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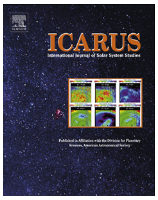

Dielectric properties of Asteroid Vesta's surface as constrained by Dawn VIR observations

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ABSTRACT

Earth and orbital-based radar observations of asteroids provide a unique opportunity to characterize surface roughness and the dielectric properties of their surfaces, as well as potentially explore some of their shallow subsurface physical properties. If the dielectric and topographic properties of asteroid's surfaces are defined, one can constrain their surface textural characteristics as well as potential subsurface volatile enrichment using the observed radar backscatter. To achieve this objective, we establish the first dielectric model of asteroid Vesta for the case of a dry, volatile-poor regolith—employing an analogy to the dielectric properties of lunar soil, and adjusted for the surface densities and temperatures deduced from Dawn's Visible and InfraRed mapping spectrometer (VIR). Our model suggests that the real part of the dielectric constant at the surface of Vesta is relatively constant, ranging from 2.3 to 2.5 from the night- to day-side of Vesta, while the loss tangent shows slight variation as a function of diurnal temperature, ranging from 6×10^{-3} to 8×10^{-3}. We estimate the surface porosity to be ~55% in the upper meter of the regolith, as derived from VIR observations. This is ~12% higher than previous estimation of porosity derived from previous Earth-based X- and S-band radar observation. We suggest that the radar backscattering properties of asteroid Vesta will be mainly driven by the changes in surface roughness rather than potential dielectric variations in the upper regolith in the X- and S-band.

1. Introduction

NASA's Dawn mission is targeting two uniquely large asteroids for orbital investigation, Vesta and Ceres, which are thought to be remnant building blocks of the terrestrial planets (Russell and Raymond, 2011). The structural and textural properties of asteroids are observed primarily using Earth-based radar, and provide insight into the processes that shaped their surfaces: whether through impact cratering, lava flows, or stress fracturing as a result of the diurnal thermal erosion arising from the expansion and contraction of volatiles embedded in the surface material. The first target of the Dawn mission, Vesta, was expected to have depleted its volatile content long ago through global melting, differentiation, and later regolith gardening by impacts from smaller bodies (Russell and Raymond, 2011). However, multiple observations from Dawn's year-long orbital mission point to the ephemeral presence of volatiles: localized hydrogen concentrations in regions thought to contain impactor-delivered hydrated materials (Prettyman et al., 2012; Reddy et al., 2012), widespread hydroxyl absorption bands across the surface (De Sanctis et al., 2012b), pitted terrain in some crater floors, thought to be caused by the degassing of subsurface volatiles (Denevi et al., 2012), and gullies in crater walls that are morphologically consistent with formation by transient fluid flow (Scully et al., 2015).

Given radar's ability to resolve a target's overall shape and centimeter- to decimeter-scale surface roughness, and its ability to assess the potential presence of ice through polarimetric ratios (e.g. Thompson et al., 2011, 2012), radar is a particularly useful technique for aiding in the volatile investigation of Vesta's surface and that of other small bodies. Earth-based and orbital radar studies of the Moon, for example, have revealed potential sites of ice concentration at the poles (e.g. Spudis et al., 2010), while

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Earth-based radar observations of Mercury have provided the first detection of water ice in permanently shadowed craters (Slade et al., 1992). For asteroids, Earth-based radar is predominantly used for detection purposes, yielding shape, spin and qualitative surface roughness from delay-Doppler imaging (Ostro et al., 2002). Vesta has likewise been observed at a number of radar frequencies: the X-band at Goldstone and S-band at Arecibo (e.g. Mitchell et al., 1996), as well as the Ku- and C-bands with the Very Large Array (VLA) (Johnston et al., 1989).

The results of such radar observations, however, are difficult to translate into quantifiable surface physical properties, as the power and polarization of the returned radar backscatter are affected by the observing geometry (which is easily constrained) and by three intrinsic factors of the surface: (1) variations in the surface topography, (2) variations in surface roughness, and (3) variations in the surface's dielectric properties—which describes the radar reflectivity and absorptivity of a material, and is primarily dependent on the mineralogy, bulk density, temperature and volatile content of the surface material (e.g. Heggy et al., 2001, 2012; Paillou et al., 2006). While the effect of the surface topography of small bodies can be modeled from a shape model (which in turn can be derived from speckle interferometry, photometric lightcurves or stereoscopic images), surface roughness and surface dielectric properties remain poorly characterized. As a consequence, when measuring the radar backscatter from the surface of a small body, it is challenging to determine whether backscatter variations are caused by variations in surface roughness or variation in the surface's dielectric properties. The ability to construct a quantifiable surface roughness map, and subsequently to identify regions that are smooth at decimeter scales, is critical to the success of future small-body landing missions (e.g. Asphaug, 2006) and future sampling experiments (ElShafie and Heggy, 2013).

This difficulty is exemplified by Mitchell et al. (1996), who used radar Doppler spectra to qualitatively infer that Vesta's surface is overall rougher than the Moon at both decimeter and centimeter scales. While they used a shape model (derived from speckle interferometry) to constrain the topographic component of the total radar backscatter, they did not estimate the backscatter contribution that arises from potential variations in the surface's dielectric properties—which are widely used to assess the textural and compositional uncertainties of a surface (e.g. Boisson et al., 2009, 2011). On the Moon, the ability to quantify dielectric properties has proven significant for identifying distinctions between the two types of lunar terrain, the highlands and the lunar *maria* (Fa and Wieczorek, 2012).

One study that attempts to estimate the dielectric properties of Vesta's surface is conducted by Johnston et al. (1989), who find that the Ku- and C-band microwave emissions from Vesta are in disagreement with those expected of a rotating blackbody. They suggest that the asteroid may be covered by a thin layer of dust that decreases microwave reflectivity, thereby increasing the body's microwave brightness. When estimating the thickness of this layer, they rely on dielectric mixing models of generic powdered rock (discussed by Campbell and Ulrichs (1969)), and suggest a depth of 6 cm when assuming a value of 2.9 for the real part of the relative dielectric constant ε' and assuming 1.5×10^{-2} for the loss tangent $\tan\,\delta$—where ε' relates to the material's reflectivity and $\tan\,\delta$ to the material's attenuation of energy. Johnston et al.'s (1989) value of ε', however, is inconsistent with dielectric laboratory measurements of powdered basaltic samples near the same bulk density of $1.00\,\text{g cm}^{-3}$ (e.g. Campbell and Ulrichs, 1969; Alvarez, 1974). When considered alongside the study of Mitchell et al. (1996), both results suggest that there is a substantial ambiguity regarding the textural and dielectric properties of Vesta's surface, as well as in the method used to quantify them from Earth-based radar observation.

With the Dawn mission, however, an opportunity arises to address this deficiency. In this study, thermal observations by Dawn's Visible and InfraRed (VIR) mapping spectrometer are used to constrain the bulk density and temperatures of the surface, which are the main parameters that determine the surface's dielectric properties for a desiccated planetary regolith (Thompson et al., 2011). Our dielectric model is constructed specifically for the dry, volatile-poor case of Vesta's surface, given that the highest hydrogen concentration observed by Dawn's GRaND instrument is 400 ppm or 0.04 wt.% (Prettyman et al., 2012), which is well below the radar detectability limit of at least 10% of ice content in basaltic desiccated lunar-like soils (Fa et al., 2011). This model allows us to assess the expected range of dielectric properties arising from potential surface compositional variations (as described by De Sanctis et al., 2012a, 2013), as well as from variations in surface temperature and density (as described by Tosi et al. (2014) and Capria et al. (2014)).

Since the dielectric properties of asteroid analog materials have yet to be measured in the laboratory, we use existing dielectric studies of lunar soil samples to serve as suitable analogs to Vesta's upper regolith material. The compositional analogy between Vesta's surface material and basaltic lunar soil is addressed in Sections 2.1 and 2.2, and the assumptions and limitations of the resulting surface dielectric model are considered in Sections 2.3 and 2.4. Section 3 contains the results of the dielectric model for Vesta's surface, and includes suggested validation sites where the dielectric constant of Vesta's surface may be estimated from future in-situ radar observations. In Section 4, the implications of our findings are discussed for existing and future Earth- and space-based radar studies of Vesta and other asteroids, with emphasis on volatile detectability. Overall, this dielectric model is an essential step toward retrieving quantifiable surface roughness from radar backscatter measurements by Earth-based and orbital X- and S-band radar observations (e.g. Mitchell et al., 1996; Nolan et al., 2005), which will develop understanding of the processes that govern Vesta's surface texture, as well as support the planning of potential future landing and sampling experiments, such as NASA's Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-REx) (Lauretta et al., 2015).

2. Dielectric model construction and parameter constraint

The dielectric properties of a material describes the intrinsic mechanisms by which the material reflects and attenuates the electric field component of the incident radar wave, and is quantified by the complex relative dielectric constant ($\varepsilon = \varepsilon' + i\varepsilon''$). For brevity, the relative dielectric constant, a dimensionless quantity, is hereon referred to as the dielectric constant. As previously mentioned, the real part of the dielectric constant, ε', relates to the reflectivity of the material, while the ratio of the imaginary part to the real part ($\varepsilon''/\varepsilon'$) is termed the loss tangent ($\tan\delta$), and quantifies the loss of energy during transmission through a given material (such as Vesta's regolith). For small desiccated terrestrial bodies, including the Moon and Mercury, the dielectric properties of the surface mainly depend on the material's (1) mineralogy, (2) bulk density, (3) diurnal surface temperature, (4) potential volatile content (e.g. Heggy et al., 2012), and (5) frequency, which falls in the range of 2–8 GHz for Earth-based radar observations. In the following sections, the first four of these geophysical parameters are constrained for the material of Vesta's upper regolith using observations by the Dawn VIR spectrometer. In Section 3, these constraints are utilized to construct a numerical model of ε' and $\tan\delta$ for the general case of a volatile-poor, dry surface and shallow subsurface of Vesta.