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Saturn's inner moons: why are they so radar-bright?

Alice Le Gall (1), Richard D. West (2), Léa E. Bonnefoy (1, 3), Valérie Ciarletti (1), Syphax Rahmouni (1) and Yann Hervé (1)
(1) LATMOS/IPSL, UVSQ (Université Paris-Saclay), UPMC (Sorbonne Univ.), Guyancourt, France, (2) Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109-8099, (3) Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris-Meudon, Meudon, France (alice.legall@latmos.ipsl.fr)

Abstract

Saturn's inner moons are the radar-brightest objects in the Solar System. The radar brightness of Mimas, Enceladus and Tethys at 2.2-cm wavelength exceeds that of the Galilean satellites. This points to extremely fresh and clean water ice in their subsurface but also to the presence of scattering structures that are especially efficient at returning waves in the backscattering direction. In this paper, we present the final results of the Cassini radar observations of Saturn's moons and explore subsurface models that could explain the extremely high recorded radar returns in the inner system. Using a 3D electromagnetic code, we first test models in which the subsurfaces of these moons contain a random distribution of centimetric inclusions (pores or ice spheres).

1. Cassini Radar observations

For more than 13 years, the Cassini spacecraft (2004-2017) has explored the Saturnian system and revealed the complexity of Saturn's moons providing dramatic images of their surfaces and evidence of past, and even present, geological activity on Dione and Enceladus, respectively [1].

While it was initially designed to examine the surface of Titan through the veil of its opaque atmosphere, the radar on board Cassini was occasionally used to observe Saturn's airless moons, and in particular the six mid-sized satellites (in order of distance to Saturn) Mimas, Enceladus, Tethys, Dione, Rhea and Iapetus [2, 3, 4]. Most of these observations were distant i.e., unresolved and designed to provide full-disk albedos at 2.2-cm wavelength.

Fig. 1 presents the result of the reduction of 85 distant observations of the Saturnian moons, including Titan. It shows significant variations among the satellites with Enceladus having the highest average radar albedo (2.96$\pm$0.39) and Titan the lowest (0.23$\pm$0.03). All of Saturn's inner moons (from Mimas to Rhea) display extremely high radar albedos with values above unity even when accounting for all possible sources of uncertainties. Enceladus is twice as bright as Europa, the radar brightest of the Galilean satellites which is equivalent in term of total-power radar albedo to Dione [5].

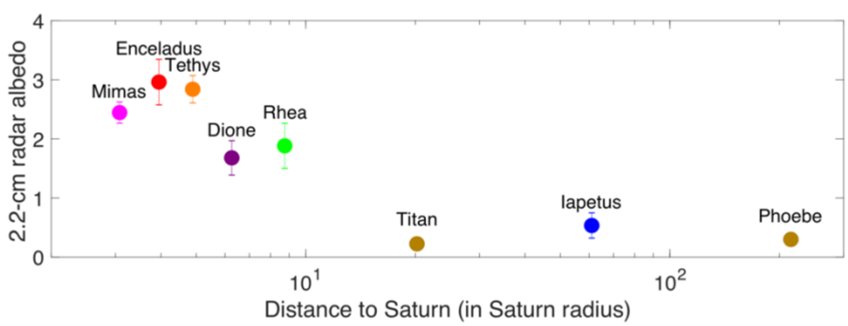

Figure 1: Averaged 2.2-cm disk-integrated radar albedos of Saturn's major satellites. The error bars show the dispersion of the dataset for each satellite.

2. Data interpretation

The analysis of the Cassini radar observations of Saturn's moons shows that the exchange of material between Saturn's dust rings and moons, which is specific to the Saturnian system, plays a key role in the current state of the satellite regolith [5]. Far away from Saturn, the vast debris ring from Phoebe progressively coats the leading side of Iapetus with optically-dark material reducing its radar brightness. On the contrary, close to the planet, the extreme radar brightness of the innermost moons Mimas, Enceladus and Tethys is mostly due to Enceladus' activity and their interaction with the E-ring which envelopes them and brings ultra-clean water ice to their near-surface.

It is clear that the high degree of purity of Saturn's innermost moons' water ice regolith favors the opportunities for high order scattering in the near-surface. Nevertheless, the composition alone can explain neither the large measured radar albedos nor the observed weak dependence on incidence angle. The "snow cover" of Saturn's icy inner moons must contain scattering structures that are especially efficient in returning waves in the backscattering direction.

In order to explain the high radar returns from Jupiter's satellites, some authors have invoked the coherent backscatter effect (CBE) [6, 7] which results from the constructive interferences of waves in the backscattering direction after a multiplicity of random scattering events. Such an effect is expected in presence of wavelength-scale scatterers embedded in a weakly absorbing regolith and is all the more efficient as scatterers are themselves made of low-loss material i.e., void or pure ice. However, the capacity of the CBE to boost the intensity in the backscattering direction is limited and an extremely high density of scatterers (as much as 80% of the scattering layer must be occupied by scatterers) is already required for Europa [7]. We decided to further test this theory as well as models of "organized" subsurfaces to find a plausible explanation for Cassini measurements.

3. Electromagnetic simulations

We first investigate the scattering behavior of subsurfaces with different densities of randomly distributed spherical inclusions (filled with vacuum or solid water ice) using the 3D simulator TEMSI-FD, developed by the XLIM laboratory, in Limoges, France. This code is based on the finite difference time domain (FDTD) method that solves the set of Maxwell equations in a rigorous manner. In order to compute the far-field scattered field, TEMSI-FD applies the equivalence theorem that takes the scattered field to be due to a set of surface currents located coincident with the surface of the scattering object.

Fig. 2A shows an example of subsurface model where the scatterers embedded in the snow cover have a volumetric density of 30%. The computational box is 0.5mx0.5mx1.7. The mesh size was set equal to 1 mm in all axes, which is small enough to prevent numerical dispersion. Fig. 2B displays the radiation pattern of the subsurface model shown in Fig. 2A once lighted by a plane wave with an incidence angle of 20°. The signal is mainly radiated in the specular and transmission directions whereas the return in the backscattering direction is very small. Models with a higher density of scatterers and different size distributions will be tested as well as subsurface models including organized/ordered structures.

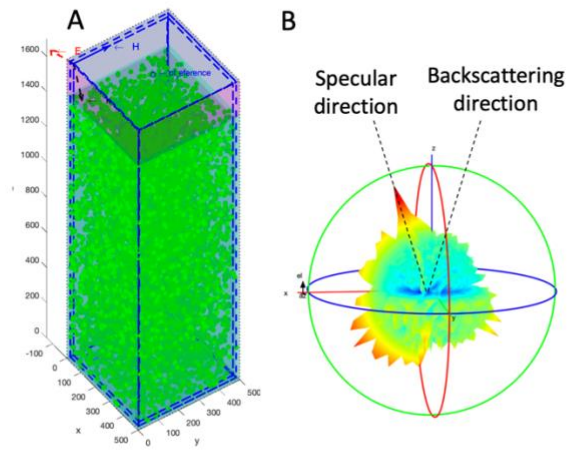

Figure 2: **A**: Subsurface model where 30% of the snow layer is occupied by randomly distributed 1-cm radius vacuum inclusions. **B**. Radiation pattern of the model shown in A for an incident plane wave arriving with an incidence angle of 20°. The signal returned in the backscattering direction is very small.

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