Selecting Orbits for Safe Storage of Space Debris in the GNSS Region

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Abstract. The problem of selecting disposal orbits for global navigation system satellites is considered. Averaged analytical models were used to interpret the results of numerical simulation. The dynamic evolution of objects in the studied region is determined by the competition between two resonances. Luni-solar resonances, dependent on the inclination, lead to an increase in orbital eccentricity. The secondary secular apsidal-nodal resonance, caused by the influence of solar radiation pressure, in the vicinity of the stationary point limits the variation of eccentricity. It is recommended to choose disposal orbits from 100 to 500 km higher on the semi-major axis with respect to corresponding navigation constellation orbits. By suitable positioning of the orbital plane with respect to the direction to the Sun, it is possible to achieve a minimal variation in eccentricity over a long-time interval of up to 200 years for area-to-mass ratios less than 1 m^2 kg^{-1}.

Introduction

Typically considered two possible disposal strategies for the GNSS (Global Navigation Satellite System) region involving either stable or unstable orbits from the eccentricity growth point of view [1]. Unstable scenario seems favorite from point of view the possibility to dilute the collision risk and to aim at the re-entry in the atmosphere. Stable scenarios seem to minimize the interactions (crossings) with the operational constellations and, therefore, might be preferred for operational reasons. The aim of the study is to justify the choice of disposal orbits within the framework of the Stable scenario. Requirement for disposal orbits is that objects in disposal orbits should not enter the areas of motion of GNSS and IGSO (Inclined Geosynchronous Orbits) satellites over tens or hundreds of years (up to 200 years). During this time, effective systems for the active debris removal (ADR) from disposal orbits must be developed.

1. Methodology

Our research is based on interactions between analytical methods and numerical simulations. We use numerical simulation to accurately predict the motion of objects in the medium Earth orbit (MEO) region. Analytical methods are used to analyze and interpret the results of numerical modeling, justify the choice of disposal orbits and their stability.

The theoretical part of our research is based on the following fundamental results. Firstly, the theory of the secular luni-solar resonances dependent on inclination [2, 3]. Secondly, the theory of the secondary secular apsidal-nodal resonances due to solar radiation pressure [4, 5]. Thirdly, consideration of orbital evolution under the influence of solar radiation pressure in the vicinity of a stationary point on the "eccentricity – longitude of perigee" plane [6].

The dynamic evolution of space debris in the vicinity of the area of motion of satellites of global navigation systems is studied based on numerical simulation. The orbital evolution of space objects is modeled in "Numerical Model of the Motion of an Artificial Satellites" [7] developed at the Tomsk State University. The model of perturbing forces takes into account the major perturbing factors:

- the gravitational field of the Earth (EGM96 model, harmonics up to the 29^{th} order and degree, inclusive, for the correct description of the movement of objects in eccentric orbits and before re-entering),
- the gravitation of the Moon and the Sun,
- the tides of the Earth,
- the direct solar radiation pressure including the eclipses due to the Earth's shadow,
- the Poynting-Robertson effect,
- the atmospheric drag.

The equations of motion are integrated by Everhart's method of the 19^{th} order. The coordinates of the Moon and the Sun during the numerical integration of the equations of motion are extracted from the JPL Planetary and Lunar Ephemerides DE405/LE405.

We used several sets of initial data to study the dynamic evolution of objects in the vicinity of the GNSS region. We chose initial conditions for the space objects in MEO near the GNSS regions (GLONASS, GPS, BeiDou, and Galileo). We varied the initial values of the semi-major axis and the longitude of the ascending node. The initial value of the eccentricity corresponds to a near-circular orbit with $e_0 = 0.0001$. The initial value of the argument of perigee is 270°. The area-to-mass ratio A/m is equal to 0.001, 0.01, 0.1, and 1 m^2 kg^{-1} from values corresponding to satellites to values corresponding to space debris. The orbital evolution covers 200 years.

2. Results

One of the two resonances, either the secular luni-solar resonance or the secondary secular apsidal-nodal resonance, dominates and determines the evolution of the orbital eccentricity for a given initial value of the longitude of the ascending node. Luni-solar resonances, dependent on inclination, operate in all regions of the GNSS. These resonances lead to increased orbital eccentricity. For this reason, regions dominated by luni-solar resonances are excluded from the disposal orbit analysis for the Stable scenario from the eccentricity growth point of view.

The secondary secular apsidal-nodal resonance due to solar radiation pressure ensures evolution in the vicinity of a stationary point, which limits the growth of the orbital eccentricity. The areas of dominance of secondary secular apsidal-nodal resonances are suitable for the selection of disposal orbits within the Stable scenario. Space debris, including objects with high ratios A/m, could potentially accumulate in the vicinity of this region.

We propose placing the end-of-life GNSS satellites in orbits from 100 to 500 km higher on the semi-major axis with respect to corresponding operational orbits. By suitable positioning of the orbital plane with respect to the direction to the Sun, it is possible to achieve a minimal variation in eccentricity over a long-time interval of up to 200 years for area-to-mass ratios $A/m < 1$ m^2 kg^{-1}.

Conclusion

Interaction between analytical methods and numerical simulation made it possible to interpret the results of numerical modeling and determine the initial values of the semi-major axes and longitudes of the ascending nodes of the disposal orbits for each of the global navigation satellite systems. The evolution of objects in MEO is controlled by luni-solar resonances and secondary secular apsidal-nodal resonance caused by solar radiation pressure. In combination with the evolution in the vicinity of the stationary point, this resonance provides a limited variation of eccentricity, which is necessary to ensure the Stable disposal scenario. It is recommended to select disposal orbits in areas where secondary secular apsidal-nodal resonances caused by solar radiation pressure dominate.

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