RIME: Radar for Icy Moon Exploration

L. Bruzzone[1], J. J. Plaut[2], G. Alberti[3], D.D. Blankenship[4], F. Bovolo[5], B.A. Campbell[6], W. Kofman[7], G. Komatsu[8], W. Mckinnon[9], G. Mitri[10], C. Notarnicola[11], R. Orosei[10], G.W. Patterson[12], E. Pettinelli[13], D. Plettmeier[14], R. Seu[15]

[1]University of Trento, Trento, Italy; [2]Jet Propulsion Laboratory, CALTECH, USA; [3]C.O.R.I.S.T.A., Naples, Italy; [4]University of Texas at Austin, Austin, USA;
[5]Fondazione Bruno Kessler (FBK), Trento, Italy; [6]Smithsonian Institution, Washington DC, USA; [7]Laboratoire de Planetologie de Grenoble CNRS/UJF, Grenoble, France; [8]Università "G. d'Annunzio", Pescara, Italy;
[9]Washington University in St. Louis, Saint Louis, USA; [10]INAF, Rome, Italy; [11]European Academy of Bolzano, Bolzano, Italy; [12]Johns Hopkins University, Laurel, USA; [13]University Roma Tre, Rome, Italy;
[15]Technical University of Dresden, Dresden, Germany; [15]University of Roma "La Sapienza", Rome, Italy.

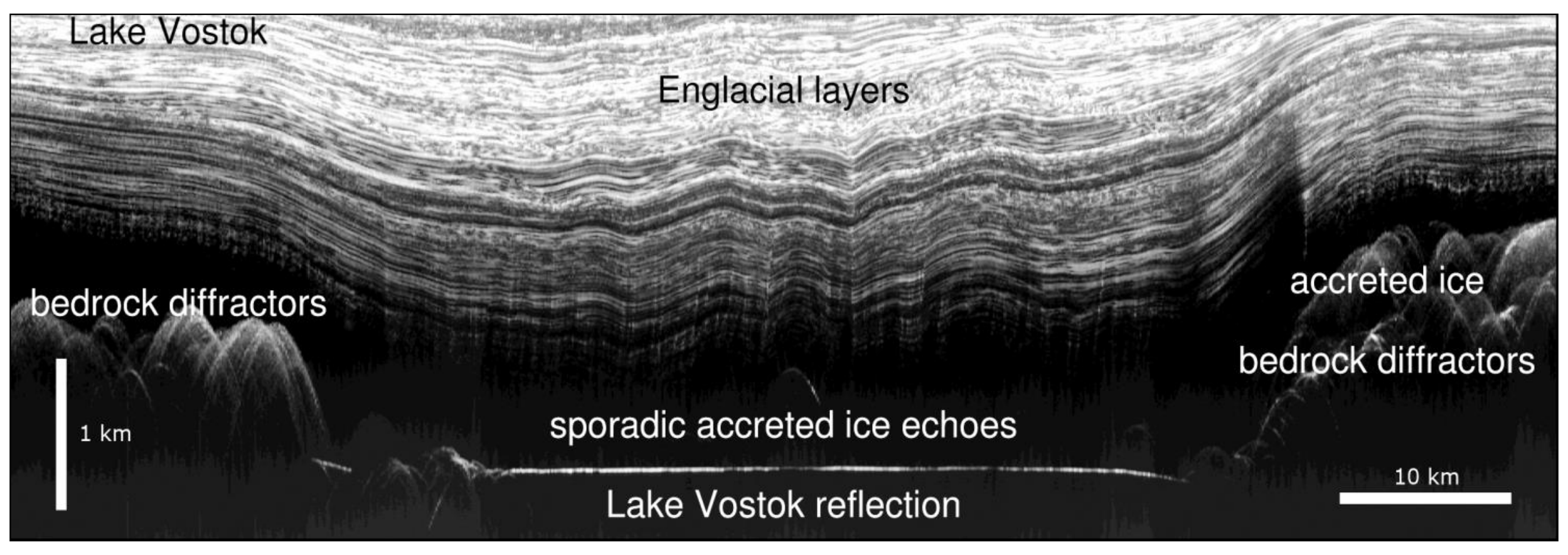
Corresponding author: *lorenzo.bruzzone@ing.unitn.it*

1. Introduction

In May 2012 the European Space Agency approved the JUpiter ICy moons Explorer (JUICE) mission. This is the first Large-class mission chosen as part of the ESA's Cosmic Vision 2015-2025 programme. JUICE is aimed to study Jupiter and to investigate the potentially habitable zones in the Galilean icy satellites: Ganymede, Europa and Callisto.
One of the most important sets of science goals for JUICE is related to the study of the subsurface geology and geophysics of icy moons and to detect possible subsurface water [1]. According to these goals, the Radar for Icy Moon Exploration (RIME) instrument has been selected as a payload for the mission. RIME is a radar sounder optimized for the penetration of the Galilean icy moons, Ganymede, Europa and Callisto, up to a depth of 9 km. This is an active instrument which transmits relatively low frequency radio waves with the unique capability to penetrate deeply into the subsurface.

2. Radar sounder measurements in icy bodies

Radar sounders are nadir-looking active instruments which transmit radio waves with the capability to penetrate deeply into the subsurface. When these radio waves travel through the subsurface, their reflected signal varies as they interact with subsurface horizons and structures with differing dielectric constants. These varying reflections are detected and used to create a depth image of the subsurface. Because of the high transparency of ice at radar frequencies, sounders have proven to be an extraordinary tool for characterizing internal structures of ice sheets and glaciers on Earth [2],[3],[4] and Mars [5],[6]. While pure water ice is transparent at radar wavelengths, contaminants can increase the opacity of the ice. The thermal state and resulting temperature profile of the ice also affect opacity; radar attenuation in ice decreases exponentially with lower temperatures. The figure below shows an example of radargram obtained with an airborne radar sounder used to detect and characterize Lake Vostok 4.5 km beneath the Antarctic ice sheet.



Radargram of the reflected echo power showing the liquid surface of Lake Vostok, Antarctica. The lake surface appears as a strong horizontal reflector. Data were acquired with the airborne 60 MHz University of Texas Institute of Geophysics HiCARS radar [7].

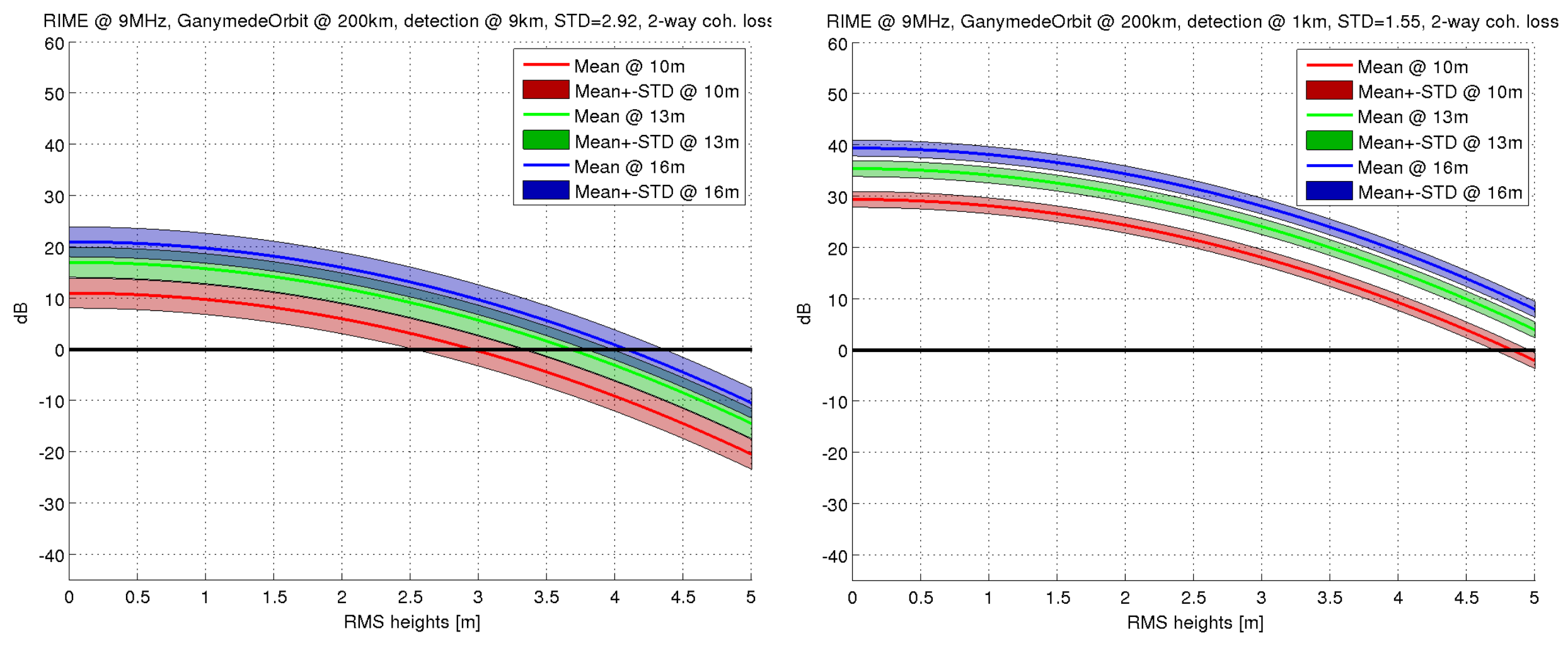
5. Selection of the central frequency

RIME will operate in a single frequency band, centered at 9 MHz, with a chirp pulse having maximum nominal bandwidth of 3 MHz. The frequency was selected as the result of extensive studies of penetration capabilities, surface roughness of the moons, Jovian radio noise, antenna accommodation, and system design. To first order, compared to a higher frequency, a lower frequency will penetrate deeper, be less susceptible to rough surface scattering, and require a longer antenna. However, when the disk of Jupiter is not hidden by the target (e.g., Ganymede), radio noise from the planet will be detected by the radar receiver, compromising the Signal-to-Noise Ratio (SNR) value; this effect is much more pronounced at frequencies lower than about 40 MHz [9]. Thus there is no "perfect" operating frequency for a Galilean icy moon sounder. The frequency selection was necessarily a compromise to account for environmental, target and accommodation constraints. The 9 MHz frequency provides penetration capabilities and mitigation of surface scattering (which can cause signal loss and clutter issues), at the expense of mapping coverage, as it is likely to obtain high SNR observations only on the anti-Jovian side of the target moons.

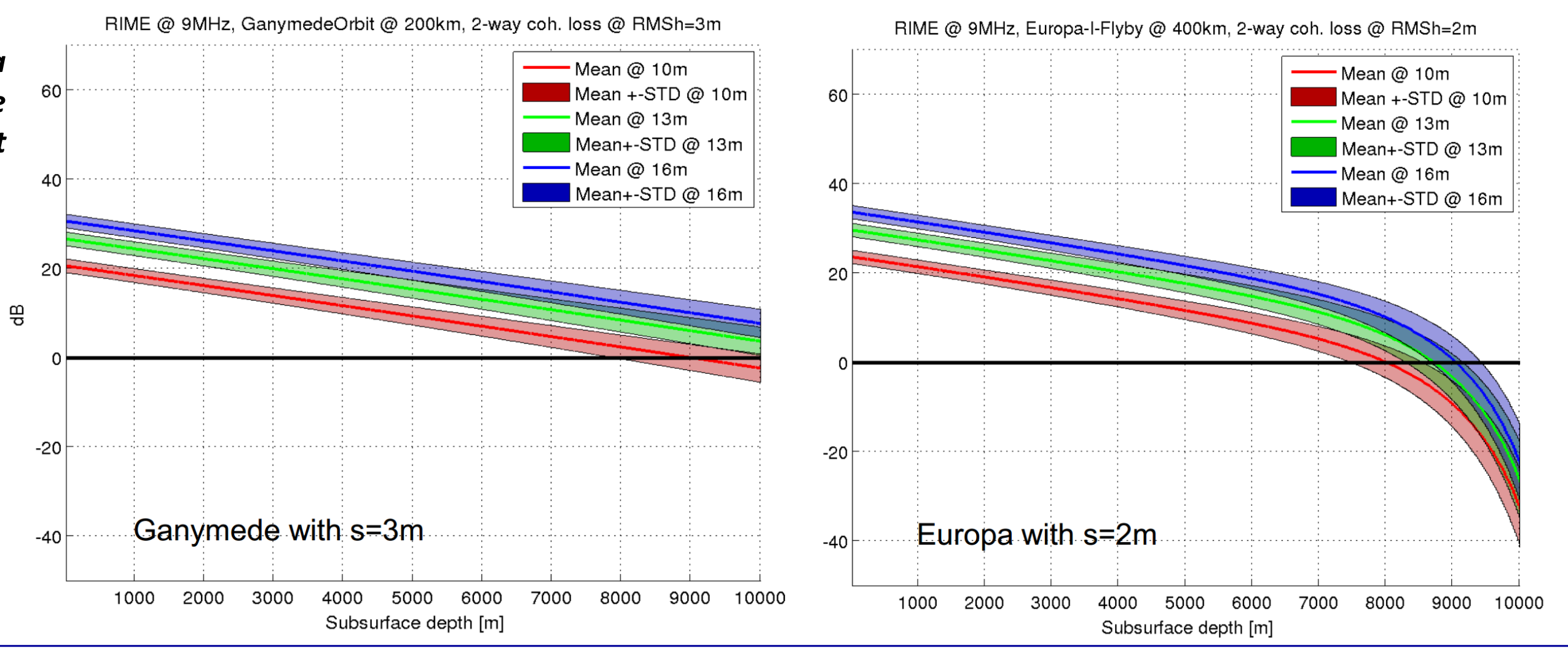
6. RIME performance study

The most common source of dielectric discontinuities that we expect to detect in the ice shells will likely be due to different contamination levels of the ice with soluble and insoluble impurities and brine. To demonstrate the capability of RIME to detect these subtle interfaces, as well as those caused by the presence of liquid water, we have developed parametric geo-electrical and structural models of Ganymede, Europa and Callisto subsurface. This allows us to assess the testability of various geological and geophysical hypotheses. The models have been employed to evaluate the RIME system performance in terms of its penetration depth capability, echo detectability and assessment of compositional signatures. A simple ray-propagation model accounts for transmission and reflection of the signal, both at the surface and at the subsurface interface, considering a large variety of mechanisms of signal loss, competition from surface clutter, galactic and Jovian noise, the system response and processing gain. The following figures shows the outcome of the performance study developed for RIME. Although 16 m represents the optimal antenna length, technical constraints related to S/C and the antenna design needed extensive performance studies considering also antenna lengths of 10 m and 13 m.

Total SNR for the different antenna lengths (10m, 13m, 16m) for Ganymede at 1 km depth versus the surface roughness.



Total SNR for the different antenna lengths (10m, 13m, 16m) versus the penetration depth for a constant value of the surface roughness.



3. RIME science goals

1. **Characterize Ganymede as a planetary object and possible habitat:** i) Characterize the ice shell; ii) Formation of surface features and search for past and present activity; iii) Global composition, distribution, evolution of surface materials.
2. **Explore Europa's recently active zones:** i) determine the composition of the non-ice material, especially as related to habitability; ii) Look for liquid water under the most active sites.
3. **Study Callisto as a remnant of the early Jovian system:** i) Characterize the outer shells, including the ocean; ii) Determine the composition of the non-ice material; iii) Study the past activity.

	Radar return	Cause	Example
Interface (water)	Strong radar return off of an interface below which there is no returned energy.	Interaction at an interface between layers with dramatically different dielectric properties.	Interaction with water layer or pocket larger than radar wavelength.
Interface (composition)	Partial reflection or change in signal strength; can result in single or multiple returns.	Varying dielectric properties in a thermally homogenous region.	Layers of soluble impurities or dust layer, e.g., from an impact event.
Interface (structure)	Partial reflection or change in signal strength; can result in single or multiple returns.	Varying dielectric properties due to crystal properties.	Crystal size or fabric contrast at a brittle-ductile transition over a convecting layer.
Offset	Radar returns off of two identical horizons vertically offset.	Geological offset of an otherwise continuous layer.	Compositionally distinct layer bisected by a normal fault.
Distributed Subsurface Scatterers	Isolated or diffuse returns.	Physical scattering of radar waves by structures or interfaces on RIME wavelength scales.	Fields of wavelength- scale, unconnected water pockets.
Absorption	Loss of signal strength; weak or no radar return below a given depth.	Propagation through a highly conductive dielectric medium.	Accreted marine (warm, salty) ice.

RIME subsurface observations with the expected radar return, the physical cause and an example [8].

4. Properties of the Ganymede sub-surface targets

The physical and electromagnetic modelling of the surface and sub-surface targets has been one of the main issues for the design of RIME. The main geologic classification of the surface of Ganymede is between dark and bright terrains:

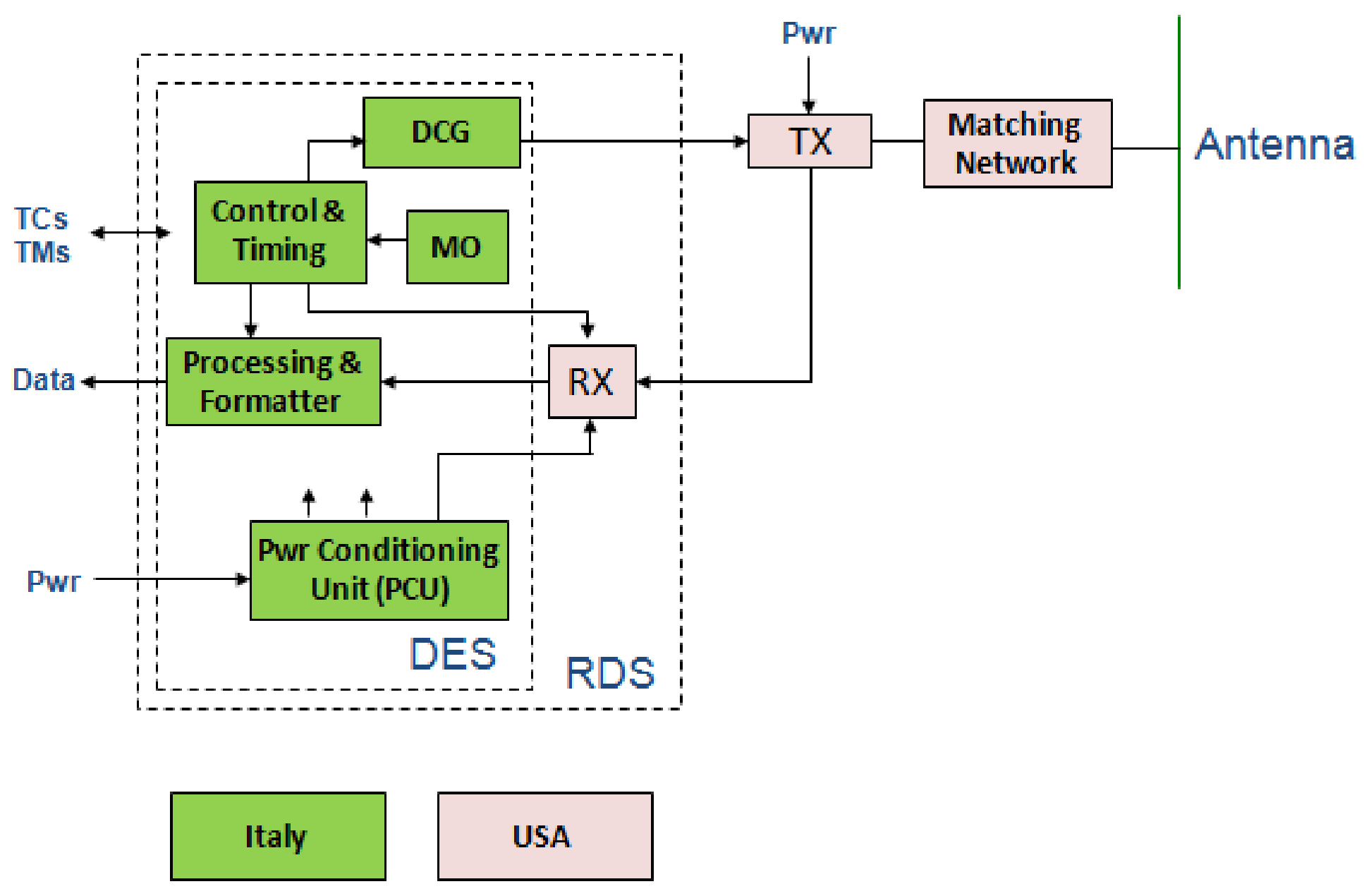
- **Dark terrain** covers about one third of the surface and is heavily cratered, suggesting a very ancient, if not primordial, origin.
- **Bright terrain** separates dark terrain into polygons, and contains both smooth bright surfaces and material with closely spaced parallel ridges and troughs (termed grooved), which are dominated by extensional tectonic features.

The Ganymede surface is more cratered and ancient than the Europa one. This is consistent with a much thicker outer shell of solid ice. There is ambiguous evidence for cryovolcanic processes modifying the surface of Ganymede.

7. RIME parameters and architecture

The RIME instrument has been designed on the basis of several years of studies. It will operate in a single frequency band, centered at 9 MHz, with a chirp pulse of up to 3 MHz bandwidth. The table below summarizes the main RIME parameters.

Transmitted central frequency (MHz)	9
Antenna type	Dipole
Optimal antenna length (m)	16
Peak radiated power (W)	10
Penetration depth (km)	As deep as 9
Chirp length (µs)	50 - 100
Vertical resolution in ice (m)	30 - 90
Cross-track resolution (km)	2 - 10
Along-track resolution (km)	0.3 - 1.0
Instrument modes	Off, Initialisation, Stand-by, Safe, Measurement
Operative modes	Calibration, Raw data, On-board processing



Block scheme of the RIME architecture.

8. Conclusions

RIME can address a large number of groundbreaking science goals related to the JUICE mission. It is the result of an accurate tradeoff study between the need to fulfill the mission scientific objectives, the technical constraints imposed by a low-resource outer Solar System mission such as JUICE, and the environment in which the instrument will operate. The current studies confirm that RIME can reach all the expected science goals.

9. References

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