Assessing the Positional Divergence of Asteroid 99942 Apophis from J2000-Based Orbital Simulations Using Astronomical Observation.

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Abstract

This study examined how long simulated trajectories of asteroid 99942 Apophis remain accurate compared to observational data. Using J2000 initial conditions and NASA JPL ephemeris data, two models were simulated with the RK4 method: a simple Sun-asteroid two-body system and an N-body model including Earth, Venus, and Jupiter. Both simulations deviated from the actual trajectory by more than 0.01 AU after around five years. The minimal difference in divergence suggests that planetary perturbations have limited short-term influence on Apophis's orbit, or that finer time steps are required to resolve their effects and distinguish between the accuracy of the two models.

Introduction

Asteroid 99942 Apophis is a near-Earth asteroid discovered in 2004. It is projected to have a close encounter with Earth in 2029, and another close encounter in 2036. It is classified as a potentially hazardous object, since it passes relatively close to Earth on every orbital period and may have a possibility to impact Earth in the far future [1]. As such, since it is an object of interest, the asteroid's position in the last 20 years is well documented. In fact, it is determined that the possibility of an impact in the near future is negligible [2].

Orbital trajectory simulations are used to predict the positions and trajectory of an orbital body over time using classical differential equations and numerical integration, and, ideally, in a 2-body problem, this trajectory is invariant [3], since the forces acting on two bodies are well known. However, orbital perturbations from the presence of other orbiting significant masses (such as planets) cause deviations from the projected trajectories over time [4] and thus projected trajectories are not always accurate in predicting the actual trajectory that the asteroid, or any orbiting body, may take.

The aim of this project is to assess the deviation of the actual position of Asteroid 99942 Apophis from the simulated positions over time using historical astronomical data and the J2000 Epoch initial conditions as an initial value for the simulations.

Methodology

Ephemeris and observational data for asteroid Apophis 99942 were retrieved from NASA's Jet Propulsion Laboratory (JPL) Horizons System [5]. This dataset includes highly accurate positional and velocity measurements since its discovery in 2004. To simulate the asteroid's trajectory from an earlier epoch, its position was numerically backtracked to the year J2000 using initial conditions derived from Horizons.

To predict the orbital motion of Apophis under gravitational forces, 4th-order Runge-Kutta (RK4) method — a widely used numerical technique for solving differential equations with high accuracy – was used. The RK4 algorithm estimates the asteroid's position and velocity at small time steps, using weighted averages of acceleration at intermediate points. This scheme was used with a Δt of 0.5 days and the simulation was run for 20 years of internal time.

Two types of simulations were carried out to observe how gravitational perturbations affect the predicted path of Apophis: Only the Sun and the asteroid were considered (2 body system), modeling the simplest gravitational interaction to establishes a baseline for how Apophis would move in a purely heliocentric system

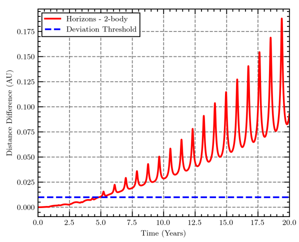
$$\ddot{\mathbf{r}} = -\frac{GM_\odot}{r^3}\mathbf{r} \tag{1}$$

where $M_\odot$ is the solar mass and $\mathbf{r}$ the heliocentric position vector, and another simulation modeling N-body major perturbers (Earth, Venus, Jupiter) in Near Earth Orbit dynamics

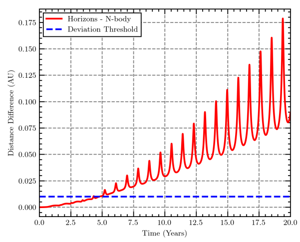
$$\ddot{\mathbf{r}}_i = -\sum_{j\neq i}\frac{GM_j}{r_{ij}^3}\mathbf{r}_{ij} \tag{2}$$

This more realistic setup allows us to assess how these bodies cause the trajectory to diverge from simpler predictions and how accurate these assumptions are. To evaluate simulation accuracy, the resulting trajectories were compared against Horizons reference ephemerides. We tracked the time it takes for the simulated path to diverge from the real trajectory by more than 0.01 AU — roughly four times the Earth-Moon distance. This deviation timescale serves as a practical estimate of predictability under these modeling assumptions.

Results and Discussion



(a) 2 Body



(b) N Body

Figure 1: Deviations between the positions compared from the Horizons ephemeris and the RK4 2 and N body simulations. The blue dash line indicates the 0.01 AU threshold marker

Comparing both the 2 Body simulation devoid of any other perturbers, and the N body simulation which has most of the major solar system orbital perturbers, we see that there is no significant difference between the divergence of the two. Both simulations start to diverge and reach the critical threshold of 0.01 AU in about 5 years, while continuously going back and forth in deviations, but never returning to minimum deviation. This either suggests that there is no significant difference between a perturbed asteroid and a nonperturbed asteroid, or negligible, at least, or a smaller Δt must be used to further discern any differences.

Conclusion

This study examined how simulated trajectories of asteroid 99942 Apophis diverge from observed data using two models: a two-body Sun-asteroid system and an N-body system including Earth, Venus, and Jupiter. Both simulations, run with a 4th-order Runge-Kutta method, showed divergence beyond 0.01 AU after around five years. The minimal difference between models suggests that planetary perturbations are either negligible over this timescale or require higher-resolution integration to resolve. These results show the limits of current models in long-term orbital prediction and emphasize the need for refined methods to account for subtle perturbative effects in future simulations.

References

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