Evaluation of orbital decay of a satellite at low altitude due to atmospheric drag as a function of solar activity

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Abstract. Artificial satellites in low Earth orbit have as main disturbance the atmospheric drag, which is a non-conservative disturbance that causes the satellite to lose orbital energy due to the friction with the air. Basically, the drag force is a function of the velocity, the local air density and the satellite’s constructive parameters. The air density is a function of altitude, longitude, latitude, geomagnetic index and solar activity. Solar storms are responsible for a wide range of terrestrial effects, especially in damage to telecommunications systems. Another relevant effect of solar activity is the variation in the volume of the atmosphere and consequently in the value of the air density for a given altitude, longitude and latitude. This work provides an initial approach, through simulation, in the engineering effort to deal with this disturbance.

1. Introduction
Space weather phenomena can significantly impact the operating conditions of space technologies [1]. One of the most important effects of the space weather is the influence of the solar activity in the atmospheric density and therefore, the effect in the atmospheric drag applied in low orbit spacecrafts. In the literature there are several studies related to atmospheric drag which have been providing useful tools for aeroassisted mission [2, 3]. In this work, the evolution of the orbit of a space vehicle traveling through the upper atmosphere of the Earth was simulated considering periods of high activity and low solar activity. The simulation is performed so that the vehicle does not perform propulsive maneuvers, in order to evaluate the impact of the atmospheric disturbance in the orbital decay. Thus, the objectives of this study include:

(i) Simulate orbital satellite evolution in low orbit without propulsive maneuvers with focus on disturbance due to atmospheric drag.
(ii) Verification of the short-term effects of solar storms.
(iii) Evaluation of the accumulated effect of the atmospheric drag on the deviations of velocity.

2. Atmospheric disturbance
The main forces that act on objects in the Low Earth Orbit (LEO) are the atmospheric drag and gravitational pull of Earth. Atmospheric drag, in turn, represents the most
relevant uncertainty for orbital accuracy determination for low-altitude satellites up to approximately 600 km [4].

The atmospheric drag acts in the direction of the motion of vehicle movement in an opposite sense and its magnitude is satisfied by equation:

\[ a_D = -\left(\frac{C_D A}{2M}\right)\rho V^2 \]  

(1)

where \( a_D, C_D, A, M, \rho, V \) are, respectively, orbital drag acceleration, drag coefficient, satellite section area, vehicle mass, atmospheric density and vehicle velocity. The quantity \( (C_D A/M) \) is known as ballistic coefficient [5].

In this investigation, the inertial geocentric system is used as reference frame, described as follows: the origin is in the planetary center, the X axis points to the vernal point, the Z axis to the mean north pole, and the Y, situated in the plane of the equator, completes the dextrogiro orthogonal system.

The atmospheric density prediction applies to the orbital critical accuracy determination of satellites and space debris, including the tracking problem, collision avoidance alerts, lifetime estimation, and prediction of reentry [4]. Associated with orbital determination is the topic of reliability engineering, which deals with ensuring the system operates specified functionality over a period of time under certain environmental conditions [6]. The relevance of this issue has increased due to the constellation deployment plans of thousands of communications nanosatellites. Therefore, predictive capability becomes crucial in assessing the extent and duration of the impact of future problems related to more intensive LEO exploration.

Finally, we still have meteoroid flight applications, laser communications, and interplanetary missions with aeroassisted techniques, or fuel reduction and payload increase [2].

In this work, the statistical model NRLMSISE-00 was used to predict the atmospheric density [7].

3. Solar activity

The chain of physical events that connects the increase in solar activity to the effects of space-time perceived on Earth is grounded in the outermost layers of the Sun. Although the Sun is a system Magnetohydrodynamics (MHD) not yet fully understood, it is credited to the phenomenon of magnetic reconnection to the explosive release of energy and hot plasma that crosses the interplanetary space until interacting first with the outermost layers of the magnetosphere [1].

In order to monitor solar activity, the flux density at wavelength 10.7 cm, index \( F_{10.7} \), serves as a proxy variable since it is very sensitive to the conditions at the base of corona and of the upper chromosphere [8]. The index \( a_p \), in turn, quantifies the geomagnetic perturbation for a period of 3 hours [9]. Both indices inform the statistical model adopted to predict the density of the upper atmosphere.

The representative period chosen for the storm time was November 20-23, 2003, which encompasses a solar storm. For the Quiet time, it was chosen November 28 to December 1, 2012, during which solar and geomagnetic indices had no major fluctuations.

4. Simulation and results

The computational environment of the orbit trajectory, the Spacecraft Trajectory Simulator (STRS), developed by Rocco [10, 11, 12, 13, 14], was used to simulate 3 arbitrary orbits, one being equatorial, one polar and one with 45 degrees of inclination. The study cases are those shown in the table 1.
Table 1: Simulation cases

| keplerian elem.            | case (1) | case (2) | case (3) |
|---------------------------|----------|----------|----------|
| semimajor axis [km]       | 6670     | 6670     | 6640     |
| eccentricity              | 0.01     | 0.003    | 0        |
| inclination [degrees]     | 0        | 45       | 90       |
| RAAN [degrees]            | 0        | 163.123  | 163.123  |

Argument of perigee and mean anomaly were simulated with initial values respectively, in degrees, of 100 and 0, for the 3 cases.

Quiet time versus Storm time, case (1)

Fig. 1: Altitude, apogee, perigee, eccentricity

Fig. 2: Inclination, RAAN, drag force, mean anomaly
Quiet time versus Storm time, case (2)

Fig. 3: Altitude, apogee, perigee, eccentricity

Fig. 4: Inclination, RAAN, drag force, mean anomaly
Quiet time versus Storm time, case (3)

For each step of the simulation, the force due to the perturbation of atmospheric drag on each axis of the inertial frame is determined, so that an analysis of delta-v, for one revolution with inclination 45 degrees, could be performed.

| Geomagnetic activity | Delta-v [m/s] |
|----------------------|--------------|
| Quiet time           | 0.2200       |
| Storm time           | 0.2265       |
5. Conclusions
The simulations and results of orbital evolution indicated conformity to the theory. The eccentricity of the orbit is attenuated, indicating that the long-term effect is circularization. Another theoretical result observed in the simulation is the increase in velocity, since the satellite is continuously transferred to orbits with decreasing altitude. As the low-altitude vehicle continues to lose energy, and without propulsive maneuvers, it will eventually come out of orbit and crash into Earth.

The level of solar activity, having a direct impact on atmospheric density, must be taken into account in the most realistic way. We did a simulation verification of a simple case that this effect is quantifiable. After this preliminary study, we consider that evaluations of orbital decay effects, rather than deterministically consider case-based modeling, may also include probabilistic evaluations.

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