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Predicting the Earth encounters of (99942) Apophis

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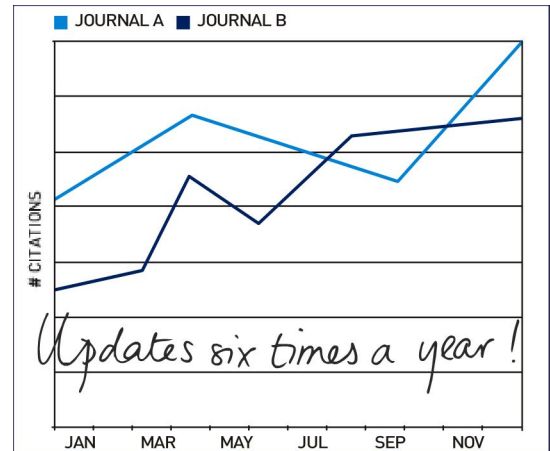
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Abstract

Arecibo delay-Doppler measurements of (99942) Apophis in 2005 and 2006 resulted in a five standard-deviation trajectory correction to the optically predicted close approach distance to Earth in 2029. The radar measurements reduced the volume of the statistical uncertainty region entering the encounter to 7.3% of the pre-radar solution, but increased the trajectory uncertainty growth rate across the encounter by 800% due to the closer predicted approach to the Earth. A small estimated Earth impact probability remained for 2036. With standard-deviation plane-of-sky position uncertainties for 2007–2010 already less than 0.2 arcsec, the best near-term ground-based optical astrometry can only weakly affect the trajectory estimate. While the potential for impact in 2036 will likely be excluded in 2013 (if not 2011) using ground-based optical measurements, approximations within the Standard Dynamical Model (SDM) used to estimate and predict the trajectory from the current era are sufficient to obscure the difference between a predicted impact and a miss in 2036 by altering the dynamics leading into the 2029 encounter. Normal impact probability assessments based on the SDM become problematic without knowledge of the object's physical properties; impact could be excluded while the actual dynamics still permit it. Calibrated position uncertainty intervals are developed to compensate for this by characterizing the minimum and maximum effect of physical parameters on the trajectory. Uncertainty in accelerations related to solar radiation can cause between 82 and 4720 Earth-radii of trajectory change relative to the SDM by 2036. If an actionable hazard exists, alteration by 2–10% of Apophis' total absorption of solar radiation in 2018 could be sufficient to produce a six standard-deviation trajectory change by 2036 given physical characterization; even a 0.5% change could produce a trajectory shift of one Earth-radius by 2036 for all possible spin-poles and likely masses. Planetary ephemeris uncertainties are the next greatest source of systematic error, causing up to 23 Earth-radii of uncertainty. The SDM Earth point-mass assumption introduces an additional 2.9 Earth-radii of prediction error by 2036. Unmodeled asteroid perturbations produce as much as 2.3 Earth-radii of error. We find no future small-body encounters likely to yield an Apophis mass determination prior to 2029. However, asteroid (144898) 2004 VD17, itself having a statistical Earth impact in 2102,

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will probably encounter Apophis at 6.7 lunar distances in 2034, their uncertainty regions coming as close as 1.6 lunar distances near the center of both SDM probability distributions.


Keywords: Asteroids; Asteroids, dynamics; Radar observations; Near-Earth objects; Orbit determination

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