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The First Ground Track Maintenance Manoeuvre of THEOS Spacecraft

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***Abstract*—**THEOS is the first earth observation spacecraft of Thailand which was launched on the 1st October 2008 and is currently operated by GISTDA. The transfer phase has been performed by Astrium Flight Dynamics team leading to a hand over to GISTDA teams starting mid-October 2008. The THEOS spacecraft's orbit is LEO and has the same repetitivity (14+5/26) as the SPOT spacecraft, i.e. the same altitude of 822 km but it has a different mean local solar time (LST). Ground track maintenance manoeuvres are performed to maintain the ground track within a predefined control band around the reference ground track and the band is ±40 km for THEOS spacecraft. This paper presents the first ground track maintenance manoeuvre of THEOS spacecraft and the detailed results. In addition, it also includes one and a half year of operation as seen by GISTDA operators. It finally describes the foreseenable activities for the next orbit control manoeuvre (OCM) preparation.

***Keywords*—**Orbit Control Manoeuvre, Ground Track Error, Local Solar Time Error, LEO, THEOS

I. INTRODUCTION

THEOS spacecraft, the first Low Earth Orbit-LEO satellite of Thailand government, was launched on the 1st October 2008 and had been in operation of GISTDA operators [1]. After THEOS was aligned with in the operational orbit, all sub-systems had determined the status and checked all redundancy equipments. All of equipments performed as expected, payloads demonstrated excellent performance with good geometric and radiometric accuracy and image evaluation was confirmed and guaranteed the quality of the images by GISTDA and specialists in Thailand.

GISTDA operators have fully operated nominal THEOS Control Ground Segment (CGS) throughout and have been able to handle anomaly situation and analyze telemetry. The CGS is composed of three main elements: The Flight Dynamics Centre (FDS), the Satellite Control Centre (SCC) and the Mission Planning Centre (MPC). The Image Ground Segment is dedicated to image data acquisition and production [2], currently over 48,000 of PAN and 18,000 of MS scenes are available in THEOS archive.

II. FDS ROUTINE ACTIVITIES

The daily routine activity of FDS team starts when the GPS data, which contains co-ordinate position and velocity of the spacecraft, is downloaded [1]. The routine activity consists of orbit determination, station keeping monitoring, event prediction and generation all of needed files, such as satellite visibility file for antenna tracking or satellite ephemeris file for image-capture mission planning, etc. In section III, focusing on prior orbit maintenance which is ground track correction and describe the manoeuvre scenario. The maneuver efficiency computation and propellant accounting are discussed in this section. In section IV is emphasized on foreseen maneuver which is simulated from satellite simulator and feasibility study to optimize maneouver performance.

III. THEOS 1st MANOEUVRE SCENERIO

A. SK Activities

There are two parameters to be considered for Station Keeping (SK) which one is Ground Track error and another is Local Solar Time error. Ground Track is defined the locus of points projected on the Earth's surface directly "beneath" the spacecraft orbit. Due to the time varying nature of the perturbations on the orbit, either gravitational force or solar wind, deviations from the reference orbit lead to ground track drift. Ground Track error is to drift of current orbit from the reference orbit crossed the equator to westward or eastward. Ground track maintenance manoeuvres must be performed to maintain the ground track within a predefined control band around the reference ground track. For THEOS spacecraft, the maintenance band is ±40 km. Figure 1 is the prediction of ground track error for 6 months forward.

From figure 1, as described in section II, SK evolution is checked by weekly basis from Quartz++, the Flight Dynamic Software was developed by EADS-ASTRIUM. The orbit propagation is carried out an order 11 Adam-Moulton integer (predictor-corrector method), initialized by an order 7 Runge-Kutta integrator. The orbit perturbations that can be taken into account are geo-potential, solar radiation pressure, Sun/Moon attraction and atmospheric drag. The figure 1 illustrates the evolution of ground track exceed limitation (±30 km) in the beginning of February 2010. The negative value means that the spacecraft is ascending or expanding because it is drifting to westward. In fact, the spacecraft should be dropped or descended by the earth gravitational force but the gravitational force of the sun and moon have directly affected to the spacecraft ascending.

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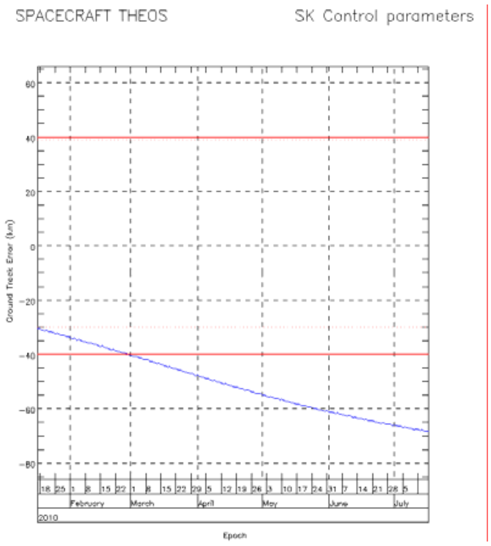

Fig. 1 Ground Track Error

Another one is Local Solar Time (LST) error. The LST of an orbit is defined as the angle between the orbit's ascending node and the mean Sun [1]. The LST is often presented in units of time with 10:00 PM – or noon describing a low earth orbit (LEO) Sun-synchronous orbit that places the Sun directly at zenith when the spacecraft is at the ascending node. Orbital perturbation caused by the Sun and the Moon are responsible for the deviation of the actual LST of a spacecraft from a fixed value [3]. For THEOS spacecraft is required to maintain a LST between 22:00±2 mins to provide a nearly constant geometry despite these deviations. In-plane manoeuvres are used for altitude adjustment to compensate for the effects of air-drag. This altitude decrease affects the ground-track repeatability, mainly in the equatorial regions. The frequency of these manoeuvres is determined by the rate of the semi-major decrease. Out-of-plane corrections are used to correct the steady drift of inclination mainly caused by solar and lunar gravity perturbations. The figure 2 is the foreseen result of LST error which predicted for 6 months

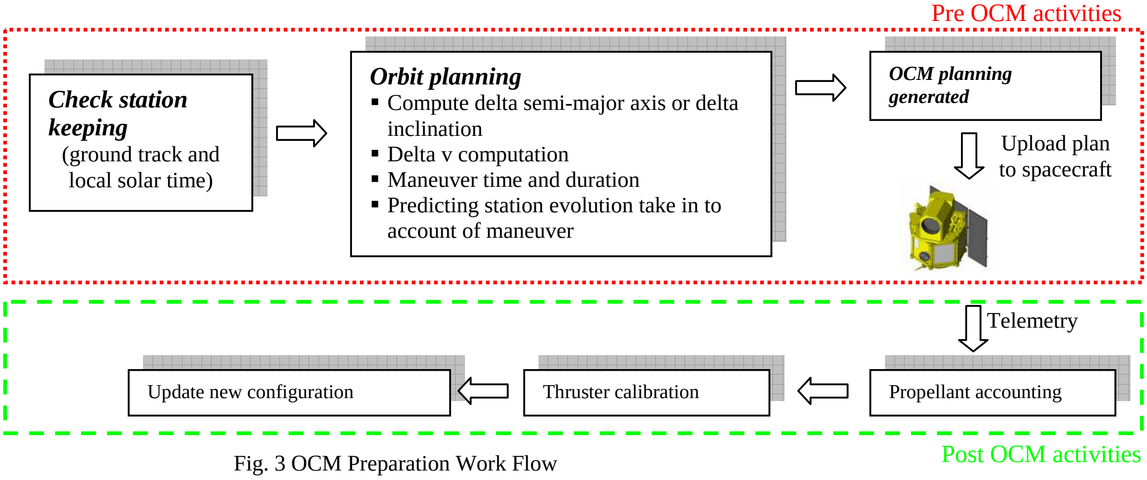

Fig. 3 OCM Preparation Work Flow

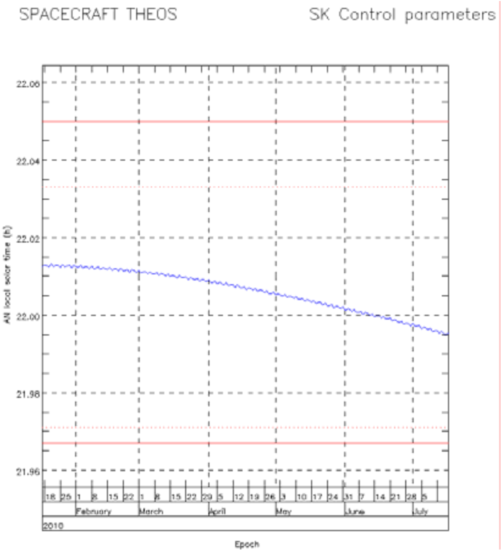

Fig. 2 Local Solar Time Error

The figure 2 illustrates the LST error which does not exceed the warning limitation (±2 minutes). From their figures, figure 1 and 2, the maintenance manoeuvre must explicitly do the ground track manoeuvre.

B. *OCM Preparation and Simulation*

As mentions from above, we had to prepare the maneuver of ground track maintenance. In this case, evolution of semi-major axis was the primary factor of ground track error and the figure 1 was long-term prediction started on December 2009 to 6 months forward. Although the Quartz++, orbit determination software, was very precise, the errors had remained much more for long-term prediction. Therefore, the duration of manoeuvre was concisely performed on February 10, 2010. The need of a maneuver had been established, it was necessary to compute the maneuver i.e. to compute delta velocity, OCM epoch date and duration and to check that all the constraints were verified. Then, the corresponding satellite Tele-command planning orders should be generated and uploaded. The work flow to prepare the OCM was shown in figure 3 which composes of:

- Check the results of SK prediction for both parameters
- OCM planning/generation
- OCM simulation
- Technical meeting with Astrium
- Upload OCM plan to satellite
- Thruster calibration / Update new configuration (satellite position/GPS)
- Propellant accounting / Update new configuration (Tank temperature/pressure)

Check the results of SK prediction for both parameters: Ground Track error and Local Solar Time error, as figure 1 and 2, were very importance parameters as above describe. Correctly, we used the Quartz++ software to predict the event forward 2 weeks, as shown in figure 4 and 5 below.

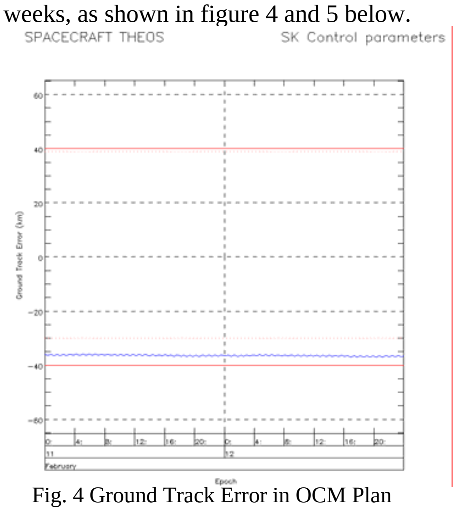

Fig. 4 Ground Track Error in OCM Plan

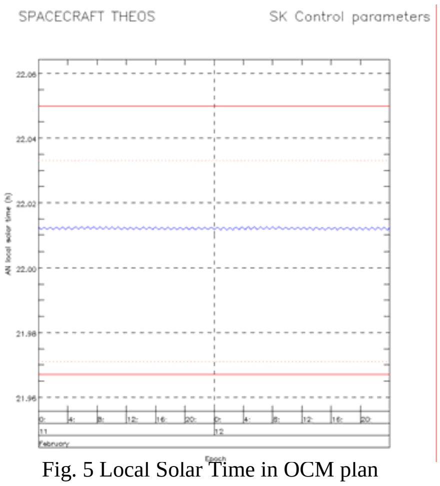

Fig. 5 Local Solar Time in OCM plan

OCM planning/generation: Due to propellant tank temperature and pressure were significant parameters to interact with trust performance so we had to predict the tank temperature and pressure to correspond with OCM epoch. In this case, we had collected the temperature data and history of the data to calculate the temperature of spacecraft on the OCM epoch. The figure below was the temperature cycle of propellant tank.

From figure 6, the propellant's tank temperature shown was a primary data. It was used to calculate the propellant's pressure bar. The statistical history was used to compute the tank temperature on the OCM duration. Due to the OCM epoch, the propellant temperature and pressure bar had to correctly perform for supporting the manoeuvre propulsion calculation. In this case, we used temperature 19.1093 ˚c, pressure 12.2773 bars and mass 54.1608 kg. After this, updated spacecraft's physical states preparing to orbit manoeuvre vector set.

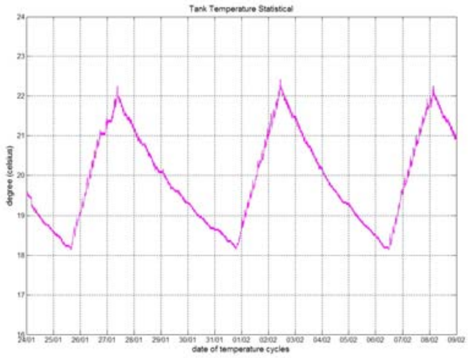

Fig. 6 Temperature Cycle of Propellant Tank

OCM simulation: Inevitably simulated the event, we had to simulate or test the procedures by nothing time-tag file sent to spacecraft. After spacecraft's physical states configured, we used the Quartz++, orbit determination software in part of OCM module, computed the simulated result of this manoeuvre. The evolution of both operational parameters was parabolic. In fact, the ground track error evolution was a bit less smooth as it was highly dependent on solar activity that was varying. The evolution was considered as parabolic step by step. The evolution equation was:

$$\ddot{F} \quad = \quad Ka * \dot{a} \;+\; Ki * \dot{i} \qquad (1)$$

Determination of the set of coefficients (1) which was used for manoeuvre computation should be controlled. The value of the ground track coefficient was recalled hereafter:

$$\begin{aligned}\Delta\ddot{l}_0 = -a_e \left\{ \dot{a}\frac{3}{2a}(w_{si} - \dot{\Omega})\left[1 + \frac{7}{3}\frac{\dot{\Omega}}{w_{si} - \dot{\Omega}} + \frac{7}{2}J_2\left(\frac{a_e}{a}\right)^2\left(4\cos^2 i - 1\right)\right]\right\} \\ - a_e\left\{\ddot{i}\left[\dot{\Omega}\tan i + 6J_2\left(\frac{a_e}{a}\right)^2\left(w_{si} - \dot{\Omega}\right)\sin 2i\right]\right\} \qquad (2)\end{aligned}$$

Although the (2) used to compute the ground track error value, the result of (2) could be negligent. The intelligent software, Quartz++, had computed the initiative ground track manoeuvre value was -24.0345 m by the equation above. However, the value could be properly changed. Especially, the LST error forwarding to the middle of October 2010 might be maneuvered along with ground track evolution again. Due to the LST correction in the next OCM, the proper values in this

OCM should be simulated that were -35 m and -40 m respectively. The simulated results of ground track manoeuvre were shown in figure 7-8.

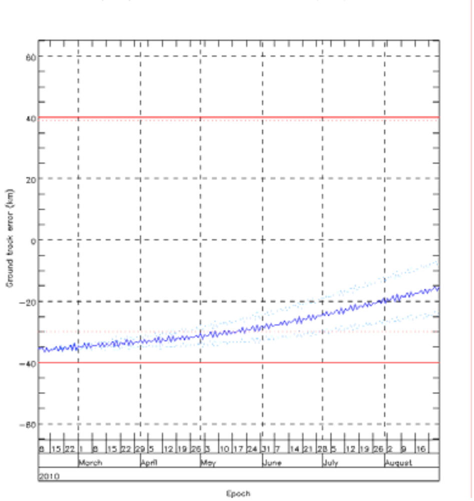

Fig. 7 Target Frozen Eccentricity Δ*a* = -35 m

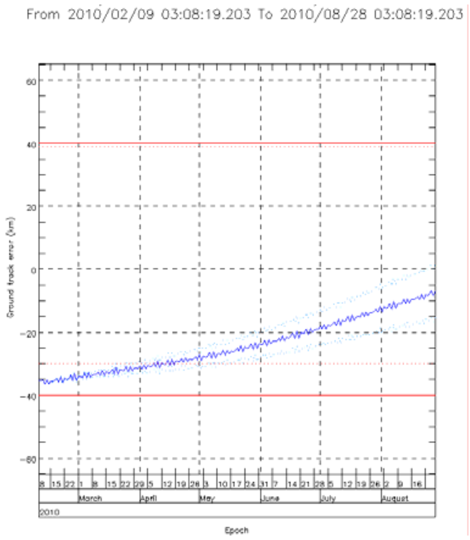

Fig. 8 Target Frozen Eccentricity Δ*a* = -40 m

Due to maintain ground track error evolution without the LST error maintenance, we desired the minimum effect to eccentricity. Using target frozen eccentricity module was the way selected to do. Significantly, the target frozen eccentricity module had hardly affected the inclination Δi .

In the sample simulation, the figure 7 and 8, the negative value (-35 m and -40 m) were Δa (delta semi-major axis) meant reducing altitude and changed the spacecraft's momentum direction to opposite side. The Δa = -40 m reducing altitude was chosen because suppose that manoeuvre performed under performance and uncertainty and this wasn't impact to LST evolution.

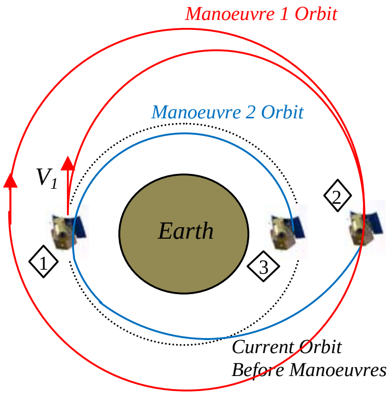

Fig. 9 Simplified Orbit Control Manoeuvres

In OCM planning, there were 2 manouvres, the first OCM epoch started on Feb 10 at 19:05:51 and second on Feb 11 at 21:38:03. There was no image capture mission performed on that date. The simulated manoeuvres had ΔV_T delta tangential velocity which one was V_1 = 0.0298 m/s and another one was V_2 = -0.0505 m/s. The interval of manoeuvre period between 2 maneuvers was about one and a half orbit shown the simplified graphic of manoeuvre orbit in figure 9.

From the figure 9, before manoeuvres, the spacecraft was in the current orbit as state ①. After manoeuvre 1, the spacecraft was driven by thrust into the bigger orbit. After 150 minutes passed, the spacecraft was on the state ② and started the manoeuvre 2 immediately. After 150 minutes again, the spacecraft would be in the desire orbit as state ③ the smallest orbit as shown in the figure 9.

The manoeuvre was computed considering the nominal solar activity and a nominal manoeuvre performance but taking into account specified margin on the window limited (either ground track at equator control or LST). Therefore, the sun activity parameters were very importance to be updated.

Technical meeting with Astrium: The first ground track maintenance manoeuvre of THEOS-FDS engineers lacking expert experience needed consultation with full experience engineers. The Astrium FDS, expert engineers, reviewed and approved the schedule of OCM plan and the results of OCM simulation.

Upload OCM plan to satellite: OCM plan consisted of manoeuvre time starting and ending was sent to the spacecraft on Feb 10, 2010 19:00:00.000 UTC.

Thruster calibration/Update new configuration: After OCM done, the thrust calibration to calculate the performance and new configuration was updated.

Propellant accounting/Update new configuration: After OCM done, the current tank temperature and pressure was updated to new configuration.

C. OCM Maintenance/Calibration

Due to correct ground track evolution, the results of ground track error and LST error prediction had changed as Figure 10 and 11 which was predicted to 6 months forward.

According to Figure 9 illustrated, the current orbit would be expanded and decreased later by hydrazine-thruster. The objective of this maintenance was to correct the ground track error with decreased semi-major axis correction 40 m. The commanded OCM manoeuvres forced only the tangential velocity of spacecraft's orbit but, in fact, the spacecraft moving couldn't be controllable as needed because the spacecraft heading in the initial time of thruster starting had not lain in the direction of tangential orbit vector. This major caused directly affected to V_N and V_W the normal velocity and radial velocity respectively. Detail in Table I and II.

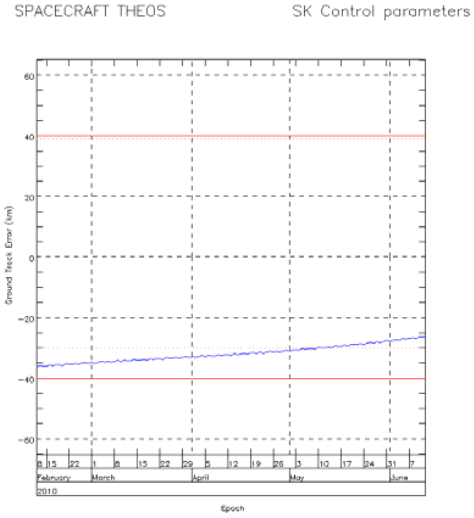

Fig. 10 Ground Track Evolution After Manoeuvres

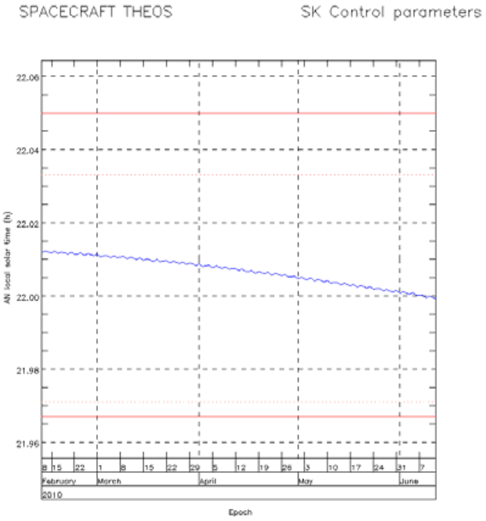

Fig. 11 LST Evolution after Manoeuvres

TABLE I
COMMANDED OCM MANOEUVRES

Delta semi-major axis correction:	-40 m		
Number of Manoeuvres	ΔV_T (m/s)	ΔV_N (m/s)	ΔV_W (m/s)
MAN 1	0.02950	0	0
MAN 2	-0.05032	0	0

Table 1, the commanded OCM manoeuvres consisted of 2 maneuvers in only tangential velocity without normal velocity and radial velocity, and aimed to correct the ground track error at -40 m (as table I). After OCM done, the calibration of manoeuvre was to calculate the efficiency of the manoeuvres. As describe, in the real action of manoeuvres had happened the normal velocity and the radial velocity, and the delta semi-major axis was not as needed (as table II).

TABLE II
CALIBRATED OCM MANOEUVRES

Delta semi-major axis correction:	-35 m		
Number of Manoeuvres	ΔV_T (m/s)	ΔV_N (m/s)	ΔV_W (m/s)
MAN 1	0.00838	0.05733	-0.00106
MAN 2	-0.04795	-0.00681	-0.01199

The efficiency of manoeuvres calibrated OCM basically determined hereafter:

$$ME = \frac{\sqrt{\Delta V_{T_{cal}}^2 + \Delta V_{N_{cal}}^2 + \Delta V_{W_{cal}}^2}}{\sqrt{\Delta V_{T_{com}}^2 + \Delta V_{N_{com}}^2 + \Delta V_{W_{com}}^2}} \qquad (3)$$

The Manoeuvre Efficiencies (ME), which used (3) solved Calibrated DV / Commanded DV, were 1.9642 and 0.9916 of MAN 1 and MAN 2 respectively. Explicitly, The MAN 1 couldn't be calibrated due to the uncertain velocity vectors that had got scaled of magnitude similar with the tangential velocity forced. The proper calibration result should be 0.99 approximately as MAN 2. Considerably, the numerical method that was used to calculate this efficiency had a weakness in this situation. The uncertain velocities V_N and V_W were the dominant of manoeuvre.

D. OCM Analysis

To solve the problem of numerical method that could be eliminated by using another method was the way chosen. We preferred to use the method of graph called *The Graphical Method* (GE) to calculate the ME. The Graphical Method recommended by Astrium was the technical of graph of mean semi-major axis. Basically, we had to find the mean of semi-major axis of each point from GPS data before manoeuvres and collected every mean point to find the mean of all. And then, did it again after both manoeuvres. Figure 12 below illustrated for understanding.

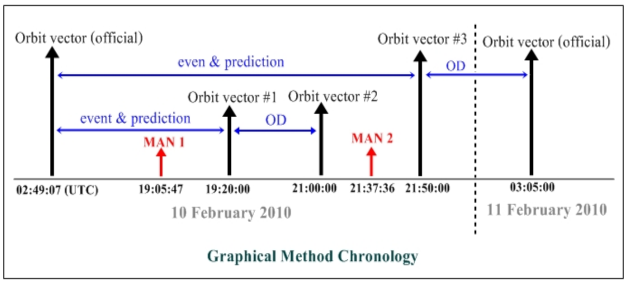

Fig. 12 The Graphical Method

Orbit vector official was determined before manoeuvre duration and predicted the evolution of mean semi-major axis over one day. The generic plot utilities was determined graphically the average value of the mean semi major axis. And then, compared the reach semi-major axis to predict one and deduced the manoeuvre efficiency hereafter:

$$ME = \frac{achieved\ \Delta a - predicted\ \Delta a}{predicted\ \Delta a} \tag{4}$$

$$New\ Calibration = Old\ calibrated\ value * (1 + ME) \tag{5}$$

The graphical method generated the achieved Δa = -35 m. Finally, the manoeuvre efficiency was -0.1211 from (4) and the new calibration was 0.804 from (5). However this values was not representative for long manoeuvres (assume that next OCM would be corrected inclination for LST). The manoeuvre calibration efficiency still remained as prior.

IV. FORESEEN OCM ACTIVITIES

A. SK Prediction

Unfortunately, the SK monitoring has not only ground track error evolution but the LST error evolution has been monitored also. As above describe, in the middle of October 2010, the LST error has to be maneuvered. THEOS-FDS duty is to monitor the station keeping and the event prediction is one of our duties. We have to predict the LST error evolution for 1 year forward (figure 13).

Inevitably the next OCM, the LST correction will be carefully determined in the middle of October 2010. In the next OCM is to correct the inclination of orbit plane and is the out-of-plane manoeuvre.

The simulation of the next OCM is very important to provide because the next OCM is the essential OCM because it is to correct both ground track error and LST error. However, it is possibly possible that the real result of the next OCM can be uncertainly changed from what we get in this simulation.

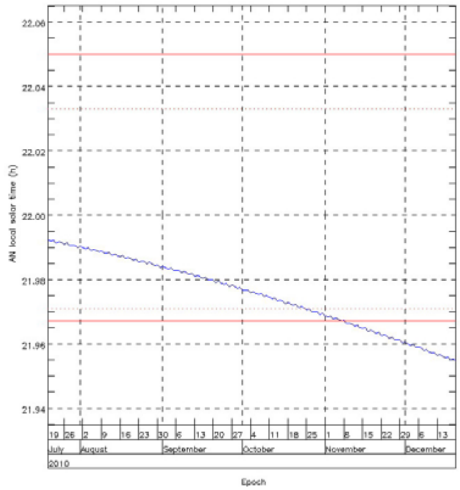

Fig. 13 LST Error Evolution in The Middle of October 2010

B. Simulation results

Following by steps of manoeuvre, firstly, the SK evolution will be predicted by Quartz++. As mentioned, the next OCM will be in the middle of October 2010. From simulation results, we have to exactly predict the date of manoeuvre. In this case, we do decide to maneuver on Oct 23, 2010 at 19.00 UTC.

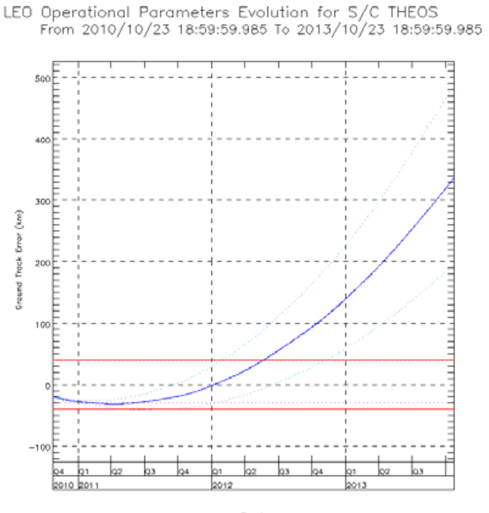

Fig. 14 Ground Track Error Evolution (for 3 years forward)

From figure 14-15, the ground track error evolution and LST error evolution are predicted for 3 years forward. In this case, the Quartz++ computes the Δa and Δi correction that is 0.1539 km and 0.07185 degree respectively.

The figure 15 above shows the tendency of the next OCM will be combined maneuver which will correct semi-major axis and inclination. In this case, we have 4 manouevres to correct the Δi (figure 16).

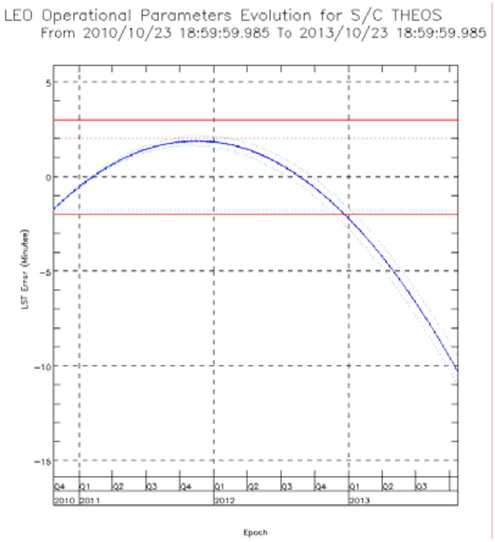

Fig. 15 LST Error Evolution (for 3 years forward)

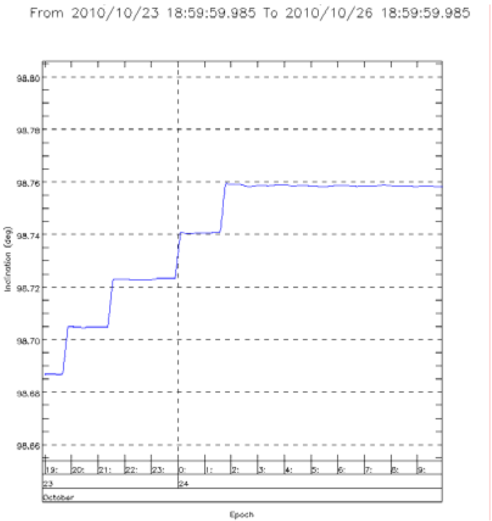

Fig. 16 The Inclination (changed by 4 manoeuvres)

For the description of each maneuver can find more in table III, the appointment of manoeuvres of inclination correction are at ascending and descending node 4 times (180˚, 180˚, 360˚ and 360˚). The semi-major axis is also changed 4 times as figure 17.

From the figure 15, the predicted LST error evolution after taken into account the next OCM can be in the threshold at least 2 years.

V. CONCLUSION

The first ground track correction of THEOS spacecraft is performed according to the OCM plan which consumes 0.028 kg propellant mass. The semi-major axis is decreased about 0.035 km as expected. The GM (Graphical method) is suitable for computing OCM efficiency.

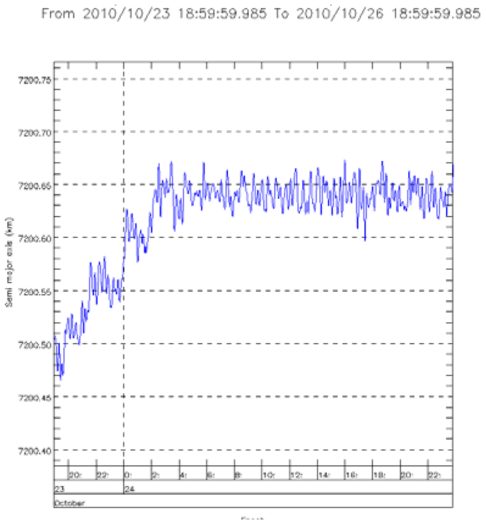

Fig. 17 The Semi-Major Axis (changed by 4 manoeuvres)

TABLE III
COMMANDED OCM MANOEUVRES

Delta semi-major axis correction:	0.15392 km		
Delta inclination correction:	0.07185 deg		
Number of Manoeuvres	ΔV_T (m/s)	ΔV_N (m/s)	ΔV_W (m/s)
MAN 1	0.0198553	0	-2.332152
MAN 2	0.0198950	0	-2.332506
MAN 3	0.0198910	0	2.332049
MAN 4	0.0198942	0	2.332440

From the simulation results, the next OCM will be in the middle of October 2010. The inclination and semi-major axis will be corrected simultaneously for the time. After performing the next out-of-plane maneuver, the LST error evolution can be in the threshold at least 2 years. However, the ground track error evolution can be corrected more often and this lesson learnt, our first manoeuvre, provides us much more experience.

In the future work is to analyze the manoeuvre efficiency (ME) that directly affects to result of maintenance by using the results of next OCM.

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