Radar Reconnaissance of 99942 Apophis. M. Brozović[1], L. A. M. Benner[1], S. P. Naidu[1], M. W. Busch[2], J. D. Giorgini[1], P. A. Taylor[3], E. G. Rivera-Valentin[3], A. K. Virkki[4], F. C. F. Venditti[4], S. E. Marshall[4], M.C. Nolan[5], E. S. Howell[5], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (marina.brozovic@jpl.nasa.gov), [2]SETI Institute, Mountain View, CA, USA, [3]Lunar and Planetary Institute, Universities Space Research Association, Houston, TX, USA, [4]Arecibo Observatory, University of Central Florida, Arecibo, PR, USA, [5]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: Goldstone (X-band, 8560 MHz) and Arecibo (S-band, 2380 MHz) radar observations of 99942 Apophis in 2012–2013 at ~0.097 au revealed an elongated, asymmetric object that could be bi-lobate (Fig. 1). The delay-Doppler images placed a lower bound on the long axis of 450 m and yielded an equivalent diameter of 340±40 m [1]. The radar data are consistent with short-axis mode non-principal axis rotation (NPA) reported by Pravec et al. [2].

Apophis will make relatively distant passes within 0.22 au in 2020, 0.11 au in 2021, 0.26 au in 2028, and then make an extremely close flyby within six Earth radii from the geocenter in April, 2029.

In 2029, Apophis will be the strongest near-Earth asteroid (NEA) radar target since radar observations began in the 1960s. The close flyby will enable observations using a variety of radar techniques, and may include some that have never been applied to an asteroid previously. This will provide an unprecedented opportunity for scientific discoveries.

Radar observations prior to 2029 : Apophis will be observable by radar in October 2020 at Arecibo; in 2021 at Goldstone and Arecibo; in September 2028 at Arecibo; and in 2029 at Goldstone, Arecibo, and numerous other radar facilities around the world. New ranging measurements in 2020 and 2021 should reveal the magnitude of the Yarkovsky acceleration, which is currently the dominant source of orbital uncertainties for Apophis. In 2021, Goldstone observations can begin in February and could provide coarse-resolution images with bistatic reception at Green Bank. Arecibo will be able to observe Apophis for weeks at closer distances than in 2013, and the SNRs will be about three times stronger. We expect to obtain Arecibo delay-Doppler images with a resolution as fine as 15 m/pixel that should yield thorough rotational coverage and substantial improvement in the 3D model, size, and spin state. If the thermal inertia is estimated from thermal infrared observations in 2021, then the updated radar model, coupled with a Yarkovsky effect detection, could provide an estimate of the asteroid's mass and bulk density. Apophis will also have a favorable optical apparition for photometry which should provide a refined spin state estimate. The combined optical and radar spin state uncertainties could be small enough to predict the orientation of Apophis in 2029 which would lead to better predictions of the spin and surface/shape changes due to tidal effects during the closest approach.

Science in 2029: In 2029, Apophis will approach Earth from the south at a declination of about 30 deg, rapidly move past Earth, and then recede at a declination of +17 deg. Observations at Goldstone could start as early as mid-March and last until mid-May. Observations at Arecibo could start one day after closest approach and continue into at least early June.

The extremely close flyby will enable delay-Doppler imaging at the highest resolutions available at Goldstone (1.875 m/pixel), Arecibo (7.5 m/pixel), and Canberra (1.875 m/pixel) that will place in excess of 10000 pixels on the asteroid and reveal considerably more detail than in 2021. We expect detail in Goldstone images twice as fine as achieved for 2014 HQ124 (Fig. 2), an object similar in size to Apophis. High-resolution radar imaging will span weeks before and after the flyby, cover multiple rotations, and yield detailed 3D models and spin state estimates before and after the encounter, which will be compared to determine the extent to which terrestrial tides cause Apophis to reorient. Detailed modeling should provide 3D models with sufficiently small uncertainties in the moment of inertia ratios to constrain the asteroid's mass distribution and to check for changes due to the flyby. The 2029 model will have substantially more detail than the model estimated from images obtained in 2021, and will dramatically improve estimates of the asteroid's volume and bulk density.

A comparison of the pre- and post- flyby high-resolution images could also detect changes to the spin state and might even reveal subtle tidally-induced changes on the surface. Dual-polarization imaging will enable polarimetric investigation of the surface roughness, regolith distributions, and changes that may occur during the flyby. 70 cm radar observations at Arecibo and Green Bank may be able to map the depth of regolith and reveal features not visible on the surface. Ground-based long-wavelength radar sounding of the interior may also be possible.

The very close approach in 2029 will enable other radar facilities such as Haystack (Massachusetts) and

TIRA (Germany) to image Apophis with resolutions of several centimeters, which should reveal dramatically more detail than images obtained at Arecibo or Goldstone.

Due to the southern declinations prior to April 13, 2029, Goldstone and Canberra will be the best facilities for high-resolution radar imaging during the approach. Apophis becomes observable at Arecibo one day after the closest approach and it remains detectable at signal-to-noise ratios strong enough for ranging measurements until at least early June. The most effective use of Arecibo in the week following the close approach may be as a receiver of Goldstone transmissions due to the higher resolution (1.875 m versus 7.5 m) available. Bistatic imaging will be necessary while Apophis is within several lunar distances due to the short round-trip light travel times and the asteroid's slow rotation of ~31 h. The 100-m antenna at Green Bank has long observing overlaps with Goldstone, and we plan to use it as a receiver after the object sets at Arecibo.

Radar speckle observations will be crucial for detecting spin state changes because they precisely measure the instantaneous spin state vectors. The strong SNRs will enable speckle measurements for at least 10 days pre- and post- flyby between Goldstone, Arecibo and elements of the Very Large Baseline Array (VLBA). Radar speckle observations may also be possible in Australia using the 70 m DSS-43 antenna at Canberra to transmit and Modra and a single antenna the Australian Telescope Compact Array (ATCA) to receive.

Astrometry obtained in 2029, coupled with significant improvements in estimates of the Yarkovsky effect acting on Apophis, will enable accurate orbital predictions for decades into the future and vastly improved estimates of future close encounters.

References: [1] Brozovic M. et al. (2018) *Icarus, 300,* 115-128. [2] Pravec P. et al. (2014) *Icarus, 233,* 48–60.

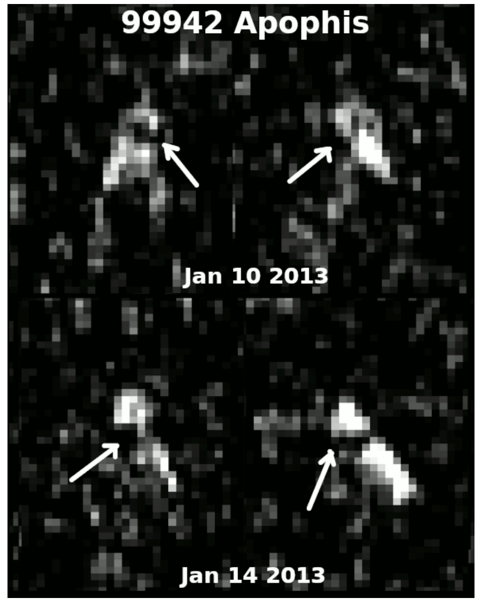

Figure 1. Goldstone delay-Doppler images of 99942 Apophis from 2013 (modified from [1]). Time delay (range) increases from top to bottom and Doppler frequency increases from left to right. The range pixel resolution is 18.75 m. Arrows point to a bifurcation in the radar echo.

Figure 2. Delay-Doppler image of 2014 HQ124, an object similar in size to Apophis, obtained in 2014 using DSS-13 to transmit and Arecibo to receive. The range resolution is 3.75 m/pixel. Goldstone images of Apophis in 2029 should achieve a resolution of 1.875 m/pixel and reveal even more detail than is evident on 2014 HQ124.