An estimation of the Yarkovsky effect for (99942) Apophis via high-order Taylor polynomials

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- Using `TaylorIntegration.jl`[1], we propagate the orbit of Apophis as a Taylor polynomial w.r.t. time t, changes in the initial position/velocity $\delta\mathbf{x}_0$ and the Yarkovsky parameter A_2. This technique is known as *jet transport*.

- From this, we compute the (weighted) mean square residual $Q(\delta x_0, A_2) = \chi^2/n_{\mathrm{obs}}$ as a Taylor polynomial in the unknown orbital parameters. We use all available radar astrometry for this object (17 delay, 29 Dopplers) and selected optical astrometry (472 RA/Dec pairs) following Vokrouhlický et al. (2015).

- We obtain two orbital fits to radar+optical data: a gravity only 6-DOF (**OR6**) and a 7-DOF fit (**OR7**) which accounts for Yarkovsky. We find local minima of the Taylor expansion of Q via Newton method.

- We find a mean semi major axis drift $\langle \dot{a} \rangle = (-341 \pm 158)\ \mathrm{m/yr}$, corresponding to $A_2 = (-5.0 \pm 2.8) \times 10^{-14}\ \mathrm{au/d^2}$.

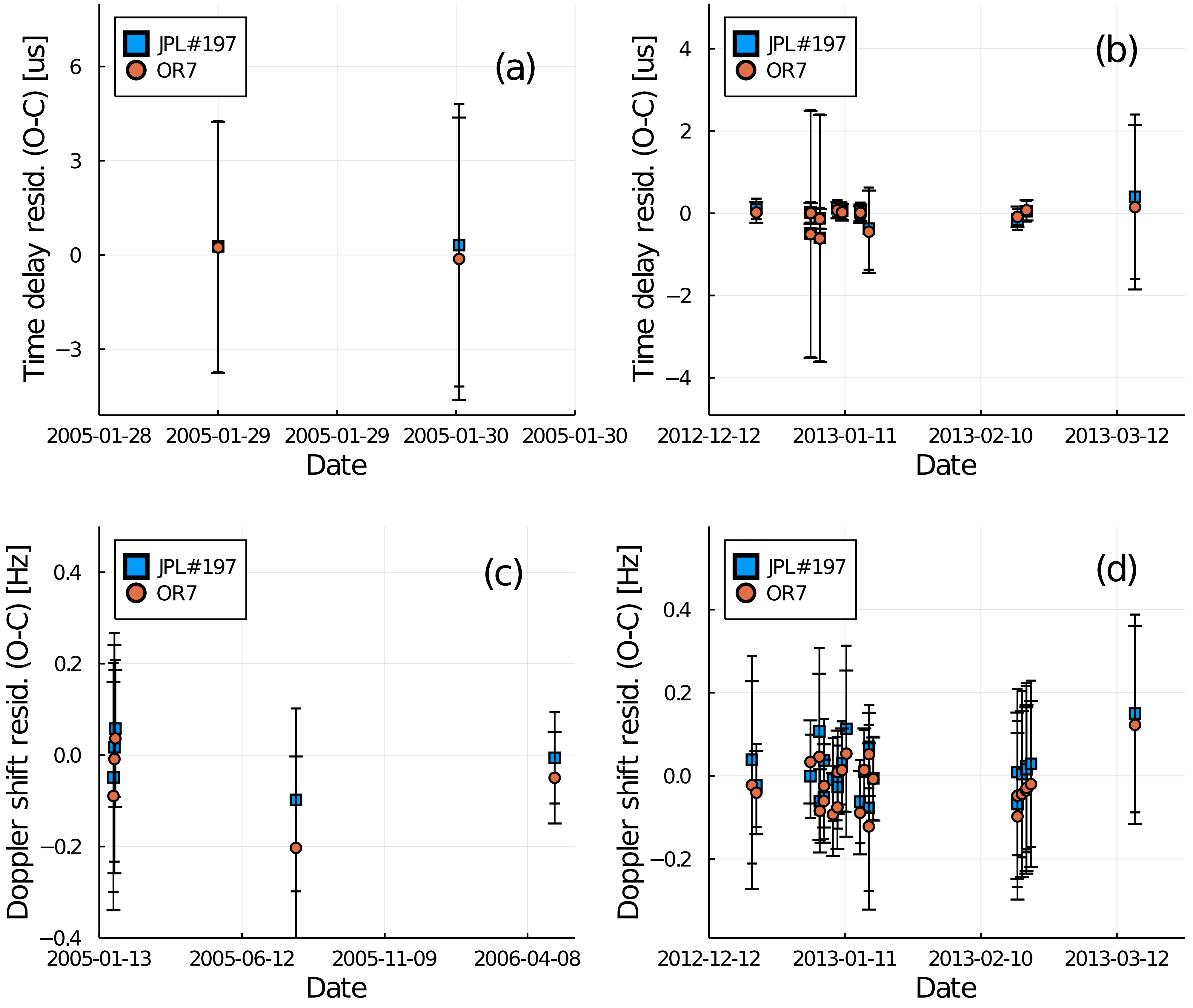

Fig: Post-fit delay/Doppler astrometric residuals (OR7).

[1] URL: github.com/PerezHz/TaylorIntegration.jl

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Optical astrometry postfit residuals

- Our optical astrometry error model accounts for biases present in star catalogs, and accounts for other sources of systematic errors via an appropriate weighting scheme.
- We compare the post-fit astrometric residuals for observations from Tholen et al. (2013), for two debiasing tables: Farnocchia et al. (2015) and Eggl et al. (2020).
- Using Eggl. et al. (2020) debiasing table, we find a mean RA/DEC postfit residual $(0.011'', -0.009'')$ for the Tholen et al. (2013) astrometry.

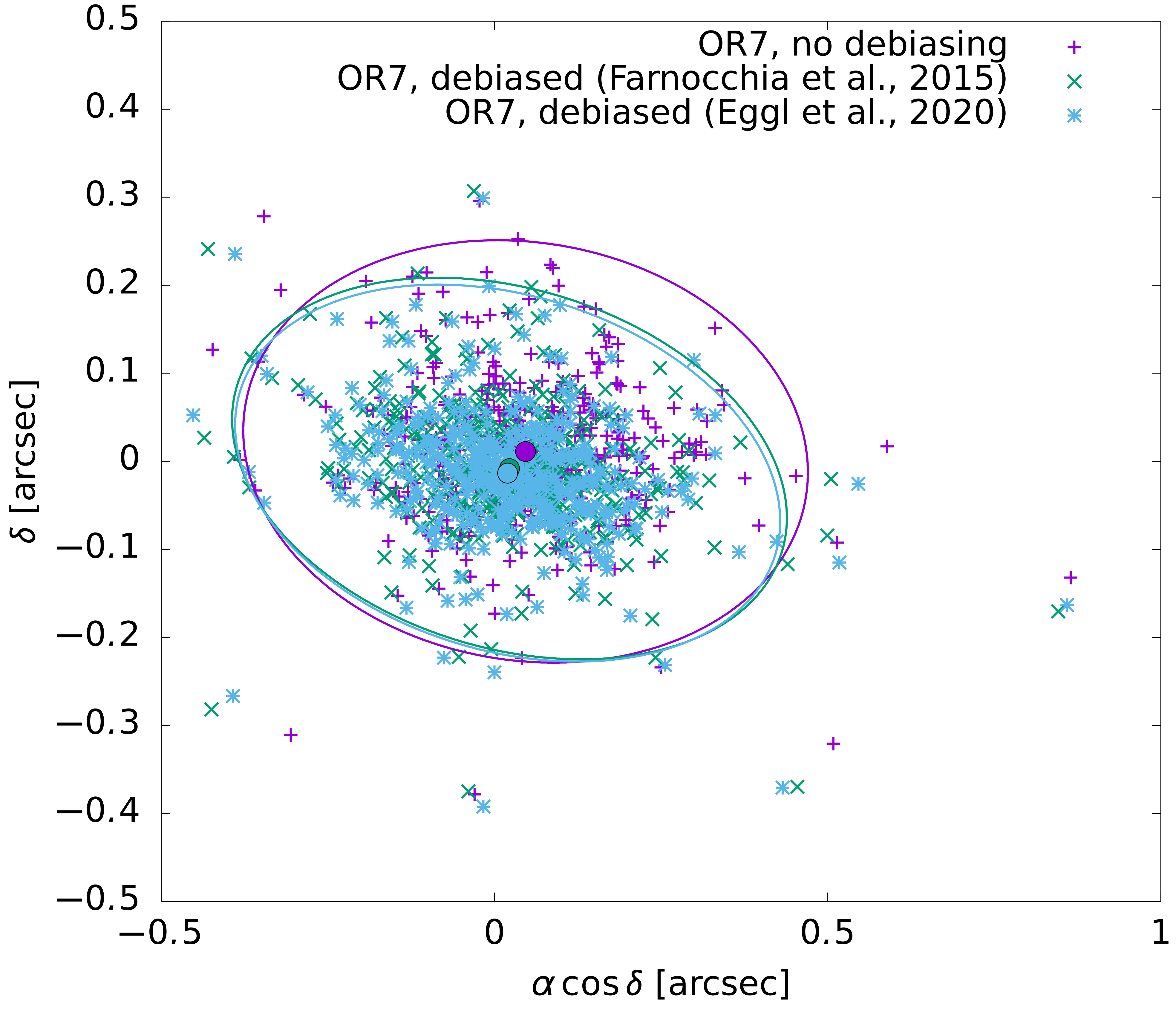

Fig: Post-fit residuals for Tholen et al. (2013) optical astrometry. Ellipses correspond to 3-σ level.

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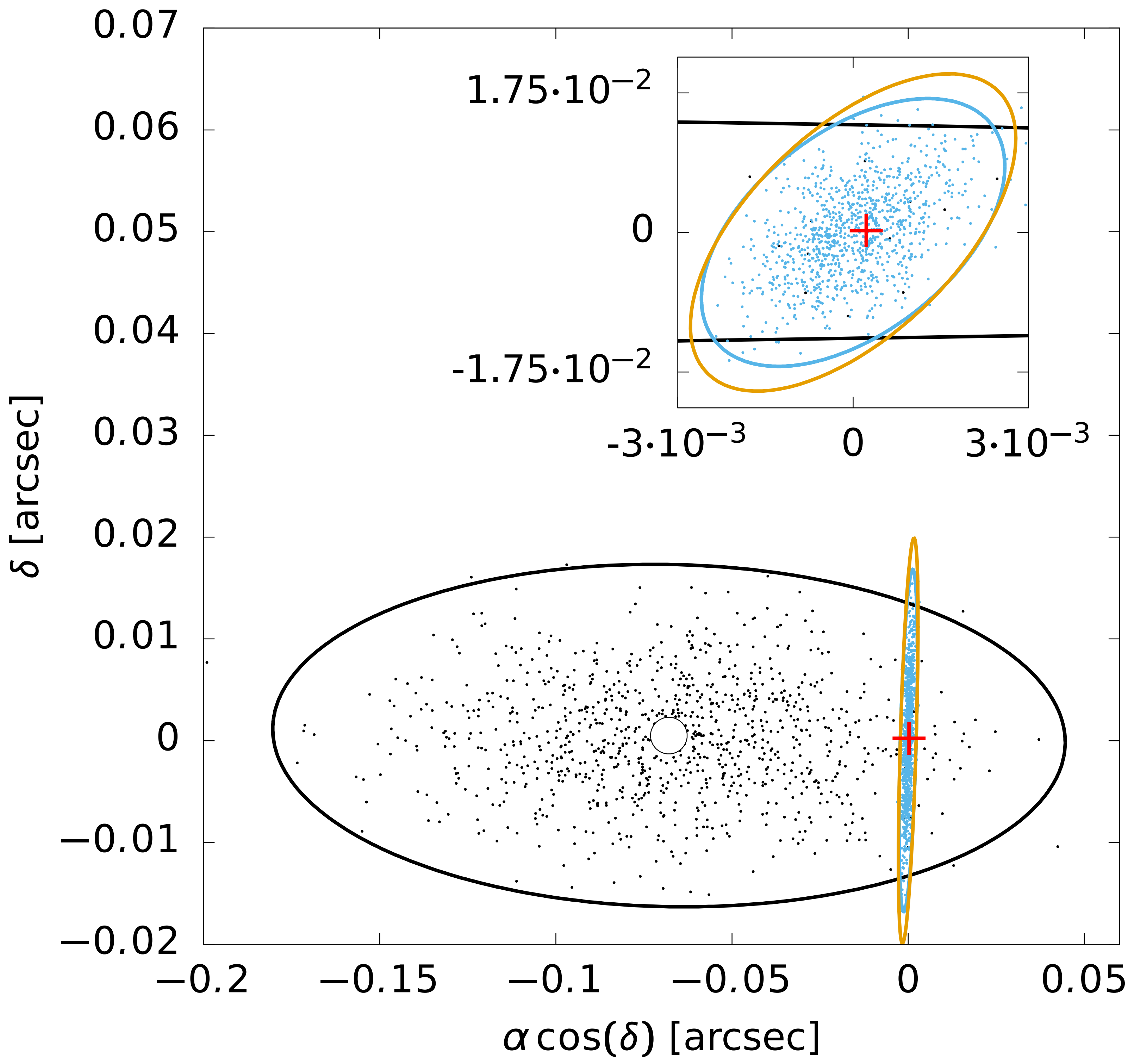
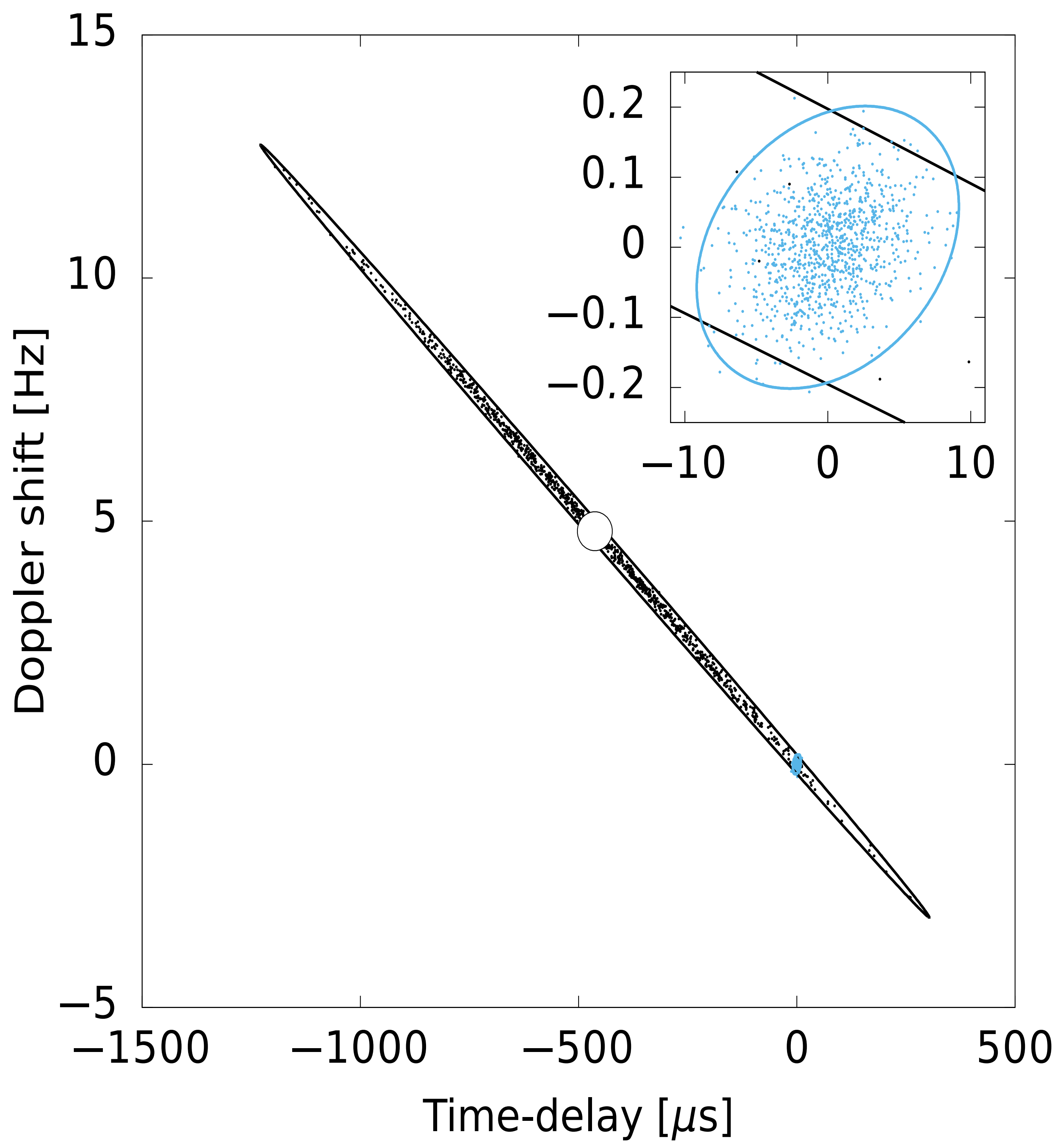
Optical astrometry residuals: OR6, OR7 prediction vs observed value (Mt. Lemmon G96, 2020-Jun-08)

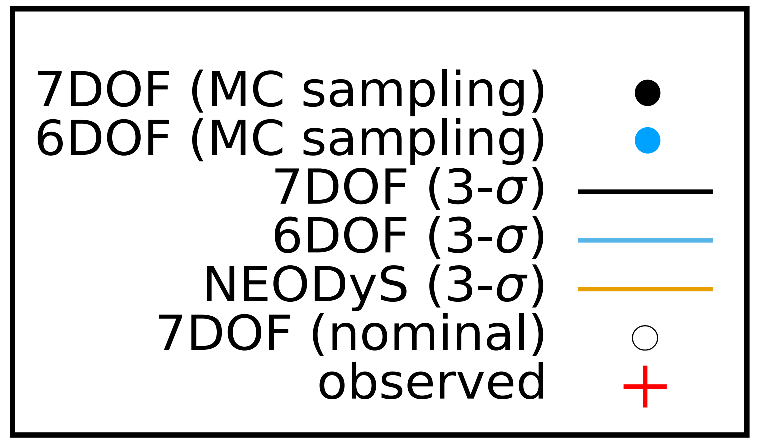


$$\alpha_{\mathrm{OR6}} = 143.806 \text{ deg}$$
$$\delta_{\mathrm{OR6}} = 14.646 \text{ deg}$$

Radar astrometry prediction: OR6 vs OR7. (Goldstone, 2021-Mar-06 11:00 UTC)



$$\tau_{\mathrm{OR6}} = 112{,}427{,}832.2\ \mu s$$
$$\nu_{\mathrm{OR6}} = -\,24485.179\text{Hz}$$



- OR6: gravity-only 6-DOF orbital fit to radar+optical
- OR7: non-grav. 7-DOF orbital fit to radar+optical

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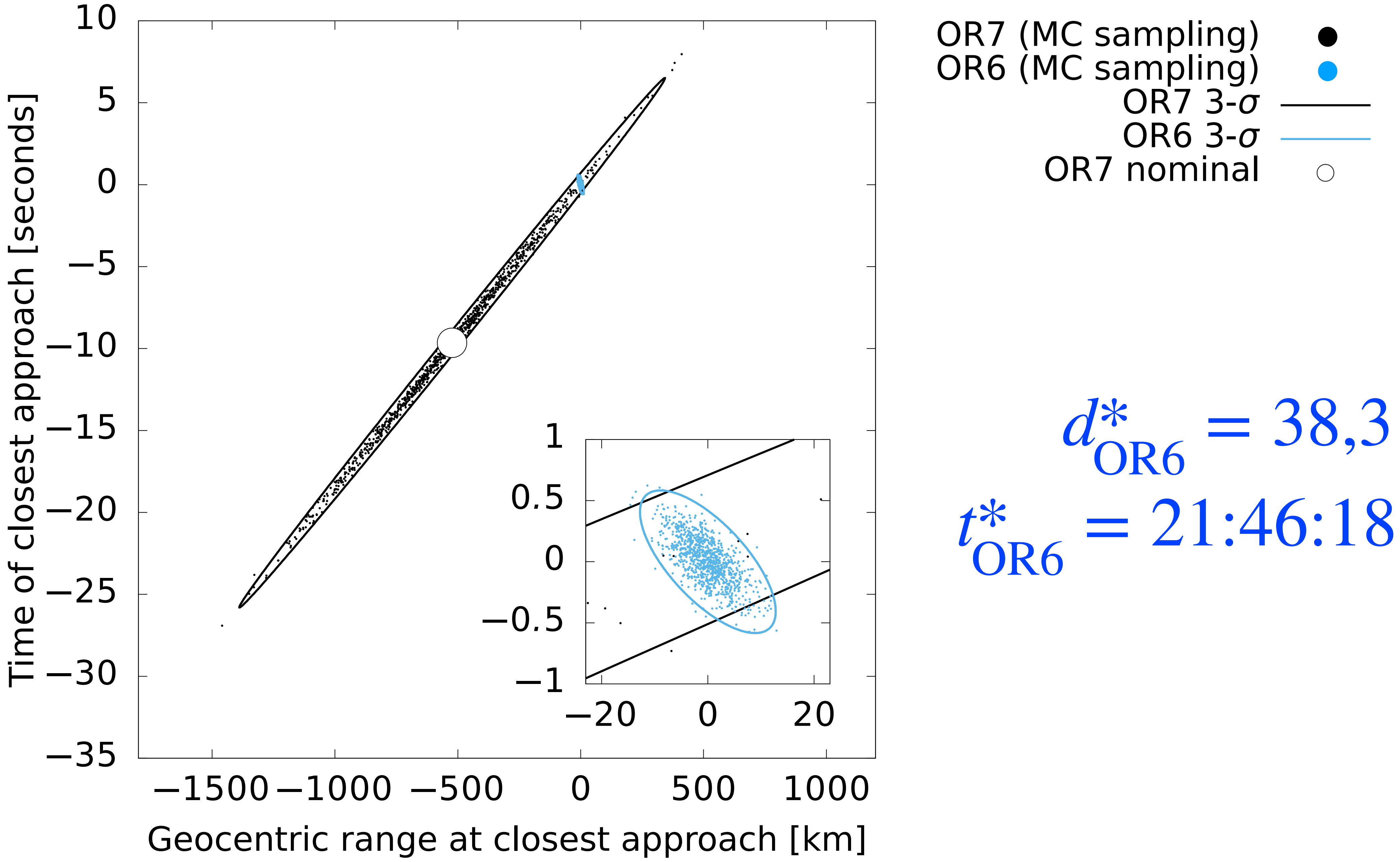
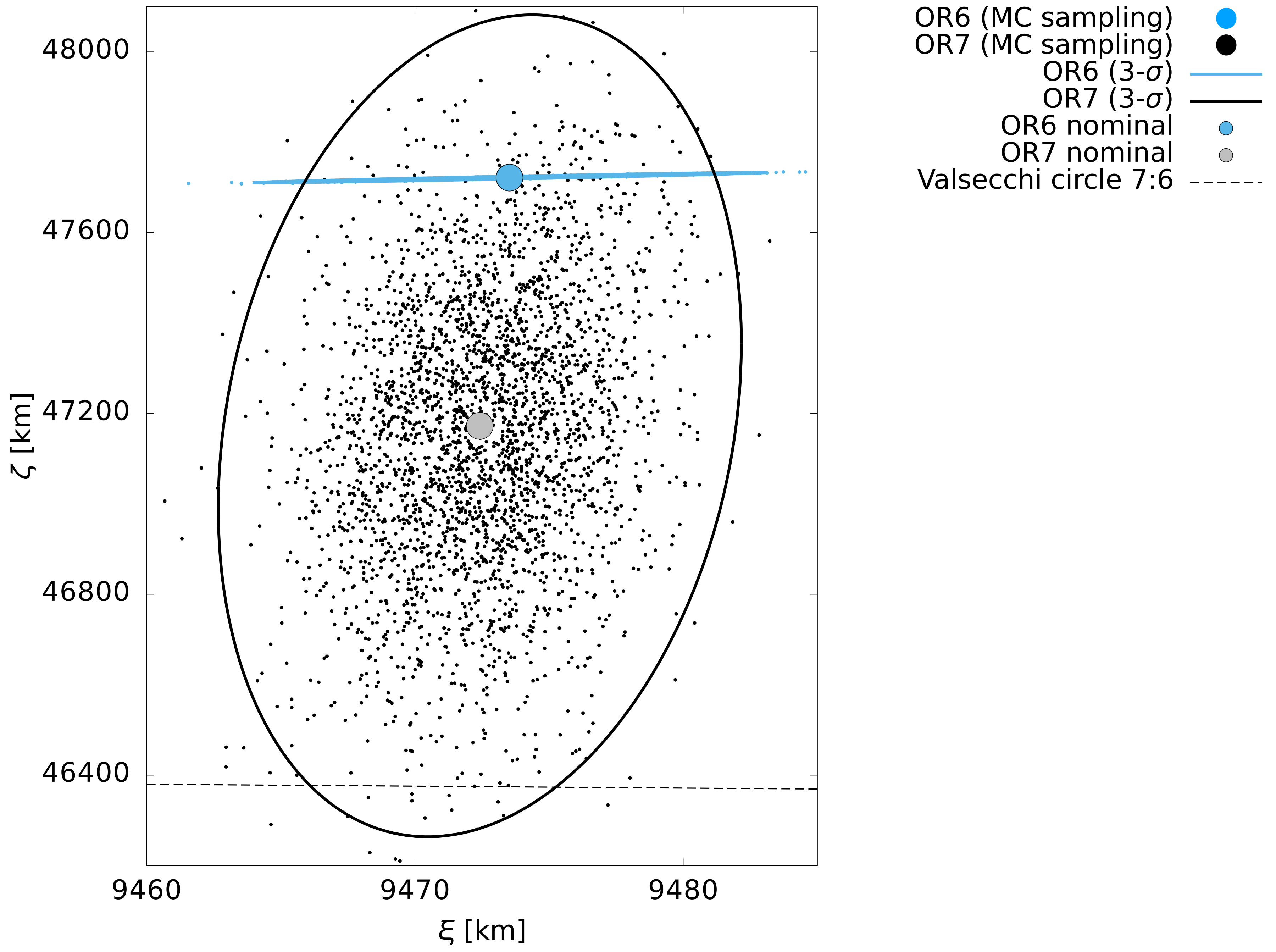
2029 close approach: OR6 vs OR7



$$d^*_{\mathrm{OR6}} = 38{,}314\ \mathrm{km}$$

$$t^*_{\mathrm{OR6}} = 21{:}46{:}18.475\ \mathrm{TDB}$$

2029 B-plane (Öpik's frame)



Conclusions:

- We implemented a software package for NEA orbit determination and uncertainty propagation based on high-order Taylor method. To be made public soon; stay tuned!
- We provide an independent (marginal) estimation of Yarkovsky effect for Apophis from data, consistent with previous results.
- WIP: updating orbital fits with 2019-2020 data.

Github:
@PerezHz
PerezHz/TaylorIntegration.jl

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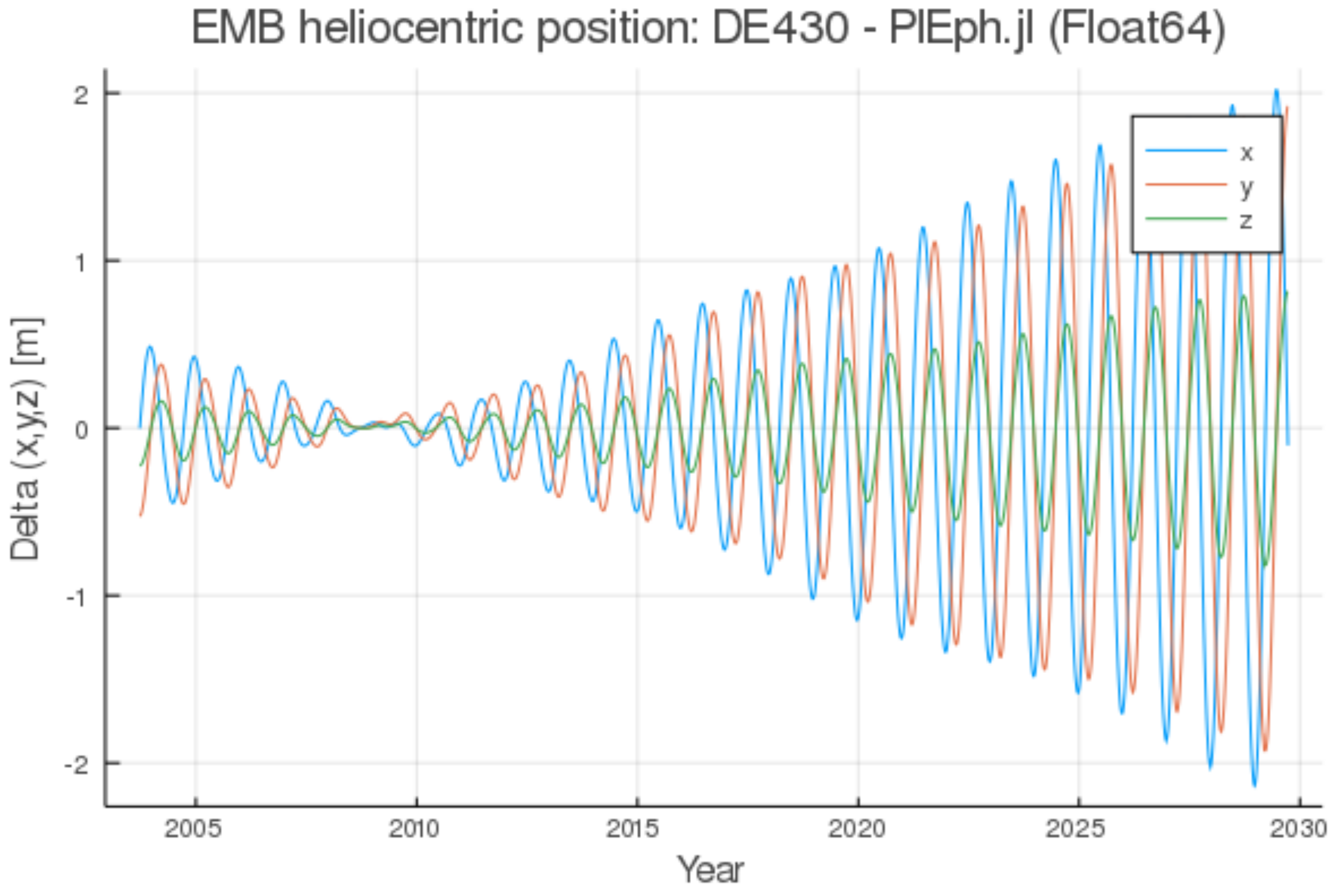
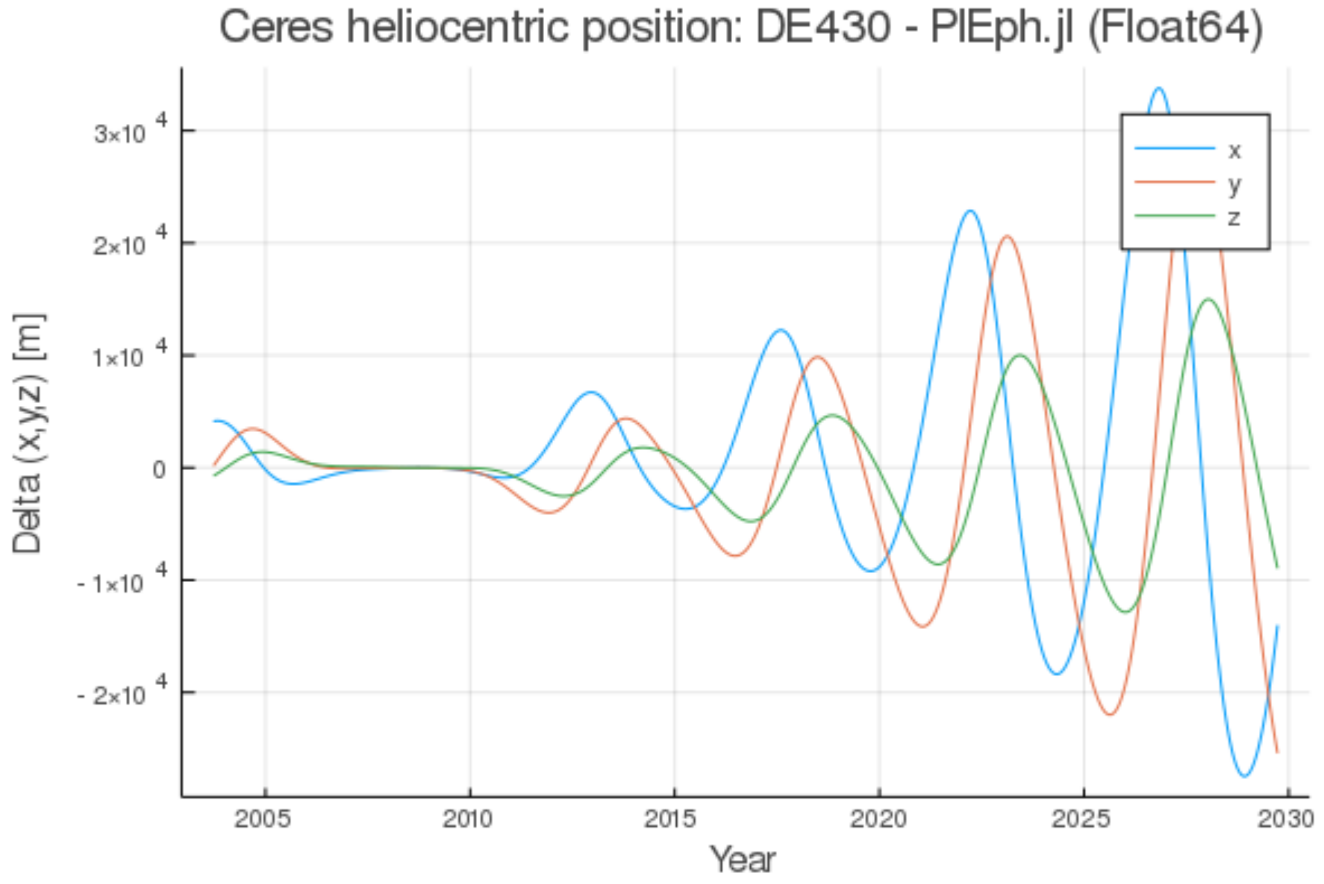
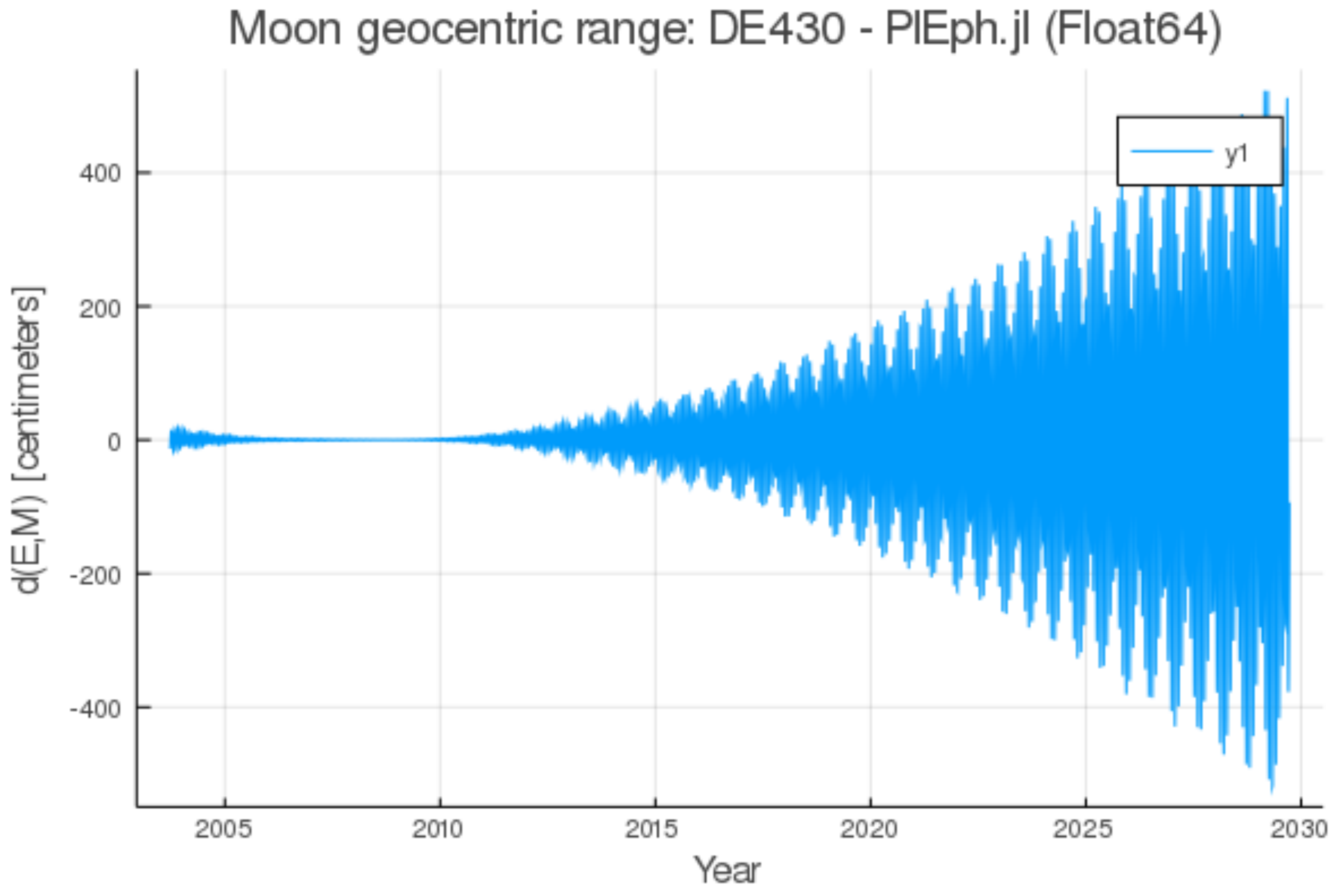
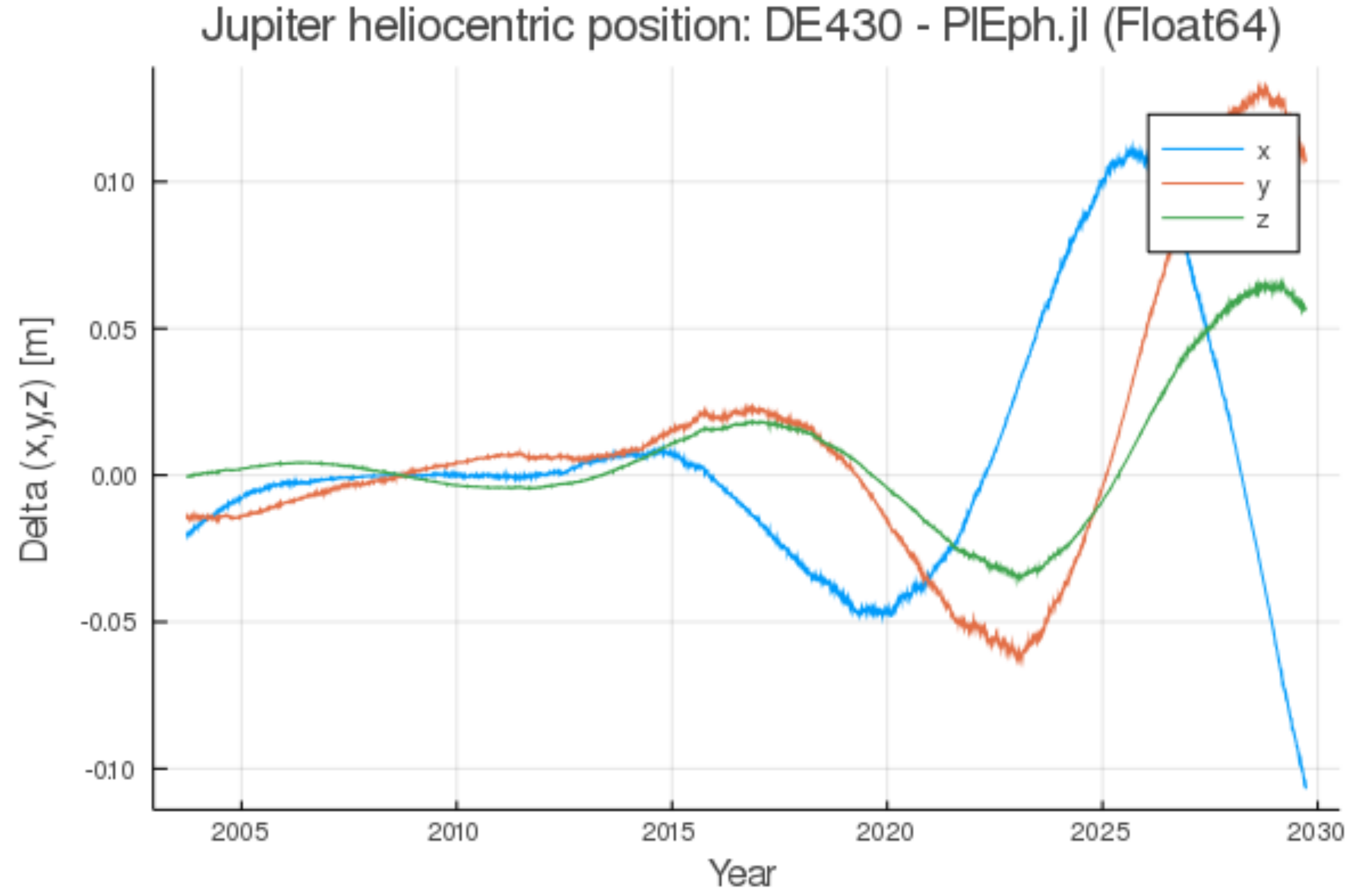
Planetary ephemeris

- To integrate the orbit of Apophis, as planetary ephemeris we use our own numerical integration of the JPL DE430 dynamical model (Folkner et al., 2014).
- In the time-span of our numerical integrations (2004-2029), we are able to reproduce the planetary heliocentric positions and lunar geocentric range below the ~5 m level.









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Apophis orbital motion model

Our dynamical model for Apophis orbital motion includes:

- Post-Newtonian interactions with the Sun, the eight planets, the Moon and Pluto.
- Newtonian interactions with 16 most-massive asteroids.
- Acceleration due to Earth's J_2.
- We model the Yarkovsky effect as an acceleration in the transverse direction: $\mathbf{a}_t = A_2/r^2\ \hat{\mathbf{t}}$.
- We integrate the equations of motion exploiting jet transport techniques, as implemented in `TaylorIntegration.jl`. Jet transport allows us to compute the q-th order Taylor expansion of the orbit around a given set of orbital parameters $\mathbf{x}_0$:

$$\tilde{\mathbf{x}}(\delta\mathbf{x}_0, t) = \mathbf{x}^{[0]}(t) + \sum_{l=1}^{q} \mathbf{x}^{[l]}(t)(\delta\mathbf{x}_0)^l.$$