Yarkovsky Acceleration of (99942) Apophis

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Importance of Yarkovsky Effect

The unknown size of the Yarkovsky acceleration on Apophis is the largest source of uncertainty in the distance of the 2029 close approach to Earth.

A gravity-only solution rules out a 2068 impact possibility, while the inclusion of Yarkovsky acceleration allows for a 2068 impact.

We are attempting to directly measure the Yarkovsky acceleration of Apophis from our extensive set of astrometric data to provide a better constraint on the size of the acceleration and ascertain whether Apophis remains an impact threat in 2068.

from Farnocchia et al. (2015)
Systematic Errors

The Yarkovsky acceleration on an object as large as Apophis (~300 m diameter) is very small. It would be fairly easy for a systematic error to mimic Yarkovsky acceleration, so it is essential to work with data that is free of systematic error.

Experience has shown that astrometric reference catalogs such as USNO-B1.0 and PPMXL suffer from zone errors that can introduce systematic offsets into the astrometry of Apophis. To eliminate this source of error, all of our astrometric observations are being newly reduced against the Gaia-DR2 catalog.

Clock errors or shutter delay can also introduce a systematic offset in the astrometry. To estimate the size of this effect, we have been making numerous observations of GPS satellites and comparing the resulting positions to their well-known ephemerides to measure a 0.1 sec shutter delay of our camera that will be taken into account in the new reductions. For many years, our camera has recorded two independent NTP-synchronized clocks in the FITS header to guard against clock error. The accuracy of the GPS satellite astrometry confirms the accuracy of the clocks.
Systematic error can also be introduced if the observatory site coordinates are wrong. Our astrometry of GPS satellites has shown that the elevations of the Mauna Kea telescopes have been incorrectly referred to sea level rather than the WGS84 reference ellipsoid. The difference is about 25 m. At the typical 21,000 km distance of an observed GPS satellite, 1 m corresponds to about 0.01 arcsec, so astrometry good to a few hundredths of an arcsecond measures the position of the telescope to a few meters. Many thanks to Bill Gray for providing his GPS satellite ephemeris services.
Strategy

- Reduce all of our own existing observations against Gaia DR2 (over 800 observations)
- Apply shutter delay time correction (amounts to about 0.1 sec)
- Update observatory site parallax constants
- Acquire new observations (the 2021 close approach's observability window opened in 2018 briefly; remains visible throughout 2019; extends arc from 11 to 15 years)
Latest Results

- Set of Subaru observations on 2019 Jan 08 and Mar 05 UT, the former of which are good to 0.02 arcsec (near lightcurve maximum)
- $A2 = -1.11 \pm 0.97 \times 10^{-14} \text{ AU/d}^2$
- Value is consistent with the expectation from the physical model
- But the night of 2013 Feb 09 UT stands out
Apophis on 2013 Feb 09 UT

- 504 Gaia reference stars; astrometric solution contributes 5 mas of uncertainty
- Apophis is G = 16.3; SNR is about 240 in a 10 sec exposure; target centroid contributes 13 mas of uncertainty (0.03 pixels)
- But orbit solution residuals are over 100 mas
Atmospheric Dispersion

Unfiltered observations at large zenith distances suffer from atmospheric dispersion. If the color of the target asteroid differs from the mean color of the reference stars, a systematic error can be introduced. The figure shows the right ascension residual in arcsec against the Gaia B-R color index for 517 reference stars in an exposure taken at a zenith distance of 65 deg on 2013 Feb 09. Assuming a B-R color of 1.3 for Apophis, based on the Sq classification of Binzel et al. (2009), the offset could be as large as 0.1 arcsec. Modifications to the astrometric reduction software that incorporate a color correction are in progress.
Dealing with Dispersion

- Eventually include dispersion correction in the astrometric solution software, but until then...
- 2019 Subaru observations were filtered
- 2006 December observations recently added to solution were filtered
- Restrict solution to observations with zenith distance less than 60 deg
- $A_2 = -1.2 \pm 1.0 \times 10^{-14} \text{ AU/d}^2$
Lots of options for showing residuals: RA, DEC, along-track, cross-track, versus year, azimuth, altitude, rate of motion, to name a few.

Shown here are RA and DEC versus time.

The RMS is less than 0.07 arcsec.
Next Steps

- Add atmospheric dispersion correction to astrometric solution software
- Continue remeasuring existing observations against Gaia DR2
- Re-run astrometric solution with dispersion correction on ALL observations
- Continue extending observational arc through 2019, 2020, and 2021 when radar becomes possible
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