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

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Abstract: *In July 2009 NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS), a medium-class Explorer mission launched in February 2007 to study the sequence of magnetospheric substorm events, was transformed into two extended missions. The two outermost probes from the original macro-scale constellation of five identical probes are now on a unique journey to 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 Moon's Interaction with the Sun (ARTEMIS) mission. Here we focus on the remaining three probes, which will stay in low-Earth, near-equatorial orbits to continue studying magnetospheric processes as the THEMIS-Low Extended mission. The magnetospheric region that holds critical information about plasma processes is a very thin layer at the center of the night-side plasma sheet called the neutral sheet. In order to find answers to questions about substorm onset and its coupling to the ionosphere, we must bring the probes closer to that thin layer by decreasing the distance from two Earth radii during the primary mission to less than one Earth radius (<6300 km).*

By targeting a certain magnetic latitude of the probe, we can reset its alignment with the neutral sheet and center its apogee pass there. In this paper we present this element of the extended THEMIS mission design and first results. By taking advantage of the dependence of the midnight magnetic latitude on UT, we can adjust the probe's position on the orbit to be closer to the neutral sheet. Changing the orbital period at appropriate times and locking it in by means of the sidereal period, avoids fuel-expensive inclination changes. We will address how this concept is integrated into our long and short term formation maintenance planning.

Keywords: *multi-spacecraft mission, orbit design, THEMIS, maneuver targeting, magnetosphere*

1. Introduction

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

The primary mission's objective was to determine the sequence of substorm-related events along the Earth's magnetotail from about 10 to 30 Earth radii (Re) and their correlation with the gigantic auroral displays they trigger in the polar ionosphere. The extended mission seeks insight into plasma processes on much smaller scales. The magnetospheric region that holds the critical information about plasma processes is a very thin layer at the center of the night-side plasma sheet called the neutral sheet with a characteristic magnetic field reversal (Bx=0). In order to answer still unresolved questions about substorm onset and its coupling to the ionosphere, we must bring the probes closer to that layer, decreasing the distance from two Earth radii during the primary mission to less than one Earth radius. All probes are equipped with identical field and particle instruments and have their own propulsion system that we utilize to retarget the orbit.

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 probe at apogee, we can reset the probe's alignment with the neutral sheet by in-plane maneuvers, thus avoiding costly plane-change maneuvers. Here we introduce this new orbit design criterion and explain 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 criterion emerged from our analysis and how we can fulfill the science objective by small, in-plane maneuvers. 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 comprises the three probes in low-Earth orbits (P3,P4,P5) with perigee heights around 1.6 Re and apogee heights around 11.5 Re. All probes have inclinations

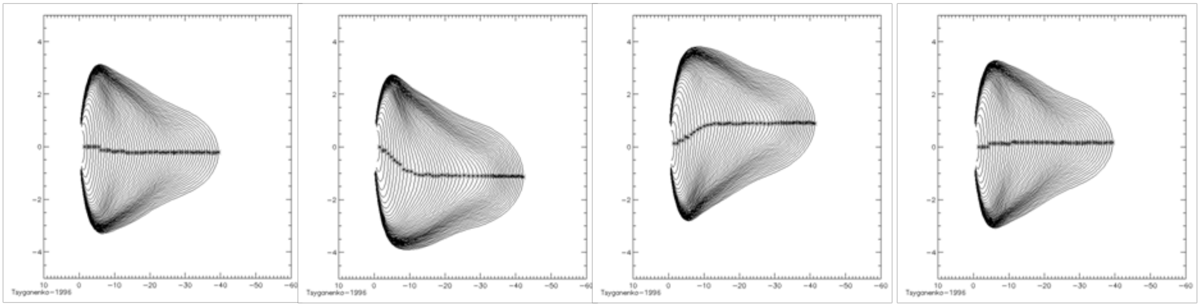


Figure 1: Meridional cuts through the central tail magnetosphere in the xz-GSM plane with the neutral sheet marked for varying times over 24h. Major tick marks are 10 Re on x-axis and 2 Re on z-axis, respectively. The lines are magnetic field lines according to the Tsyganenko T96 [2] model.

below 10 degrees; one probe (P5) is about 3 to 5 degrees higher. All probes have sidereal period in order to maintain alignment with ground observatories located across North Canada. Around apogee the three probes fly in close formation. The probes originally formed a nearly isolateral triangle in the orbital plane; they now form a triangle in the meridional plane. Conjunctions with the neutral sheet are key to the science when the orbits are inside the Earth's magnetotail, during the so-called tail season. This configuration is best analyzed in the geocentric solar magnetospheric (GSM) coordinate system, where the x-axis points toward the sun, the z-axis is along the magnetic dipole pointing north, and the y-axis completes the orthogonal system. In this sun-referenced system, the magnetotail lies in the anti-sunward direction. The orbits precess once per year, moving in and out of the tail over about 120 days. The moment when the line of apsides coincides with the negative x-axis (y=0) defines the center epoch of the tail season. The y-component is a suitable measure of orbital alignment in the tail. The position of the neutral sheet, which is confined to the magnetic dipole and the solar wind-aligned magnetotail, is determined by dipole tilt angle, time (see Fig. 1), radial distance, and magnetic activity. With the resulting time dependence of the relative geometry of the neutral sheet, the Earth's equator, and the orbital plane, it has always been a challenge to keep the probes in the vicinity of the neutral sheet [3]. After the probes have been in space for three years the precession of their orbits in the sun-referenced frame and the perturbation of their inclinations 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. In 2008, the center epoch was February 2nd; in 2011 it is May 15th .

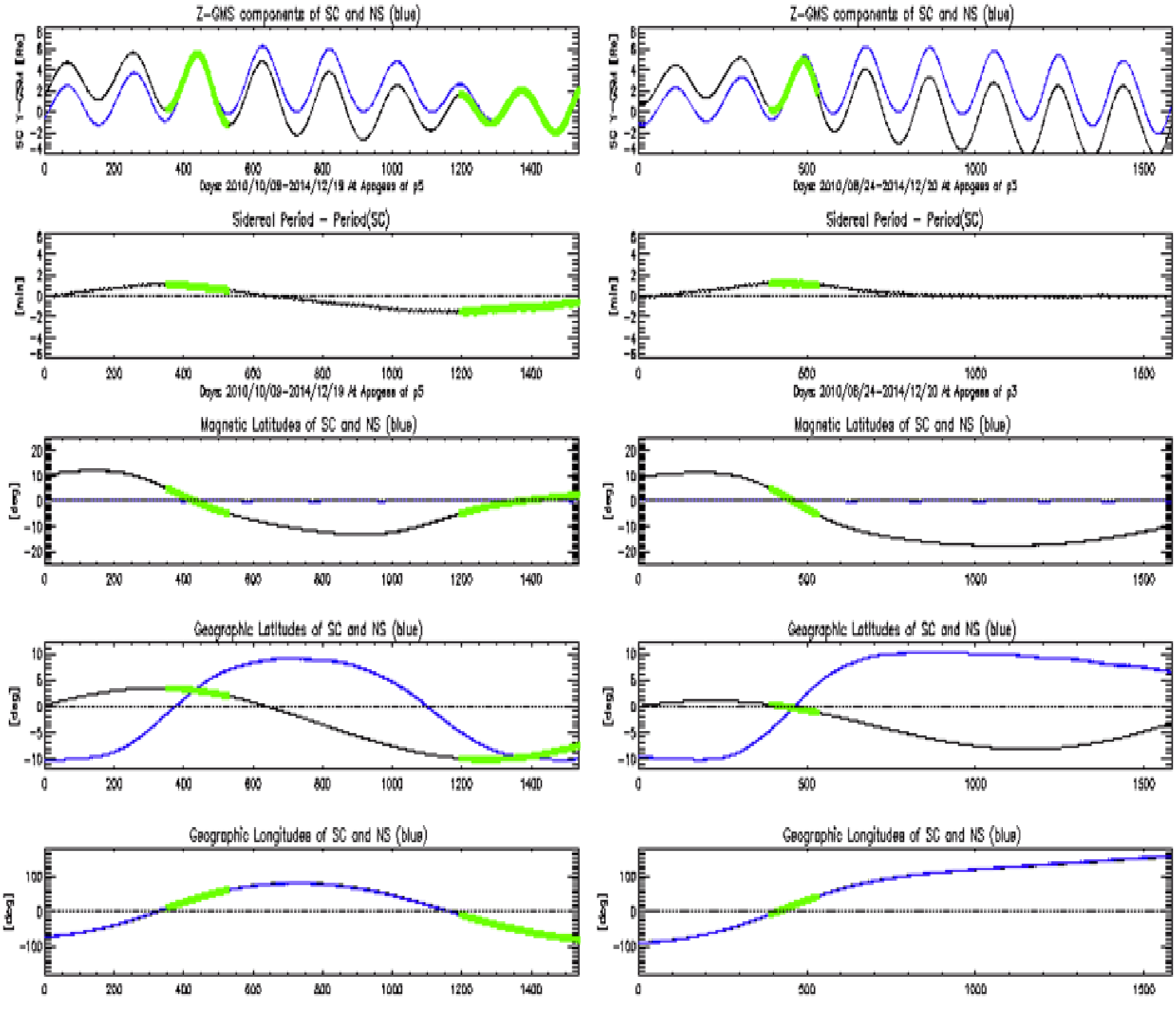
For orbit design purposes, we successfully applied a simple neutral sheet model during the nominal mission. Inside a radial range of 12 Re, we consider the magnetic equator a good estimate of the neutral sheet's mean location and structure, as stronger or weaker geomagnetic activities decrease or increase the radial range and the magnitude of neutral sheet deviation from the magnetic equator. In this model the magnetic latitude of the neutral sheet is zero by definition. We define distance to the neutral sheet as separation of the z-GSM components. For the extended mission our design goal is to get within one Earth radius and sometimes even within one half Earth radius to the neutral sheet.

2.2. Searching for a Suitable Orbit Design Criterion

Inclination and argument of perigee define how the orbit intersects the neutral sheet, as both determine the orientation of the orbital plane in inertial space. Hence, our initial approach was to look for small plane change maneuvers, primarily inclination changes, in order to re-align the probes with the neutral sheet while the argument of perigee was favorable for such maneuvers. In our analysis we utilize natural precession and perturbations of the argument of perigee and semi-major axis that our orbits would experience without orbital maintenance. Furthermore, we consider the entire magnetic equator as neutral sheet in order to take advantage of the entire data set. Whereas physical processes related to the neutral sheet take place only on the night side, the relative geometry between magnetic equator and orbital plane applies to night side and dayside. While looking at the rate at which the orbit moves in and out of the neutral sheet as a function of inclination and time of the apogee passes, we discovered a way to avoid those costly out-of-plane maneuvers.

Figures 2 to 4 show the orbital evolution for two of the three THEMIS probes with regard to their distance to the neutral sheet (top panels). Orbits have been propagated out of summer 2010 over nearly four years sampling the annual variations of the dipole tilt angle multiple times. Significantly, both probes differ in inclination and argument of perigee. The probe on the left side has the higher inclination. The blue lines represent neutral sheet coordinates. The probe data highlighted in green fulfill our requirement for being close to the neutral sheet (green conditions).

Figure 2, in particular, compares the z-GSM components of the probes and the neutral sheet with coordinates that relate to the neutral sheet's diurnal origin. In addition to the magnetic latitudes, we added geographic latitudes, which indicate inclination, and geographic longitudes, which indicate universal time (panels 3, 4, 5 from top). The latter parameter is of particular interest to us because of conjunctions with ground observatories. Panels 2 from the top show orbital period deviations from the sidereal period (our nominal probe period) induced by orbital perturbations. Although it is striking that the green intervals start when the period offsets reach about a minute, as further analysis will show, this is a means rather than a condition to meet the green conditions. In panels 3 from the top, during the green intervals the magnetic latitude of the probes cross zero, indicating that the probes are crossing the neutral sheet. As long as the probe's magnetic latitude is positive, the probe's z-GSM component is larger than that of the neutral sheet and vice versa. The geographic coordinates of probe and neutral sheet show no obvious correlations except that the latitudes from probe and neutral sheet cross each other during the green intervals.


Z-GMS components of SC and NS (blue)

Sidereal Period - Period(SC)

Magnetic Latitudes of SC and NS (blue)

Geographic Latitudes of SC and NS (blue)

Geographic Longitudes of SC and NS (blue)

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Figure 2: The time evolution of various parameters for two probes at apogee with P5 on the left side and P3 on the right side. In both columns panels show, from top to bottom, the z-GSM components in Re, the deviation from sidereal period in minutes, the magnetic latitudes, the geographic latitudes, and the geographic longitudes, all in degrees. The x-axis is in days from 2010-08-24 to 2014-12-20. Colors are: blue - neutral sheet data, black - probe data, green - probe distance to neutral sheet meets requirement.

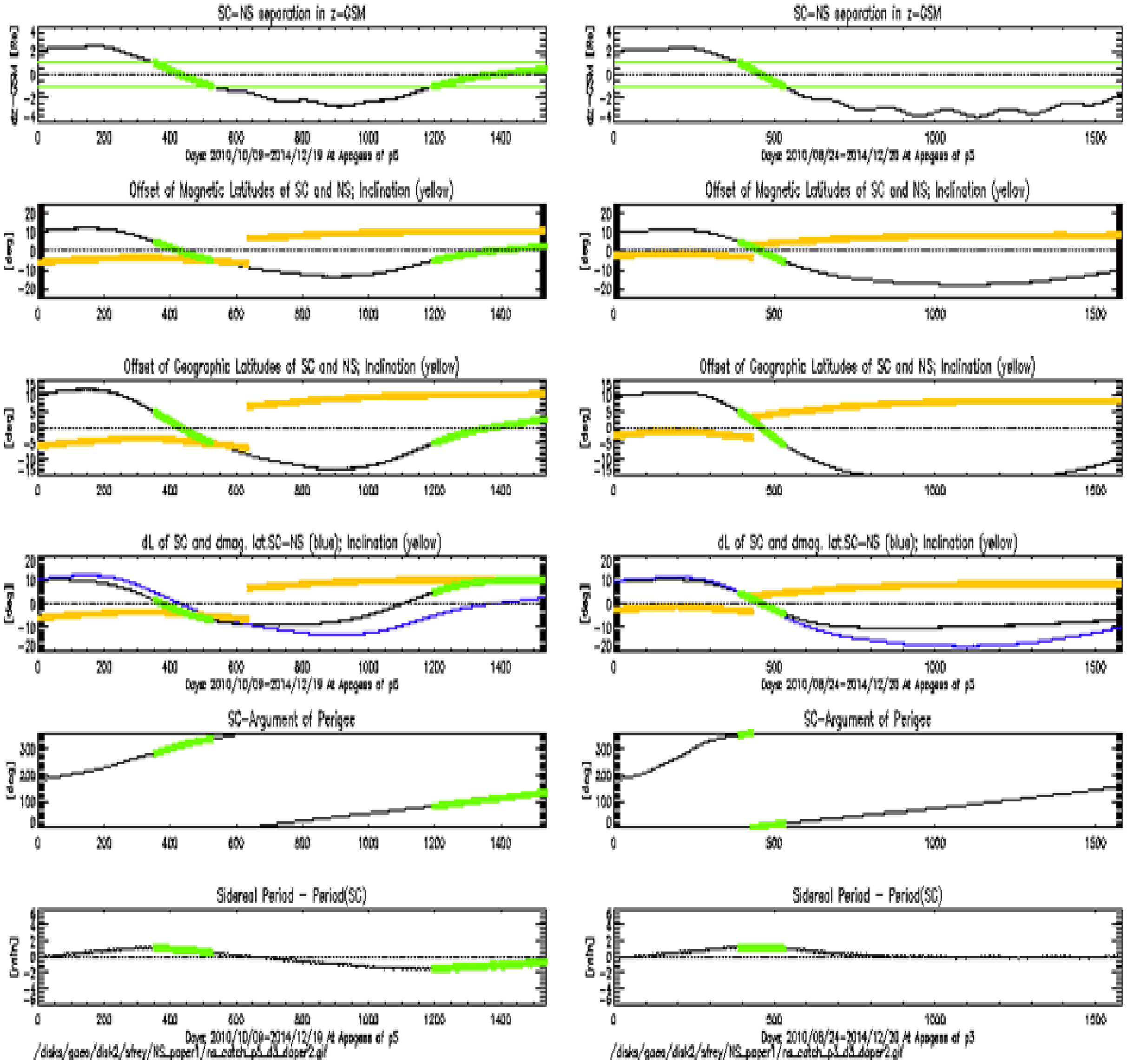

Figure 3: As in Fig. 2, both columns show the time evolution of additional parameters for the same two probes at apogee, with P5 on the left side and P3 on the right side. In detail these panels show, from top to bottom, the dz-GSM components in Re, the magnetic latitude offset between probe and neutral sheet, the geographic latitude offset between probe and neutral sheet, and dL, all in degrees. Panels 2,3,4 from the top show inclination in yellow. The x-axis is in days from 2010-08-24 to 2014-12-20. Colors are: blue - neutral sheet data, black - probe data, green - probe distance to neutral sheet meets requirement.

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 probes is shown in Fig. 3, where the probe inclination is overlain in yellow where appropriate. For reference, the top panels show the orbit design goal, this time as the difference in the z-GSM components, and the bottom panels show the deviation of the orbital period from sidereal period. As expected, as long as the magnetic latitude offsets (panels 2 from top) and the geographic latitude offsets (panels 3 from top) between probe and neutral sheet are zero, the probe is lined up with the neutral sheet. Neither one by itself is correlated with the inclination during the green intervals. However, as panels 4 from the top in Fig.3 show, there is a correlation between the probe's offset between magnetic and geographic latitudes

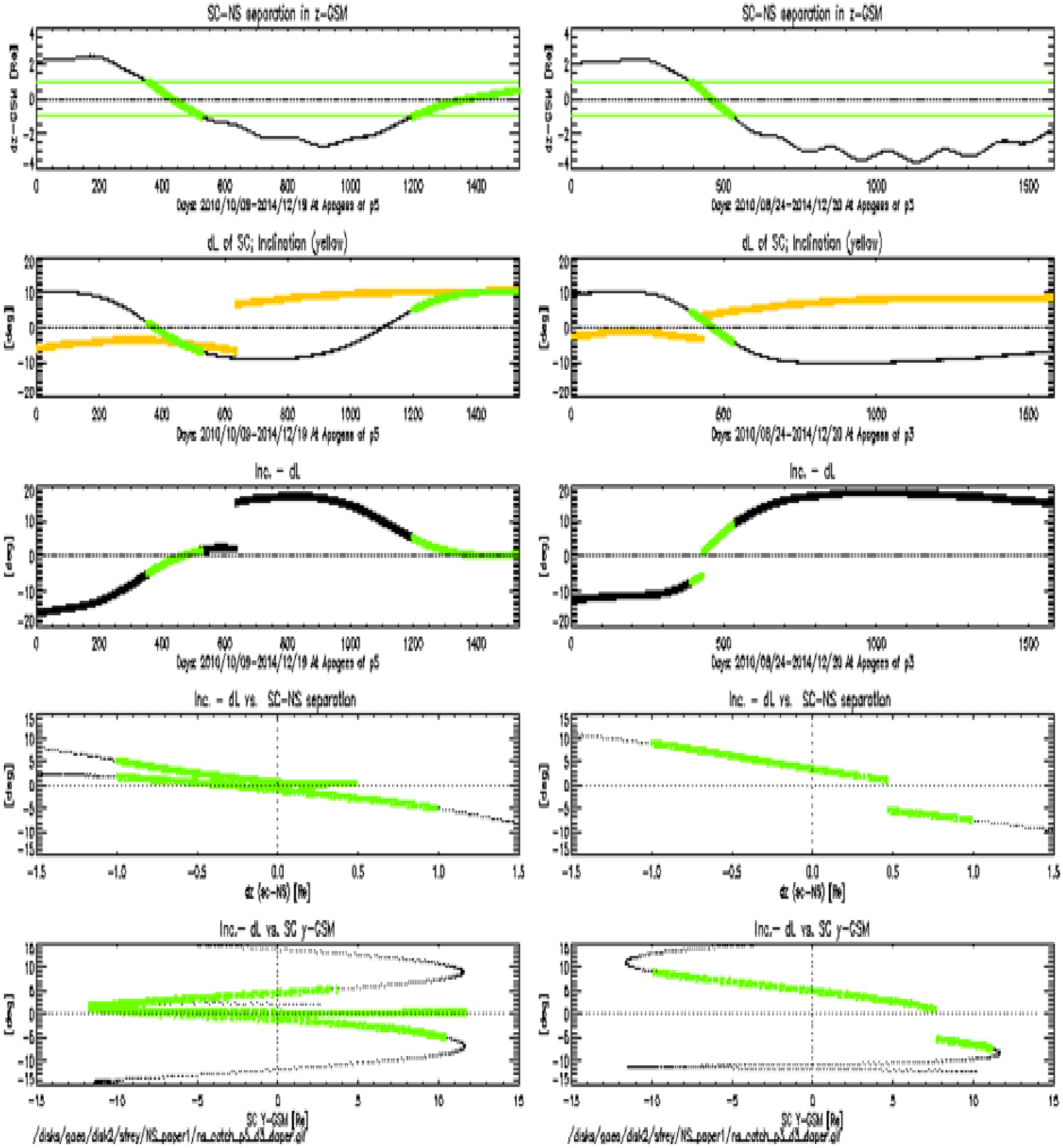

Figure 4: As in Fig. 3, both columns show the time evolution of the parameters used for relation (1) for the same two probes at apogee, with P5 on the left side and P3 on the right side. The upper three panels show, from top to bottom, the dz-GSM components in Re, the offset of the probes' magnetic and geographic latitudes (dL) and the signed inclination (Inc*) in degrees, the left side of relation (1) (Inc*-dL) in degrees. The two lower panels show, from top to bottom, Inc*-dL in degrees vs. dz-GSM in Re, Inc*-dL in deg vs. y-GSM in Re. The x-axis is in days from 2010-10-09 through 2014-12-20. Colors are: yellow - inclination, green - probe distance to neutral sheet design meets requirement.

and its inclination if we take into account whether the argument of perigee is less than or greater than 180 degrees. The inclination shown in Figures 3 and 4 is set negative when the argument of perigee, shown in Fig. 3 in the second panels from the bottom, is larger than 180 degrees.

Regardless the magnitude of its inclination, the probe is within the neutral sheet (green intervals) only when the offset between the probes's magnetic and geographic latitude is in the order of the inclination with its sign set according to the argument of perigee. With that we are provided with an orbit design criterion that can be expressed by the empirical relation (1).

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

where Inc.*-dL is the target parameter in order to reach the orbit design goal regarding the vicinity of the neutral sheet. In (1) Inc* is the signed inclination, with Inc*>0 for arguments of perigee <180 and Inc*<0 for arguments of perigee >180. The parameter dL is the difference between the probe's magnetic and geographic latitudes, and C is the critical value. For apogee passes crossing the Sun-Earth line (ygsm=0), the value of C is zero. Our neutral sheet model with zero magnetic latitude and zero C is a special case of relation (1). Whenever the sum of geographic latitude and signed inclination equals zero, the probe is within the neutral sheet. If they do not cancel each other, the orbital plane and the neutral sheet are on opposite sides of the equator. Further evaluation of relation (1) with our data set is given in Fig. 4 for relatively low and high inclinations. In the upper three panels we show the time evolution of the distance of the probe from the neutral sheet (dz), the difference between the probe's magnetic and geographic latitudes (dL) together with the signed inclination (Inc*), and the parameter of relation (1) (Inc*-dL). Either probe is above the neutral sheet as soon as its magnetic latitude becomes larger than its geographic latitude (dL>0). Likewise, either probe is below the neutral sheet as soon as its geographic latitude becomes larger than its magnetic latitude. Large negative values of Inc*-dL indicate that the probe is above the neutral sheet and vice versa.

The lower two panels of Fig. 4 correlate the parameter Inc*-dL with the orbit design goal, the z-separations between probe and neutral sheet (2nd from the bottom), and the y-GSM component of the probe (bottom panel), which is constantly changing. The 2nd panel from the bottom clearly shows that the more closely dL matches Inc*, the smaller the z-separation. The lower green interval on the left side corresponds to the first green interval in the top panel. In both green intervals the minimum separation between probe and neutral sheet does not coincide with crossing the Sun-Earth line, and the y-GSM components for both instances are about -7 Re and -1 Re. Hence, C is not zero. The bottom panels address the dependence of C on the y-GSM component or the angle between the line of apsides and the Sun-Earth line, respectively. The lowest green curve on the left side corresponds to the first green interval. On the right side the minimum separation occurs at y-GSM=3 Re. The discontinuity here is due to the change in sign of the inclination as the argument of perigee passes through zero.

Once the value of C has been determined, we can assess the relative position to the neutral sheet from probe data alone by using relation (1). This makes it very favorable for automated orbit design. In addition, this parameter does not require use of neutral sheet models to plan individual maneuvers. Once the maneuver plan has been established, the neutral sheet model is only needed to assess the final trajectory, which makes operations very efficient. Figures 2 to 4 provide the information needed to evaluate the relative geometry between the orbit and the neutral sheet.

2.3 Application to Orbit Design

Here we are concerned with realignment of orbits with the neutral sheet after natural perturbations have caused substantial drift out of the nominal configuration, and our requirements have become more stringent. As shown in Figure 2, Missions without an onboard propulsion system must wait until the configuration is again favorable. For those with propulsion and sufficient fuel reserves there are 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, but may not be feasible. The opposite signs of Inc* and dL in Fig. 3 indicate that the orbital plane and neutral sheet are on opposite sides of the equatorial

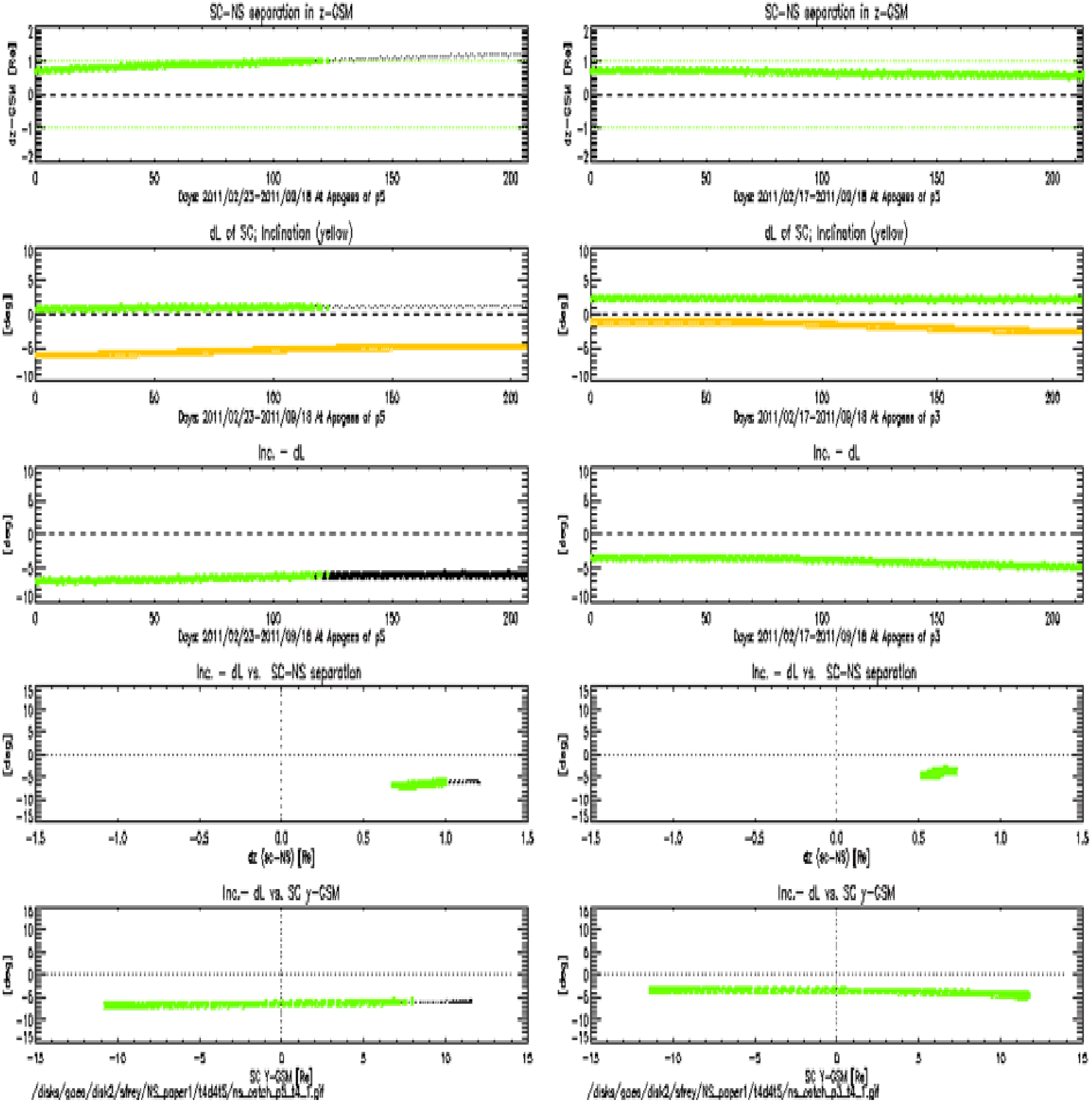

Figure 5: Same as Fig. 4 but x-axis is in days from 2011-02-23 to 2011-08-18

plane. Raising inclination will increase the separation to the neutral sheet, and lowering inclination alone will not solve the problem. A full flip of the orbit plane is required. When both planes are on the same side of 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. Option iii employs a few small maneuvers to change orbital period so as to unlock the phase between magnetic and geographic latitude that was frozen in by the orbits' sidereal period. Whether the drift period must be larger or smaller than the sidereal period depends on the direction in which dL must change in order to match Inc* in the shortest time. Since the geographic longitude is also changing but at a different rate its final choice is dictated by relation (1). Once relation (1) has been 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 consist of as little as three maneuvers, changing apogee back and forth by 100 km and resetting sidereal period, requiring less than 10 m/s DeltaV. If time is not an issue, these maneuvers can be done with much less DeltaV. The probe maintains its position relative to the neutral sheet as long as the orbital period equals the sidereal period. For most applications, relation (1) can be relaxed into relation (2) by allowing some tolerance D:

$$C - D < Inc^{*} - dL < C + D \qquad (2)$$

For most missions the probes do not have to be exactly at the center of the neutral sheet; the mission requirement is to be within a certain distance from the neutral sheet. The tolerance D holds the potential for orbit design tradeoffs. For us that is mainly D versus the geographic longitude. It also can be D versus time. The two bottom panels in Figures 2-4 are empirical tools to convert tolerance D, provided as the dz-GSM design goal, into the offsets measured in degrees. In Fig. 5 we repeat Fig. 4 with the same probes but after small maneuvers have been executed. The time ranges overlap with days 200 to 400 from Fig. 4. 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 in order to maintain conjunction with ground observatories. Without the small maneuvers of option iii, both probes would be at 2 Re.

3. Summary

We have shown how the difference between magnetic and geographic latitude of the probe 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 [4]. We demonstrated that we can control the time when the probes will be in the vicinity of the neutral sheet by taking advantage of the time dependence of the magnetic latitude. By changing orbital period at the appropriate times and locking in by means of the sidereal period, we found an alternative to expensive inclination changes. Furthermore, the analysis shown here provides easy guidance in long-term planning and selection of maneuvers. Once the maneuver schedule is determined in an off-line step, relation (2) is integrated into our short term planning of formation maintenance. Keeping maneuvers small helps maintain a low risk level of operations and allows us the cost effective return of cutting edge science [5]. Future work will focus on further analysis of the dependences of C and apply different neutral sheet models.

4. Acknowledgement

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