ENCELADUS' BRILLIANT SURFACE: RADAR MODELING. U. K. Khankhoje[1], K. L. Mitchell[2], J. C. Castillo-Rogez[2], M. Janssen[2], [1]Electrical Engineering, University of Southern California (University Park campus, Los Angeles, CA 90089, uday@alumni.caltech.edu), [2]Jet Propulsion Laboratory, California Institute of Technology (4800 Oak Grove Dr., Pasadena, CA 91109).

Introduction: Various natural icy satellites in the outer Solar system have unusually high RADAR albedo. One of these, Enceladus, was recently investigated by a 2.17 cm SAR RADAR for the first time, and was found to exhibit a very high normalized RADAR cross section (NRCS). In an attempt to explain these high RADAR returns, a rigorous, fully numerical two-dimensional (2D) electromagnetic computational tool based on the finite element method (FEM) is used. Geologically plausible scattering geometries that explain the observed trends in RADAR data are investigated using this tool. It is found that highly porous substrates, possibly combined with nearly circular pebbles of ice atop can explain the RADAR observations.

RADAR Observations of Enceladus: Initially observed with terrestrial RADAR telescopes operating at 3.5- to 70-cm [1] and later with Cassini's 2.17-cm RADAR instrument [2], several icy satellites of the outer Solar System have high RADAR albedo [3] that cannot be explained using conventional surface scattering mechanisms on ice, and require some sort of coherent backscattering mechanism.

In November 2011, Cassini RADAR had its only opportunity to observe Enceladus up close: to 500 km at closest approach. It revealed that not only was it remarkably RADAR bright, but also that some tectonically-bounded areas were brighter than others. This suggests that either, (a) Tectonically-bounded (thermal or mechanical) processes (particularly dominant in the South Polar Region, but also occurring elsewhere), cause the brightness, or (b) that radar-bright surfaces exist all over, but burial by plume ejecta over time darkens all but the youngest surfaces (providing an additional constraint on plume deposition depths and surface ages). One region, close to the thermally-active tiger stripes, exhibited a mean NRCS of ~6 dB, which is brighter than any other surfaces observed in the Solar System at these resolutions (~100-300 m), including terrestrial icy surfaces with known coherent scatterers [4]. Finally, it is observed that backscatter shows a weak dependence on incidence angle – a vital clue in constraining scattering models.

Finite Element Modeling: The finite element method is a numerical technique used to solve differential equations with specified boundary conditions. In particular, we use this method [5] to solve Maxwell's equations for computing electromagnetic scattering from one-dimensional, randomly rough ice surfaces with heterogeneous substrates. The core idea in such a method is that the vector wave equation is enforced in a weak sense over each element of a tessellated computational domain, which when combined with appropriate boundary conditions gives a large system of equations to be solved.

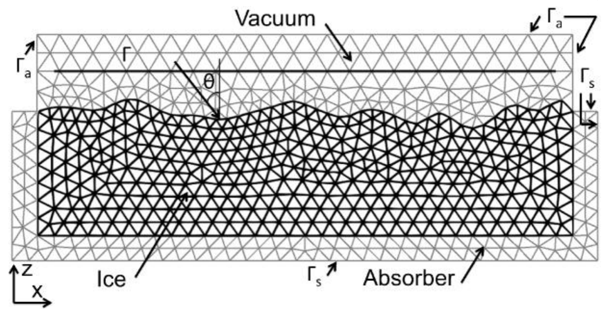

Figure 1: Finite element mesh showing vacuum-air interface and an incident radar wave of wavelength, λ= 2.17 cm. The horizontal extent of ice is 70λ, and the average depth is 3.5 λ.

Technical details: The typical steps in an FEM calculation for a randomly configured media, such as the vacuum-ice interface shown in Figure 1, are as follows.

First, the RADAR excitation source is chosen to be a single frequency, Gaussian-amplitude tapered [6] electromagnetic wave that is incident from vacuum onto the ice surface at a specified incidence angle.

Secondly, the scattered electromagnetic waves are absorbed at the domain boundaries by a local first order absorbing boundary condition [7] which seeks to simulate a reflectionless boundary. An additional adiabatic absorber [8] is added to the boundaries of the ice substrate in order to eliminate numerical reflections that arise due to imperfect boundary conditions.

Thirdly, the backscattering coefficient is calculated by the application of the surface equivalence theorem over an (incomplete) contour above the vacuum-ice interface. Finally, in order to capture the statistical properties of randomness (for instance, of surface roughness), it is necessary to repeat the simulation over many instances of random ice configurations until the ensemble average converges within an acceptable limit; this Monte Carlo process [9] is typically performed over 70-100 instances.

Evaluation of Scattering Geometries: For a homogeneous rough surface, RADAR backscatter increases with surface roughness and refractive index, while it decreases with surface correlation length. Pure ice has much lower reflectivity than liquid water and soil at microwave frequencies. Thus, to get a higher backscatter from an icy substrate than say, terrestrial soil [1] requires the presence of some sort of a coherent scattering process.

Before proceeding further, it must be mentioned that the FEM modeling presented here is for a 2D geometry, i.e. the third dimension is infinite. This is a reasonable assumption for various geometries, and it allows the investigation of several different scattering geometries within a reasonable computational time.

Rough Surfaces: The first types of structures investigated are homogeneous rough surfaces with roughness comparable with the wavelength (2.17 cm), and low correlation lengths, i.e. surfaces that appear to the RADAR as highly rough and not very correlated. A subset of the results is shown in Table 1.

Incidence angle	**h=0.25cm, c=h**		**h=0.25cm, c=5*h**	
	H-pol	**V-pol**	**H-pol**	**V-pol**
50	-13.0	-13.3	-24.9	-22.5
40	-13.7	-12.8	-19.9	-17.8
30	-13.4	-14.8	-13.3	-13.3

Table 1: Ensemble averaged (over 100 runs) backscatter in dB as a function of incidence angle (from normal) and polarization for randomly rough surfaces with specified root mean square (r.m.s.) height, *h*, and correlation length, *c*.

Circular Pebbles: Based on the above case, and related experiments (varying *h* and *c*), it is found that he backscatter is rather sensitive to the surface parameters. Thus more robust scattering mechanisms are sought – leading to the second type of scattering geometry – randomly sized circular ice pebbles sprinkled (also randomly) on top of the (rough) surfaces. Circular pebbles have an interesting scattering property, where nearly as much energy is reflected in the backscatter direction as is reflected in the specular direction (with relatively smooth surfaces, most of the energy is reflected in the specular direction alone). The backscatter results are seen in Table 2, and it is evident by comparing with Table 1 that the pebbles have “masked” the effect of the rough surface.

Incidence angle	**h=0.25cm, c=h**		**h=0.25cm, c=5*h**	
	H-pol	**V-pol**	**H-pol**	**V-pol**
50	1.3	1.9	0.1	0.8
40	2.3	0.9	1.1	2.0
30	2.4	1.0	3.1	2.8

Table 2: Ensemble averaged (over 70 runs) backscatter in dB as a function of incidence angle (from normal) and polarization for circular pebbles atop randomly rough surfaces. The pebbles have radius in the range 0.75λ to 1.25λ, and spaced between 5λ and 7λ apart.

As an aside, it can be mentioned that a set of experiments were also done where the eccentricity of the pebbles was varied. It was found that the overall magnitude of backscatter decreased, and dependence on incidence angle increased.

Porous Substrates: The third type of scattering geometry is of a highly porous substrate below a rough ice surface. Pores (vacuum filled) are inserted at random locations in the ice, leading to the creation of multiple scattering interface and increasing the overall backscatter. The porosity is fixed at 50%, and the minimum pore sizes investigated are 5, 10, and 20mm. A gradual increase in backscatter with pore size is observed. The results are seen in Table 3, and like in the previous case, the effects of the rough surface are “masked” by the pores.

Incidence angle	**h=0.25cm, c=h**		**h=0.25cm, c=5*h**	
	H-pol	**V-pol**	**H-pol**	**V-pol**
50	0.9	0.6	0.4	-1.2
40	2.0	2.5	1.4	2.0
30	3.6	2.1	2.5	2.2

Table 3: Ensemble averaged (over 71 runs) backscatter in dB as a function of incidence angle (from normal) and polarization for a porous icy substrate below a rough surface. Minimum pore size is 10mm.

Finally, random pebbles are sprinkled on top of rough surfaces that have porous substrates. On expected lines, the backscatter increases, though not in a linear sense. An overall enhancement of 1-3 dB is observed as compared to the values in Table 3.

Conclusions: It is likely that the substrate is comprised of fragmented ice debris at the cm-scale. Further, at the low temperatures (~75K) of Enceladus' surface, the substrate would help preserve porosity over the long term. Several important scattering mechanisms that are geologically plausible are identified by using the FEM, and we plan to follow up our studies with a full 3D FEM model in the future.

References: [1] Ostro, S. J. et al. (1992) *J. Geophys. Res.* 97, 18227-44. [2] Ostro, S. J. et al. (2006) *Icarus, 183*, 479-490. [3] Black, G. J. et al. (2001) *Icarus, 151*, 167-180. [4] Rignot, E. (1995) *J. Geophys. Res., 100(E5)*, 9389-9400. [5] Khankhoje U. K. et al. (2012) *IEEE Trans. on Geoscience & Remote Sensing, 51(6)*. [6] Thorsos E. I. (1988) *The Journal of the Acoustical Society of America, 83(1)*, 78-92. [7] Bayliss A. and Turkel E. (1980) *Communications on Pure and Applied Mathematics*, 33(6), 707-725. [8] Oskooi A. F. et al. (2008) *Optics Express, 16(15)*, 11376-11392. [9] Lou S. H. et al. (1991) *Waves in random media 1(4)*, 287-307.

Acknowledgements: We would like to acknowledge useful discussions with Stephen Wall, Richard West, Jakob van Zyl, and the Cassini RADAR Science Team. This research was carried out at the Jet Propulsion Laboratory, Caltech, under a NASA contract. It was supported by the Cassini project, and a JPL R&TD Innovative Spontaneous Concept grant.