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Mapping orbits with low station keeping costs for constellations of satellites based on the integral over the time of the perturbing forces

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A B S T R A C T

The present paper is concerned with the search for orbits that have potential to require low fuel consumption for station-keeping maneuvers for constellations of satellites. The method used to study this problem is based on the integral over the time of the undesired perturbing forces. This integral measures the change of velocity caused by the perturbation forces acting on the satellite, so mapping orbits that are less perturbed, which generates good candidates for orbits that requires low fuel consumption for station-keeping maneuvers. The integral over the time depends only on the orbit of the spacecraft and the dynamical system considered. The type of engine and the control technique applied to the spacecraft are not considered to search for those orbits. It can be a good strategy to be applied for a first mapping of orbits. For this search, it is analyzed the integral of orbits with different values of the Keplerian elements in order to find the best ones with respect to this criterion. The perturbations considered are the ones caused by the third body, which includes the Sun and the Moon, and the J_2 term of the geopotential. The results presented here show numerical simulations to obtain the integral of those perturbing forces for different orbits. The GPS and the Molniya constellations are used as examples for those calculations.

1. Introduction

The study of orbital maneuvers is one of the most important topics in orbital mechanics. It has been studied for a long time and still today is a current topic of research, since it can be studied with different goals and using several types of propulsion systems. An orbital maneuver involves several aspects and its performance depends on the initial and final conditions imposed, the fuel consumption, the maneuvering time, etc. The most common requirement of orbital maneuvers is the optimization of the fuel consumption, since it is not convenient to refuel the satellite in orbit and the fuel left usually defines the end of the life of the satellite.

The orbital maneuvers have a wide range of applications, including the initial phases of placing a satellite in its orbit and the station-keeping maneuvers required to keep this orbit. This second type of maneuver is directly related to the topic of the present paper. There is a wide range of researches on this topic, like Refs. [1–3], where it is studied the potential use of electric propulsion for station-keeping maneuvers, from the control to reliability. Ref. [4] proposes geostationary orbits insertions and north–south station keeping maneuvers. In Ref. [5], the east–west station

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keeping maneuvers with resonant tesseral harmonics are studied. Ref. [6] presents a complete work of station-keeping maneuvers for geostationary orbits with feedback control techniques and, in Ref. [7], the orbital change in station-keeping maneuvers is considered with a low thrust for the propulsion system.

Station-keeping is an essential study for each mission because it guarantees the maintenance of the final orbit where the satellite was planned to operate. The vehicle requires regular adjustments of its orbit due to external perturbation forces such as the solar wind, the gravity of the Sun and the Moon, aerodynamic drag, the non-spherical form of the Earth and so on. In particular, this point is very important for constellations of satellites, because they usually have very strict requirements for the orbital parameters of the satellites.

Regarding the third-body perturbations, one of the forces considered in the present paper, the literature shows several studies, especially considering the perturbations of the Sun and the Moon in an artificial satellite of the Earth. Kozai [8,9], for example, considers the Lagrange equations for the secular and long periodic terms for the Sun and the Moon perturbations. Blitzer [10] obtains estimates for the equations of motion including this perturbation with the help of the classical mechanics. In this last study, only the secular terms were included and it presents the effect of the precession of the orbital plane. Musen [11] makes two kinds of studies for the long periodic perturbations. One study uses the Gauss equation and numerical methods for the long period effects, and the second one uses Legendre polynomials and the stability of the orbits. Kaula [12] includes the Sun and the Moon perturbations in his work. It contains the general perturbed equations of motion for the orbit and it uses the equatorial elements for the Moon. Extending previous works, Giacaglia [13] obtains the general perturbed equations of motion using equatorial elements for the satellite and the elliptic elements for the Moon.

Later, Broucke [14], Prado [15] and Domingos et al. [16] used an average approach in their studies to eliminate periodic terms. This approach included a double average technique based on truncated expansions to eliminate the short periodic terms due to the motions of the spacecraft and the perturbing body. An approach considering only a single average was also studied by Solórzano and Prado [17], where only the short periodic terms due to the motion of the spacecraft are eliminated. Applications of those techniques for orbits around Europa [18] and the Moon [19] are also available in the literature.

Concerning the J_2 perturbation, the other force considered in the present paper, there is also a very extensive literature, like Hua-Yi [20], which studies the correction of the semi-major axis to reduce the J_2 perturbation or Wang et al. [21], which studies frozen orbits based on the J_2 perturbation.

Usually, the station keeping maneuvers use propellant to perform the maneuvers and, since the economy of fuel can extend the life of the satellite, this paper is concerned with the search for orbits that are less perturbed, and so have good potential to require lower fuel consumption for the station keeping maneuvers. The final evaluation of the fuel consumed for these maneuvers depends on the requirements of the mission, the type of engine used and the control strategy adopted, but this indirect approach of mapping the orbits can help in orbit selection. To map those orbits, this paper uses the idea of integrating the perturbing forces, so measuring the total effects of the perturbation during one period of the orbit, which is a good indication of the effort required to keep the satellite in its nominal orbit. The integrals are evaluated numerically in the present research, but analytical approximations based on series expansions of the integrand can be obtained to any degree of accuracy desired. So, given an initial condition, the equations of motion, including the perturbation forces, are integrated over the time to obtain the total change of velocity that the satellite received from those perturbing forces. In particular, this type of approach is very important in the case of elliptical orbits. In this situation the spacecraft passes by different regions of the space and the perturbations have different effects in each part of the orbit. So, to have a more complete view for a whole orbital period, the integral of the effects over the time of the perturbations is a good technique. For equatorial circular orbits it is possible to estimate the effects of those perturbations just by looking at its altitude with respect to the Earth, but when the orbits are eccentric or inclined, the result is not so trivial and the use of the integral is an interesting and useful tool.

The approach presented here can be used for any dynamical system, so it is possible to include any kind of perturbation. In the present paper, it is considered the perturbations of the gravitational forces caused by the Sun and the Moon and the J_2 term of the geopotential of the Earth.

It is important to point out that this approach can find orbits that are less perturbed, so with potential to have low cost for its maintenance, but does not consider specific details of how to make the orbital maneuvers. The idea behind this approach is to analyze the value of the integral and, if there is a low value, the orbit is expected to require lower fuel expenditure for station keeping maneuvers when compared to orbits with higher value for this integral. In others words, the orbits related to the lower values for the integral might be better choices to reduce the fuel consumption for station-keeping maneuvers, regardless of the propulsion system used on the satellite and the control technique applied for that. Another point that has to be considered is that this integral is evaluated at every instant of time, so taking into account short periodic effects, or considering only the long periodic effects, by using averaged equations of motion. This choice will depend on the goals of the missions and how much freedom is given to the spacecraft to deviate from a Keplerian orbit. The choice of evaluating the integral at every instant of time represents an extreme situation where the spacecraft has to stay in a Keplerian orbit all the time.

The idea of evaluating the integral of the magnitude of the perturbing forces is based on the fact that all components of the forces acts in the trajectory of the spacecraft, either by changing the magnitude of the velocity of the satellite, with its component in the direction of motion, or