RADAR OBSERVATIONS OF 99942 APOPHIS IN 2021 AND PLANS FOR 2029. M. Brozović[1], L. A. M. Benner[1], S. P. Naidu[1], M. W. Busch[2], J. D. Giorgini[1], J. Lazio[1], T. Hall[3], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (marina.brozovic@jpl.nasa.gov), [2]SETI Institute, Mountain View, CA, USA, [3]Lincoln Laboratory, MIT, Lexington, MA, 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. 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 the short-axis mode non-principal axis rotation (NPA) reported by Pravec et al. [2].

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 in 2021: We conducted the last radar observation of Apophis prior to the 2029 flyby at Goldstone and the Green Bank Telescope (GBT) from 2021 Mar 3−11. Arecibo was no longer available due to its collapse in December of 2020. The signal to noise ratios (SNRs) at Goldstone were weak due to the relatively distant 0.11 au approach, but we still imaged Apophis with a coarse resolution of 75 m x 0.1 Hz, resulting in about two dozen pixels on the object.

New ranging measurements eliminated any chance for an Apophis impact in 2068 [3] and removed Apophis from JPL's Sentry risk website. The 2020−2021 optical and radar observations yielded a strong detection of the transverse non-gravitational (i.e., the Yarkovsky effect) acceleration of $-2.901 \pm 0.0194 \times 10^{-14}$ au/d^2 [3].

Radar images in 2021 did not resolve Apophis sufficiently to improve the shape model [1], but the orientation of the radar echoes revealed that the spin state needed an update. This was expected given that the spin state [1, 2] estimated from 2012−2013 data contained significant uncertainties that could not precisely predict the 2021 orientations. We did a preliminary spin state update to help with the occultation campaign led by D. Dunham and M. Buie, although lightcurves obtained from an extensive optical campaign led by P. Pravec should provide much better spin constraints and perhaps even allow for orientation predictions in 2029.

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. After the closest approach, Apophis will become a daytime object less than 45 degrees from the Sun until late May, so radar will provide the principal technique for ground-based observations after the flyby that can detect spin state changes until Apophis reaches 17th magnitude near opposition in late November, 2029. Apophis will be observed by the Deep Space Network radars at Goldstone (DSS-14 and DSS-13) and Canberra (DSS-43), and possibly with other radar facilities such as Haystack and EISCAT-3D. It is possible that the 100-m Green Bank Telescope will have a radar transmitter by 2029 and could also observe Apophis.

The 2029 observations at Goldstone could start as early as mid-March and last until mid-May with the highest resolution imaging lasting ~20 days centered on April 13 (Figure 1). From April 10−19, Apophis will be visible from Goldstone for more than 70 hours. Apophis will undergo considerable plane-of-sky orientation changes around the hours of the closest approach because of the sky motion, its intrinsic rotation, and tides. The finest range resolutions currently available are 3.75 m/pixel at the 70-m DSS-14 antenna, and 1.875 m/pixel at the 34-m DSS-13 antenna. Installation of an 80 kW, 80 MHz C-band (7190 MHz) transmitter is also planned at DSS-14 also, well before 2029, and will enable 1.875 m/pixel imaging. Apophis will be so close that the SNRs will not be the limiting factor for radar imaging at any of the DSN antennas. Loss of Arecibo will not affect this exceptional radar imaging opportunity significantly because Goldstone has finer range resolution and can track Apophis inbound for weeks at declinations that were too far south for Arecibo.

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 which limits the Doppler resolution of monostatic images. Possible bistatic configurations could involve transmitting at DSS-14 and receiving at DSS-13 or Green Bank; transmitting at DSS-13 and receiving at Green Bank; other combinations are also possible.

The extremely close flyby will enable delay-Doppler imaging at DSS-14 that will place tens of thousands of pixels on the asteroid, reveal considerable detail, cover multiple rotations, and probably show the entire surface at high resolution. This will yield a very detailed 3D model and estimates of the spin state before and after the encounter. Changes in the spin state due to terrestrial tides should be conspicuous [4, 5]. The 2029 model may have surface features as small as a few meters and will dramatically improve estimates of the asteroid's volume and, through the Yarkovsky effect detection, bulk density. Because Apophis is a non-principal axis rotator, estimation of the shape and spin state will also provide precise estimates of the moment of inertia ratios [6, 7] that will constrain the internal structure pre- and post- flyby. The images might reveal surface feature changes if localized events occur (e.g., if a boulder moves or if there are landslides).

Dual-polarization imaging will enable polarimetric investigation of the surface roughness, regolith distributions, and changes that may occur during the flyby. Ground-based long-wavelength radar (wavelengths of decimeters to meters) could map the depth of regolith, reveal features not visible on the surface, and image the interior of the asteroid [8].

The very close approach in 2029 will enable the 10 GHz Haystack Ultrawideband Satellite Imaging Radar (HUSIR) at Tyngsborough, Massachusetts to image Apophis with resolutions as fine as 25 cm, which would place hundreds of thousands of pixels on the asteroid and reveal dramatically more detail than images obtained at Goldstone. Additionally, the transmitter power at the 96 GHz HUSIR radar is being increased by a factor of 50. This upgrade is scheduled to be completed by 2027 and will enable HUSIR to image the asteroid with resolutions as fine as 3 cm.

Radar speckle observations will be crucial for detecting spin state changes because they precisely measure the instantaneous spin state vectors and do not need a formal shape modeling analysis. The strong SNRs will enable speckle measurements for at least 10 days pre- and post- flyby between Goldstone and elements of the Very Long Baseline Array (VLBA). Radar speckle observations may also be possible in Australia using the 70-m DSS-43 antenna to transmit and Mopra and/or 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, more detailed investigation of keyholes, and vastly improved estimates of future close encounters. After 2029, the next opportunities to obtain images and precise ranging measurements of Apophis with Goldstone (assuming current sensitivity) will be at 0.080 au in 2044 and 0.041 au in 2051.

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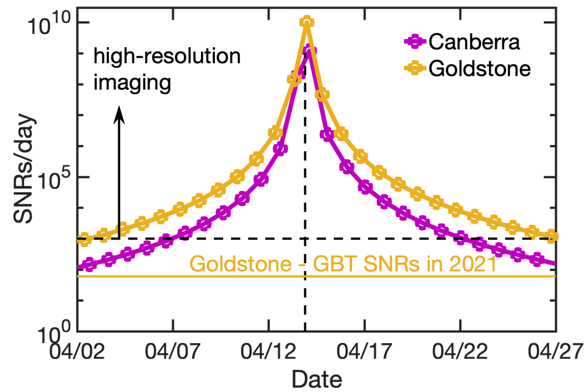

Figure 1. Signal-to-noise ratio predictions for DSS-14 (Goldstone) and DSS-43 (Canberra) for Apophis in 2029. The high-resolution imaging will be possible plus/minus 10 days of the close encounter.