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Improvements on effective permittivity measurements of powdered alumina: Implications for bulk permittivity properties of asteroid regoliths

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Abstract

Accurate measurements of the dielectric properties of materials are essential in constraining interpretations of radar observations of planetary bodies. For bodies whose surfaces are comprised of regolith this requires an understanding of the behaviour of the bulk permittivity of powders. In this research we measure the effective permittivity of powdered aluminium oxide (or alumina, Al_2O_3) in a 7 mm and 14 mm (diameter) coaxial airline at 7.5 GHz for multiple samples with varying grain size. The dielectric constant of alumina is extracted from these measurements using the Bruggeman (Effective Medium Approximation) mixing equation. We develop a model to account for heterogeneity within the airline, specifically in regards to local variation in porosity. The results of the model show good correlation to experimental data and effectively correct for grain size effects on the measured bulk permittivity. We show that particle shape can have a significant impact on the output of the model and can be accounted for by modelling particles as ellipsoids rather than perfect spheres, where the depolarization factor must be measured and averaged for a specific sample batch.

Keywords: Asteroid regolith; OSIRIS-REx; Radar; Permittivity; Alumina; Dielectric

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1. Introduction

Active remote sensing techniques in the microwave regime are used in observing planetary bodies through terrestrial/orbiting radar and ground penetrating radar (GPR). The reflectivity and penetration depth of a radar signal incident on a non-conducting surface are largely determined by those materials' dielectric response at a given frequency (Griffiths, 1999; Feynman et al., 1979). For planetary bodies whose surfaces consist of regolith material, such as the Moon and asteroids, properties of that regolith may be extracted from a radar return if the effective permittivity of the regolith is known (Heiken et al., 1991).

Polarimetric radar is used to measure the degrees of circular/linear polarizations received from a surface which are sensitive to a variety of target features including subsurface structure, surface roughness, regolith thickness, bulk density, and composition (Carter et al., 2011). Models that derive these features from radar data intrinsically make assumptions about physical characteristics of the target

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that greatly affect the returned signal properties, such as the dielectric permittivity, introducing large sources of uncertainty to interpretations. To overcome this, radar images of planetary bodies are often compared with terrestrial analogues (Carter et al., 2011); however, this is not appropriate for bodies for which no adequate terrestrial analogues exist, such as asteroids. A correlation between circular polarization ratio and visible-infrared taxonomic class has been identified in near-Earth asteroids that would be better understood if the bulk (effective) dielectric properties as a function of mineralogical composition were known (Benner et al., 2008). Providing information on the dielectric permittivity of regolith materials is therefore relevant for missions to asteroids such as 101955 Bennu, the target of NASA's Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-REx) mission. To constrain the analysis of radar data on planetary bodies, specifically asteroids, laboratory measurements are needed to better understand the dielectric permittivity of regolith materials (Nolan et al., 2013; Carter et al., 2011).

A popular and effective approach for measuring the permittivity of any dielectric material is the transmission line method utilizing a coaxial airline and network analyser (Chen et al., 2004). This technique has the advantage of broadband measurement, being relatively inexpensive, and recently has been shown to have the capability of measuring powdered samples (Grosvenor, 1993; Stillman and Olhoeft, 2008; Sotodeh, 2014). By measuring powdered samples the effects of grain size distribution, grain shape, and porosity on the effective permittivity can be determined. Measurement techniques for powdered samples have been investigated in the literature (Tuhkala et al., 2013; Ebara et al., 2006); however, the aforementioned effects on the effective permittivity are not well understood.

For a powdered sample, the measured value in the transmission line method is the effective permittivity of the sample. The effective permittivity is a combination of each phase within the airline: water adsorbed on grain surfaces, air, and the solid sample. Samples can be oven baked to remove residual moisture, resulting in a two phase mixture of air and solid sample. Electromagnetic mixing theory can be used to extract the permittivity of the solid phase of the mixture (true permittivity of the sample). Mixing theory is based on the assumption of homogeneity within the sample and uniform particle shape (Sihvola, 1999). These assumptions are not valid when considering a powdered sample in a coaxial airline.

In this research a theoretical model is developed to account for heterogeneity at the boundary of the coaxial airline and shows potential to compensate for particle shape effects. The effective complex permittivity of alumina is measured (using the transmission line method) and input to this model to calculate the dielectric constant of alumina. While both the real (dielectric constant) and imaginary (dielectric loss) parts of relative permittivity affect radar scattering, this paper is focused on using the real part of permittivity measurements to test the validity of the model. Given the results of our experiment, future work will be done applying this model to the dielectric loss. Alumina was chosen for this study as it has well known dielectric properties and is readily available in powdered form at a variety of grain sizes, making it a suitable standard to test the model with. The average grain sizes and porosities of samples measured in this research were chosen to correspond to asteroidal surface regolith material (Shepard et al., 2010; Magri et al., 2001; Clark et al., 2002). Section 2 discusses our measurement procedure and presents the raw, unprocessed permittivity data. Section 3 describes the model developed in this research to correct the raw data. Section 4 discusses the results of processing the data presented in Section 2 with the technique shown in Section 3. The corrected dielectric constant values are compared to results from the literature. Improving the accuracy of measurements of the permittivity of powders will tighten constraints on radar/GPR data and allow more accurate interpretations of planetary datasets.

2. Experimental procedure

2.1. Sample preparation

Seven sample batches of alumina grit with average grain sizes ranging from 76 μm to 940 μm supplied by Kramer Industries, Inc. were used in the experiment. The particle size distribution for each sample conform to ANSI B47-12-2001 grit size grading standards. The samples were oven baked at a constant temperature of 200 °C for 48 h prior to measurement to evaporate residual moisture. The mass of the sample before and after oven baking was measured using a digital scale within ±1 mg (Sotodeh, 2014). The volume of each airline was measured with a hole gauge micrometer within ±0.25 mm to calculate the bulk density of each sample. The sample bulk density and specific gravity were used to calculate the porosity within the coaxial airline for a given measurement. A custom airline filling fixture was created to vibrate the airline and ensure maximum and uniform particle packing density. Tests run on the filling/vibrating procedure showed porosity in the sample holder reaches an asymptotic limit after a given vibration time. By vibrating the airline throughout the filling process there is no suspected gradient in porosity along the airline's length. Each sample's complex permittivity was measured in a 7 mm diameter (HP 85051B, 10 cm length) and 14 mm diameter (GR 900-LZ, 15 cm length) coaxial airline connected to an Agilent E5071C-280 ENA series vector network analyser. A full two-port short, open, through, and load (SOTL) calibration of the network analyser was completed before all measurements to reduce systematic errors following the manufacturer's instructions (Agilent, 2011; Sotodeh, 2014). The complex permittivity of each sample was calculated from the S-parameters measured by the network analyser using the non-iterative algorithm outlined in Boughriet et al. (1997).

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