Evaluating the disturbances acting on a spacecraft on orbit around Europa

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Abstract. Jupiter is a tempting body as a target for a space mission. Since this planet owns a complex system of moons, many discoveries and analyses can be done. Its Galilean moons, Io, Europa, Ganymede, and Callisto, are also of interest, especially Europa with the intriguing hypothesis of the oceans below its icy surface. This work aims to study the perturbations on a spacecraft in an orbit around Europa, the gravitational attraction of the Sun, Jupiter, Io, Ganymede, Callisto, and the gravitational potential of Europa are considered.

1. Introduction
The Jovian system is a complex environment, and not only Jupiter is a body of interest when it comes to this system, but also its moons, especially the Galilean moons: Io, Europa Ganymede, and Callisto. Europa is an appealing body to study. There are many hypotheses that agree that this moon has an ocean [1] and is even said to be a propitious environment to microbial life [2]. Many missions have had an encounter with Jupiter, but focusing on the moons, the European Space Agency (ESA) has a mission planned for launch in 2022, the JUICE (JUpiter ICy moons Explorer) mission, that will study Ganymede, Callisto and Europa, and will help to characterize the Jovian environment [3].

When it comes to the idea of a space vehicle that orbits a body, there are some issues we must consider for the mission success, including perturbations of different origins. Disturbances of gravitational origins are relevant because can completely degenerate the orbit of a spacecraft, a perturbation that plays a lead role when it comes to gravitational disturbances is the one due to a third body. The importance of analysing the Sun and Moon’s perturbation on artificial satellites on orbit around Earth is clear [4].

The gravitational potential of a body also generates an important perturbation, which includes the analysis of the Spherical Harmonics. The gravitational potential of a polyhedron was derived using spherical harmonic coefficients [5]. The spherical harmonic expansion of the Earth gravitational field has already been the focus of study [6], where they considered the expansion until degree and order 360. Using some Pioneer 11 data improved harmonic coefficients of Jupiter were obtained, a useful data to study the gravitational field of the planet [7].

2. Objectives
This work aims to study gravitational perturbations acting on a spacecraft orbiting Europa. We consider the gravitational attraction of the Sun, Jupiter, Io, Ganymede, and Callisto. The perturbation of the gravitational potential of Europa is also estimated in order to have an idea of its magnitude and influence. This study is done by means of simulations using a trajectory simulator, that will be present later in this work.
3. Spherical Harmonics

Planets, satellites, and other bodies are not perfect spheres, and neither have a perfect mass distribution. This lack of symmetry brings us the fact that the gravitational force acting on a satellite when in an orbit around these bodies does not point to the center of the bodies. The most important term that quantifies this fact is the harmonic coefficient $J_2$. Depending on the body of interest, there are $n$ terms known as $J_{nm}$. These terms represent the harmonic coefficients.

The harmonic coefficients are defined in terms of $J_{nm}$, $C_{nm}$, $S_{nm}$, and are divided in the categories below [8]:

- Zonal harmonics: when $m = 0$, describe the variation of the latitude, and divide the sphere on latitude zones;
- Sectorial harmonics: when $n = m$, and divide the sphere into sectors;
- Tesseral harmonics: when $n \neq m$, the sphere is divided into a checkboard array.

The perturbing accelerations are given by equation (1).

$$\mathbf{r}_a = \frac{\mu}{r^2} \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \frac{(2e)^n}{n!} \left[ -\frac{(n+1)}{m \sec \phi} \frac{C_{nm} \cos m \lambda + S_{nm} \sin m \lambda}{P_{nm}} \right] \left[ \cos \left( C_{nm} \cos m \lambda + S_{nm} \sin m \lambda \right) p_{nm}' \right]$$

where $\theta$ is the latitude, $\lambda$ the longitude, $P_{nm}$ are the associated Legendre polynomials, $a_e$ is the equatorial semi-major axis. We also have the relations given by equation (2) to equation (5).

$$\sec \phi P_{11} = 1$$

$$\sec \phi P_{nm} = (2n - 1) \cos \phi (\sec \phi P_{n-1,n-1})$$

$$\sec \phi P_{nm} = \frac{2n-1}{n-m} \sin \phi \left( \sec \phi P_{n-1,m} \right) - \frac{n+m-1}{n-m} (\sec \phi P_{n-2,m})$$

$$\cos \phi p_{nm}' = -n \sin \phi (\sec \phi P_{nm}) + (n + m) (\sec \phi P_{n-1,m})$$

4. Perturbations due to a third body

Jupiter’s moons disturbances are considered here as perturbations due to a third body. The function of the gravitational potential according to [8] is given by equation (6).

$$F' = \left( \frac{r'}{r^2} \right) \left[ 1 + \sum_{n=2}^{\infty} \left( \frac{r'}{r} \right)^n P_n \cos \psi \right]$$

where $\mu$ is the gravitational parameter, $r'$ the absolute position vector related to the center of Jupiter, $\psi$ is the angle between the spacecraft’s position vector related to Jupiter and the spacecraft’s position vector related to the third body, $r$ is the absolute position related to Jupiter.

The disturbing accelerations due to a third body are shown from equation (7) to equation (9) according to [9] and [10]:

$$\ddot{r}_1 = -Gm_2 \frac{r_2 - r_3}{|r_2 - r_3|^3} + Gm_3 \frac{r_2 - r_1}{|r_2 - r_1|^3}$$

$$\ddot{r}_2 = -Gm_3 \frac{r_1 - r_2}{|r_1 - r_2|^3} + Gm_1 \frac{r_1 - r_2}{|r_1 - r_2|^3}$$

$$\ddot{r}_3 = -Gm_1 \frac{r_3 - r_2}{|r_3 - r_2|^3} + Gm_2 \frac{r_3 - r_2}{|r_3 - r_2|^3}$$

$\ddot{r}_1, \ddot{r}_2, \ddot{r}_3$ are accelerations of the bodies of mass $m_1, m_2, m_3$, $G$ is the gravitational constant. The bodies of mass $m_1, m_2, m_3$ can be said as the spacecraft, Jupiter and each one of the moons. This is done for each of the moons individually.
5. Trajectory Simulator

The results presented here were obtained using the Spacecraft Trajectory Simulator (STRS) [11-15] which uses a Drag-Free approach, that represents the state of the art in space vehicle trajectory control. This simulation environment was developed in a suitable architecture in order to simulate the trajectory of a space vehicle controlled by a closed-loop control system, considering the modeling of the actuators and sensors, with the nonlinearities inherent to this equipment, besides considering the orbital disturbance models applied to the vehicle along its trajectory. Therefore, the STRS can simulate the control, in a closed loop, of the three degrees of liberty in relation to the translation of the vehicle.

Thus, to execute the simulation, first, it’s necessary to know the relative positioning of all moons in time. These data are obtained from the HORIZONS-Web interface and then are introduced in the STRS, after that. The orbital elements were generated for February the thirteenth, 2017. The orbital motion is obtained by determining the state of the spacecraft at each step of the simulation.

As already said, these work aims to evaluate the perturbations on the spacecraft trajectory, so we must know how the orbital elements evolved. We do so integrating the rates of the semi-major axis (\(a\)), eccentricity (\(e\)), inclination (\(i\)), right ascension of ascending node (\(\Omega\)), argument of periapsis (\(\omega\)), and mean anomaly (\(M\)), respectively, from equation (10) to equation (15) [8].

\[
\frac{da}{dt} = \frac{2e \sin \theta}{nx} F_r + \frac{2ax}{nr} F_s \tag{10}
\]

\[
\frac{de}{dt} = \frac{x \sin \theta}{na} F_r + \frac{x}{na^2 e} \left( \frac{a^2 x^2}{r} - r \right) F_s \tag{11}
\]

\[
\frac{di}{dt} = \frac{x \cos u}{na^2} F_w \tag{12}
\]

\[
\frac{d\Omega}{dt} = \frac{x \sin u}{na^2 x \sin i} F_w \tag{13}
\]

\[
\frac{d\omega}{dt} = -\frac{x \cos \theta}{na} F_r + \frac{p}{eh} \left[ \sin \theta \left( 1 + \frac{1}{1+e \cos \theta} \right) \right] F_s - \frac{r \cot i \sin u}{na^2 x} F_w \tag{14}
\]

\[
\frac{dM}{dt} = n - \frac{1}{na} \left( \frac{2r}{a} - \frac{x^2}{e} \cos \theta \right) F_r - \frac{x^2}{na} \left( 1 + \frac{r}{ax^2} \right) \sin \theta F_s \tag{15}
\]

where \(F_r, F_s, F_w\) are perturbing accelerations along the position vector \(r\), \(\theta\) is the true anomaly, \(n\) the mean motion, \(u\) the argument of latitude, and \(x, p\) and \(h\) are given by equation (16) to equation (18).

\[
x = \sqrt{1 - e^2} \tag{16}
\]

\[
p = a(1 - e^2) \tag{17}
\]

\[
h = \sqrt{\mu p} \tag{18}
\]

6. Results

This study was divided into two scenarios, all of them using results of simulations performed with the STRS. The first scenario shows how the gravitational attraction of the Sun, Jupiter, Io, Ganymede and Callisto, and also the disturbance due to the gravitational potential of Europa act on a stable orbit, what means that at this point of the study, the disturbances were calculated but they were not implemented on the trajectory of the spacecraft. Thereby, this approach was possible to analyse with more accuracy the magnitude of the disturbances.

The second scenario presents a study of how the Keplerian elements evolve considering the disturbances of the first scenario, at this point the disturbances are applied on the dynamics of the
vehicle and we can see how the trajectory is compromised, so it is possible to have an idea of the adjustments to be done in the design of the trajectory.

6.1. First Scenario

For the first scenario, a low orbit of 100 km was considered, because with a lower orbit it would be possible for the spacecraft to feel more effectively Europa’s gravitational, and a better analysis related with this could be done. As mentioned in this paper earlier stable orbits were considered, and the simulations were performed to obtain a complete orbit around Europa, the other orbital parameters are shown in table 1.

| Table 1. Spacecraft orbital parameters (first scenario) |
|-------------------------------------------------------|
| Semi-major axis (km) | 1660.8 |
| Eccentricity | 0 |
| Inclination (degrees) | 45 |
| Right ascension of ascending node (degrees) | 0 |

Starting with figure 1 that shows the increment of velocity, $\Delta v$, due to the gravitational attraction of the Sun, the order of magnitude is of $10^{-10}$ m/s, which is a small value, this was expected because Jupiter distance from Sun is of approximately 779 million km.

From figure 2 to figure 4, we can see the $\Delta v$ due to the gravitational attraction of Io, Ganymede, and Callisto. Io and Ganymede have a magnitude of $10^{-4}$ and $10^{-5}$ m/s, of $\Delta v$, Europa is in between these moons, and this result shows that with these initial orbital parameters Io can approximate more from Europa. Callisto is the furthest satellite from Europa, and presents the lower value, with a magnitude of $\Delta v$ equal to $10^{-6}$ m/s.

The velocity increment due to the attraction of Jupiter is greater than the previous ones, Jupiter exerts a great attraction not only on Europa, but on all its moons, because of its mass, and the order of magnitude of the $\Delta v$ is of $10^{-6}$ m/s, as we can see from figure 5.

The higher value of the increment of velocity belongs to the gravitational potential of Europa with a magnitude of $10^{-3}$ m/s, figure 6.

![Figure 1. Velocity increment due to Sun disturbance.](image1)

![Figure 2. Velocity increment due to Io disturbance.](image2)
6.2. Second scenario
In this scenario, the disturbances of the previous scenario are implemented on the spacecraft’s trajectory. As a spacecraft usually keeps orbiting the body of interest for at least a month, the time of simulation was of 30 terrestrial days. Therefore, we could have a more accurate idea of what happens with a vehicle trajectory in a possible mission.

| Table 2. Spacecraft orbital parameters (first scenario) |
|----------------------------------|
| Semi-major axis (km) | 2341.2 |
| Eccentricity | 0 |
| Inclination (degrees) | 45 |
| right ascension of ascending node (degrees) | 0 |

Beginning the analysis from the semi-major axis, figure 7, this parameter oscillates approximately from -2 km to 12 km, what is not much, considering an orbit with a nominal semi-major axis of 2341.2 km.

The eccentricity, figure 8, presents a small error, but the evolution of the error increases with time, what means that it would be worse if the simulation was performed considering a longer period of
Finally, it’s possible to see the evolution of the spacecraft’s orbit around Europa, figure 9, that illustrates how these disturbances can spoil the trajectory of a spacecraft, and the whole mission.

Figure 7. Semi-major axis deviation.  
Figure 8. Eccentricity deviation.

Figure 9. Spacecraft’s trajectory evolution

7. Conclusions
With all these analyses we come to some conclusions. The first is that, as already mentioned, the perturbation of Europa’s potential is the one that degenerates more the trajectory. Secondly the disturbances of the other Galilean moons can’t be ignored, as they cause a substantial influence on the trajectory, and they have the power to degenerate the orbit of the spacecraft what would probably mean the end of a mission. Considering that space missions last more than the time of the simulations here performed, usually some months or years, and knowing that the result of disturbances is a summation over time, the perturbations would get even higher, what would make the study of these perturbations during the mission analysis phase even more important.

All these facts lead us to the second conclusion, that is the deviation of the trajectory must be corrected, otherwise, the requirements of the mission can be not achieved, probably they won’t, because the summation of the perturbations over time won’t allow this. Knowing this last conclusion,
the analysis of the necessary corrections of the trajectory, and also the fuel expense for these corrections must be done. This analysis could be done using the procedures developed in this work and the data obtained in the simulations presented here.

Therefore, this work represents an effort to realistically model the space environment to which a spacecraft would be immersed in a mission around Europa. Once these models have been obtained, enhanced simulations of the effect of perturbations can be done. This can be very useful in mission analysis of future vehicles aiming to orbit Europe, or other moons of the Jupiter system, under similar conditions to those considered in this article.

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