Mapping the Galilean moon’s disturbance acting on a spacecraft’s trajectory

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Abstract. The prime objective of this work is to map the disturbance of Jupiter’s Galilean moons, Io, Europa, Ganymede and Callisto, on a spacecraft trajectory. The study is done using an orbital trajectory simulator, the STRS (Spacecraft Trajectory Simulator). This mapping is made first considering the four moons as a group, and after that the disturbances of each of the Galilean moons are considered individually.

1. Introduction
This work aims to evaluate the disturbance of the four Galilean moons (Io, Europa, Ganymede and Callisto) on a spacecraft’s trajectory orbiting Jupiter. These results were obtained by a short period simulation, of only 17 days, the same period of Callisto’s orbit. It’s important to emphasize that the goal of the study is not to analyze the dynamic evolution of the Jovian moons system for a long period of simulation, where the Laplace resonance must be considered due to its strong influence [2], but to consider a short period of time, a few days, equivalent to the orbital period of the farthest Galilean moon from Jupiter, to evaluate the magnitude of the Galilean moons gravitational disturbance applied in the spacecraft trajectory during this period of time. In this case, although, the resonance effect on Io, Europa and Ganymede orbits were considered, the changes in their orbits are not large in this short period of time. At the beginning of the simulation, the relative position of all moons was obtained from the Jet Propulsion Laboratory HORIZONS-Web interface [1]. From these data it is possible to propagate the relative position of the bodies during the whole simulation. However, when it comes to longer simulations, updating the relative positions using the HORIZONS-Web interface data is done more frequently in order to consider the effect of Laplace resonance.

2. Orbital trajectories simulator
The study of the Galilean moons disturbance acting on a spacecraft trajectory is done with the STRS (Spacecraft Trajectory Simulator), developed by [3, 4] and used by [5 - 10] at INPE. In the STRS, the orbital motion is obtained determining the spacecraft’s state (position and velocity) at each step of the simulation. Moreover, the STRS propagates the relative positioning of all four Galilean moons in time [11], starting with the data obtained in the HORIZONS-Web interface, besides it considers the orbit propagation of other 58 Jupiter’s moons.

3. Orbital disturbances
The Galilean moons disturbances are considered as disturbances generated by a third body individually, then the STRS sums all of them to ensure a complete simulation. The function of the
gravitational potential due to the presence of a third body is given by equation 1 and can be found in Chobotov [12] and was used by [13] and [14].

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

\(\mu\) is the gravitational parameter, \(r'\) is 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 with the third body, and \(r\) is the absolute position related to Jupiter. The disturbing accelerations due to a presence of a third body are shown from equation 2 to 4. According to [15] and [16].

\[
\ddot{r}_1 = -Gm_2 \frac{r_1 - r_2}{|r_1 - r_2|^3} + Gm_3 \frac{r_3 - r_1}{|r_3 - r_1|^3}
\] (2)

\[
\ddot{r}_2 = -Gm_3 \frac{r_2 - r_3}{|r_2 - r_3|^3} + Gm_1 \frac{r_1 - r_2}{|r_1 - r_2|^3}
\] (3)

\[
\ddot{r}_3 = -Gm_1 \frac{r_3 - r_1}{|r_3 - r_1|^3} + Gm_2 \frac{r_2 - r_3}{|r_2 - r_3|^3}
\] (4)

where \(\ddot{r}_1, \ddot{r}_2\) and \(\ddot{r}_3\), are positions of the bodies of mass \(m_1\), \(m_2\) and \(m_3\) and \(G\) is the gravitational constant. At this point, it is important to explain that the three bodies involved here are Jupiter, the spacecraft and each of the Galilean moons, this calculus are done for all moons. The STRS computes the disturbing accelerations for each moon and sum all of them, considering, by this way, all of the four moons on results.

4. results

The orbital inclination and the semi-major axis were varied in a way to allow the mapping of the gravitational perturbation due to gravitational attraction of Io, Europa, Ganymedes and Callisto. In order to complete the mapping, the simulations have been done varying the inclination by 15°, from 0° to 90°, and the semi-major axis were also varied with values that could guarantee the spacecraft to always be positioned between two different Galilean moons. The 3D graphs and some of its projections are presented in figure 1 to 3.

The simulations were carried out using step of 1 minute, considering 17 terrestrial days as total time for the simulation, since Callisto’s period, the farthest Galilean moon from Jupiter, is 16.69 days. It is important to point out that the simulations were performed to obtain the sum of the velocity increment due to the disturbance during this period of 17 days, for each combination of orbital inclination and semi-major axis.

To map the disturbing velocity increment, in each simulation a stable trajectory was considered only to determine what would be the sum of the disturbing velocity increment that a vehicle would be subjected on this trajectory. This sum can be equalized to the integral of the perturbation to which the vehicle would be subjected on this trajectory during the simulated period. The sum of the velocity increment is a characteristic of the chosen trajectory that could be considered in the mission analysis in order to obtain the minimally disturbed trajectory around Jupiter. Therefore mapping gravitational disturbances in this region is fundamental for the future missions toward Jupiter's system.

Some results are presented individually for each one of the Galilean moons (figures 4 to 15), however, the simulation of the spacecraft dynamics consider the gravitational attraction of all the four moons simultaneously. The results are presented in this way to make easier to understand how each moon contributes with the total gravitational disturbance applied to the spacecraft. However, figures 1 to 3 present the results for the sum of the disturbances due to all Galilean moons.

From figure 1 to 3, on the x axis is shown the semi-major axis, on the y axis the inclination and on z the velocity increment due the Galilean moons disturbances. As can be analyzed from the figures,
the disturbances do not follow a rule when it comes to the semi-major axis, the greatest velocity increments happen when the spacecraft perform high approaches from the moons. However Fig. 3 shows that the lowest the inclination the higher the disturbances, this was expected as the Galilean moons have almost equatorial orbits.

![Figure 1. Galilean moons mapping.](image_url)

![Figure 2. Galilean moons mapping (x-z projection).](image_url)

![Figure 3. Galilean moons mapping (y-z projection).](image_url)

Now the same graphs are shown for each of the Galilean moons, Io, Europa, Ganymede and Callisto from figure 4 to 15.

As can be seen in figure 4 to 6, for Io, the disturbances are greater for smaller semi-major axis, that's when the spacecraft approaches to the moon, and when it comes to the inclination, again as analyzed for the Galilean moons as a group the more equatorial the orbits, the greater the disturbances. For the other moons, from figure 7 to figure 15, Io’s pattern keeps repeating, when the spacecraft...
perform great approaches, the velocity increment increases, and for all the Galilean moons as a group or individually when the inclination is small there are greater disturbances.

Figure 4. Mapping of Io’s disturbances.

Figure 5. Mapping of Io’s disturbances (x-z projection).

Figure 6. Mapping of Io’s disturbances (y-z projection).

Figure 7. Mapping of Europa’s disturbances.

Figure 8. Mapping of Europa’s disturbances (x-z projection).

Figure 9. Mapping of Europa’s disturbances (y-z projection).
Figure 10. Mapping of Ganymede’s disturbances.

Figure 11. Mapping of Ganymede’s disturbances (x-z projection).

Figure 12. Mapping of Ganymede’s disturbances (y-z projection).

Figure 13. Mapping of Callisto’s disturbances.

Figure 14. Mapping of Callisto’s disturbances (x-z projection).

Figure 15. Mapping of Callisto’s disturbances (y-z projection).
5. Conclusion
The Galilean moons, as a group or individually, have a large influence on the spacecraft’s trajectory. The velocity increments generated by their disturbances are not small, and should be considered when it comes to missions involving Jupiter. As these disturbances are a sum, they are greater as time increases, and generally this type of mission lasts some years, so these disturbances, that are already great, affect more and more the trajectories through time. By this way, it is evident that the disturbances on trajectory owing to the gravitational attraction of the Galilean moons cannot be neglected in mission analysis of a space vehicle that aims to orbit Jupiter. Thus the disturbance models due to the Galilean moons were considered in the trajectory simulator STRS and simulations were successfully performed showing the disturbance velocity increments caused by these moons.

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