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# Near surface bulk density estimates of NEAs from radar observations and permittivity measurements of powdered geologic material

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ABSTRACT

The variations in near-surface properties and regolith structure of asteroids are currently not well constrained by remote sensing techniques. Radar is a useful tool for such determinations of Near-Earth Asteroids (NEAs) as the power of the reflected signal from the surface is dependent on the bulk density, $\rho_{bd}$, and dielectric permittivity. In this study, high precision complex permittivity measurements of powdered aluminum oxide and dunite samples are used to characterize the change in the real part of the permittivity with the bulk density of the sample. In this work, we use silica aerogel for the first time to increase the void space in the samples (and decrease the bulk density) without significantly altering the electrical properties. We fit various mixing equations to the experimental results. The Looyenga–Landau–Lifshitz mixing formula has the best fit and the Lichtenecker mixing formula, which is typically used to approximate planetary regolith, does not model the results well. We find that the Looyenga–Landau–Lifshitz formula adequately matches Lunar regolith permittivity measurements, and we incorporate it into an existing model for obtaining asteroid regolith bulk density from radar returns which is then used to estimate the bulk density in the near surface of NEA's (101955) Bennu and (25143) Itokawa. Constraints on the material properties appropriate for either asteroid give average estimates of $\rho_{bd} = 1.27 \pm 0.33$ g/cm$^3$ for Bennu and $\rho_{bd} = 1.68 \pm 0.53$ g/cm$^3$ for Itokawa. We conclude that our data suggest that the Looyenga-Landau-Lifshitz mixing model, in tandem with an appropriate radar scattering model, is the best method for estimating bulk densities of regoliths from radar observations of airless bodies.



## 1. Introduction

Asteroids are of significant interest in planetary science as they are generally acknowledged as being relatively unaltered material left over from the formation of the solar system. At present there are two space missions aimed at returning regolith samples from C- group carbonaceous asteroids to better understand these primitive objects. NASA's Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) mission is scheduled to arrive at Near-Earth asteroid (NEA) (101955) Bennu, a B- type asteroid according to the Bus-DeMeo taxonomy, in 2019 for analysis and sample acquisition (Lauretta et al., 2017, 2015; Clark et al., 2011; DeMeo et al., 2009). JAXA's Hayabusa2 mission is targeting (162173) Ryugu, a Cg- type NEA according to the SMASSII taxonomy, for analysis and sample acquisition and is scheduled to arrive at the asteroid in 2018 (Yoshikawa et al., 2014; Binzel et al., 2001; Bus and Binzel, 2002). A previous asteroid sample return mission, JAXA's Hayabusa, rendezvoused with (25143) Itokawa, an S- type chondritic asteroid, in 2005 and returned small grains of regolith for analysis in 2010 (Yoshikawa et al., 2015). Collective constraints on the NEA and main belt asteroid (MBA) populations suggest that for most asteroids total bulk density is significantly lower than supposed grain densities, indicating substantial porosity (Britt et al., 2002). Remote sensing of asteroids is necessary to constrain their densities for science objectives and to provide engineering constraints for current and future space missions.

### 1.1. Asteroid radar astronomy

Planetary radar has been widely used to survey and characterize numerous NEAs as well as some MBAs (Benner et al., 2015). Re-

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flections contain information about the near-surface regolith material of the target asteroid within the penetration depth of the radar signal, typically on the scale of a few metres (Campbell, 2016; Harmon et al., 2004). Modern radar systems such as the Arecibo Observatory and Goldstone Solar System Radar that are used to observe asteroids make use of polarimetry, in which a circularly polarized radar beam is transmitted towards a target and the power and polarization of the returned radar echo is measured. Polarized radar echoes received in the same sense as that transmitted are termed SC and are indicative of multiple and diffuse scattering caused by surface roughness and embedded rocks in the regolith on the scale of the incident wavelength (Ostro et al., 1985; Harmon et al., 2004). Specular reflections from smooth (on the scale of the observing wavelength) surfaces will reverse the handedness of an incident radar signal and cause the reflection to be received in the opposite sense to that transmitted, termed OC (Ostro et al., 1985; Carter et al., 2011). The radar cross section, $\sigma$, of a given asteroid is defined by the radar equation for a given receiving mode polarization (Ostro, 1993):

$$P_{rcv} = \frac{P_{tx} G_{ant}^2 \lambda^2 \sigma}{(4\pi)^3 r^4}. \tag{1}$$

The radar cross section $\sigma$ can be converted into the geometric radar albedo, $\hat{\sigma} = \frac{\sigma}{A_p}$, if the apparent projected area $A_p$ is known. The circular polarization ratio is defined as $\mu_c = \frac{\sigma_{SC}}{\sigma_{OC}}$, and is an indication of the surface roughness on wavelength scales. With the assumption of an appropriate radar scattering law, the Fresnel reflectivity of the material within the penetration depth of the radar signal can be calculated from the OC geometric radar albedo, e.g. (Mitchell et al., 1996; Ostro et al., 1985). For targets with low surface roughness (and hence low $\mu_c$) the dominant scattering mechanism is specular reflection, making this approximation valid. The Fresnel reflectivity is dependent on the index of refraction of the regolith which is driven by the relative (to vacuum) complex permittivity, $\tilde{\epsilon_r} = \epsilon_r^{'} + i\epsilon_r^{''}$ of the material, assuming a magnetic permeability equal to unity. The real part of the relative complex permittivity, $\epsilon_r^{'}$, will be referred to as the dielectric constant for the remainder of this paper, and is proportional to the stored electrical energy in a material, controlling its reflectivity. The imaginary part of the relative complex permittivity, $\epsilon_r^{''}$, is related to the energy loss with wave propagation in a material. The loss tangent, $tan(\delta) = \frac{\epsilon_r^{''}}{\epsilon_r^{'}}$, is the ratio of the imaginary part to the real part of the relative complex permittivity and is an indication of how significant energy loss is in a material. For asteroid regolith with low metal content (and magnetic permeability equal to unity, or one) the Fresnel reflectivity is determined by the dielectric constant. Therefore the effective dielectric constant relating to all of the material making up the near surface regolith on an asteroid can be indirectly measured using radar. An understanding of how the dielectric constant of regolith constituents, essentially powdered rock, changes with environmental properties would allow such properties to be interpolated from radar data. One property, the bulk density of a material, has been shown to have a strong correlation with the dielectric constant (Campbell and Ulrichs, 1969; Olhoeft and Strangway, 1975; Ulaby et al., 1990).

### 1.2. Inversion of dielectric constant for bulk density

Electromagnetic mixing equations have been used extensively in many areas of research to solve for the dielectric properties of a wide range of composite materials and geometries (Sihvola, 1999). Porous regolith can be treated as a composite material comprised of solid particle grains and void space (vacuum). In order for homogenization of the dielectric properties to be valid for a mixture, the scale of the dielectric heterogeneity must be smaller than the wavelength of the incident electric field. This requirement is usually satisfied for planetary radar as Lunar and asteroidal regolith grain sizes are generally in the range of 30–800 μm and are much smaller than S- and X- band radar ($\lambda$ = 12.6 cm, 3.5 cm) wavelengths typically used for asteroid surveys, though the unusual scattering properties of E- and V- type asteroids could be the result of large grains (Benner et al., 2015; Clark et al., 2002; McKay et al., 1991; Benner et al., 2008). In the field of planetary science there have been several attempts to use mixing equations to extract meaningful surficial interpretations from planetary radar reflections. Campbell and Ulrichs (1969) investigated the electrical properties of terrestrial rocks, minerals, and several meteorites in order to constrain radar investigations of the Lunar regolith. They found that the Rayleigh mixing formula (also referred to as Maxwell-Garnett) provided the best fit for the measured dielectric constant of powdered rock samples at varying densities. In another study, Olhoeft and Strangway (1975) compiled 92 measurements of the complex permittivity of Lunar regolith samples returned from NASA's Apollo missions. They found that the dielectric constant varied with rock bulk density and the loss tangent was dependent on both density and iron oxide and titanium dioxide concentrations. They fitted the dielectric constant data with a power law of the form:

**Table 1**
Values of $a$ found in the literature. *excluding temperature dependence term.

| Reference | Form of Eq. (2) |
|---|---|
| Olhoeft and Strangway (1975) | $\epsilon_{eff} = 1.93^{\rho_{bd}}$ |
| Bussey (1979) | $\epsilon_{eff} = 2.10^{\rho_{bd}}$ |
| Garvin et al. (1985) | $\epsilon_{eff} = 1.87^{\rho_{bd}}$ |
| Ulaby et al. (1990) | $\epsilon_{eff} = 1.96^{\rho_{bd}}$ |
| Carrier et al. (1991) | $\epsilon_{eff} = 1.92^{\rho_{bd}}$ |
| Campbell (2002) | $\epsilon_{eff} = 1.96^{\rho_{bd}}$ |
| Barmatz et al. (2012) | $\epsilon_{eff} = 2.15^{\rho_{bd}}$ |
| Palmer et al. (2015)* | $\epsilon_{eff} = 1.85^{\rho_{bd}}$ |

$$\epsilon_{eff} = a^{\rho_{bd}}. \tag{2}$$

Here, $\epsilon_{eff}$ is the effective dielectric constant of the regolith sample, $a$ is a constant, and $\rho_{bd}$ is the bulk density of the regolith sample. Olhoeft and Strangway (1975) showed that Eq. (2) is identical to the Lichtenecker mixing equation (Lichtenecker, 1926):

$$log(\epsilon_{eff}) = \sum_i f_i log(\epsilon_i) \tag{3}$$

Here, $f_i$ is the volume fraction of the $i$th component of a mixture and $\epsilon_i$ is the dielectric constant of the $i$th component. Eq. (2) is equivalent to Eq. (3) for a two phase mixture approximating planetary regolith with one component constrained as vacuum ($\epsilon_{vacuum} = 1$) and $a = \epsilon_s^{1/\rho_s}$, where $\epsilon_s$ is the dielectric constant of the solid rock grains and $\rho_s$ is the solid density, or particle density, of the solid rock grains. The regression of the 92 Lunar regolith dielectric constant measurements by Olhoeft and Strangway (1975) resulted in the expression: $\epsilon_{eff} = (1.93 \pm 0.17)^{\rho_{bd}}$, which corresponds to a solid rock grain dielectric constant of $\epsilon_s$ = 7.7 and a particle density of $\rho_s = 3.1\,\text{g/cm}^3$. These values are in agreement with accepted values in the literature for average Lunar regolith properties (Carrier et al., 1991).

Eq. (2) has been used by several authors in the years following its introduction by Olhoeft and Strangway (1975) for planetary radar applications; however, the value for the constant, $a$, varies (Table 1). The studies shown in Table 1 derived a value for $a$ from statistical regression analysis of dielectric measurements of a variety of Lunar regolith samples and terrestrial rocks. In the context of the Lichtenecker formula, the variation in $a$ in Table 1 implies that the physical properties $\epsilon_s$ and $\rho_s$ must vary across the samples used for the dielectric measurements referenced in these