ORBIT PROPAGATION AND DECAY IN CUBESATS IMPLEMENTING ROTATIONAL ATTITUDE AND VARIATIONS IN DRAG COEFFICIENT

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Abstract. *It is estimated that more than 18,000 objects are in orbit around the Earth, with a total mass above to 7.000,000 kg. These numbers consider only objects with dimensions above to 10 cm and, most of them non-operational and without control (debris). The debris represent a hazard to operational satellites and aerospace operations due to the increase in the collisions probability. Since 2000, the development of CubeSat missions are increasing the number of objects in Low Earth Orbits and the number of debris due to the low operational time. Due to the interaction of the CubeSat's with the atmosphere of the Earth, they lose energy and decay. During the de-orbit process, the CubeSats fall into the Earth's atmosphere at hypersonic speeds in rarefied flow and these objects can be destroyed and/or fragmented due to the aerodynamics, thermal and mechanical loads. It is important to obtain the trajectory and attitude of the CubeSats to determine the decay as a function of time. Traditionally, the orbit propagation is estimated from the radar data Two Line Elements - TLE. The propagation of orbit applying analytical solutions into the orbital models to reduce the computational cost and to obtain an approximation of the general orbit, but, in this case, the decay error is around months. To obtain a better accuracy of the CubeSat's decay process, in this case, it is implemented a computational code to integrate the equations of motion including the Drag perturbation to propagate the dynamics and kinematics of 1U, 2U and 3U CubeSat's with and without rotation, that affects the Ballistic Coefficient. A voxel method is implemented to calculate the Drag and Ballistic Coefficients as a function of the CubeSat´s attitude and Spin in the 2D orbital plane. The mathematical model consists of a Runge Kutta F-7/8 numerical integrator, the atmospheric model NRLMSISE-00 and Earth Gravitational Model EGM-08. Results were validated with data from the TLE of historical CubeSat´s missions and other results available in the scientific literature. The results show a good approximation with reported cases of study. New results are generated in the simulations of rotational bodies, due to the influence of aerodynamic forces in the trajectory and the changes in the incident angle with the atmospheric flow. Due to the implementation of the mathematical models and the CubeSat rotation, the decay times are significantly lower in satellites with rotation (Ballistic Coefficient variance) compared with the traditional models with a constant value of Drag Coefficient.*

I. INTRODUCTION

The Cubesat´s missions have the low operational time (weeks to months) compare with other satellites. The operational altitudes that in most of the cases are in LEO, the standard mass and geometry and the available data collected from the TLE´s during the decay process, allow to reduce the uncertainly in the Ballistic Coefficient (B). B is an essential parameter for orbital propagations, Debris mitigation and decay. Some catalogue and studies of the Cubesat´s decaying are presented in Oltrogge and Leveque (2011); Qiao et al. (2013). In the case of satellites in LEO, the forces that influences the movement are the Gravity-two body, Gravity J2, Gravity J4 and atmospheric Drag. The Third-body perturbation by the Sun and Moon and the Solar Radiation Pressure are negligible at altitudes lower than 400 km, (Dell'Elce et. al. 2015). The magnitude of the J4 gravitational perturbation is in same order of the Drag force and is determinant for the satellite decay, it´s influence at lower altitudes accelerates the decay. Many problems are present to determine the Drag force, like the uncertainly in the density value from the atmospheric models, the atmospheric dynamics, variations due to the solar activity, year, month, hour and locations, winds, the attitude of the satellite in the wind direction, the real satellite mass and impact area, the shape-form and others. To solve the Drag problem, estimations of the B from the TLE historical data are presented in Zhejun and Weidong (2017). An estimation of the uncertainly in the atmospheric models for satellite propagations is presented by Vallado and Finkleman (2016) and Emmert et al. (2017). A review of the methods to estimate the coefficient is presented in Prieto et al. (2014). The goal of the present research is to determine the influence of the satellite Spin in the Drag coefficient estimation and the orbit propagations. The CubeSat's configuration is selected to observe the phenomenun, because it is well known the standard geometry and mass of the satellites and the operations are growing (NASA, 2014). With the application of the Drag variations, it is estimated a better estimation of the decay time of future CubeSat's during the debris phase.

II. MATHEMATICAL MODEL

The system is formed by a set of two bodies, the Earth central body (M) and the satellite second body (m) moving in orbits around the center of mass M , because the satellite mass is negligible. The equations of motion are derived from the perturbative satellite problem with the influence of the force derived from the atmospheric – satellite interaction (Drag force, D). The equation of motion of the system is:

$$\ddot{\vec{r}} = \nabla\vec{\mathrm{U}} - \vec{a}_D, \tag{1}$$

Where $\nabla\vec{\mathrm{U}}$ is the Earth´s geopotential and $\vec{a}_D$ is the acceleration due to Drag. The Drag force acts in the direction opposite to the motion of the satellite. Components of the aerodynamics forces are functions of the dynamic pressure ($q = \rho V_\infty^2/2$), because the satellite is travelling in a fluid atmosphere. The density decay as a function of the altitude increment. The satellite is moving around the Earths with an inertial velocity, but in the atmosphere with a relative velocity vector $\vec{V}_\infty$, that includes the Earth´s rotation, the winds and the incident angle of the satellite. To simplify the calculations, it is used the Ballistic Coefficient term, that includes the drag coefficient and the inverse of the spacecraft mass/area ratio ($B = AC_D/2m$) (Vallado & Finkleman, 2016).

III. METHODOLOGY

To determine the influence of the CD variations in the Cubesat´s decay, it was selected four configurations to be analyzed; 1U, 2U, 3U and 6U. For each configuration, the Ballistic Coefficients were calculated, with a mean CD value of 2.2 (Qiao et al. 2013). The spin rate was used to calculate the Ballistic Coefficient as a function of time, implementing in the simulations the B variations. In this case it was selected 0.1 Hz (Nielsen et al. 2014). Generally, the Cubesat´s missions are developed to stay in LEO orbits, with an orbital lifetime inferior to 25 years, (NASA STD-8719-14A). For the present analysis, it was selected LEO´s with a perigee altitude from 140 km to 350 km and eccentricity from 0.0 to 0.005. These orbits were selected, assuming that:

- All non-operational satellites are debris decaying without control.
- During the decay, the drag reduces the semi-major axis and reduces the orbit eccentricity.
- In some point of the orbital lifetime, the debris must pass by these altitudes with low eccentricities.
- At these altitudes, the decay time is around some days, inferior to years. These evaluations time reduce the computational cost of the simulations and the numerical error propagations.
- The influence of the aerodynamic force is larger, because the highest values of the density are at low altitudes.

The orbits were propagated without influences of the radiation pressure and third body perturbations, because they are low in comparison with the magnitude order of the Drag and gravitational perturbations. The equation of motion was numerically integrated with a RKF7/8 (Fehlberg, 1968), a 5E-4 s Step-Size, numeric tolerance of 1.11E-16. The model simulations are complemented with the EGM-08 with 50x50 order (Kuga & Carrara, 2013; Pavlis et. al. 2012), the atmosphere NRLMSISE-00 (Picone et. al. 2002) and wind model HWM-93 (Hedin et. al. 1996). A panel method is selected to determine the Drag Coefficient as a function of the fluid incident angle. The method reduces the computational cost with acceptable accuracy (Koppenwallner & Fritsche, 2006).

IV. RESULTS

More than 2,100 trajectories were simulated to analyze the influence of the B variations in the decay time. Trajectories with rotation have a lower decay time compared to trajectories with constant B, see Fig. 3-5.

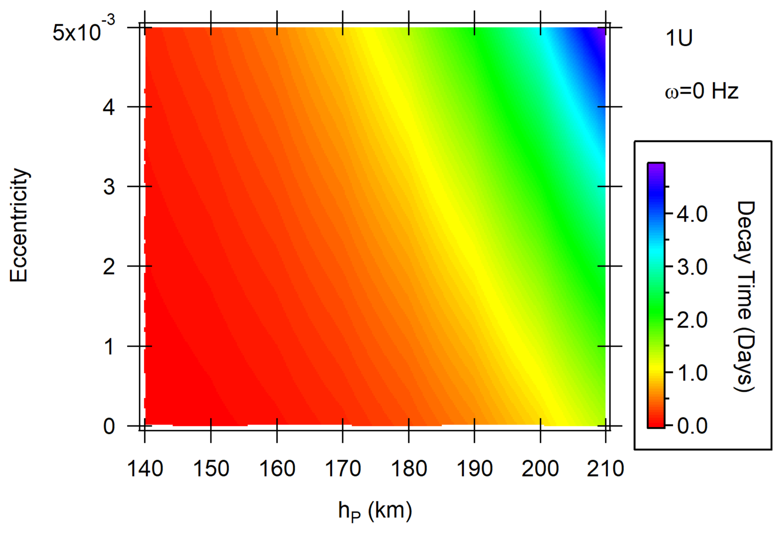

Figure 1. 1U Decay time without rotation.

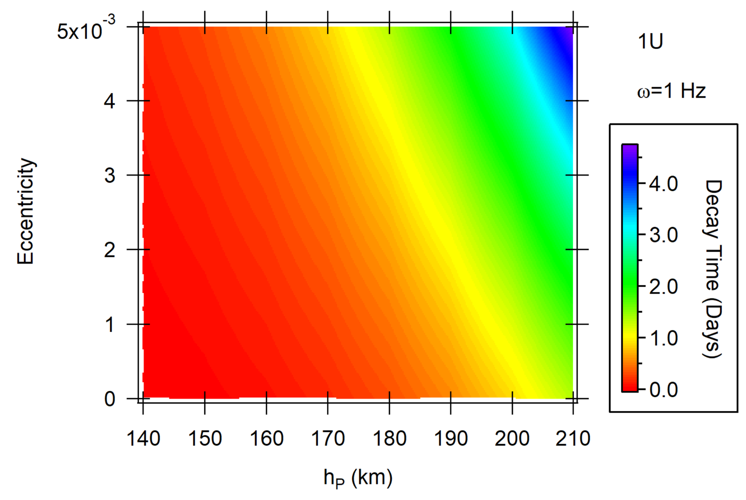

Figure 2. 1U Decay time with rotation.

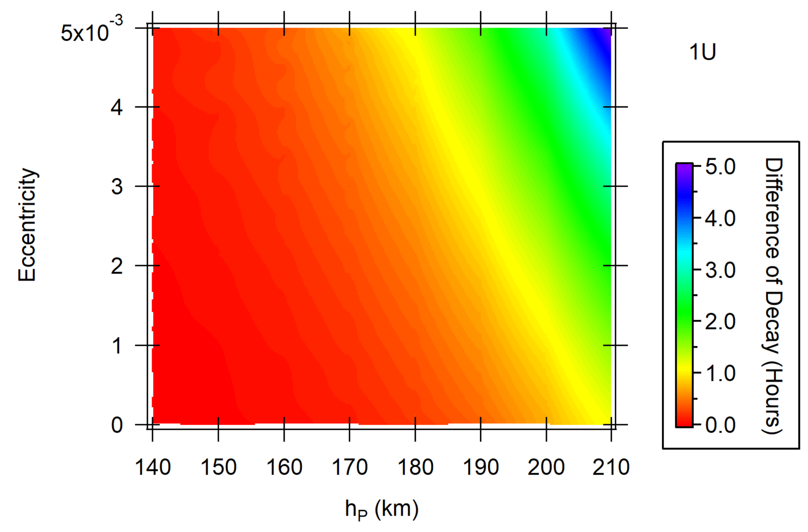

Figure 3. Difference in the Decay time for 1U.

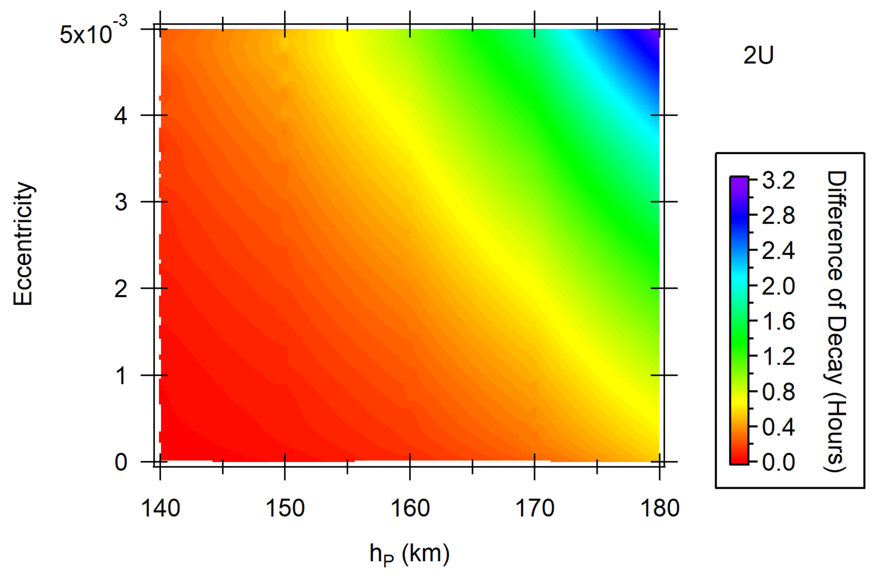

Figure 4. Difference in the Decay time for 2U.

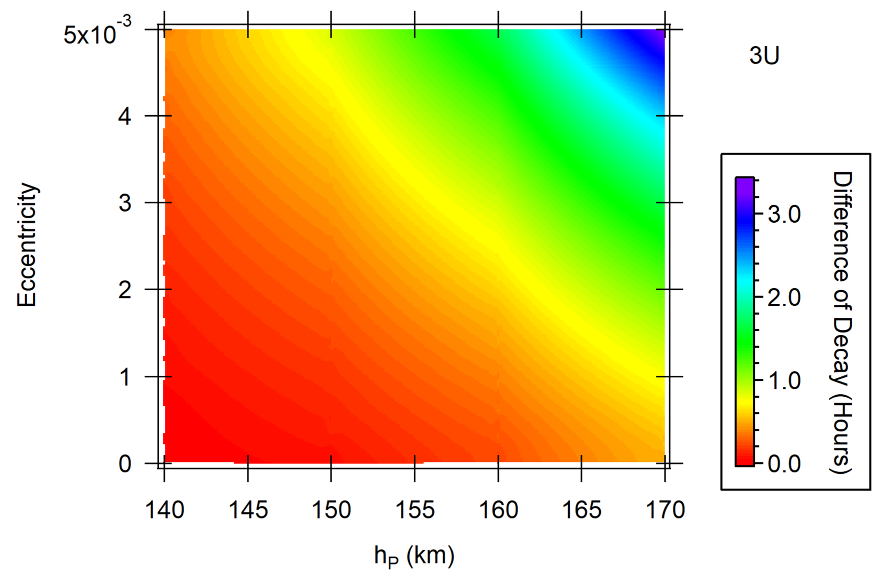

Figure 5. Difference in the Decay time for 3U.

V. FUTURE WORKS

- Include the solar activity and third body perturbations.
- Analyze with different rotational rates to observe the influence of the rotation in the decay and to analyze the effect of area-mass variation.
- Include a better technique for Drag Coefficient determination as a function of the rotational angles and attitude.
- Compare the results from simulations versus CubeSat TLE´s data, to adjusted the model.
- Implementation of the model to determine the decay of the satellite RaioSat.

CONCLUSIONS

More than 2,100 trajectories were propagated. Results shows that CubeSat's with periodic Drag variations increase the deceleration rate and reduce the decay time compare to the CubeSat's whit constant Drag Coefficient. These differences increase proportional to the orbit altitude and eccentricity.

The periodic Drag Coefficient represent with good accuracy the real attitude of the satellite in orbit. However it is necessary to validate the results with observations of CubeSat's (TLE´s) and adjust to the atmospheric model errors.

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