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# A large-scale anomaly in Enceladus' microwave emission

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ABSTRACT

The Cassini spacecraft flew by Enceladus on 6 November 2011, configured to acquire synthetic aperture RADAR imaging of most of the surface with the RADAR instrument. The pass also recorded microwave thermal emission from most of the surface. We report on global patterns of thermal emission at 2.17 cm based on this data set in the context of additional unresolved data both from the ground and from Cassini.

The observed thermal emission is consistent with dielectric constants of pure water or methane ice, but cannot discriminate between the two. The emissivity is similar to those of other icy satellites (≈0.7), consistent with volume scattering. The most intriguing result, however, is an anomaly in the thermal emission of Enceladus' leading hemisphere. Evidence presented here suggests the anomaly is buried at depths on the order of a few meters. This anomaly is located in similar geographic location to anomalies previously detected with the CIRS and ISS instruments on Mimas, Tethys, and Dione (Howett, C.J.A. et al. [2011]. Icarus 216, 221–226; Howett, C.J.A. et al. [2012]. Icarus 221, 1084–1088; Howett, C.J.A. et al. [2014]. Icarus 241, 239–247; Schenk, P. et al. [2011]. Icarus 211, 740–757), but also corresponds with a geological feature on Enceladus' leading terrain (Crow-Willard, E., Pappalardo, R.T. [2011]. Global geological mapping of Enceladus. In: EPSC-DPS Joint Meeting 2011. p. 635). Simple models show that the Crow-Willard and Pappalardo (Crow-Willard, E., Pappalardo, R.T. [2011]. Global geological mapping of Enceladus. In: EPSC-DPS Joint Meeting 2011. p. 635) model is a better fit to the data. Our best-supported hypothesis is that the leading hemisphere smooth terrain is young enough (<75–200 Myr old) that the micrometeorite impact gardening depth is shallower than the electromagnetic skin depth of the observations (≈3–5 m), a picture consistent with ground and space radar measurements, which show no variation at 2 cm, but an increase in albedo in the anomaly region at 13 cm.



## 1. Introduction

### 1.1. Radiometry background

Microwave radiometry is, first and foremost, a measurement of the thermal emission of an object, probing the Rayleigh–Jeans tail of an object's blackbody emission. Resolved radiometry measurements can show thermal variations across the surface of an object. For Enceladus, one might expect to find a seasonal thermal gradient as observed previously on Enceladus (Howett et al., 2010) or Iapetus (Le Gall et al., 2014).

Two factors other than temperature can modulate the thermal emission of an object in the microwave regime: scattering properties and the dielectric constant. Scattering is important in understanding the microwave surface properties of Enceladus, as scattering has frequently been invoked to explain low emission of icy satellites in the microwave (cm/mm) regime (Muhleman and Berge, 1991; Ostro et al., 2006; Ries, 2012). Variation in microwave emission across different types of terrain has also been attributed to changes scattering properties across different types of terrain of Titan (Janssen et al., 2009; Le Gall et al., 2011) and Iapetus (Ries, 2012).

The dielectric constant can also modulate the thermal emission of icy satellites. According to the model of White and Cogdell (1973), a higher dielectric constant material will have lower overall emission and become more polarized away from normal incidence.

One other important feature about microwave emission is that the emission is observed at depth rather than at that surface. The given emission depth can be estimated from the formula (by way of Muhleman (1972) and many others):

$$l_{R,\lambda} = \frac{\lambda}{2\pi\sqrt{\epsilon_d}\tan\Delta} \quad (1)$$

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where $l$ is the dominant emission depth, sometimes also called the electromagnetic skin depth, $\lambda$ is the wavelength, $\epsilon_d$ is the dielectric constant and $\tan\Delta$ is the loss tangent when the loss tangent is small ($\ll 1$). This formula neglects to account for volume (multiple) scattering which results in a shallower emission depth than that given by this estimate. After inserting appropriate physical constants, the equation yields that the emission depth is some multiple of the wavelength (e.g. $l_{R,\lambda} = \alpha\lambda$).

For metals (e.g. Fe and related compounds such as hematite), the formula's assumptions break down due to the very high loss tangents. Nonetheless, we can safely say $\alpha \ll 1$ for such materials. For rocky/dusty regolith (e.g. Moon, Mercury, asteroids), $\alpha \approx 10$–$20$ (Mitchell and de Pater, 1994). For icy surfaces, the depth can be even greater, with values of $\alpha \approx 100$ for realistic ices (Paillou et al., 2008) or as high as $\alpha \approx 10{,}000$ for pure water ice (Thompson and Squyres, 1990).

As a result of microwaves' long wavelength and the low loss tangents of ice, microwave instruments probe substantially below the surface at depths of order meters, revealing buried scattering and/or thermal features.

Emissivity and reflectivity are inversely related, although the proportion can vary (Janssen et al., 2011). This relation is caused by scattering off of structures in the surface, with emission scattered away from the observer (resulting in lower observed emission) and reflections being scattered back towards the observer (resulting in higher returned signal) as the amount of scattering increases. In observations of Solar System bodies such as Enceladus, coherent backscatter is thought to be a substantial contribution to the radar reflectivity since the transmitter and receiver are co-located due either to the distance involved (for Earth-based measurements) or the fact that only a single spacecraft is orbiting (e.g. Cassini). Coherent backscatter can be caused by scattering interactions with particles at or near the wavelength scale (Hapke, 1990). Substantial variation in scattering has been detected across the icy satellites of Saturn and Jupiter using active RADAR measurements as well passive radiometry (Ostro et al., 2006).

Thus, by examining the microwave radiometry and scatterometry provided by the RADAR instrument on Cassini, we can obtain information on the thermal, dielectric, and structural properties of the surface and subsurface of icy bodies.

### 1.2. The RADAR instrument

The Cassini RADAR instrument (Elachi et al., 2004) is hybrid instrument capable of operating in a variety of modes: radiometry, scatterometry, synthetic-aperture RADAR (SAR), and altimetry. These modes are not mutually exclusive. The instrument itself consists of a five linearly-polarized feeds operating at 2.17 cm coupled with the 4 m diameter high-gain communication antenna, providing a 0.24° full-width, half-maximum (FWHM) beam from the central feed. The first sidelobe occurs approximately 0.3° from center, peaking at 2.3% of the main beam's intensity. The other feeds provide wider beams offset from the boresight of the high-gain antenna.

At great distances (>25,000 km), the signal-to-noise is too low for any modes other than scatterometry and radiometry, which can be obtained simultaneously. For scatterometry mode, pulses are transmitted in a linear polarized fashion and the intensity of the returned radio waves is measured in the same, linear (SL) polarization after scattering off of the target. The radiometry mode obtains antenna temperature in the single linear polarization. Such observations are done with the central beam only.

In the SAR mode of the instrument, anywhere from just one to all five of the feeds can send pulses and receive echoes from the surface of the target body, though they must be used in a sequence rather than in parallel (i.e. only a single beam is recording at any given time). The returned pulses are then combined into a map of the surface using an interferometric technique that yields much higher resolutions that of any of the beams (Elachi et al., 2004). Radiometry is obtained simultaneously, but without any interferometric gains in resolution.

## 2. Observations

### 2.1. E16

"E16" denotes Cassini's 16th targeted flyby of Enceladus on 6 November 2011, which was the only Enceladus flyby dedicated to the RADAR instrument. RADAR data was acquired over a period of over 4 h, primarily for the purpose of making maps of Enceladus' surface using the SAR mode of the instrument with the main beam only (beam 3). In the process, most of the surface was also mapped by the radiometer. However, because this particular dataset was not designed as a radiometry observation, the coverage and geometries vary widely and tasks such as mapping or retrieving the dielectric constant are challenging. Fig. 1 shows the coverage and maximum resolution of Enceladus radiometry data analyzed in this paper. The leading hemisphere, and particularly its northern half, is well-resolved (≈40 km resolution), though the leading southern hemisphere is less well-resolved (≈150 km resolution). The trailing hemisphere is barely resolved at all (≈200 km resolution).

The geometry of the flyby can be broken down into three segments for the purposes of this paper: (1) Inbound, with Saturn directly behind Enceladus. (2) Inbound, with Saturn's rings behind Enceladus and (3) Outbound, with cold space (the Cosmic Microwave Background (CMB)) behind Enceladus. These three segments are preceded by a distant radiometry scan with Enceladus in front of Saturn and followed by distant radiometry scans with cold space behing Enceladus. A very high latitude scan coincident with a SAR pass of the south polar region is being analyzed by others (Le Gall et al., 2012) and excluded from this analysis. The changing backgrounds were an observational challenge since brightness temperature measurements are made relative to a variable background. In this case, the CMB in case 3 is the coldest background at 2.7 K and Saturn in case 1 is the brightest at ≈150 K (Janssen et al., 2013). Table 1 shows a timeline of events for the E16 flyby while Fig. 2 shows the antenna temperature (raw data) vs. time with the three main segments labelled.

The highest resolution data used occurs at 05:07:00 UTC and is centered on the northern part of the leading hemisphere. The highest resolution is approximately 20 km, and most of the northern leading hemisphere is covered at better than 50 km resolution.

One final note on the observing run itself is that Enceladus entered solar eclipse about 20 min before segment 3 started and exited it about 40 min before the end of segment 3, with exact times provided in Table 1.

### 2.2. Other data sets

Several other microwave observations are available and are important in the interpretation of the E16 data set. One such data set is the distant radiometry observations of Enceladus, also made by the Cassini RADAR. The distant radiometry scans do not resolve the surface, but provide a brightness temperature for the whole disk. A few such measurements have been published previously (Ostro et al., 2006), but most of them have not. These observations are reduced again using current calibrations for the observations previously published in Ostro et al. (2006) and for the first time for the remainder. The Ostro et al. (2006) results are re-analyzed