Non-gravitational perturbations in NEODyS: the case of asteroid (410777) 2009 FD.

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Abstract

For more than ten years both the University of Pisa and the Jet Propulsion Laboratory (JPL) have been operating impact monitoring systems [1]. These online information systems continually and automatically update the list of asteroids with potential Earth impacts in the next 100 years. The attempt to extend the monitoring time span to a longer interval and to go beyond planetary scattering encounters is at the frontier of research on the theory of chaos, nongravitational perturbations, and new observation error models. Some special cases, as (99942) Apophis [2], (101955) Bennu [3], and (29075) 1950 DA [4] were successfully handled. In all these cases the authors modeled and solved for parameters appearing in the non-gravitational perturbations, especially the Yarkovsky effect.

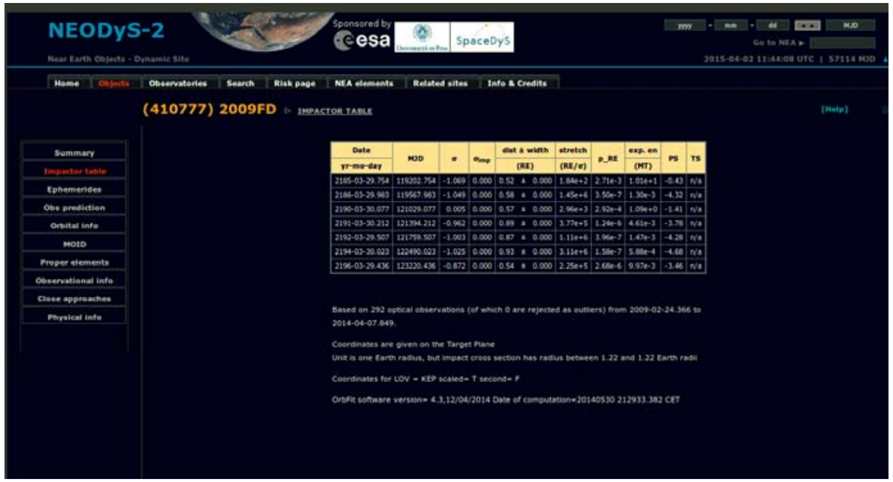
The presence of cases for which non-gravitational perturbations are relevant in the orbit determination and in the impact monitoring process led us to develop a new, experimental software. All the orbit determination process has to be done with seven parameters. The new software version also implements a full seven-dimensional Line of Variations [5] and a seven-dimensional impact monitoring.

As an example, we analyze asteroid (410777) 2009 FD, which recently appeared as a new special case. 2009 FD currently is the asteroid with the highest value of the Palermo Scale in the risk list with an impact probability of 2.7×10^{-3}.

NEODyS

The team of the NEODyS Consortium has already developed some experimental code that includes the capability of propagating and determining orbits with more than 6 parameters. This new code has also the capability of performing the impact monitoring in more than 6 dimensional parameter space. We already published some results on the NEODyS Risk Page, namely for (99942) Apophis and **(410777) 2009 FD** [6].

Impactor table



Date yr-mo-day	MJD	σ	σ_{imp}	dist ± width (RE)	stretch (RE/σ)	p_RE	exp. en (MT)	PS	TS
2185-03-29.754	119202.754	-1.069	0.000	0.52 ± 0.000	1.84e+2	2.71e-3	1.01e+1	-0.43	n/a
2186-03-29.983	119567.983	-1.049	0.000	0.58 ± 0.000	1.45e+6	3.50e-7	1.30e-3	-4.32	n/a
2190-03-30.077	121029.077	0.005	0.000	0.57 ± 0.000	2.96e+3	2.92e-4	1.09e+0	-1.41	n/a
2191-03-30.212	121394.212	-0.962	0.000	0.89 ± 0.000	3.77e+5	1.24e-6	4.61e-3	-3.78	n/a
2192-03-29.507	121759.507	-1.003	0.000	0.87 ± 0.000	1.11e+6	3.96e-7	1.47e-3	-4.28	n/a
2194-03-30.023	122490.023	-1.025	0.000	0.93 ± 0.000	3.11e+6	1.58e-7	5.88e-4	-4.68	n/a
2196-03-29.436	123220.436	-0.872	0.000	0.54 ± 0.000	2.25e+5	2.68e-6	9.97e-3	-3.46	n/a

Based on 292 optical observations (of which 0 are rejected as outliers) from 2009-02-24.366 to 2014-04-07.849.

Coordinates are given on the Target Plane

Unit is one Earth radius, but impact cross section has radius between 1.22 and 1.22 Earth radii

Coordinates for LOV = KEP scaled= T second= F

OrbFit software version= 4.3,12/04/2014 Date of computation=20140530 212933.382 CET

Figure 1: Impactor table of (41077) 2009 FD.

(410777) 2009 FD

Asteroid (41077) 2009 FD could hit the Earth between 2185 and 2196. The Yarkovsky effect has been modeled by using the available physical characterization of 2009 FD, and general properties of the Near Earth Asteroid population. The standard impact monitoring algorithms in use by NEODyS generate orbital samples in a seven-dimensional space that includes orbital elements and the parameter characterizing the Yarkovsky effect. The highest impact probability is $\mathbf{2.7 \times 10^{-3}}$ for an impact during the **2185 Earth encounter**.

Modeling the Yarkovsky effect

The Yarkovsky effect is modeled as a purely transverse acceleration $\mathbf{A_2/r^2}$ [7]. Since in the case of 2009 FD A_2 is not significantly constrained by the fit to the astrometry, we adopted an a priori value $A_2 = (0 \pm 32.5) \times 10^{-15}$ au/d^2, which is based on the available physical model for 2009 FD. [6, Sec.3]. In these conditions, the best fit value is $\mathbf{A_2 = (-2 \pm 32.5) \times 10^{-15}}$ au/d^2.

Results

- The 2185 VI has the highest $\mathbf{PS = -0.43}$ among all the asteroids currently on NEODyS Risk Page.
- Its **IP** $\mathbf{\sim 1/369}$ is quite high, especially for an impact with an estimated energy of $\sim 3\,700$ Mt of TNT.
- The computation of the Yarkovsky effect were crucial for a reliable assessment of the impact risk.

Conclusions and Future work

- The most difficult task is to properly select the right objects for which we need to include the non-gravitational perturbations.
- The software for the computation of the non-gravitational perturbations will be operational very soon.

References

[1] A. Milani, S. R. Chesley, M. E. Sansaturio, et al. Nonlinear impact monitoring: line of variation searches for impactors. *Icarus*, 173:362–384, February 2005.

[2] D. Farnocchia, S. R. Chesley, P. W. Chodas, et al. Yarkovsky-driven impact risk analysis for asteroid (99942) Apophis. *Icarus*, 224:192–200, May 2013.

[3] S. R. Chesley, D. Farnocchia, M. C. Nolan, et al. Orbit and bulk density of the OSIRIS-REx target Asteroid (101955) Bennu. *Icarus*, 235:5–22, June 2014.

[4] D. Farnocchia and S. R. Chesley. Assessment of the 2880 impact threat from Asteroid (29075) 1950 DA. *Icarus*, 229:321–327, February 2014.

[5] A. Milani, M. E. Sansaturio, G. Tommei, et al. Multiple solutions for asteroid orbits: Computational procedure and applications. *Astronomy & Astrophysics*, 431:729–746, February 2005.

[6] F. Spoto, A. Milani, D. Farnocchia, et al. Nongravitational perturbations and virtual impactors: the case of asteroid (410777) 2009 FD. *Astronomy & Astrophysics*, 572:A100, December 2014.

[7] D. Farnocchia, S. R. Chesley, D. Vokrouhlický, et al. Near Earth Asteroids with measurable Yarkovsky effect. *Icarus*, 224:1–13, May 2013.

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