Detection of Yarkovsky acceleration with old observations and Gaia

Josselin Desmars

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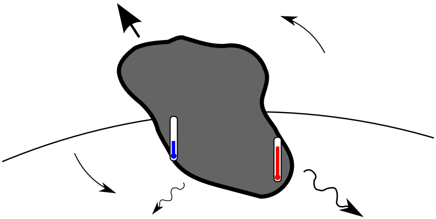
Introduction

Yarkovsky effect

- The Yarkovsky effect is a weak non gravitational force associated with anisotropic emission of thermal radiation
- It affects mainly small NEAs (about 10 cm to 10 km in diameter)
- Despite its small magnitude, it has important effect in dynamical evolution of NEAs
- One of the main effects is to modify the semimajor axis



Brief story of Yarkovsky effect

~1900 The effect was discovered around 1900 by I.O. Yarkovsky

1951 E.Öpik discussed the possible importance of the effect in meteroids motions

2003 Chesley *et al.* →first measure of Yarkovsky effect on a asteroid (6489 Golevka) using radar measurements

2008 Vokrouhlický *et al.* →first measure of Yarkovsky effect on a asteroid (152563) 1992BF using astrometrical observations

2010s Nugent *et al.* (2012), Farnocchia *et al.* (2013), Desmars (2015), Del Vigna *et al.* (2018) → Detection of Yarkovsky acceleration for dozens of NEAs

Igor O. Yarkovsky

Aim: How old observations and Gaia will help to detect Yarkovsky effect?

Modelling the Yarkovsky effect

Modelling the Yarkovsky effect

Complex Modelling

- Vokrouhlický *et al.* (2000) modeled the force by solving the surface heat diffusion problem.
- Diurnal effect (dominant) and seasonal effect
- With linear method, the rate of change of semimajor axis **da/dt** depends on γ obliquity of spin axis, ρ_b bulk density, D diameter and Θ diurnal thermal parameter

$$\frac{da}{dt} \propto \frac{\cos\gamma}{\rho_b D} \frac{\Theta}{1+\Theta+0.5\Theta^2}$$

Aim: Detect da/dt from astrometry

Simple Modelling

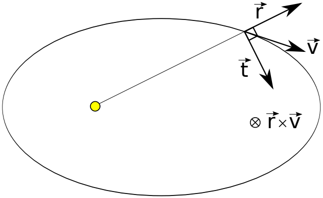
Yarkovsky acceleration can be modeled as a comet like model presented in Marsden *et al.* (1973) with a transverse acceleration:

$$\mathbf{a_Y} = \frac{A_2}{r^2}\mathbf{t}$$

which is equivalent to the relation used in Chesley *et al.* (2008):

$$\mathbf{a_Y} = \frac{n}{2}\frac{a^2(1-e^2)}{r^2}\left(\frac{da}{dt}\right)\mathbf{t}$$

Yarkovsky effect can be modeled as a transverse force, depending on orbital elements, the heliocentric distance and on a drift in semi major-axis $\dot{a} = \frac{da}{dt}$ where n is mean motion, a semi-major axis, e excentricity and $\mathbf{t} = \frac{(\mathbf{r}\times\mathbf{v})\times\mathbf{r}}{|(\mathbf{r}\times\mathbf{v})\times\mathbf{r}|}$ the transverse vector.



Dynamical model

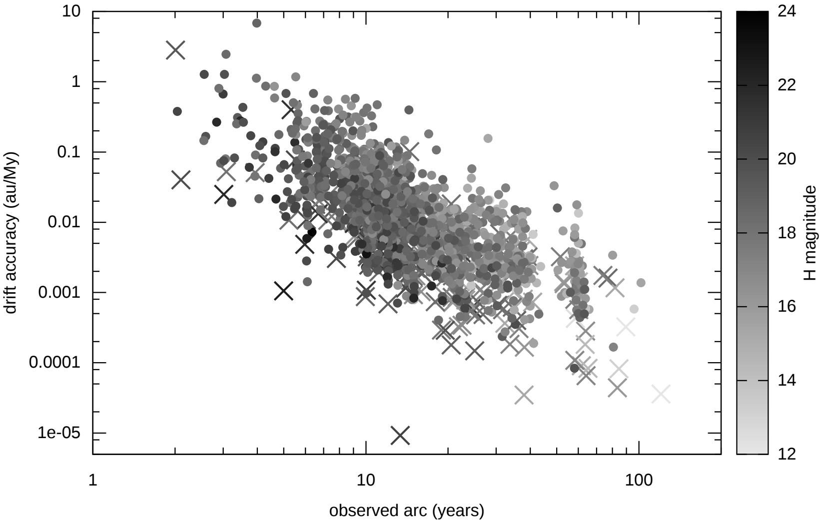
The dynamical model takes into account:

- gravitational perturbations of planets + Pluto + Moon
- gravitational perturbations of 3 main asteroids (Ceres, Vesta, Pallas)
- relativistic effects
- Yarkovsky acceleration ($\mathbf{a_Y}$)

Computation

- Numerical integration of the equations of motion and equations of variation
- Determination of initial parameters (initial position & velocity + semi-major axis drift rate $\dot{a}$ or A_2) by least-square method, giving also the covariance matrix of the parameters

Drift detection vs orbital arc



Desmars (2015)

Yarkovsky acceleration with astrometry

- A reliable drift in semi major axis da/dt (or A_2) can be detected for about 50-100 NEAs: Nugent *et al.* (2012), Farnocchia *et al.* (2013), Desmars (2015), Del Vigna *et al.* (2018)
- Statistics on these detections show:
  - $1/D$ dependence
  - a ratio pro/retrograde (given the sign of the drift) compatible with NEA transport mechanism La Spigna *et al.* (2004)

Example: (152563) 1992BF

Example: (152563) 1992 BF - importance of precovery observations

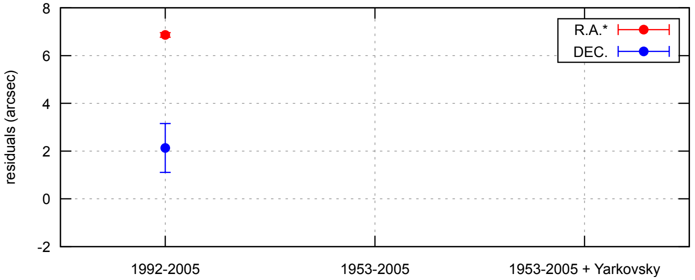
- Asteroid was discovered on 1992
- 4 **precovery** observations on January 1953 are available
- Vokrouhlický *et al.* (2008) reduced again 1953 precovery observations and detect a drift in semimajor axis using astrometric observations

$$\frac{da}{dt} = -(10.7 \pm 0.7) \times 10^{-4} \text{au.Myr}^{-1}$$

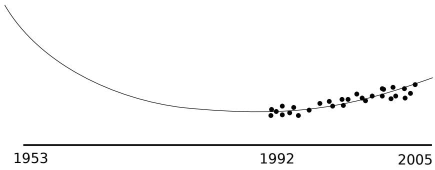
Astrometry (with 1953-2005 observations)

140 observations (1992-2005) + 4 observations (1953)

Orbit determination with 1992-2005 observations and no Yarkovsky effect



Residuals of 1953 observations



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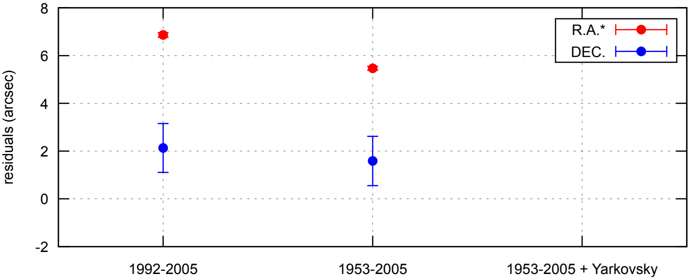

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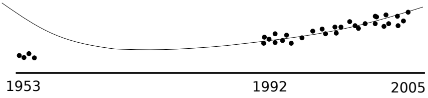

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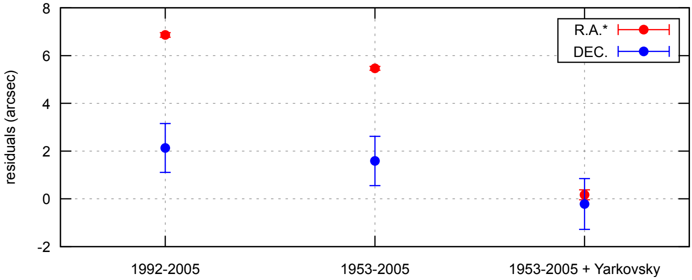

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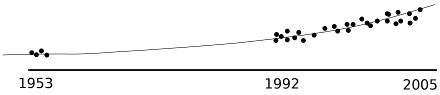
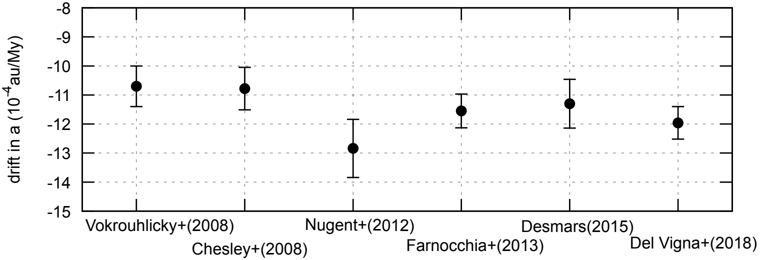


Drift of semimajor axis for 1992 BF

Vokrouhlický *et al.* (2008) with 1953-2008 observations:

$$\frac{da}{dt} = -(10.7 \pm 0.7) \times 10^{-4} \text{au.Myr}^{-1}$$

Other studies:



Importance of old/precovery observations

Influence of precovery observation for (152563) 1992BF

- What is happen if there is no precovery observations on 1953 but on other period?
- What is the influence of the precovery observation's date on the uncertainty of the drift in semimajor axis?
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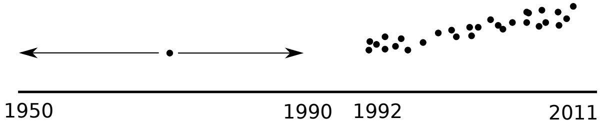
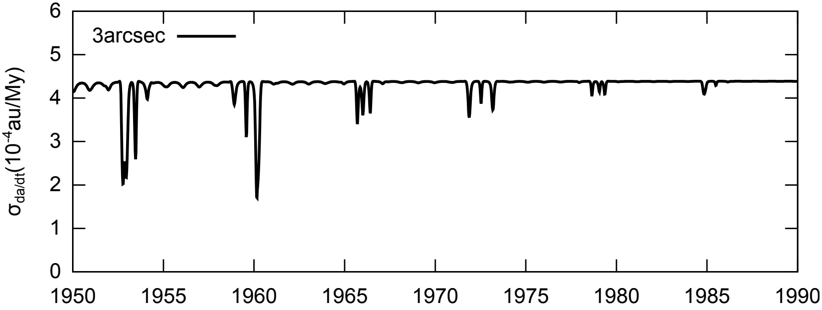


Influence of precovery observation for (152563) 1992BF

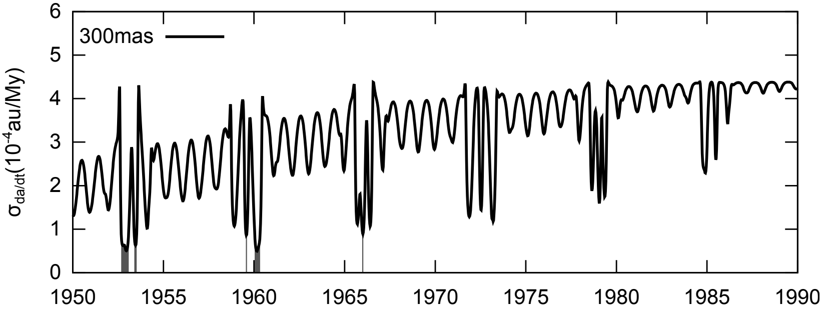
We reduced the first observation with a precision of $\sigma = 3$ arcsec



Desmars (2015)

Influence of precovery observation for (152563) 1992BF

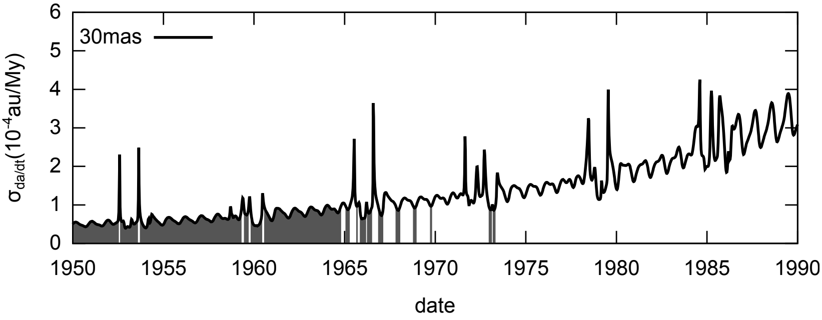
We reduced the first observation with a precision of $\sigma = 300$ mas



Grey area corresponds to $\sigma_{\dot{a}} < 10^{-4}$au/My (corresponds to SNR∼10)

Influence of precovery observation for (152563) 1992BF

We reduced the first observation with a precision of $\sigma = 30$ mas



Grey area corresponds to $\sigma_{\dot{a}} < 10^{-4}$au/My (corresponds to SNR$\sim$10)

Precovery observations

- Precovery observations, by increasing the observational period, can help to detect Yarkovsky acceleration with good precision
- Better precision when object is close to Earth (and so brighter)
- Even a precovery with $\sigma = 300$mas can be very useful

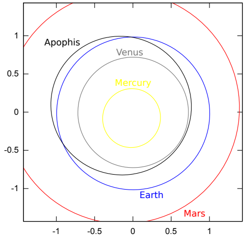
New astrometry of old observations with NAROO and Gaia

Strategy of reduction with Gaia catalogue

- All observations could not be reduced again
- Which part of observations should be reduced first?
- Which observations ?

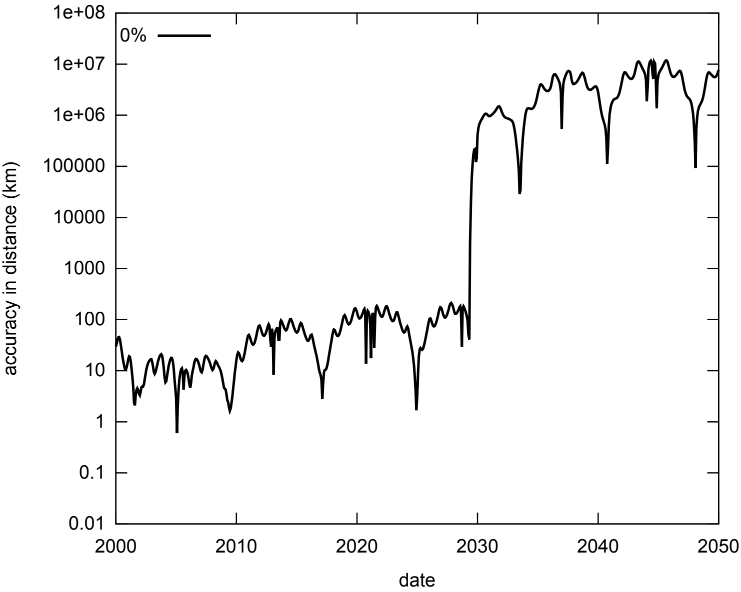
(99942) Apophis

- Near-Earth asteroid (even a PHA) discovered in 2004
- size: ∼325m
- Observations: ∼ 6300 obs. (2004-2015) and 20 radar measurements (13 ranging (2005-2013) + 7 doppler (2005-2013))
- Close approaches: 2004, 2013, 2021, 2029, ... possible risk of collision

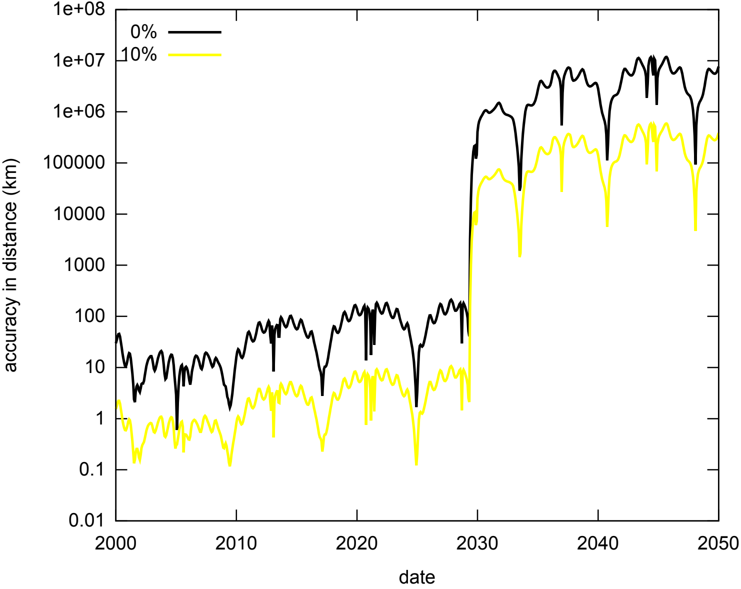


Observations

- We assume that a new reduction of observations with the Gaia catalogue will have a precision of 10mas
- What is the improvement in the orbit's precision if a *random* part (10%, 25%, 50%, 100%) of observations could be reduced with Gaia catalogue?



Desmars *et al.* (2013)



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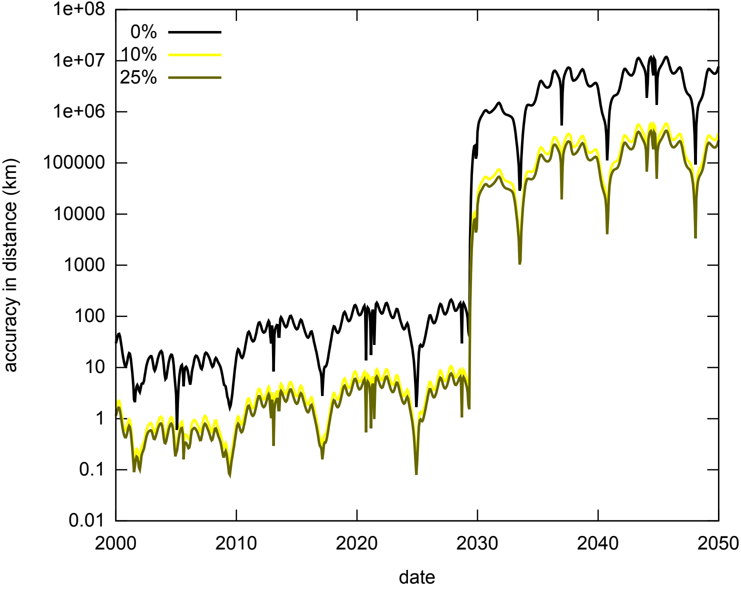

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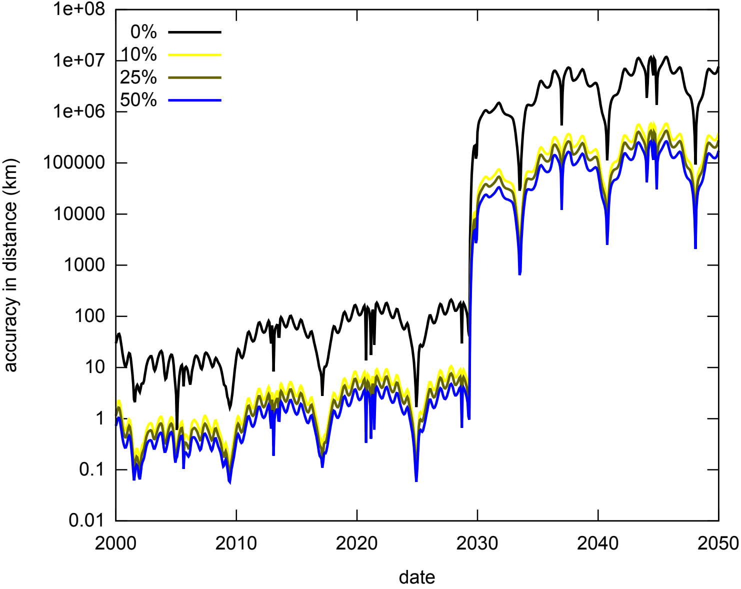

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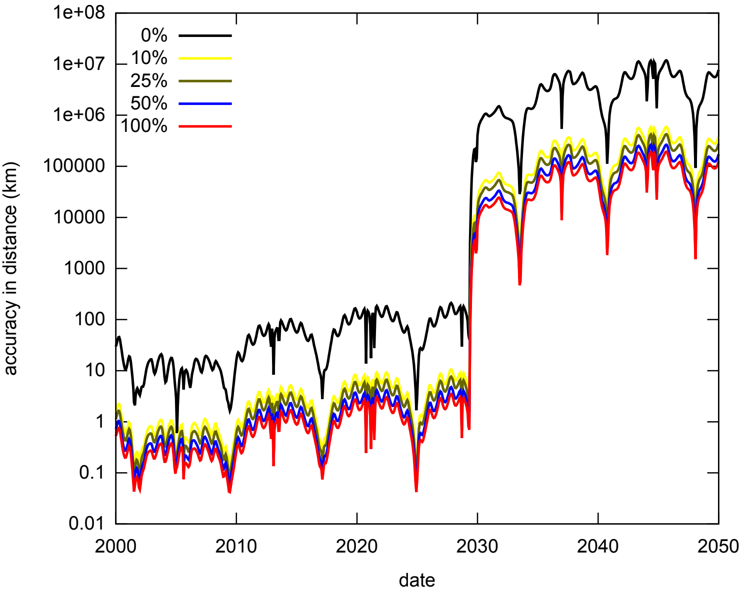


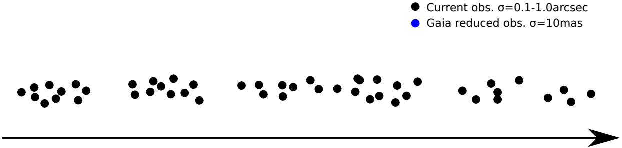
Desmars *et al.* (2013)

Which observations should be reduced first?

- Set 1: new reduction of a random set of $2N$ observations
- Set 2: new reduction of the first N and last N observations
- Comparisons show that Set 2 provide a better precision for the orbit

Reduction with Gaia stellar catalogue

1. Current observations (no reduction with Gaia catalogue)
2. Only the first and the last observation can be reduced with Gaia catalogue
3. Only the first 5 and the last 5 observations can be reduced with Gaia catalogue
4. Only the first 10 and the last 10 observations can be reduced with Gaia catalogue
5. All observations can be reduced with Gaia catalogue



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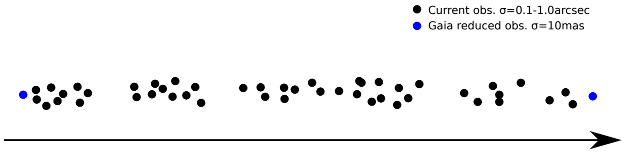

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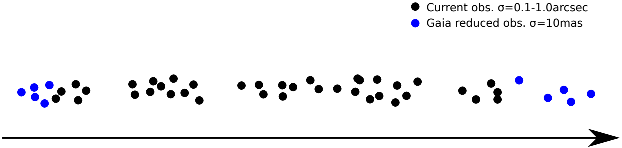

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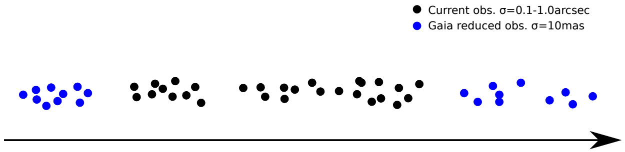

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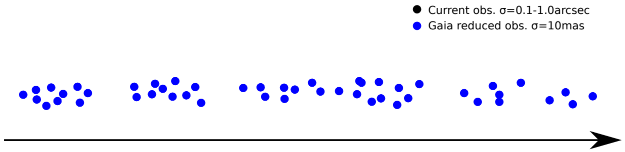

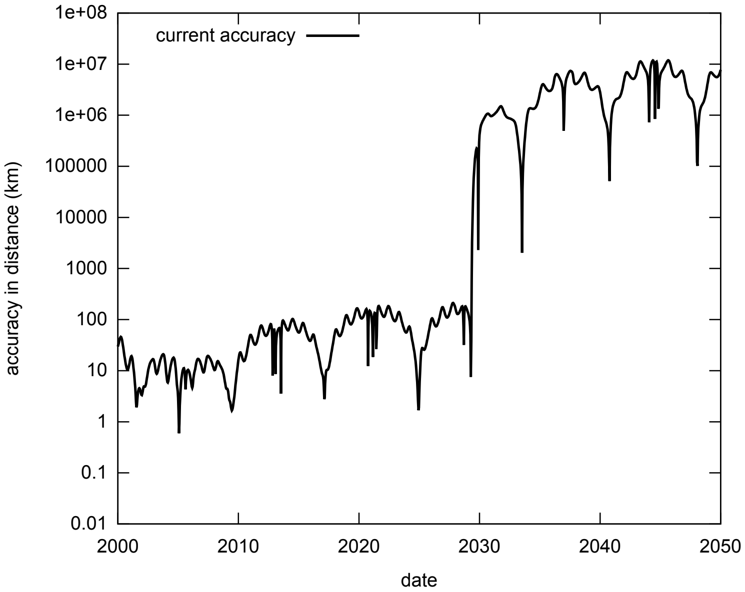

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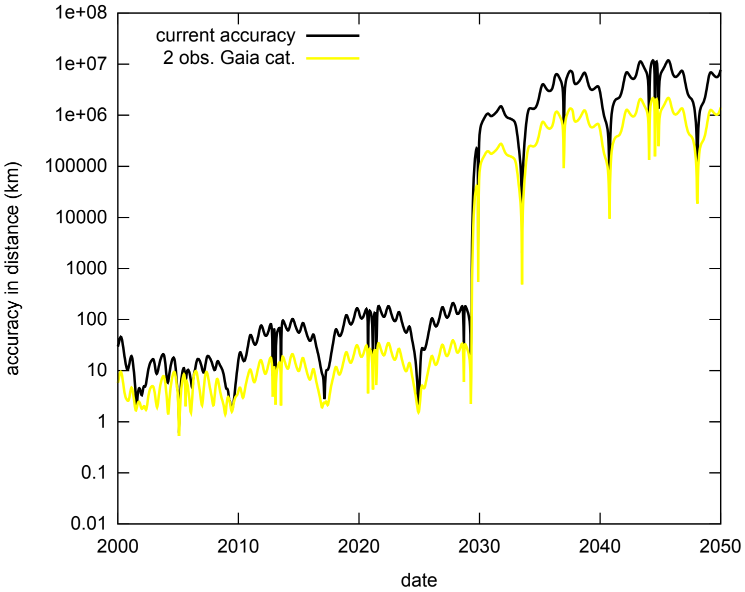

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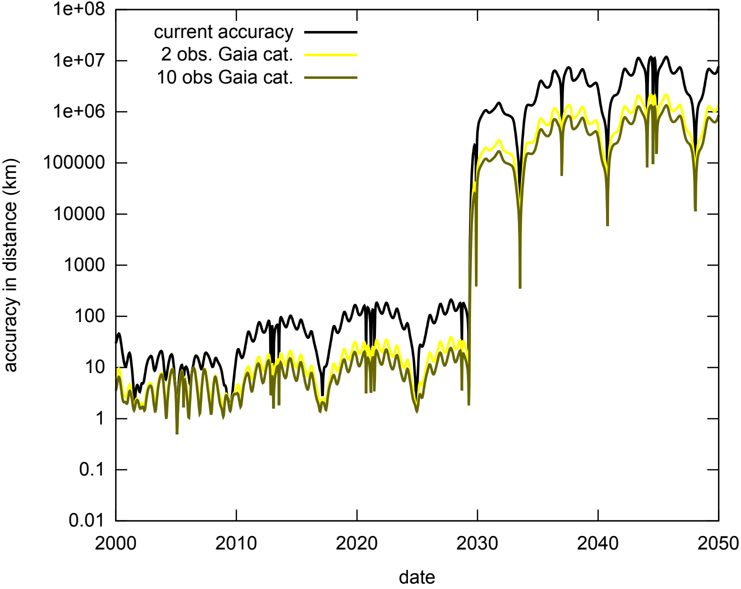

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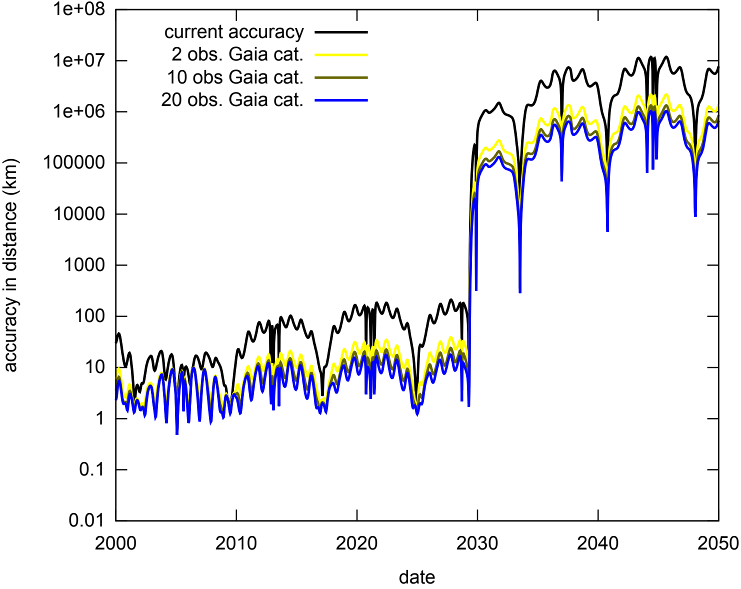

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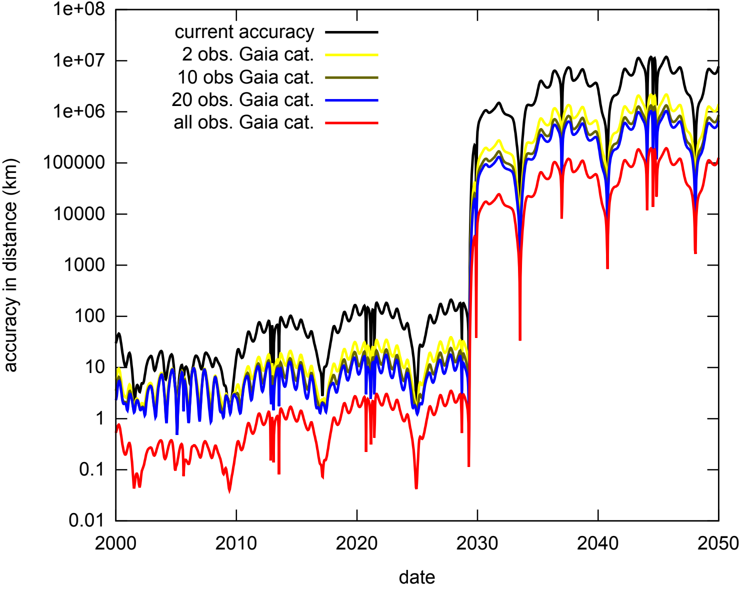

Desmars *et al.* (2013)

Conclusion

- In order to have more accurate ephemerides, reduction of the first and last observations is preferable
- Even with only two new reductions, the precision of orbit can be improved

Reduction with Gaia stellar catalogue and Yarkovsky acceleration

1. Current observations (no reduction with Gaia catalogue)
2. Only the first and the last observation can be reduced with Gaia catalogue
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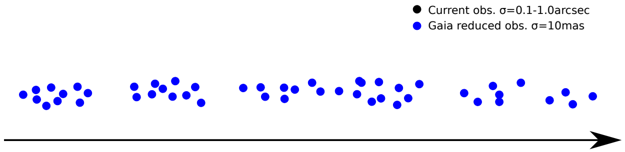
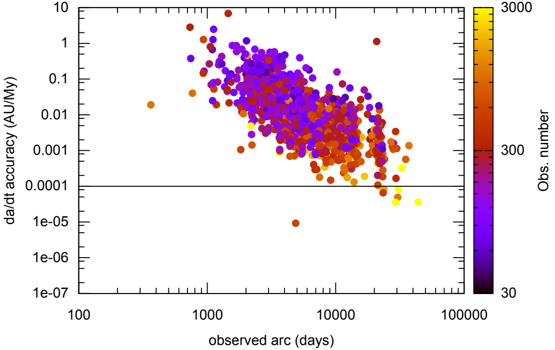


Precision of da/dt for 1629 numbered NEAs

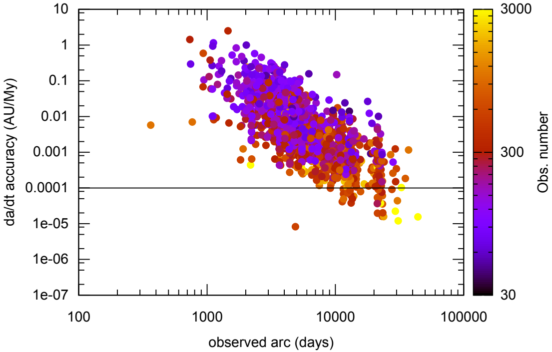
1. Precision with current observations – no reduction with Gaia catalogue –



NEAs with $\sigma_{\dot{a}} \leq 10^{-3}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-4}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-5}$au/My
107 (6.6%)	8 (0.5%)	1 (0.1%)

Precision of da/dt for 1629 numbered NEAs

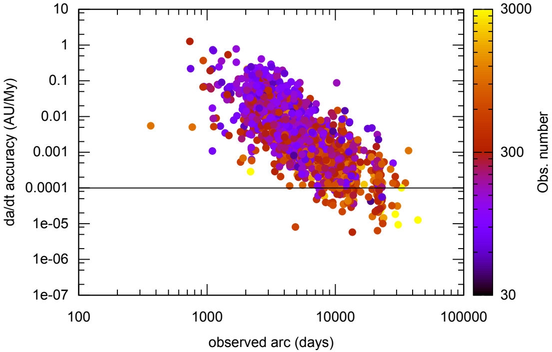
2. Precision with first and last obs. reduced with Gaia cat.



NEAs with $\sigma_{\dot{a}} \leq 10^{-3}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-4}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-5}$au/My
346 (21.2%)	31 (1.9%)	1 (0.1%)

Precision of da/dt for 1629 numbered NEAs

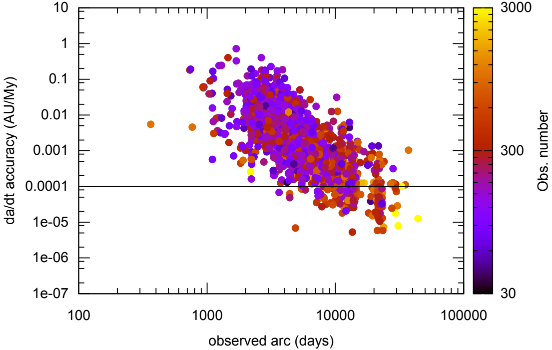
3. Precision with 5 first and 5 last obs. reduced with Gaia cat.



NEAs with $\sigma_{\dot{a}} \leq 10^{-3}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-4}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-5}$au/My
494 (30.3%)	93 (5.7%)	4 (0.2%)

Precision of da/dt for 1629 numbered NEAs

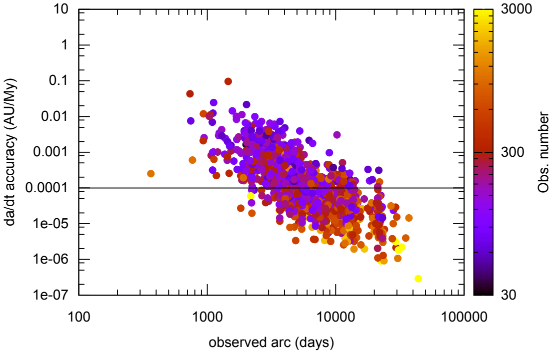
4. Precision with 10 first and 10 last obs. reduced with Gaia cat.



NEAs with $\sigma_{\dot{a}} \leq 10^{-3}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-4}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-5}$au/My
644 (39.5%)	149 (9.1%)	6 (0.4%)

Precision of da/dt for 1629 numbered NEAs

5. Precision with all observations reduced with Gaia cat.



NEAs with $\sigma_{\dot{a}} \leq 10^{-3}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-4}$au/My	NEAs with $\sigma_{\dot{a}} \leq 10^{-5}$au/My
1442 (88.5%)	688 (42.2%)	91 (5.6%)

Conclusion

Old observations and Yarkovsky acceleration

- Increase the orbital arc
- New astrometry with Gaia $\rightarrow$ new dynamical constrains
- Better estimation of Yarkovsky acceleration

Limitation

- Affects mainly small asteroids ($D < 20$km) $\rightarrow$ faint magnitude
- In case of isolated precovery observations, strong dependence

Yarkovsky for planetology

- Better orbit determination
- Better estimation of close approaches and impact probabilities
- Constrain physical parameters $\rightarrow$ obliquity, diameter, density
- Constrain dynamical evolution (transport NEA population)
- Also direct observations of asteroids with Gaia-DRX

see Federica's presentation