Station-Keeping Simulation and Planning for LAPAN-A4 Satellite Using Finite-Burn Thruster

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Abstract

To be a Sun-synchronous orbit (SSO), the orbit must have a certain value of nodal precession rate, which equals 360°/year. However, the value of nodal precession rate is usually drifted by orbit perturbations, mainly by the oblateness of the Earth and atmospheric drag, to be no longer 360°/year as expected for SSO. Thus, the local time of the satellite will change too, so it needs to be corrected by some correction maneuvers. In this research, the authors studied station-keeping planning for SSO satellite via inclination correction maneuver by simulation using GMAT, a software developed by NASA, with a finite-burn propulsion approach. In this research, LAPAN-A4 satellite is chosen to be the satellite that will be simulated. Some alternative plans of inclination correction maneuver based on maneuvering intervals are chosen, they are maneuvers for every 2 months, 4 months, 6 months, 12 months, and 24 months. The simulation results show that the station keeping planning with correction maneuver for every 2 months is recommended. This alternative gives the lowest fuel consumption so that the fuel and launch cost will be minimum, and the local time drift that is still may be tolerated.

Keywords*: LAPAN-A4; SSO; inclination maneuver; finite-burn thruster*

1. Introduction

Sun-synchronous orbit (SSO) is an orbit that allows the satellite to pass over the same point of the Earth's surface at the same instant of the true solar time (Kuznetsov & Jasim, 2016). Figure 1-1 illustrates a Sun-synchronous orbit over a year. As depicted in the figure, the satellite would pass over certain regions on the Earth at the same local time every day, 22.30 in this case. This will give advantages for imager satellites as the images taken would have the same proportion of lighting from the Sun.

To achieve this, i.e. the same local time every day, the orbit needs to precess at the same pace that the Earth revolves around the sun (Llop et al. 2015), or equals to 360°/year. This precession is called nodal precession rate as the orbit precession is indicated by the precession of its nodes. This nodal precession rate is affected by some orbital elements, those are eccentricity (*e*), semi major-axis (*a*), and inclination (*i*) (Kuznetsov & Jasim, 2016).

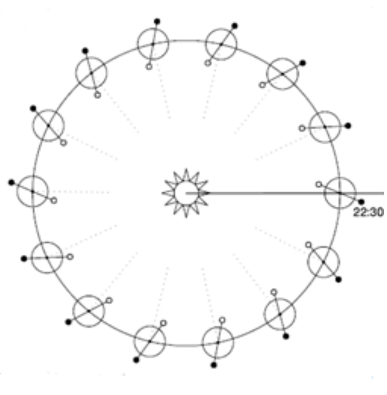

Figure 1-1: Sun-synchronous orbit (Capderou, 2005).

The nodal precession rate could be approximated by the effect of J_2 perturbation. The nodal precession rate caused by the Earth's zonal harmonic coefficient (J_2) is expressed by equations below (Utama, Saifudin, & Mukhayadi, 2018):

$$\dot{\Omega} = -\frac{3}{2} n J_2 \left(\frac{R_e}{p} \right)^2 \cos i \tag{1-1}$$

$$n = \sqrt{\frac{\mu}{a^3}} \tag{1-2}$$

$$p = a(1 - e^2) \tag{1-3}$$

where $R_e = 6378\, km$ is the Earth's equatorial radius, n is mean anomaly, and $\mu = 3.986 \times 10^5\ km^3 s^{-2}$ is the Earth's standard gravitational parameter.

SSO satellites are mostly also LEO satellites (Macdonald et al., 2010), hence the orbit perturbation caused by the oblateness of Earth's shape and atmospheric drag will be greater. These perturbations will lead to the changes of some orbital parameters value. Consequently, the value of nodal precession rate may change too, so its value will be no longer 360°/year as would be expected for SSO.

Indonesian aerospace agency, LAPAN, has three satellites currently in orbit (Utama, Hakim, & Mukhayadi, 2019). Two of the satellites are SSO, they are LAPAN-TUBSAT (Triharjanto et al., 2004) and LAPAN-A3 (Hasbi & Suhermanto, 2013). After years in orbit, LAPAN-TUBSAT and LAPAN-A3 show drifted orbit (Utama et al., 2018). Figures 1-2, 1-3, and 1-4 respectively show the time history of LAPAN-A3 orbital parameters; semi major-axis, eccentricity, and inclination. There are drifts on those orbital parameters over time which could be an indication that the nodal precession rate value may be no longer 360°/year or, in other words, its orbit is no longer Sun-synchronous since the local time will be drifted. Figure 1-5 shows the local time drift that occurred on LAPAN-TUBSAT.

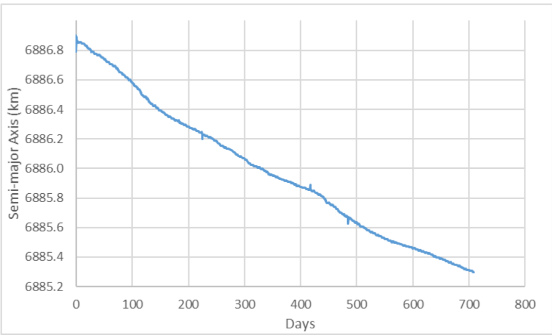

Figure 1-2: Semi-major axis drift of LAPAN-A3.

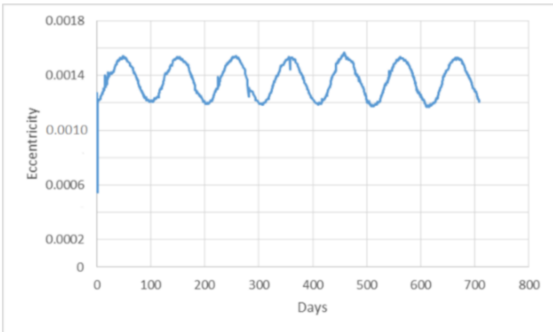

Figure 1-3: Eccentricity drift of LAPAN-A3.

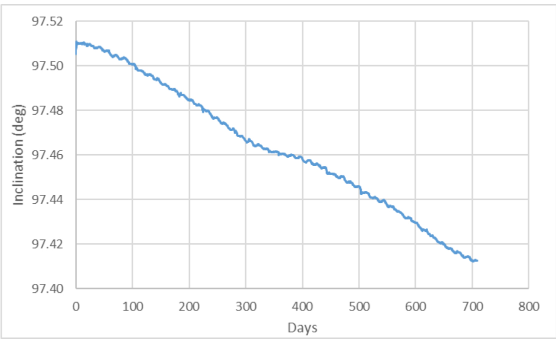

Figure 1-4: Inclination drift of LAPAN-A3.

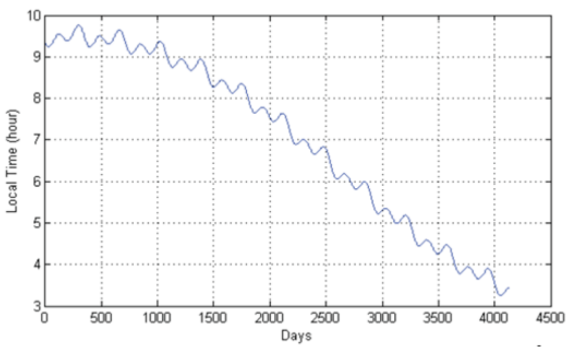

Figure 1-5: Local time drift of LAPAN-TUBSAT (Utama et al., 2018).

To deal with this problem, a certain method of correction maneuver needs to be carried out so that the nodal precession rate value remains at the desired value of 360°/year. According to Eq. (1-1), inclination, eccentricity, or semi-major axis changes would lead to the changes in the nodal precession rate value. Hence, those three are the possible maneuvers available to maintain the desired value of the nodal precession rate. However, as depicted in Figure 1-3, the time history of eccentricity is only sinusoidal with more or less a constant mean value. Moreover, the inclination maneuver is more effective to change the nodal precession rate value compared to the semi-major axis maneuver with the same ΔV applied (Zuhri, 2020).

LAPAN is planning to launch another SSO satellite, LAPAN-A4, in 2021 (Jemadu, 2020) with an expected local time of about 9.30 p.m. (Saifudin, Karim, & Mujtahid, 2018). This satellite is designed to have a propulsion system in order to carry out correction maneuvers including correction maneuvers to maintain the desired nodal precession rate as explained before. In this research, the authors schedule and simulate several alternative plans of station-keeping planning for the LAPAN-A4 satellite via inclination maneuver in the finite burn thruster approach by using GMAT (The GMAT Development Team, 2012), an open-source trajectory design and optimization software developed by NASA and private industry. A finite burn approach is adopted since it represents how thruster actually works, and GMAT is chosen because it is one of the best tested NASA's open-source software for space mission analysis (Hughes et al., 2014). The result and performance of the alternative plans will be compared, and a recommended alternative plan would be chosen to be a station-keeping planning recommendation for the LAPAN-A4 satellite.

2. Methodology

As mentioned before, this research focuses on a station-keeping simulation for the LAPAN-A4 satellite. The station-keeping planning was selected based on maneuvering intervals via inclination correction. The simulation was conducted using GMAT with a finite burn thruster approach.

2.1. Satellite Data

Satellite data used for this research is the proposed design of the LAPAN-A4 satellite. Table 2-1 shows the main characteristics of the LAPAN-A4 satellite.

Table 2-1: LAPAN-A4 Main Characteristics (Saifudin et al., 2018)

Data	Value
Dry mass (kg)	150
Dimension (mm×mm×mm)	744×700×520
Altitude (km)	500
Inclination (deg)	97.38[a]

[a]Decimal values are assumed to provide $\frac{d\Omega}{dt} = 360°/year$

LAPAN-A4 satellite is designed to have a propulsion system to support correction maneuvers in orbit. The thruster used in this satellite is 1 N HPGP (High-Performance Green Propulsion) (Utama et al., 2018), a thruster fueled by LMP-103S with blow-down operation mode developed by ECAPS. The data of this thruster is provided in Table 2-2. However, in this simulation, the satellite is assumed to carry fuel with maximum capacity.

Table 2-2: Thruster Data (Anflo & Möllerberg, 2009)

Data	Value
Tank Capacity (L)	4.5
Thrust (N)	1
Feed Pressure (MPa)	2.2
Blow-down ratio	4:1

2.2. Maneuver and Simulation Scenario

Alternative plans for station-keeping are scheduled to be based on maneuvering intervals. By assuming that the LAPAN-A4 satellite has 5 years of operation time, the alternative plans are:

1. Inclination maneuver for every 2 months.
2. Inclination maneuver for every 4 months.
3. Inclination maneuver for every 6 months.
4. Inclination maneuver for every 12 months.
5. Inclination maneuver for every 24 months.

Maneuvering targets are obtained by analyzing the $d\Omega/dt$ graph of no-maneuver simulation based on Eq. (1-1) (Figure 2-1). Since the value of $d\Omega/dt$ is oscillating over time, it would be useful to take a polynomial regression as shown by the red line of Figure 2-1. The regression yields the equation as a function of days below:

$$\frac{d\Omega}{dt}(°/year) = 360 + 5.636{\times}10^{-3}(days) + 8.619{\times}10^{-7}(days)^2 \tag{2-1}$$

The desired value of $d\Omega/dt$ is 360°/year. Hence, the deviation of $d\Omega/dt$ from the desired value ($\Delta\dot{\Omega}$) in the function of days is:

$$\Delta\dot{\Omega}(°/year) = 5.636{\times}10^{-3}(days) + 8.619{\times}10^{-7}(days)^2 \tag{2-2}$$

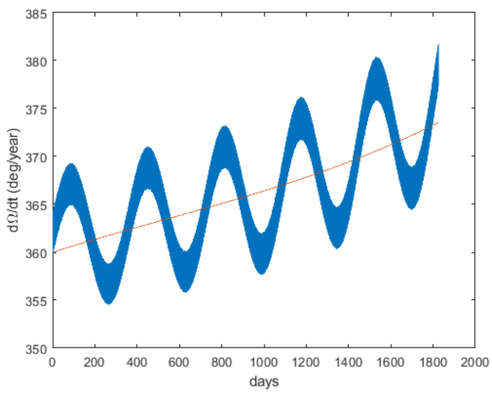

Figure 2-1: $\dot{\Omega}$ graph of no-maneuver simulation.

Computing the value of $\Delta\dot{\Omega}$ for every maneuvering intervals (i.e. 2 months, 4 months, 6 months, etc.), then we will come up to the required $\Delta\dot{\Omega}$ to be achieved by applying inclination maneuver for every alternative plan for each maneuver applied as provided by Table 2-3.

Table 2-3: The Required $\Delta\dot{\Omega}$ Correction Data

Maneuver intervals (Months)	Required $\Delta\dot{\Omega}$ correction (°/year)
2	0.34126
4	0.68873
6	1.04241
12	2.14066
24	4.50472

Since the simulation is using a finite-burn approach, the burning time of the maneuver will be significant. In the simulation, the required burning time to achieve $\Delta\dot{\Omega}$ requirement for each maneuver will be iterated along with orbit propagation. The error target of the iteration is set to be less than 0.001°/year.

Figure 2-2 shows the flowchart of the simulation built in GMAT. The mission is modeled to be a *while* loop with 5 years of operation constraint. While the propagation is still below 5 years of the operation, the satellite would be propagated for X days, with X is representing the alternative plan simulated (e.g. X = 60 for 2 months alternative plan). After that, the satellite is propagated to the node as an inclination-only maneuver must occur at this point (Vallado & McClain, 2013). At this point, it is still not clear whether the satellite is at ascending node or descending node. In contrast, for uniformity, the satellite is set to apply the maneuver at ascending node. Therefore, a conditional statement is needed to ensure that the satellite will be around ascending node before the inclination maneuver is applied.

After the conditional statement, the value of burning time (*bt*) is iterated with an initial guess to be 0 s. Furthermore, if before conditional statement the satellite is at descending node, it will be propagated for $t = \frac{P}{2} - \frac{bt}{2}$ as represented by the white trajectory in Figure 2-3, where P is the orbit period. If before conditional statement the satellite is at ascending node, it will be propagated for $t = P - \frac{bt}{2}$ as represented by the white trajectory in Figure 2-4. This propagation is intended to ensure that the burning time of the inclination to be equally divided between above and below the ascending node as represented by the brown trajectory in Figure 2-3 and Figure 2-4.

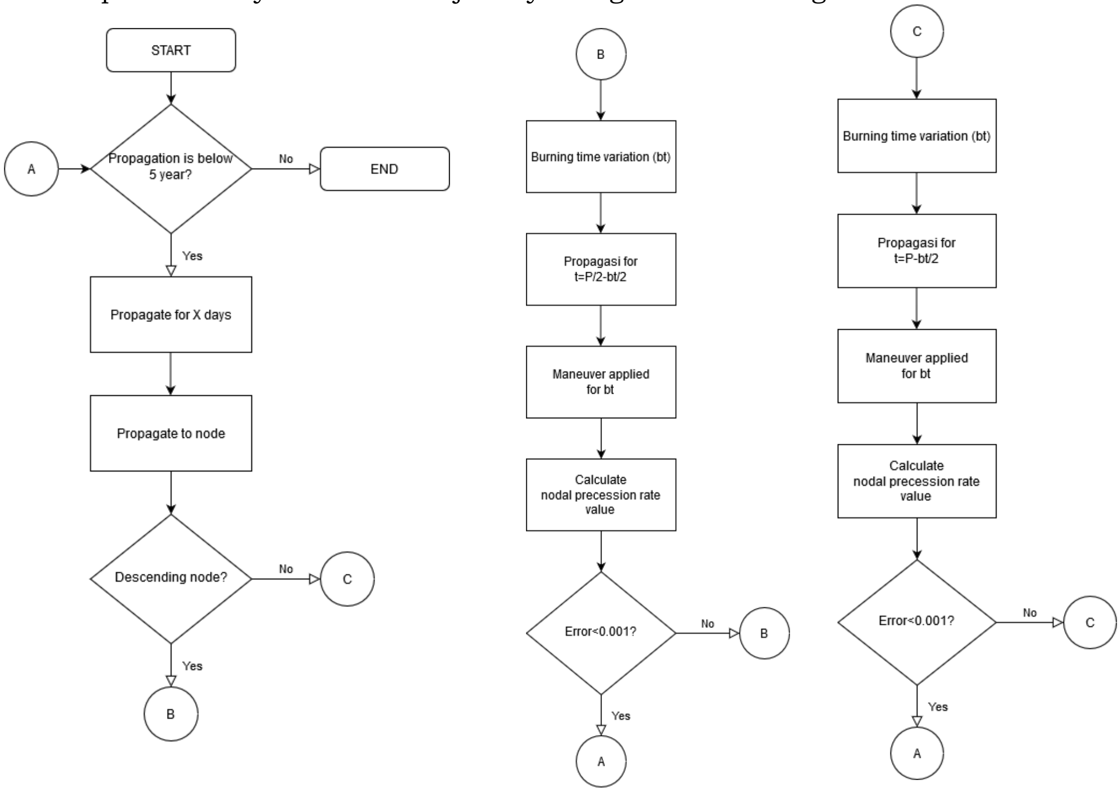

Figure 2-2: Simulation flowchart.

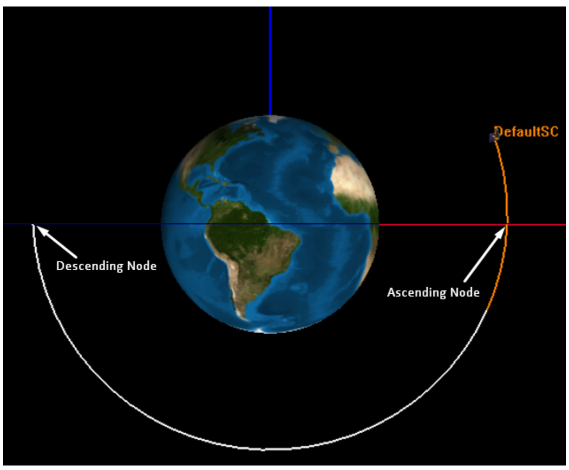

Figure 2-3: Trajectory if the satellite is at descending node before the conditional statement.

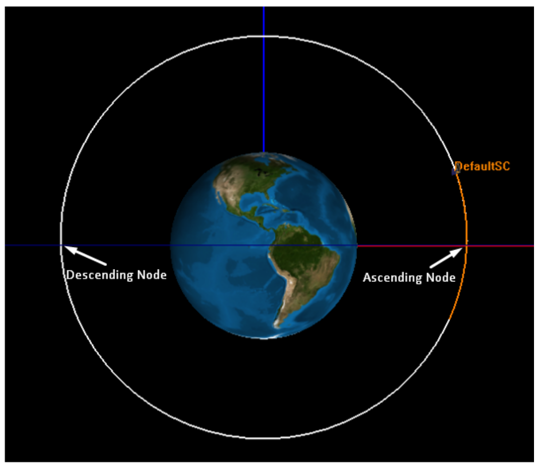

Figure 2-4: Trajectory if the satellite is at ascending node before the conditional statement.

Afterward, the inclination correction maneuver is applied for bt. The maneuver is directed perpendicular to the orbit where the maneuver inclination best performed (Ruggiero et al., 2011). The real value of $\Delta\dot{\Omega}$ after the maneuver applied is subsequently calculated and compared to the desired value of $\Delta\dot{\Omega}$. If the error is still beyond the desired error range, i.e. 0.001, the process will be repeated to iterate the value of burning time (bt) automatically in GMAT using the Newton-Raphson Algorithm. If the error is within the desired error range, the simulation will be repeated to propagate for X days. These processes repeat until the propagation has gone for 5 years of operation.

3. Result and Analysis

The $d\Omega/dt$ graph is oscillating as indicated by Figure 2-1. So, the same approach will be used for the resulting $d\Omega/dt$ graph of alternative maneuver plans, i.e. taking a second-order polynomial regression. Figure 3-1 shows the comparison of the regressed $d\Omega/dt$ graph for every alternative maneuver plan along with the no-maneuver simulation. Compared to the no-maneuver simulation, all of the alternative maneuver plans successfully lower the trend to be close to the desired value of 360°/year instead of increasing all the time. Notice that the longer the maneuver intervals, the closer the graph to the no-maneuver graph. Longer maneuver intervals mean the $d\Omega/dt$ value is left increasing during a longer time that leads to alternative maneuver plans with longer intervals to have a steeper graph.

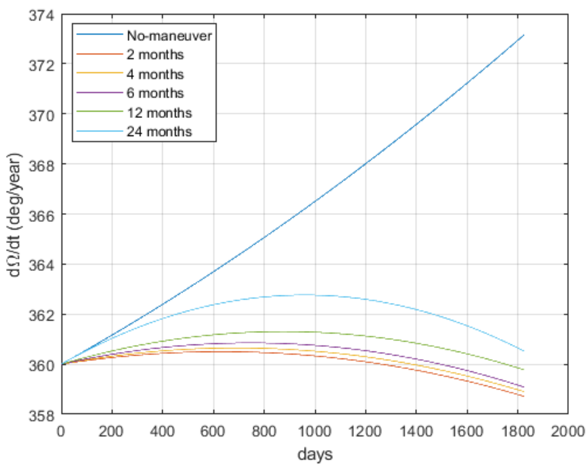

Figure 3-1: Regressed $d\Omega/dt$ graph comparison.

Moreover, if we look closely, the value of $d\Omega/dt$ goes below the desired value of 360°/year. This could happen because of the assumption used for the required $\Delta\dot{\Omega}$ correction. It is assumed that all of the required $\Delta\dot{\Omega}$ correction provided in Table 2-3 is not changing. In fact, the required $\Delta\dot{\Omega}$ is changing after each maneuver, the required $\Delta\dot{\Omega}$ for the first maneuver of the 2-month alternative plan might differ from the second or third maneuver for example. This assumption is used because regression is needed to calculate the required $\Delta\dot{\Omega}$ before maneuver applied. However, the $d\Omega/dt$ value oscillates with a considerably high period (approximately 1 year). For alternative maneuver planning with a short interval, the data for regression becomes unrepresentative as the maneuver interval is shorter than 1 year.

Furthermore, Figure 3-2 provides the comparison of the local time drift for all of the alternative maneuver plans along with the no-maneuver simulation. The local time drift is calculated by computing the difference between the time-history value of actual RAAN (Ω) obtained from GMAT and the time-history value of RAAN should be for SSO. The same as the $d\Omega/dt$ graph depicted by Figure 3-1, the local time drift for alternative maneuver plans with longer intervals is closer to the no-maneuver local time drift. There are also excesses where the local time drift goes to negative values as a consequence of the value of $d\Omega/dt$ which goes below 360°/year. However, all of the alternative maneuver plans give considerably small local time drift results. The largest local time drift occurs on the 24-month maneuver plan with ~24.5 minutes drift, while the smallest occurs on the 12-month maneuver plan with ~3.5 minutes drift only (see Table 3-1).

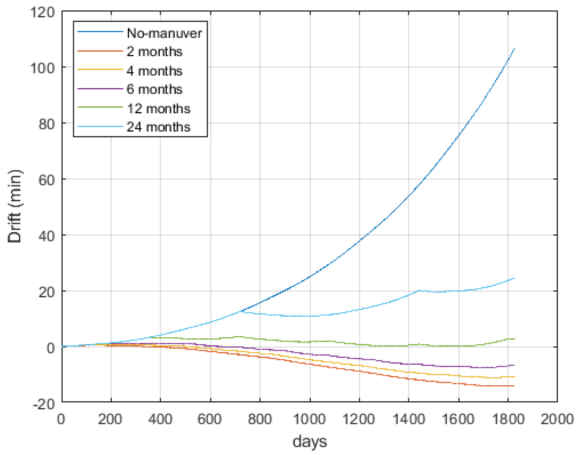

Figure 3-2: Local time drift comparison.

Table 3-1: Maximum Local Time Drift

Maneuver intervals (Months)	**Maximum local time drift (minutes)**
2	14.2
4	11.1
6	7.6
12	3.5
24	24.5

The local time drift would affect the image quality produced by LAPAN-A4 since the sunlight proportion of the images would be different. Also, this local time drift would affect the work hours of LAPAN employees. The bigger the local time drift, the bigger the issue to the quality of the produced images and LAPAN daily scheduling on LAPAN-A4 tracking. But, as the maximum local time drift resulted after the correction maneuver is in a few minutes range only, the local time drift should not too much disrupt the image quality and work hours of LAPAN employees, especially on LAPAN-A4 tracking.

Besides analyzing the local time drift, it also useful to analyze the burning time and the required fuel for each alternative maneuver plan. Figure 3-3 until 3-7 and Table 3-2 provides the burning time and the required fuel data for each alternative maneuver plan respectively. Alternative maneuver plan with shorter maneuvering interval gives less required fuel as accumulative effects from orbit perturbations are less. So, the required burning time for the maneuver is less too. Because of the less required burning time, the maneuver applied will be closer to the node, which leads to a more effective inclination maneuver as the inclination maneuver performs best at the nodes. As consequence, the required fuel obtained from the GMAT result is less for an alternative maneuver with a short interval.

The burning time graphs provided show decreasing trends. The decreasing trend of burning time is caused by the fact that the mass of the satellite is decreasing over maneuvers as fuel is consumed. Since the mass is decreasing, the maneuver could be performed ‘easier’ than the previous maneuver, and consequently, the required burning time is less. However, the decreasing trends are not always decreasing. There are fluctuations since the maneuvers also depend on the current value of orbital elements when the maneuver is applied.

Table 3-2: Total Required Fuel

Maneuver intervals (Months)	**Required fuel (kg)**
2	1.889
4	1.902
6	1.944
12	2.090
24	2.521

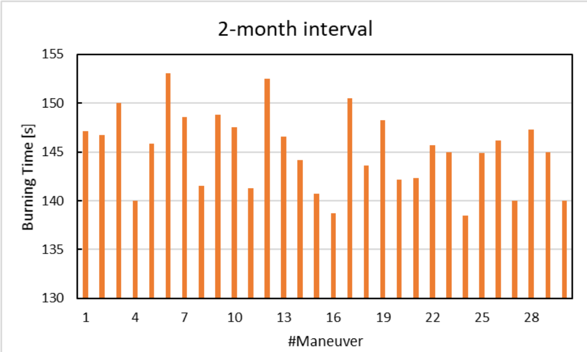

Figure 3-3: Burning times of 2-month interval maneuver.

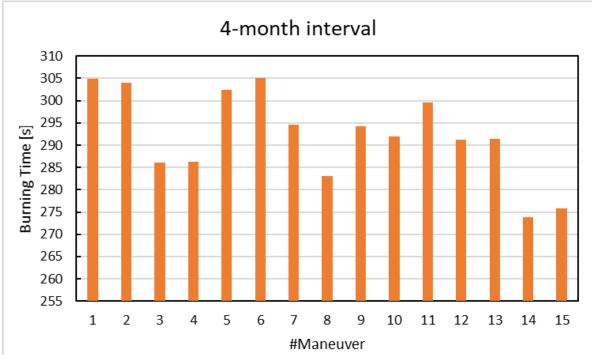

Figure 3-4: Burning times of 4-month interval maneuver.

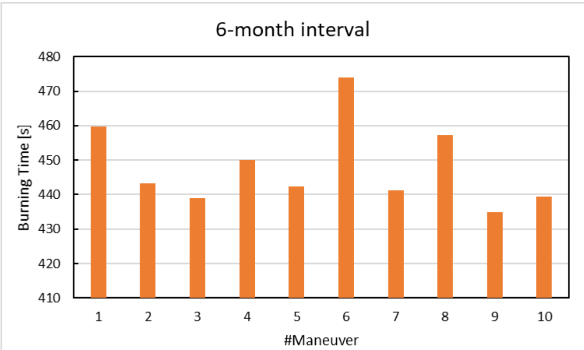

Figure 3-5: Burning times of 6-month interval maneuver.

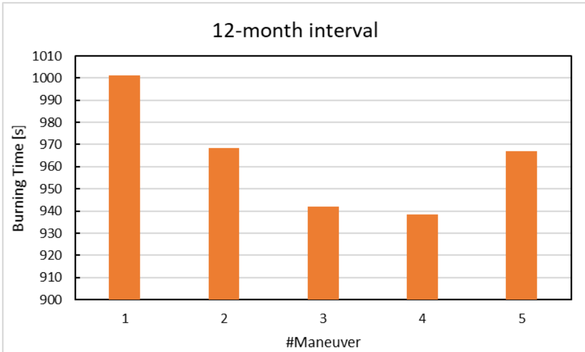

Figure 3-6: Burning times of 12-month interval maneuver.

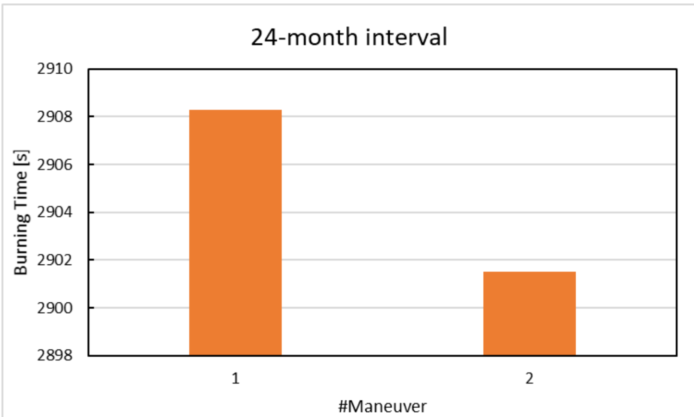

Figure 3-7: Burning times of 24-month interval maneuver.

The required fuels provided in Table 3-2 are the 'worst case' required fuel as the maneuvers are excessive for some alternative maneuver plans ($d\Omega/dt$ becomes lower than 360°/year). If the maneuvers are not excessive, the required fuel will be less. Moreover, in the simulation, the satellite is set to carry fuel with maximum tank capacity as stated in Section 2.1. As the required fuel is less than maximum tank capacity, the satellite could carry less fuel and the maneuver applied would be more effective. In conclusion, the actual required fuel will be less than the required fuel yielded by the simulation.

If we assume that the cost of thruster fuel, LMP-103s, to be 5000 USD/kg, the fuel cost for every alternative maneuver plan is as depicted in Table 3-3. The 2-month maneuver plan gives minimum required fuel compared to other maneuver plans. This alternative maneuver plan is $\frac{3}{4}$ times cheaper than the 24-month maneuver plan which gives the most expensive fuel cost.

Table 3-3: Required Fuel Cost

Maneuver intervals (Months)	Cost (USD)
2	9,445
4	9,501
6	9,720
12	10,450
24	12.605

More fuel to be carried means that the satellite will be heavier. This will affect to launch cost of the satellite. LAPAN-A4 launching will be a secondary payload of CARTOSAT launching from India via PSLV in which the cost depends on satellite mass. Therefore, more fuel to be carried means that the launch cost will be more expensive, especially the launch cost of previous LAPAN satellites are around 15% of the total cost (Paskalis, 2015).

By some considerations, the authors recommend the 2-month maneuver plan to be recommended maneuver plan compared to others. The main consideration is that this maneuver plan gives the cheapest cost either for fuel or launching. This maneuver plan indeed gives a disadvantage as the local time drift resulted is not the smallest. However, as mentioned before, the local time drift resulted is arguably tolerable.

Nevertheless, the 2-month maneuver plan is still not the best compared to all possible maneuver plans. If we watch carefully, the shorter the maneuver interval, the smaller the fuel required. So, maneuver plans with shorter maneuver interval (e.g. 1 month, 20 days, etc.) may give less required fuel and, along with arguably tolerable local time drift, be more optimum than the 2-month maneuver plan. However, in this research, the authors only analyze and choose a recommended maneuver plan from the selected alternatives (i.e. 2-month, 4-month, 6-month, 12-month, and 24-month maneuver plan). Hopefully, further research will be conducted to analyze the most optimum maneuver plan from all possible maneuver plans.

4. Conclusions

The recommended maneuver plan resulted from this research is the 2-month maneuver plan. This maneuver plan gives the lowest cost either for fuel or launching. On the other hand, this maneuver plan does not give the smallest local time drift. However, the local time that occurred in this maneuver plan is arguably tolerable (only 14.2 minutes).

But, this maneuver plan is not the best compared to all other possible maneuver plans. Maneuver plans with lower maneuver intervals may be more optimum than the 2-month one as the fuel required tends to be lower as the maneuver interval becomes shorter. Hopefully, further research will be conducted to analyze the most optimum maneuver plan from all possible maneuver plans. Moreover, the investigation of correction maneuver strategies controlling other parameters other than inclination could also reveal the most optimum correction maneuver in terms of controlled parameters.

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Contributorship Statement

MRZ designed the methodology, developed the simulation, analyzed the results, and prepared the manuscript; REP designed the methodology and analyzed the results.

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