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GOLDSTONE AND ARECIBO RADAR OBSERVATIONS OF (99942) APOPHIS IN 2012-2013

Marina Brozović(1), Lance A. M. Benner(1), Joseph G. McMichael(1), Jon D. Giorgini(1), Petr Pravec(2), Petr Scheirich(2), Christopher Magri(3), Michael W. Busch(4), Joseph S. Jao(5), Clement G. Lee(1), Martin A. Slade(1), Michael C. Nolan(5), Patrick A. Taylor(6), Ellen S. Howell(5), and Kenneth J. Lawrence(1)

(1)Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109-8099, USA,
marina.brozovic@jpl.nasa.gov,lance.benner@jpl.nasa.gov,
joseph.g.mcmichael@jpl.nasa.gov, jon.d.giorgini@jpl.nasa.gov,
joseph.s.jao@jpl.nasa.gov, clement.g.lee@jpl.nasa.gov,
martin.a.slade@jpl.nasa.gov, kenneth.j.lawrence@jpl.nasa.gov

(2)*Astronomical Institute, Academy of Sciences of the Czech Republic,*
petr.pravec@asu.cas.cz, petr.scheirich@gmail.com

(3)*University of Maine at Farmington, Preble Hall,*
Farmington, ME 04938, USA, magri@maine.edu

(4)*SETI Institute, Mountain View, CA 94043, USA, mbusch@seti.org*

(5)*The University of Arizona, Tucson, AZ 85721, USA,*
nolan@orex.lpl.arizona.edu,
ehowell@orex.lpl.arizona.edu

(6)*Arecibo Observatory, Universities Space Research Association, Arecibo, PR 00612, USA, ptaylor@naic.edu*

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We report radar observations of Apophis obtained during the 2012–2013 apparition. We observed Apophis on fourteen days at Goldstone (8560 MHz, 3.5 cm) and on five days at Arecibo (2380 MHz, 12.3 cm) between 2012 December 21 and 2013 March 16. Closest approach occurred on January 9 at a distance of 0.097 au. We obtained relatively weak echo power spectra and delay-Doppler images. The highest range resolution we achieved was 0.125 μs or ~20 m/pix at Goldstone. The data suggest that Apophis is an elongated, asymmetric, and possibly bifurcated object. The images place a lower bound on the long axis of 450 m. We used the Pravec et al. (2014) lightcurve-derived shape and spin state model (Figure 1) of Apophis to test for short axis mode (SAM) non-principal axis rotation (NPA) and to estimate the asteroid's dimensions. The radar data are consistent with the NPA spin state and they constrain the equivalent diameter to D = 0.34 ± 0.03 km (1σ bound). This is slightly smaller than the most recent IR observation estimates of 375^{+14}_{-10} m and 380–

393 m, reported by Müller et al. (2014) and Licandro et al. (2016) respectively. Delay-Doppler images from Jan. 10 and 14 show two clusters of bright pixels with a narrow radar-dark region between them, hinting that Apophis could be bifurcated (Figure 2). The radar astrometry has been updated using a 3D shape model and was included in JPL orbital solution 195. The Yarkovsky acceleration has not been detected with solution 195, but if the position error in the 2021 encounter exceeds 8–12 km, then this could be evidence for non-gravitational acceleration. Orbital solution 195 enables reliable orbit computation from 1829–2059 and extends the Earth encounter predictability window by 67 years relative to solution 142 (Giorgini et al. 2008).

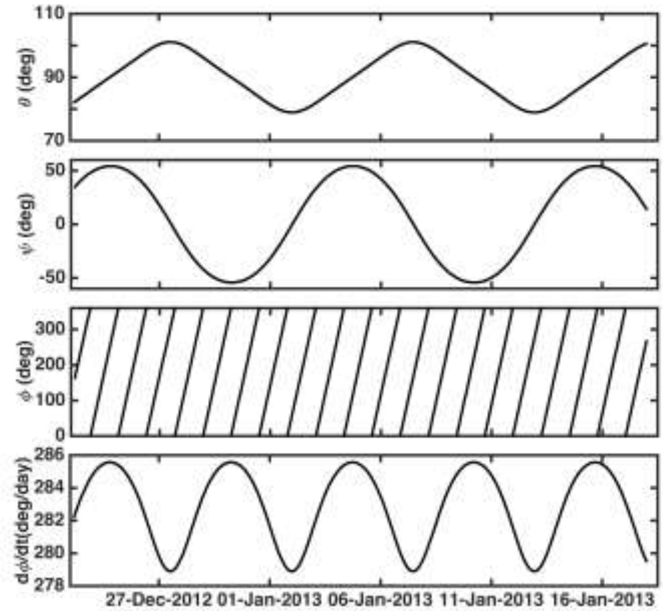

Figure 1. The Euler angles θ, ψ, and ϕ describe Apophis SAM NPA rotation between 2012 December 21 and 2013 January 17. We converted the Pravec et al. (2014) S-convention spin state into the Samarasinha and A'Hearn (1991) L-convention spin state. In the L-convention, θ is the nodding amplitude of the long axis with respect to the total rotational angular momentum vector, ψ is the rolling amplitude about the long axis, and ϕ is the rotation angle of the long axis about the angular momentum vector. ϕ is the only angle that circulates. The average rotation period is P_{ϕ}=30.56 hours. The rolling and nodding periods are the same and have a value P_{ψ}=P_{θ}=262.66 days. The rotation rate $d\phi/dt$ of the long axis about the angular momentum vector varies by only a few percent and has a period of $P_{\psi}/2$.

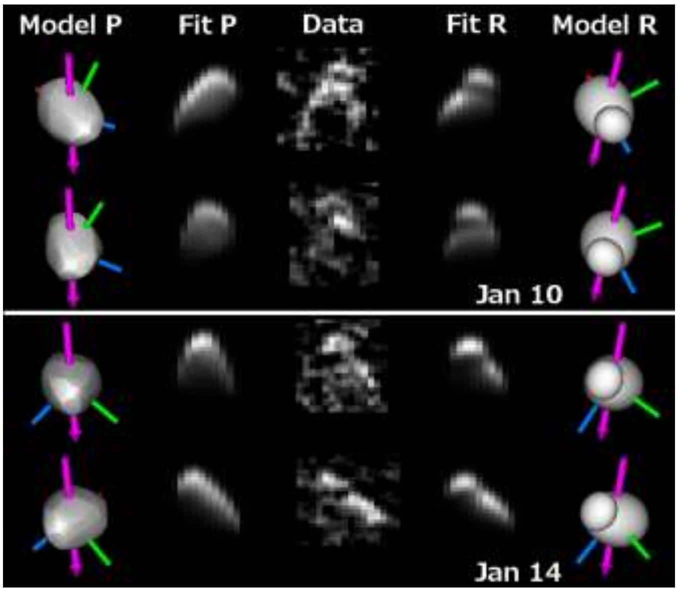

Figure 2. Collage of, from left to right: plane-of-sky renderings of the Pravec et al. model (Model P) scaled to D = 0.34 km, corresponding fits (synthetic images), delay-Doppler radar images, fits produced with radar improvements to the spin state and shape (Model R), and corresponding plane-of-sky renderings for this model. The plane of sky view is contained in a 0.7 km × 0.7 km square with 151×151 pixels. The magenta arrow shows the instantaneous orientation of the spin vector, and

the red, green, and blue shafts denote the positive ends of the long, intermediate, and short principal axes.

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