Medium and long-term perspectives of radio sounding & radar instrumentation techniques for the study of the surfaces & subsurfaces of solar system objects

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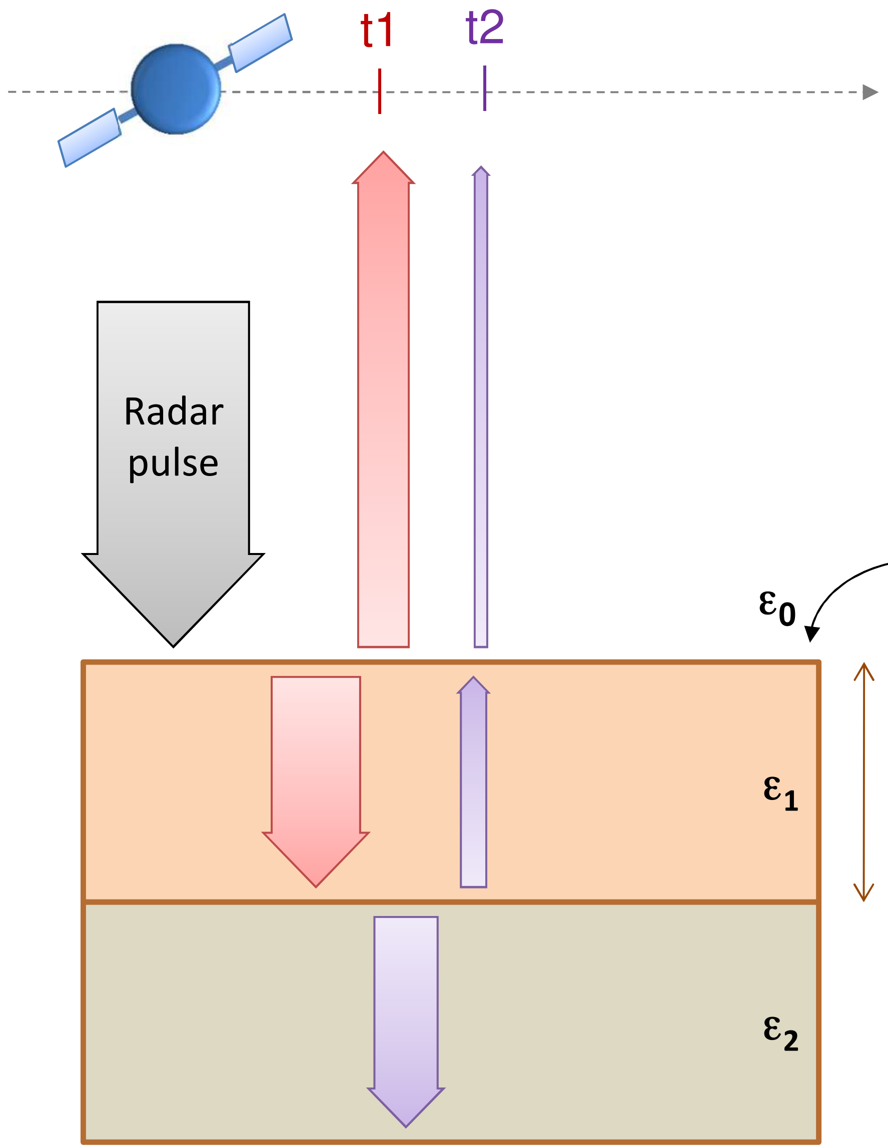
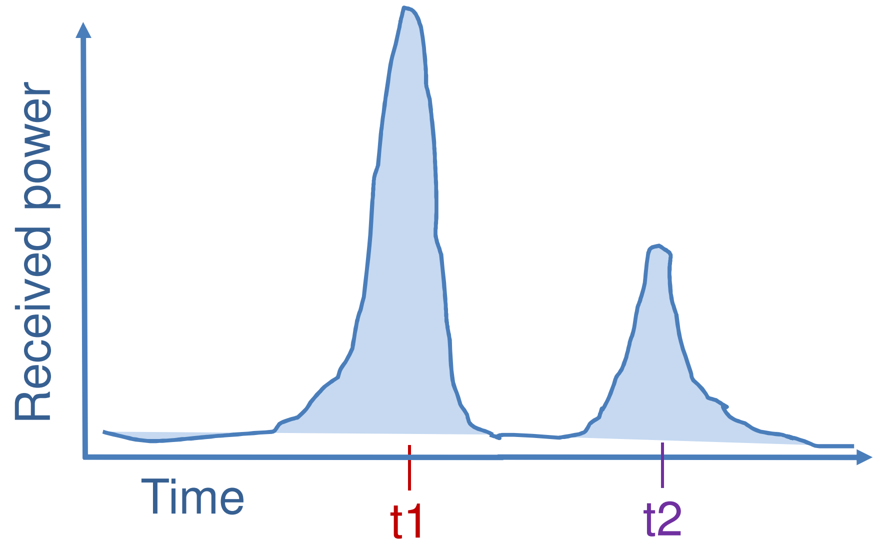
Outline

1. How do radars work?
2. A few examples & results
3. Perspectives

How do radars work?





Reflection : $\propto (\sqrt{\varepsilon_a} - \sqrt{\varepsilon_b}) / (\sqrt{\varepsilon_a} + \sqrt{\varepsilon_b})$

Propagation : $h = (t.c) / (2 \sqrt{\varepsilon})$

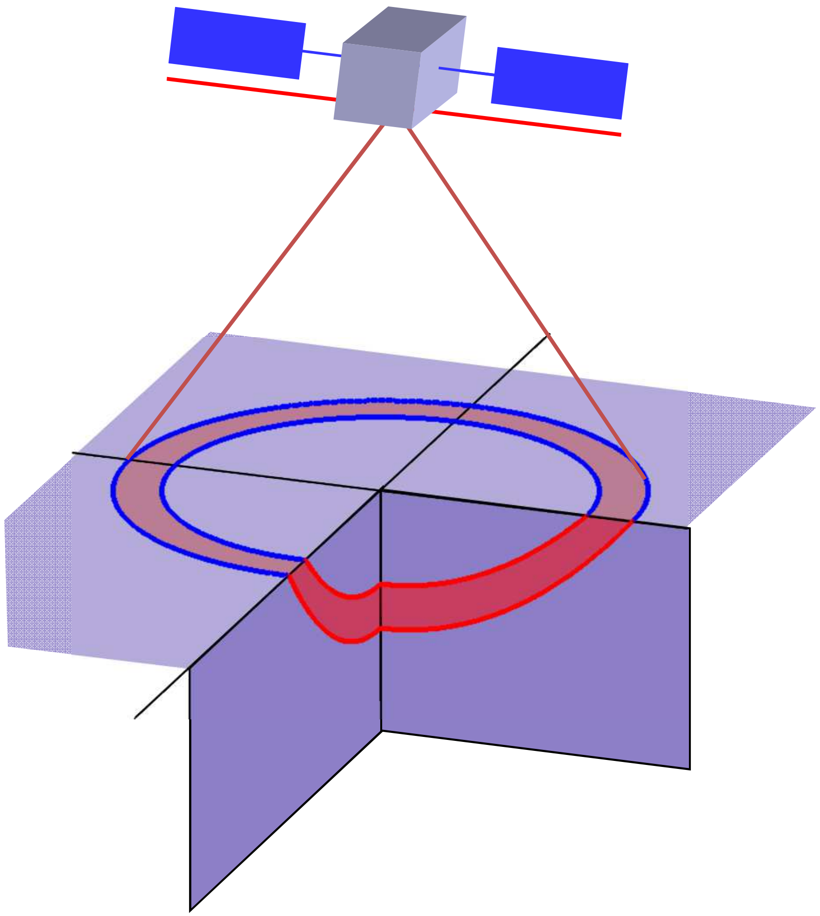
And also…

… scattering and absorption in the medium

… scattering at interfaces

(sensitive to roughness)

Nadir Looking Radar



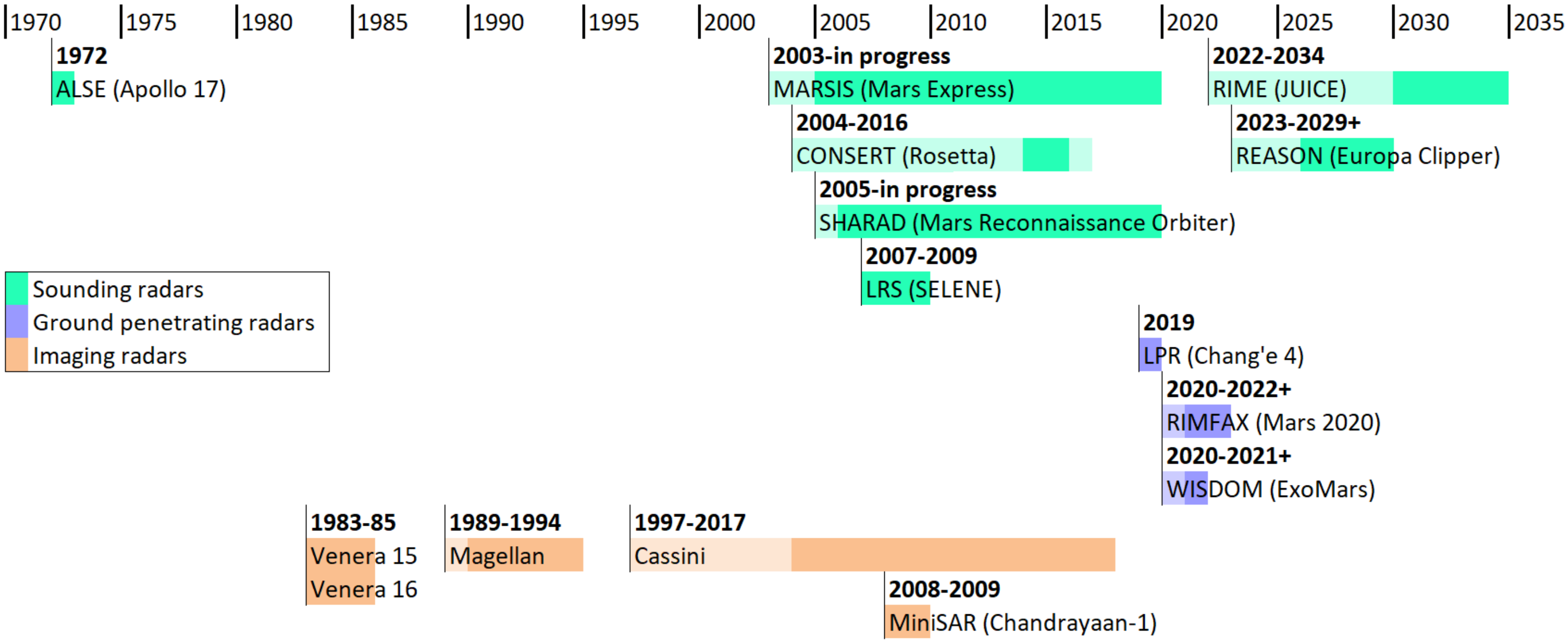
- Roughness-dependant
  - Large Roughness:

    coherence loss / limited penetration depth / no stratigraphy

    → like altimeter signals
  - Low roughness:

    low surface scattering / reflection in the nadir direction / detection of internal reflections / vertical resolution = RF bandwidth / horizontal resolution = Fresnel zone
- Time ambiguity
  - Surface / subsurface signal
- Surface simulation
  - Ambiguity reduction
  - Data interpretation level

Planetary radars



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   - **Monostatic sounding radars on Mars & Moon**
   - Bistatic sounding radar: CONSERT on Rosetta
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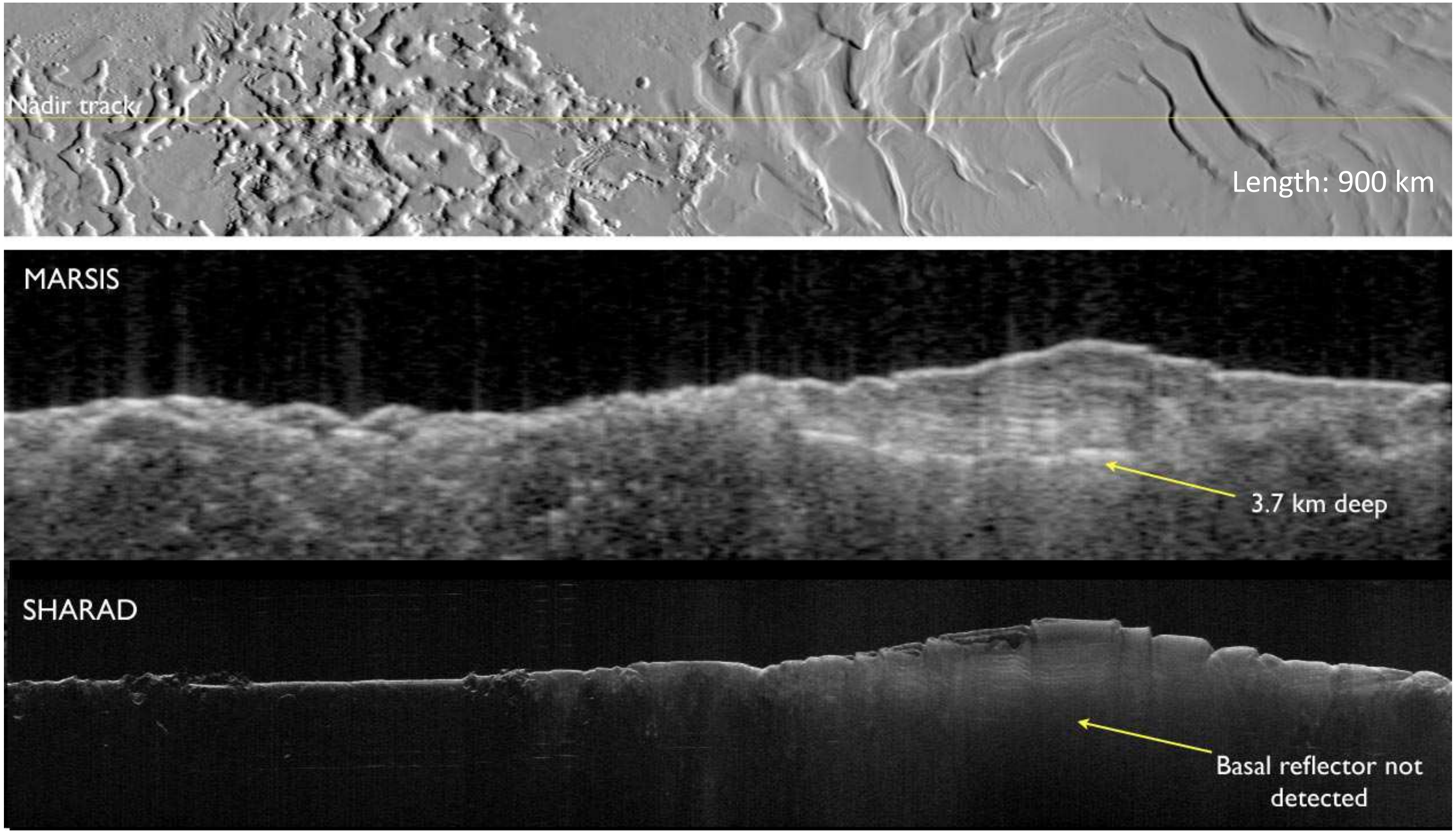
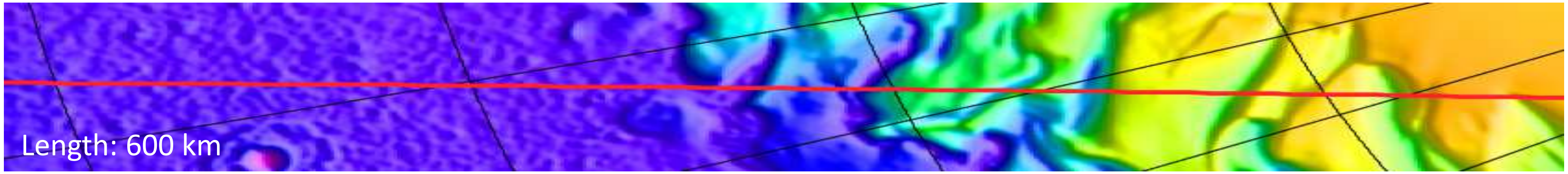
Monostatic sounding radars on Mars

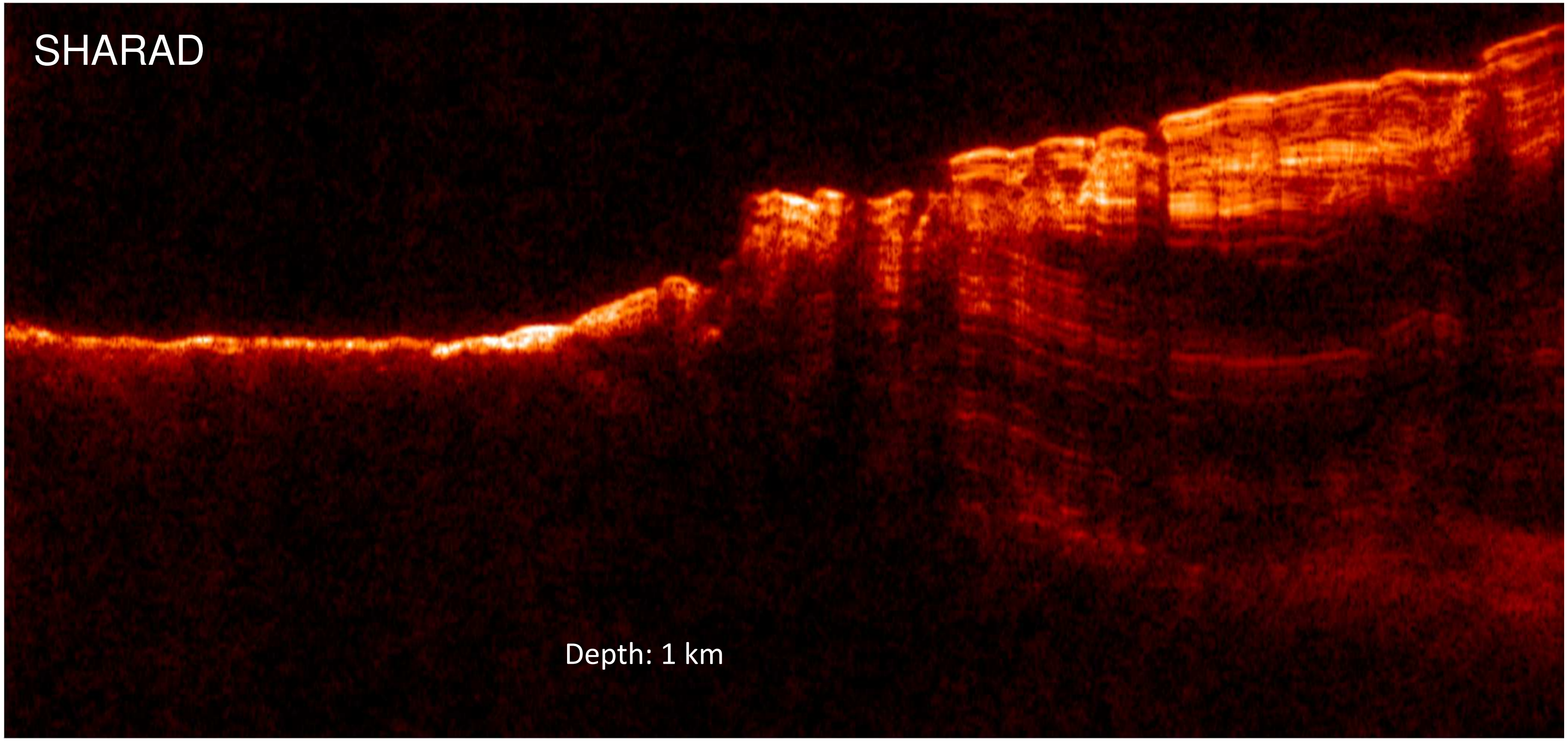
Mars South Polar cap



Monostatic sounding radars on Mars

Mars North Polar cap

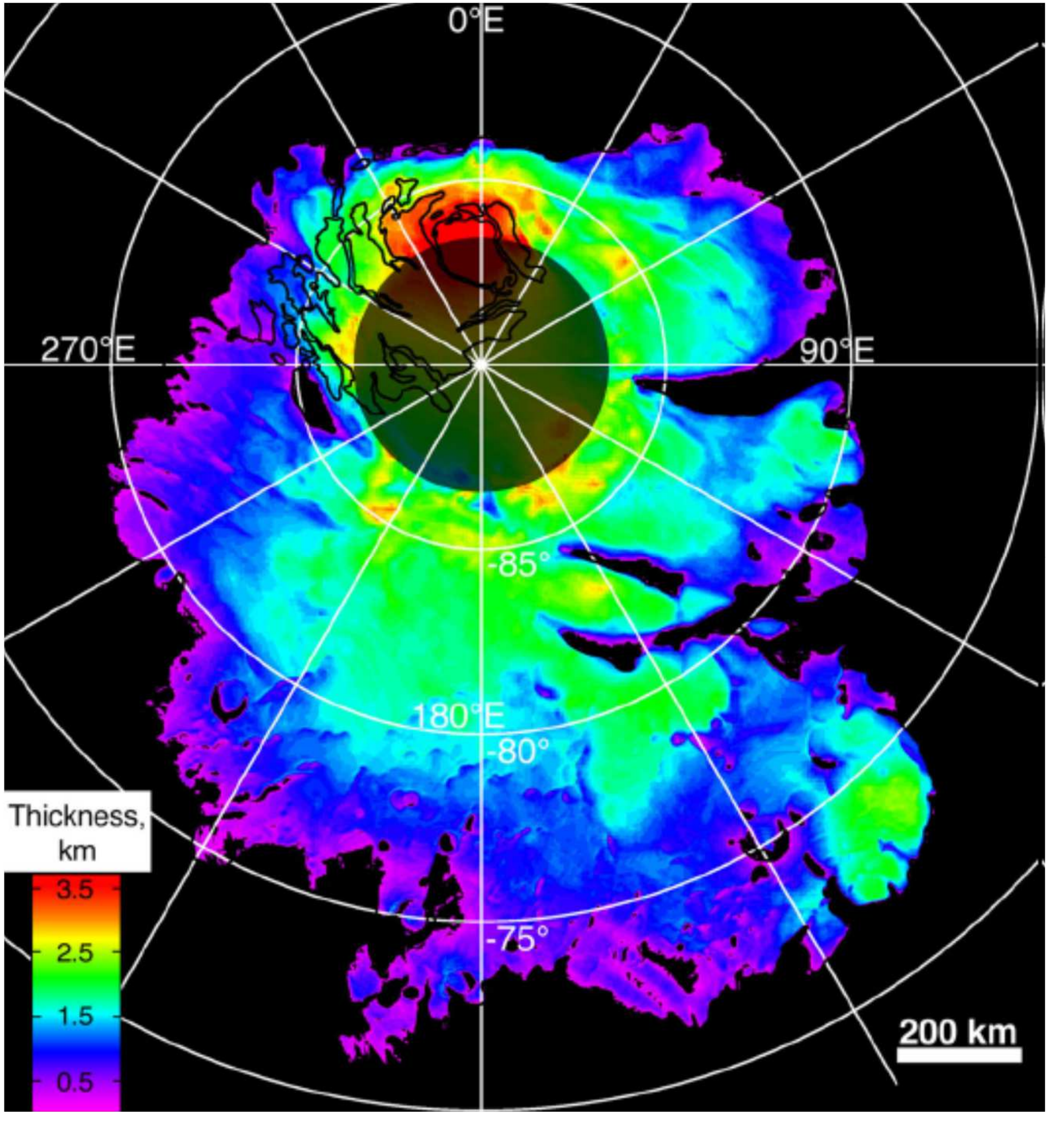




Map of Mars South Polar Layered Deposit

Bedrock detection (MARSIS)

- Maximum thickness: 3700 m
- Volume: 1.6 10^6 km^3
- Equivalent water level: 11 m

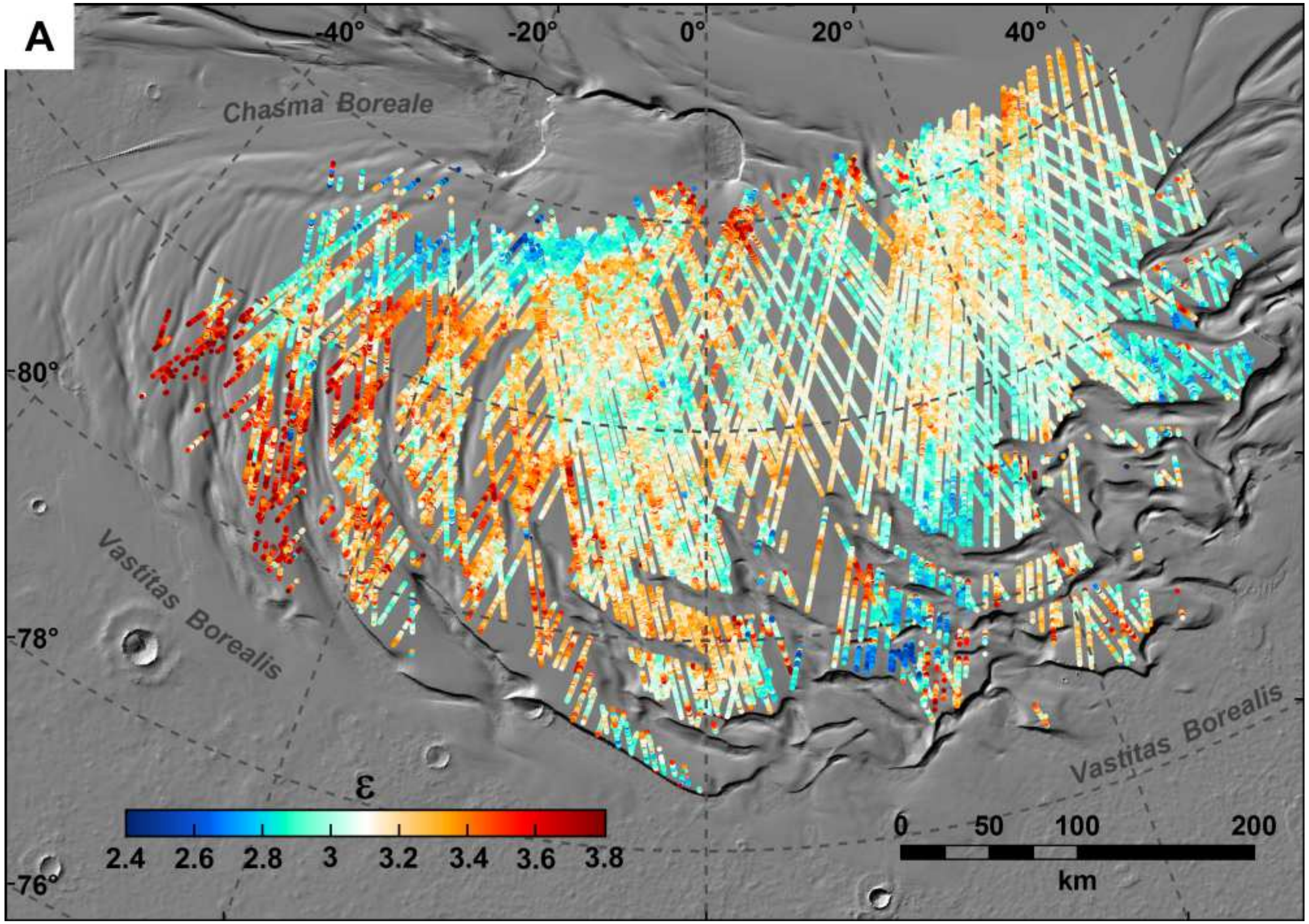


Plaut *et al., 2007, Science*

Dielectric mapping of Mars North Polar Layered Deposit with SHARAD

$\varepsilon = 3.10$ ($\sigma = 0.12$)

$\tan \delta \leq 0.0015$ ($\sigma = 0.0005$)



- At Martian conditions:

$3.0 < \varepsilon < 3.2$

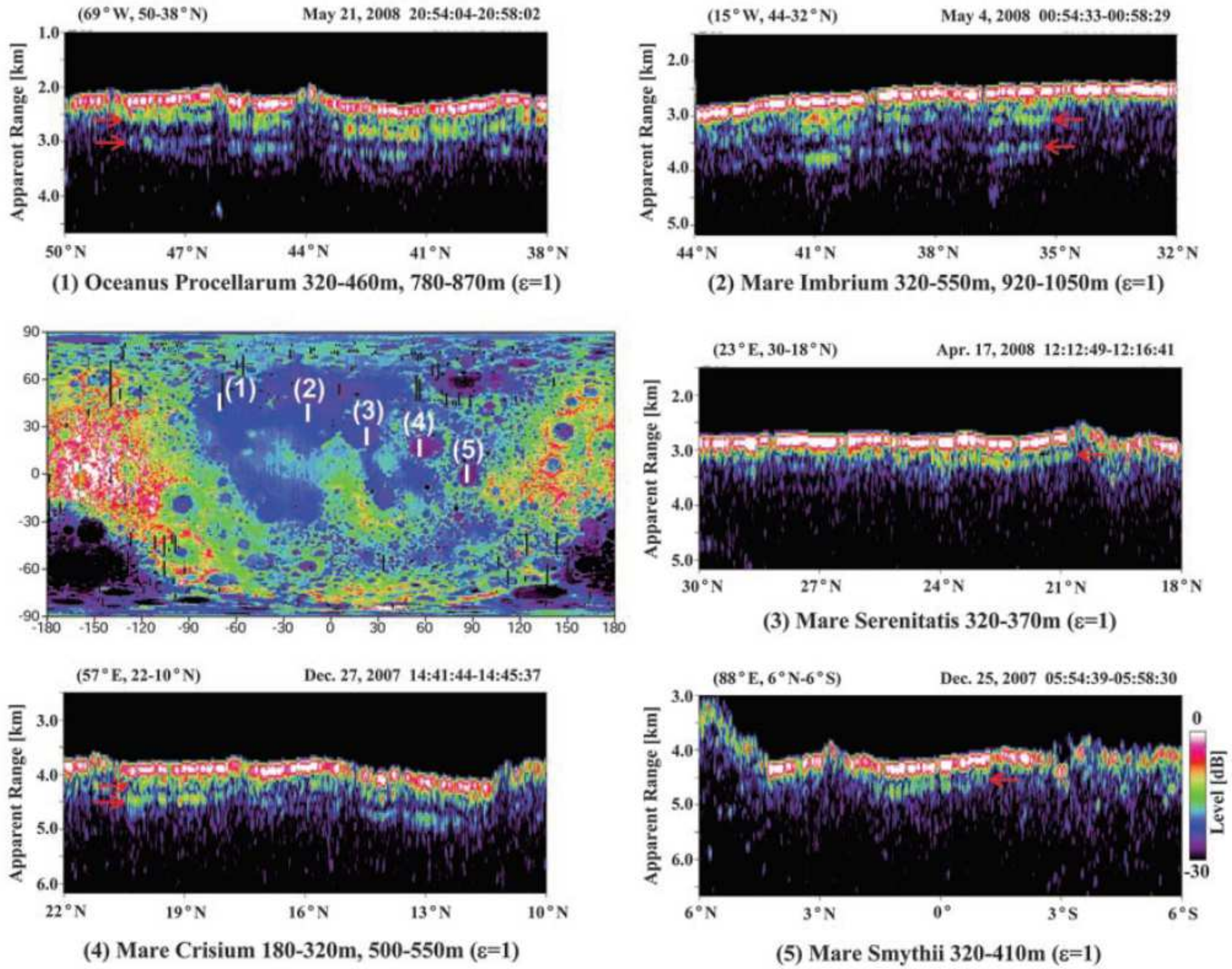
impurities ≤ 5% (Maxwell-Garnett)

- Impurities concentrated at margins

- No signature of basal melting

Grima *et al., GRL 2009*

LRS observations of subsurface layers on the Moon



Subsurface geology of the Moon:

Subsurface layers at several 100s m depth under nearside maria

- Burried regolith layers

- Tectonic quiescence between 3.55 & 2.84 By

Ono *et al., Science 2009*

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Tomography in transmission

Information on average composition

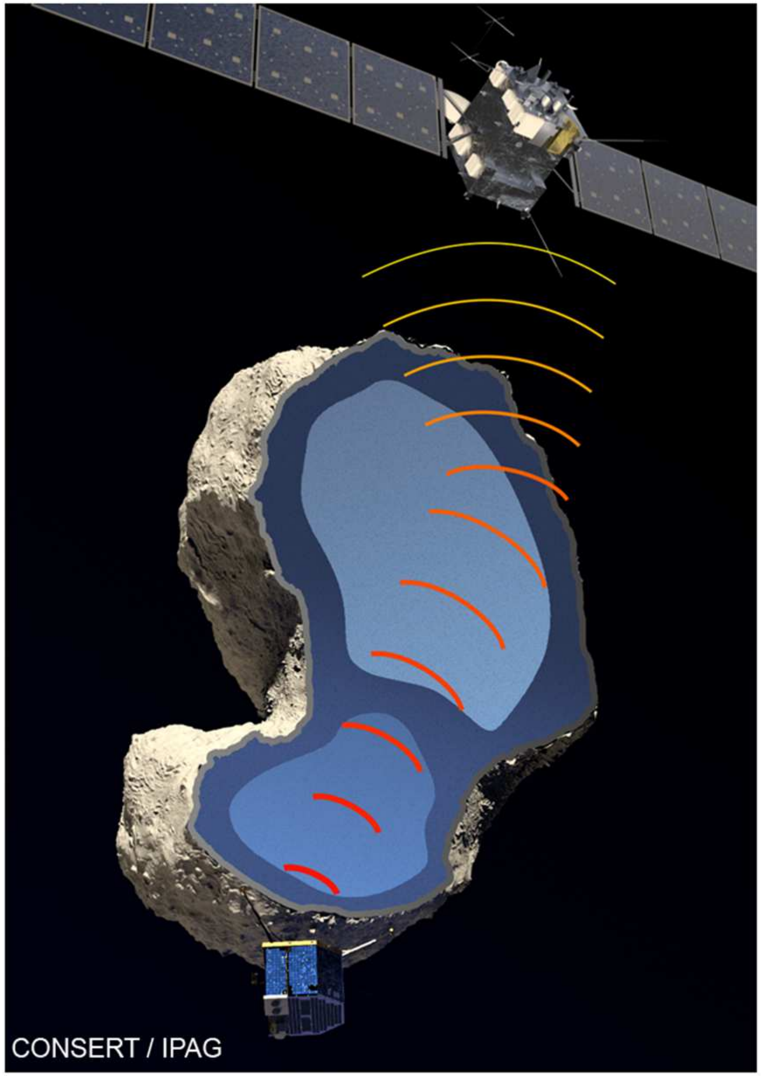
- Average Permittivity
- Absorption

Information on internal structure

- Variation of propagation delay
- Signal scattering

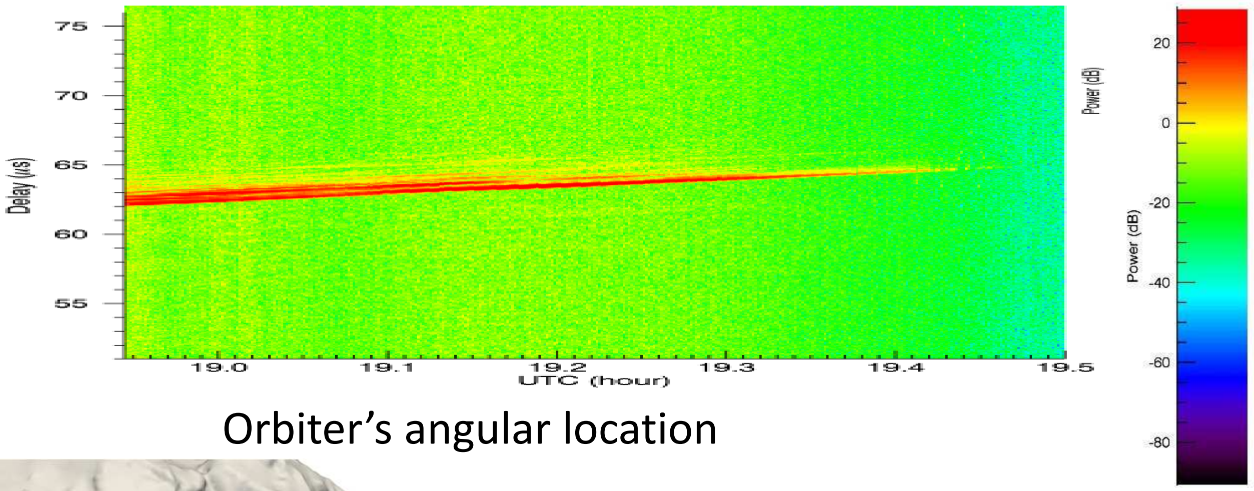
Statistical tomography

- Typical size
- Typical amplitude



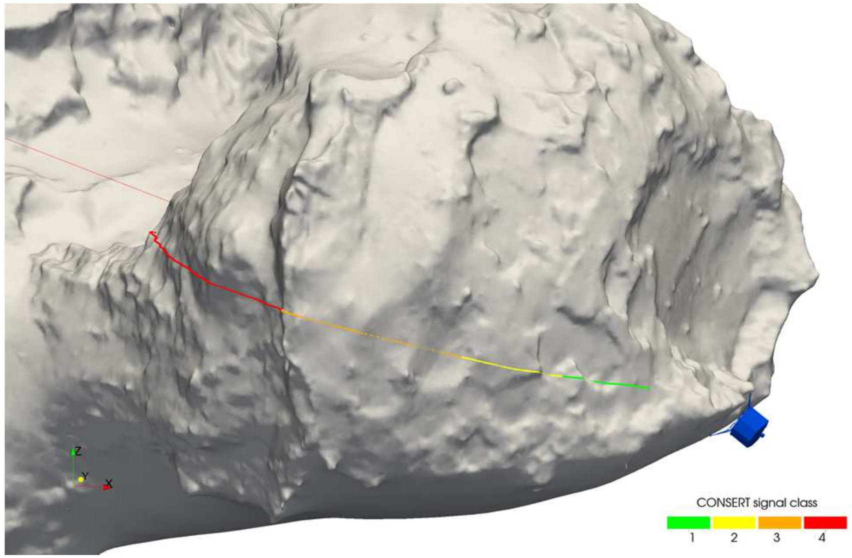
Consert Measurement nov 14

Propagation delay



Power (dB)

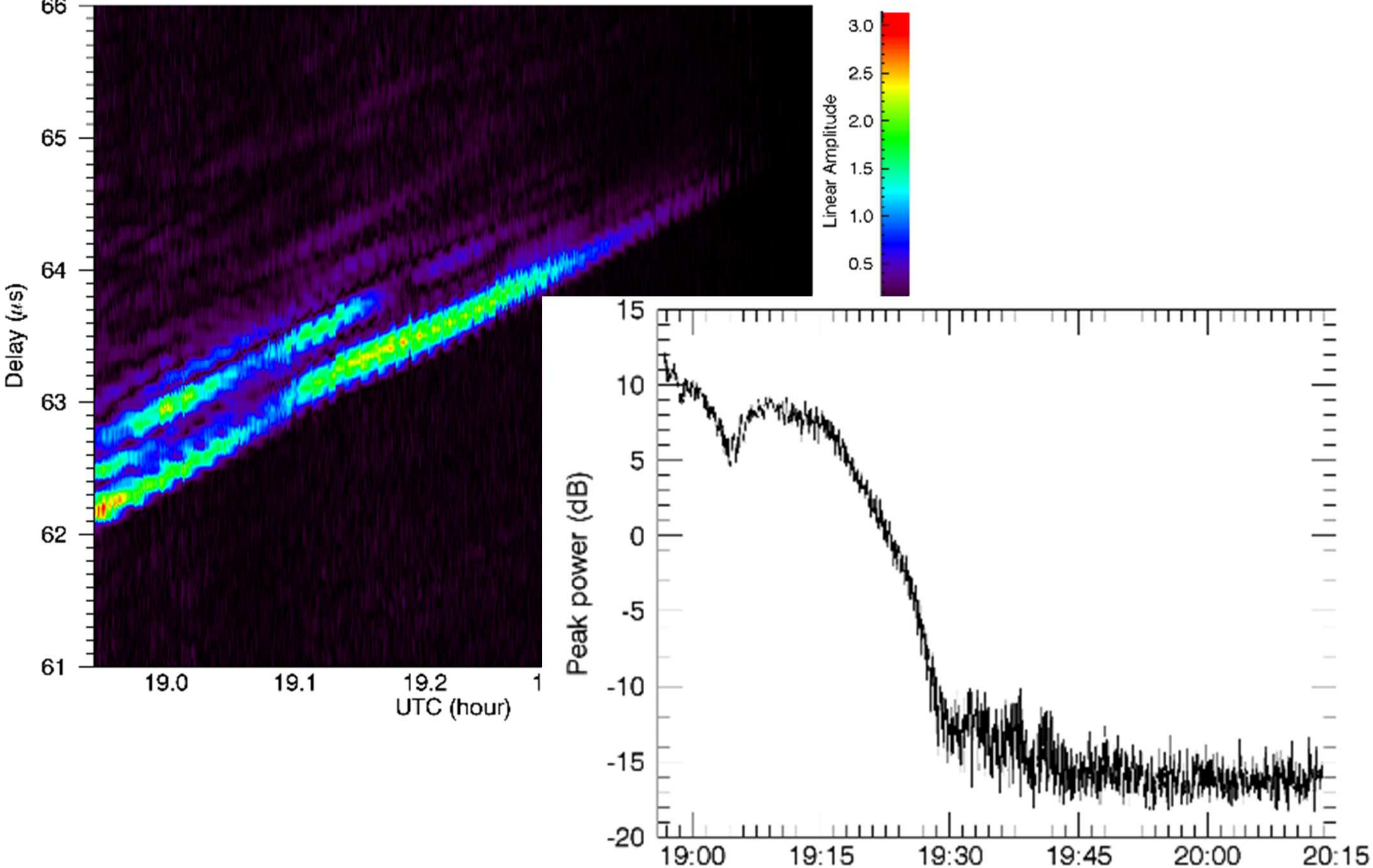
Orbiter's angular location



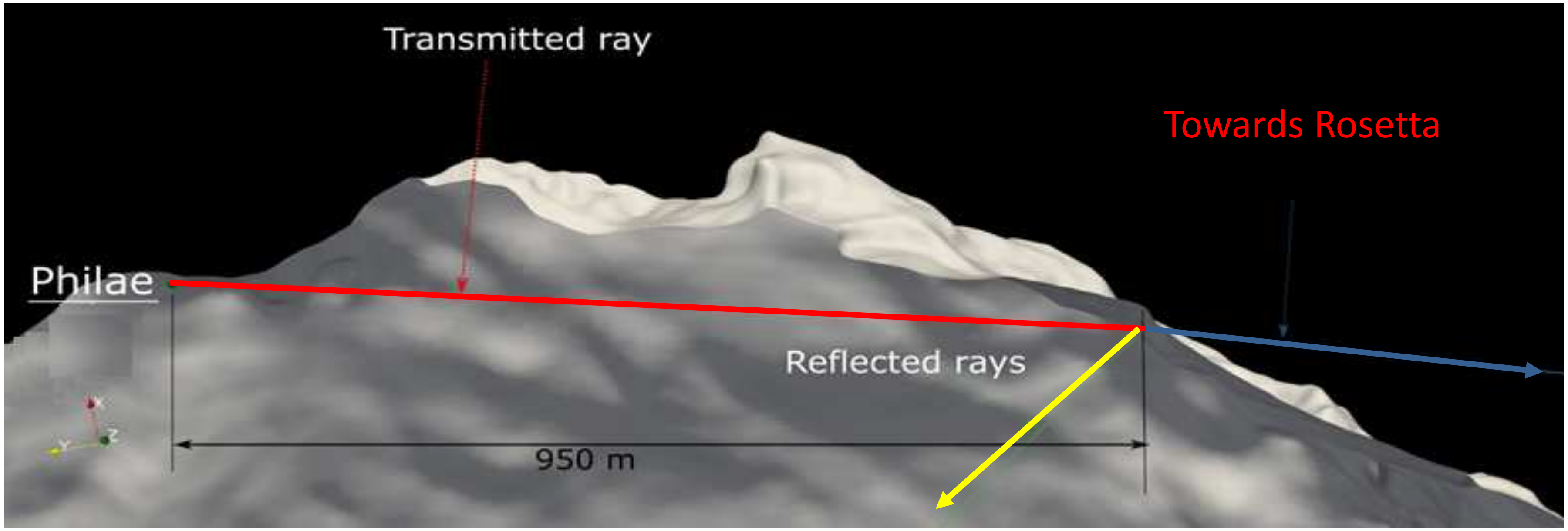
- Very limited coverage
  - No full tomography
  - Global characterization + Statistical Approach
  - Fit on direct problem

ESA/Rosetta/Consert/Philae/IPAG, LATMOS, MPS, CNES, DLR

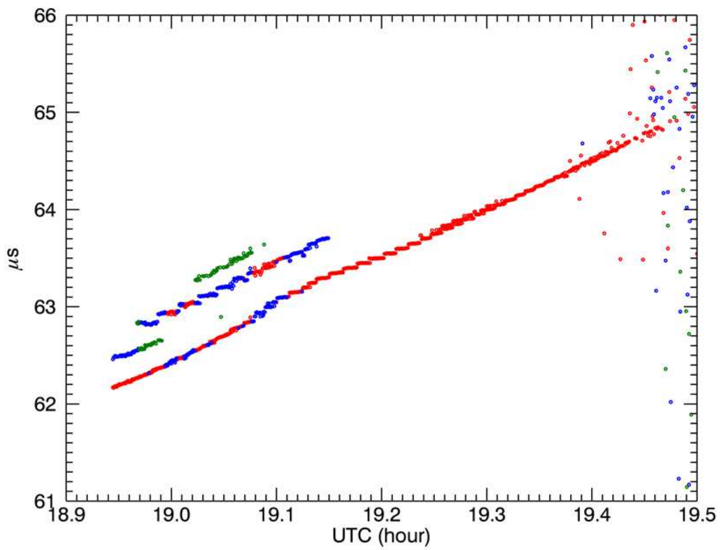
West of Abydos – Received signals

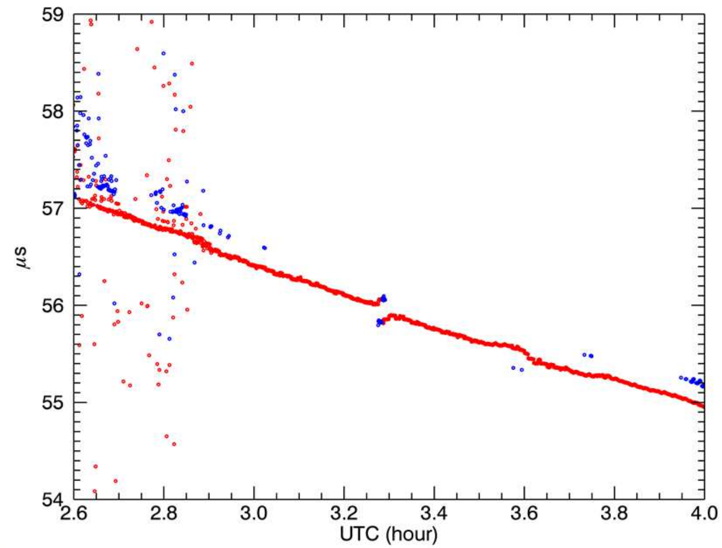


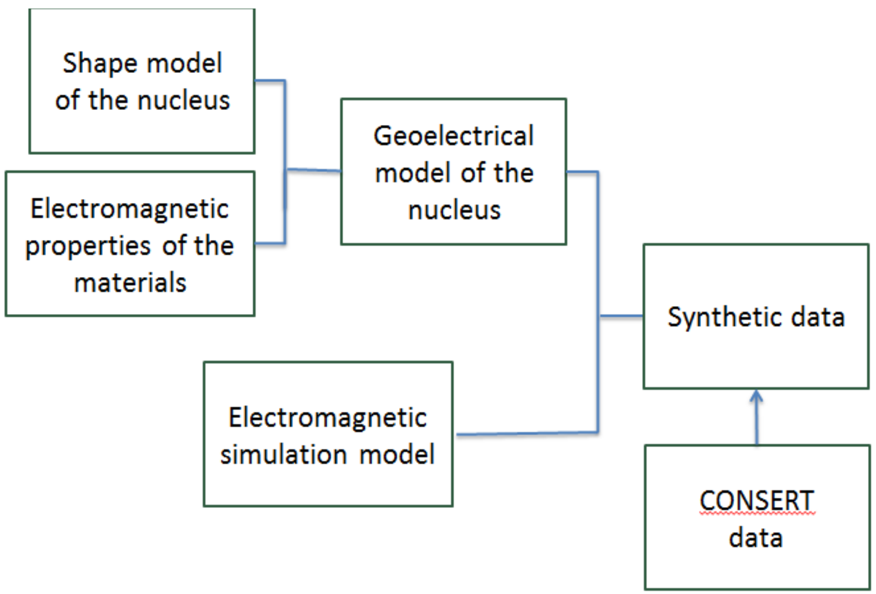
West of Abydos : distances inside

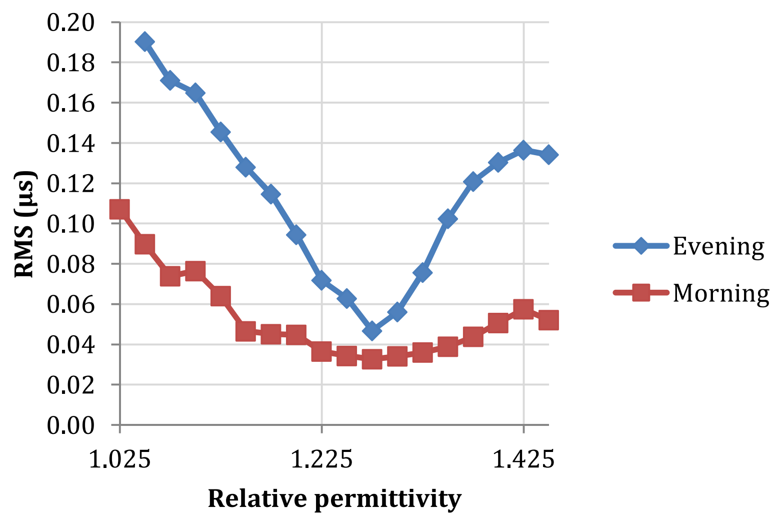


Permitivity = 1.27 ± 0.05



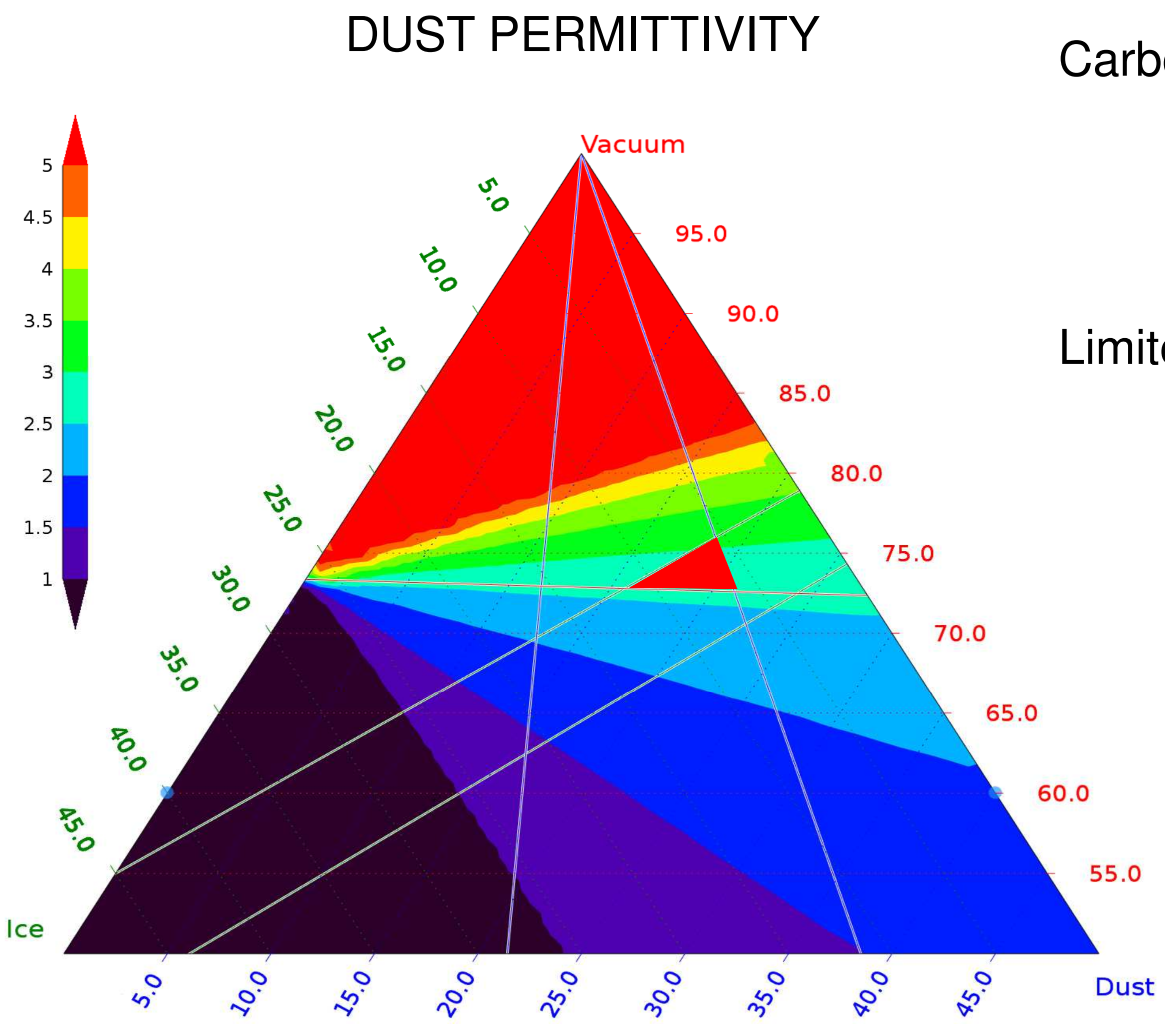






(Kofman et al., SCIENCE 2015)

Cosmochemical implication



Carbon with 25% silicates

Density = 2.3

Permittivity = 2.6

Limited range of volume fraction

porosity 73~82%

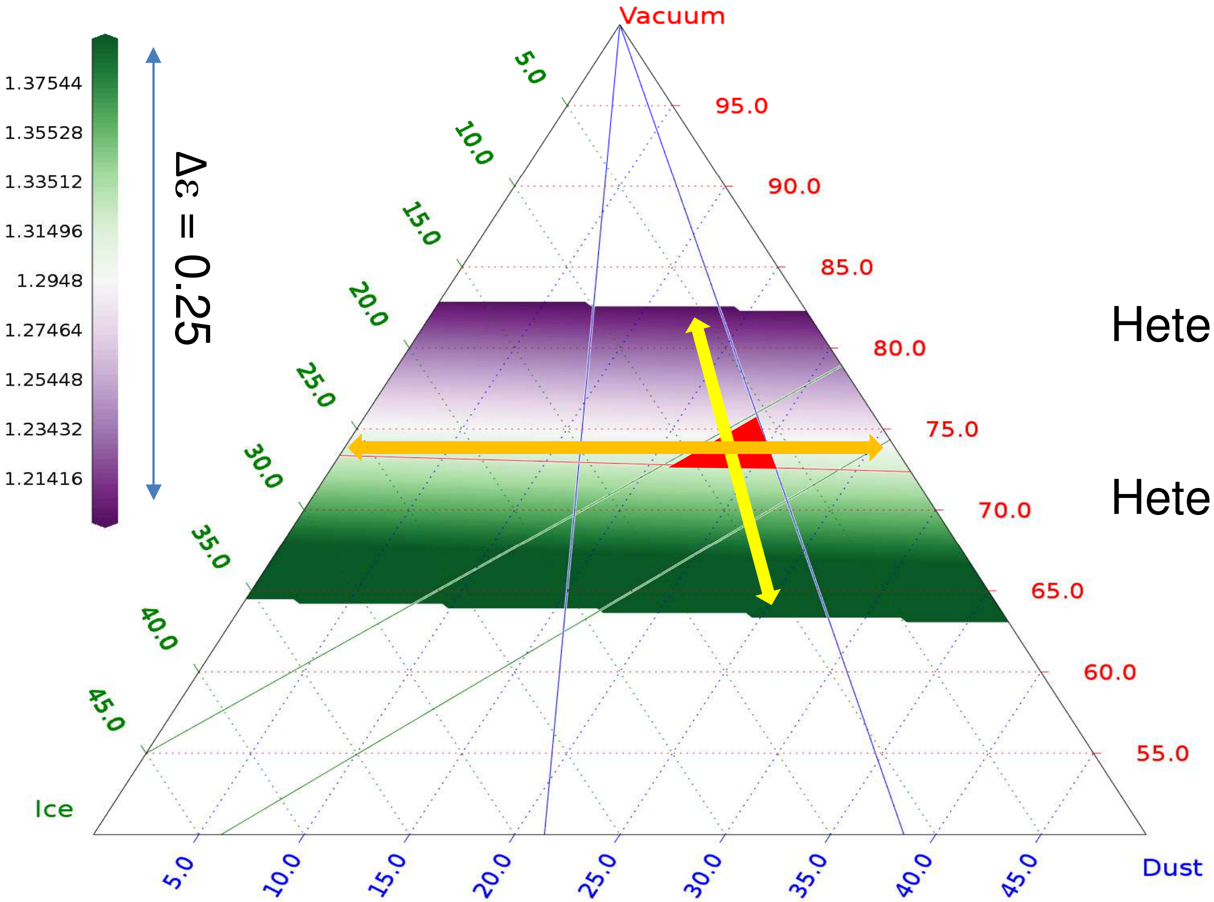
ice 5 ~12 %

dust 16 ~ 22%

(Herique et al., MNRAS, 2016)

How homogenous ?

COMET PERMITTIVITY



Effective permittivity

- Carbon with 25% silicates
- Ice mixture
- Porosity

Heterogeneity from porosity

- porosity ± 10points

Heterogeneity from D/I

- From pure porous ice to dry porous dust

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   – Sounding radars for small bodies
   – Orbiting imaging radar

Specificity of radar missions

Design very dependant on

- Medium (composition / structure)
- Acquisition geometry
- Repetition

<u>No standard system</u>

➔ Tradeoffs to be assessed for each mission and each body:

medium / penetration depth / resolution

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Internal structure of asteroids

- Sounding asteroids:

  Science

  – To validate and to improve our understanding of asteroids evolution from accretion to now

  – To improve models of low gravity mechanics

  Spacecraft interactions with asteroids

  – Planetary defense, Exploration, Sample return

Characterization of heterogeneities
from metric scale to global scale

MBC, Trojan and other icy bodies

- Understanding the origins of MBC, Trojan, …
  - Space weathered surfaces
  - Pristine material covered by dry regolith

- Sounding icy bodies
  - Origins: Rocky bodies vs icy bodies
  - Accretion : Deep interior structure
  - Evolution : Surface activation processes, layers

Internal structure : How ?

The radar is the instrument to characterize
the interior from metric scale to global scale

- **Deep Interior Radar : LFR / AIM**

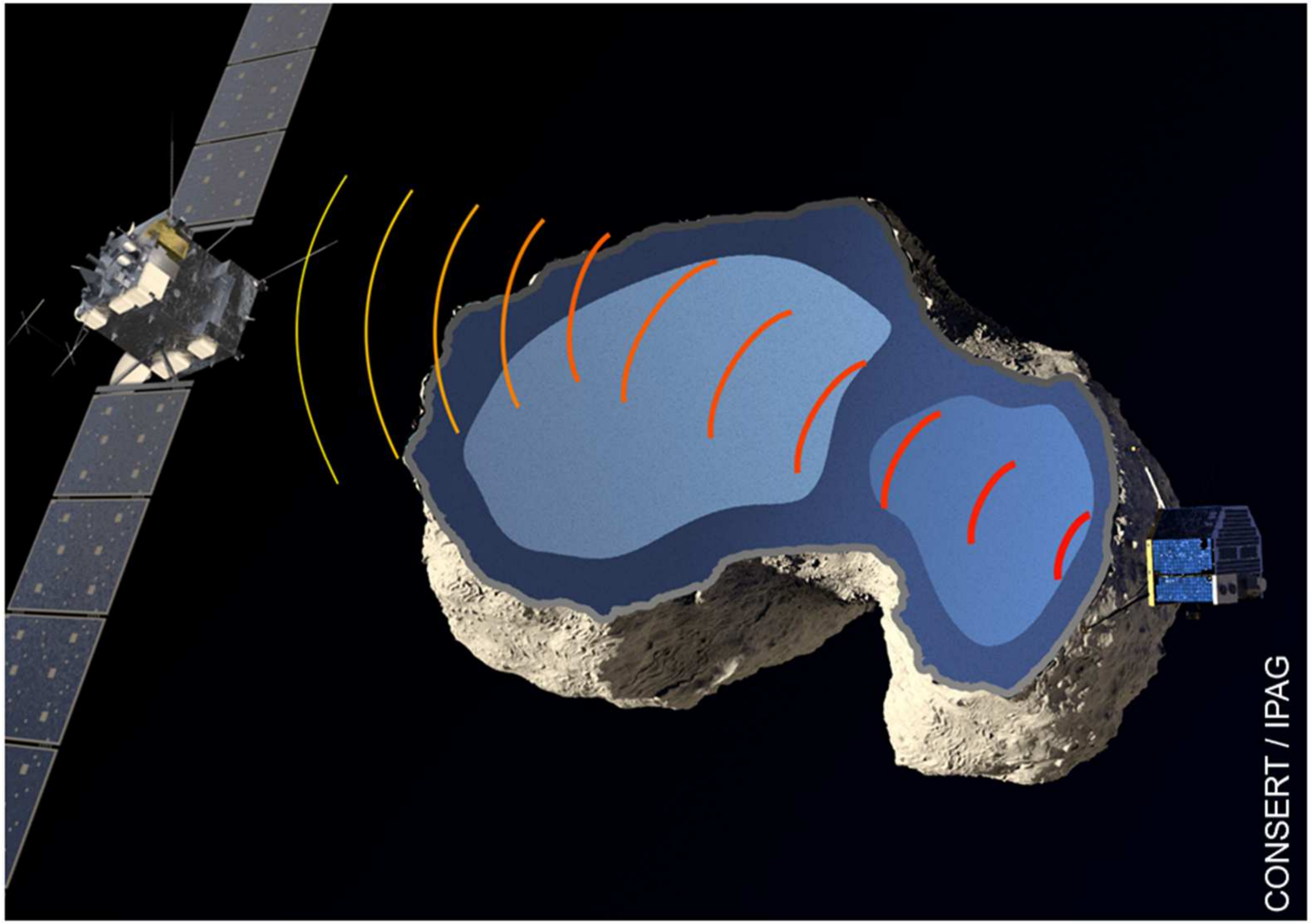
  A Low Frequency Radar to perform the tomography of the deep interior (structure, size of block and compositional heterogeneity)
  → Bistatic radar (Consert-like) with Mascot 2 on Didymoon, or Cubesat

- **Shallow Subsurface Radar : HFR / AIM**

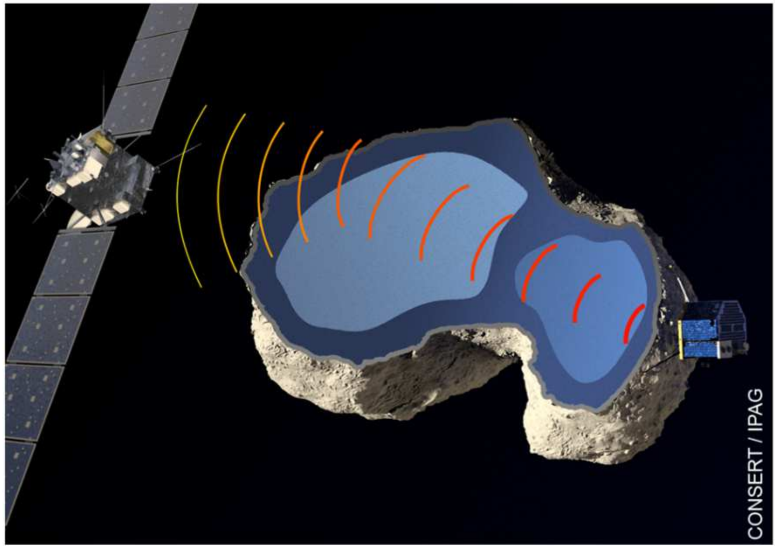
  A Higher Frequency Radar channel to fathom the regolith (depth and structure)

(Herique, ASR, 2017)

LFR : concept



LFR : Objectives

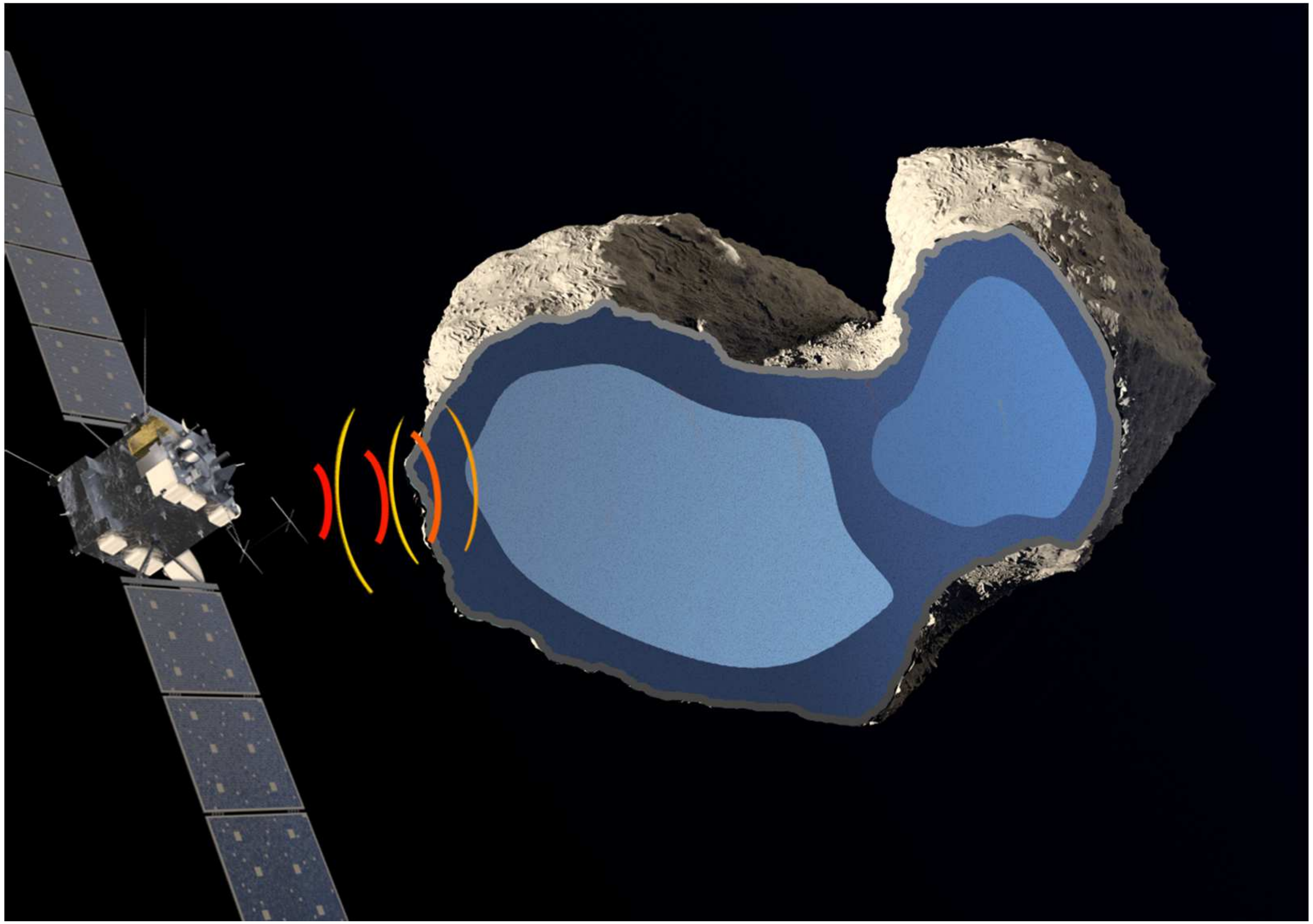


- **Global characterisation (one orbit)**
  Average permittivity → composition & porosity
  Average heterogeneity (few metres) → local variation
  Spatial variation of these average parameters (1 to a few orbits)
  Large structures & stratifications

- **Tomography (numerous orbits)**
  3D Tomography of the interior

- **Secondary objectives**
  Gravimetry & dynamic state (direct link Lander / Orbiter)

HFR : concept

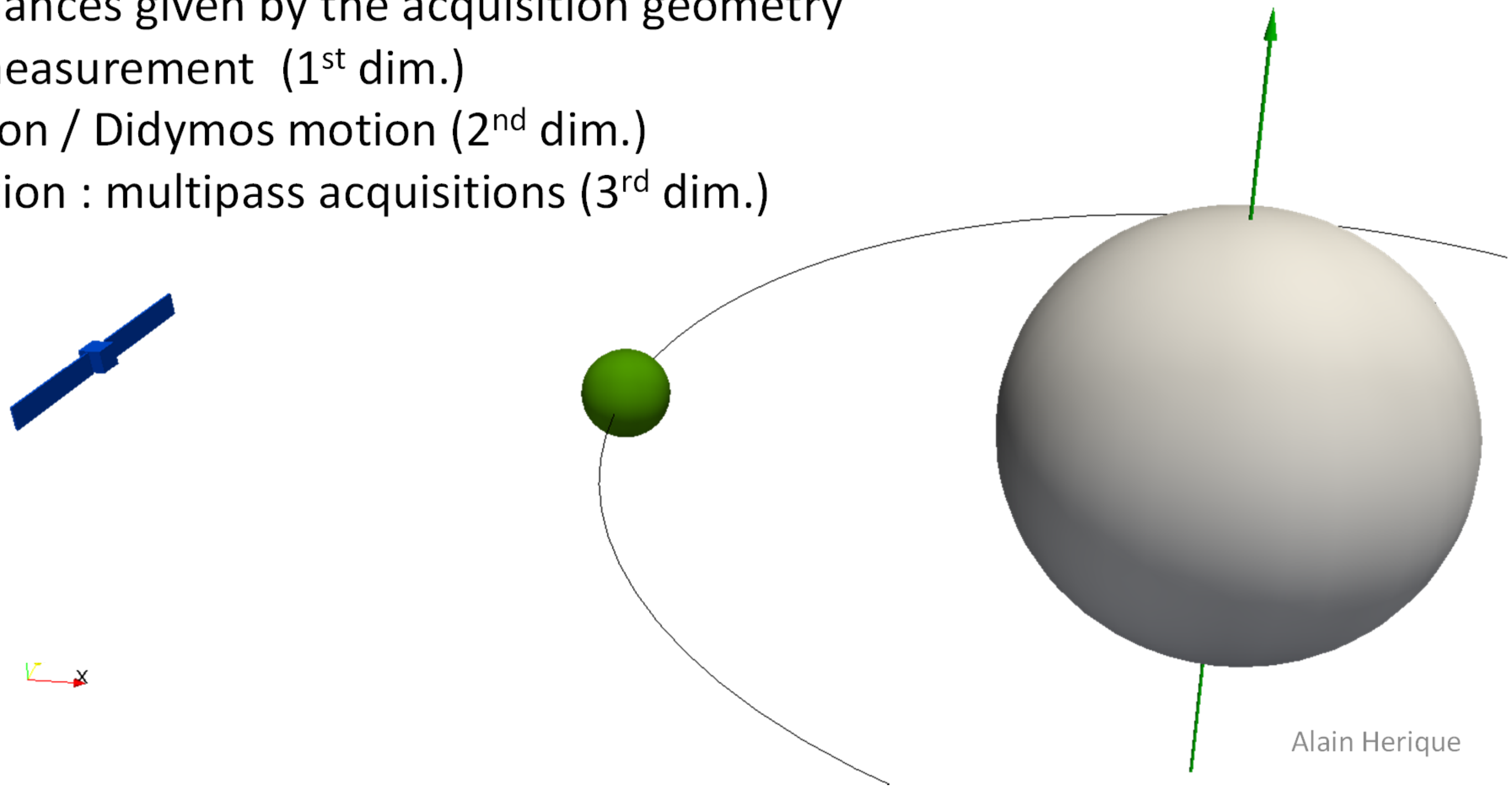


Alain Herique

HFR : Tomographic SAR

- Synthetic Aperture Radar 400 MHz - 3 GHz
- Mapping of the backscattering coefficient (power)
- Penetration depth: first tens of meters

- Performances given by the acquisition geometry
– range measurement (1st dim.)
– Didymoon / Didymos motion (2nd dim.)
– S/C motion : multipass acquisitions (3rd dim.)



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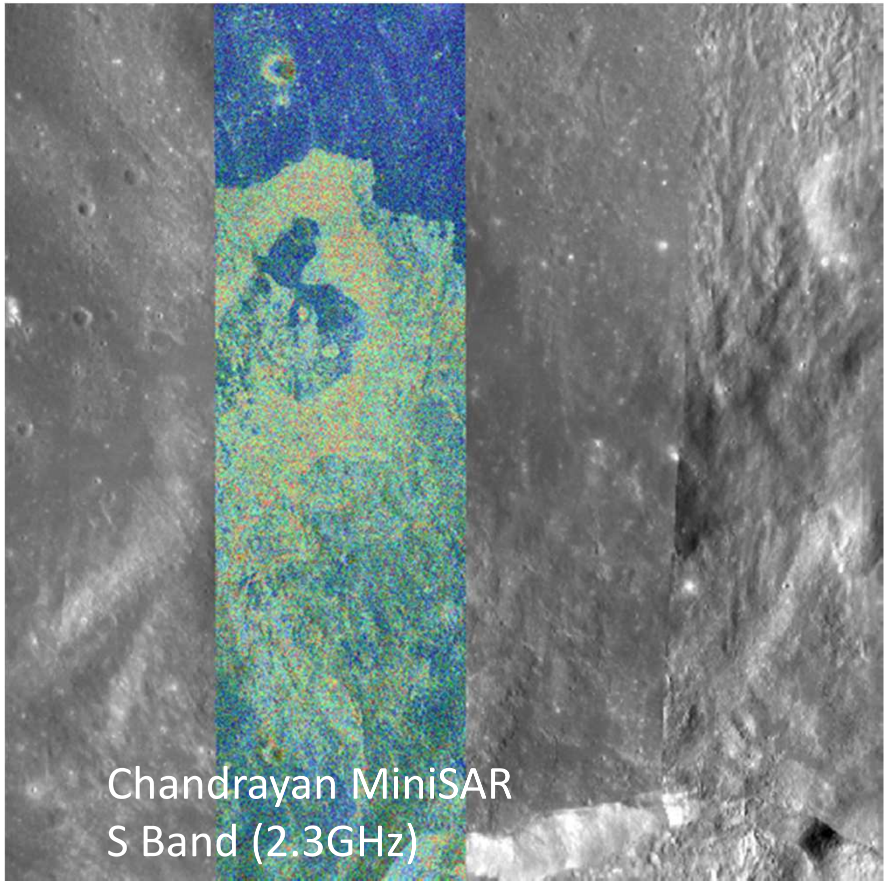
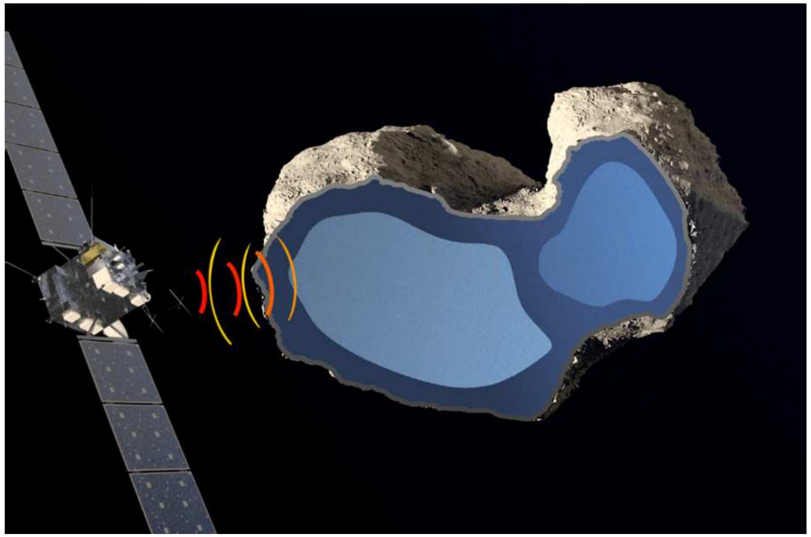
HFR : regolith

1 pass
- 2D mapping
- including surface and subsurface
- 2 Polarizations

~20 passes
- 3D tomography
- Resolution ~1 m
- Sensitivity -40 dB.m^2/m^2
- Dynamic range -20 dB



HFR : Objectives



- **2D Cartography (one orbit)**
  3D Tomography (20 acquisitions)

  Detection of structures close to the surface (20 m in rocks → 100 m in ices)
  Stratigraphy, cavities, structures linked to activity
  Regolith diversity, stratigraphic connection of units

- **Interferometry**

  Shape model (vertical resolution ~ λ / 10)
  Temporal evolution (re-deposition, mobility)

- **Secondary objectives**

  Gravimetry & dynamic state (direct link Orbiter/surface)

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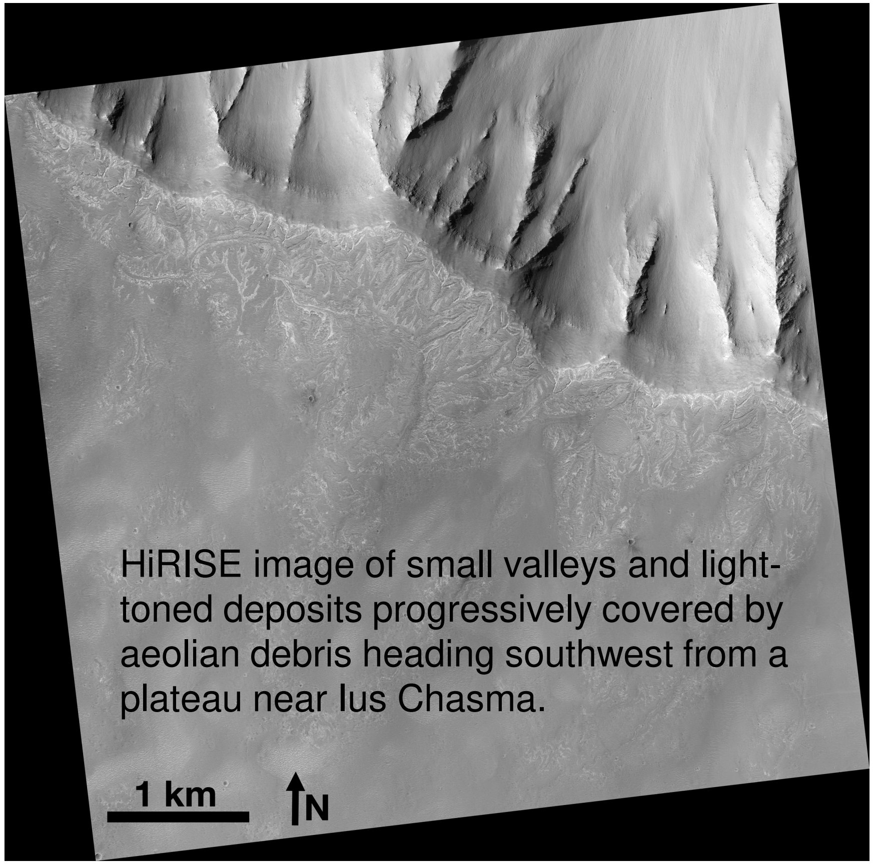
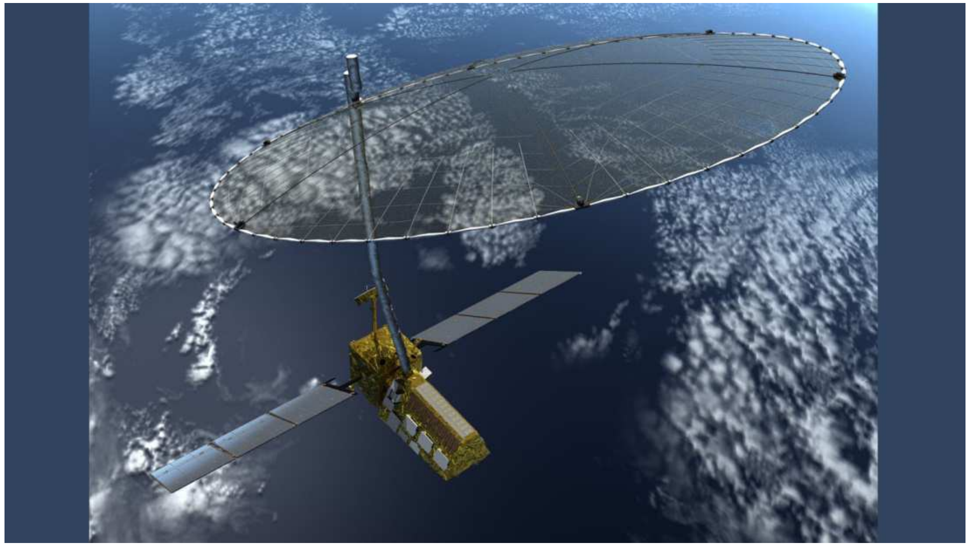
Orbital Radar for Mars



HiRISE image of small valleys and light-toned deposits progressively covered by aeolian debris heading southwest from a plateau near Ius Chasma.

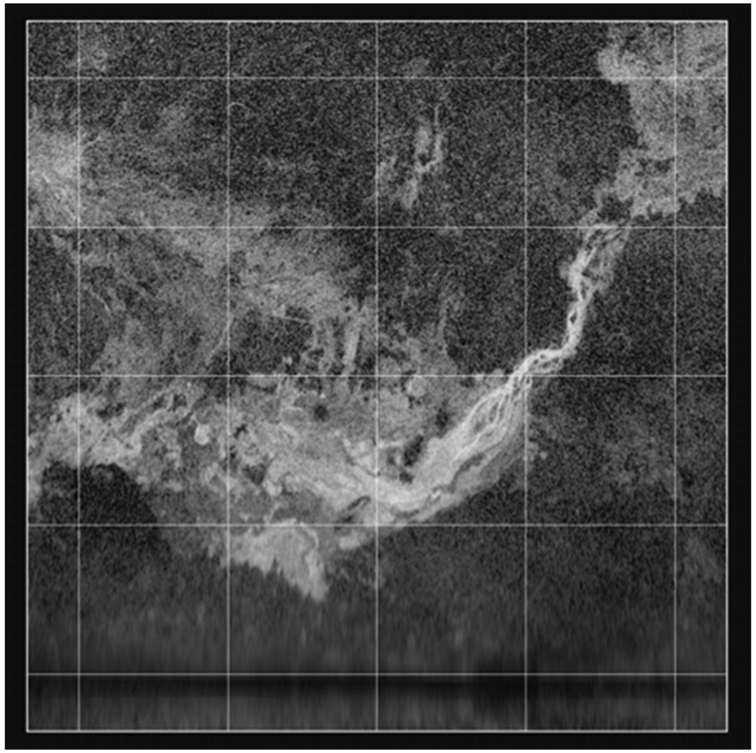


Deployable mesh antenna makes long-wavelength SAR possible for Mars

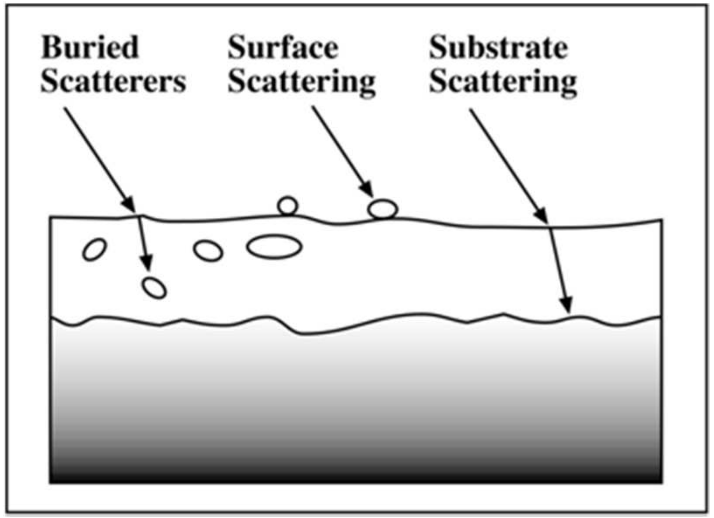
- The shallow subsurface of Mars contains clues to geologic and climate processes that cannot be fully understood through VIS-IR images, no matter how fine their resolution.
- These clues are recorded by:
  - The morphology of bedrock and the occurrence of ice lenses beneath layers of fine material.
  - The physical character (rock abundance and loss properties) of deep regolith or mantling layers.
  - The detailed layering and spatial variability in dust loading of the polar caps.
- Imaging radar at 30-60 cm wavelength, with penetration measured in meters and sensitivity to decimeter-scale roughness and rocks, is the ideal tool for characterizing the near-surface environment on a global scale.

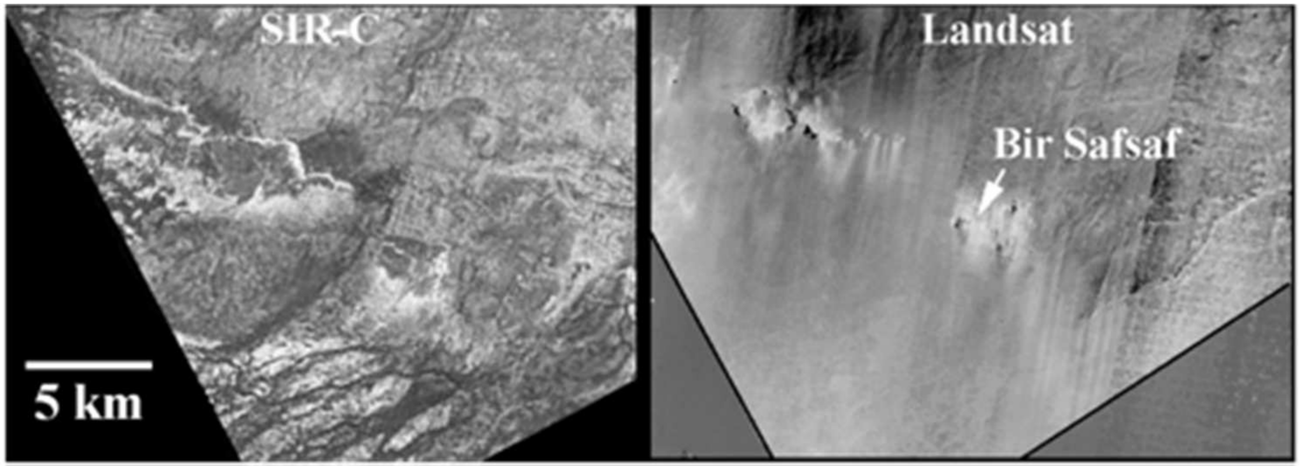
Bruce Campbell, Smithsonian Institution

Mapping The Hidden Past - Buried Bedrock



Earth-based 13-cm imaging radar showing bright echoes from lava flows in Elysium Planitia buried by 2 m or more of debris (Harmon and Nolan, 2007).

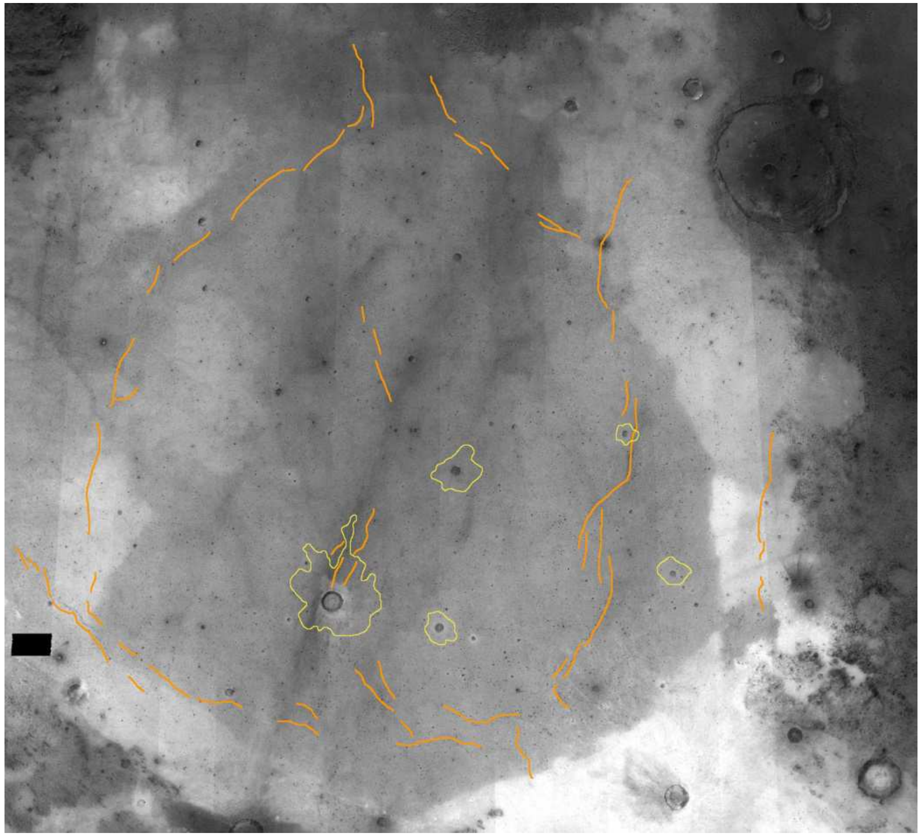




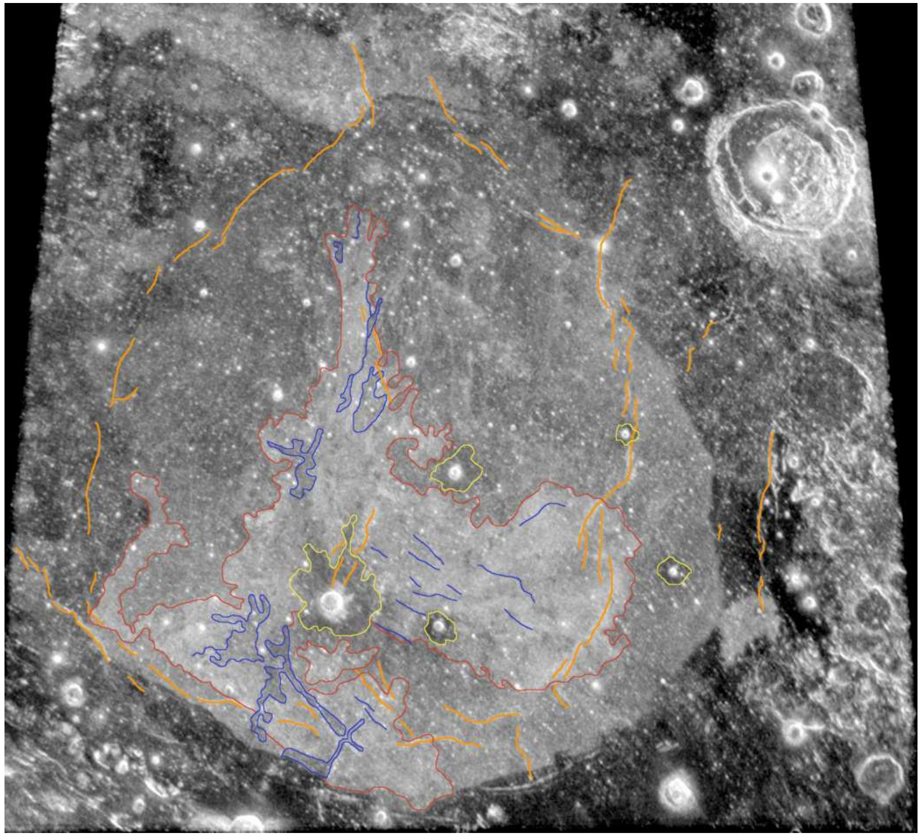
The “radar rivers” of the Sahara, detected due to differences in scattering from buried rough bedrock and sand-filled channels.

Bruce Campbell, Smithsonian Institution

An Example from the Moon



Clementine UV-VIS derived map of TiO_2 content in Serenitatis mare units.



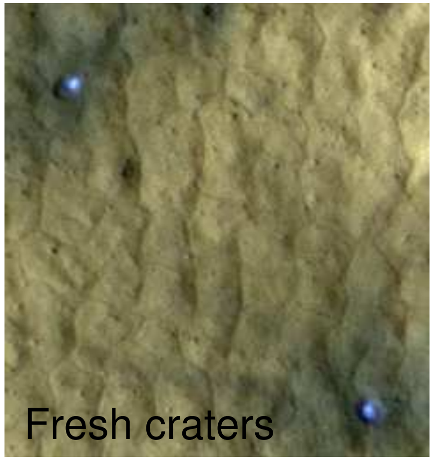
70-cm wavelength radar backscatter image of Mare Serenitatis.

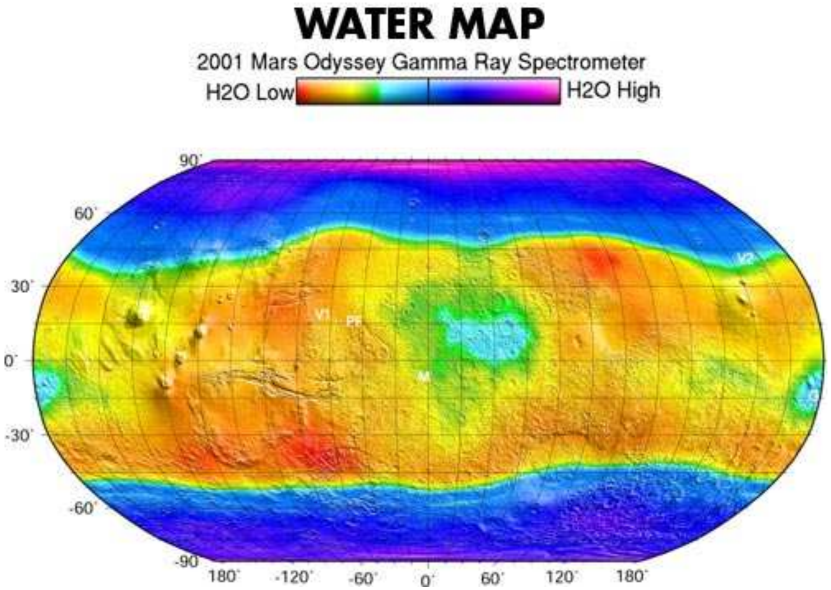
Rugged plates or rubble at the base of the lunar regolith help to reveal very subtle changes in the chemistry of the overlying basalts - unseen flow patterns emerge.

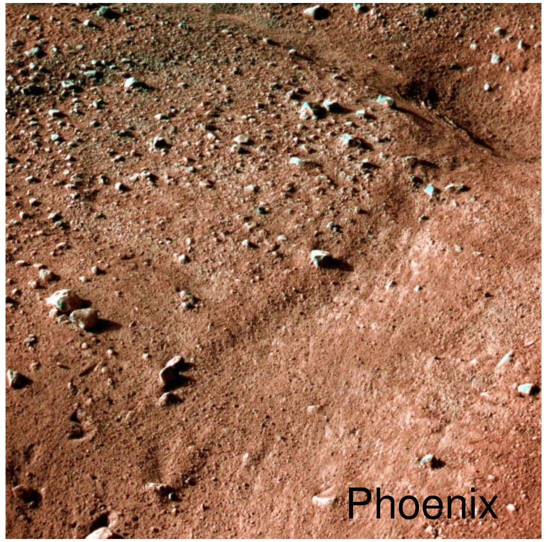
Similar data for Mars will unveil vast areas mantled by meters of dust.

Bruce Campbell, Smithsonian Institution

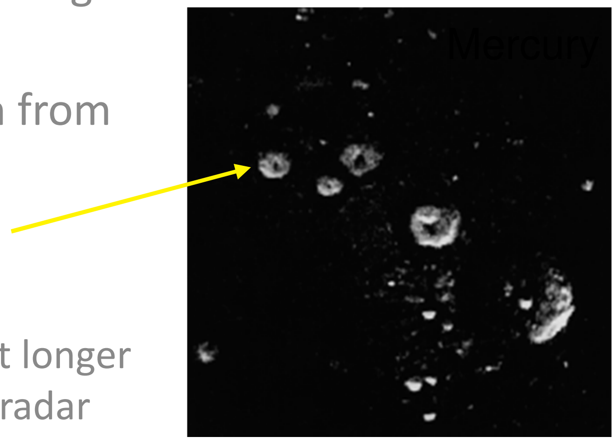
Shallow Ground Ice







- Ground ice clearly exists near the surface across much of the high-latitude region.
- Radar echoes from "clean" ice layers will very different than from deep weathered soil.
    - Clean ice with cracks can be exceptionally radar-bright.
    - Requires ice to be thick with respect to wavelength (1-3 m)
    - Circular polarization ratio a better discriminator of thick ice at longer wavelengths, where small rocks do not dominate the diffuse radar return.



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