Close proximity motion relative to (99942) Apophis.

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Introduction: In this work, we orientate our study to provide a detailed discussion on the dynamics of a spacecraft in orbit close the asteroid (99942) Apophis during its Earth close approach, on April 13, 2029. We consider the polyhedral shape of our target, obtained from photometric observations [1], assigning each tetrahedron to a point mass in its center ([2], [3], [4]). That considerably reduces the total processing time compared to other methods to evaluate the gravitational potential. We obtained the physical properties and analyzed the equilibria near Apophis. The surfaces of section technique in a body-fixed frame is used to describe the behaviors of orbits considering or not the perturbations of the planets in our Solar System and the Solar Radiation Pressure.

Equations of motion: The motion of a test particle close to the asteroid, during the close approach is integrated with the classical equations of motion in the body-fixed frame of reference, considering the gravitational action of all the planets in our Solar System and also the Solar Radiation Pressure [5], [6], [7].

Results: In Fig. 1, we compare, in the top panel, the perturbations of the SRP and Earth at different epochs in a region extending from 0.5 to 20 km from the center of Apophis. In the bottom panel, we present the evolution of these perturbations over time, on the acceleration of a spacecraft on a circular orbit at a distance of 1 km from the center of our target. We can notice that the Earth perturbations quickly increases and becomes larger than the asteroid's gravitational attraction itself. That leads to highly perturbed orbits in Apophis system.

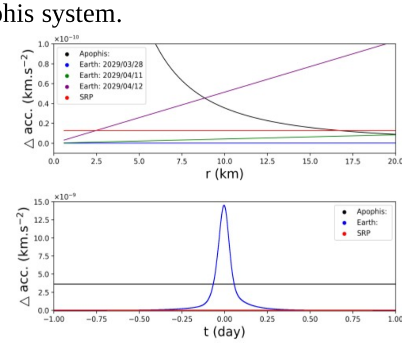

Figure 1: The relevant perturbations on the acceleration of a spacecraft close to (99942) Apophis

In order to characterize the less perturbed regions around Apophis, massless particles orbiting the system with initial semimajor axis between 0.5 and 10 km with an interval of 25 m have been integrated. We vary the initial eccentricities from 0 to 1 with a step size of 0.005, and tested equatorial and polar orbits. The initial conditions of the planets are computed by the JPL's HORIZONS ephemerides on March 1, 2029.

Almost all the tested orbits collide or escape from the system after 43 days of integration, just after the close approach with Earth. In Fig. 2 we present the type of the tested orbits integrated for 40 days (right column) and 60 days (left column).

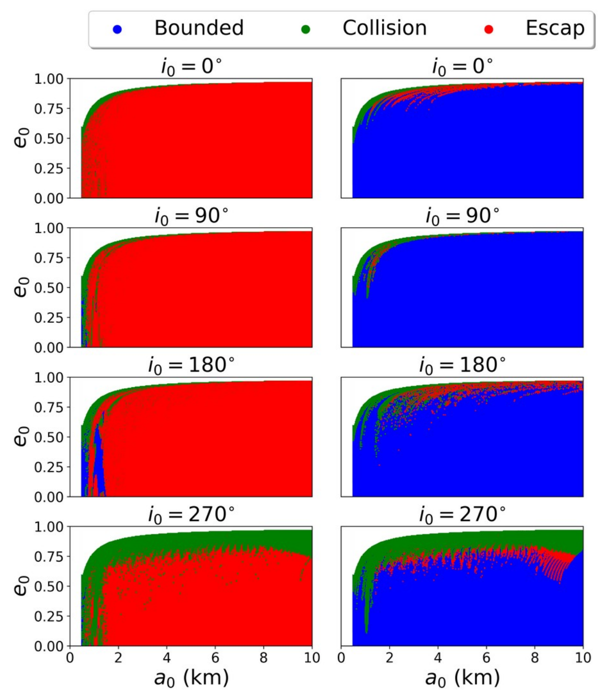

Figure 2: Type of orbits around the asteroid (99942) Apophis for 60 days (left column) and 40 days (right column) starting from March 1, 2029.

Considering our results for 40 days of integration, we delineated the less perturbed regions in the system using the variation of the semimajor axis. The minimum value founded of this variation is 0.05 km, the variation of the corresponding eccentricity is of

0.128, which is still a non-negligible variation presented in Fig. 4. However, an interesting part of the region around Apophis is heavily perturbed, that appears in the Fig. 5, beyond 4 km from the center of Apophis.

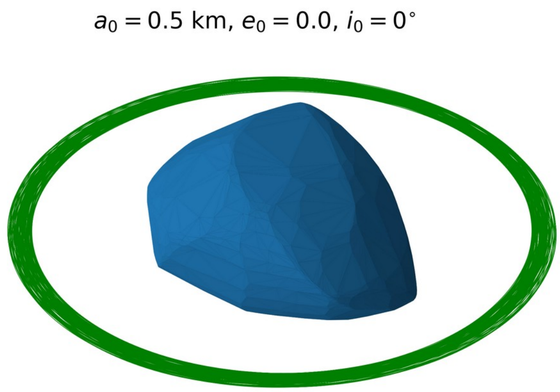

Figure 3: An example of the less perturbed orbits close of Apophis over 40 days.

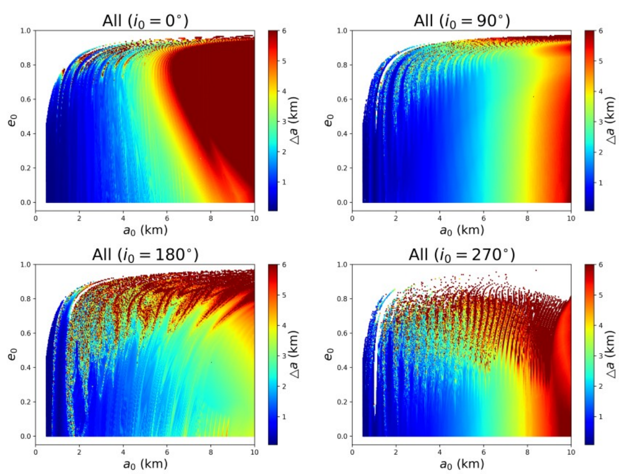

Figure 4: The variation maps of the semimajor axis coming from the ensemble perturbations on real system of Apophis.

In order to solve the stabilization problem for the system around Apophis, We applied the sliding mode control theory, controlling only the geometry of the orbit, trying to keep the orbital elements nearby the desired values ([8], [9]). In Fig. 5 we present an example of orbit successfully stabilized using a total Δv of 0.495 m/s for 60 days of operation.

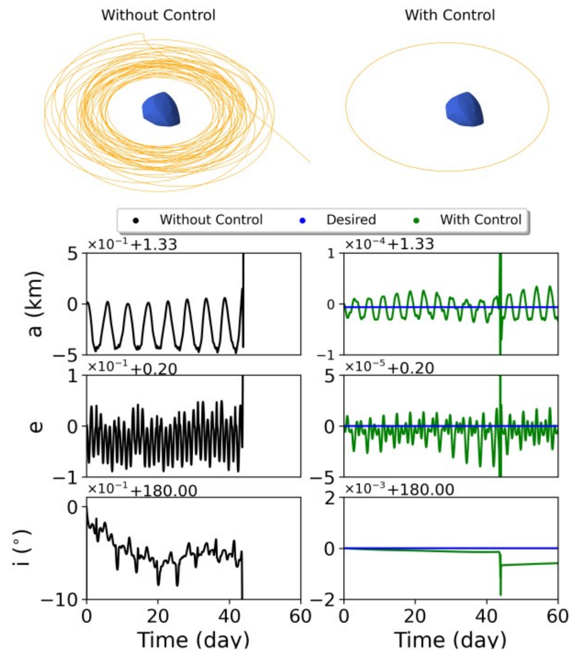

Figure 5: Controlled orbit close to (99942) Apophis, in the inertial frame.

References:

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