Apophis T-9 Years, Virtual event on November 4-6, 2020

Close proximity motion relative to (99942) Apophis

S. Aljbaae[1], D. M. Sanchez[1], A. F. B. A. Prado[1], J. Souchay[2], M. O. Terra[3], R. B. Negri[1], L. O. Marchi[1]

1). INPE, São José dos Campos, SP, Brazil. 2). SYRTE, Observatoire de Paris, Paris, France. 3). ITA, São José dos Campos, SP, Brazil.

Introduction

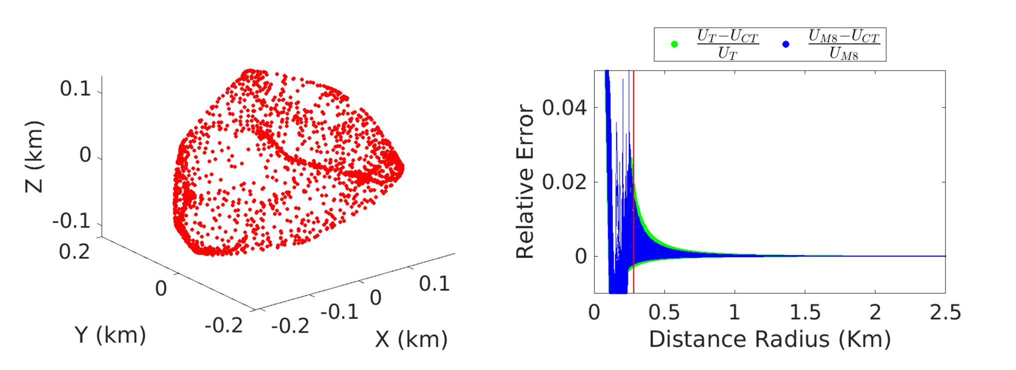
- (99942) Apophis: A near-Earth asteroid with $d \simeq 385$ m, $\rho = 1.75 \pm 0.11$ g/cm^3, M $\simeq 5.31 \pm 0.9 \times 10^{10}$ kg.
- Discovered at the Kitt Peak National Observatory, on June, 2004.
- First simulations → impact with the Earth in 2029 → improbable but could not be completely rejected.
- Close approach with Earth at a distance of $\sim$ 38,000 km on April 13$^{\text{th}}$, 2029. → change Apophis' orbit and spin.
- Observing Apophis → An important knowledge that could be used for planetary defense.

- In this work:
  - Dynamics of a spacecraft in orbit about Apophis.
  - Perturbations: The shape of the asteroid, the gravitational action of the Earth and other planets of the Solar system, and the SRP.
  - The surfaces of section in a body-fixed frame.
  - The less perturbed region around Apophis suitable to place a spacecraft around the asteroid.
  - Orbital correction maneuvers to compensate all the perturbations in the Apophis system

(1)

Apophis shape model and Gravity field

- Pravec et al (2014) $\xrightarrow{\text{lightcurve}}$ Shape of Apophis with 2024 triangular facets defined by 1014 vertices → 3D Asteroid Catalogue.
- Comparing with the observation (Muller et al., 2014) → A correction coefficient of 0.285 must be applyed to the shape.
- Mirtich (1996)→ The shape is perfectly oriented along the principal axes of inertia.
- Apophis is considered as a sum of 2024 points (Venditti 2013 (2014); Chanut et al (2015a); Aljbaae et al (2016)).
- The gravitational potential → in good agreement with Tsoulis and Petrovic (2014) and Chanut et al (2015a).
- Advantage: very fast model with high accuracy.



(2)

Equations of motion

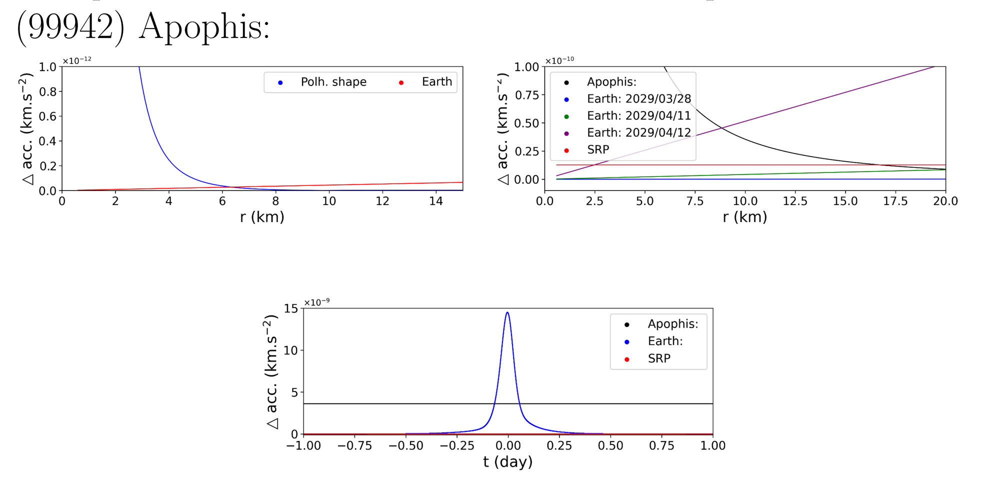
- In the body-fixed reference, The motion close to Apophis:

$$\ddot{\mathrm{r}}_j = -2\Omega \times \dot{\mathrm{r}}_j - \Omega \times (\Omega \times \mathrm{r}_j) + U_{\mathrm{r}_j} + \mathcal{A}(\mathcal{P}) + \mathrm{P_E} + \mathrm{P_M} + \nu\mathcal{A}(\mathrm{P_R})$$

- The mechanical energy of orbits around our target:

$$H = \frac{1}{2}(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - \frac{1}{2}\omega^2(x^2 + y^2) - U$$
$$U = +\sum_{i=1}^{2024} \frac{\mathcal{G}m_i}{r_i}$$

- The perturbation on the acceleration of a spacecraft close to (99942) Apophis:



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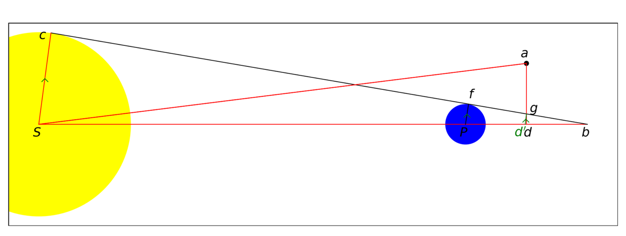
The SRP and the shadowing phenomenon

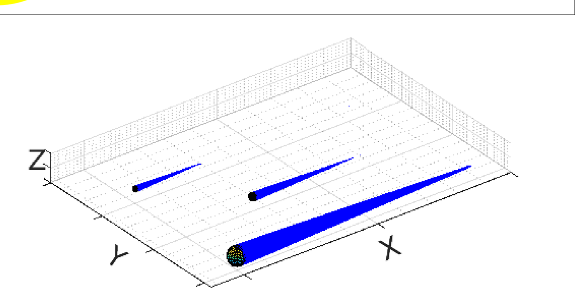
- Beutler (2005) → SRP model.

$$\mathrm{P_R} = (1+\eta)\ \mathrm{au}^2\ \frac{A\,S}{m\,c}\frac{\mathrm{r_S} - \mathrm{r_\odot}}{|\mathrm{r_S} - \mathrm{r_\odot}|^3}$$

We considered the case of an OSIRIS-REx-like spacecraft with low area-to-mass ratio ($\sim$ 0.017) and reflectance of 0.4.

- Shadowing phenomenon.



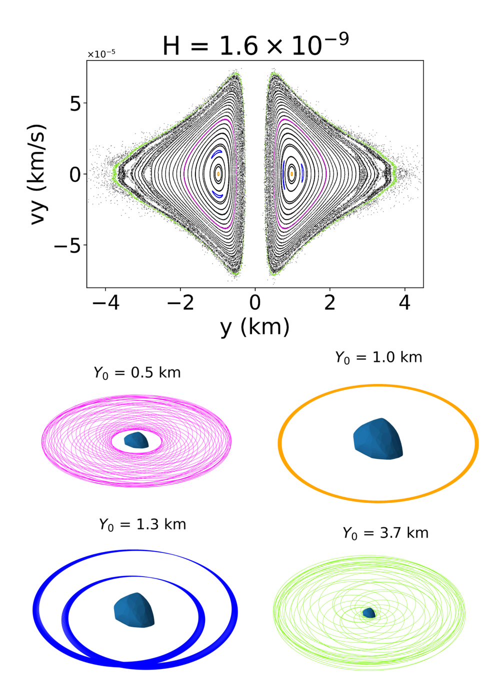


(4)

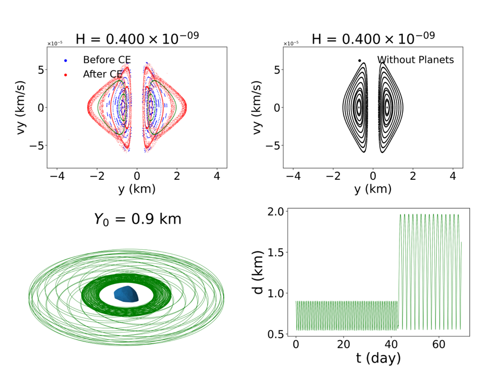
Surfaces of Section

- $x_0 = z_0 = \dot{y}_0 = \dot{z}_0 = 0$ and $\dot{x}_0$ was computed according to the mechanical energy of the orbit.

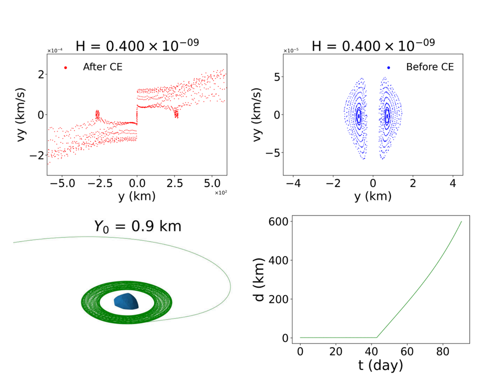
- Only the perturbations coming from the shape.



- The perturbations of the shape and the planets.



- The perturbations of the shape, the planets and the SRP.



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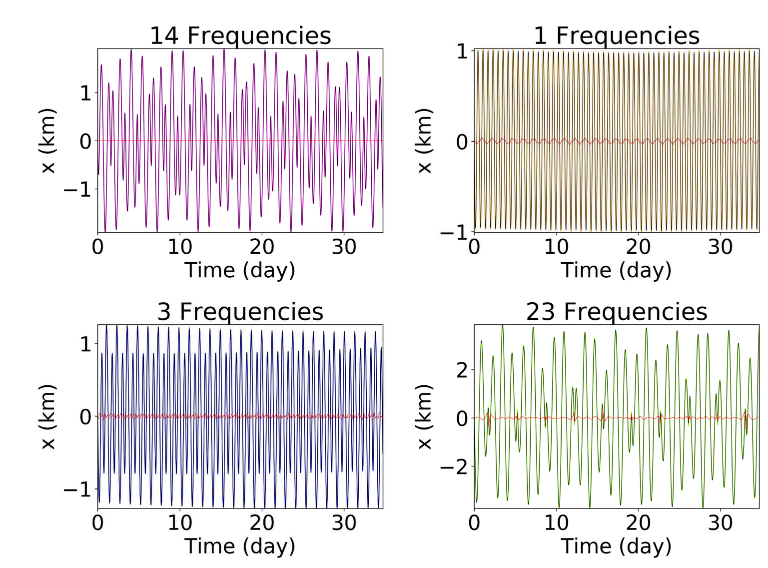
Ephemeris around Apophis

- Frequency analysis of the x, y, and z-coordinate of the orbit.
  - Removed the quadratic variation of the form: $\alpha + \beta t + \gamma t^2$.
  - (FFT) $\xrightarrow{\text{TRIP}}$ determine the leading frequencies.
  - Nonlinear regression approach → model the signal (Fourier-type and Poisson-type):

$$x(t) = \sum_{i=1}^{N}\left[A_i \sin(f_i t) + B_i \cos(f_i t) + C_i t \sin(f_i t) + D_i t \cos(f_i t)\right]$$



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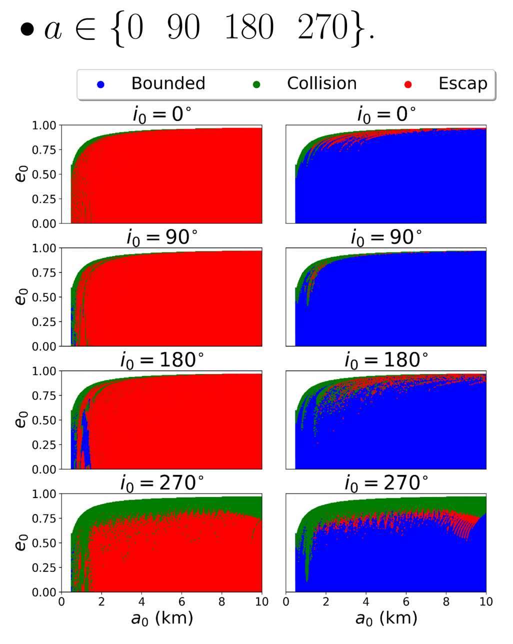
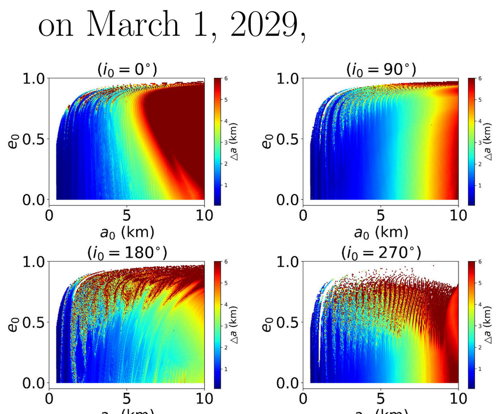
Search for less perturbed regions

- $a \in [0.5 \ \ 10]$, step of 25 m.
- $e \in [0 \ \ 1]$, step of 0.005.
- $a \in \{0 \ \ 90 \ \ 180 \ \ 270\}$.

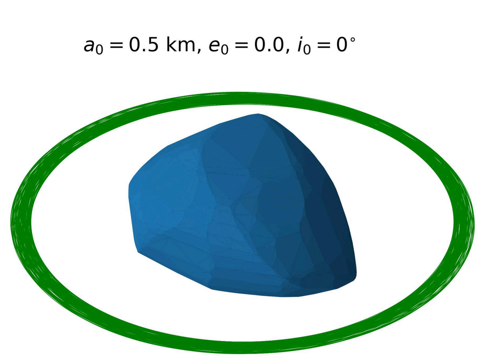


- Type of orbits for 60 days (left column) and 40 days (right column). → Majority of orbits collide or escape at the time of the close approach with Earth.

- Results for 40 days $\xrightarrow{\triangle a}$ identify suitable regions for a spacecraft on March 1, 2029,



- Minimum value of $\triangle a$ is 50 m. Corresponding $\triangle e$ is 0.128 → Non-negligible variation



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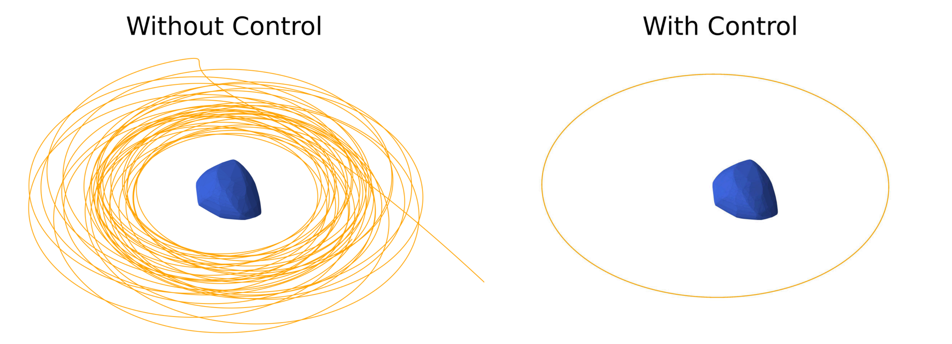
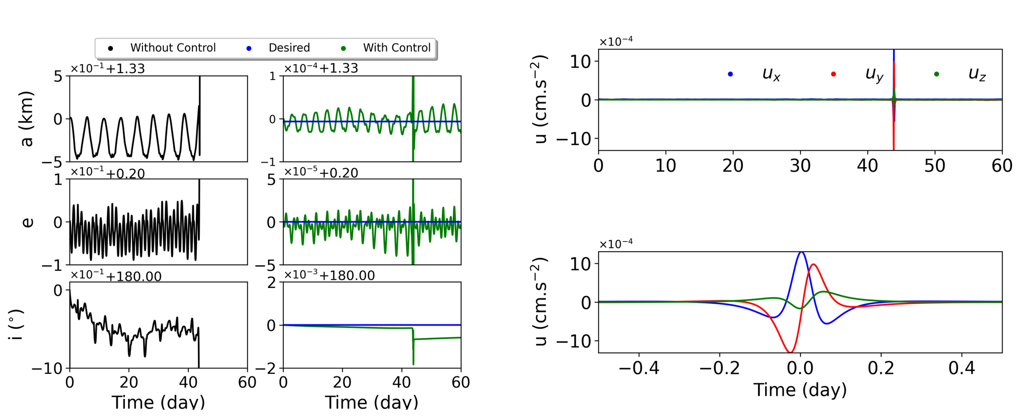
Orbital control around Apophis

- No stable regions around our target during the close approach → Sliding mode control theory to solve the stabilization problem.
- With a total $\triangle V$ of 0.495 m/s for 60 days of operation, we successfully stabilized an orbit with $a_0 = 0.5$ km, $e_0 = 0.2$, $i_0 = 180°$.





- Variation of the Orbital parameters (right) and the control components of the orbit (left)

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Conclution

- Generalized discussion on the dynamics around Apophis during its Earth close approach.
- CPM-Asteroid (Close Proximity Motion relative to an Asteroid) database in the GitHub repository under an MIT public license. https://github.com/safwanaljbaae/CPM-Asteroid.
- We used a web application framework developed with Shiny in R.
- Any other data presented in this paper can be obtained directly from the corresponding author upon reasonable request.
- It may be difficult, from a ballistic point of view, to launch a probe close to Apophis, but the idea deserves some interest.

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