From Cat's eyes
to
the Rings of Saturn:
Solving a cosmic mystery

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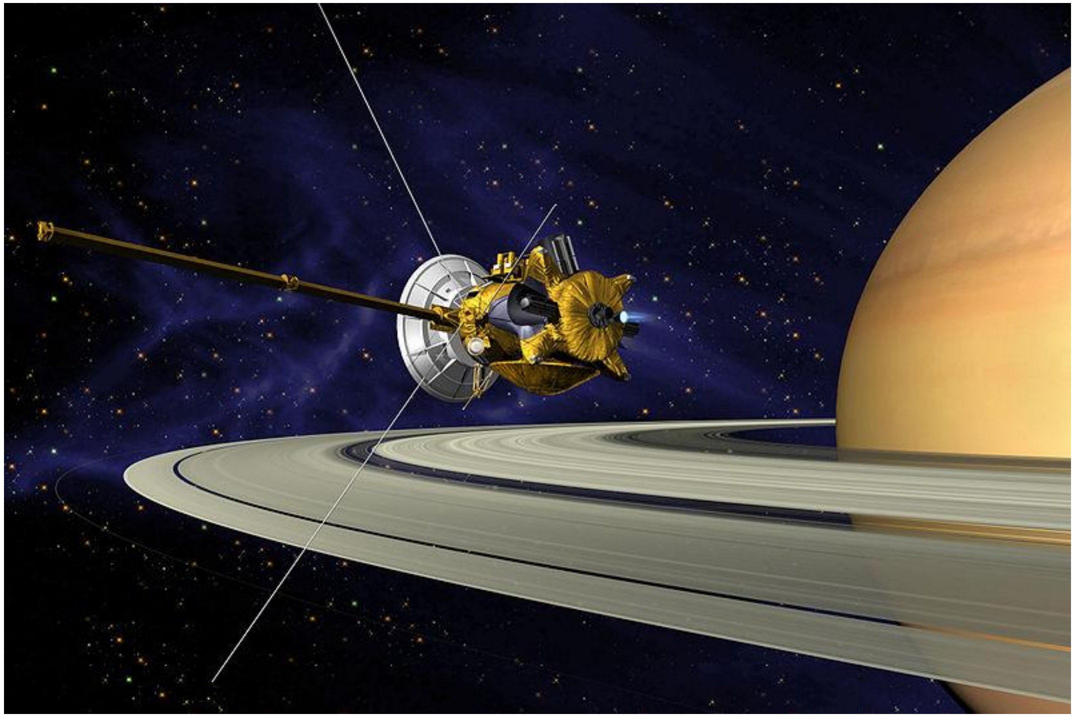
The Cassini-Huygens spacecraft

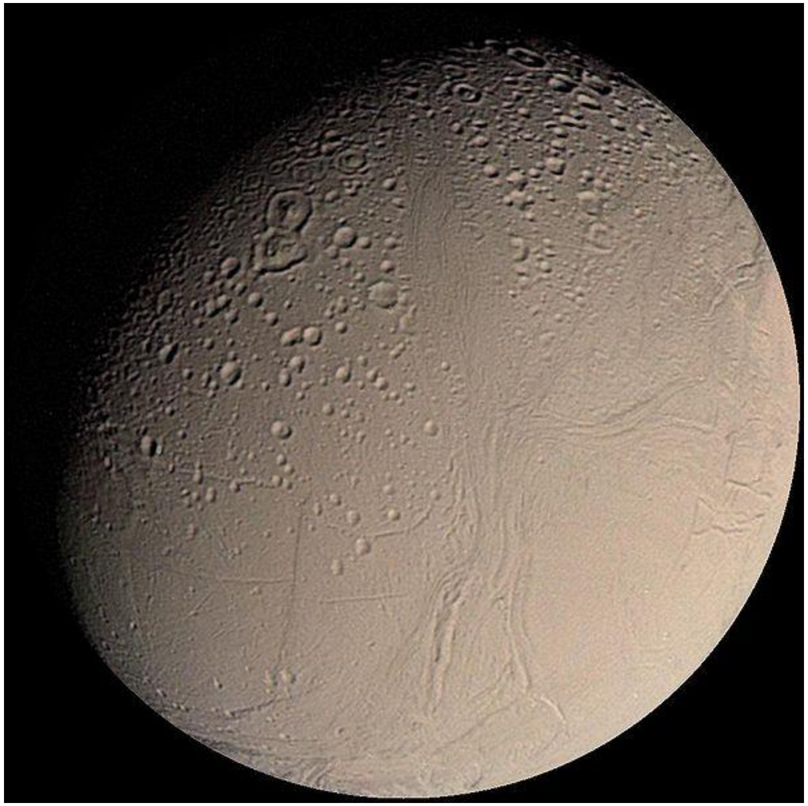
Saturn orbiter

Titan lander



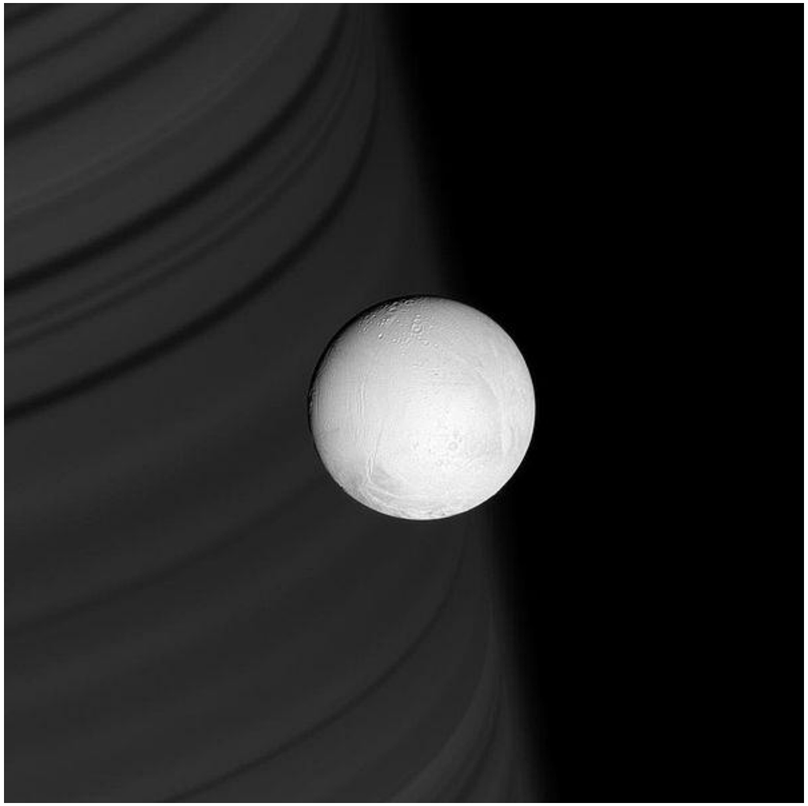
- 1997 : Launch
- 2004 : Reaches Saturn
- 2005 : Huygens lands on Titan.
- Cassini has made fly-bys of Enceladus since 2005.

Views of Enceladus



Voyager 2 in 1981

Cassini in 2007



Why is Enceladus interesting?

- One of the brightest objects to Radar in the solar system (up to 4 dB backscatter)
- Ice covered, temp: 33K (min) / 145K (max)
- Ice covered regions on Earth are not as bright
- Other ice covered moons of the outer Solar System are also very bright.

Why?

How well does ice reflect radar?

- Consider highly simplistic case:
  normal incidence on semi-inf medium
- Reflectivity, $\Gamma = \left|\frac{n-1}{n+1}\right|^2$, where n is refr. indx.

Wet soil (on Earth)	Ice (at 125K)
$n = 2.65 - 0.3i$, Γ = 0.21	$n = 1.76 - 8.8\text{x}10^{-7}i$, Γ = 0.08
Observed $\approx -12\ dB$	Observed $\approx 4\ dB$

Whereas, ice should be at least 4 dB *below* soil!

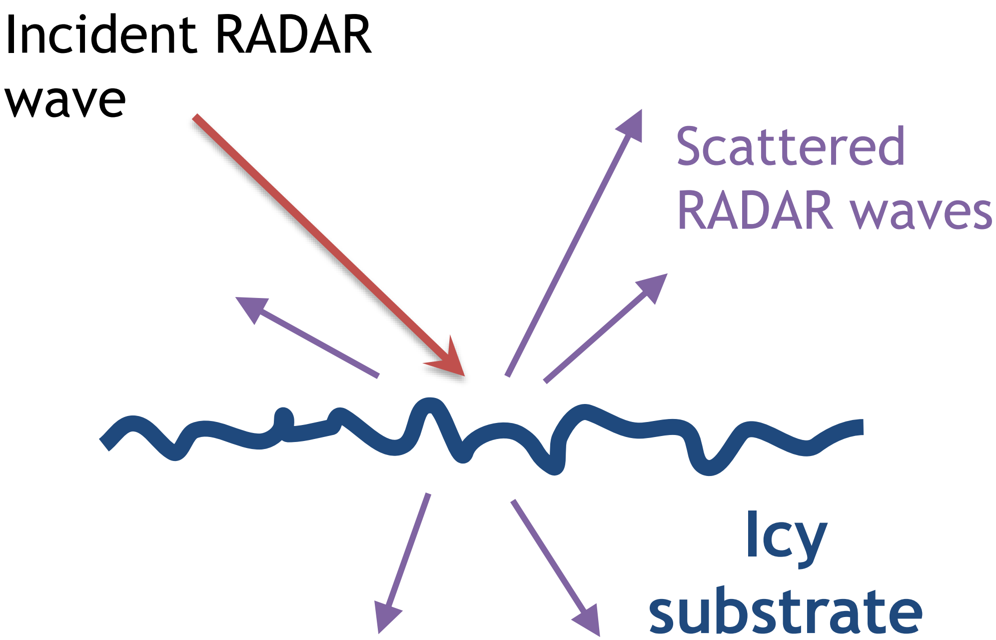
How well does ice reflect radar?

↓

(Bulk) ice is a poor reflector!

Challenge : find explanations for ice to be highly reflective *without* adding any new material (where will it come from!?)

Basics - Radar Scattering

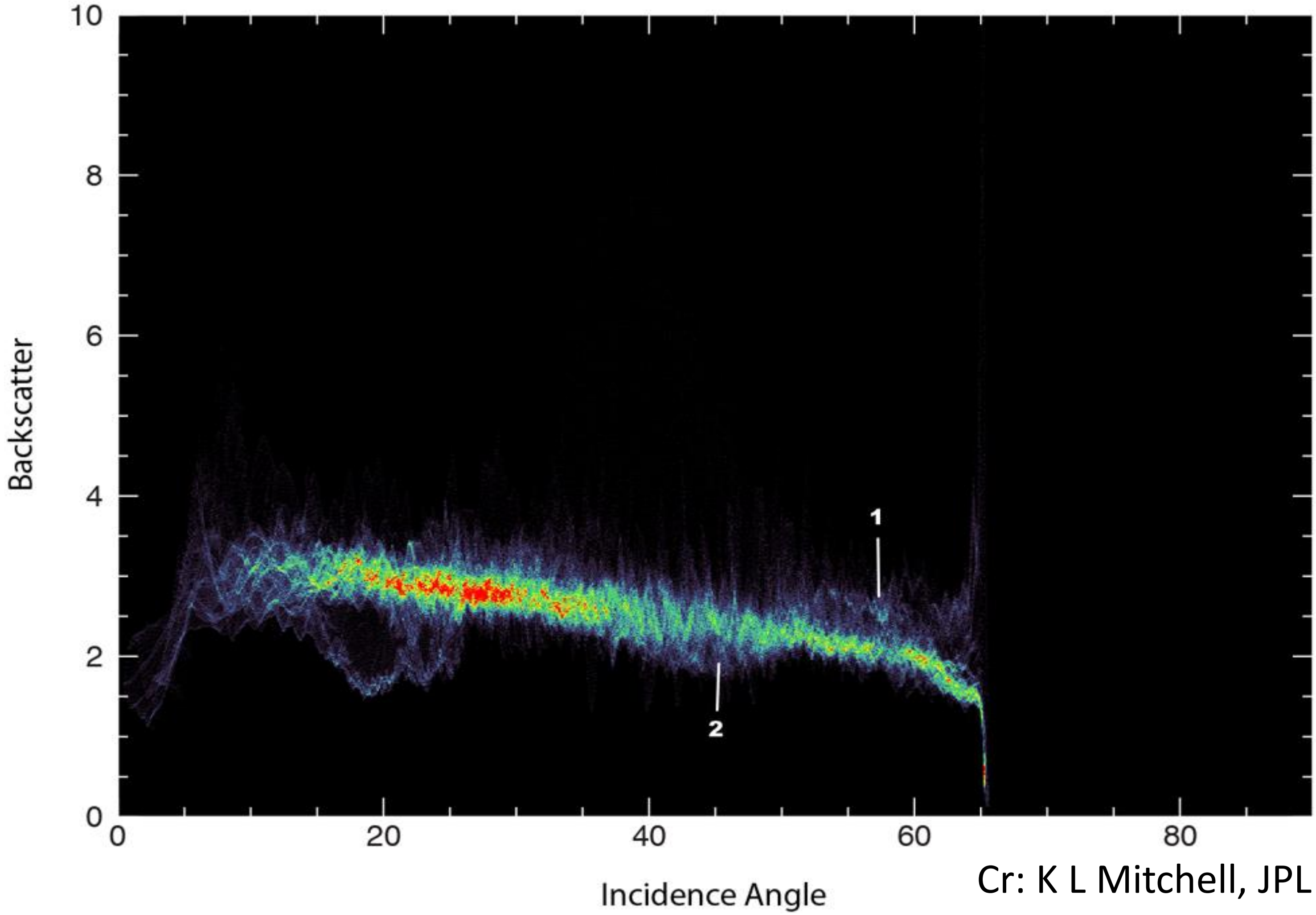


Two items of interest

1. Back-scatter : What comes directly back to the RADAR

2. Bi-static RCS: Properties as a function of scattering angle

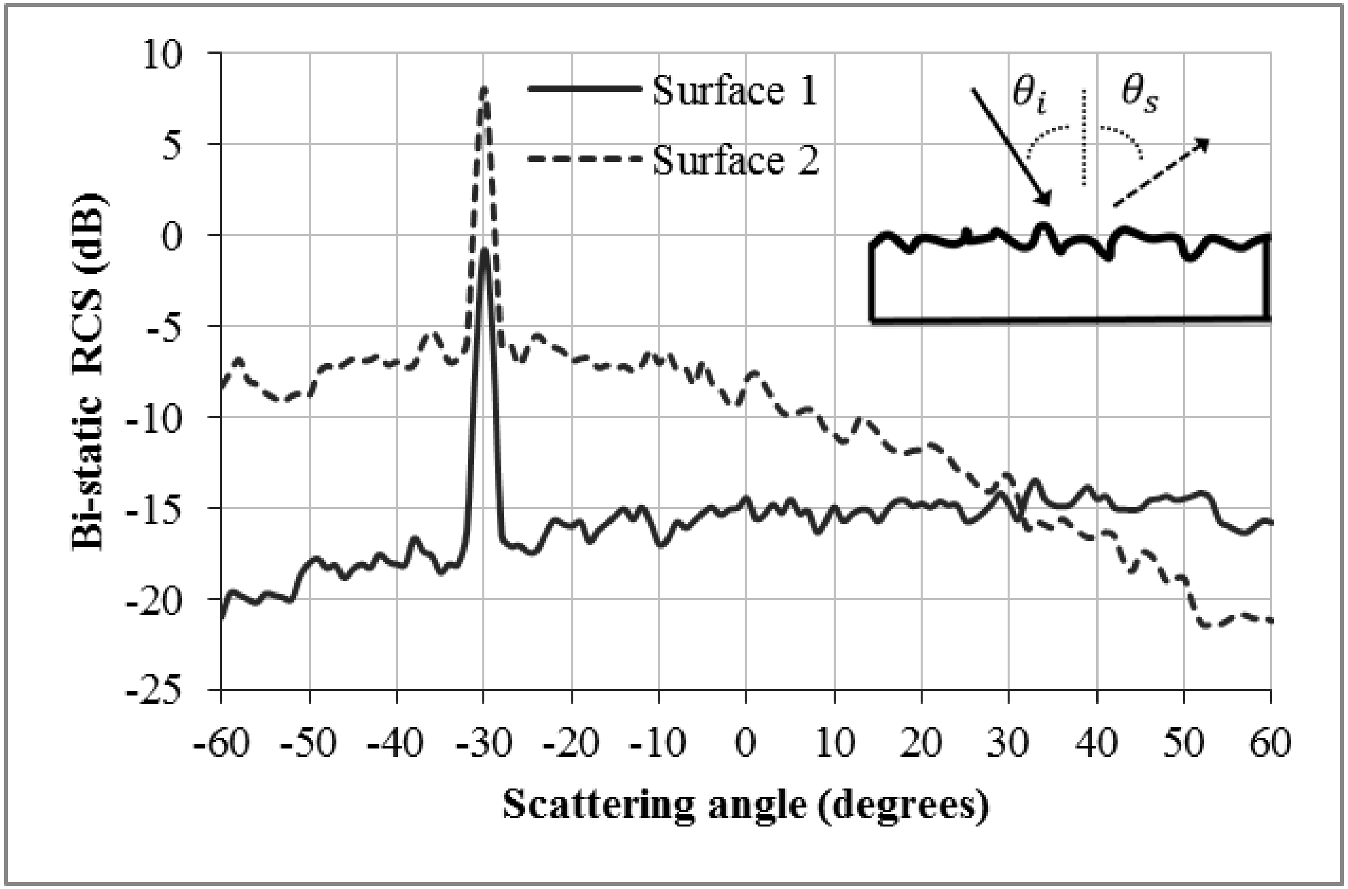
Cassini's observations of Enceladus



Cr: K L Mitchell, JPL

Let's start with bulk ice

- Realistic surfaces are rough in nature



Surfaces are treated as random processes characterized by:

1. Roughness
2. Correlation length
3. Correlation type

How reflective is rough, bulk ice?

Rough, bulk ice

θ_i	Surface 1 HH	Surface 2 HH
50	-13.0	-24.9
40	-13.7	-19.9
30	-13.4	-13.3

Surface 1:
rms h=2.5 cm
corl c=h

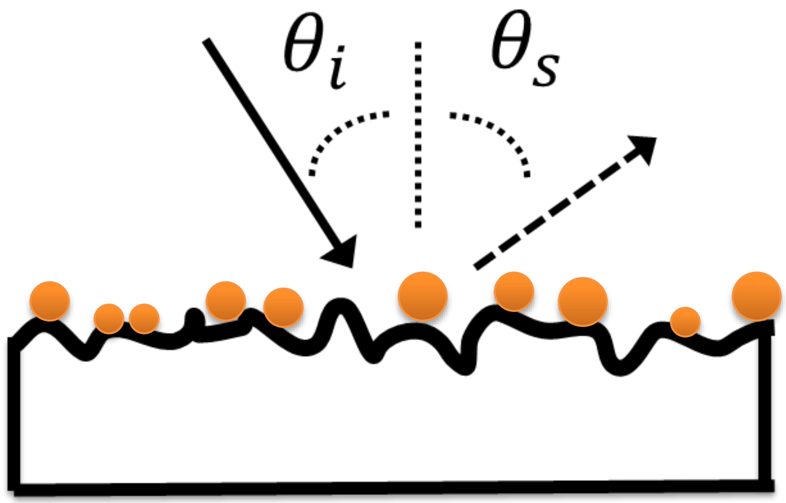
Surface 2:
rms h=2.5cm
corl c=5h

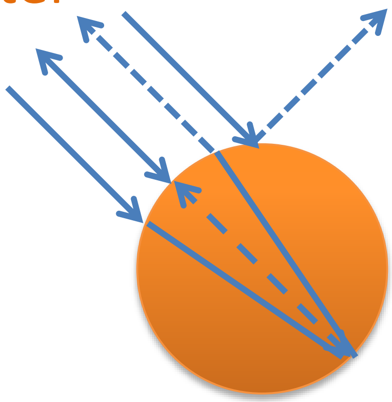
Gaussian corl statistics

Back-scatter dependent on:

1. Incidence angle
2. Surface statistics

Now sprinkle some ice pebbles





Like cat's eyes, or bike reflectors, pebbles are good retro-reflectors

Does radar backscatter change? Yes!

Pebbles atop rough, bulk ice

θ_i	Surface 1 HH	Surface 2 HH
50	1.3	0.1
40	2.3	1.1
30	2.4	3.1

Rough, bulk ice

θ_i	Surface 1 HH	Surface 2 HH
50	-13.0	-24.9
40	-13.7	-19.9
30	-13.4	-13.3

Surface 1:
rms h=2.5 cm
corl c=h

Surface 2:
rms h=2.5cm
corl c=5h

Pebble size:
(1 ± .25) λ
Spacing:
(5-7) λ

Does radar backscatter change? Yes!

Pebbles atop rough, bulk ice

θ_i	Surface 1 HH	Surface 2 HH
50	1.3	0.1
40	2.3	1.1
30	2.4	3.1

Retro-reflector effect has **weakened** dependence on:

1. Incidence angle
2. Surface statistics

Surface 1:

rms h=2.5 cm

corl c=h

Surface 2:

rms h=2.5cm

corl c=5h

Pebble size:

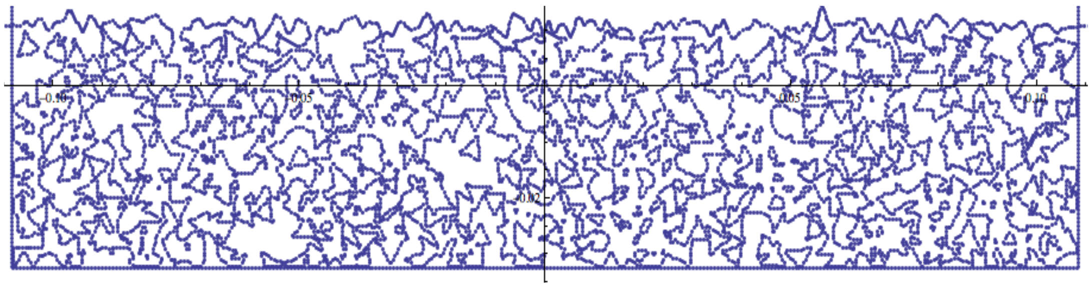
(1 ± .25) λ

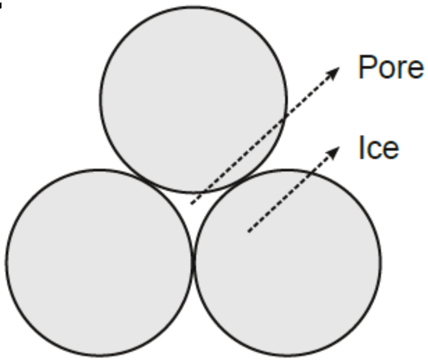
Spacing:

(5-7) λ

Any other ideas?

- What if the substrate is not pure ice but full of vacuum voids/fractures?





θ_i	Surface 1 HH	Surface 2 HH
50	0.9	0.4
40	2.0	1.4
30	3.6	2.5

Diffuse scattering has **weakened** dependence on:

1. Incidence angle
2. Surface statistics

Realistic?

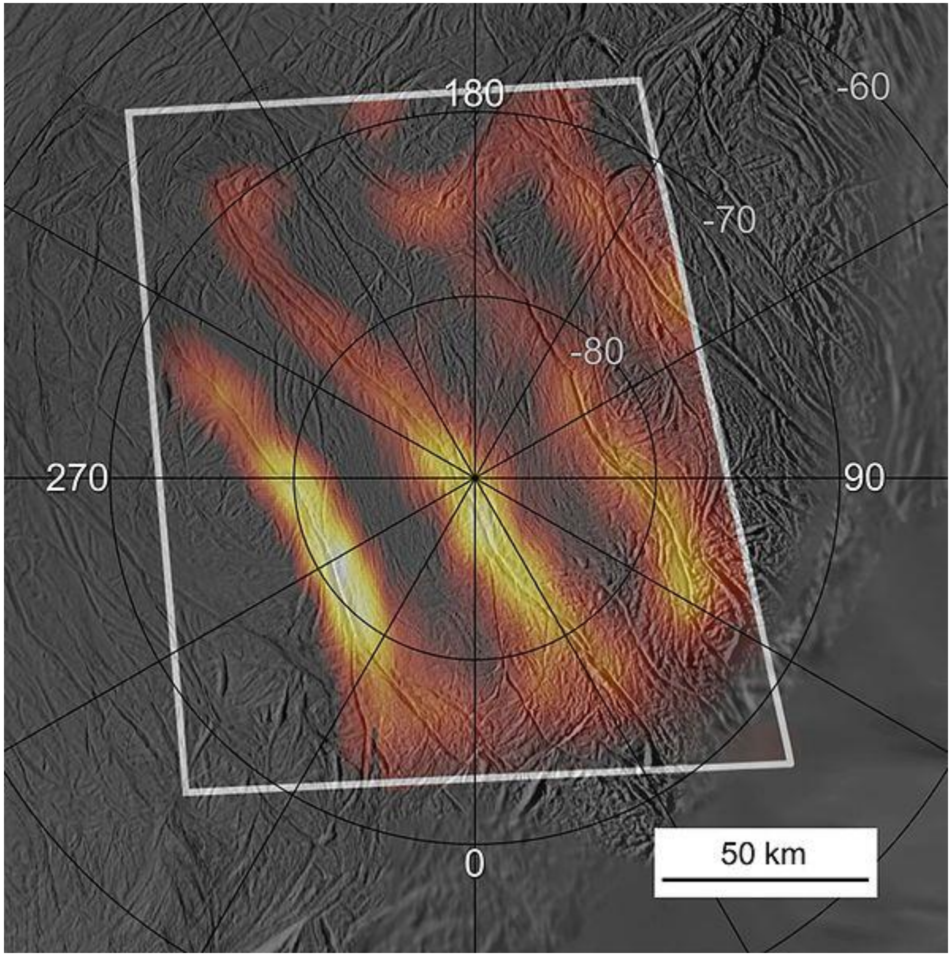
Cr: NASA/JPL/Space Science Institute

Realistic?

Thermal image of the South Pole of Enceladus:

What's going on?

[Max T: 180K
Surf T: <72K]

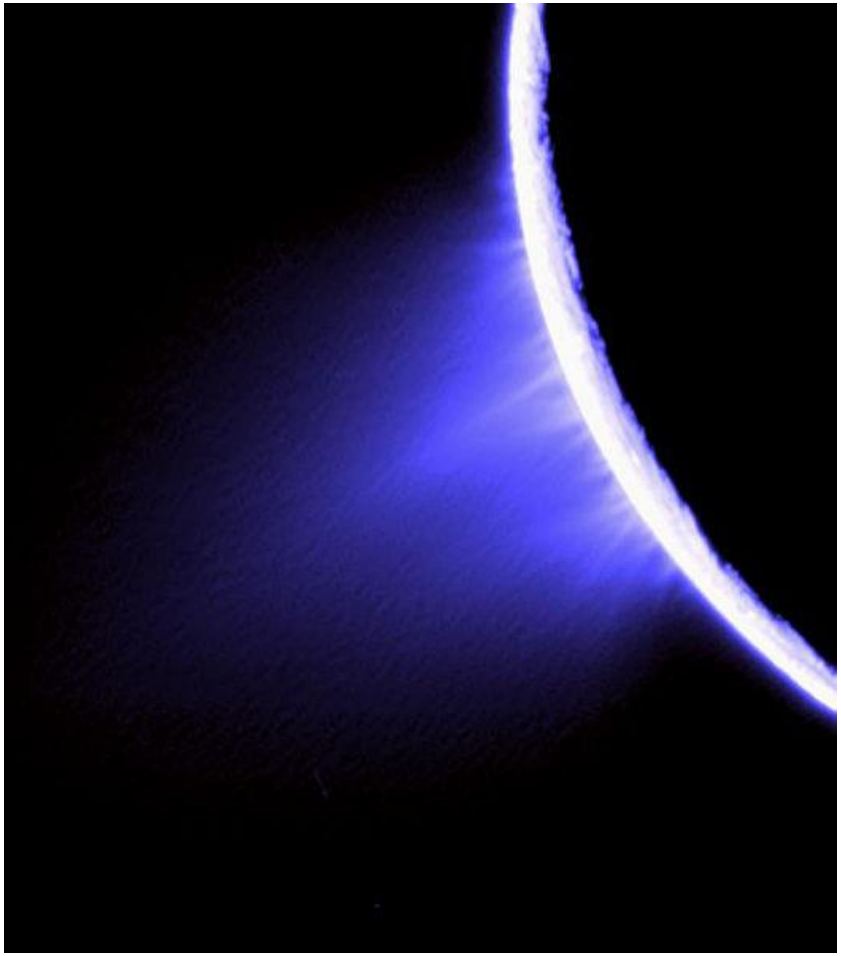


Cr: NASA/JPL/GSFC/SwRI/SSI

Realistic!

Enceladus is one of the few places in the Solar System that displays cryo-volcanism.

i.e., volcanoes throw up ice and water vapour instead of molten lava!



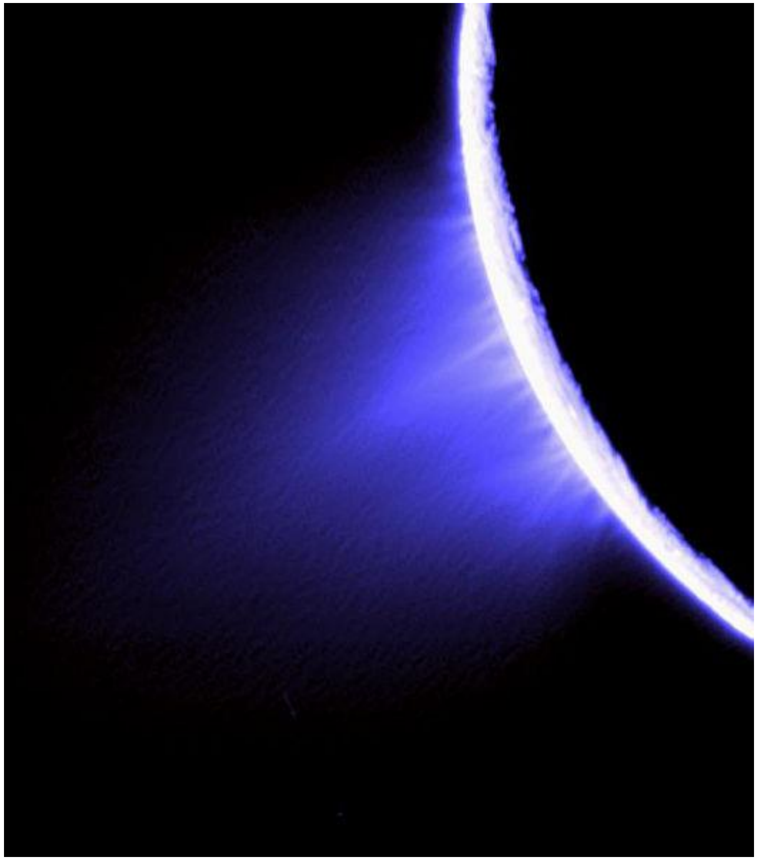
Cr: NASA/JPL/Space Science Institute

Realistic!

Cryo-volcanism on Enceladus:

1. Source of ice-crystals for Saturn's E-ring
2. Covers the surface with ice-rubble:

ice pebbles/porous substrate both possible!



Cr: NASA/JPL/Space Science Institute

- Enceladus' Brilliant Surface: RADAR Modeling
  U. Khankhoje, K. Mitchell, et. al, Lunar & Planetary Science Conference 2013
- Enceladus' Brilliant Surface: Cassini RADAR observations & interpretation
  K. Mitchell , U. Khankhoje, et. al, Lunar & Planetary Science Conference 2013

Enceladus summary

- Cassini Radar observations will be our *only* window into Enceladus for a LONG time!
- To the rescue:
  Computational EM
  +
  Planetary geology
  +
  Rocket Science

The difficult, yet most important question:

How to compute?

How to compute?

- Start with Maxwell's equations

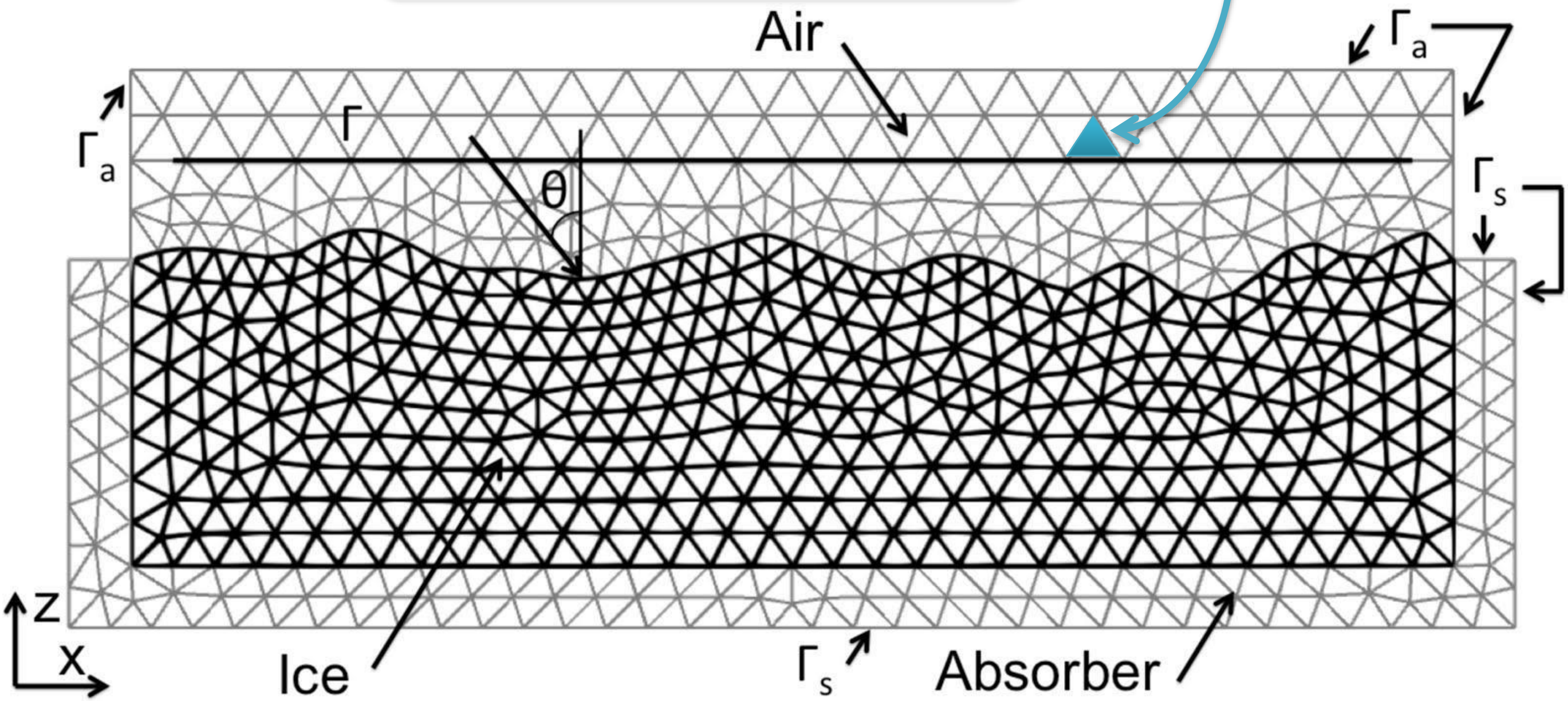
$$\nabla \times \vec{H}(r) = jw\,\varepsilon(r)\,\vec{E}(r)$$
$$\nabla \times \vec{E}(r) = -jw\,\mu(r)\,\vec{H}(r)$$

- Combine it into a single equation

$$\nabla \times \left(\frac{1}{\varepsilon_r(r)} \nabla \times \vec{H}(r)\right) = k_0^2\,\mu_r(r)\,\vec{H}(r)$$

How to compute: FEM

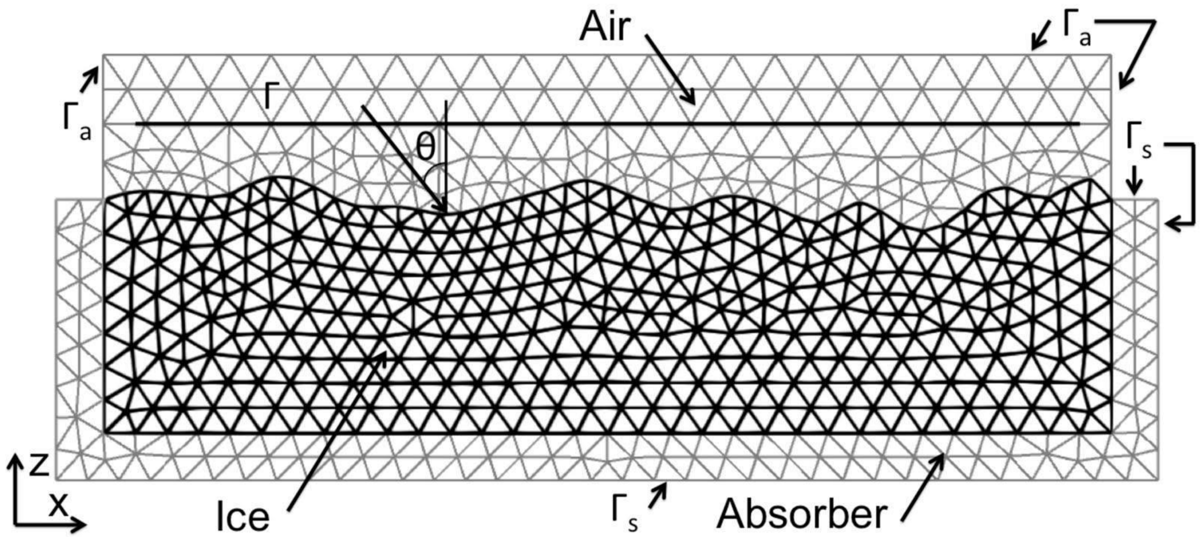
Solve → $$\nabla \times \left(\frac{1}{\epsilon_r(\vec{r})} \nabla \times \vec{H}(\vec{r}) \right) = k_0^2 \mu_r(\vec{r}) \vec{H}(\vec{r})$$ in each



FEM : Monte Carlo

- Challenge is unique to remote-sensing:
  One computation is not good enough
- Statistical properties are desired:
  Ensemble average over ≈ 100 instances
- Each instance – Unique mesh
  8 min per mesh generation, ≈ 1 min to solve
- Mesh changes only slightly / instance.
  Inefficient! => Opportunity to innovate!

Remote Sensing from bare surfaces ...



IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 51, NO. 6, JUNE 2013

Computation of Radar Scattering From Heterogeneous Rough Soil Using the Finite-Element Method

Uday K. Khankhoje, Jakob J. van Zyl, *Fellow, IEEE*, and Thomas A. Cwik, *Fellow, IEEE*

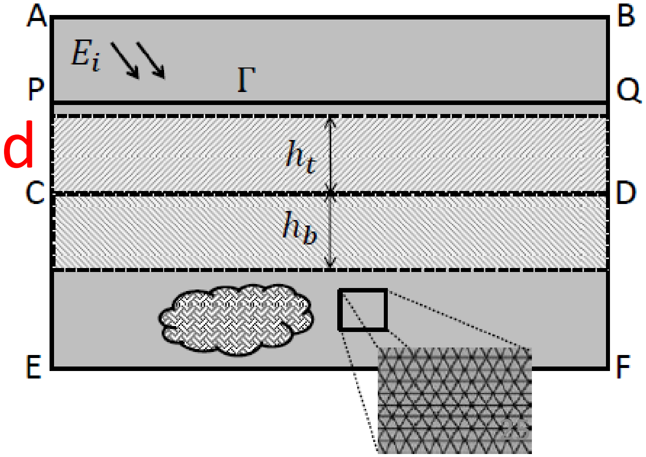
Remote Sensing from bare surfaces …

- A mesh reconfiguration scheme for speeding up Monte Carlo simulations of electromagnetic scattering by random rough surfaces
  U K Khankhoje, T A Cwik, Computer Physics Comm. 2014

Comparison of parameters for the two solution methods when considering 100 rough surface instances.

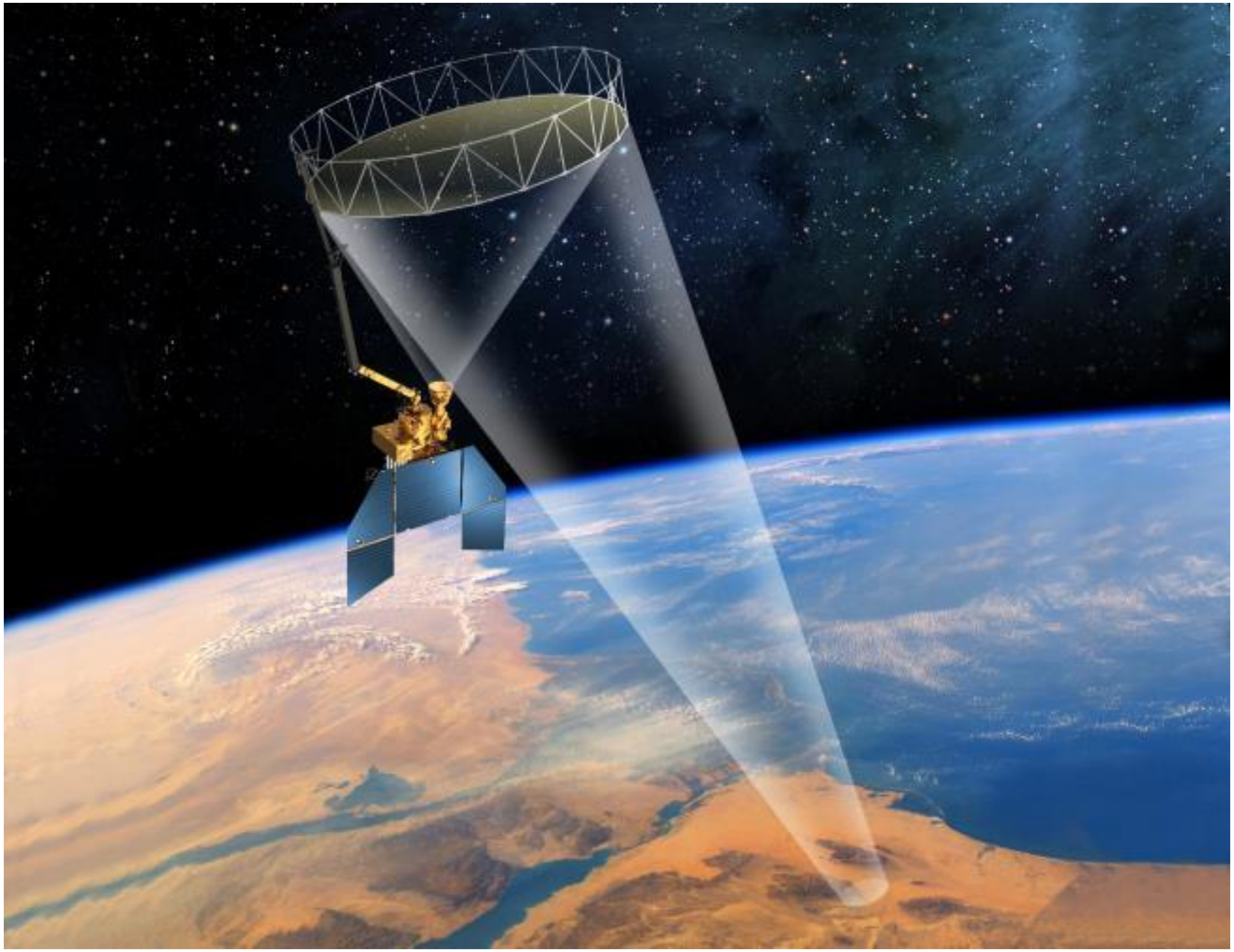
	Mesh creation time	Avg. no. of elements per mesh	FEM time per instance	Total time
Multiple-mesh	10 h 34 min	1,030,000	1 min 07 s	12 h 19 min
Single-mesh	8 min	1183,000	1 min 41 s	2 h 50 min

- Stochastic Solutions to Rough Surface - Scattering using the Finite Element Method
  U K Khankhoje and S Padhy
  Manuscript in revision, Jan 2017



What else can we figure out remotely?

Soil moisture, ocean salinity, etc.



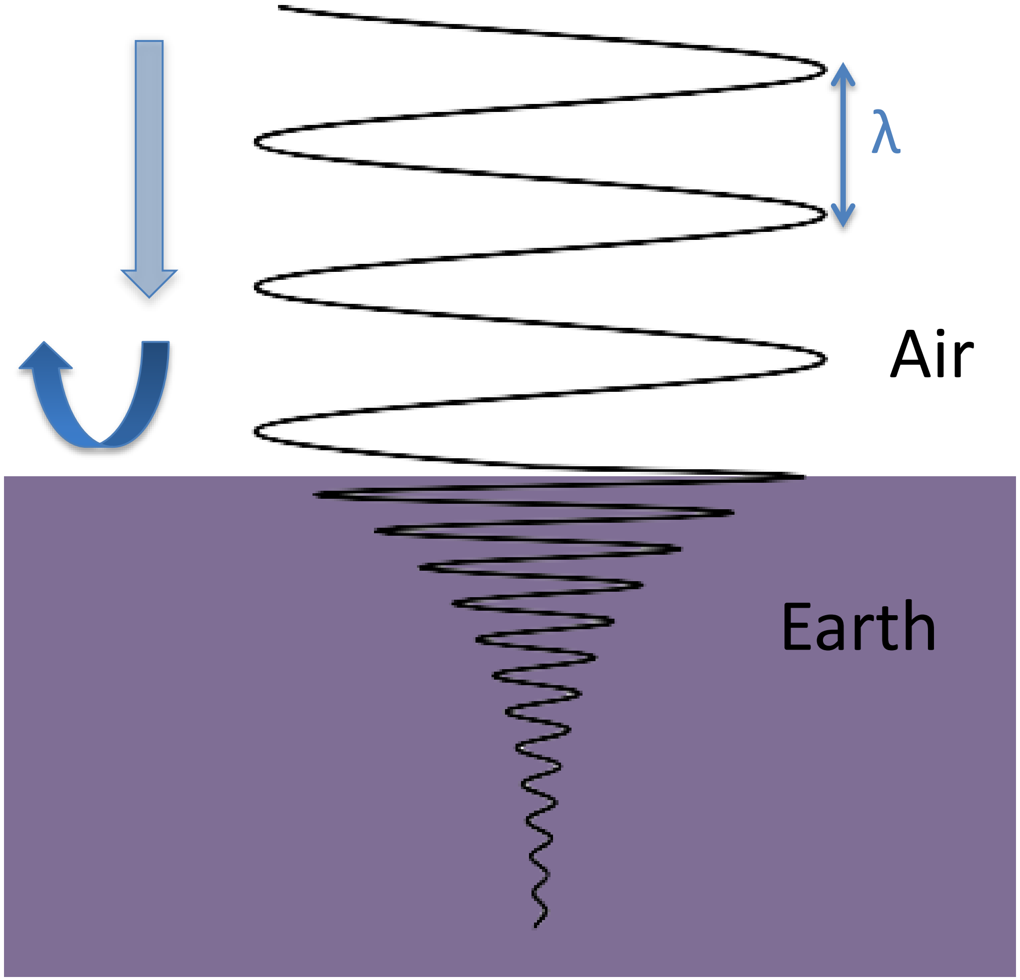
[SMAP mission website]

Radar – Earth interaction

- X–band: 3 cm
- C–band: 6 cm
- L–band: 24 cm
- P–band: 74 cm

Loss depends on medium:

Sand – less
Clay – more
Ocean – more+



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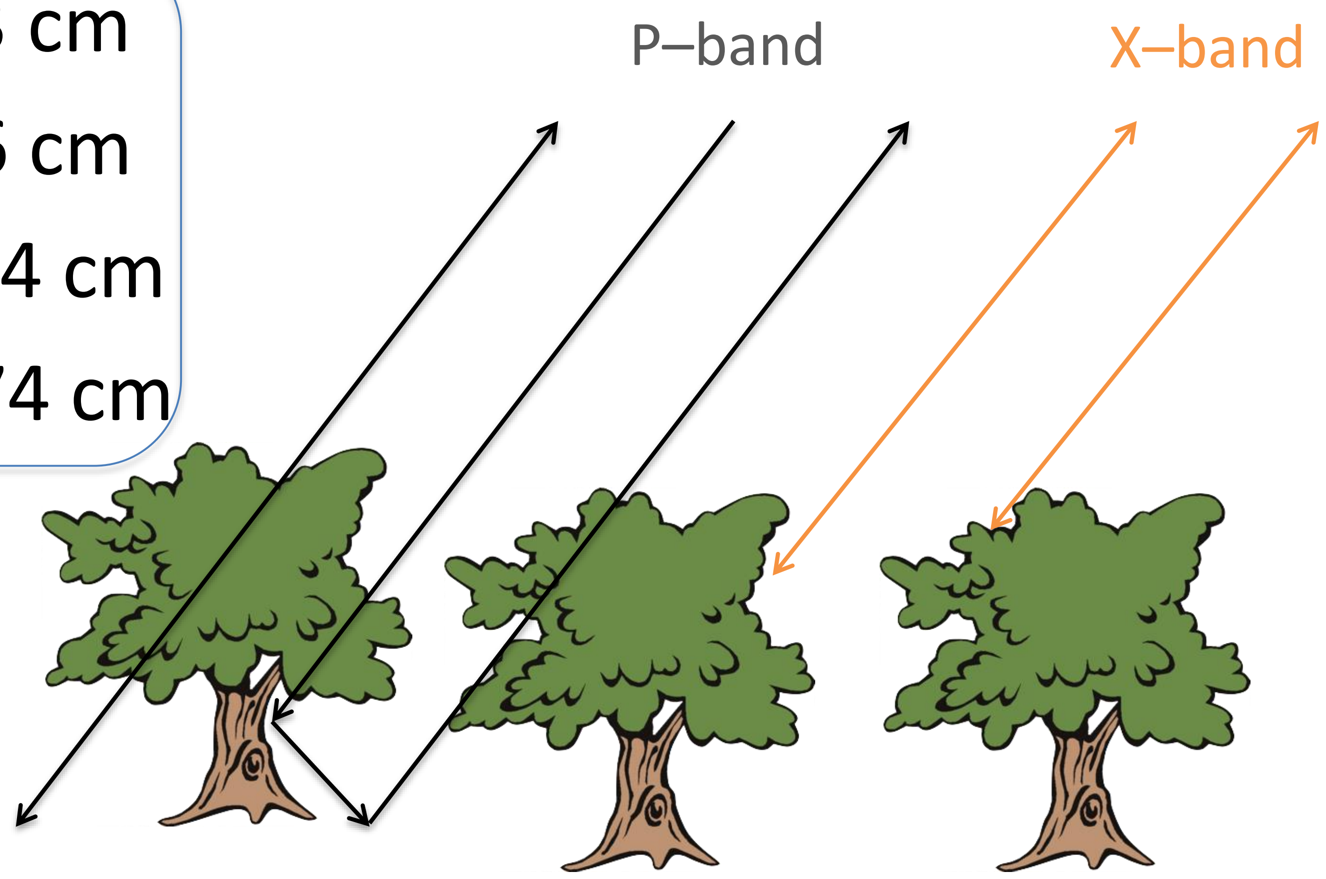

Diverse skill sets needed

- Electromagnetism (Maxwell’s equations, radars)
- Probability, random processes (Rough surface characterization)
- Numerical methods (Solving large system of sparse equations)
- Optimization (to solve inverse problems)
- Earth Sciences (geology, planetary science)
- Programming (duh!)

Something for everyone!

Thanks!

visit: http://www.ee.iitm.ac.in/uday

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