Exploring Ceres’s Unusual Regolith Porosity and Its Implications for Volatile Retention

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Abstract

Asteroid Ceres, the only dwarf planet located in the inner solar system, shows unique surface mineralogy and geomorphology as observed by the Dawn mission. Of particular interest is understanding the role that upper regolith porosity plays in retaining volatiles and shaping Ceres’ surface. Unfortunately, Ceres’ near-surface porosity remains largely uncharacterized, compromising the ability to quantify volatile occurrence and identify the mechanisms for volatile retention at shallow depths, a topic of ongoing debate. Herein, we estimate Ceres’ shallow-subsurface porosity by reinterpreting existing S- and X-band Earth-based radar observations combined with dielectric laboratory measurements of analog materials that have been recently suggested by spectral observations from the Dawn VIR spectrometer and in the far-ultraviolet from the Hubble telescope. Contrary to previous assumptions, our results suggest that Ceres’ surface is more porous than the lunar regolith, with a bulk porosity ranging from ~53% to 72% or even higher in the top meter of the regolith, as opposed to ~39% to 50% for both bodies. The above suggests that Ceres’ regolith is on average 15% more porous than the Moon, hence explaining its higher potential for volatile retention. We propose that lofting and gradual redeposition of fine particles by avalanches, continuous micrometeorite bombardment, and localized volatile outgassing are possible mechanisms for generating a globally high-porosity regolith. In addition to Ceres’ proximity to the snowline of the early solar system, such a highly porous regolith may explain its efficiency at retaining volatiles at shallow depths into the present, as revealed by Dawn’s GRaND observations.

1. Introduction

Mechanisms for the capture and retention of volatiles during the formation and evolution of airless small bodies are not fully understood (e.g., Drake & Campins 2005; Elkins-Tanton 2012; Morbidelli et al. 2012; Sarafian et al. 2017). The potential occurrence of water ice buried in the regolith of the Moon remains a subject of debate, including, for instance, whether it is exogenic or endogenic (e.g., Benn et al. 2019). Similarly, on Asteroid Vesta, geomorphological evidence and bistatic radar observations by the Dawn mission have suggested that buried ice may have played a role in shaping the asteroid’s surface, even though its original volatile content is thought to have been depleted during its differentiation (Scully et al. 2015; Palmer et al. 2017). One of the key parameters in volatile preservation on an airless body is its regolith porosity, where pore spaces create potential host environments, provided suitable thermal conditions, for volatile retention, such as the thick dust mantles thought to shield the icy cores of inactive comets (e.g., Schöorghofer & Aharonson 2014; Schöorghofer 2016; Küppers 2019; Yu et al. 2020).

Of particular interest is Asteroid Ceres, an airless small body thought to have retained ice since its formation (Russell & Raymond 2012). Ceres is the only dwarf planet located in the inner solar system and is the largest object in the asteroid belt, spanning 950 km in diameter and comprising almost a third of the belt’s mass alone (Russell & Raymond 2012). Ceres is thought to have retained an abundance of water ice in large part due to its location in the middle of the asteroid belt (~2.8 au), which coincides with estimates of the early solar system’s snowline position (~2.7 au), beyond which temperatures were sufficiently low for water ice to condense and be accreted (e.g., Dodson-Robinson et al. 2009).

Retention of water ice within Ceres is also supported by several decades of Earth-based spectral observations that suggest the presence of aqueously altered minerals on its surface, including clays and carbonates (e.g., Lebofsky et al. 1981; Rivkin et al. 2011). Spectral signatures of water vapor have also been detected—first tentatively in 1990–1991 with the International Ultraviolet Explorer satellite, and then in 2014 at far-infrared wavelengths with ESA’s Herschel Space Observatory (A’Hearn & Feldman 1992; Küppers et al. 2014). In 2015, NASA’s orbital Dawn mission to Ceres confirmed the widespread occurrence of aqueously altered minerals across the surface via high-resolution orbital hyperspectral mapping by the onboard Visible and Infrared Mapping spectrometer (VIR) (De Sanctis et al. 2015; Ammannito et al. 2016). VIR has also provided spectral evidence for surficial ice in areas with relatively low illumination, such as the shadowed parts of high-latitude craters (Combe et al. 2016, 2019). Likewise, geomorphological analyses of Dawn’s high-resolution optical framing camera (FC) images reveal that Ceres’ surface topography is consistent with shaping by abundant shallow-subsurface water ice in the first 10–100 m that results in low relief, a lack of craters larger than 280 km in diameter, extensive lobate landslides, and precipitated carbonates and salts (De Sanctis et al. 2015; Buczkowski et al. 2016; Schmidt et al. 2017).
The depth to shallow ground ice, however, is not explicitly known. The Gamma-Ray and Neutron Detector (GRaND) aboard Dawn observes 17 ± 2 wt% water-equivalent elemental hydrogen abundance (WEH) at equatorial latitudes, increasing to ∼30 wt% WEH at the poles (Prettyman et al. 2017). Prettyman et al. (2017) suggest that this observation can be interpreted as a buried, pore-filling ice table of 10 wt% water ice at a depth of about 1 m at the equator, rising to just a few centimeters beneath the surface at the poles. However, Prettyman et al. (2017) assume that the regolith’s dry-material grain density is 2.5 g cm⁻³ (typical of carbonaceous chondrite meteorites), which yields a relatively low regolith porosity of 20% in this first meter. Alternatively, Prettyman et al. (2017) consider that if the pore-filling ice table contains 30 wt% water (the maximum observed at the poles), and again assuming a dry-material grain density of 2.5 g cm⁻³, then the regolith’s bulk porosity would be 50% (comparable to the Moon in its uppermost meter) and that the ground-ice table would be at least a few meters deep at the equator, if not more.

Regolith porosity has not been thoroughly explored on Ceres, however, including the role of globally observed landslides that can launch avalanche-like dust clouds that settle down with extremely loose packing (e.g., Schmidt et al. 2017). Moreover, considering that Ceres’s regolith is subjected to much less gravitational force than on the Moon, holds more ice, and significantly differs in composition from lunar regolith, the oft-employed assumption that airless small bodies have a lunar-like range of regolith densities may not be appropriate or sufficient for thermophysical modeling on Ceres or for subsequent estimates of the depth to its icy volatiles. Hence, a key factor in understanding icy volatile retention within Ceres’ shallow subsurface is to accurately constrain the bulk porosity of its first few meters of regolith, which we attempt to address herein using a new interpretation of existing Earth-based radar observations, combined with laboratory dielectric measurements of Ceres analog materials.

Earth-based radar observations at S- and X-band frequencies are particularly useful for remotely assessing bulk porosity in the upper meter of desiccated planetary regoliths, as they provide unique insights into the regolith’s electrical and textural properties (e.g., Campbell 2002). Several Earth-based radar observations of Ceres have been collected at S-band frequencies (∼2 GHz) using the Arecibo Observatory radio telescope in the following years: first in 1977 (Ostro et al. 1979); 1984 (Ostro et al. 1985); 1986 and 1990 (Mitchell et al. 1996; Magri et al. 1999); 2000 (Nolan et al. 2000); 2004 (Benner 2021); and most recently in 2018 (Bhiravarasu et al. 2018). One set of X-band (∼8 GHz) frequency observations was collected in 1995 using the Goldstone Deep Space Communications Complex (Mitchell et al. 1996; Magri et al. 1999). Ceres has been observed from a geocentric distance between ∼1.6 and 1.9 au for all radar collects except those in 1984, at a distance of ∼2.1 au. At both S- and X-band frequencies, the quasi-specular component of Ceres’ radar albedo has consistently been measured as δ∞ = 0.037 ± 0.01, with a diffuse component of δ∞ ≈ 0 (i.e., below the noise of the receiver)—where weak diffuse scatter suggests that the surface is relatively smooth on scales of centimeters to meters (Mitchell et al. 1996; Bhiravarasu et al. 2018).

The ability to infer Ceres’ shallow regolith porosity from the above-mentioned radar observations requires the disentanglement of radar backscatter signal contributions coming from (1) surface slopes (topography), (2) wavelength-scale surface roughness, and (3) the intrinsic radar reflective and absorptive properties of the regolith’s constituent material. For Ceres, we are able to constrain surface slopes from Dawn mission topographic shape models, and we can assume from the above-mentioned Arecibo and Goldstone radar observations that Ceres’ weak diffuse scatter suggests a lack of surface roughness at the centimeter to meter scale. The material’s radar reflective and absorptive properties, in turn, are quantified by their complex dielectric constant or relative permittivity ε = ε′ − iε″, the value of which depends on the observing radar frequency (S- and X-band for Earth-based planetary radar observations) and on the physical properties and composition of the regolith material itself (i.e., bulk density, ice fraction, mineralogy, and temperature).

Unfortunately, the dielectric properties of small bodies, as well as their regolith porosity, are largely uncharacterized, in part because spectral analogs among meteorites have not been identified for most asteroids, and very few dielectric laboratory studies have been performed with sufficient sample desiccation to replicate the environment of airless, desiccated planetary surfaces. Sample desiccation is particularly important as ambient atmospheric moisture is rapidly absorbed by dry samples, measurably altering their dielectric properties as first realized for Apollo lunar samples (e.g., Olhoeft & Strangway 1975; Heggy et al. 2001).

In order to address this deficiency for Ceres and to be able to invert the bulk porosity of the shallow regolith from radar backscatter data, we perform dielectric laboratory measurements of hypothesized Ceres spectral analog materials and report their dielectric properties as functions of bulk porosity, ice fraction, and temperature. We then use our laboratory results combined with estimates of Ceres’ dielectric properties from Earth-based radar observations to infer near-surface porosity. In light of our findings, we suggest physical mechanisms responsible for the inferred range of regolith bulk porosity and how they may have played a role in retaining volatiles on Ceres, along with implications for sampling such volatiles on future missions to rocky, icy bodies.

2. Methods

2.1. Earth-based Radar Observations of Ceres

The radar albedo of an asteroid is a measure of the total received radar backscatter power averaged over the geometric cross section of the target’s surface. For circularly polarized waves, the total radar albedo δtot is the sum of the opposite-sense circular (δoc) and same-sense circular (δsc) backscatter returns, where the first is predominantly generated by quasi-specular reflections from smooth surfaces and radar-facing surface slopes (i.e., topography), and the second by diffuse scatter associated with surface roughness at the scale of the observing wavelength. In the case of Asteroid Ceres, Earth-based radar observations from Arecibo and Goldstone observatories have measured a total radar albedo δtot of 0.037 ± 0.01 at S-band (Bhiravarasu et al. 2018) and 0.037 ± 0.01 at X-band (Mitchell et al. 1996), with no measurable same-sense circular component (δsc ≈ 0) at either frequency (i.e., below the receiver noise), suggesting that most of the measured backscatter return comes from specular reflections rather than diffuse scatter (e.g., Mitchell et al. 1996). As a result, we can express the radar albedo in terms of its specular component (e.g., Mitchell et al. 1996):

\[ δ_{\text{tot}} = δ_{\infty} ≈ gρ_0, \]  

where the radar backscatter gain g ≥ 1 and is a function of surface slopes (topography) and wavelength-scale surface
roughness ($g = 1$ for a perfectly smooth sphere); and $\rho_0$ is the Fresnel power reflection coefficient of the material as observed at normal incidence (i.e., normal radar reflectivity).

Radar backscatter gain $g$ can be estimated by fitting quasi-spectral scattering models to the target’s radar spectrum as a function of rms surface slope $\theta_{\text{rms}}$ (e.g., Mitchell et al. 1996). However, when the target is fully illuminated by the observing radar footprint, the radar return is an average of the scattering properties of the target’s surface, and for a spherical body with an arbitrary surface, an equal number of radar-facing and away-facing slopes are illuminated. Hence, radar backscatter is only weakly dependent on surface topography and wavelength-scale surface roughness when observing the target’s full disc.

Furthermore, surface slopes are not well constrained on Ceres at the scale of $S$- or $X$-band radar wavelengths (i.e., centimeters to meters). The vertical resolution of Ceres’ highest-resolution digital elevation models retrieved by the Dawn mission, for example, are only accurate to the nearest $\pm 10$ m (Park et al. 2019).

For simplicity, i.e., to minimize the number of assumptions when inverting the dielectric constant from $S$- and $X$-band radar observations of Ceres, we therefore consider all solutions of $\rho_0$ where $g \geq 1$.

The normal radar reflectivity (from Equation (1)) depends on the complex dielectric constant of the observed material:

$$\rho_0 = \left| \frac{1 - \sqrt{\varepsilon_r}}{1 + \sqrt{\varepsilon_r}} \right|^2. \quad (2)$$

Because $g \geq 1$, it follows from Equation (1) that $\varepsilon_{\text{tot}} \geq \rho_0$, yielding

$$\varepsilon_{\text{tot}} \geq \left| \frac{1 - \sqrt{\varepsilon_r}}{1 + \sqrt{\varepsilon_r}} \right|^2, \quad (3)$$

which can then be solved for $\varepsilon_r$ as

$$\left( \frac{1 - \sqrt{\varepsilon_{\text{tot}}}}{1 + \sqrt{\varepsilon_{\text{tot}}}} \right)^2 \leq |\varepsilon_r| \leq \left( \frac{1 + \sqrt{\varepsilon_{\text{tot}}}}{1 - \sqrt{\varepsilon_{\text{tot}}}} \right)^2, \quad (4)$$

where the magnitude of the complex dielectric constant $|\varepsilon_r| = \sqrt{(\varepsilon_r)^2 + (\varepsilon_i)^2}$. Given that $|\varepsilon_r| > 1$, the permittivity of free space, we can then remove the lower limit term (because it is always $\leq 1$) from Equation (4) and rewrite it as

$$1 < |\varepsilon_r| \leq \left( \frac{1 + \sqrt{\varepsilon_{\text{tot}}}}{1 - \sqrt{\varepsilon_{\text{tot}}}} \right)^2. \quad (5)$$

From Equation (5), we calculate that $1 < |\varepsilon_r| \leq (2.2 \pm 0.3)$ for Ceres’ upper regolith at $S$- and $X$-band frequencies based on past Earth-based radar observations of Ceres (Ostro et al. 1979, 1985; Mitchell et al. 1996; Magri et al. 1999; Nolan et al. 2000; Bhirararsu et al. 2018; Benner 2021).

2.2. Spectral Analogs to Ceres’ Regolith

Mineralogical studies of Ceres’ surface inform our choice of suitable electrical analog materials for dielectric measurements. At 1 km scales, the majority of Ceres’ surface appears spectrally dark from visible to IR wavelengths based on observations by Dawn’s optical framing camera and VIR spectrometer (De Sanctis et al. 2015; Ammannito et al. 2016). De Sanctis et al. (2015) provide an extensive analysis of the average spectral signature of Ceres’ surface to identify best-fit spectral analog end-members. In this study, we use the best-fit spectral model from Figure 4(a) of De Sanctis et al. (2015), which consists of 84% “dark material,” 6% ammoniated montmorillonite (a clay mineral), 5% antigorite (a serpentine mineral), and 5% Mg carbonate, where percentages are given in mineral abundances (see Extended Data Table 2 of De Sanctis et al. 2015).

The opaque mineral “dark material” dominating the surface’s spectral signature has been suggested to be magnetite or amorphous carbon (such as soot or carbon black) (De Sanctis et al. 2015; Raponi et al. 2018; Marchi et al. 2019). However, Dawn’s Gamma Ray and Neutron Detector (GRaND) has found that the equatorial average elemental iron abundance (16 ± 1 wt% Fe) is too low for abundant magnetite to exist across Ceres’ surface—no more than 6 vol% magnetite, assuming a regolith grain density of $\sim 2.5$ g cm$^{-3}$ (Prettyman et al. 2017, 2019). Although the dark material is spectrally flat at visible to IR wavelengths, observations of Ceres’ far-UV spectrum by the Hubble Space Telescope (116–570 nm) reveal a spectral “bump” at 400 nm that is characteristic of up to 80–95 wt% highly processed, graphitized carbon consistent with an anthracite-like (hard coal) composition (Hendrix et al. 2016a, 2016b). In addition, Prettyman et al. (2019) suggest that the regolith surface could be devolatilized, yielding a low hydrogen-to-carbon ratio (H/C) through the process of graphitization of carbonaceous material by solar weathering (Hendrix et al. 2016a). In turn, Prettyman et al. (2019) suggest that this could yield progressively less graphitization with depth (i.e., increasing H/C with depth), implying that organic materials higher in [H] such as tholins could be present at greater depths.

Alternatively, Marchi et al. (2019) suggest a spectral analog mixture for Ceres’ surface material that combines Ivuna-type (CI) carbonaceous chondrite at 60 vol% with 22 vol% amorphous carbon, 2.5 vol% magnetite, and spectrally bright components 12.5 vol% clay minerals, 2 vol% antigorite, and 1 vol% dolomite. Because GRaND observes $\leq$1.5 wt% [H] for Ceres’ dry regolith (Supplementary Materials, Prettyman et al. 2017), Marchi et al. (2019) set an upper limit of $\sim 22$ vol% of amorphous carbon in Ceres’ regolith, assuming that the hydrogen content of such carbon is $\geq 5$ wt% [H]. However, as previously mentioned, if this amorphous carbon has been devolatilized through graphitization, stripped of its hydrogen to only a few weight percent, e.g., by space weathering processes, then the low amount of hydrogen observed by GRaND in the dry portion of Ceres’ regolith does not place an upper limit on the amount of carbonaceous material that can be present (Hendrix et al. 2016a, 2016b; Prettyman et al. 2019).

Localized areas of bright material on Ceres have also been observed by Dawn, ranging in size from <1 km$^2$ to more than 120 km$^2$, and are thought to include magnesium- and ammonium-bearing phyllosilicates (e.g., serpentine and clay minerals), as well as Mg-rich carbonates (e.g., dolomite) and salts (De Sanctis et al. 2015, 2016; Ammannito et al. 2016; Stein et al. 2019). Bright material has been observed on the floors and walls of several craters and among crater ejecta (Stein et al. 2019) and found atop Ahuna Mons, a large dome thought to have formed from a slurry of salt-rich liquid and non-soluble phyllosilicates (Ruesch et al. 2019). Laboratory spectral reflectance measurements of different clay minerals suggest that smectites, particularly nontronite and montmorillonite, are the
most likely candidates for the ammoniated clays detected on Ceres, as they readily accept NH$_4^+$ into their crystal structure (De Angelis et al. 2017).

Combining the above results with the best-fit spectral model of De Sanctis et al. (2015), which represents the average spectral signature of Ceres’ surface, we select the following analog materials for this study: anthracite coal to represent Ceres’ dark material (characterized by $>87$ wt% carbon Papoular et al. 1996), three different types of smectite clay minerals to represent ammoniated phyllosilicates (Al-poor nontronite, Al-rich nontronite, and montmorillonite), antigorite to represent Mg-bearing phyllosilicates, and dolomite to represent Mg carbonates.

Next, we convert mineral abundances from De Sanctis et al. (2015) to mass fractions using Equation (9) from Stack & Miliken (2015) along with the following assumptions regarding solid density $\rho_0$ and grain diameter $D_{\text{clay}}$ for the different clay minerals: $\rho_0(\text{montmorillonite}) = 2.6$ g cm$^{-3}$, $\rho_0(\text{nontronite}) = 2.3$ g cm$^{-3}$, and $D_{\text{clay}} = 10$ $\mu$m. The resulting mass fractions for the spectral mixture suggested above by De Sanctis et al. (2015) are then 95 wt% anthracite coal, 3 wt% antigorite, 1.5 wt% ammoniated clay, and 0.5 wt% dolomite.

It is important to note that while anthracite coal (the highly processed, low-grade metamorphosed remnants of organic matter) is not an appropriate geochemical analog to Ceres’ regolith composition, this highly graphitized coal (86–98% carbon) serves as an electrical analog to the polarization properties of a highly carbonaceous substance at radar frequencies. Materials for future dielectric laboratory measurements at radar frequencies should include desiccated samples of carbon black as well as carbonaceous chondrite meteorites to further support this assertion.

Because anthracite coal significantly dominates the mass of the mixture at 95 wt%, we note that the dielectric properties of this analog mixture, regardless of the chosen clay mineral, will be indistinguishable from the dielectric properties of pure anthracite coal. Hence, for this analysis, we have performed dielectric measurements on pure anthracite coal as the spectral analog for Ceres’ average regolith composition. We also include dielectric measurements of the three above-mentioned clay minerals to provide a benchmark for how effectively we are able to desiccate our samples during the measurement process, as smectite clays are particularly hydrophilic and hence susceptible to ambient moisture contamination. All samples are listed in Table A1.

2.3. Additional Constraints on the Bulk Density of Ceres’ Uppermost Meters of Regolith

Only a few studies estimate the density or porosity of the upper centimeters to meters of the regolith on Asteroid Ceres. Porosity modeling by Magri et al. (2001) using Earth-based radar observations of different small bodies finds that Ceres’ near-surface bulk porosity is 67% ± 4% based on S-band frequency observations by Mitchell et al. (1996). However, the underlying formula used to retrieve bulk porosity from observed radar reflectivity is based on measurements of the dielectric properties of Apollo lunar samples—essentially assuming that the dielectric constant of Ceres’ regolith material has the same dependence on bulk density as measured for the Apollo lunar samples, which again were notably contaminated with atmospheric moisture and measured under widely varying non-standardized laboratory conditions (Olhoeft & Strangway 1975; Carrier et al. 1991; Heggy et al. 2001, 2020). Furthermore, the solid density of the material assumed for C-class asteroids (which includes Ceres) is $\sim 2.5$ g cm$^{-3}$ (Magri et al. 2001), which is considerably denser than the suggested analog material of anthracite coal, which has a specific gravity of $1.4$–$1.7$ g cm$^{-3}$ (Stoek 1902). Given that the underlying assumptions of Magri et al. (2001) model are inconsistent with our own, we exclude their estimate of porosity from our analysis.

One of the only studies providing constraints on Ceres’ near-surface density is that of Rognini et al. (2020), who construct a thermophysical model of Ceres’ regolith to infer its thermal inertia and assess whether the upper meter of regolith is composed of a “fine dust” or “fine-grained regolith.” They use the hyperbolic density-depth profile modeled by Carrier et al. (1991) for the lunar regolith, which is expressed as

$$\rho_{\text{bulk}}(z_{\text{cm}}) = \frac{z_{\text{cm}} + 12.2}{z_{\text{cm}} + 18},$$

where $z_{\text{cm}}$ is the thickness of the observed layer, and define “fine dust” as having a maximum compaction density of $\rho_{\text{bulk(max)}} = 1.80$ g cm$^{-3}$, and “fine regolith” as having $\rho_{\text{bulk(max)}} = 1.95$ g cm$^{-3}$. Rognini et al. (2020) model diurnal surface thermal curves to determine which of the two possible density profiles yields best-fit surface temperatures to those retrieved from VIR thermal observations and find that Ceres’ uppermost meter of regolith most likely comprises fine dust. In the next section, we explore the interplay between porosity and estimates of depth to the ice table.

2.4. Constraints on the Vertical and Spatial Distribution of Subsurface Ice

Geomorphologic analyses of landslides across Ceres using high-resolution Dawn FC images, coupled with physical models, suggest the occurrence of 10–50 vol% ice within the first 10–100 m of the subsurface (Buczkowski et al. 2016; Schmidt et al. 2017; Chilton et al. 2019). At high latitudes, several discrete sites of exposed ice (each spanning <7 km$^2$) have been detected by VIR near shadowed areas within craters, four of which are collocated with smaller <0.1 km$^2$ optically bright features observed by Dawn’s optical framing camera (Combe et al. 2019). In addition, the GReND neutron spectrometer has detected widespread high concentrations of elemental hydrogen [H] on a regional scale (<400 km resolution) within the first meter of regolith—specifically, $\sim 17$ wt% water-equivalent-hydrogen (WEH) at the equator and increasing to $\sim 29$ wt% WEH at the poles, or equivalently $\sim 1.9$ to 3.2 wt% [H] (Prettyman et al. 2017). For perspective, hydrogen concentrations on desiccated Asteroid Vesta were measured to be <0.04 wt% [H] by the same instrument aboard Dawn and are interpreted to be mineralogically bound hydrogen rather than water or water ice (Prettyman et al. 2012; Prettyman et al. 2019). The observation of higher [H] at Ceres’ poles has been interpreted as the shallowing of a global ice table that starts at some depth greater than 1 m at the equator and rises to less than a centimeter deep at the poles, where lower solar illumination conditions provide stable temperatures for ice occurrence at or near the surface (Hayne & Aharonson 2015; Ermakov et al. 2017; Prettyman et al. 2017, 2019).

Because thermal ice-stability models indicate that water ice is not stable at equatorial latitudes in at least the first 0.5 m of...
regolith that is sensed by GRaND (Hayne & Aharonson 2015; Schörghofer 2016), Prettyman et al. (2017) suggest that the equator’s observed 17 wt% WEH (equivalently ~1.9 wt% [H]) represents mineralogically bound hydrogen—i.e., Ceres’ non-icy regolith. Hence, the 29 wt% WEH observed at the poles is interpreted to be a combination of both non-icy regolith materials and the shallowing of the water-ice table. By subtracting the non-icy regolith WEH of the equator from that at the poles and applying thermal stability models to a layer of porous dry regolith overlying a pore-filling ice table, Prettyman et al. (2017) find that GRaND’s observations are best modeled by a global ice table composed of ~10 wt% (20 vol%) water ice that ranges in depth from ~1 m at the equator up to <1 cm at the poles. However, this estimate of water-ice fraction and depth relies on assumptions of a dry-material grain size of 1 μm, a grain density of 2.5 g cm$^{-3}$ consistent with CI and CM meteorites, and a subsequent porosity (ice-filled) of 20% (Prettyman et al. 2017). Given the low grain density of anthracite coal of 1.4–1.7 g cm$^{-3}$ (Stoek 1902), this could change the vapor diffusion model to suggest a higher porosity and subsequently (1) a higher water-ice fraction and therefore (2) buried at much at greater depths.

For this study, we adopt the deepest, most porous case considered by Prettyman et al. (2017)—specifically, 30 wt% water ice, buried much more than 1 m at the equator but still rising to the surface at the poles. This corresponds to an ice-filled porosity of ~39%–44% when factoring in the grain density of anthracite as ~1.4–1.7 g cm$^{-3}$. Ice-table depth, as adapted from model (b) in Figure 3(B) by Prettyman et al. (2017), can then be fit by the following empirical expression:

$$z_{\text{ice\ table}} = (330 \text{ cm}) \cos^4(\theta_{\text{latitude}}).$$  

The modeled ice-table depth is plotted as a function of latitude in Figure 1.

Figure 1. Simplified two-layer model of Ceres’ shallow subsurface. Depth to the ice table is adapted from the results of Dawn/GRaND observations for the case of a pore-filling ice table with 30 wt% water ice (Prettyman et al. 2017). The ice table is deepest at equatorial latitudes and reaches the surface at the poles.

2.5. Constraints on Surface and Shallow-subsurface Temperatures

At a heliocentric distance of 2.86 au, daytime surface temperatures on Ceres are observed to range from 240 K at the equator to 180 K near the poles at ~11 km resolution as retrieved from VIR infrared observations (De Sanctis et al. 2015). Notably, surface temperatures may be lower than 180 K at the poles, as VIR is unable to accurately retrieve temperatures below this limit (Capra et al. 2014; Rognini et al. 2020). Thermophysical models of Ceres’ regolith by Hayne & Aharonson (2015) suggest that at night, surface temperatures at equatorial latitudes may fall below ~110 K, and below ~70 K at the poles; and in partially or permanently shadowed areas of high-latitude craters, surface temperatures may fall below ~30 K (Platz et al. 2016). In the first tens of meters below the regolith’s diurnal skin depth of ~1 cm, subsurface temperatures are expected to remain constant at a value equal to the average of night and day surfaces temperatures (e.g., Vasavada et al. 2012), which we estimate from the above-observed daytime and modeled night temperatures to be ~175 K at the equator and ~125 K near the poles, consistent with subsurface Ceres temperatures modeled by Hayne & Aharonson (2015).

Given that the Ceres analog materials selected in this study for laboratory measurements lack water (due to the desiccation process) and are metal free, their dielectric properties are expected to be temperature independent in the 1–10 GHz range because ionic polarization is the primary polarization mechanism at these frequencies. Hence, room temperature measurements are sufficient to characterize their dielectric properties at the low surface temperatures inferred on Ceres.

2.6. Analog Sample Preparation

Anthracite coal samples were crushed with a mortar and pestle and dry-sieved to reach the desired grain size of $D_{\text{grain}} \leq 120$ μm. For laboratory dielectric measurements, grain size determines the degree to which the material can be compacted and therefore the range of bulk porosities that can be measured.

In a study of potential clay mineral analogs matching the spectral signature of ammoniated phyllosilicates observed on Ceres by VIR, De Angelis et al. (2017) found that only smectite clays were efficient adsorbers of ammonium. We ordered the same three smectites from the Clay Mineral Society that were used in their study: two nontronites (one Al-rich with a bright yellow-green color, hereafter NAu-1; and the other Al-poor, bright yellow-brown, hereafter NAu-2) and montmorillonite (pink-brown, hereafter SCA-3). Similar to De Angelis et al. (2017),
we followed the procedure for ammoniating the clays detailed by Bishop et al. (2002): desiccating the clays overnight in an oven, then leaving them to soak in an NH$_3$OH solution overnight under a fume hood, redesiccating the samples, and grinding them into powders.

2.7. Experimental Procedure and Measurement Uncertainties

The dielectric measurement technique employed in this analysis is the transmission/reflection (TR) method that uses a vector network analyzer (VNA) coupled to a dielectric cell connected by two coaxial cables as shown in Figure A1. During initial setup and calibration of the VNA using EpsiMu software, developed by Sabouroux & Ba (2011), the powdered sample is desiccated for 1 minute at 160°C, poured into the sample holder cell, and shaken to evenly distribute the material inside. After connecting the sample holder to the coaxial cables, broadband dielectric measurements of the samples are performed under the following conditions: (1) frequency (set in EpsiMu): 500 MHz–10 GHz, (2) temperature: room temperature (after 160°C desiccation), and (3) bulk density: 0.8, 0.9, and 1.0 g cm$^{-3}$ for coal samples, and 1.0, 1.3, and 1.6 g cm$^{-3}$ for pure clay samples. Measurement uncertainties for the real ($\varepsilon_r'$) and imaginary ($\varepsilon_r''$) parts of the dielectric constant are less than ±5% and ±10%, respectively (Ba & Sabouroux 2010; Sabouroux 2018). We assume a conservative estimate of ±5% uncertainty for sample density.

Notably, while the range of bulk densities appears narrow for the coal samples, the solid density of anthracite coal is so low (1.4–1.7 g cm$^{-3}$) that the above range of sample densities correspond to sample porosities of 28% to 50%, which is the typical range of porosities achievable for a powdered material that has been hand-compacted into a sample holder in a laboratory setting. Similarly, given a solid density of clay $\sim$2.3–2.6 g cm$^{-3}$, the above clay sample densities correspond to sample porosities between 30% and 61%.

3. Results

In order to interpret the dielectric constant retrieved from Earth-based radar observations in terms of regolith porosity (Ostro et al. 1979, 1985; Mitchell et al. 1996; Magri et al. 1999; Nolan et al. 2000; Bhiravarasu et al. 2018; Benner 2021), we provide laboratory measurements that relate the dielectric constant of the Ceres spectral analog material—the mineralogy of which is constrained by Dawn and Hubble observations (De Sanctis et al. 2015; Hendrix et al. 2016b)—to bulk porosity. Our results fall into two categories, describing the surface and shallow subsurface of Ceres’ regolith (i.e., the first meter), as shown in Figure 1.

3.1. Dielectric Measurements of Spectral Analog for Ceres’ Equatorial and Mid-latitude Areas: Desiccated Regolith

The upper desiccated portion of Ceres’ regolith—i.e., the unconsolidated material layer overlying the ice table—is observed to contain a specrally opaque material at visible and infrared wavelengths with a strong spectral bump in the far-ultraviolet range, hypothesized to be highly graphitized carbon (Hendrix et al. 2016a, 2016b). We selected anthracite coal (hard coal) as a suitable spectral and electrical analog owing to its low hydrogen content and high carbon content (>87 wt% carbon) (e.g., Papoular et al. 1996; Peng et al. 2016).

The complex dielectric constant of desiccated, powdered anthracite coal is observed to be nondispersive over the broad frequency range of 5–6.5 GHz as shown in Figure 2, suggesting no frequency dependence of this material’s dielectric properties within this same polarization regime (i.e., constant $\varepsilon_r'$ and $\varepsilon_r''$ over $\sim$1–10 GHz). Hence, we are able to extrapolate measurements of $\varepsilon_r'$ and $\varepsilon_r''$ to those at S- and X-band frequencies ($\sim$2 and $\sim$8 GHz).

Notably, although the dielectric laboratory equipment utilized in this study is capable of performing broadband dielectric measurements over frequencies <1 MHz up to 10 GHz (Ba & Sabouroux 2010; Sabouroux & Ba 2011), one of the disadvantages of the TR line method is that there are sample cell resonances at multiples of half the wavelength in the medium (e.g., Costa et al. 2017). Given that the EpsiMu sample cell length is $\sim$2.3 cm and $\varepsilon_r' \approx 5$ for desiccated anthracite at our highest measured sample density, this yields resonances at free-space wavelengths that are multiples of 10.3 cm, i.e., resonances at free-space frequencies of 2.9 GHz, 1.5 GHz, 1 GHz, and so on. In other words, accurate measurements of the dielectric constant of a material with $\varepsilon_r' \approx 5$ and a sample length of
materials containing in Figure 3, suggest that the complex dielectric constant of Figure 2. Desiccated clays are also shown to exhibit no dielectric properties of desiccated clay minerals are also measured imaginary part. In this case, \( f < \sim 10 \text{ GHz} \), the signal may be too attenuated to fully penetrate any of the samples that would be responsible for inducing a frequency-dependent dielectric constant in this frequency range. Desiccated clay minerals were chosen for calibration purposes owing to their hydrophilic properties and subsequent dielectric sensitivity to the smallest amount of residual moisture.

It is notable that the imaginary part of the dielectric constant for desiccated anthracite is high compared to silicates, which have \( \varepsilon''_d < 1 \) such as the clays in Figure 2(b). Because the imaginary part of the dielectric constant \( \varepsilon''_d \) quantifies the energy absorptivity of the material, higher values of \( \varepsilon''_d \) suggest higher conductivity. Our results for anthracite are consistent with the knowledge that electrical conductivity increases with increasing graphitization of coals, owing to the availability of more free carbons as the carbon-to-hydrogen ratio increases (Parkhomenko 1967).

The real part of the dielectric constant \( \varepsilon'_r \) of rocks and powders increases exponentially with bulk density, where the base parameter \( \varepsilon'_0 \) is specific to the material (Campbell & Ulrichs 1969; Ulaby et al. 1990; Carrier et al. 1991). Our results, plotted in Figure 3, suggest that the complex dielectric constant of materials containing >90 wt% anthracite can be quantified by the following best-fit empirical formulas when accounting for 5% uncertainty in \( \varepsilon'_m \), 10% uncertainty in \( \varepsilon''_m \), and \( \sim 5\% \) uncertainty in \( \rho_{\text{bulk, sample}} \):

\[
\varepsilon'_\text{anthracite} = (6.0 \pm 0.5)\rho_{\text{bulk}}
\]

and

\[
\varepsilon''_\text{anthracite} = (0.13 \pm 0.01)(\varepsilon'_0^{(3.1 \pm 0.1)\rho_{\text{bulk}}} - 1)
\]

for \( 1 < f < 10 \text{ GHz} \), where bulk density is in units of g cm\(^{-3}\).

The present dielectric measurements of anthracite coal are consistent with similarly desiccated anthracite samples as those of Peng et al. (2016), who find \( \varepsilon'_r \approx 15 \) at room temperature for a sample of compacted Korean anthracite coal powder with a sample density of \( \sim 1.69 \text{ g cm}^{-3} \) that had first been dried at 105 °C for 15 hr prior to measurement. Compared to the desiccated clay samples, anthracite shows a much stronger dependence on bulk density owing to its higher content of free electrons, which particularly impacts polarization mechanisms at higher densities. This is supported by further comparison with basaltic silicate Apollo lunar samples (∼2.3 cm are only observable at frequencies well above at least 3 GHz.

At frequencies above the observed nondispersive range (in this case, >6.5 GHz), if the material is lossy (as is the case for anthracite), the signal may be too attenuated to fully penetrate through the sample, hence yielding inaccurate measurements at higher frequencies. The resulting nonphysical values of the complex dielectric constant are not representative of the material but rather the limitations of the sample cell and are easily distinguished from actual dielectric resonances, which are characterized by a strong decrease (relaxation) of the real part accompanied by a steep increase (resonance) in the measured imaginary part.

To calibrate the error range in these measurements, the dielectric properties of desiccated clay minerals are also measured and plotted over the same frequency range in Figure 2. Desiccated clays are also shown to exhibit no frequency dependence for either the real or imaginary parts of their dielectric properties, suggesting that our desiccation process is effective and that there is no residual moisture in any of the samples that would be responsible for inducing a frequency-dependent dielectric constant in this frequency range. Desiccated clay minerals were chosen for calibration purposes owing to their hydrophilic properties and subsequent dielectric sensitivity to the smallest amount of residual moisture.

(Figure 3(a)), which also exhibit a weaker density-dependence than anthracite coal (Carrier et al. 1991).

Given the high dependence of anthracite’s dielectric constant on the smallest changes in bulk density—unlike the Moon, for which small variations in regolith density yield relatively small changes in the dielectric constant (Carrier et al. 1991)—this highlights the importance of using the dielectric constant of a spectral analog for its regolith to constrain the bulk density, and hence bulk porosity, of Ceres’ shallow regolith. The above results, combined with the fact that Ceres has a smooth surface...
at $S$- and $X$-band radar frequencies, make it an ideal target to use its electrical properties to assess its surface density and hence porosity.

### 3.2. Dielectric Assessment for Ceres’ Polar Areas: Ice Table

While the sample above represents most of the nonpolar areas of Ceres’ surface and shallow subsurface, in this section we apply a dielectric mixing model of anthracite coal (from the above measurements) with 30 wt% water ice to represent the polar areas of Ceres (Mätzler & Wegmüller 1987, 1988; Simpkin 2010). We opt to perform this numerical approach as dust and ice mixtures in the laboratory always contain minor amounts of unfrozen water that bias both the real and imaginary parts of the dielectric constant (Heggy et al. 2001, 2012).

Applying the Lichtenecker dielectric mixing model, which assumes a random distribution of the mixed components (Simpkin 2010), we find that a solid ice/anthracite mixture composed of 30 wt% ice (i.e., having 39.44 vol% ice, assuming the solid density of anthracite is 1.4 to 1.7 g cm$^{-3}$) has $\varepsilon_r \approx (9 \pm 2) - i(5 \pm 2)$. However, we show in the following section that after retrieving the porosity of Ceres’ regolith from Earth-based radar observations, 39.44 vol% of ice does not completely fill the porosity of Ceres’ anthracitic regolith. Hence, after retrieving the porosity of Ceres’ dry regolith, we will again apply Lichtenecker’s mixing model to the ice table to account for unsaturated porosity. These results are used as input in the following section to generate global maps of Ceres’ dielectric properties at $S$- and $X$-band.

### 3.3. Inferring the Bulk Porosity of Ceres’ Shallow Subsurface

Earth-based radar observations of Ceres suggest that $1 < \left| \varepsilon_r \right| < (2.2 \pm 0.3)$ from $S$- to $X$-band frequencies (Ostro et al. 1979, 1985; Mitchell et al. 1996; Magri et al. 1999; Nolan et al. 2000; Bhiravarasu et al. 2018; Benner 2021). Considering that most of this observed backscatter comes from equatorial and mid-latitude areas of Ceres due to the observing geometry, there is little to no contribution to this inferred dielectric constant from icy polar areas. Hence, the retrieved dielectric constant at $S$- and $X$-band frequencies represents the top ~13 cm or less of Ceres’ non-icy regolith. Applying desiccated anthracite coal as an electrical analog to Ceres’ regolith, this upper thin layer’s bulk density is $\rho_{\text{bulk(ovsb)}} \leq 0.43 \pm 0.06$ g cm$^{-3}$ as inverted from Equations (8) and (9)—i.e., a bulk porosity of $P_{\text{ovsb}} \geq 72% \pm 7%$ in the top few centimeters of Ceres’ regolith.

Notably, such a low near-surface density is not compatible with the vertical density profile inferred from VIR thermal modeling of Ceres’ dry regolith, which assumes a minimum surface density of $\rho_{\text{bulk}} = 1.22$ g cm$^{-3}$ and a maximum of $\rho_{\text{bulk(max)}} = 1.80$ g cm$^{-3}$ (i.e., the maximum compaction density of unconsolidated regolith material) (Rognini et al. 2020). Hence, our results suggest that the maximum compaction density of the anthracitic material comprising most of Ceres’ upper regolith is much less than 1.80 g cm$^{-3}$—i.e., much more porous than lunar regolith.

Furthermore, such a high porosity also suggests that a 30 wt% ice table (i.e., 39.44 vol% ice, assuming anthracite has a solid density of 1.4 to 1.7 g cm$^{-3}$) is only partially pore-filling at the poles. Considering a realistic upper limit of no more than ~90% porosity for loose anthracitic regolith at the surface, this suggests an unsaturated porosity of between ~20% and 50% at the icy poles. Incorporating unsaturated porosity into the Lichtenecker dielectric mixing model of Ceres’ ice table decreases its effective dielectric constant to a minimum of $\varepsilon_r = 2.7 - i0.5$ (calculated for an unsaturated porosity of 50% and an anthracite solid density of 1.7 g cm$^{-3}$) and a maximum of $\varepsilon_r = 6.8 - i2.9$ (calculated for 20% unsaturated porosity and anthracite solid density of 1.4 g cm$^{-3}$), as listed in Table 1 (Simpkin 2010).

Next, assuming a lunar-like vertical density gradient (Carrier et al. 1991; also see Equation (6)), we estimate that the maximum compaction density of loose anthracitic regolith is $\rho_{\text{bulk(max)}} \leq 0.60 \pm 0.10$ g cm$^{-3}$, whereas the maximum compaction density of lunar regolith is estimated to be $\rho_{\text{bulk(max)}} > 1.80$ g cm$^{-3}$. Notably, although the absolute range of densities modeled for lunar regolith should not be assumed the same on Ceres, the vertical density gradient—which describes the increasing compaction of fine, desiccated regolith on an airless body as a function of depth, resulting from regolith gardening processes and overburden pressure—can be reasonably applied to both the Moon and Ceres provided that the most-compact density having $\rho_{\text{bulk(max)}}$ remains an adjustable variable in Equation (6).

For further comparison, the first meter of lunar regolith is calculated from Equation (6) to have a bulk density of $\rho_{\text{bulk}} \approx 1.7 - 1.8$ g cm$^{-3}$ for a maximum compaction density $\rho_{\text{bulk(max)}} = 1.8 - 1.9$ g cm$^{-3}$, or ~39%-50% bulk porosity (assuming a lunar basalt grain density of $\rho_{\text{solid}} = 3.0 - 3.4$ g cm$^{-3}$). On Ceres, the first meter of regolith is calculated to have $\rho_{\text{bulk}} \leq 0.47 - 0.66$ g cm$^{-3}$ for a maximum compaction density $\rho_{\text{bulk(max)}} \leq 0.50 - 0.70$ g cm$^{-3}$, or $\geq 53% - 72%$ bulk porosity in the top meter (for $\rho_{\text{solid}} = 1.4 - 1.7$ g cm$^{-3}$) (Stoek 1902).

Next, we apply the measured dielectric properties of anthracite coal to the two-layer geophysical model from Figure 1 and calculate the maximum radar penetration depths for $S$- and $X$-band observations into the overlying desiccated layer from the following expression (e.g., Campbell 2002):

$$z_{\text{penet}} = \frac{\lambda}{2\pi} \sqrt{\frac{\varepsilon_r}{2} \left(\sqrt{1 + \tan^2 \delta} - 1\right)^{-1}}.$$

Penetration depths are calculated to be $4.6 \times 10^2 \pm 3 \times 10^2$ cm at $S$-band and $17.0 \times 10^2 \pm 4 \times 10^2$ cm at $X$-band (or 1.3 times the wavelength) when accounting solely for electrical losses through desiccated anthracite. The actual penetration depth into Ceres’ desiccated regolith is expected to be a lower value than estimated by Equation (10), however, due to signal losses associated with surface and volume scattering that can compromise penetration depths of radio waves by as much as 50% in heterogeneous geologic environments, such as regolith or karst environments (e.g., Heggy et al. 2006; Scabia & Heggy 2021).

It is also important to note that we do not model the radar backscatter coefficient $\sigma^0$ of Ceres’ icy polar regions in this study, as such modeling requires accurate knowledge of surface roughness at centimeter to decimeter scales and the distribution of ice within this first meter (e.g., Campbell 2002; Thompson et al. 2011), which are not available at this current stage. Hence, modeling the complex radar backscattering mechanisms at Ceres’ poles is beyond the scope of this study.

Instead, we report the Fresnel normal radar reflectivity $\rho_0$, which is solely a function of the effective dielectric constant of Ceres’ upper few centimeters of regolith (see Equation (2)) and can be used as input for future backscatter observations once the ambiguity of surface roughness is constrained. Herein, we
report $\rho_0$ for the poles assuming the ground-ice table is a uniform mixture of highly porous anthracitic dust with partially pore-filling ice, as established at the beginning of this section. Furthermore, considering the maximum penetration depths into desiccated anthracite mentioned above, neither X- nor S-band radio waves will reach the ice-table interface except at high latitudes where the partially pore-filled icy regolith approaches the surface (i.e., $>70^\circ$ at X-band and $>60^\circ$ at S-band). This suggests that for equatorial and mid-latitudes, the surface’s Fresnel normal radar reflectivity $\rho_0$ is uniform (on average), as shown in Figures 4 and 5.

We consider the possible range of near-surface depths observed by X- and S-band radar (i.e., less than one wavelength) into a dusty anthracitic regolith by plotting $\epsilon'_r$ and $\epsilon''_r$ in Figure 4 as a function of latitude and radar-observed depth (a maximum of 13 cm depth at S-band frequency). We also plot $\epsilon'_r$ and $\epsilon''_r$ on a globe in Figure 5 assuming the maximum observed depth of 4 cm at X-band and 13 cm at S-band, for a maximum compaction density of $\rho_{\text{bulk(max)}} = 0.60 \text{ g cm}^{-3}$. The calculated normal radar reflectivity, attenuation factor, and maximum penetration depth at the equator and poles are listed in Table 1.

4. Discussion

4.1. Potential Mechanisms for a Highly Porous Upper Regolith

Comparably high porosities (of 55%–70%) have been suggested for the 1–2 m-thick deposits of unconsolidated material on Comet 67P (Kuchki & Nakamura 2014; Heggy et al. 2019) and are thought to be formed by airfall deposits following outgassing events and overhang collapses (Mottola et al. 2015; Thomas et al. 2015; Pajola et al. 2017). However, such resurfacing is unlikely to occur on a global scale across Ceres for several reasons. First, the detection of water vapor outgassing from Ceres appears to be localized; likewise, no evidence of a global, sustained exosphere has been found (e.g., Küppers et al. 2014; Landis et al. 2017). Second, the gravitational pull at Ceres’ surface is three orders of magnitude greater than on Comet 67P, limiting the size and distance of debris launched by an equivalent outgassing event (Landis et al. 2017). Third, the low concentrations of organic material detected by VIR on Ceres’ surface (De Sanctis et al. 2017), as opposed to the strong FUV signature of graphitized carbon observed on Ceres (Hendrix et al. 2016b), may suggest that
Ceres’ surface organic material is present in high abundance (Kaplan et al. 2018) but highly graphitized (spectrally neutral in the visible and infrared), and that Ceres’ surface has therefore not undergone frequent resurfacing that would bring up fresh unprocessed organics (e.g., Prettyman et al. 2019). Other suggested mechanisms for generating loose, highly porous deposits are aeolian processes such as those seen on Mars as the result of its windy atmosphere that recycles and transports dust across the surface, but again, no signs of an atmosphere or a global exosphere, however tenuous, have been detected on Ceres (Landis et al. 2017; Küppers 2019).

Instead of global resurfacing events, we suggest that a highly porous upper regolith can be formed through a combination of continuous global micrometeorite bombardment, which breaks down consolidated regolith material into small fines as on the Moon; localized outgassing events (e.g., Küppers et al. 2014); and the deposition of loosely packed particles by debris avalanches, which are observed to be common across Ceres (Schmidt et al. 2017). Examples of fine-particle landslides are shown in the high-resolution Dawn FC images in Figure 6 of Occator crater’s walls on Ceres.

By contrast, mechanisms that act to consolidate material include shaking and sorting by impacts. However, the regolith of Ceres may be highly attenuating toward seismic activity owing to a low-density regolith and/or the occurrence of a shallow ice table. Furthermore, given that anthracite coal (and perhaps other organics) has a very low grain density, such materials may preferentially rise to the top of the regolith surface where shaking and sorting occur.

### 4.2. Porosity and Volatile Retention for Airless, Desiccated Regoliths

The occurrence of a highly porous regolith on Ceres changes input parameters for thermophysical models that are used for estimating ice-table depth and thermal inertia on airless, desiccated bodies (e.g., Prettyman et al. 2017; Rognini et al. 2020). As a consequence, if porosity is underestimated due to
the assumption of lunar-like regolith properties, then the ice table may actually be buried tens of meters deeper at equatorial latitudes than estimated, which has important consequences for future sampling missions as well as for geomorphological studies (e.g., ElShaﬁe & Heggy 2013). Furthermore, the ice table may not be completely pore-ﬁlled as suggested by the results of this study, but could be comparable in its physical and radar properties to ice-poor, porous permafrost (e.g., Boisson et al. 2011). Similarly, when modeling the thermal inertia of the upper shallow regolith, both self-heating surface topographic effects at the subpixel scale (i.e., surface roughness at the meter-scale) and the bulk density of the regolith itself must be considered (e.g., Capria et al. 2014; Rognini et al. 2020). Hence, if the density of the regolith is overestimated (i.e., porosity is underestimated), then surface roughness may be underestimated, i.e., the surface is estimated to be ﬂatter on subpixel scales than in reality.

In addition to the importance of accurately assessing the regolith porosity of bodies with higher carbonaceous content than the Moon, we also note that desiccated, powdered anthracite coal is much more reﬂective and attenuating at radar frequencies than lunar dust at the same bulk densities. Hence, in the case of a landing mission to Ceres, which uses radar reﬂections from the surface to estimate descending altitude (e.g., Golombek et al. 2017), surface reﬂections are likely to yield deceptive measurements of altitude due to high attenuation of the signal by highly graphitized carbon.

Overall, we ﬁnd that the literature is lacking relevant measurements of the dielectric properties of high-carbon-content analog materials that will likely be applicable to many other planetary surfaces, such as comets and other rocky-icy small bodies (Hérique et al. 2016). To address this deﬁciency, future work will include dielectric measurements of carbonaceous chondrite samples (including CI-type as suggested for Ceres; e.g., Marchi et al. 2019) as well as other possible high-carbon-content analogs, such as carbon black.

In conclusion, the interpretation of existing Earth-based radar data for Ceres, combined with laboratory dielectric measurements of Ceres spectral analog material—recently revealed from the Dawn mission—suggest that its near-surface porosity ranges from 53% to 72% or higher in the ﬁrst meter, differing from lunar regolith, which has been previously suggested as an analog.

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Appendix

The Ceres regolith analog laboratory samples prepared for this study are described in Table A1 below (see also Section 2.2). The vector network analyzer and the dielectric cell used to perform laboratory dielectric measurements of these samples are depicted in Figure A1 (see also Section 2.7).
Figure A1. (a) The Anritsu MS2036C vector network analyzer (VNA) generates frequencies from <1 MHz to 10 GHz and computes the complex permittivity and permeability of a solid or powder using the transmission/reflection coaxial cable method. (b) The central sample holder is cylindrical with a diameter of 6 mm and is used for loose powder samples and is housed within the PE13 conical cell (Sabouroux & Ba 2011; Sabouroux 2018).

Table A1
List of Samples Prepared for Dielectric Laboratory Measurements

| Sample Name | Description                                      | Anthracite (hard coal) | $D_{\text{grain}} \leq 120 \mu m$ |
|-------------|--------------------------------------------------|------------------------|-----------------------------------|
| Coal        | Desiccated and powdered                         |                        |                                   |
| Ammoniated clays |                                               |                        |                                   |
| NAt1       | Saturated in ammonium solution, desiccated and powdered | Al-rich nontronite     | $D_{\text{grain}} \leq 10 \mu m$ |
| NAt2       | Saturated in ammonium solution, desiccated and powdered | Al-poor nontronite     | $D_{\text{grain}} \leq 10 \mu m$ |
| SCA-3      | Saturated in ammonium solution, desiccated and powdered | Montmorillonite        | $D_{\text{grain}} \leq 10 \mu m$ |

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