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EVALUATION OF A SPACECRAFT TRAJECTORY DEVIATION DUE TO THE LUNAR ALBEDO

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Abstract. *This work presents a study evaluating the influence of the lunar albedo in the satellite orbit. It was used a perturbation model based on the reflectivity of the Moon surface. Due to the variation of the reflectivity of the lunar soil, the moon surface was divided into cells allowing studying the behavior of incident light in each cell. The model provides the velocity increment applied to the satellite due to the force caused by the lunar albedo. The orbital motion of the satellite and some orbital correction maneuvers were simulated considering the albedo disturbance and using continuous thrust to control the trajectory. Studies were performed with success, evaluating the behavior of all orbital elements over time. The fuel consumption and the applied thrust utilized to correct the trajectory were estimated.*

Keywords: *Lunar albedo, orbital correction, keplerian elements, continuous thrust*

1. INTRODUCTION

The light that reaches the surface of a satellite can be reflected or absorbed. This light energy causes a change in the momentum of the satellite, altering its trajectory.

The incident solar radiation directly on the satellite or the solar radiation diffusely reflected by the surface of the Moon, the lunar albedo, are the main sources of radiation capable to modify the satellite orbital elements. Although the source of these forces is the Sun light, there is considerable difference in their mathematical formulation, so it is necessary to treat them separately. Thus, in this paper only the perturbation due to the lunar albedo was considered.

In this study the lunar albedo was implemented based on the model for the terrestrial albedo presented in Rocco (2008a, 2009a). The model provides the velocity increment applied to the satellite due to the force caused by the lunar albedo.

Two cases were analyzed: the lunar satellite at an altitude of 15 km; and lunar satellite at an altitude of 115 km. The simulations were performed using the Spacecraft Trajectory Simulator-STRS, Rocco (2008b), which evaluate the behavior of orbital elements, the light power incident on the satellite, the fuel consumption necessary to minimize the effects of the perturbation and the thrust applied on the satellite over time.

2. LUNAR ALBEDO

The lunar albedo is the fraction of solar energy reflected diffusely from the lunar surface into space, measured from the surface reflectivity of the Moon. Then:

$$albedo = \frac{radiation\ reflected\ to\ the\ space}{incident\ radiation} \tag{1}$$

The possible values for the lunar albedo can range from 0 (completely opaque) to 1 (fully bright) and depend of the surface conditions.

The albedo effect of the artificial satellite can vary depending on some factors: the satellite position, the satellite attitude, and the optical properties of the satellite surface.

The solar radiation includes all electromagnetic waves emitted by the Sun. The radiation incident with a right angle in an area of 1 m² at a distance of 1 AU (149 598 200 ± 500 km) is 1371 ± 5 W / m², which is known as the solar constant (Stark, 1994). The solar radiation of a distance d is given by:

$$J_S = \frac{P}{4\,\pi\, d^2} \tag{2}$$

where P is the total energy emitted by the sun (3.8 x 10^{25} W) and d is the distance from the satellite to the Sun.

The reflectivity of each point of the Moon surface is calculated by measuring the amount of radiation received by the satellite, given by:

$$E_C = \frac{\rho\, f}{1 - S\,\rho}\, E_{AM0} \tag{3}$$

where: ρ is the reflectivity of the reflector surface; f is the fraction of the reflected radiation that reaches the satellite; S is the fraction of the reflected radiation scattered back to the surface reflective; E_{AM0} is the amount of the radiation that reaches the reflective surface.

Considering that Moon does not have atmosphere $f = 1$ and $S = 0$. Thus, for the Moon case, the Eq. (3) reduces to:

$$E_C = \rho\, E_{AM0} \tag{4}$$

The incident solar radiation E_{AM0} reaches the Moon surface with an angle of incidence ϕ_{in}. An amount of radiant flux E_C reflected with an angle ϕ_{ref}, that depends on the characteristics of the lunar surface, reaches the surface of the satellite, as seen in Fig. 1.

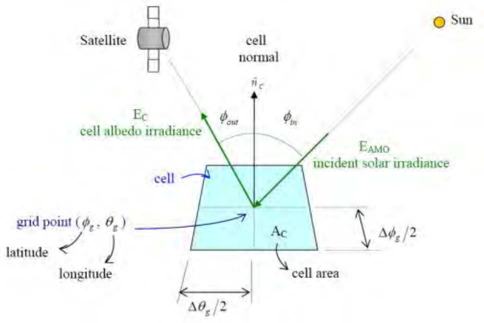

Figure 1. Solar radiation reflected by the lunar surface
Source: Rocco (2008a)

3. MODELING THE PERTURBATION DUE TO THE LUNAR ALBEDO

The model of the perturbation caused by the lunar albedo was based on the reflectivity of the Moon surface.

Due to the variation of the reflectivity of the lunar soil, the moon surface was divided into cells allowing studying the behavior of incident light in each cell. The incident light on the Moon reflected by each cell is used to calculate the total flux incident on the satellite surface. Such radiation on the satellite is calculated using as base the model developed by Rocco (2008a, 2009 and 2010), who studied the behavior of the terrestrial albedo.

The amount of cells, and also the dimensions of the cells, can vary from one cell and the maximum of 51840 cells. Taking into account the maximum number of cells, the dimension of each is 1.25 degree of longitude and one degree of latitude.

To consider the effect on the satellite orbit due to the solar radiation reflected on the Moon surface, it is necessary to know the positions of the Sun, Moon and the satellite, whose movement was modeled and inserted in the simulator.

For each cell is assigned a value for reflectivity: 1 represents the complete reflection of the incident light and 0 represents the total absorption, in other words, white cells receives values near to 1 and the black cell receives values near to 0.

Thus, initially it is made a analysis of the Moon image, in a way that for each division is assigned values for the reflectivity, but first it is necessary to convert the image to a degree of gray. Then a calibration is done in the image brightness so that the value of the average of the reflectivity is coincident with to the medium albedo of the Moon, which is 0.12.

In the present study some cases were treated in which the lunar surface was divided in 1, 12, 160, 240, 360, 416, 504, 640, 792, 1025, 1440, 2052, 3240, 5760, 12960 and 51840 cells.

4. EFFECT OF LUNAR ALBEDO ON THE SATELLITE TRAJECTORY

The Fig. 2 shows the reflectivity of the Moon surface.

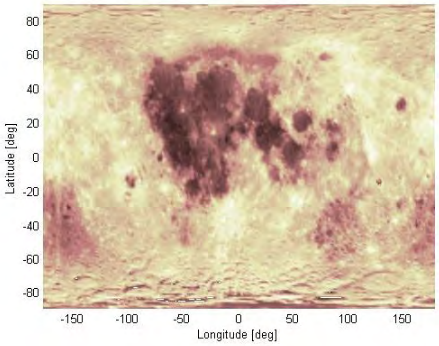

Figure 2 Lunar reflectivity (image in 2 dimensions)

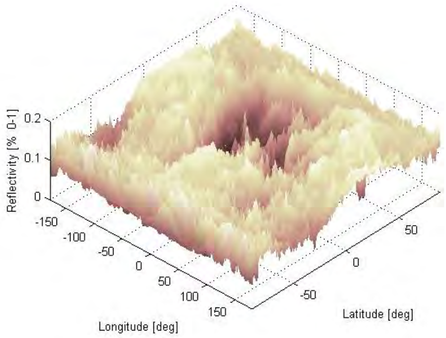

Figure 3 Lunar reflectivity (image in 3 dimensions)

The Fig. 2 and 3 shows the matrix of the Moon reflectivity in function of the latitude and longitude. Due the inexistence of Moon atmosphere, the value of the albedo for each cell remains constant, ensuring that the matrix reflectivity is not changed.

The Fig. 4 and 5 show the albedo of all the lunar surface.

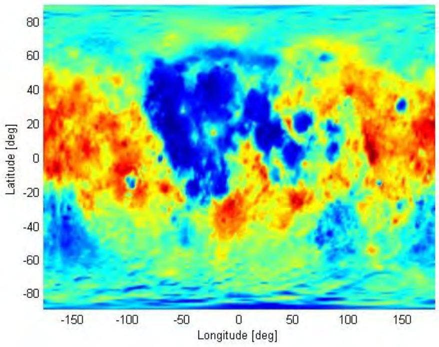

Figure 4 Lunar albedo to 15 km of altitude (image in 2 dimensions)

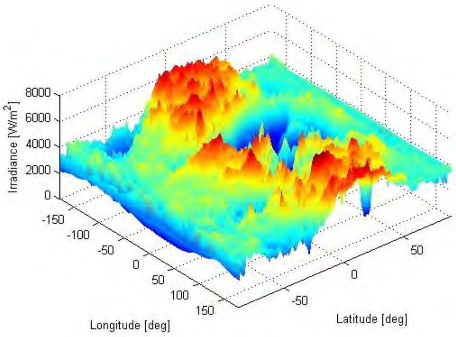

Figure 5 Lunar albedo to 15 km of altitude (image in 3 dimensions)

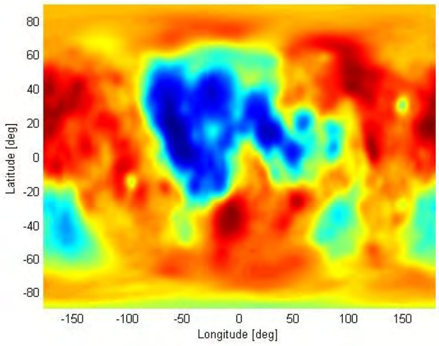

Figura 6 Lunar albedo to 115 km of altitude (image in 2 dimensions)

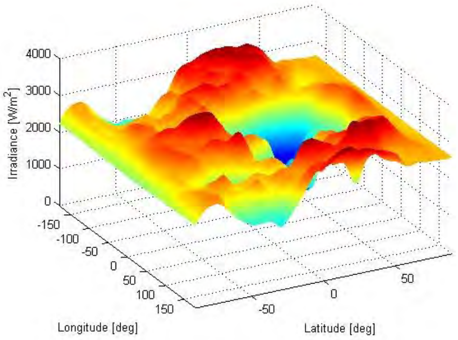

Figura 7 Lunar albedo to 115 km of altitude (image in 3 dimensions)

The Fig. 4, 5, 6 and 7 show the light power in W/m², reflected by the lunar surface in a hypothetical situation in which the Moon is full illuminated, as if the Sun could remain on the zenith of each cell. If it were possible to place a vehicle over each cell, we could analyze which is the maximum energy, due to the lunar albedo, that the vehicle would be subject. We can see this situation for an altitude of 15 km in the Fig. 4 and 5, and for an altitude of 115 km in the Fig. 6 and 7.

We can see, from Fig. 5 and 7, a significant difference in the radiation power when it is considered different altitudes. When the altitude is 15 km the maximum radiation power almost reach 7000 W/m² and for 115 km the radiation power is 3500 W/m². It also can be seen that for 115 km the figure has soft peaks, the increase of altitude allows to merge the effect of adjacent cells.

The Fig. 8 to 19 show the increase in the velocity due to the albedo force applied on an artificial lunar satellite when adopted 12, 160, 504, 1025, 12960 and 51840 cells, in the altitude of 15 km, regular feature of some mapping lunar missions, and in the 115 km, altitude common to lunar orbit satellites.

All cases were simulated for 14400 s, with the following initial conditions: semi-major axis: 1800000 m; eccentricity: 0.001, inclination: 45°, right ascension of the ascending node: 20°; argument periapsis: 100°; mean anomaly: 1°.

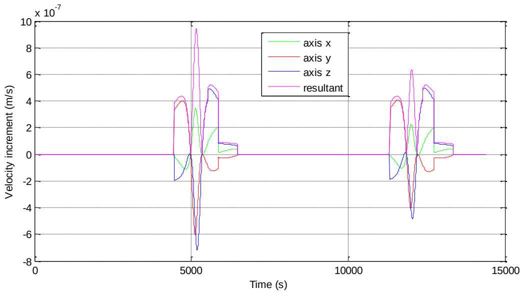

Figure 8 – Lunar albedo considering 12 cells at 15 km altitude

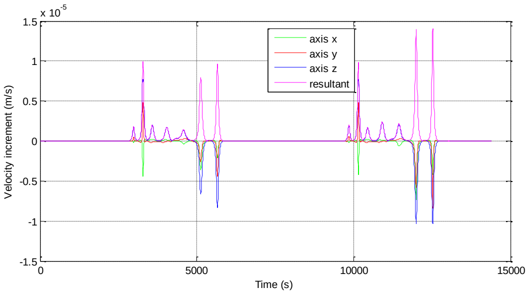

Figure 9 – Lunar albedo considering 160 cells at 15 km altitude

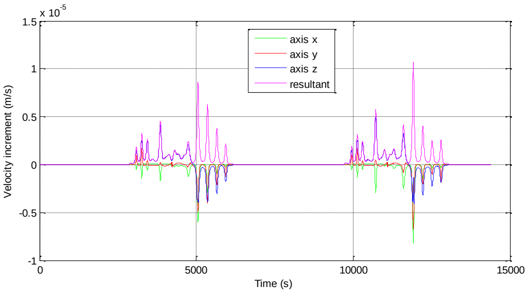

Figure 10 – Lunar albedo considering 504 cells at 15 km altitude

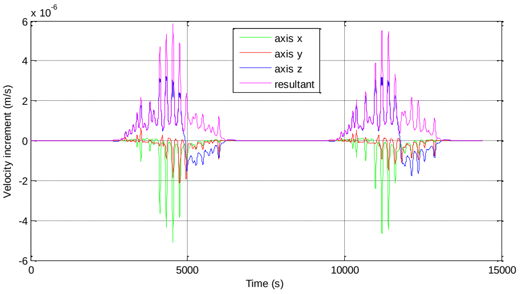

Figure 11 – Lunar albedo considering 1025 cells at 15 km altitude

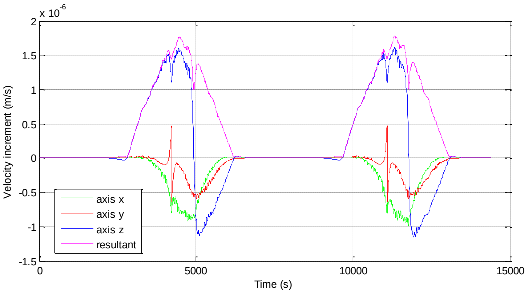

Figure 12 – Lunar albedo considering 12960 cells at 15 km altitude

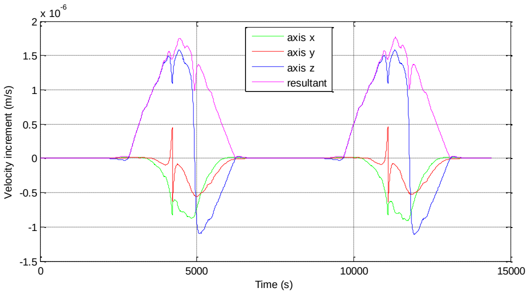

Figure 13 – Lunar albedo considering 51840 cells at 15 km altitude

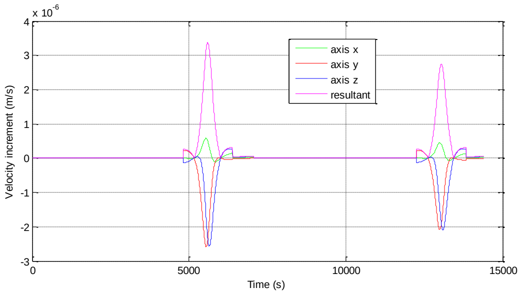

Figure 14 – Lunar albedo considering 12 cells at 115 km altitude

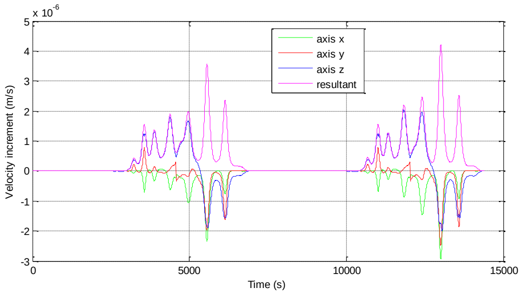

Figure 15 – Lunar albedo considering 160 cells at 115 km altitude

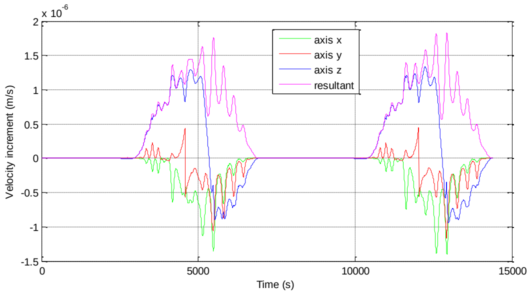

Figure 16 – Lunar albedo considering 504 cells at 115 km altitude

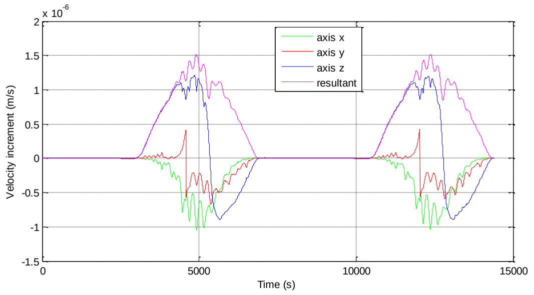

Figure 17 – Lunar albedo considering 1025 cells at 115 km altitude

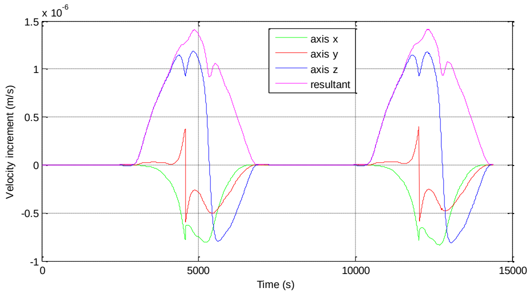

Figure 18 – Lunar albedo considering 12960 cells at 115 km altitude

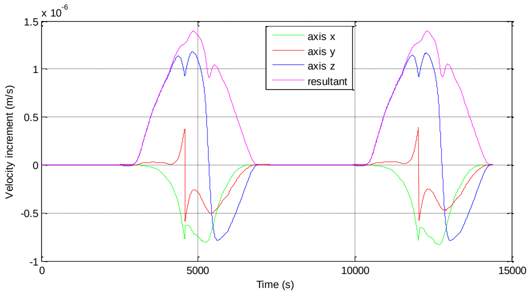

Figure 19 – Lunar albedo considering 51840 cells at 115 km altitude

From previous studies using one cell and by the Fig. 8 and 14, it is notice that the result obtained for 12 cells is similar to the result for the average of the albedo. Thus, the use of 12 cells does not ensure a good approximation of the lunar surface.

From the Fig. 9 to 13 we conclude that increasing the amount of cells implies in increasing the amount and intensity of peaks on the curve obtained for the albedo in function of the time. The Fig. 17 to 19 show that the peaks existing in the curve of the albedo in function of time tend to smooth out with the increasing the number of cells in which the Moon is divided. Increasing the number of cells implies increasing the accuracy of the model, so, with more cells is smaller the size of each cell and also lower the chance of error with respect to the real Moon surface reflectivity.

Thus, despite the intensity of radiation on the satellite for 115 km is smaller, the satellite remains longer time illuminated and, consequently, receiving more radiation reflected from the surface of the Moon.

5. SIMULATIONS AND RESULTS

The results of simulations 1 and 2 are presented in Fig. 20 to 31 considering the perturbation due to the lunar albedo, during 86400 seconds, using the reflectivity array of 51840 elements. Were used the following initial conditions: semi-major axis of 1800000 m for the simulation 1 and 1900000 m for the simulation 2. For both simulations, eccentricity 0.001, inclination 45°, right ascension of the ascending node 20°, periapsis argument 100º and mean anomaly 1°.

During the simulations were performed correction maneuvers and analyzed the behavior of the orbital elements due to lunar albedo, the consumption of propellant used in the maneuver and the thrust applied on the satellite.

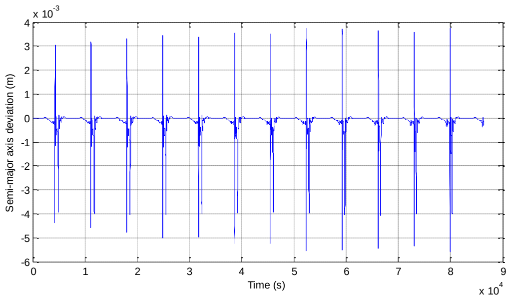

Figure 20 – Semi-major axis deviation during the simulation 1

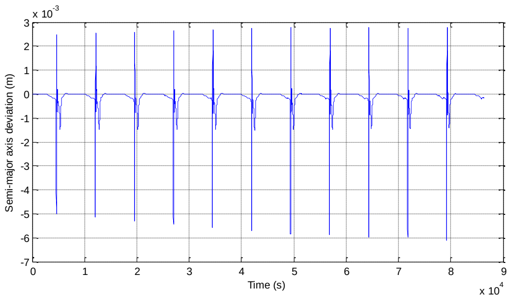

Figure 21 – Semi-major axis deviation during the simulation 2

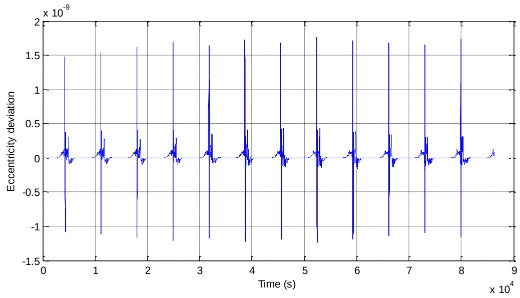

Figure 22 – Eccentricity deviation during the simulation 1

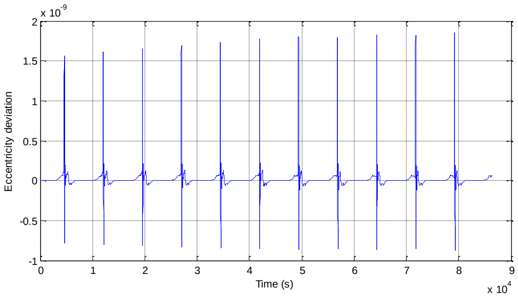

Figure 23 – Eccentricity deviation during the simulation 2

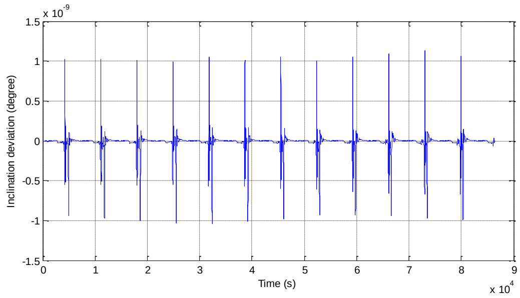

Figure 24 – Inclination deviation during the simulation 1

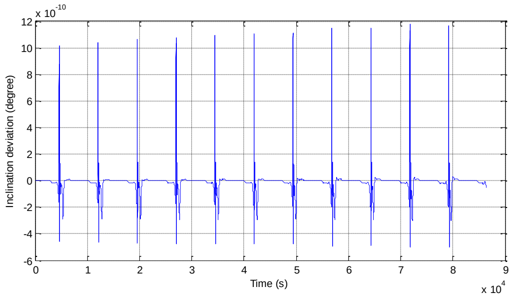

Figure 25 – Inclination deviation during the simulation 2

The Fig. 20 to 25 show that the lunar albedo force cause small deviations in the orbital elements. Such deviations occur more intensely when the satellite crosses an area of larger lighting due to the lunar reflection, but tend to be stabilized with the performance of the control system. We can also observe that the action of the control system is more pronounced for simulation 1, since the intensity of radiation on the satellite is considerable.

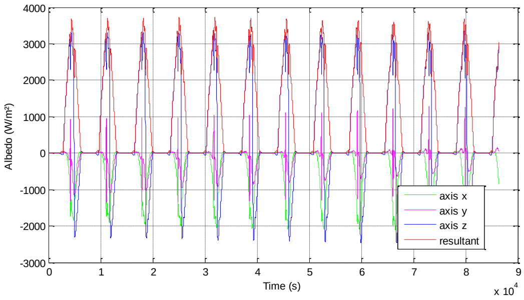

Figure 26 – Light power incident on the satellite during simulation 1

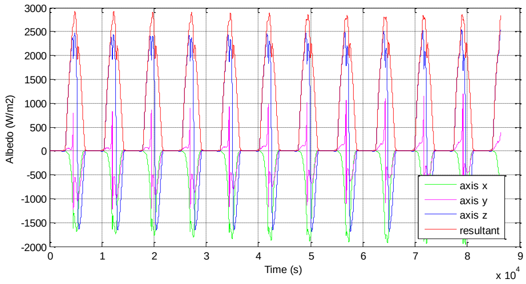

Figure 27 – Light power incident on the satellite during simulation 2

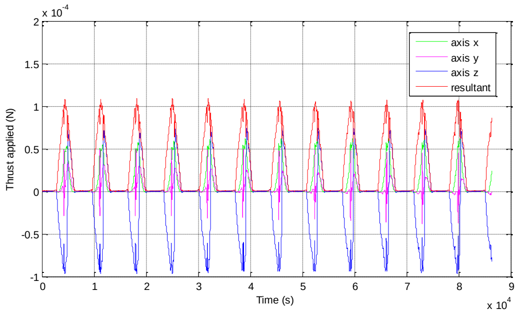

Figure 28 – Thrust applied on the satellite during simulation 1

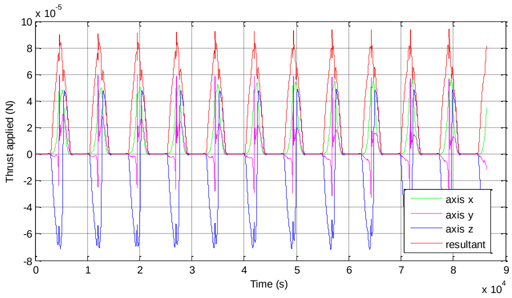

Figure 29 – Thrust applied on the satellite during simulation 2

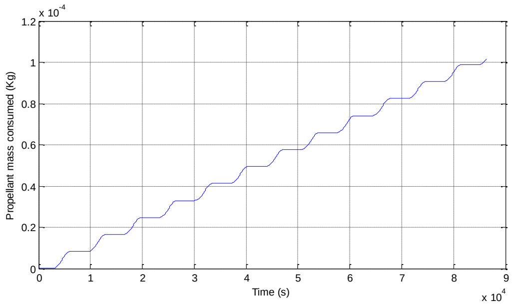

Figure 30 – Propellant mass consumed during simulation 1

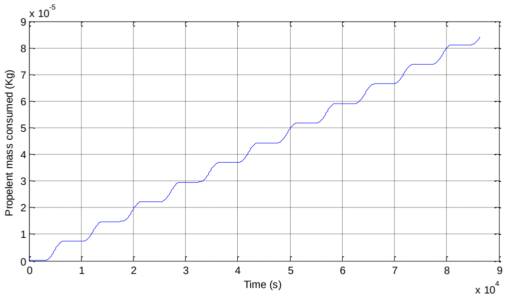

Figure 31 – Propellant mass consumed during simulation 2

The Fig. 26 and 27 show the intensity of radiation incident on the satellite in the two simulations. We note that the intensity of radiation of the satellite decreases with the increasing of the altitude. The maximum value of the incident light for 15 km of altitude is 3500 W/m², while for 115 km is less than 3000 W/m². We can also observe from Fig. 26 and 27 that there are some peaks of lighting on the satellite which contrasts with intervals when the satellite passes through a region of null albedo. The difference of incidence radiation found in both cases influences the thrust applied to the satellite, resulting in the velocity increment, and, consequently, the fuel consumption, as can be seen in Fig. 28 to 31.

The Fig. 32 and 33 show similar results of the effect of the albedo on the trajectory of a satellite, but using the Earth albedo model (Rocco 2008a, 2009), for a entire day. The figures show the deviation in the position and velocity of the satellite, without orbital correction, enhancing the importance of the trajectory control system, since without the correction on the trajectory, the deviation of the position and velocity increase significantly over time which could jeopardize the mission accomplishment. The behavior of a lunar satellite is similar and, again, the trajectory control system is very important to the mission accomplishment.

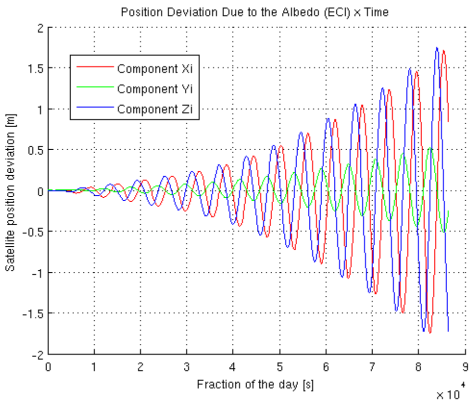

Figure 32 – Position deviation for the entire Day (GB-B)
Source: Rocco (2008a)

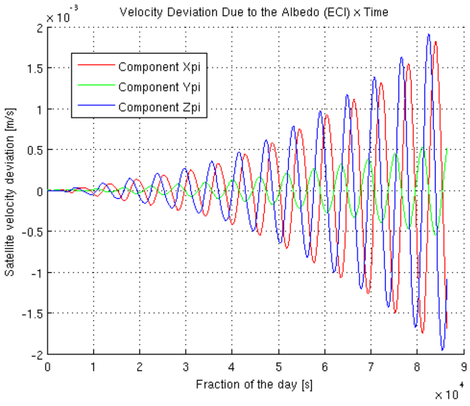

Figure 33 - Position deviation for the entire Day (GB-B)
Source: Rocco (2008a)

From the Fig. 32 and 33, we can see that the deviations in the position and velocity of the satellite tend to increase along of the time. Therefore the performance of the orbital control for artificial lunar satellites subject to perturbation due to the albedo could be necessary.

6. CONCLUSIONS

We can observe that the deviations in the state variables were always small, in other words, the control system was able to reduce the error in the state variables by the action of the thrusters. The Fig. 26 and 27 show that the intensity of light power due to the lunar albedo when the satellite is at an altitude of 15 km is greater than when it is at an altitude of 115 km. However, we realize that the effect caused by lunar albedo in the orbital elements is bigger when the satellite is at an altitude of 115 km. From this situation, we can conclude that the satellite positioned at lower altitudes does not ensure a larger intensity of incident radiation, featuring a greater variation in the orbital elements.

Since the total incident radiation on the satellite is the sum of all radiation reflected from the lunar surface, a higher altitude allows that the satellite be visible from a larger number of cells. Therefore, in this case, the satellite receives more reflected light from the Moon. However, as higher the altitude of the satellite less will be the light intensity from each cell. But adding all the light that reaches the satellite may result in considerable variation in orbital elements. Furthermore, at high altitudes the effect of a force becomes more remarkable in the Keplerian elements than at lower altitudes. Therefore, in the examples studied the effect of albedo to 115 km of altitude was more pronounced when compared with an altitude orbit average of 15 km.

The results show that the variation of orbital elements due to the effect of lunar albedo on the satellite is relatively small. However, the simulation time considered in this work is not the real time of a mission of an artificial satellite. In Rocco (2008a, 2009) were shown cases of missions around the Earth, Gravity Probe B (NASA), Microscope (CNES) and Step (ESA) and found the evolution of the orbital elements due to the albedo. It was verified that if it was not used a control system capable of correcting the trajectory deviations due to the albedo, would be impossible to realize such missions successfully. Thus, this perturbation can become relevant, depending of the type of mission to be performed.

7. ACKNOWLEDGMENTS

This work was supported in part by FAPESP, CNPq and CAPES.

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