

Analysis of fuel consumption for orbital correction maneuvers to mitigate injection errors after launch

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Abstract – The BiomeSat mission satellite, which is being developed by the National Institute for Space Research (INPE), consists of a remote sensing nanosatellite, CubeSat type, in the 12 kg class, with a dimension of 6U. The objective of the mission is to collect radiometric data from Brazilian territory in the visible and near-infrared bands of the electromagnetic spectrum. In addition, the satellite must be capable of receiving transmissions from environmental data collection platforms and information about vessels that use the AIS system. To ensure mission success, preliminary studies must be carried out carefully. Among them, we can highlight the studies presented in this paper, which define the possibilities of transfer and correction maneuvers necessary to transfer the satellite from the orbit into which it was injected by the launcher to the nominal orbit, as well as an analysis of the fuel budget necessary to perform such maneuvers in Launch and Early Orbit Phase (LEOP) operations.

Keywords – BiomeSat mission, AOCS, Orbital maneuver, Fuel budget.

I. INTRODUCTION

The National Institute for Space Research (INPE) is currently working on the BiomeSat mission. This time, the studies and work are focused on a remote sensing nanosatellite, a CubeSat type, in the 12 kg class, with a dimension of 6U, with the objective of collecting radiometric data of the Brazilian territory in the visible and near-infrared bands of the electromagnetic spectrum. In addition, the satellite must be capable of receiving transmissions from environmental data collection platforms and information about vessels that use the AIS system.

The development of the satellite considers the designs of the various subsystems that compose it, including the Attitude and Orbit Control System (AOCS) subsystem, responsible for controlling the satellite's orbit and attitude. A

distinctive feature of the BiomeSat mission satellite is that it has a thruster, measuring 0.8 U and a total impulse of 450 Ns.

The problems to be faced and analyzed by the AOCS subsystem are numerous and varied. We can highlight the study presented by [1], who proposed an algorithm to estimate and correct the three most common errors in sensor measurements: bias, misalignment, and non-orthogonality. Another interesting study involving problems to be analyzed and faced by the AOCS subsystem can be found in [2], in which they analyzed the impact of a thruster's PWM parameters in the non-latching flexible booms dynamics, motivated by the ITASAT-2 mission. Focusing on the problem of a CubeSat flight formation, [3], also motivated by the ITASAT-2 mission, evaluated simulation and movement control techniques to verify and evaluate the behavior of the following vehicles using different phase angles in detachment and rendezvous maneuvers in relation to the movement of the chief CubeSat. Independent of the central body, orbital maneuvers to be performed by the AOCS subsystem may be necessary. In [4] we see a discussion about changing the orbital plane using swing-by maneuvers for an artificial satellite around the Moon.

Thus, with the aim of contributing to the preliminary studies to be carried out for the BiomeSat mission, and with the studies and analyses involving the application of small satellites, the present work proposes to analyze the possibilities of maneuvers that transfer the satellite from the orbit in which it was injected by the launcher, to the nominal orbit. Since fuel is an important and limiting factor in space missions, an analysis of the fuel budget needed to perform the correction and transfer maneuvers is also necessary.

As with any space mission, preliminary studies must be carried out. Among them, we can highlight the analysis of the possibilities of maneuvers that transfer the satellite from the orbit in which it was injected by the launcher, to the nominal orbit. Since fuel is an important and limiting factor in space missions, an analysis of the fuel budget needed to perform the correction and transfer maneuvers is also necessary.

It has already been defined that the orbit of the BiomeSat mission satellite will be sun-synchronous and frozen. There are several possibilities of orbits with combinations of semi-major axis, eccentricity and inclination that meet this requirement. However, in this work, to estimate the fuel

consumption of the Launch and Early Orbit Phase (LEOP) operations, a nominal circular orbit with an altitude of 600 km will be considered. Since the launcher of the BiomeSat mission has not yet been defined, possibilities of injection orbits are adopted and, from them, correction limits are established for the orbital elements, depending on the capacity of the fuel tank, and the orbital requirements already defined for the mission.

II. METHODS

The methods used to calculate correction and transfer maneuvers, as well as the fuel consumption to perform each of them, will be presented below.

A. Correction and transfer maneuvers

One of the most common and efficient maneuvers in orbital mechanics is the Hohmann maneuver, presented in Figure 1. This maneuver can be used to correct the semi-major axis, in which, from an insertion orbit, the transfer to the final orbit is made using two impulses.

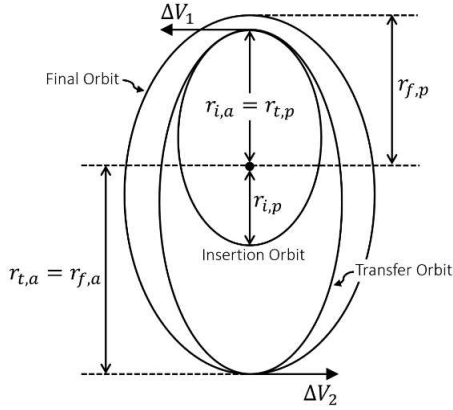


Fig. 1. Configuration of the Hohmann maneuver for the LEOP semi-major axis correction stage.

The first impulse, ΔV_1 , creates the so-called transfer orbit and the second impulse, ΔV_2 , regularizes the transfer orbit to the final orbit. In the presented case, the perigee of the final orbit ($r_{n,p}$) is aligned with the apogee of the insertion orbit ($r_{i,a}$), therefore, the apogee of the final orbit ($r_{n,a}$) is aligned with the perigee of the insertion orbit ($r_{i,p}$). The transfer orbit to be created by the ΔV_1 given in $r_{i,a}$, will have its perigee ($r_{t,p}$) equal to $r_{i,a}$, and its apogee ($r_{t,a}$) equal to $r_{n,a}$. Finally, ΔV_2 will be given in $r_{t,a}$ to complete the maneuver, reaching the final orbit. The impulse ΔV_1 , given by the difference between the velocities at $r_{t,p}$ ($V_{t,p}$) and $r_{i,a}$ ($V_{i,a}$) defined by the vis-viva equation, is given by (1) [5]:

$$\Delta V_1 = V_{t,p} - V_{i,a} = \sqrt{\mu} \left(\sqrt{\frac{2}{r_{t,p}} - \frac{1}{\left(\frac{r_{t,a} + r_{t,p}}{2}\right)}} - \sqrt{\frac{2}{r_{i,a}} - \frac{1}{\left(\frac{r_{i,a} + r_{i,p}}{2}\right)}} \right) \quad (1)$$

where, μ , the Earth's gravitational parameter, is equal to $3.9860064 \times 10^{14} \text{ m}^3/\text{s}^2$.

The impulse ΔV_2 , given by the difference between the velocities at $r_{t,a}$ ($V_{t,a}$) and $r_{f,a}$ ($V_{f,a}$) defined by the vis-viva equation, is given by (2):

$$\Delta V_2 = V_{f,a} - V_{t,a} = \sqrt{\mu} \left(\sqrt{\frac{2}{r_{f,a}} - \frac{1}{\left(\frac{r_{f,a} + r_{f,p}}{2}\right)}} - \sqrt{\frac{2}{r_{t,a}} - \frac{1}{\left(\frac{r_{t,a} + r_{t,p}}{2}\right)}} \right) \quad (2)$$

The total velocity increment of the semi-major axis correction phase, ΔV_h , is given by (3):

$$\Delta V_h = \Delta V_1 + \Delta V_2 \quad (3)$$

The inclination correction maneuver (Δi) will be performed by using an impulse (ΔV_3) to be given in the direction perpendicular to the plane of the nominal orbit at the moment the satellite passes through the intersection with the final orbit, resulting from the Hohmann maneuver phase described above. In order to simplify the problem, and considering the low eccentricity of the final orbit, we will consider the orbit as circular. Thus, the impulse (ΔV_3) is given by (4):

$$\Delta V_3 = 2v \sin\left(\frac{\Delta i}{2}\right) \quad (4)$$

The total velocity increment, ΔV_t , for the LEOP phase is given by:

$$\Delta V_t = \Delta V_1 + \Delta V_2 + \Delta V_3 \quad (5)$$

In a space mission, the satellite passes through different orbits, since in most cases it is not injected by the launcher exactly into the nominal orbit. In addition, adjustments may be necessary, and, whether small or large, every change requires energy.

B. Fuel Budget

As mentioned in Section A, the total velocity variation, ΔV_T , of a mission is the sum of all velocity changes that are transmitted to the satellite throughout the mission. Thus, with the total velocity variation, or the total velocity increment, ΔV_T , the propellant cost to be spent throughout the orbital maneuvers can be obtained, since there is a direct correlation between the velocity increment and the fuel consumption.

For a preliminary study, we can estimate the propellant mass, m_p , required to apply all velocity increments using the rocket equation, given by [6]:

$$m = m_0 e^{(\Delta V_T / I_{sp} g)} \quad (6)$$

where m_0 is the dry mass of the satellite, ΔV_T the total velocity increment applied to the satellite, $I_{sp} = \frac{V_0}{g}$ the specific impulse, with V_0 being the thruster exhaust velocity, and g the acceleration of Earth's gravity at the surface.

III. RESULTS AND DISCUSSIONS

The results and discussions regarding the possibilities of maneuvers to correct and transfer the satellite from the orbit into which it was injected by the launcher to the nominal orbit will be presented below.

Figures 2, 3 and 4 present a generic study of the variation in the velocity increment required to perform the maneuvers, in which the altitude varies between 500 km and 700 km, considering a semi-major axis error of -20 km, an inclination error of 0.2 degrees and an eccentricity error of 0.005. Figure 1 presents the results obtained for the velocity increments related to the first and second impulses of the Hohmann transfer added together ($\Delta V_1 + \Delta V_2$), situation in which coplanar maneuvers are performed to adjust the semi-major axis and eccentricity of the orbit. Figure 2 presents the results obtained for the non-coplanar maneuver to adjust the orbital inclination (ΔV_3) and Figure 3 presents the results for the velocity increments of all maneuvers, coplanar and non-coplanar, added together (ΔV_T).

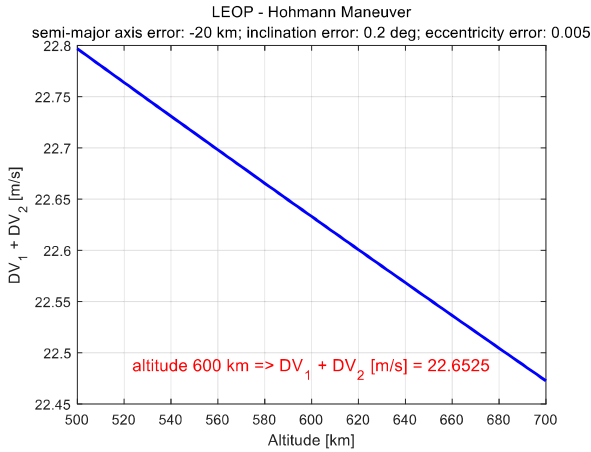


Fig. 2. Velocity increment of the first two maneuvers ($\Delta V_1 + \Delta V_2$).

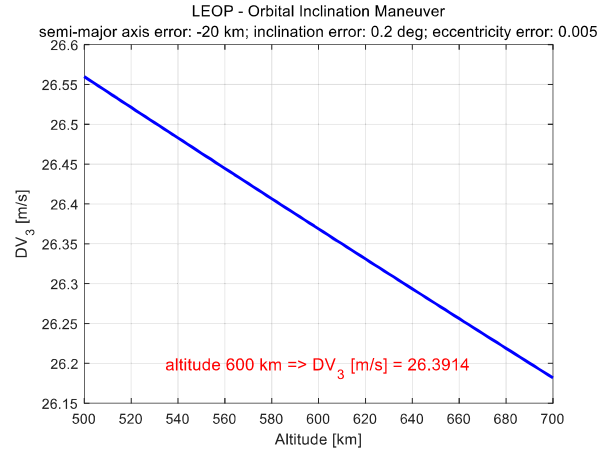


Fig. 3. Velocity increment of the third maneuver (ΔV_3).

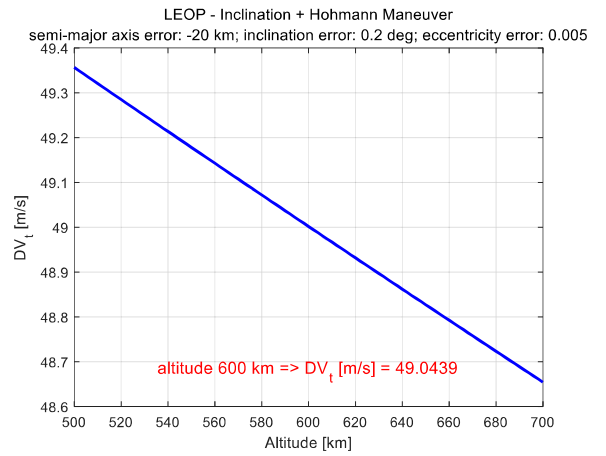


Fig. 4. Total velocity increment (ΔV_T).

From this study, the satellite altitude is restricted to around 600 km, with an error of 20 km below and 20 km above, for an analysis of fuel budget as a function of the error of the semi-major axis, the error of the injection eccentricity and the injection inclination, from the application of the Hohmann maneuver and the inclination adjustment maneuver, respectively. The results are presented in Figures 4 to 8.

Figure 5 shows the fuel budget for performing the Hohmann maneuver considering the injection error in the semi-major axis and in the eccentricity. From a numerical analysis, it was concluded that, for this case, the maximum velocity increment is 22.6655 m/s, resulting in a maximum fuel budget of 0.1122 kg. The fuel consumption for the inclination adjustment maneuver is shown in Figure 6, requiring a maximum velocity increment of 26.3687 m/s to perform the maneuver, with a maximum fuel budget of 0.1292 kg. The velocity increment and fuel budget required to perform the Hohmann and orbital inclination adjustment maneuvers, are shown in Figure 7, with a maximum velocity increment of 49.0343 m/s and a fuel mass of 0.2414 kg.

The results presented in Figure 7 represent a fuel budget greater than the fuel tank capacity of the propellant found on the market for satellites in the BiomeSat type category. Therefore, it became interesting to restrict the requirement for

injection error in orbit by the launcher. This scenario is presented in Figure 8, with an eccentricity error of 0.004 and an inclination error of 0.1 degrees. The results show a more suitable situation, with a fuel budget of 0.1585 kg. However, since this consumption would be spent only in LEOP, the remaining fuel may be small or not sufficient for routine orbital maintenance maneuvers. Even in a more favorable scenario, it is still interesting that less fuel is spent in LEOP, so that the satellite has a longer useful life and has enough fuel for any necessary deviation, or even for de-orbit.

Therefore, Figure 9 presents another case, with an eccentricity error of 0.0025 and an inclination of 0.1 degrees, with a maximum velocity increment of 26.4116 m/s and fuel budget of 0.1307 kg. It is worth remembering that the greatest fuel expenditure is for changing the orbital inclination and, in the case of Figure 8 and Figure 9, the error in the inclination was maintained. A restriction on the requirement for the maximum orbital inclination error that the launcher can inject the satellite into orbit could bring even more significant savings in the fuel consumption.

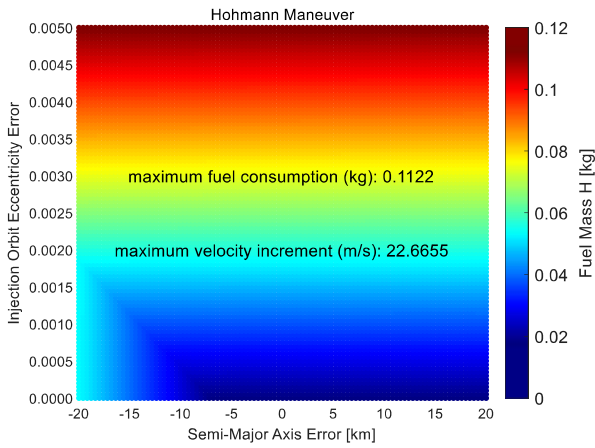


Fig. 5. Fuel budget for Hohmann maneuver.

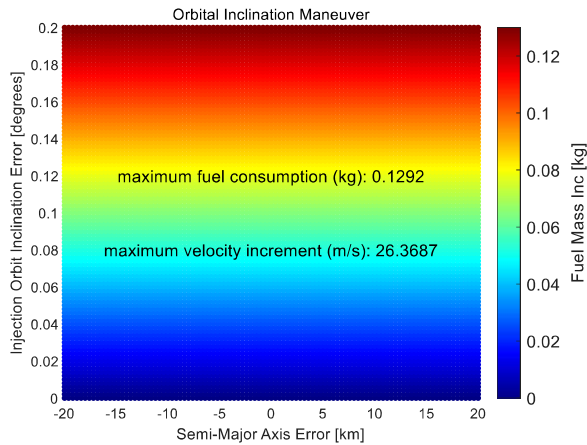


Fig. 6. Fuel budget for inclination maneuver.

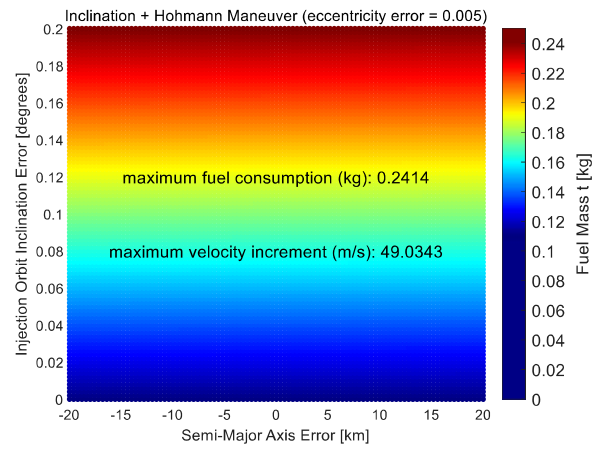


Fig. 7. Fuel budget for Hohmann and inclination maneuver ($e = 0.005$).

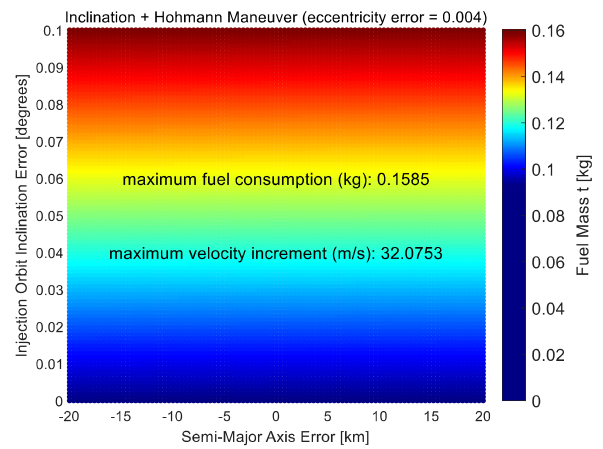


Fig. 8. Fuel budget for Hohmann and inclination maneuver ($e = 0.004$).

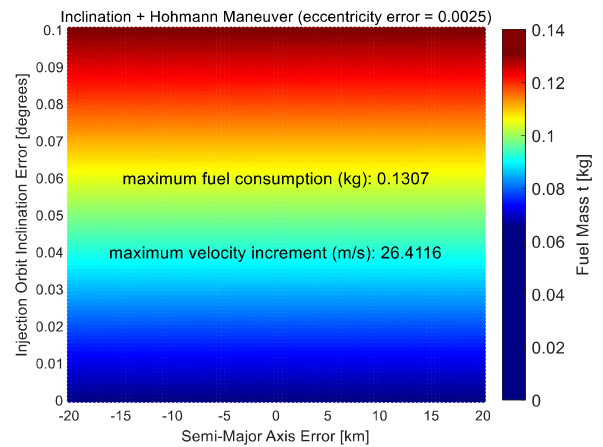


Fig. 9. Fuel budget for Hohmann and inclination maneuver ($e = 0.0025$).

CONCLUSIONS

The design of a space mission requires preliminary studies and analyses that define the scenario in which the project is

inserted, presenting important needs and limitations that must be taken into consideration to guarantee the success of the mission.

With the aim of contributing to such studies and analyses, the present work presents possibilities of correction and transfer maneuvers, with the aim of correcting the semi-major axis and the eccentricity of the satellite, and orbital inclination adjustment maneuvers.

The first results found showed the possibility of maneuvers whose fuel budget could exceed the tank capacity of satellites in the BiomeSat type category. Therefore, the results were refined and new results were obtained, restricting the possibilities in which the fuel budget in LEOP remains within the tank capacity, and still prioritizing a leftover in the fuel for margin of error, guaranteeing a longer useful life, any deviation that may be necessary during the mission, or even for carrying out the de-orbit.

The results presented are in agreement with the theory, showing that inclination change maneuvers are those that require the highest fuel consumption, bringing a need for attention to the type of maneuver. Minimizing the need for this type of maneuver can bring significant savings in fuel budget, increasing the chances of mission success.

Finally, it is worth highlighting that a good choice of launcher is essential for the success of the mission, since this criterion directly impacts the need to carry out transfer and correction maneuvers.

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