BISTATIC ARECIBO PLANETARY RADAR OBSERVATIONS OF 99942 APOPHIS.

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Introduction: Planetary radar observations provide a strong tool to characterize the orbital and physical properties of near-Earth objects. The close approach of 99942 Apophis in April 2029 will provide one of the best opportunities for planetary radar observations of any near-Earth asteroid due to its proximity to the Earth. We will present how Arecibo Observatory planetary radar program can contribute in the observation efforts of 99942 Apophis using monostatic (Arecibo only) versus bistatic radar observations (one radar telescope or a spacecraft transmitting, other radio telescopes or a spacecraft receiving). Arecibo Observatory hosts the world's most powerful S-band (2380 MHz, 12.6 cm) radar transmitter with up to ~900 kW of output power, a pulsed P-band (430 MHz, 70 cm) radar transmitter with up to ~100 kW of effective output power (based on the duty cycle of a pulsed transmission), and a high-frequency (HF; 8.175 MHz, 37 m) heating facility transmitter with up to ~500 kW of output power. Monostatic Arecibo radar observations maximize the antenna gain, whereas the benefit of bistatic observations is the longer continuous integration time, which can provide a finer frequency resolution, and in some cases the possibility to observe different scattering angles.

2021 Apparition: 99942 Apophis will be in the Arecibo Observatory's 305-m radio telescope's field-of-view in March and April 2021, the best observation days lasting from March 17th to March 22nd. Apophis will pass the Earth at the closest distance since January 2013, when the close-approach distance was 0.0967 au opposed to 0.113 au in 2021. During this apparition only monostatic observations are expected, but also bistatic observations with Arecibo transmitting and Green Bank Telescope (GBT), Goldstone Solar System Radar (GSSR), or smaller telescopes forming part of the Very Long Baseline Array (VLBA), receiving the echo are possible. This apparition should be able to provide coarse-resolution images similar to those observed in 2013 [1].

2029 Apparition: In April 2029, Apophis will pass the Earth at a distance as close as 0.00025 au on April 13th. It will enter Arecibo's field of view on April 14th and remain observable for several weeks. Due to the transmit-to-receive switch time of 6-7 seconds, monostatic observations will not be possible until April 16th. April 14th and 15th would be optimal for bistatic radar observations, when the asteroid is less than 3 lunar distances away. At a declination of 18-20 degrees during April 14th-15th Apophis will be in the fields of view of the GBT, GSSR, and several smaller telescopes that can be used for VLBA observations (e.g., radar speckle measurements). Also, some European telescopes, such as the 70-meter DSS-63 of Madrid Deep Space Communications Complex could receive bistatic echoes at S band. GSSR transmitting at C band (7190 MHz, 4.2 cm, up to 80 kW) with Arecibo receiving could provide better range resolution than vice versa.

Bistatic Arecibo-to-Spacecraft Radar Observations: Spacecraft radar systems can provide a tool for asteroid tomography that is the only way for direct observations of the internal structure of asteroids. Asteroid tomography has not so far been tested in practice between spacecrafts and ground-based telescopes, but the close-approach of Apophis could provide an opportunity for such an experiment. Numerical modeling gives promising results for tomographic observations revealing boulders inside asteroids [2]. Arecibo has provided support for the Lunar Reconnaissance Orbiter's Mini-RF instrument since 2011 when the spacecraft's own radar transmitter failed. A similar concept could be used to observe 99942 Apophis with a spacecraft equipped with an appropriate radio receiver either orbiting Apophis or a lander on its surface during the asteroid's close approach. In the presentation, we will present a mission concept study discussing which distance and other constraints should be considered if such spacecraft was launched to obtain tomography and other radio/radar measurements of Apophis, either from Apophis' orbit or by a lander on the surface of Apophis. The concept could be of interest for other close-passing targets as well.

The radar equation for received echo power is:

$$P_{rx} = \frac{P_{tx} \mathrm{G}_{rx} \mathrm{G}_{tx} \lambda^2 \sigma}{(4\pi)^3 (d_{tx} d_{rx})^2}$$

where P_{tx} is the transmitted power, G_{rx} and G_{tx} are the antenna gains of the transmitter and the receiver, λ is the wavelength of the transmitted wave, σ is the radar cross section of the target, and d_{tx} and d_{rx} are the distance of the transmitter and the receiver from the target. It should be noted that the radar cross section depends on the wavelength so that when using longer wavelengths, the echo includes more volume-scattering contribution than when using, e.g., S band. The antenna gain G can also be written out as a function of the effective antenna area, A_{eff}: $G = 4\pi A_{eff}/\lambda^2$. For the spacecraft, we use $\mathrm{G}_{rx} = 3$ dB, and the values for the transmitters are listed in Table 1. The noise power is defined as $P_n = k_B T_{sys} B$, where k_B is the Boltzmann constant ($1.38 * 10^{-23}$ J/K), T_{sys} is the system temperature (i.e., 25-65 K for monostatic measurements, but including the sky and receiver temperatures and other system losses in our calculations), and B is the bandwidth of the signal. The listed bandwidths in Table 1 apply for coded signal. For a continuous wave, the bandwidth depends on the asteroid diameter (D), sub-radar latitude (δ_r), the spin period (P) and the wavelength so that $B = 4\pi D \cos\delta_r/(P\lambda) = 0.4$ Hz using 2380-MHz transmitter [1] and 0.0014 Hz using 8.175 MHz.

Using these equations, we can derive the signal-to-noise ratio (SNR) as P_{rx}/P_n.

Table 1. Radar transmitter parameters at Arecibo (Tsys includes sky and receiver temperatures).

Frequency (MHz)	8.175	430	2380
Wavelength (m)	37	0.7	0.126
Power (kW)	500	100	900
Gain (dB)	25	61	73
Tsys (K)	10^6	300	300
Beamwidth (deg)	8.5	0.18	0.033
Bandwidth (MHz)	0.05	0.01-0.5	0.1-20

The link budget per 1 second of integration for a direct path without Apophis is (without system losses)

$$\mathrm{SNR}_{\mathrm{inst}} = \frac{P_{tx}\mathrm{G}_{rx}\mathrm{G}_{tx}\lambda^2}{(4\pi)^2(d_{tx}+d_{rx})^2 k_B T_{sys} B}$$

The SNR for a pure reflection from Apophis:

$$\mathrm{SNR}_{\mathrm{R}} = \frac{P_{tx}\mathrm{G}_{rx}\mathrm{G}_{tx}\lambda^2\sigma}{(4\pi)^3(d_{tx}d_{rx})^2 k_B T_{sys} B}$$

and for a refracted (transmitted) signal:

$$\mathrm{SNR}_{\mathrm{T}} = \frac{P_{tx}\mathrm{G}_{rx}\mathrm{G}_{tx}\lambda^2(1-|R_F|^2)10^{-\alpha D}}{(4\pi)^2(d_{tx}+d_{rx})^2 k_B T_{sys} B}$$

where $\sigma = 0.02$ km^2 at S band [1], R_F is the Fresnel reflectivity (derivable from the radar albedo of ~0.19 [1]), and the attenuation function of the signal power is defined as $\alpha = 0.091 f\sqrt{\varepsilon'}\tan\delta$ [3], which gives attenuation of 0.0045 dB/m, 0.26 dB/m, and 1.45 dB/m for 8.175 MHz, 430 MHz, and 2380 MHz, when the real part of the electric permittivity $\varepsilon' = 5$ and the loss tangent $\tan\delta = 0.003$ (as reported by Heggy et al. [4] for ordinary chondrites at 90 MHz).

Using the values presented above, the link budget for the direct path at one lunar distance (400,000 km) without reflection or transmission is 119 dB (CW) or 43.9 dB (B = 0.05 MHz) using 8.175-MHz transmitter, 63.7 dB (B = 0.5 MHz) using 430 MHz, and 131 dB (CW) or 54.3 dB (B = 20 MHz) using 2380 MHz. Increasing integration time (τ_{int}) increases the received power as $\sqrt{\tau_{int}B}$. For the 8.175 MHz transmitter, the maximum tracking time is less than 30 min because the transmitter cannot track, whereas 430 MHz and 2380 MHz transmitters can track the asteroid up to 2.6 hours. Reflected and refracted (transmitted) SNR estimates will be presented for different observation scenarios. Space-based transmitters are discussed in the presentation of A. Herique in more detail.

Conclusions: Although longer wavelengths, or frequencies less than 100 MHz are crucial for a detectable transmission through an asteroid of tens or hundreds of meters across [2], the high sky temperatures and ionospheric plasma frequency greater than 8.2 MHz in the case of the HF transmitter can pose problems for a sufficient energy density reaching the target. Also, spacecraft radar transmitters tend to utilize higher frequencies. For example, CONSERT radar instrument [5] designed for ESA's Rosetta mission used a bistatic low-frequency radar transmitting at 90 MHz, whereas ESA's AIM mission was planned to include a similar low-frequency radar but transmitting at a frequency 50-70 MHz with up to 12 W of transmit power [6]. Also, Europa Clipper's REASON instrument will use a 60-MHz transmitter. Installment of a 60-MHz receiver or radar system at Arecibo would be crucial to assist in tomography measurements with signals transmitted from spacecrafts.

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