# ALIGNMENT OF THE THEMIS EXTENDED MISSION WITH THE MAGNETOSPHERIC NEUTRAL SHEET

**S. Frey (1), V. Angelopoulos (2), M. Bester (3)**

*(1)Space Sciences Laboratory, University of California,*
*7 Gauss Way , Berkeley, CA 94720-7450,*
*phone: 510-643-3323*
*email: sfrey@ssl.berkeley.edu*

*(2 )ESS/IGPP, University of California, Los Angeles*
*405 Hilgard Avenue, Los Angeles, CA 90095-1567*
*Phone: (310) 794-7090*
*Email: vassilis@ucla.edu*

*(3)Space Sciences Laboratory, University of California,*
*7 Gauss Way , Berkeley, CA 94720-7450,*
*phone: 510-643-7450*
*email: mbester@ssl.berkeley.edu*

**Keywords:** Multi-spacecraft mission, orbit design, THEMIS, Maneuver targeting, Magnetosphere
.

## 1. Introduction

Since July 2009 NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) [1], a Medium-class Explorer Mission launched in February 2007, has been transformed into two extended missions. From the original macro-scale constellation of five identical spacecraft to study the sequence of magnetospheric substorm events the two outermost probes are now on a unique journey to eventually arrive in elliptical, low-inclination lunar orbits by July 2011. These two probes are now referred to as the Acceleration, Reconnection, Turbulence and Electrodynamics of the Moons interaction with the Sun (ARTEMIS) mission. The remaining three inner spacecraft will stay in low-earth near equatorial orbits to continue studying magnetospheric processes as the THEMIS-Low extended mission that is the focus of this paper.

While the primary mission’s objective was to determine the sequence of substorm related events along the Earth magnetotail from about 10 to 30 Earth radii distance in correlation with the gigantic auroral displays they trigger in the polar ionosphere, the extended mission is now looking for insight into plasma processes on much smaller scales. The magnetospheric region that holds the critical information about the plasma processes is a very thin layer at the center of the plasma sheet on the night side called neutral sheet with regards to its characteristic magnetic field structure. In order to find the answers to yet to resolve questions about substorm onsets and its coupling to the ionosphere we have to bring the probes closer to that thin layer decreasing the distance from two Earth radii during the primary mission to less than one Earth radius now. All probes are equipped with identical field and particle instruments and have their own propulsion system that we utilize to retarget the orbit design.

In our analysis of what it takes to close in on the neutral sheet we found that by targeting a certain magnetic latitude of the spacecraft at apogee we can reset our alignment with the neutral sheet by small in-plane maneuver thus avoiding costly plane change maneuvers.

It is the purpose of our paper give a first introduction of this new orbit design criteria and how it can be applied to maneuver planning. After we have given an overview of the THEMIS orbits and the neutral sheet, we describe how this criteria emerged from our analysis and how we can fulfill the science objective by small in plane maneuvers. With a few examples we then demonstrate the cost reducing potential of the method.

## 2. Realigning THEMIS Orbits With The Neutral Sheet

### 2.1. THEMIS Orbit Overview and Neutral Sheet

The extended THEMIS mission is made off the three probes on the low-Earth orbits with apogee hights around 1.6 Re and apogee heights around 11.5 Re. All probes have low inclinations two of them currently stay as low as 2 to 4 degrees while the third one is about 5 degrees higher. All probes have sidereal period in order to maintain alignment with ground observatories. Around apogee the three probes fly in a close formation. The conjunctions with the neutral sheet are key to the science of the tail season that is when the orbits are inside the magnetotail. This configuration is best analyzed in the GSM-coordinate system. In that Earth centered system the x-axis points in the direction of the sun, and the z-axis is along the magnetic dipole pointing north. The y-axis completes the orthogonal system.It is a good measure how the orbits are aligned in the tail. Over one year the orbits have precessed once in this sun referenced frame. In the tail season the apogees line up in the anti-sunward hemisphere. The ideal alignment is when the line of apsides coincides with the x-axis. This moment defines the center epoch of the tail season.

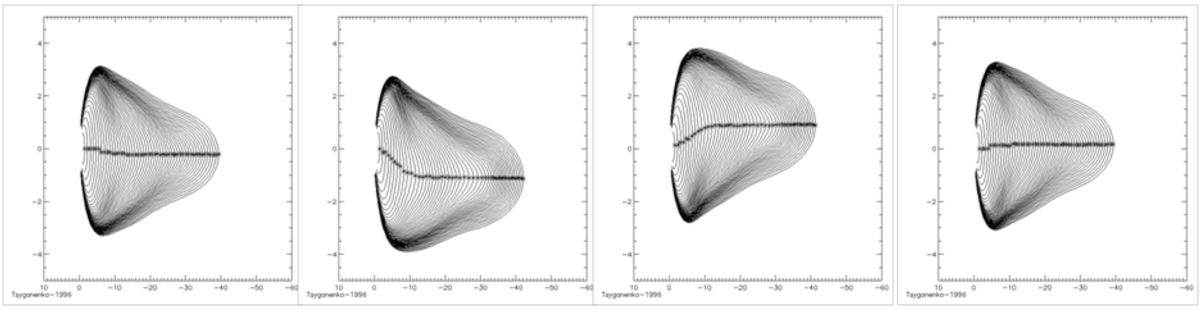


**Figure 1: Meridional cuts through tail magnetosphere in xz-GSM plane with neutral sheet marked for varying local time over 24h**

Confined to the magnetic dipole and the solar wind aligned magnetotail the position of the neutral sheet is determined by the dipole tilt angle, the local time (see Fig. 1), radial distance and magnetic activity. The resulting time dependence of the relative geometry between the neutral sheet, the Earth equator and the orbital plane has always been a challenge to keep the probes in the vicinity of the neutral sheet [2]. After three years in space the precession of the orbits in the sun referenced frame and the perturbation of the inclination have become significant. For example, in one year the center epoch has moved by about one month resulting in an offset of the seasonal alignment with the neutral sheet. This year we have the center epoch on May 15th. A tailseason lasts about 120 days.

The neutral sheet is still a difficult to model magnetosheric region. Though the general origin and location has been known for years, it has been difficult to supply the theories with insitu measurements in order to develop analytical models. For orbit design purposes we successfully applied a simple model during the nominal mission. Up to about 12 Re we consider the magnetic

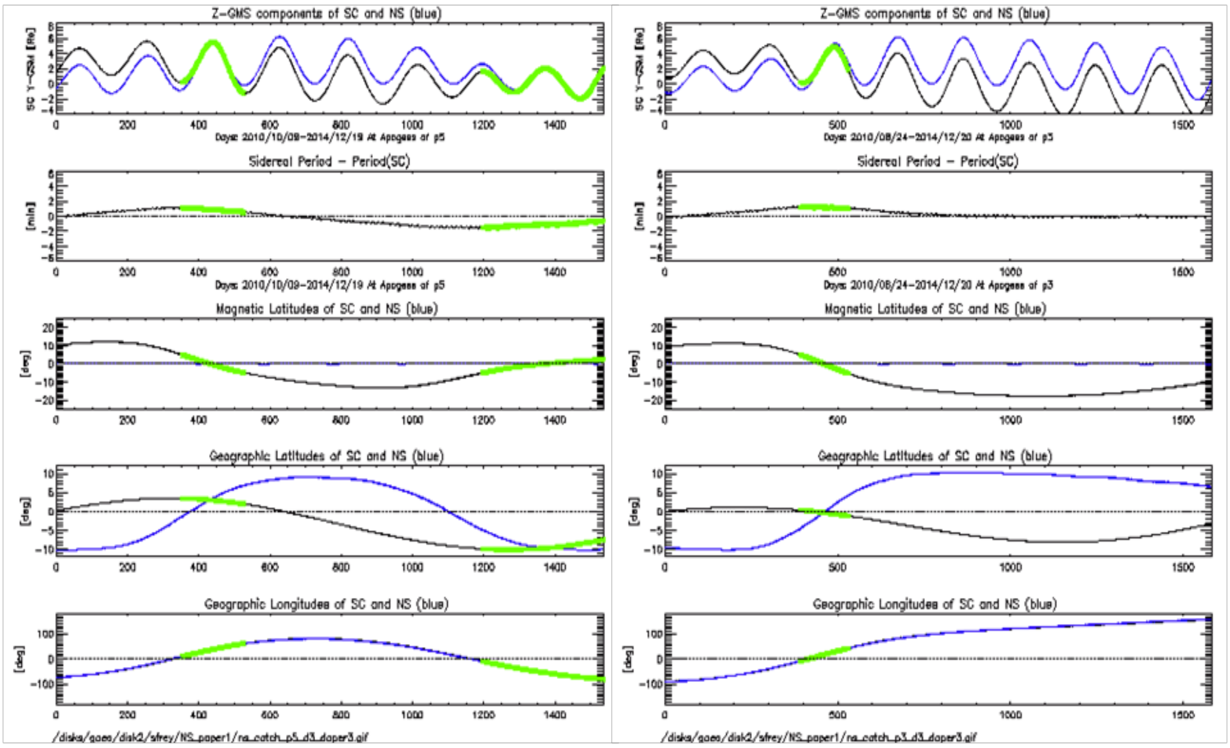



**Figure 2: From top to bottom time evolution of z-GSM components in Re, Deviation from sidereal period in min ,Magnetic Latitude ,Geographic Latitude ,Geographic Longitudes all in deg, x-axis days from 2010-08-24-2014-12-20 , blue neutral sheet data, black probe data, green within design requirement ; left side P5,right side P3**

equator a good estimate of the mean location of the neutral sheet. Our distances to the neutral sheet are referenced to its center and defined as separation of the z-GSM components.. The thickness of the neutral sheet, one of the most debated parameters, is taken into account by our distance parameter. For the extended mission our design goal is to get within 1 Re and sometimes even within .5 Re.

### 2.2. Searching for a Suitable Orbit Design Criterion

Our initial approach was to look for small plane change maneuvers in order to re-align the THEMIS probes with the neutral sheet in the extended mission while the argument of perigee was favorable for such maneuvers. As both define the orientation of the orbital plane in inertial space they determine how it intersects with the neutral sheet. However the relative motion between the neutral sheet and orbit become very complex over time due to the diurnal and annual motion of the neutral sheet and orbit perturbations. For our analyis we took advantage of the natural precession of the argument of perigee and the fact that at arguments of perigee of 0 and 180 degrees the apogees always lie in the neutral sheet. While looking at the rate at which the orbit moves out of the neutral sheet as a function of inclination and the local time of the apogee passes we also discovered an

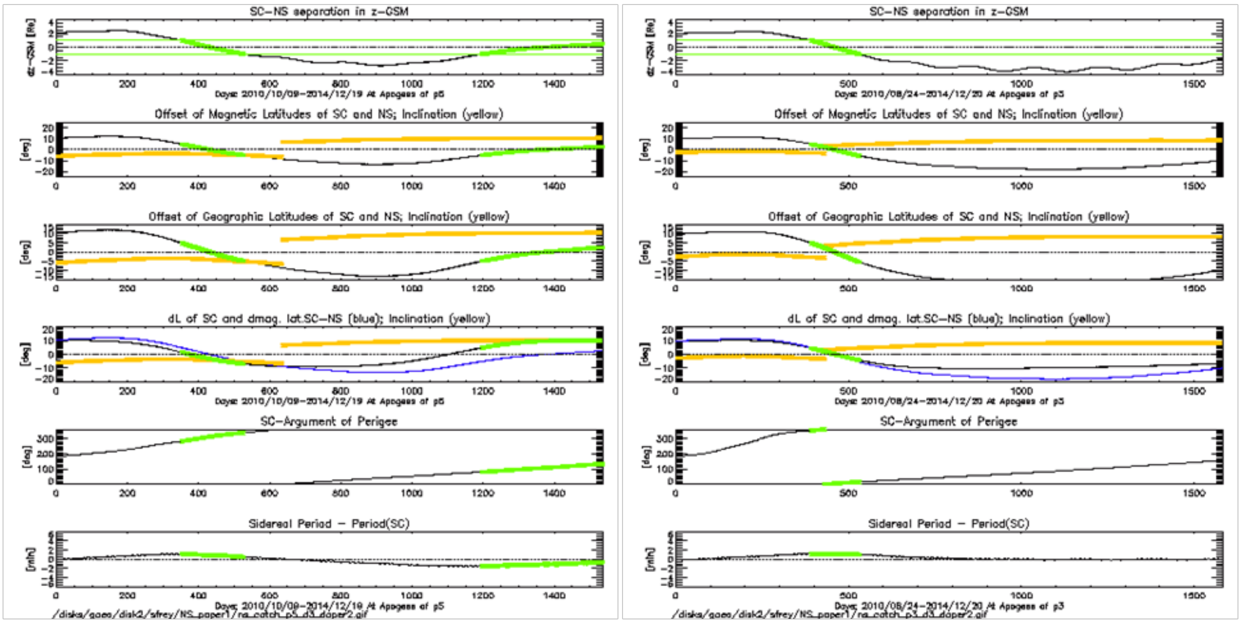


**Figure 3: From top to bottom time evolution of dz-GSM components in Re, Offset of,magnetic Latitudes ,Geographic Latitude for probe to neutral sheet, dL in blue: Offset of,magnetic Latitudes all in deg, Argument of perigee in deg, Deviation from side real period;same x-axis as in Fig. 2, yellow Inc* in deg, green within design requirement ; left side P5,right side P3**

alternative way avoiding those costly maneuvers. Figures 2 to 4 show the evolution of the orbits with regards to their distance to the neutral sheet (top panel) propagated out of summer 2010 over about four years, no active orbit changes applied. Figure 2 compares the z-GSM components of the probes and the neutral sheet with coordinates that relate to the diurnal origin of the neutral sheet. In addition to the magnetic latitude we added the geographic latitudes as an indicator of inclination. The geographic longitude which indicates local time was included since it is of particular interest to us because of conjunctions with ground observatories (panels 3,4,5 from top). For comparison the neutral sheet coordinates at the probe positions are also shown (blue line). Panel 2 from top shows the deviation from the sidereal period, our nominal probe period. In this case these deviations are induced by orbital perturbations. Highlighted in green, and so done on in all figures, are the instances that fulfill our criteria for being close to the neutral sheet (green criterion). Though it is striking that the green intervals start when the period offsets reach about a minute as further analysis will show this is rather a means than a condition to meet the green criteria. In panels 3 to 5 the coordinates do not exhibit obvious correlations except that the latitudes from probe and neutral sheet cross each other during the green intervals which in the case of magnetic latitude is of course expected. A further investigation of these offsets between the latitudes of the probes and the neutral sheet and their correlation with inclination and argument of perigee of the probe orbits is shown in Fig. 3 with the probe inclination overlaid where appropriate. For reference purpose the top panel shows the orbit design goal, this time as the difference of the z-GSM components, the bottom panel shows the deviation of the orbital period from sidereal period. The inclination shown in Figures 3 and 4 is set negative when the argument of perigee (second panel from bottom) is larger than 180 degrees. As expected when the offsets in magnetic latitudes (panels 2 from top) between the probe and the neutral sheet are zero the probe plane is inside the neutral sheet. However, as we deviate from the ideal condition it becomes difficult to determine from this parameter what it takes to improve the situation. Eventually, the comparison with the offset between magnetic and geographic latitude of the probe reveals its correlation with the inclination if we take into account whether the argument of perigee is less or greater than 180 degrees. Panel 4 from top in Figure 3 shows that during the green intervals the offset between magnetic and geographic latitude of the probe is in the order of the inclination Figures 2 to 4 compare the analysis for the probes with different inclination. After having analyzed several cases with different combinations of inclination and argument of perigee we have found relation (1) to be the suitable orbital design criterion:

$$Inc.^* - dL \approx c \qquad (1)$$

where Inc.*-dL is the parameter for an orbit design when the vicinity to the neutral sheet is the mission goal. In (1) Inc* is the orbital inclination with Inc*>0 for aper <180 and inc*<0 for aper >180, dL is the difference of magnetic and geographic latitude of the probe, and c is the critical value. In the case of apogee passes at the center of the magnetotail the value of c is zero. Figure 4 summarizes for the two cases of low and higher inclinations in terms of nearly

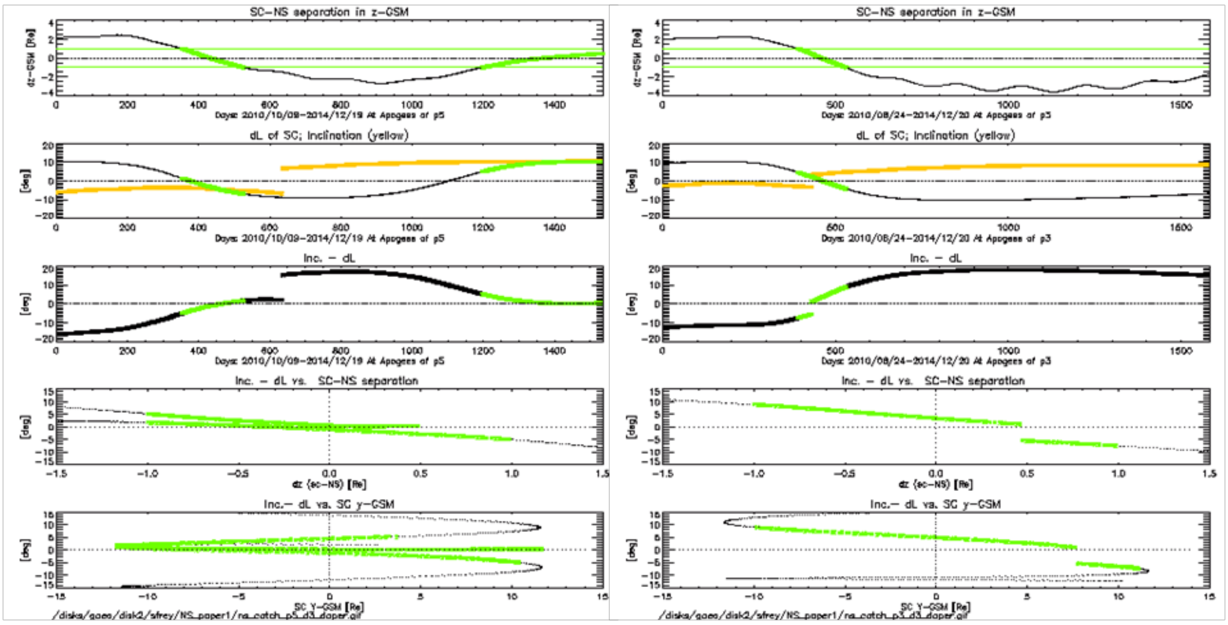
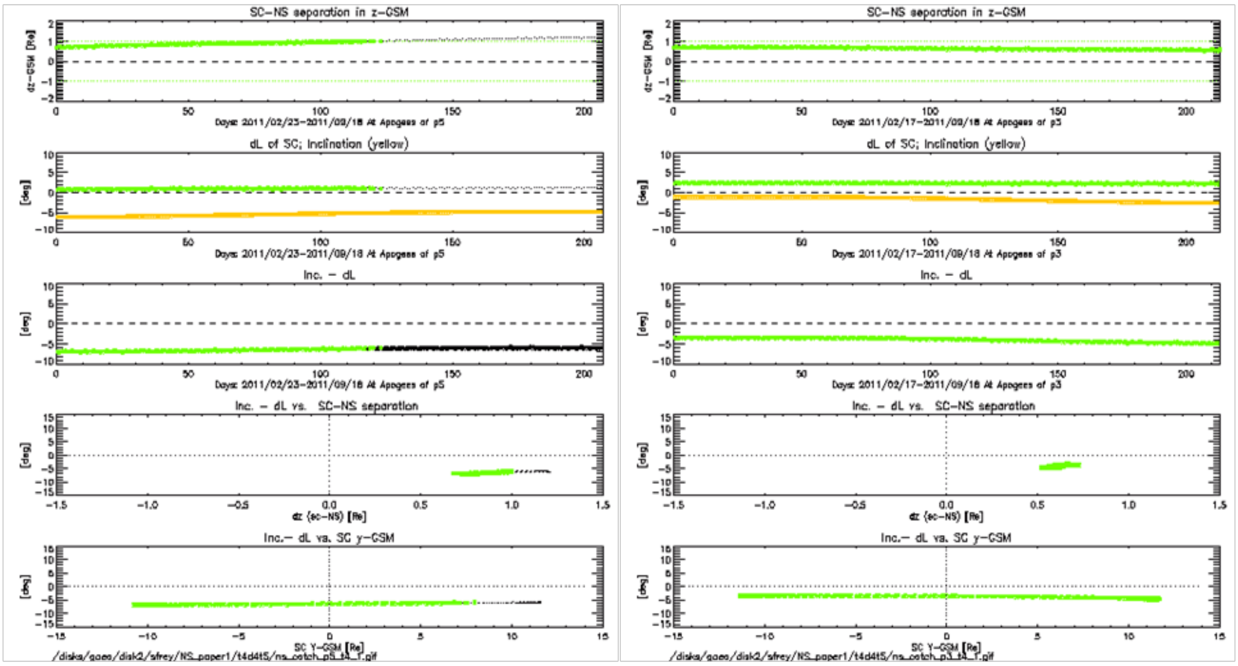


**Figure 4, From top to middle: time evolution of dz-GSM components in Re, dL in degInc*-dL in deg, x-axis as in Fig. 2, yellow Inc* in deg,;middle to bottom: Inc*-dLin deg vs. dz_GSM in Re, Inc*-dL ind deg vs. y_GSM in Re, green within design requirement ;**
**left side P5,right side P3**

equatorial orbits the evaluation of the relation (1). Again for reference purpose we show the time evolution of the probe's distance to the neutral (top panel), the parameters dL and inclination (panel 2 from top), and that of relation (1) (panel 3 from top). The two panels at the bottom of Figure 4 correlate our parameter inc*-dL with the orbit design goal, the z-separations between probe and neutral sheet (2nd from bottom) and with the y-GSM component of the probe (bottom panel). The former clearly shows the closer dL matches inc* the smaller the z-separation. The bottom panel shows an offset in the y-GSM component which is explained by the fact that c is actually a function of the y-GSM component or the angle between the lines of apsides and the sun-earth line. Here we are at y~7.5 Re which way out at the flanks and c becomes larger than zero. The main advantage of this parameter is its dependence on orbital parameters only, that is inclination and argument of perigee which tremendously simplifies orbit design. In addition, this parameter does not require to include neutral sheet models in the process of planning the individual maneuvers.

**Figure 5 Same as Fig. 4 but x-axis days from 2011-02-23-2011_08-18**




Once the maneuver is established the neutral sheet model is only needed to assess the final trajectory which makes operations tremendously efficient. Also, Figures 2 to 4 provide all information needed to evaluate the relative geometry between the orbit and the neutral sheet.

## 2.3 Application to Orbit Design

We want to point out that here we are concerned with a realignment of the orbits and the neutral sheet after natural perturbations have caused some substantial drift out of the nominal configuration. Missions without a propulsion system have to wait until the favorable configuration is met again as shown in Figure 2. Those with propulsion and sufficient fuel reserves have essentially three options:

i. Changing inclination
ii. Changing argument of perigee
iii. Changing offset between magnetic and geographic latitude.

Options i and ii are not only fuel intensive they may not be feasible at all as it is in the case of the probe shown in Fig. 3 . As the opposite sign of Inc* and dL indicates orbital plane and neutral sheet are on opposite sides of the equatorial plane. Raising inclination will increase the separation to the neutral sheet and lowering inclination alone will not solve the problem either. A full flip of the orbit plane is required. When both planes are on the same side with respect to the equatorial plane small inclination changes are feasible and the target inclination can be determined according to relation (1). Option ii may be feasible when small adjustments are sufficient to improve the configuration for a short time period. Option iii employs a few small maneuvers to change orbital period in order to unlock the phase between magnetic and geographic latitude that was frozen in by the sidereal period of the orbits. Whether the drift period must be larger or smaller then sidereal period depends on the direction dL has to change in order to match inc* in the shortest time possible. Since the geographic longitude is changing for the same reason though on a very different rate its final choice is dictated by relation (1). Once relation (1) is fulfilled the orbital period is set back to the sidereal period and the apogee passes are locked inside the neutral sheet. All in all option iii can be as little as three maneuvers changing apogee back and forth by 100 km and fine tune sidereal period requiring less than 10 m/s DeltaV . If time is not an issue it can be done with much less DeltaV. The advantage of the natural drift still remains ,only the probe maintains its position relative to the neutral sheet over a longer period of time.

For most applications relation (1) can be relaxed into relation (2) by allowing some tolerance d:

$$\mathrm{c} - \mathrm{d} < Inc.^* - dL < c + d \qquad (2)$$

For most missions the probes don’t have to be exactly at the center of the neutral sheet and the mission requirement is to be within a certain distance. In the tolerance d lies the potential for orbit design trade offs. For us that is mainly d versus the geographic longitude. It also can be d versus time. The two bottom panels in Figures 4 are very handy tools to convert tolerance d provided as dz-GSM design goal into the offsets measured in degrees. In Fig. 5 we show the probes from Figures 2. The time ranges overlaps with days 200 to 400 from figure 2 . The timing of the small maneuvers was selected to keep one probe at 1 Re to the neutral sheet and the other one within .5 to 1 Re . Without the small maneuvers of option iii both probes were at the 2 Re mark at that time.

### 3. Summary

We have shown how the difference of magnetic and geographic latitude of the spacecraft and its inclination is correlated to the distance to the neutral sheet and how easily this can be implemented as the orbit design criterion in our highly automated maneuver planning process [3]. We demonstrated that we can control when the probes will be in the vicinity of the neutral by taking advantage of the dependence of the magnetic latitude on local time. With the method of changing orbital period at the appropriate times and locking in by means of the sidereal period we found an alternative way to expensive inclination changes. Further more, the analysis shown here provides easy guidance in the long term planning and selection of maneuver plans. Once the maneuver schedule is determined in an off line step relation (2) is then integrated in our short term planning of the formation maintenance. Keeping maneuvers small helps to maintain a low risk level of operations, and allows us the cost effective return of cutting edge science [4].

### 4. Acknowledgement

This mission is the result of the combined efforts of the members of the THEMIS team and individuals that steadfastly supported our ambitious endeavor. When it comes to mission design and

implementation the reliable and diligent work by the operations team and the flight dynamics group at the mission operations center at SSL/UCB deserves special recognition.
The THEMIS is funded by NASA contract NAS5-02099.

## 5. References

[1]. Burch J.L. and Angelopoulos V., *The THEMIS Mission,* Space Science Reviews, Vol. 141, Issues 1-4, 2008.

[2] Frey S. et al., *Orbit Design for the THEMIS Mission*, Space Science Reviews, Vol. 141, Issues 1-4, 2008.

[3] Frey S. et al. THEMIS: Implementation of a Challenging Missions Design , Proceedings 20th International Symposium on Space Flight Dynamics – 19th ISSFD, T, MD, Toulouse, France, 2009.

[4] Bester M. et al., *THEMIS Operations*, Space Science Reviews, Vol. 141, Issues 1-4, 2008.

.