MULTIWAVELENGTH RADAR OBSERVATIONS OF APOPHIS. M. C. Nolan[1], L. A. M. Benner[2], M. Brozović[2], M. W. Busch[3], J. D. Giorgini[2], D. C. Hickson[4], E. S. Howell[1], S. E. Marshall[4], S. P. Naidu[2], E. G. Rivera-Valentín[5], P. A. Taylor[5], F. C. F. Venditti[4], and A. K. Virkki[4], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 USA (nolan@lpl.arizona.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [3]SETI Institute, Mountain View, CA, USA, [4]Arecibo Observatory, University of Central Florida, HC3 Box 53995, Arecibo, PR, 00612, USA, [5]Lunar and Planetary Institute, Universities Space Research Association, Houston, TX 77058, USA.

Introduction: Because of Apophis' extremely close approach in 2029, it will be observable at reasonable SNR using facilities not usually suitable for asteroid observations. Planetary radar systems are designed based on a combination of technical and direct scientific criteria. The long lead time and physical properties of Apophis will allow observations at many wavelengths, which can inform future decision about radar studies of NEAs and the design of radar facilities.

Background: For a given antenna and power, shorter wavelengths will allow higher SNR and resolution, while longer wavelengths will allow deeper surface penetration. Most existing ground-based planetary radar systems are designed to use the highest frequency technically available at that telescope, in order to maximize SNR (which intrinsically varies as wavelength $\lambda^{-1.5}$ for a given antenna and constant power) and range resolution. Range resolution is a function of bandwidth, not explicitly a function of wavelength, but practical radar systems have a bandwidth that is a more-or-less fixed fraction of the operating frequency, typically ~1%, so that resolution is ~linear in frequency, or reciprocal in wavelength. On the other hand, surface penetration depth is typically ~linear in wavelength. For measuring the surface profile, penetration is not desirable, but for measuring material properties, it often is. As an example, 70-cm observations of the Moon show flow features not visible in 13-cm observations [1]. In addition, if dual-polarization observations are available, multi-wavelength observations yield information about surface particle grain sizes at the various wavelength scales, which may be from mm to meters, e.g., [2].

2029 Observations: Apophis will approach very close to the Earth in 2029, allowing study at high SNR with many radar systems. However, its long rotation period, > 30h, has two major implications for radar observations. First, most observations will be bistatic, with separate antennas transmitting and receiving to provide Doppler resolution, and second, after a few minutes of observing, we will be waiting for the asteroid to rotate to give another view. Bistatic observations will allow dual-polarization observations even for facilities that are not normally capable of them, but will require careful planning, as the most wavelength-flexible systems (the Green Bank Telescope and the Arecibo Observatory) may need to participate in several of the observations.

Current observing wavelengths span the range from ~5 MHz to ~100 GHz, with high-power transmit capability at 5-10 MHz (Arecibo, HAARP), 50 MHz (Jicamarca, MU), 150 MHz (ALTAIR), 225 MHz (EISCAT), 430 MHz (Arecibo and others), ~1 GHz (EISCAT), ~2.4 GHz (Arecibo, Canberra), 7-9 GHz (Goldstone), 35 GHz (KaBOOM, DSN), and ~100 GHz (Haystack). The facilities mentioned are examples: others are likely possible. Of these, only Arecibo and Goldstone routinely perform planetary radar observations, though many of the facilities have done at least proof-of-concept observations of, for example, the Moon. The Green Bank Telescope can receive at many of the frequencies, and is commonly used as a bistatic receive station for radar observations. The most difficult are likely the extreme frequencies: 5 MHz and 100 GHz, where bistatic reception may be difficult, as they are outside the range of many telescopes. The lowest frequencies will also suffer from atmospheric absorption and may not be possible.

Summary: The very close approach of Apophis will allow characterization at multiple wavelengths with different resolutions and penetration depths. Because Apophis' slow rotation, multiple experiments can observe the same "face" of Apophis allowing comparison of the radar scattering properties at multiple wavelengths. Careful scheduling will be required to assure that the most in-demand facilities are used optimally, and some observations, such as high-resolution ranging for orbit determination, may have higher priority than others. Facilities that have not previously attempted planetary observations should be tested using the Moon or other available target in preparation for the Apophis observations, and to complete the multi-wavelength radar characterization of the Moon.

References: [1] Campbell, B. A. et al. (2007) *IEEE Trans. G&RS.* 45, 4032-4042. [2] Virkki, A. K. and S. S. Bhiravarasu (2019) *JGR Planets* 124, 3025-3040.