Orbit Control Manoeuver Module for Thaichote Satellite

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Abstract

In this paper, we present an orbit control manoeuvre module. Its aim is for the control of Earth-observation satellites in low-Earth orbit where the groundtrack pattern and local solar time of the orbital nodes need to be maintained. The delta-V strategy against astrodynamics disturbance especially the non-spherical Earth and atmospheric drag will be described. Some practical issues for transforming the theoretical delta-V into real implementation plan to be tele-commanded to the onboard propulsion system are included in the module. The experimental results obtained during the orbit maintenance of Thaichote satellite confirm the maturity of the proposed module.

Keywords: Orbit Control Manoeuvre, Earth-Observation Satellite, Thaichote Satellite

1. Introduction

Thaichote, also known as THEOS, is Thailand's first Earth -observation satellite [1]. It has been operating since March 2008, in a Sun-synchronous orbit at an altitude of about 822 km. The local solar time of the orbital descending node is assigned at 10:00 AM, and the satellite's ground-track repeats every 369 revolutions or about 26 days. The overall operational orbit configuration of the spacecraft is summarized in Table 1.

Table 1. Operational orbit Configuration of Thaichote-I Satellite

Orbital Parameters	**Value**
Altitude	822 km
Inclination	98.76 deg.
Frozen eccentricity	0.001146
Mean Motion	14+5/26 revolutions/day
LST of Descending Node	10.00 A.M. +/- 2 min.
Groundtrack revisit	26 days (369 revolutions)
Groundtrack Maintenance	+/- 40 km w.r.t. the reference longitude

The Orbit Control Manoeuver (OCM) Module is a part of the spacecraft's Flight Dynamics System (FDS) [2]. It takes responsibilities in achieving and keeping the above mentioned orbital conditions, throughout the spacecraft's operational life span.

In this paper, we describe an in-house development of the Thaichote's OCM Module. Its aim is not only for the current spacecraft, but also the module can be extended for the next generation of Thaichote satellites. The proposed module comprises of 2 main parts, namely the Orbit Control Computation and the Manoeuver Plan Generation, which will be described in details in the next sections. Some practical OCM scenarios will be given and discussed in the experimental results section, and the conclusions will be drawn in the final section.

2. Orbit Control Computation

Astrodynamics disturbances, especially from the Earth's oblateness and atmospheric drag, cause the satellite's orbit deviated from the desired conditions. Hence, delta-V firings are required periodically in order to keep the profile of the controlled parameters inside a tolerance gap. The computation for required delta-V and its optimal execution time is essential for effective manoeuvre, while the onboard propellant expenditure in minimized.

a. Groundtrack and Frozen Orbit Maintenance

The main cause of groundtrack drift from a reference pattern is the disturbance from atmospheric drag, which trends to reduce the orbital energy, hence nodal period. It causes the satellite's groundtrack drifts eastward relative to its reference track. In groundtrack maintenance, a control window is typically assigned, so that the groundtrack drift is allowed only within a pre-defined tolerance. If a constant atmospheric drag is assumed during a control period, a parabolic profile of ground-track drift and drift rate is expected, as depicted in Figure 1. Starting from an initial condition with positive drift rate, the groundtrack will naturally drift westward. Such condition can be achieved by putting the spacecraft into an orbit with higher altitude than the reference value. Under influence from atmospheric drag, the drift rate reduces and the groundtrack profile is brought eastward. An OCM is required at the positive limit of the control window to increase the semimajor axis and resume the control profile.

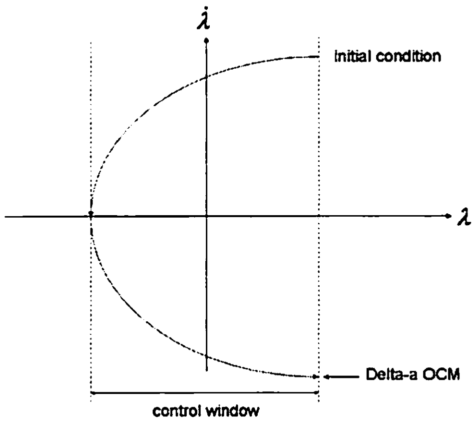


Figure 1 A typical groundtrack profile drifting inside the control window.

Only the along-track component of delta-V is required for resuming the orbital energy. The required change in semimajor axis (Δa) is a function of the estimated orbital decay rate caused by atmospheric drag, D, and the control cycle period, T_c, as

$$\Delta a = (a - a_0) + \frac{T_c}{2} D \qquad (1)$$

which, to first order approximation, relates to the required delta-V through

$$\Delta V = \frac{\Delta a \times V}{2a_0(1 - e\cos\nu)} \qquad (2)$$

where V is orbital velocity, a_0 is the reference semimajor axis, e is eccentricity and ν is true anomaly.

As frozen orbit condition is also preferable for the mission, each burn of the altitude-resuming delta-V can also be utilized for optimally adjusting the eccentricity vector towards frozen [3]. In order to preserve the eccentricity vector in the case that the orbit is already in the frozen condition, the required delta-V can be divided into 2 equivalent parts and applied at the opposite orbital phases.

b. Local Solar Time Maintenance

The desired relative angle between the orbital ascending nodes and the Sun's direction for Thaichote mission is at 10:00 am with a tolerance gap of ±1 min. The third-body attraction, especially the Sun, trends to lean the orbit inclination down at a rate of about 0.01 deg/year, as shown in Figure 2.

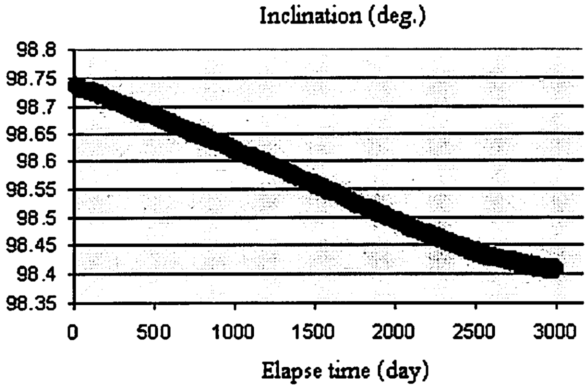


Figure 2. Long-term inclination drift caused by the 3rd-body attraction.

This causes the node's local solar time drifts in a parabolic profile as shown in Figure 3, and a similar delta-V strategy as the groundtrack maintenance can again be applied.

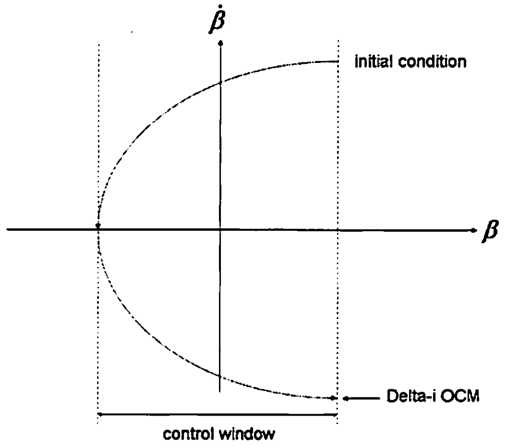


Figure 3 A typical LST profile drifting inside the control window

The initial condition can be set accordingly to the disturbance effect, and a delta-V along the cross-track direction can be applied periodically to resume the inclination:

$$\Delta V = \frac{\Delta i \times V}{\cos\lambda\ (1 - e\cos\nu)} \qquad (2)$$

where λ is the argument of latitude. Note that the most effective firing position is at the equator crossing.

3. OCM Implementation

The Thichote's propulsion system available for OCM comprises of 4 1-N Hydrazine thrusters. The OCM Implementation sub-module calculates relevant parameters obtained from the conversion of theoretical delta-V into the practical values where real data of the onboard propulsion system are taken into account. Constraints that can affect the OCM are also examined in this sub-module.

a. Manoeuvre Duration

With its limited thrust level, the onboard propulsion system can approximately implement the required impulsive delta-V by execution through a short period of time:

$$\Delta V = \int_{t_1}^{t_2} \frac{F(t)}{m(t)} dt \qquad (3)$$

Note that both thrust level, F, and the spacecraft's mass, m, are time-varying variables. They can be formulated as a function of pressure, P, as

$$\Delta V = \int_{P_1}^{P_2} \left(\frac{F}{m}(P) \varphi'(P) \right) dP \qquad (4)$$

where

$$\varphi'(P) = \frac{dt}{dP} = -\frac{\rho P_1 V_1}{P^2} \frac{1}{(1 - omc_1) q_1 + \ldots (1 - omc_n) q_n}$$

and ρ is the propellant density, q_i and omc_i are the propellant flow rate and off-modulation coefficient of each thruster. Finally, firing duration can be found from

$$\Delta t = \int_{P_1}^{P_2} \varphi'(P) dP \qquad (5)$$

b. Manoeuvre Centroid

As thrust level varies with time, the centroid of accumulated delta-V, t_c, trends to move forward because of reducing pressure, and it can be calculated from

$$t_c = \frac{1}{\Delta V} \int_{t_i}^{t_f} t \frac{F}{m}(t) dt \qquad (6)$$

c. Thrust Level

As the thrust can be different for each of the 4 thrusters, the thrust level shall represents the mean value over the number of thrusters used (2 or 4 thrusters according the configuration) at manoeuvre start epoch, i.e.

$$F = \frac{1}{P_f - P_i}\left(\int_{P_i}^{P_f} F_1(P)dP + \dots \int_{P_i}^{P_f} F_n(P)dP\right) \qquad (7)$$

d. Number of Pulses

The number of pulses, *NoP*, is the global number of pulses assuming that a pulse corresponds to the continuous activation of one thruster during a Flight Software Cycle (FSW). Therefore, the number of pulses is dependent on thruster configuration. Once the expected duration is known, having considered the right number of thrusters according to the thruster configuration and the off-modulation coefficients, the value of *NoP* can be computed as

$$NoP = Nearest\ Integer\left(\left[\frac{Theoretical\ Duration}{FSW\ Cycle\ Duration}\right] \times \left[\ 1 - omc_1\ + \dots\ 1 - omc_n\ \right]\right)$$

(8)

e. Manoeuvre Quaternion

The quaternion represents the rotation that transforms the local orbital frame into OCM attitude: +Z towards the earth, +Y opposite from the orbital angular momentum, +X completes the tridron, roughly along the delta-V direction. The OCM quaternion is the resultant quaternion of 7 successive rotations:

$$\begin{aligned} Q\_R1\_to\_R7 = {} & Q\_R7\_to\_R6 \times Q\_R6\_to\_R5 \times Q\_R5\_to\_R4 \times \\ & Q\_R4\_to\_R3 \times Q\_R3\_to\_R2 \times Q\_R2\_to\_R1 \end{aligned}$$

(9)

where $Q\_R2\_to\_R1$ is the rotation that transforms the local orbital frame (LVLH) into the TNW frame where T is along the velocity direction, W is along the kinetic momentum and N completes the triedron. $Q\_R3\_to\_R2$ is the rotation matrix around W axis to align with the in-plane delta-V, $Q\_R4\_to\_R3$ rotates the spacecraft around its own X axis to point the +Z direction towards nadir, $Q\_R5\_to\_R4$ aligns the spacecraft along the cross-track delta-V direction. Finally, $Q\_R6\_to\_R5$ and $Q\_R7\_to\_R6$ are the rotations around Z and Y axis, respectively, to correct the thruster real canting direction.

4. OCM Constraints

In this sub-module, all necessary constraints will be checked in order to make sure that the calculated values obtained from the previous sub-modules are appropriate in real situation. For each manoeuvre, the following constraints are checked:

a. Manoeuvre Maximum Duration

This constraint affects both the safety of the propulsion system and the effectiveness of delta-V execution, because the theoretical OCM calculation assumes impulsive delta-V.

b. Maximum $M_{sat} \times \Delta V$

This constraint is to limit the magnitude of delta-V that can be safety executed under the operational onboard propulsion, as well as the attitude control configuration.

c. Minimum duration between two OCMs

This constraint is to guarantee a safety margin of the duration between the end epoch of an OCM and the start epoch of the next one.

d. Minimum duration before/after automatic transition

As the attitude manoeuvre to go into OCM attitude shall not occur during an automatic transition, it is therefore necessary to check the duration before/after automatic transition. This value does not depend on the wheel configuration.

f. Minimum duration in a mode other than Sun pointing

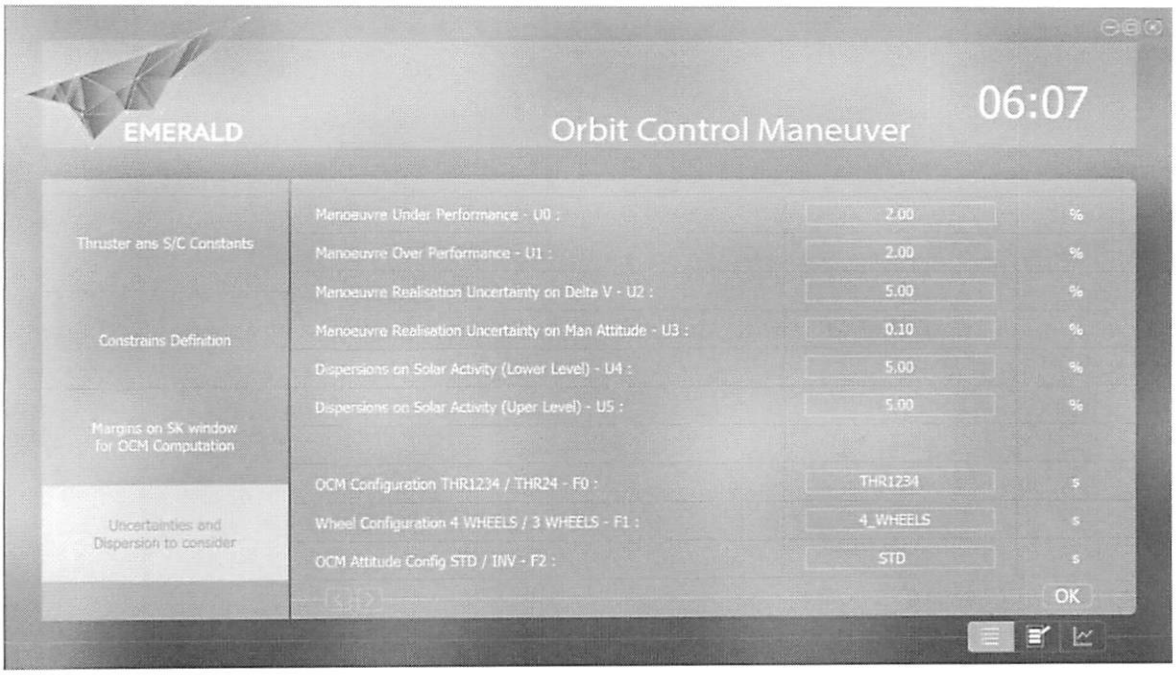
This value corresponds to the maximum duration during which the spacecraft can be in a mode other than Sun pointing mode.

g. Minimum angle between Sun direction and +Z axis

This value corresponds to the payload enlighten constraint. The payload shall not be enlighten by the sun during the attitude manoeuvre to go to OCM, the OCM and the attitude manoeuvre to go back to default pointing.

4. Experimental Results

The proposed OCM module has been successfully tested during a groundtrack maintenance of the Thaichote satellite. With the practical constraints given in Figure 4 have been verified, the OCM plan was generated and tele-commanded for the real execution of delta-V.



Manoeuvre Under Performance - U0 : 2.00 %
Manoeuvre Over Performance - U1 : 2.00 %
Manoeuvre Realisation Uncertainty on Delta V - U2 : 5.00 %
Manoeuvre Realisation Uncertainty on Man Attitude - U3 : 0.10 %
Dispersions on Solar Activity (Lower Level) - U4 : 5.00 %
Dispersions on Solar Activity (Uper Level) - U5 : 5.00 %

OCM Configuration THR1234 / THR24 - F0 : THR1234 s
Wheel Configuration 4 WHEELS / 3 WHEELS - F1 : 4_WHEELS s
OCM Attitude Config STD / INV - F2 : STD s

Figure 4. Thaichote mission's OCM Constraints

The predicted groundtrack profile and eccentricity vector preserved around the frozen condition as shown in Figure 5 and Figure 6, respectively, have been confirmed by the determined orbit using onboard GPS data.

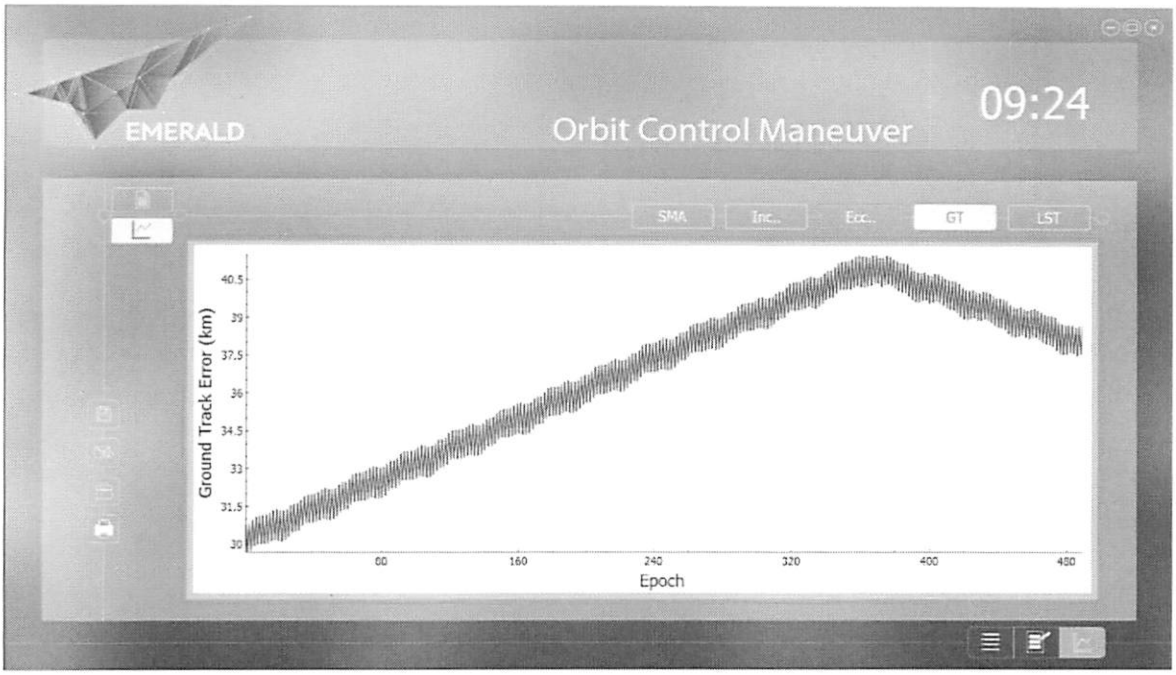


Figure 5. Groundtrack profile before and after OCM

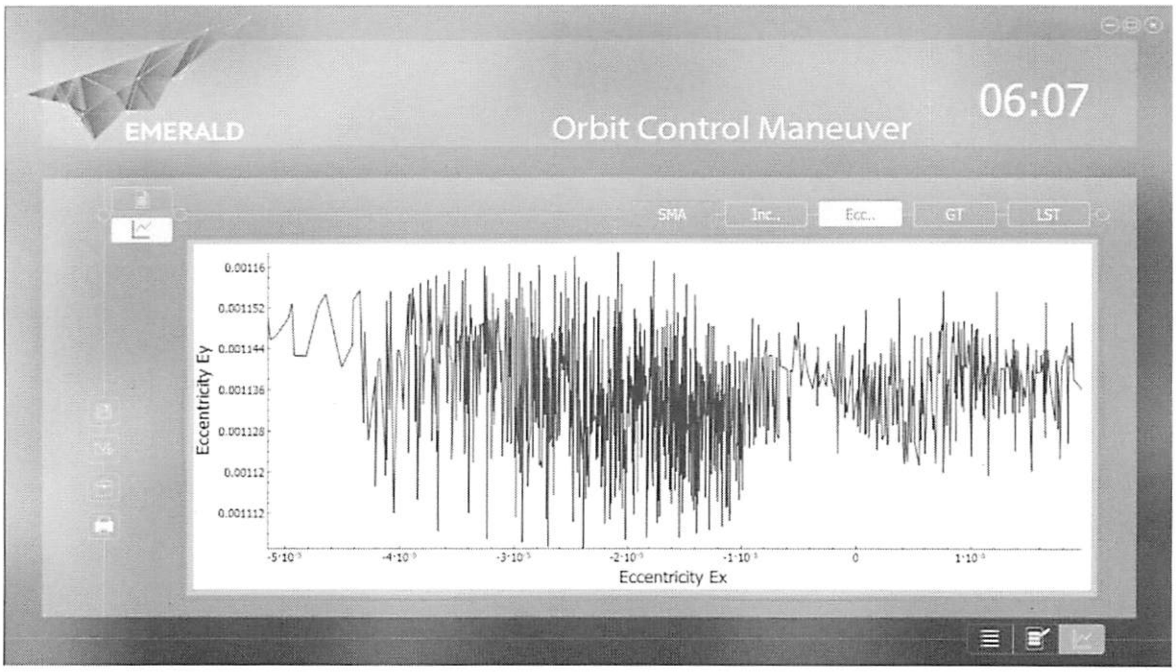


Figure 6. Eccentricity vector motion around the frozen condition during OCM

We also conducted a node's LST maintenance OCM. As the required change in inclination is 0.103 deg, the corresponding delta-V of xx m/s needed to be divided in to a series of x burns. Figure 7 shows the increasing of inclination during OCM, and Figure 8 shows the profile of LST after the OCM which again was verified by the onboard GPS orbit determination system.

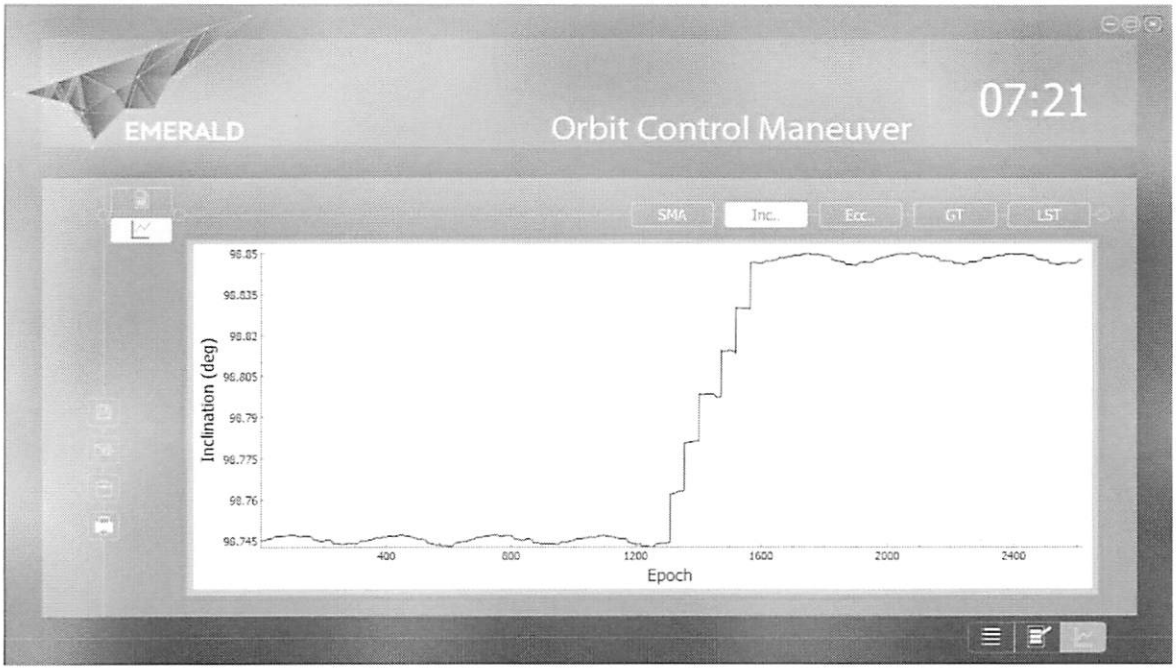


Figure 7. Change in orbital inclination during OCM

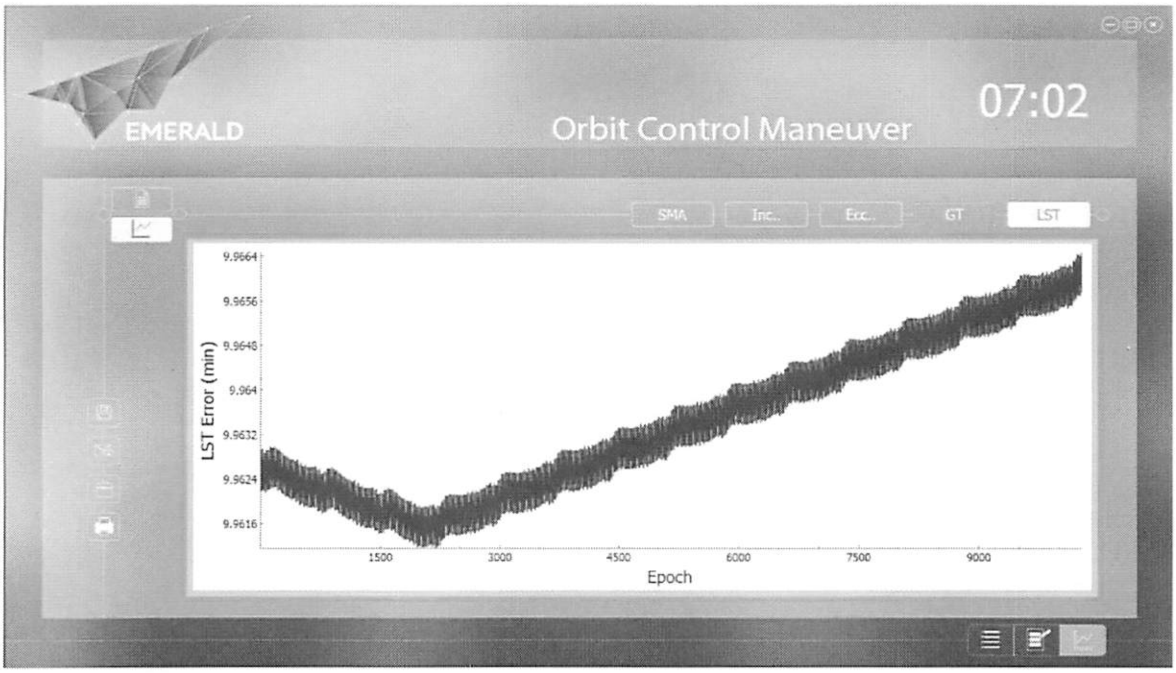


Figure 8. Profile of local solar time of the orbital node

5. Conclusions

In this paper, we have presented an in-house development of the orbit control manoeuvre module for the Thaichote mission. The module has been designed for friendly user interface operation. The simplicity of the computation and the reliability of the verification and plan generation is the keys part of the OCM module. A successful demonstration of both groundtrack and LST maintenance has been achieved using the proposed system, which guarantees its mature for deployment on the current mission and further develop for future mission.

References

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