THEOS ORBIT MAINTENANCE: ASSESSMENT OF 2 YEARS OF OPERATIONS

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Abstract: *THEOS is the first Earth Observation spacecraft for Thailand. It has been launched 1st October 2008 and is currently operated by Geo-Informatics and Space Technology Agency (GISTDA). The transfer phase operations had been performed by EADS Astrium Flight Dynamics team. Since the hand over to GISTDA team mid-October 2008, GISTDA is responsible of THEOS Flight Dynamics routine and orbit maintenance operations. This paper presents the main events during the 2 years of operations. It namely describes the 2 Orbit maintenance maneuvers that were performed in February and November 2010 respectively for Ground track and Local solar time correction. It also highlights the first experience in collision avoidance maneuver in December 2010. The analysis of orbit maintenance maneuvers performance is moreover presented. It finally describes the station keeping evolution prediction up to the next OCM.*

Keywords: *THEOS, Orbit maintenance, Ground track, Out of plane maneuver, Local solar time*

1 Introduction

THEOS spacecraft mission orbit is a polar and sun-synchronous orbit with the same repetitivity (14 + 5/26) as the SPOT spacecraft, i.e. the same altitude of 822 km, but a different mean local solar time. THEOS and SPOT satellites follow the same grid on Earth. At the end of the LEOP, the SK initial conditions were ground track (GT) error = +5 km and Local Solar Time (LST) = 21.55 PM. The Flight Dynamics Station-Keeping activities have now been performed for 2 years by GISTDA team using QUARTZ, the EADS Astrium Flight Dynamics software. The Flight Dynamics routine activities are now perfectly mastered. However a support is provided by EADS Astrium for each Orbit Control Maneuver (OCM).

During these 2 first years of operations (October 2008-December 2010) 3 OCM were executed: 2 of them were regular OCM but the third one was an emergency collision avoidance maneuver.

The first OCM took place in February 2010 for ground track correction and the second one occurred in November 2010 for local solar time correction. The pre and post OCM activities are significant: the maneuver size and epoch regarding mission constraints are designed a few weeks before the OCM expected date. Then the maneuver is refined, implemented and simulated before being sent to the spacecraft. After the maneuver, OCM performance is assessed in order to compute calibration coefficient that will be used for next maneuver. The whole OCM process and results are described in section 3.

The emergency maneuver was performed due to a space object close approach to THEOS on December 2010, 15th. GISTDA had been informed of this risk by JSpOC (Joint Space Operations Center) who sent a Conjunction Analysis Report (CAR). Indeed, the space debris has gained a lot of interest in recent years, as part of the space environment due to the increasing population of uncontrolled man-made objects orbiting the Earth. The collisions between a satellite and space debris or another satellite are more and more likely to occur. This phenomenon particularly concerns the LEO altitude as it is the region the most frequently used in space [1]. In order to avoid the collisions, these risks are specifically monitored by JsPOC who warns the operator as soon as the global miss distance is below 1 km for LEO region. All the activities performed in the frame of this emergency OCM are described in Section 4.

Finally, the section 5 gives an overview of the SK parameters evolution for the observed period as well as the prediction for the future up to end of 2013.

2. THEOS Orbit control scenario

2.1 Station keeping monitoring

There are two operational parameters to be considered for Station Keeping (SK): one is the Ground Track error at equator and the other one is the Local Solar Time. The Ground Track is defined by the locus of points projected on the Earth's surface directly "beneath" the spacecraft orbit. Due to the perturbations on the orbit, mainly the air drag effect, the real orbit deviations from the reference orbit lead to a ground track drift. Ground track maintenance maneuvers must thus 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. In-plane maneuvers are used for Ground Track maintenance thanks to altitude adjustment.

The other station keeping parameter is Local Solar Time (LST). The LST of an orbit is defined as the angle between the orbit ascending node direction and the mean Sun direction. The LST is often presented in units of time with a noon LST at ascending node describing a sun synchronous low earth orbit (LEO) with 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 orbit from a fixed value [2]. The THEOS mission requires to maintain a LST between 22:00±2 mins to provide a nearly constant geometry despite these deviations.

The theoretical evolution for both parameters is quasi-parabolic [3] as described in Eq. 1. According to these equations, the Ground Track is expected to exceed the window on the positive side (eastwards) whereas the Local Solar Time is assumed to get out of the window on the negative side.

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

The value of the coefficient *Ka* and *Ki* are recalled in Eq.2 and Eq.3

For the Ground track

$$\Delta\ddot{\mathrm{I}}_0 = -a_e \cdot \left\{ \dot{a} \cdot \frac{3}{2a} (\omega_{si} - \Omega_i) \cdot \left[1 + \frac{7}{3} \cdot \frac{\dot{\Omega}}{\omega_{si} - \dot{\Omega}} + J_2 \left(\frac{a_e}{a} \right)^2 \cdot (4\cos^2 - 1) \right] + \dot{i} \cdot \left[\dot{\Omega} \tan i + 6 J_2 \left(\frac{a_e}{a} \right) \cdot (\omega_{si} - \dot{\Omega}) \sin 2i \right] \right\} \qquad (2)$$

For the Local Solar Time

$$\Delta\ddot{H} = -\frac{T_{te}}{T_{so}} \cdot (\tan i \cdot \dot{i} + \frac{7}{2a} \cdot \dot{a}) \qquad (3)$$

2.2 OCM activities

THEOS operators perform SK prediction on a weekly basis to check the evolution of ground track and local solar time. When the need of a maneuver is established, OCM preparation activities are conducted by GISTDA in close collaboration with EADS Astrium Flight Dynamics team. It is namely necessary to discuss which parameters shall be corrected and to agree the maneuver size and schedule. The OCM may correct only semi-major axis or inclination or be a combined maneuver that corrects both parameters. After the maneuver, the calibration results are also shared with EADS Astrium Flight Dynamics team. The global work flow for OCM activities is shown in Figure 1.

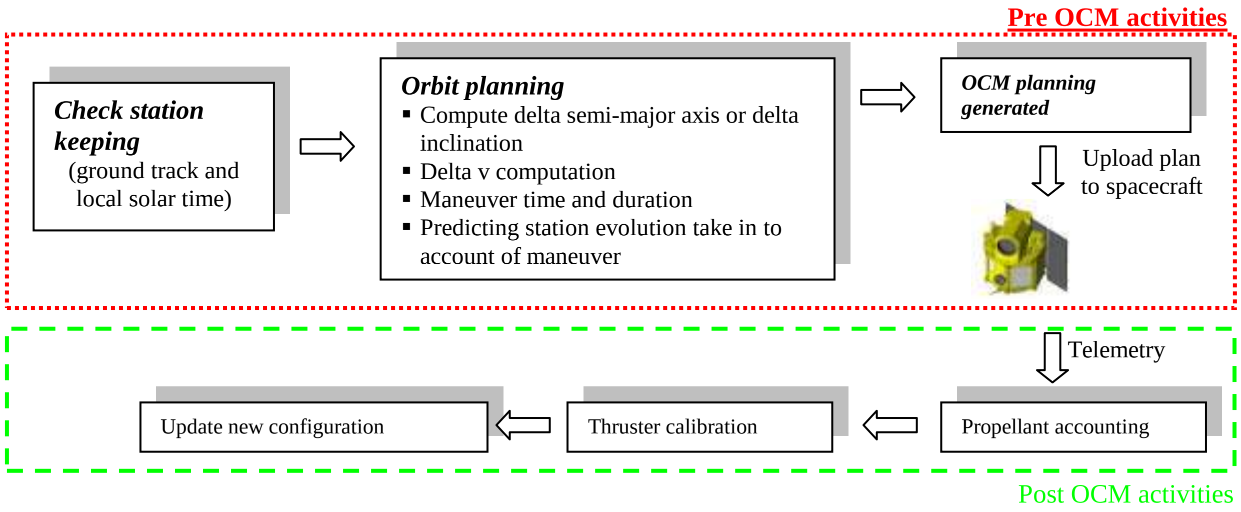

Figure 1. The work flow for OCM activities

3. Orbit control maneuver results

3.1 First OCM assessment

3.1.1 Station keeping monitoring

As mentioned in Section 2.1, the ground track maintenance control band is ±40 km for THEOS spacecraft. The Figure 2 shows the evolution of ground track error for 6 months forward, as predicted by mid-January 2010. The ground track was about to exceed the warning area (- 30 km) early February 2010 whereas the exit is usually on the positive side of the window. It means that the semi-major axis was not decreasing as fast as expected. Thus an unusual in-plane maneuver decreasing semi-major axis was necessary to maintain THEOS in its station-keeping window. The maneuver was optimized to correct eccentricity at the same time. Regarding the local solar time prediction, the SK window limit was expected to be reached by the end of October 2010. To optimize the propellant usage we decide to correct only semi-major axis at that time [5].

3.1.2 OCM simulation and planning

The target for semi-major axis decrease obtained from Quartz was about -40 meters. To correct the eccentricity as well, the maneuver was divided into 2 OCM of +60 m and -100 m. These maneuvers were designed to be robust to a 5% maneuver realization uncertainty. The simulation of evolution of Ground Track error after maneuvers is depicted in Figure 3.

From LEOP phase, we have learnt that an error on temperature and pressure has an effect on maneuver performance. The temperature was therefore extrapolated at the maneuver time using the history of the tank temperature cycle data. The pressure was then deduced by iteration method so that the propellant mass remains constant. The curve of tank temperature evolution is presented in Figure 4.

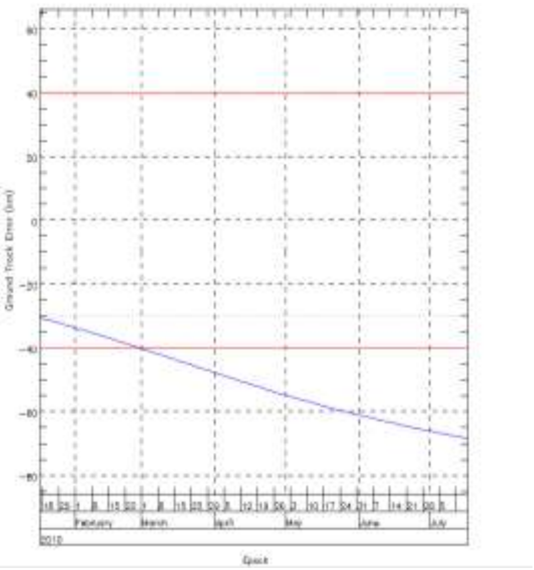

Figure 2 The prediction of ground track error evolution

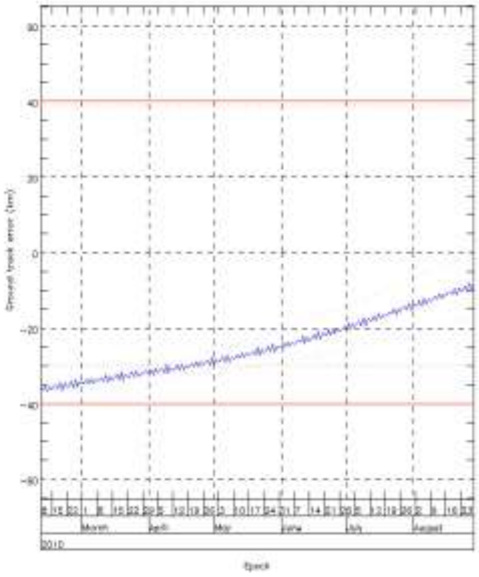

Figure 3 Target frozen eccentricity, Δa=-40 m

As said previously the maneuver was divided into 2 maneuvers on Feb 10th: one at 19:05:51 and the other one at 21:38:03. The corresponding delta velocities were 0.029m/s and -0.05 m/s respectively in tangential direction only as summarized in Table 1.

From the Fig. 5, before the maneuver performs, THEOS's orbit was in the current orbit or the 1st state (blue circle). After 1st manoeuvre activated, the spacecraft was in the bigger ellipse orbit (the red dash circle). After an orbit and a half or about 150 minutes through, the spacecraft was on the 2nd state and activated the 2nd manoeuvre immediately. After that, the spacecraft would be reduced altitude and in the desire orbit as the 3rd state (green dot circle).

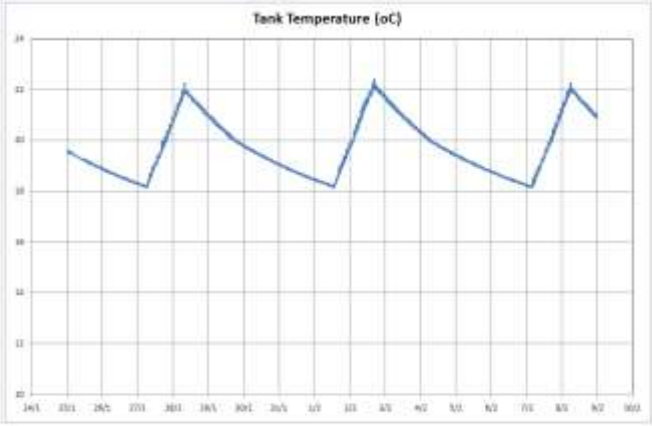

Figure 4 Tank temperature cycle

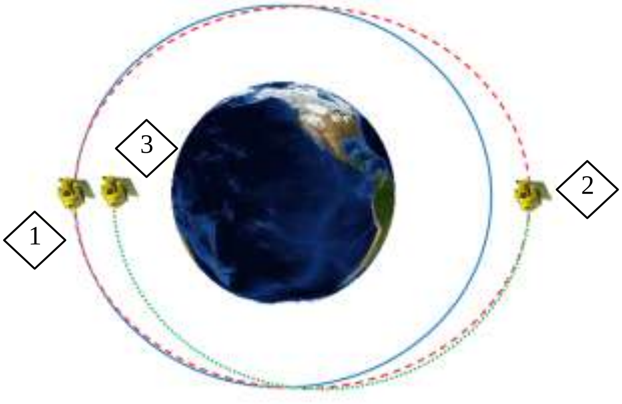

Figure 5 Simplified 1st Orbit Control Manoeuvres

Before uploading the OCM plan to satellite, GISTDA and Astrium FDS expert had a technical meeting to review and approve the OCM plan. The OCM plan was then uploaded to satellite from Siracha ground control station. After the maneuver, the post-maneuver activities have been conducted.

3.1.3 OCM results and calibration

The objective of these OCMs was to correct the ground track error with a 40m semi-major axis decrease. It has been performed as expected. Even if a 5% underperformance has been observed, the Ground Track Error has remained in its window since then. Indeed, sufficient margins had been taken into account to anticipate maneuver realization errors. The ground track evolution prediction after maneuver is shown in Figure 6. For the propellant consumption, we found that it consumed about 0.028 kg with 54.13 kg remaining.

No. MAN	Centroid Time	$\Delta V_{commanded}$(m/s)			$\Delta V_{achieved}$(m/s)			CE (Achive DV/Commanded DV)	CE_{out}	CE_{update}
		ΔV_T	ΔV_N	ΔV_w	ΔV_T	ΔV_N	ΔV_w			
1	19:49:40	0.02950	-	-	0.00838	0.05733	-0.00106	1.9642	1.4779	1.3627
2	21:31:08	-0.05032	-	-	-0.04795	-0.00681	-0.01199	0.9916		

Table 1 the summary of 1st manouver

The commanded OCM maneuvers were assumed to thrust only in the tangential direction but some transverse components were observed. They are the same order of magnitude as the tangential component as the maneuvers were very small.

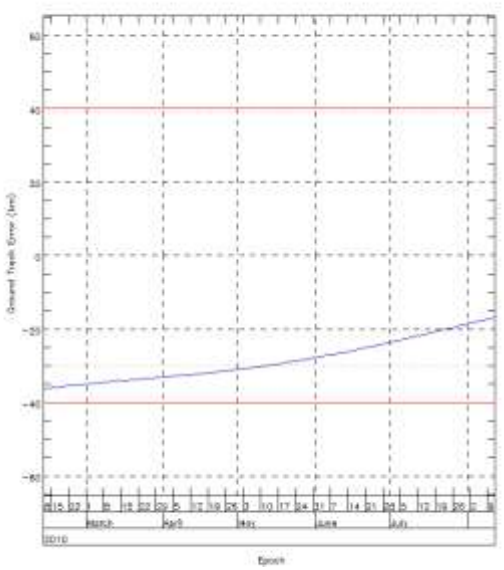

Figure 6 The ground track evolution prediction after maneuver

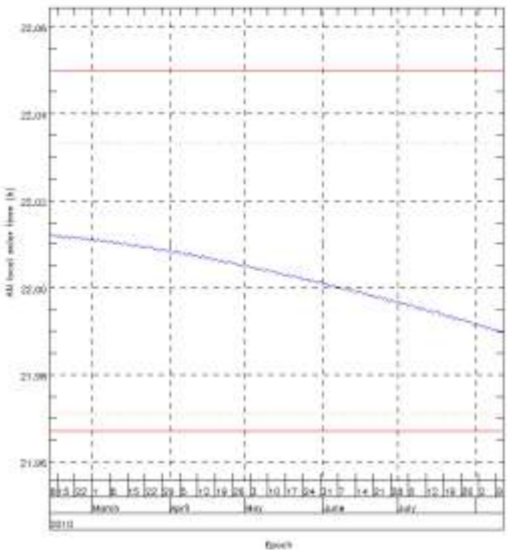

Figure 7 The local solar time evolution prediction

After the OCM, the OCM Calibration Efficiency (CE) was calculated. The last OCM calibration efficiency (CE_{old}) was 0.92209 since the end of the LEOP. CE_{out} is the mean value of each maneuver CE. The CE is basically determined as described in Eq. 3 and CE_{update} can be found using Eq. 4

$$CE = \frac{\sqrt{V_x^2 + V_y^2 + V_z^2}_{\ achieved}}{\sqrt{V_x^2 + V_y^2 + V_z^2}_{\ commanded}} \tag{3}$$

$$CE_{update} = CE_{old} * (1 + CE_{out}) \tag{4}$$

The CE were 1.9642 and 0.9916 for MAN 1 and MAN 2 respectively, And the CE_{out} is 1.4779 and CE_{update} is 1.36276 which is extremely over than expected. The main cause is the uncertainties on velocity components on the other axes that were of same magnitude as the commanded tangential delta velocity. Obviously, the weighted least square numerical method that was used to calculate this efficiency was not reliable in this situation.

To solve this issue, an alternative method was used: the *Graphical Method* recommended by EADS Astrium. The main idea is to graphically compare the mean semi-major before and after the maneuver using the ephemeris before and post maneuver. From this method, the semi-major axis decrease was about 35.1 meters. And the CE_{out} for this case is obtained with Eq. 5

$$CE_{out} = \frac{\Delta a_{achieved} - \Delta a_{commanded}}{\Delta a_{achieved}} \qquad (5)$$

This method led to an under performance of about 12.5%. After discussion with Astrium FDS expert, they recommended not to update the calibration coefficient. Indeed, the next OCM were assumed to be quite big because of LST correction (as shown in Fig 7.) thanks to inclination maneuvers and this calibration coefficient is not representative for big maneuvers.

3.2 Second OCM assessment

3.1.1 Station keeping monitoring

The second OCM consisted in correcting the inclination to maintain the LST between 22:00±2 mins to provide a nearly constant geometry.
To change the orientation of a satellite's orbital plane, one must change the inclination and thus the direction of the velocity vector. The LST evolution as predicted by the end of October for 1 month is shown in Fig 8. The LST was about to exceed the limit at the end of October 2010. This maneuver requires a ΔV perpendicular to the orbital plane. Firstly the OCM date was set up around end of Oct 2010. As we checked that the LST beyond the limit would not interfere with SPOT which is on the same grid, we decided to give us more time to prepare the OCM. Finally the maneuver date was set up on Nov 23th 2010.

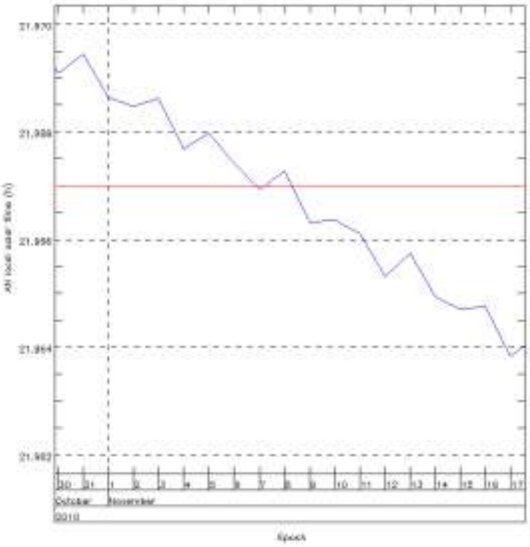

Figure 8 The LST evolution prediction for 1 month

Figure 9 Minimize impact on eccentricity, Δi=0.0895 deg

3.1.2 OCM simulation and planning

This maneuver could have been a combined maneuver to correct simultaneously inclination and semi-major axis. But regarding the propellant usage, there was no real gain to perform combined maneuver as the tangential component was really small wrt to normal component. We assumed it was better to separate the maneuvers, i.e. to perform inclination correction only and then, after estimation of the achieved orbit, to perform a semi-major axis correction to compensate for dispersions observed. Indeed, even with a combined maneuver, it was likely that a semi-major axis correction would be then necessary to compensate for the errors.

This OCM was computed from the Quartz new version (4.7.0) with increased accuracy for long term prediction. The Δi target was 0.0895 degrees. With this value, the LST evolution prediction was optimal regarding the upper warning limit considering a 5% error on maneuver performance as shown in Figure 4. The delta semi-major axis was set to 0 m for this case.

No. MAN	**Centroid Time**	**$\Delta V_{commanded}$(m/s)**			**$\Delta V_{achieved}$(m/s)**			**CE (Achive DV/Commanded DV)**	**CE_{out}**	**CE_{update}**
		ΔV_T	**ΔV_N**	**ΔV_w**	**ΔV_T**	**ΔV_N**	**ΔV_w**			
1	19:49:40	-	-	-2.90554	0.02047	-0.00132	-2.95875	1.0183365	1.0172	0.9379
2	21:31:08	-	-	-2.90605	0.01959	-0.01083	-2.95800	1.0179040		
3	23:12:35	-	-	-2.90577	0.02078	-0.00413	-2.96405	1.0200847		
4	00:54:03	-	-	-2.90626	0.02310	-0.00765	-2.94239	1.0124638		

Table 2 the summary of 2nd maneuver

The same method as for OCM 1 was used to predict pressure and temperature at maneuver time.
As the maneuver was quite big and due to limitation of thrust ($\Delta V < 3$m/s for each OCM), the maneuver was divided into 4 maneuvers, with a delta velocity in normal negative direction only as summarized in Table. 2. A "symmetric" configuration, i.e. 2 maneuvers at ascending nodes, then 2 maneuvers at descending nodes, would have been natural. Indeed, if a systematic error on attitude was observed, the effect on semi-major axis would be cumulative on the 4 maneuvers. However, the plan with all maneuvers at descending node has been maintained as the effect was not expected to be significant. We just intended to derive some lessons learnt for the next out-of-plane maneuver.
The OCM planning is simply illustrated in the Figure 10. The orbit plan was gradually changed with each thrust. The simulation of inclination correction corresponding to OCM plan is shown in Figure 11.
As mentioned in section 3.1.3, before uploading the OCM plan to the satellite, GISTDA and EADS Astrium FD specialist, had a technical meeting to review and approve the OCM plan.

3.1.3 OCM results and calibration

The maneuvers were performed successfully according to the plan. The ΔV commanded and ΔV achieved are shown in Table 4. The 2nd OCM CE for each maneuver was computed from Eq. 3. From QUARTZ results, the mean value of calibration efficiency CE_{out} is 1.0172 and the updated new OCM calibration coefficient is 0.9379 from Eq.4. Regarding the mass, these OCM consumed about 3.75 kg leading to 50.37 kg remaining propellant.

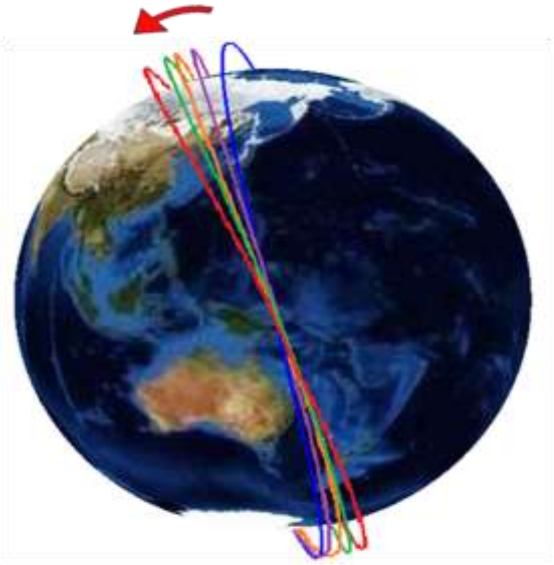

Figure 10 The simplified inclination is changed by 4 maneuvers

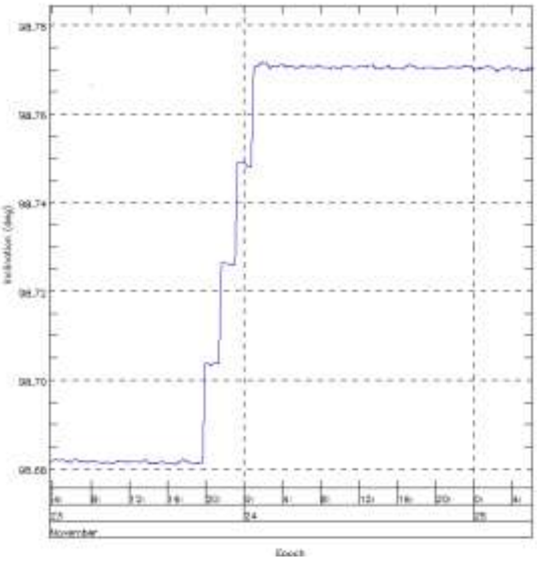

Figure 11 The inclination adjustment sequence

These results were confirmed by the graphical method. The achieved inclination and semi-major axis were 0.091 deg and 0.16655 km respectively. These values were consistent from the calibration coefficient obtained previously. The semi-major axis variation (+166m) was unexpected: it was the result of a systematic error on attitude with all the inclination maneuvers performed at the same node. However, we were lucky as this semi-major axis increase was just what was needed to make the Ground track error evolution swing back into negative area. The new expected date for semi-major axis correction was mid 2012. The unexpected tangential component of these inclination maneuvers had a negligible impact on eccentricity (3e-7). After these 4 maneuvers, there was thus no need to perform additional maneuvers to correct eccentricity and semi-major axis.

4. Emergency OCM

4.1 Strategy Analysis

One difficulty of collision risk management is the limited number of tracked objects: only 13,000 out of 100,000 potential dangerous debris. But the major difficulty is the inaccuracy of available public data needed to the properly monitor collision risk. GISTDA uses 2 different data sources.

- Celes-trak: CSSI (Center for Space Standards & Innovation) runs a list of all satellite payloads on orbit against a list of all objects on orbit using the catalog of all unclassified NORAD two-line element sets (TLEs) releasable to the public to look for satellite conjunctions over 1 week [4] and provided in SOCRATES (Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space) format. The statistical plot of space objects which were in close approach with THEOS (distance within 9 km) from September to November 2010 are shown in Figure 12.

- Space Track: JSpOC uses to send a Conjunction Analysis Report (CAR) when a risk is detected. The CARs received by GISTDA since the beginning of operational lifetime are summarized in Table 3.

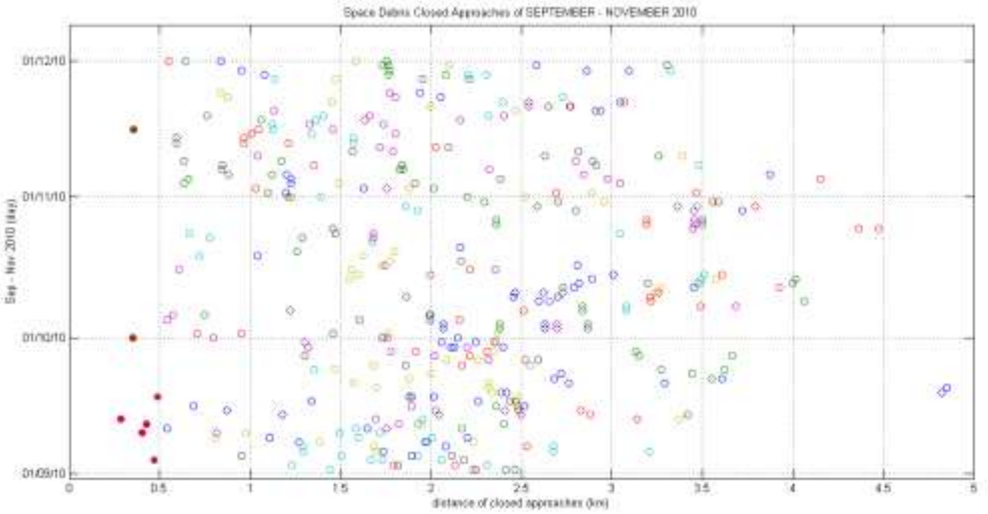

Figure 12. The statistical plot of space objects with close approach to THEOS

No. CAR	TCA (UTC)	Primary object	secondary object	Predicted distance (m)			
				Overall (m)	Radial(dU) m	In-Track(dV)m	Cross-Track(dW) m
1	10 NOV 09 08:48	THEOS	Known Object	959	**-77**	-834	468
2	14 MAR 10 13:59	THEOS	Known Object	324	-180	-198	-183
3	09 AUG 10 14:05	THEOS	Iridium 33 DEB	768	-72	721	254
4	12 OCT 10 09:33	THEOS	FENGYUN 1C DEB	602	-90	-159	657
5	15 DEC 10 06:07	THEOS	Known Object	101	76	8	67

Table 3 the summary of CAR from JsPOC

In the 5th CAR, the predicted distance was 8 m in radial direction. After the reception of this CAR, GISTDA immediately asked Astrium to analyze the risk and to check the need to perform collision avoidance maneuver. Astrium recommended in this case an avoidance maneuver. Indeed, the criteria that was used is

$$\begin{aligned}&\text{if radial distance} < (3*\text{Primary\_radial\_error}) + (3*\text{Secondary\_radial\_error}) + \\ &(\text{radius\_primary}) + (\text{radius\_secondary}) \qquad (6)\\ &\text{then Emergency OCM alert}\end{aligned}$$

In the 5th CAR, it corresponds to 76 < 3*3 + 3*64 + 3 + 5 (we did not know what was 2nd object; 5m is a conservative value). Minimum distance shall thus be 209 m. A check of the vector radius of both objects at TCA resulted in 7210.762 km for THEOS and 7210.790 km for 2nd Object which seems to show that 2nd Object was above THEOS at TCA time. The avoidance maneuver was thus computed in order to decrease THEOS altitude.

The Δa (-80m) was computed from

$$\text{delta\_a} = \frac{\left[\begin{array}{l}(3*\text{Primary\_radial\_error}) + (3*\text{Secondary\_radial\_error}) + \\ (\text{radius\_primary}) + (\text{radius\_secondary})\end{array}\right] - (\text{radial\_distance})}{2} \quad (7)$$

Indeed, the delta semi-major axis of 67 m from Eq. 7 was increased to 80m in order to take into account a 5% over/under performance and to ensure more margin. The maneuver was planned half an orbit prior to the conjunction (at an AoL of 180deg with respect to the AoL at conjunction time) with a single impulsion only.

The collision avoidance maneuver detailed plan is shown in Table 4. The collision avoidance strategy and the semi-major axis adjustment are shown in Figure 12 and Figure 13 respectively.

No. MAN	**Centroid Time**	**$\Delta V_{commanded}$(m/s)**			**$\Delta V_{achieved}$(m/s)**			**CE (Achive DV/Commanded DV)**	**CE_{out}**	**CE_{update}**
		ΔV_T	**ΔV_N**	**ΔV_w**	**ΔV_T**	**ΔV_N**	**ΔV_w**			
1	03:34:53	*-0.04118*	-	-	-0.03661	-0.02602	-0.01158	1.1263	1.1263	1.0564

Table 5 the summary of Emergency maneuver

4.2 The OCM results, analysis and post evaluation

The OCM was performed successfully as expected. As for the first OCM (very small correction on semi-major axis), it was difficult to evaluate the maneuver performance because of parasitic transverse components. The achieved semi-major axis decrease was 75 meters for 80 meters commanded, showing a 6.25% under efficiency.

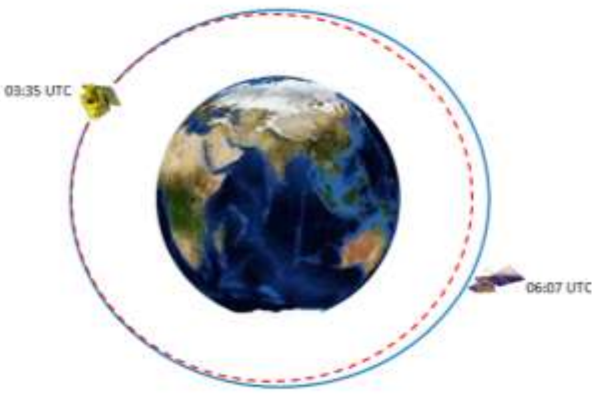

Figure. 12 Collision avoidance strategy

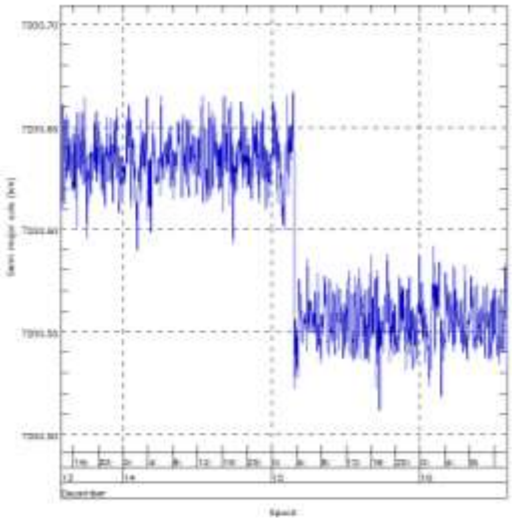

Figure. 13 semi-major axis adjustment

At 07.12 UTC (first visibility after the TCA time), THEOS could operate with normal situation through contact via Kiruna/Essrange ground station. GISTDA provided the predicted ephemeris after maneuver to JSpOC to check the minimal distance between THEOS and the “KNOWN OBJECT” but did not manage to know how close the objects were finally at TCA.

5. Station keeping evolution prediction

As part of routine activities after this emergency maneuver, the GT Error evolution and Local Solar Time evolution were predicted over 2 years as shown in Figure 12 and in Figure 13. The semi-major axis decrease performed by the collision avoidance maneuver has advanced the next OCM time from mid 2012 to April 2011. The Station-Keeping prediction shows that next maneuvers will be beginning of April 2011 for Ground Track and end of 2012 for Local Solar Time correction.

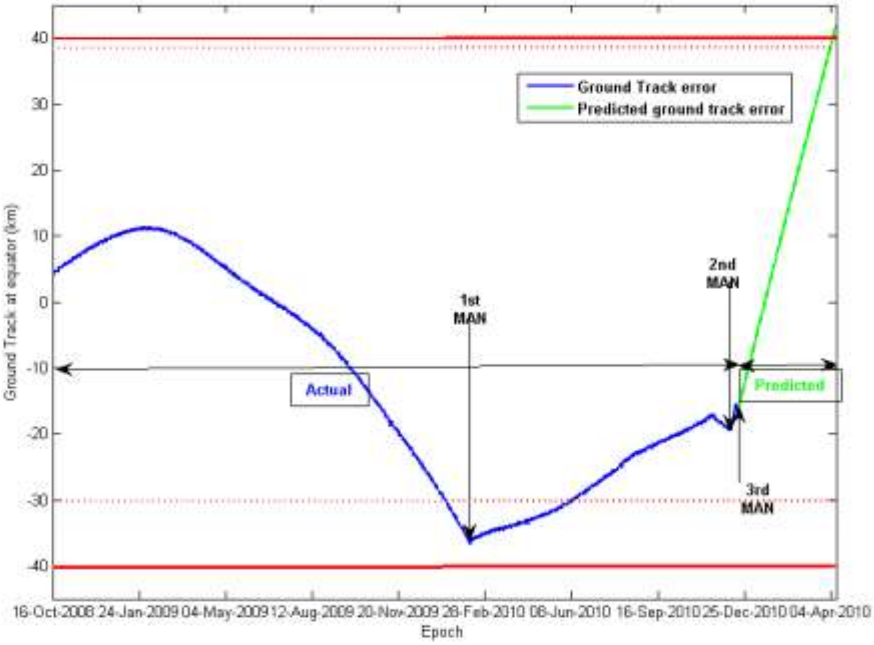

Figure. 14 Evolution of ground track error

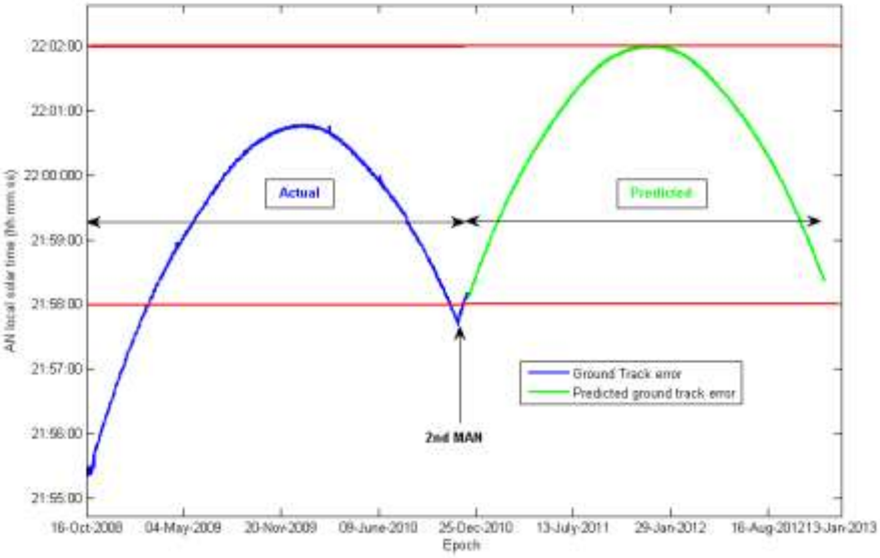

Figure. 15. Evolution of local solar time

5. Conclusion

The whole OCM operations have been conducted by GISTDA with EADS Astrium support completing thus the operational formation of GISTDA operators with OCM activities. The first maneuver was performed nominally resulting in Ground Track Error evolution close to the prediction. The second maneuver was performed as expected, the LST error evolution will remain in its window for at least 2 years. Furthermore, an emergency OCM has been performed with

success despite a very short time for preparation. GISTDA is now completely autonomous on OCM activities. The next OCM is assumed to occur around April 2011.
The global propellant consumption during these 2 years of station-keeping is 3.8 kg. The remaining 50.37 kg of propellant are coping with a 10 years lifetime. However, some provision shall be considered to perform desorbitation maneuvers at the end of the mission.

6. References

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