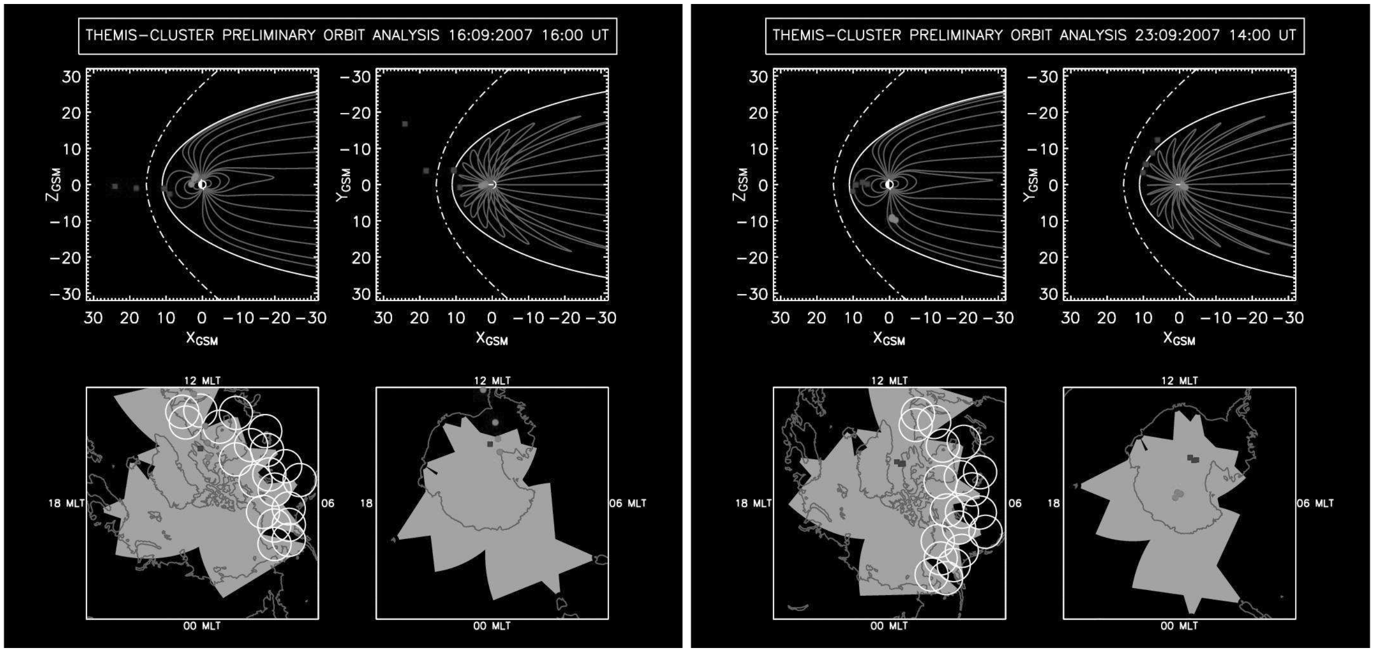

Fig. 5. Estimated THEMIS and Cluster locations and footprints on 16 September 2007 (left) and 23 September 2007 (right).

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