RIME: RADAR FOR ICY MOON EXPLORATION

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ABSTRACT

This paper presents the Radar for Icy Moons Exploration (RIME) instrument, which has been selected as payload for the JUpiter Icy moons Explorer (JUICE) mission. JUICE is the first Large-class mission chosen as part of the ESA's Cosmic Vision 2015-2025 programme, and is aimed to study Jupiter and to investigate the potentially habitable zones in the Galilean icy satellites. RIME is a radar sounder optimized for the penetration of Ganymede, Europa and Callisto up to a depth of 9 km in order to allow the study of the subsurface geology and geophysics of the icy moons and detect possible subsurface water. In this paper we present the main science goals of RIME, the main technical challenges for its development and for its operations, as well as the expected scientific returns.

***Index Terms*—** radar sounder, icy moons, Jovian system, subsurface geology, geophysics, planetary exploration.

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. The spacecraft will carry instruments for studying different aspects of the Jovian system. The overall science objectives of the JUICE mission for the icy satellites are to: (i) characterize Ganymede as a planetary object and possible habitat, (ii) explore Europa's recently active zones, and (iii) study Callisto as a remnant of the early Jovian system.

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, in this paper we present the *Radar for Icy Moon Exploration* (RIME) instrument that has been selected as a payload for the JUICE 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 a nadir-looking active instrument which transmits relatively low frequency radio waves with the unique 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 by the radar sounder and are used to create a depth image of the subsurface (a radargram). Radar sounders have been already used to investigate extraterrestrial bodies such as Mars [2], [3] and the Moon [4]. Currently there are two such radars operating at Mars. The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) [2] is an orbital radar sounder on-board ESA's Mars Express spacecraft that is optimized for deep penetration of the Martian subsurface. The SHAllow RADar (SHARAD) [3] on-board NASA's Mars Reconnaissance Orbiter is optimized for high vertical resolution with shallow penetration of Mars. The proposed RIME instrument will exploit and further develop the heritage developed for MARSIS and SHARAD by acquiring for the first time direct measurements of the subsurface of the Galilean icy moons. RIME is unique as it is the first instrument to Jupiter and the outer Solar System capable of performing direct subsurface measurements. It is a key instrument for achieving groundbreaking science on the geology and the geophysics of Ganymede, Europa and Callisto. Due to its distinctive subsurface mapping capabilities, RIME can address a large number of fundamental science objectives. In this paper we present the main science goals of RIME, the main technical challenges for its development and for its operations, as well as the expected scientific returns.

2. SCIENCE GOALS AND OBSERVATIONAL FOUNDATIONS

The JUICE mission will have different phases including flybys and orbit of Ganymede. Two main operation scenarios are foreseen for RIME: flyby observations of Europa, Ganymede and Callisto (from a distance of 1000 km to the closest approach of about 300-400 km) and circular orbital operations around Ganymede at the end of the mission (at both 500 km and 200 km of altitude). According to these scenarios, RIME will explore the icy shell of the Galilean icy satellites Ganymede, Europa and Callisto by characterizing the wide range of compositional, thermal, and structural variation found in the subsurface of these moons. These subsurface observations will provide insight into the dynamic history of the satellites, test models of the formation of their surface features, and constrain the distribution of deformation in their ice shells as well as global and regional surface ages. RIME may also constrain the ice shell thicknesses and the role of convective processes by detecting the ice-ocean interface if the ice is thin, and the brittle-ductile transition if the ice is thick. Moreover, radar sounding can be used to map the existence of thermal structures in thick ice shells. Liquid water is expected to exist in all of the icy Galilean satellites as a subsurface ocean and possibly inside shallow reservoirs within the ice shells. RIME will search for present and past reservoirs of liquid water. RIME will also relate the distribution of non-ice material to geological features and processes. Non-ice materials alter dielectric and attenuation properties, enabling RIME to characterize the depth profile of non-ice materials. The distribution of ice impurities can constrain the origin of non-ice materials and determine past or present material exchange with the subsurface. In addition, RIME provides powerful synergistic leverage to other remote sensing instruments by potentially extending identifications and inferences derived for the satellites' optical surfaces deep into their subsurfaces.

These goals can be achieved by taking into account the observation capabilities of a radar sounder. At interfaces where there is a significant difference between dielectric permittivities, such as at an ice-water interface, incident radar waves will be reflected. Like other electromagnetic radiation, radar waves are subject to scattering by interfaces or objects on the same scale as the radar wavelength. The inferred losses above detected interfaces can constrain the size of scatterers volumetrically within the ice. Attenuation of radio waves in ice is a function of both composition and temperature that change its dielectric properties. RIME will use a suite of common subsurface observations for the exploration of all three Galilean icy satellites. Tests of geophysical hypotheses relevant to each moon will be comprised of a subset of the observations summarized in Tab. 1, which is constructed both from actual observables for the ice of Mars and Earth with radar sounders as well as the extension of established physics for radio propagation in ice of the Galilean moons. Thus, RIME provides a means by which to perform both exploratory observations and focused

Tab. 1. RIME subsurface observations with the expected radar return, the physical cause and an example.

	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.

Tab. 2. Data sheet of the proposed RIME instrument.

Main Instrument parameters	**Parameter values**
Transmitted central frequency (MHz)	9
Antenna type	Dipole
Optimal antenna length (m)	16 m
Peak radiated power (W)	10
Stand-by power with cont. (W)	13.3
Avg. power during sounding with cont. (W)	25.1
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
Circular Orbital Phase	
Orbit height (km)	200 - 500
Pulse repetition frequency (Hz)	200 - 400
Chirp bandwidth (MHz)	3, 1
Chirp length (μs)	50 - 100
Receiver window length (μs)	117 - 226
Data rate (kbps)	216 - 250
Flyby Phase	
Flyby distance (km)	< 1000
Pulse repetition frequency (Hz)	500
Chirp bandwidth (MHz)	3
Chirp length (μs)	100
Receiver window length (μs)	226
Data rate (kbps)	2400

hypothesis tests within ice characterized by a wide range of compositional, thermal, and structural variations.

3. DESIGN OF THE INSTRUMENT AND SCIENTIFIC PERFORMANCE REQUIREMENTS

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. Tab. 2 summarizes the main RIME parameters. The frequency was selected as the result of extensive study 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 [5]. 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

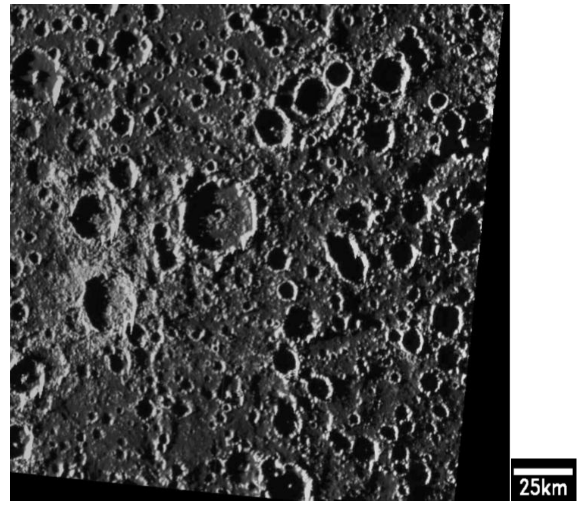
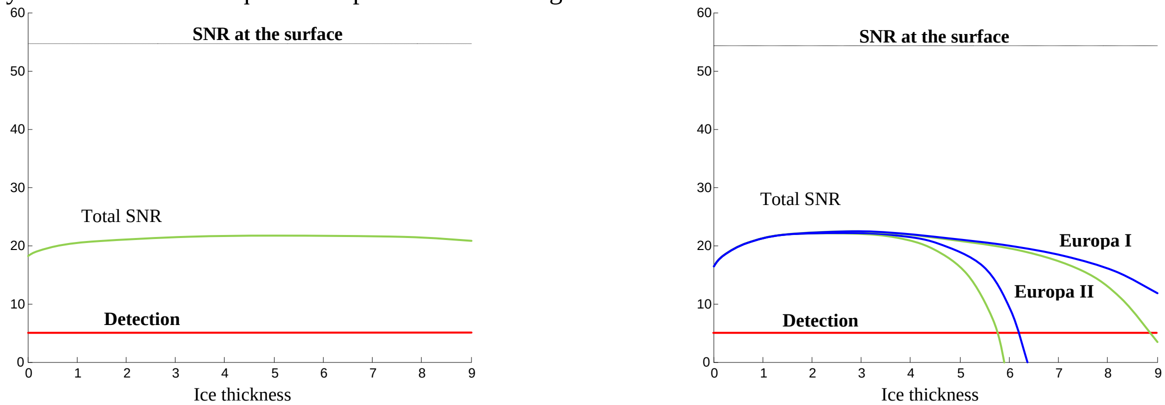


Fig. 1. Moderate-resolution (200 m/pixel) view of cratered plains typical of the regions RIME will sound (Callisto, near 5° N, 182° W, adapted from [6]).

obtain high SNR observations only on the anti-Jovian side of the target moons. Frequencies higher than the selected 9 MHz were ruled out because of the high values of topographic roughness obtained from Digital Elevation Models (DEM) of Ganymede and Europa derived from Voyager and Galileo images. Surface roughness can affect the quality of the sounding data in two ways: loss of wave front coherency during passage of the wave across the rough surface, and introduction of surface clutter from large facets off-nadir that compete with potential subsurface reflectors later in the echo record. Both of these effects are reduced at lower transmitted frequencies.

The topographic roughness statistics found in the Ganymede and Europa DEMs suggest that a typical Galilean moon surface is rougher than a typical Mars surface (e.g., see Fig. 1), and therefore a frequency lower than that of SHARAD (20 MHz) is appropriate. Our modeling of loss and clutter effects (see Fig. 2) indicates that 9 MHz provides an optimal balance among mitigating the effects of surface roughness, providing deep penetration, limiting the length of the antenna, and allowing the desired vertical resolution. The wavelength of the 9 MHz signal, 33 m in free space, can be efficiently transmitted using the proposed JUICE dipole antenna, which has a length of 16 m. The 9 MHz band also allows a relatively wide chirp pulse of up to 3 MHz, which provides vertical resolution of 50 m in free space, equivalent to ~30 m in ice. As shown in Fig. 3 on a degraded SHARAD radargram, at this resolution numerous features are visible and allow a detailed study of the subsurface.

Scientific measurements can be performed in two different resolution modes: *high resolution* and *low resolution* (using 3 and 1 MHz chirp bandwidth, respectively). The *low resolution* mode will be used to reduce data volume when observing deep sounding targets. RIME offers a wide flexibility in terms of acquisition parameters during



(a) (b)

Fig. 2. Example of results of the instrument detection capability in term of total SNR for (a) Ganymede and (b) Europa. The reference SNR at the surface includes only the effect of noise terms (thermal and galactic). The total SNR includes noise terms and clutter, making the detection curves appear rather flat as a function of depth. The green and blue lines have been obtained by considering the minimum and maximum value of ice attenuation at 250 K (0.01-0.03 dB/m). For Ganymede the two lines are superimposed. Other parameter values are: volume scattering losses, 1.4. dB/km; subsurface dielectric contrast, 0.3; S/C altitude, 500 km.

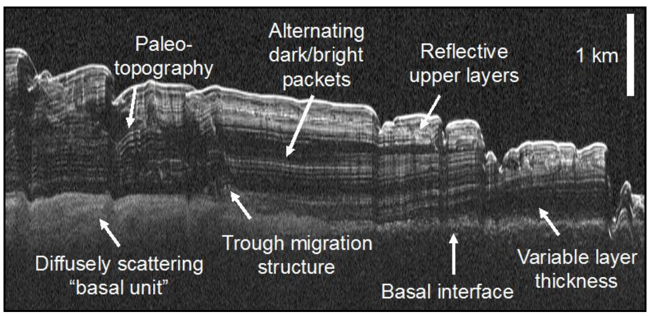


Fig. 3. SHARAD radargram of north polar plateau of Mars taken at an altitude of 300 km. SHARAD data have been degraded in resolution to the RIME resolution of 30 m in ice. Visible relevant features are noted by arrows.

measurements. Moreover, it foresees a calibration mode (*receive-only*) in which no pulse is transmitted and the instrument only records the output of the receiver.

Within the high and low resolution modes, parameters can be adjusted to change the output data rate. In particular, the on-board pre-summing can be set to values between 1 and 8, providing a corresponding factor in data rate reduction, at a potential cost of along-track resolution and sensitivity to sloping subsurface interfaces. In addition, if depth of detectible features can be anticipated, the receive window size can be adjusted to receive echoes only for the period of interest to further manage the data rate. For high-priority flybys, such as the two of Europa, the high resolution mode (3 MHz bandwidth) will be used, with no pre-summing, and a receive window of 226 μs. This results in a data rate of 2400 kbps. In nominal orbital operations at Ganymede, the high resolution mode will be utilized with pre-summing up to 8, and a window length as short as 117 μs, with a resulting data rate of 250 kbps. Similarly, for a deep sounding target (9 km depth), the low resolution mode (1 MHz bandwidth) will be used, but with a receive window of 226 μs, and with a pre-summing factor of 2 the resulting data rate is 216 kbps. Thus, RIME has great flexibility in mode parameters allowing optimization for the target depth, desired vertical resolution, along-track spacing, feature slope, and available data rate.

4. CONCLUSION

The RIME instrument has the capability of addressing a large number of groundbreaking science goals related to the JUICE mission, which is the largest ESA mission for the exploration of the Solar System expected in the next 15 years. As shown in this paper, RIME 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.

5. REFERENCES

[1] Bruzzone, L., Alberti, G., Catallo, C., Ferro, A., Kofman, W., Orosei, R., "Subsurface Radar Sounding of the Jovian Moon Ganymede," *Proceedings of the IEEE*, 99, 5, 837–857, 2011.
[2] Seu, R., Phillips, R., et al., "SHARAD sounding radar on the Mars Reconnaissance Orbiter," *J. Geophys. Res. (Planets)*, 112, 5, 2007.
[3] Picardi, G., Plaut, et al., "Radar soundings of the subsurface of Mars," *Science*, 310(5756), 1925–1928, 2005.
[4] Ono, T. *et al.* "Instrumentation and observation target of the Lunar Radar Sounder (LRS) experiment on-board the SELENE spacecraft," *Earth Planets and Space*, 60(4), 321–332, 2008.
[5] Cecconi, B., Hess, S., Herique, A., Santovito, M.R., Santos-Costa, D., Zarka, P., Alberti, G., Blankenship, D., Bougeret, J.L., Bruzzone, L., and Kofman, W., "Natural radio emission of Jupiter as interferences for radar investigations of the icy satellites of Jupiter," *Planet. Space Sci.*, 61, 32-45, 2012.
[6] Moore, J.M., et al., "Jupiter – The Planet, Satellites and Magnetosphere," *Cambridge Univ. Press*, 397–426, 2004.