DEORBIT MANEUVER STRATEGY FOR THE THREE THEMIS PROBES

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Abstract:
For our long-term planning of the THEMIS mission it is essential to design a reentry maneuver that is a robust estimate regardless of varying orbit redesigns. In this paper we analyze the evolution of the perigee altitudes for various scenarios of the Earth orbiting THEMIS probes and discuss the dynamic of the perigee altitude profile in terms of the combined effects of luni-solar forces as well as the Earth's oblateness. As our solution of a robust reentry maneuver, we demonstrate that a maneuver of fixed size can be executed at any time in order to initiate reentry at a later time. We describe how the size of this maneuver can be derived from the minima of perigee altitudes.

Keywords: *Multi-spacecraft mission, automated orbit design, THEMIS, deorbit maneuver*

1. Introduction

After ten years in orbit the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission, a NASA Medium Explorer (MIDEX), still anticipates ambitious orbit redesigns that will finally expedite its onboard propellant while still fulfilling the reentry requirement [1]. THEMIS was launched in February 2007 as a scientific magnetospheric constellation of originally five spacecraft, called probes. The probes carry an identical suite of particle and field instruments as well as a hydrazine based propulsion system. Since 2009 the mission has been split into two missions with two probes (P1, P2) now orbiting the Moon and referred to as the Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission [2]. Both missions are operated from the Mission Operations Center of the University of California at Berkeley in principal investigator mode [3, 4]. Subject of this paper is our deorbit strategy for the three THEMIS probes (P3, P4, P5) orbiting Earth near the equatorial plane in highly elliptical orbits. With apogee altitudes between 11 and 13 Re the reentry option is to reduce their perigee altitudes. THEMIS is utilizing its fuel reserves to greatly enhance its science return by frequently redesigning the orbits based on most recent observations [5, 6]. In order to ensure fuel usage towards the re-entry commitment reducing probe perigee altitude is an orbit design constraint. All coordination with other magnetospheric missions from the Heliophysics System Observatory (HSO) has facilitated the change in drift of the lines of apsides through perigee reduction [7, 8]. Since the end of the nominal science mission we have lowered perigee altitudes from nearly 4000 km to 650 km.

Provided future extended mission phases going beyond 2020 are granted by NASA the anticipated plans are ambitious and the mission will finally expedite its onboard propellant while still fulfilling the reentry requirement. For our long term planning it is essential to design a reentry maneuver that is a robust estimate regardless of varying orbit redesigns. By 2020 the three probes will align in a highly elliptical orbit with apogee geocentric distance at 13.2 Re and perigee geocentric distances at 1.18 ± 0.11 Re. Thereafter all probes will remain in a close string-of-pearls formation for an unspecified time as seen in Fig.1. Reentry from such an orbit is ensured by lowering the perigee altitude.

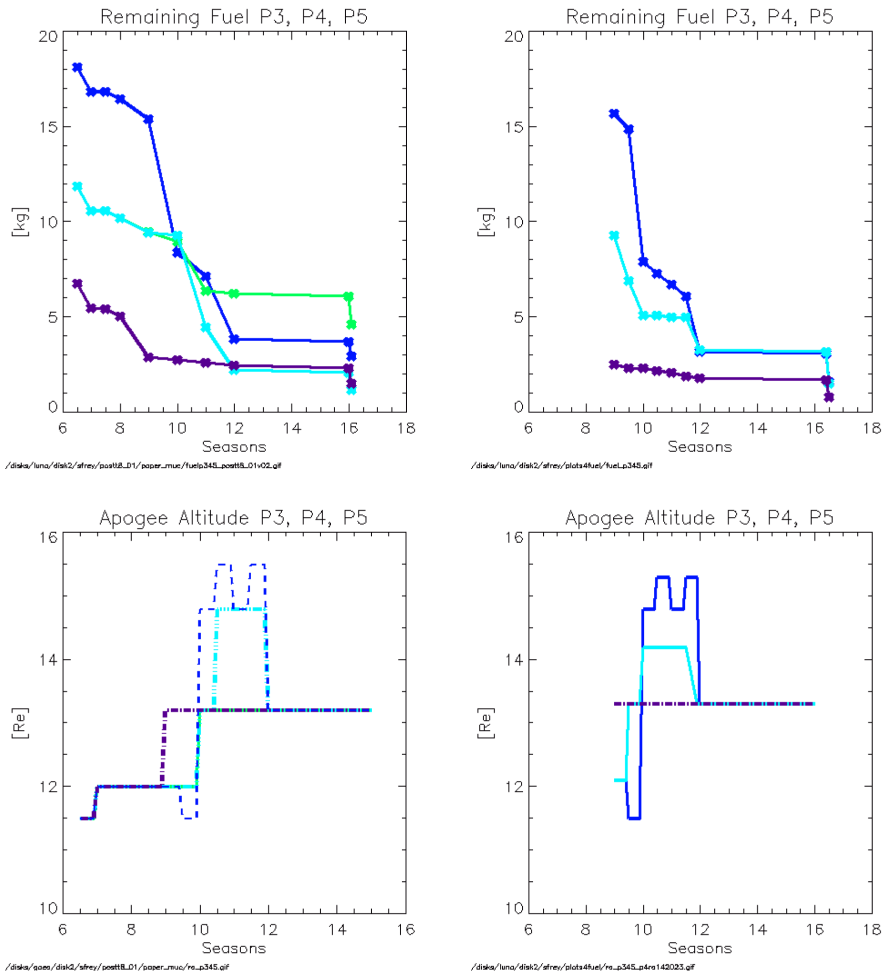

Figure 1. Top row shows remaining fuel as mission progresses with orbit redesign. The corresponding changes in apogee altitude are shown in the bottom row. Time is expressed in mission phases between 2014 and 2024. The probes are color coded with P3 in blue, P4 in cyan, and P5 in purple. Each side represents a different scenario in using the various fuel reserves to target apogee altitudes. At the end a reentry maneuver is included in the fuel budget. On the left-hand side, we explore two options for probe P4 (cyan and green).

In Fig.1 we show two scenarios of orbit redesign as an illustration of our flexibility in refining our science goals. Based on most recent scientific findings we adjust apogee altitudes to address new regions of interest. With the timing of those apogee altitudes and small variations in perigee altitudes among the probes we target certain 3-probe-formations and conjunctions with other space- as well as ground-based assets of the HSO. As can be seen in Fig.1, our fuel management relies on an estimate of a reentry maneuver for each probe that allows us to utilize our remaining fuel reserve for an optimal science output for as long as the mission is operating. An example of our exploration of the long term options is illustrated by the different apogee altitude profiles for probe P4, colored in cyan and green in Fig. 1. They have been revised multiple times in order to find a compromise between science targets and reentry commitment. What complicates estimating a reentry maneuver is the dynamic of the perigee altitude profile. Fluctuations up to 1000 km are typical for our orbit ranges. This dynamic is primarily the result of the combined effects of luni-solar forces as well as the Earth's oblateness and thus different orbit redesign scenarios can significantly alter the perigee altitude profiles. It becomes obvious that our flexibility in the long term planning requires a robust reentry maneuver that can be integrated in the automated mission design. In this paper we present results from our analysis of the perigee altitude evolution of the THEMIS probes and their relative positions to Sun and Moon. By taking advantage of luni-solar perturbations we define a reentry maneuver of fixed size that can be executed any time in order to initiate reentry within a certain time limit. Such a maneuver can easily be integrated into our automated mission design. We also describe how the size of this maneuver can be derived from the local minima of perigee.

2. Robust Reentry Maneuver Strategy

2.1. Robust Reentry Maneuver

Highly elliptical orbits, typically with eccentricities >0.5, experience a complex superposition of perturbations from the Earth oblateness and of gravitational forces from the Sun and Moon [9, 10, 11, 12]. With regard to the reentry maneuver of particular interest here is the combined effect on the perigee altitude. With increasing apogee altitudes the perturbations by Earth, mainly in the J2-terms, are decreasing and the luni-solar forces become more and more dominant and prevent the complete circularization of the orbit due to atmospheric drag.

The THEMIS probes are small enough in size, one cubic meter, and weight, 79 kg, for random reentry making the reentry maneuver time independent. As a robust reentry maneuver from our orbits we look for a maneuver that can be executed any time and ensures reentry within the next 25 years. Given our anticipated final apogee altitude around 13 Re the maneuver must reduce perigee below the decay altitude in order to prevent the raise of perigee by luni-solar perturbations. To minimize fuel and to be time independent the size of the maneuver is determined from a local minimum in the perigee evolution and the critical altitude needed for the rapid decay due to luni-solar perturbations.

2.2. Analysis of Perigee Evolution

In order to determine the minimum size of the reentry maneuver we take advantage of the tremendous amount of data we have generated during our long term mission planning as well as short term maneuver execution. These data have been generated with the high fidelity propagator Goddard Trajectory Determination System (GTDS) [13] where solar pressure, luni-solar perturbations and atmospheric drag are considered. Maneuvers have been simulated with a software package called the General Maneuver Program (GMAN) [14]. Sun and Moon positions are from the planetary ephemerides DE421 provided by NASA's Jet Propulsion Laboratory. Over these ten years in orbit, the validity of the models implemented in these tools has been confirmed by the more than 700 maneuvers which flawlessly put each probe into the targeted orbit states. Being the maneuver target we chose rather perigee altitude than eccentricity as the parameter of interest for this analysis. We looked at the perigee altitude evolution after various orbit states from 2009 through 2027, from 2015 through 2027, and from 2018 through 2027. The initial orbit states for the propagation differ in perigee and apogee altitudes. As mentioned above, the orbit evolution is a complex superposition of Earth generated and luni-solar perturbations. Furthermore, solar activity affects orbit evolution through solar pressure. The variation in time is well covered with the analyzed time ranges. The last solar minimum was from 2008 to 2010 followed by the maximum in 2013. The next solar minimum is expected in 2019 and 2020.

Five sets of orbit states to initialize long term propagation have been chosen to reflect certain states in the mission design. The initial states are from:

1) January 2008, towards the end of the nominal mission. The probes are at higher perigee altitudes than in the following years. Apogee altitudes are around 11.6 Re. The perigee altitude of P5 is 1000 km less than that of P3, P4. The inclination of P5 is about 5 degrees higher compared to P3 and P4.
2) January 2015, at the end of a controlled drift of the line of apsides to place apogee passes at a particular local time. Perigee altitudes are significantly lower than during the nominal mission and apogee altitudes are around 12.1 Re. The orbit for P5 differs from the orbits of P3 and P4 in perigee altitude by -150 km and in inclination by +5 degrees.
3) January 2018, from preliminary long term planning to assess feasibility of science goals based on fuel consumption as illustrated in Fig 1. Apogee altitudes are very different with P3 at 14.8 Re, P4 at 12.1 Re, and P5 at 13.2 Re. Perigee altitudes differ only slightly between P3 and P5 by 30 km. P4 has the lowest perigee altitude by -150 km compared to P3. The inclination of P5 is 3 degrees higher than those of P3 and P4.
4) March 2020, from the current long term plan which aims at aligning the lines of apsides of all three probes in 2022. In order to compare the same time range we also propagated back to 2018. At the initial state the probes are in the final orbits where the reentry maneuver will eventually be applied. All apogee altitudes are around 13.2 Re. The perigee altitude of P5 is about 200 km lower than those of P3 and P4. Its inclination is about 3 degrees higher.
5) January 2024, after a perigee reduction maneuver was applied to data set #4 which intentionally stopped short of the decay altitude.

The most informative parameters with regard to the perigee evolution are shown in Figures 2 to 6. In each figure the bottom panel shows the osculating perigee evolution and averaged low frequency altitudes. The center panel shows the evolution of the argument of perigee and in green the inclination which is enhanced by a factor of ten for better visibility. For argument of perigee we indicate 90 and 270 degrees. The top panel shows the ascending node of the probe, in yellow the one of the Moon, and in green their difference with negative values indicating the probe's node is ahead. In each case we determined the phase where perigee altitude is decreasing, marked in red in each panel. In blue, we highlight instances where the perigee altitude is below a reference altitude of 800 km. Fig. 2 shows the results of the high perigee data from set #1 and Fig. 3 shows the lower perigee and higher apogee data set #2. Both plots are using P3 as representative example. Results from the final orbit of set #4 are shown in Fig. 4 using P5 and in Fig. 5 using P4 as example, respectively. Fig. 6 shows the results after the perigee reduction maneuver with which we purposely missed reentry. From set #5 we chose P4 as an example. The data from set #5 are also added in Figures 4 and 5 to support the comparison of the orbital evolutions. Also added are these data shifted by the amount of perigee reduction. Both are overlaid in yellow.

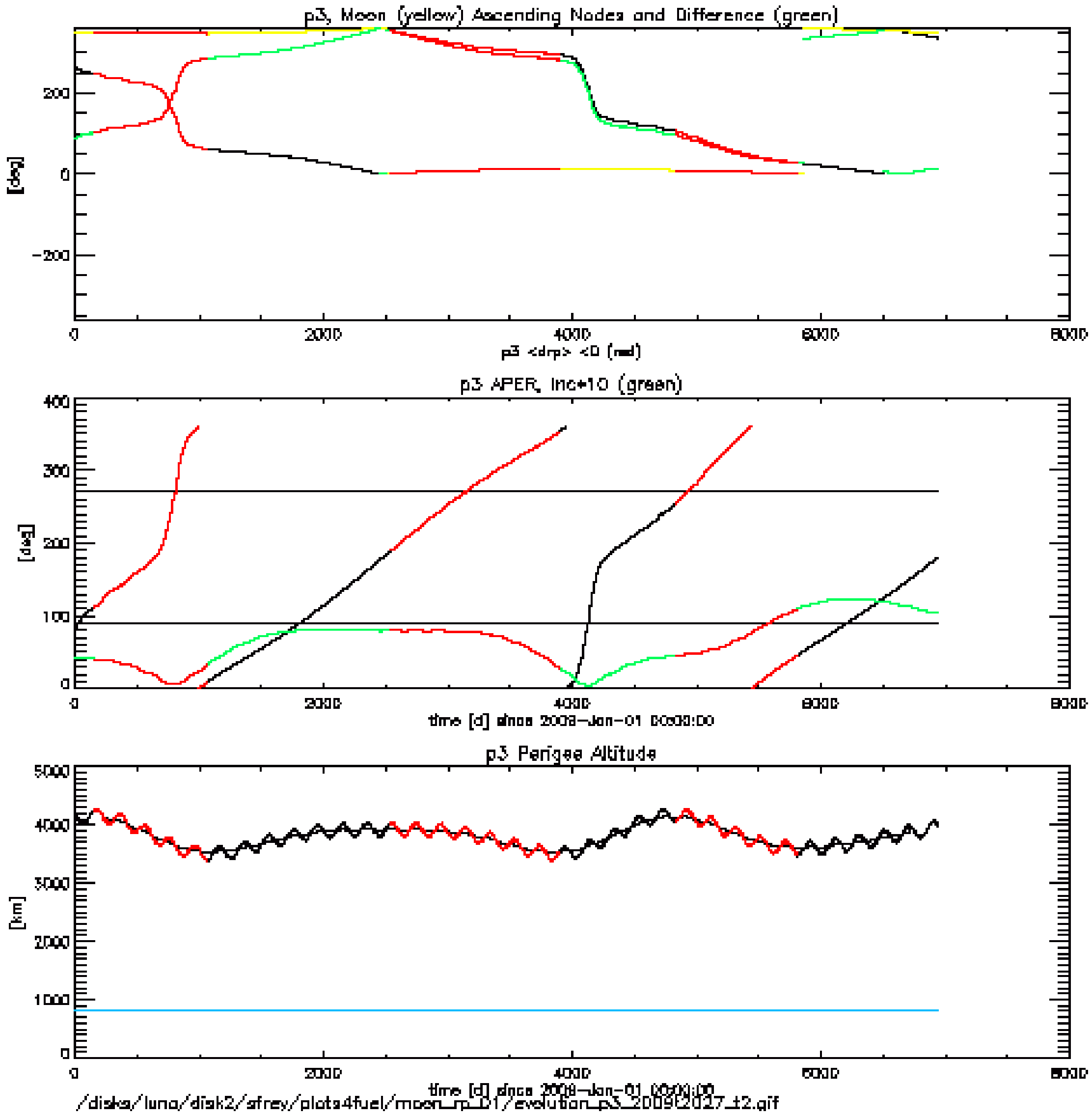

Figure 2. Orbit evolution for probe P3 from 2008 through 2027 (data set #1).

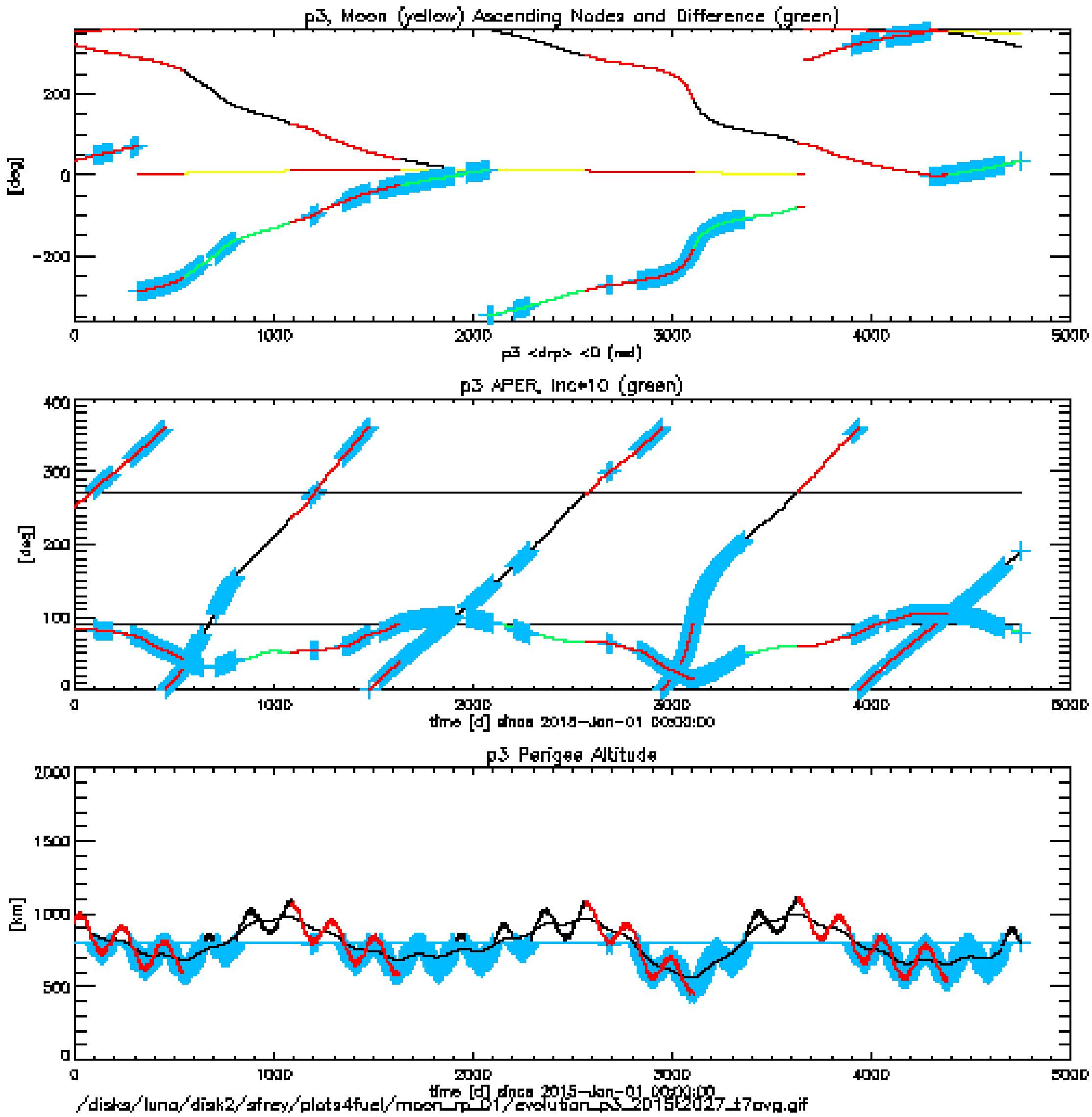

Figure 3. Orbit evolution for probe P3 from 2015 through 2027 (data set #2).

As expected according to the perturbation theory, the comparison of the perigee altitudes reveals the common profile that is composed of three periodic fluctuations corresponding to the perturbation sources. The luni-solar perturbations cause sinusoidal fluctuations in the order of 100 and 300 km with periods of approximately 14 and 183 days, respectively. The third one is the quasi-periodic sequence of local minima and maxima due to the changes in right ascension of the ascending node caused by Earth's oblateness and third body interactions fluctuating up to 1000 km. Over the analyzed apogee altitude range the mean perigee altitude does not affect the amplitudes of the semi-periodic fluctuations. Local minima occur below and above the 800 km reference altitude. Their significance is due to the change in drift of argument of perigee.

Because of the involvement of the Earth's oblateness the cadence of the local extrema depends on the initial state which most of all affects the drift in the argument of perigee. Thus it is the quasi-period of this third fluctuation that varies among the four sets. Once in a while the third body perturbations are synchronized such that the local extrema of the osculating perigee altitudes line up with those of the semi-periodic averaged altitudes. In those cases, independent of the initial orbit state, there is a well-defined local minimum of perigee altitude that corresponds to the lowest inclination and the steep slope in the right ascension of the ascending node of the probe due to the perturbing torque turning the orbit towards the ecliptic as seen in Fig 2 around day 1000 and in Fig. 3 near day 3100. In Fig. 4 that minimum is at day

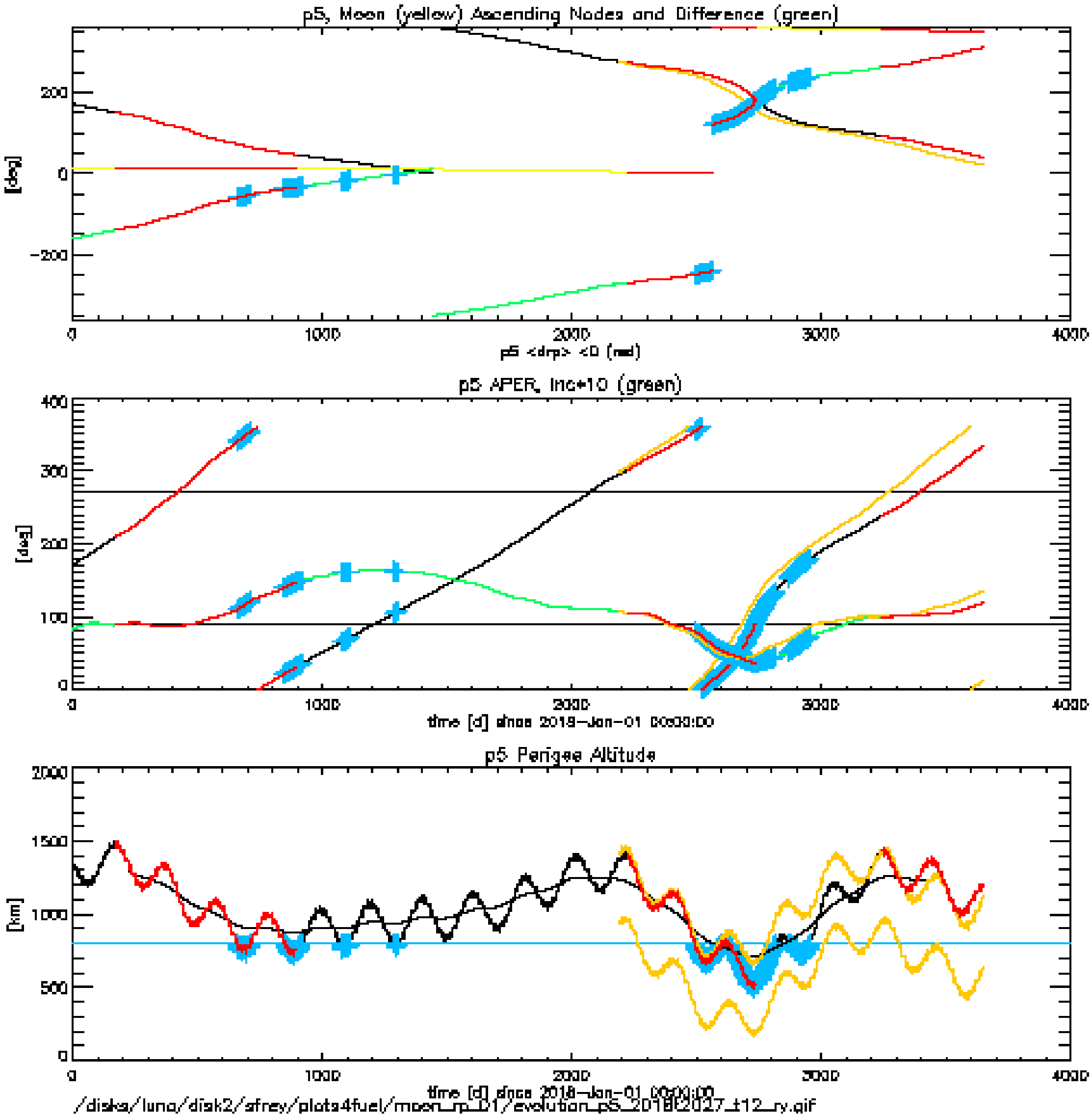

Figure 4. Orbit evolution for probe P5 from 2018 through 2027 (data set #4).

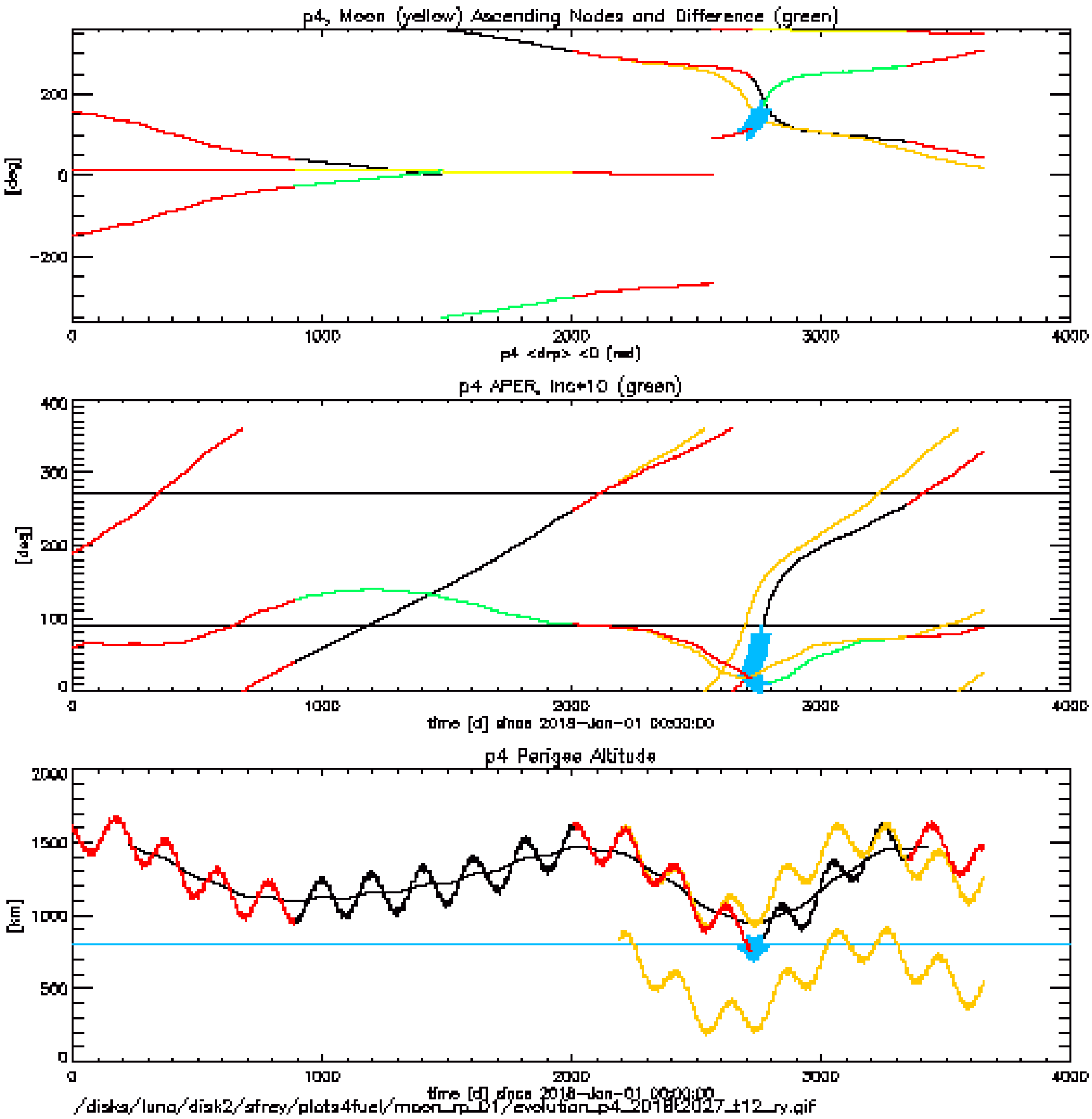

Figure 5. Orbit evolution for probe P4 from 2018 through 2027 (data set #4).

2700 for the pre and post maneuver states. In Fig. 5 that minimum occurs at day 2700 prior to the maneuver and 150 days earlier in the post maneuver states. The opposite situation results in phase shifts of the local extrema such that the maximum of the 183 days perturbation aligns with a minimum in the osculating altitudes and the osculating altitudes bounce back. This results in two or more very similar local minima of the 183 days perturbation as seen in Fig 6 around day 450. Less perturbed periods where the drift of the argument of perigee is rather constant exhibit high inclinations. These periods are longer for higher perigee altitudes such as in data set #1.

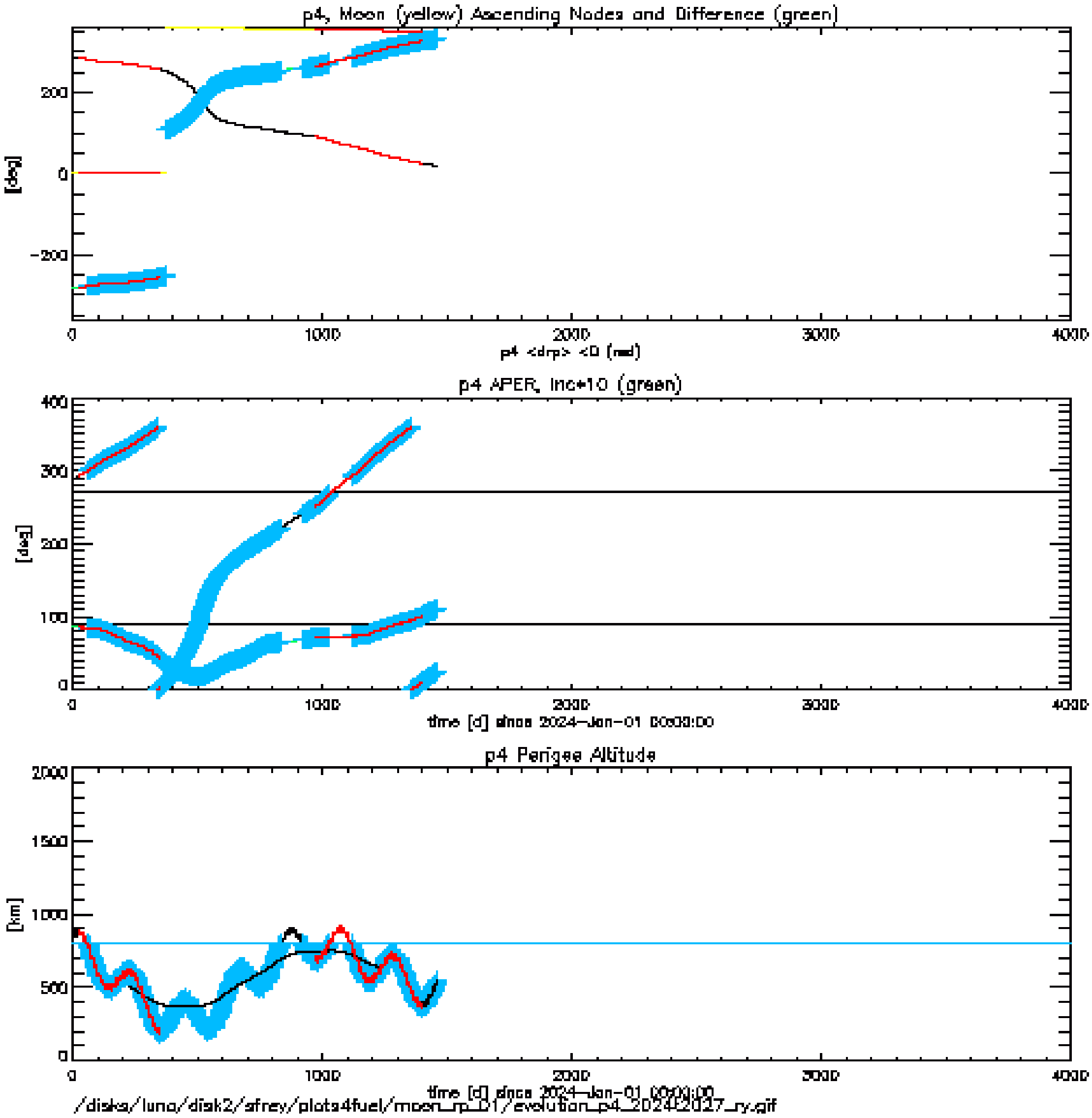

Figure 6. Orbit evolution for probe P4 from 2024 through 2027 (data set #5).

2.3. Maneuver Design

Immediate reentry can always be achieved by a maneuver that reduces the instantaneous perigee altitude to the decay altitude. However, this varies significantly with maneuver time and may not be optimal in terms of fuel usage. Furthermore, we are looking for a constant reentry maneuver that allows us to automate our analysis of the feasibility of future orbit redesigns as illustrated in Fig. 1.

In order to get the reentry maneuver time independent and of fixed size we take advantage of the local minima in the perigee altitude profiles. For the most fuel efficient one we look for that minimum that corresponds to the inclination minimum and the steep slope in right ascension of ascending node. The size of the maneuver is then defined by Eq. (1):

$$\Delta rp_{reentry} = min(rp) - rp_{critical} + drp_{bounce} + \delta rp(t_{maneuver}) \qquad (1)$$

Where $rp_{critical}$ is the decay altitude, drp_{bounce} is an offset to $(min(rp) - rp_{critical})$ in order to prevent increase of perigee altitude, $\delta rp(t_{maneuver})$ is a correction between the perigee altitude at maneuver time from the long term planning and the short term maneuver preparation time based on the most recent orbit update. The values for $min(rp)$ and drp_{bounce} are determined by a long term analysis. The drp_{bounce} accounts for the phase shift between the minima of the osculating altitudes and those of the averaged semi-periodic ones and is a function of time between maneuver and reentry. However it can be iteratively determined as part of the end-to-end run.

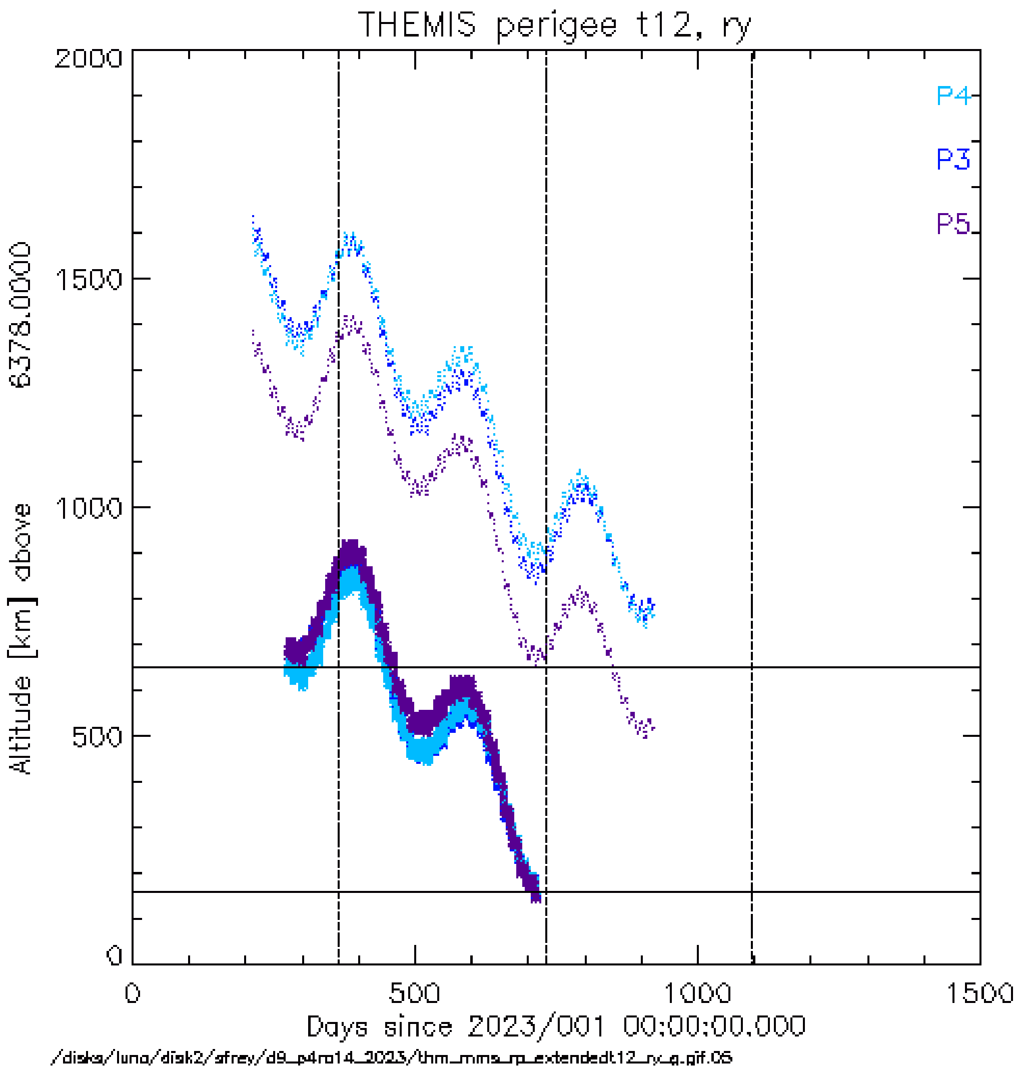

Figure 7. Perigee altitudes before and after reentry maneuver (data set #5). The probes are color coded with P3 in blue, P4 in cyan, and P5 in purple.

As long as apogee altitudes are not changed significantly Eq. 1 provides the baseline maneuver. Any perigee changes that are added to the orbit redesign prior to the reentry maneuver can be accounted for by Eq. 2:

$$\Delta rp_{reentry} = min(rp) - rp_{critical} + drp + \delta rp(t_{maneuver}) + \Sigma drp_i \qquad (2)$$

The $\Delta rp_{reentry}$ can be applied any time. Reentry will occur at or before the time of min(rp). If $\Delta rp_{reentry}$ is large enough to significantly increase the drift of the argument of perigee then reentry will happen earlier.

Figure 7 demonstrates the effect of the reentry maneuver applied to all three probes around a local maximum in perigee altitude. The thin lines represent the pre-maneuver state from data set #4. Thick lines show the post-maneuver state from data set #5. The probes reenter after one year at the new local minimum. The values for $\Delta rp_{reentry}$ are 690 km, 720 km, and 490 km for P3, P4, P5, respectively. In order to facilitate the rapid decay due to the coupling of the perturbations by the Earth's oblateness and luni-solar forces drp had to be 130 km for both P3 and P5 and 160 km for P4. Apparently, there is sufficient time between maneuver and local minimum and the changes in perigee altitudes are large enough to affect the dynamic of the perturbations as illustrated in Fig 4 and Fig 5 by the yellow lines.

3. Summary

Based on the analysis of the evolution of the THEMIS perigee altitudes we demonstrate the feasibility of a reentry maneuver that is of fixed size and yet can be executed at any time in order to initiate reentry within a required time limit. Due to luni-solar perturbations and Earth's oblateness perigee altitudes undergo semi-periodic fluctuations with local minima separated by years. With the selection of a particular perigee minimum the size of the maneuver and the time of reentry can be controlled. Such a maneuver is well suited for automated mission design.
Finally, it is our believe our analysis contributes to studies of the luni-solar effects proposing their exploitation to either avoid premature reentry or to optimize deorbit maneuvers, and its implementation into our automated mission design supports the trend towards operating swarms of satellites on a low budget.

4. Acknowledgements

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