SCATTERING LAW FITS FOR DUAL POLARIZATION RADAR ECHOES OF ASTEROIDS USING ARECIBO OBSERVATORY PLANETARY RADAR DATA. L. F. Zambrano-Marin[1,2], A. K. Virkki[2], E. G. Rivera-Valentín[2,3], P. A. Taylor[2]; [1]Escuela Internacional de Posgrado, Universidad de Granada, Spain (luisafz@correo.ugr.es), [2]Arecibo Observatory, Universities Space Research Association (USRA), Arecibo, PR, [3]Lunar and Planetary Institute, USRA, Houston, TX.

Introduction: S-band (2380 MHz, 12.6 cm) radar is an ideal method for studying the decimeter-scale surface structures on asteroids that will affect in situ exploration. Beyond constraining near-surface properties, radar data enables the refinement of orbits, the determination of target sizes, and estimates of shapes and rotation periods with which the Yarkovsky (orbit) and YORP (rotational) non-gravitational effects [1] can be studied. Following the work by Virkki et. al. [2], Thompson et al. [3], and Wye et. al. [4], we test models of radar scattering using dual-polarization radar observations to elucidate the near-surface physical properties of asteroids. Here we test radar scattering models on near-Earth asteroids (441987) 2010 NY_{65}, 2014 JO_{25}, 2007 LE, (285263) 1998 QE_2, 3122 Florence, and 3200 Phaethon, all observed with the planetary radar system at the Arecibo Observatory.

In dual-circular-polarization radar experiments, the signal is transmitted as a circularly polarized wave and the echo from the interaction between the incident beam and the reflecting surface is received in both the same circular (SC) and the opposite circular (OC) sense as transmitted. Interpretation of the quasi-specular part of the echo from the surface and the diffuse part from the wavelength-scale structures have been studied for near-Earth asteroids (NEAs) and main belt asteroids (MBAs) [2] and for the Moon [3]. These show that the OC component tends to be higher than the SC, as it is composed of both specular and diffuse components of the scattering for most NEAs and MBAs [2]. For lunar materials, SC and OC diffuse components decrease as a cosine function of the incidence angle (θ, the angle between the surface normal and the incident beam) with, on average, the OC component being roughly twice as large as the SC component [3], where the shape of the cosine function depends on the surface roughness. In this work, we study the cosine function for a number of asteroids to improve our understanding of radar scattering and, consequently, constrain their surface properties.

Methods: Analysis of the backscattering function was done by plotting the backscattered power as a function of angle of incidence for both senses of polarization, selecting primarily targets where a roughly spheroidal shape can be assumed based on radar images. Selected targets had continuous wave (CW; frequency only) spectra as well as radar images with sufficient resolution to obtain high backscatter signal per pixel at a range of incidence angles. From CW data we obtain the radar cross section (RCS or σ), the circular polarization ratio (CPR or μ_C), and the radar albedo ($\hat{\sigma}$). The addition of the OC and SC components gives the total radar cross section, which has been used as a measurement of the reflectivity of the target [5]. The ratio of the integrated echo power in SC to that in the OC sense is the circular polarization ratio μ_C, which provides a gauge of the surface roughness of the target. The radar albedo describes the radar reflectivity of the target per unit area and is directly related to the material's electric properties by the Fresnel reflection coefficient [5,6]. We use the $\hat{\sigma}$ obtained from CW data to derive a scaling factor for the signal within the radar images, to ensure the correct scaling of the reflectivity as a function of the incidence angle.

Several studies have shown the connection of the OC radar albedo to the abundance of metals and the surface density of the target [5-7]. The spatial distribution of surface elements (*e.g.*, boulders, rocks, ice, mineral deposits) also has an effect on the scattered radiation intensity [7] as it can alter the polarization, with rougher wavelength-scale surface structures providing more signal in both senses than those that are somewhat smoother which tend to have a stronger echo in the OC sense [6].

We fit a cosine law to the observed scaled radar reflectivity as a function of the angles of incidence:

$$\hat{\sigma}(\theta) = R(C+1)\cos^{2C}\theta \qquad (1)$$

where R is related to the Fresnel reflection coefficient at a normal incidence ($\theta = 0$), and C is a roughness parameter ($C = \lambda^2 R_0^2/16\pi^2 h^4_{rms}$, where λ is the wavelength of the incident signal, R_0 is the correlation length and h_{rms} is the root-mean-square (rms) height). Traditionally, C has been considered to depend only on the surface undulations so that the rms slope of an average surface facet is $s = 1/\sqrt{C}$, which does not take into account the diffuse scattering effects of the wavelength-scale boulders.

As an example, in Figure 1 we show the cosine law fit for 2010 NY_{65} in both its OC and SC echo components, and show the calculated *R* and *C* values. The goal of this research is to analyze the *R* and *C* parameters in terms of physical properties of the surface. This will help us to understand how to consider the diffuse scattering by wavelength-scale boulders in radar scattering laws as opposed to using only the rms slope.

In addition, we will fit three other functions traditionally used for modeling surface scattering: Gaussian, exponential, and Hagfors to study their suitability to model the radar reflectivity of asteroid near-surfaces.

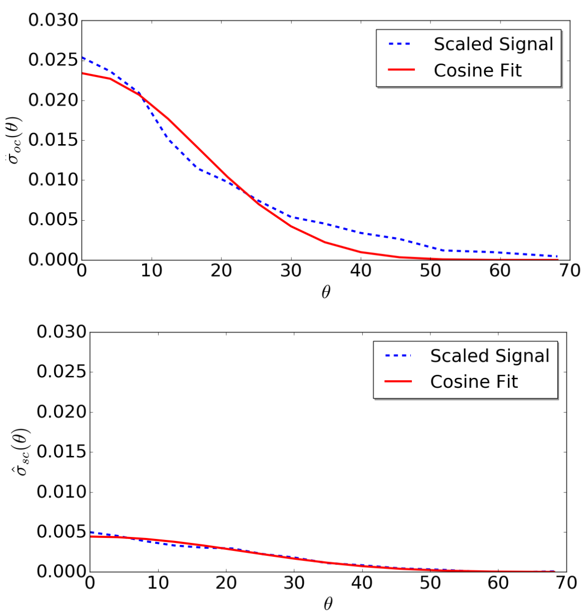

Fig. 1: The radar albedo as a function of the incidence angle for 2010 NY_{65} scaled and fit with a cosine law (Eq. 1). Opposite sense circular polarization (top) with $R = 0.0033$ and $C = 5.9530$ and same sense circular polarization (bottom) with $R = 0.0010$ and $C = 3.3879$.

Conclusions: In this presentation, we test models of radar scattering using dual-polarization radar observations to elucidate the near-surface physical properties of asteroids. Analysis of the backscattering function was done by plotting the backscattered power as a function of angle of incidence for both senses of polarization, selecting primarily targets where a roughly spheroidal shape can be assumed based on radar images.

Our preliminary work, for the example of 2010 NY65, shows that the cosine law is a good fit, assuming loose powders at the near-surface. Further work, presented at the conference, will include a larger sample size and analysis of various scattering laws.

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References: [1] Vokrouhlický, D. et. al (2015) Asteroids IV, p.509-531 [2] A. Virkki et. al (2017) EPSC, abstract id. 750. [3] T. W. Thompson (2011) J. Of Geophysical Research, Vol. 116, E01006. [4] L. C. Wye (2011), Stanford University, Dept. of Electrical Engineering. [5] Harmon et al. (1999), Planetary and Space Science 47, 1409-1422. [6] C. Magri et al (2001). Meteoritics & Planetary Science 36, 1697-1709. [7] S. K. Friedlander, Sheldon (2002), Fundamentals of Aerosol Dynamics. Oxford University Press.