A Fractionated Radar Sounder Concept for Subsurface Exploration of Saturn's Icy Moon Enceladus

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Abstract

Low-frequency radar sounders offer unique measurement capabilities for exploring the subsurface of planetary bodies. However, these instruments face limitations due to the near-omnidirectional characteristic of dipole antennas commonly used at lower frequencies. This characteristic results in the collection of clutter from off-nadir angles, potentially masking the signals of interest coming from subsurface layers in the nadir direction, thus complicating the interpretation of subsurface data. To address these limitations, we are investigating the feasibility and potential of a fractionated HF-band radar sounder satellite constellation for a mission scenario to Saturn's icy moon Enceladus, as part of an ESA study. The specific configuration of satellites, operating in formation, can enable the synthesis of a large antenna array, offering the following potential benefits: i) effective suppression of off-nadir clutter using beamforming approaches, ii) increased sensitivity, and iii) flexibility for implementing advanced imaging modes.

1 Introduction

Saturn's moon Enceladus is a differentiated geological active body with a diameter of roughly 500 km, formed out of a rocky core, a global subsurface salt-water ocean, and a several kilometer thick ice crust [1]. The discovery of plumes ejecting gas and ice particles through cracks within the ice crust in the south polar region has quickly thrust Enceladus into the spotlight of the planetary science community. As part of an ESA study, we are currently investigating the feasibility and potential of a fractionated HF-band radar sounder satellite constellation for a mission scenario to Enceladus. This approach aims to overcome the limitations of conventional low-frequency sounders, which are typically based on a single satellite.

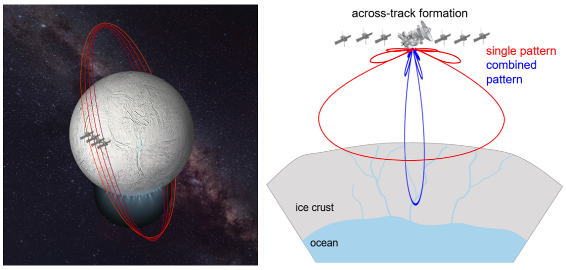

Figure 1 Illustration of the formation-flying fractionated radar sounder concept.

Radar sounders provide unique measurement capabilities for exploring the subsurface of planetary bodies, as demonstrated by the MARSIS and SHARAD instruments and planned for the REASON [2] and RIME [3] instruments of the Europa Clipper and Juice missions, aimed on the exploration of Jupiter's icy moons. Radar sounders are nadir-looking sensors that transmit pulsed electromagnetic signals which can propagate through the subsurface due to their relatively low frequency. Each dielectric discontinuity in the ground material reflects part of the signal towards the radar. The analysis of the recorded echoes provides crucial information on the subsurface structure and composition. The primary science objectives for radar sounder investigations on Enceladus include (but are not limited to): i) identifying and characterizing the ice-ocean interface and the spatial variation of ice layer thickness, ii) detecting potential near-surface water/brine reservoirs embedded in the ice shells, iii) studying dynamic processes in active regions, predominantly located in the south polar region, with a focus on understanding the connection between the ocean and the shallow subsurface/surface, and iv) characterizing the layering of the upper ice crust, such as snow, ice regolith, compact ice, to determine the past evolution, including the intensity of plume activity and geological history.

2 Problem Statement

Although conventional low-frequency radar sounders can achieve good performance, they are hindered by the near-omnidirectional characteristics of dipole antennas. These antennas are commonly used due to the large antenna

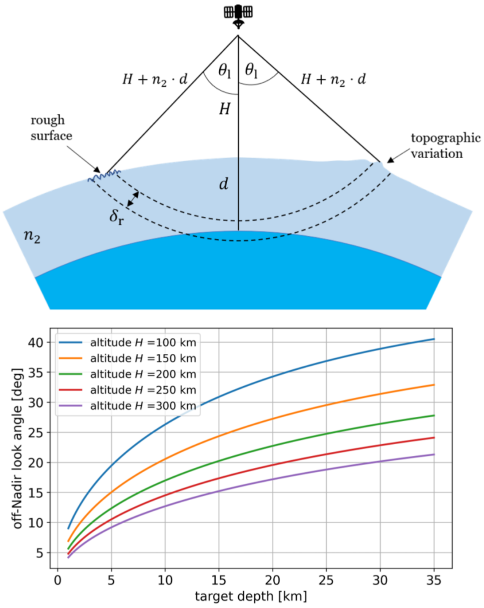

Figure 2 (Top) Acquisition geometry with respect to surface clutter that can arise from target areas at off-nadir angles, exhibiting the same optical distance as the subsurface interface of interest. The clutter may originate from a rough surface or smooth surface facets that are oriented towards the sensor due to topographic features. (Bottom) off-nadir look angle for surface areas contributing to the clutter for a certain depth within the ice and different orbit altitudes, assuming a spherical shape of Enceladus.

lengths required for long wavelengths. The omnidirectional characteristic leads to the collection of surface clutter, i.e., spurious signals from off-nadir directions, potentially masking the signal of interest emanating from subsurface layers in the nadir direction. Consequently, this phenomenon hampers the interpretation of subsurface data (illustrated in **Figure 2**). Especially for larger depths, where the nadir signal of interest experiences strong attenuation from propagation through the ice, off-nadir surface clutter may become dominant.

Clutter from along-track (i.e., azimuth) directions can be effectively eliminated using Doppler processing with unfocused or focused synthetic aperture radar (SAR) algorithms. However, clutter from across-track directions cannot be suppressed using a single sounder antenna. To address these limitations, we are investigating the feasibility and potential of a distributed radar sounder satellite constellation operating in a fractionated radar configuration (i.e., one transmitter satellite and multiple receiver satellites). Distributed radar sounding configurations have already been proposed for Earth observation of icy regions (e.g., the STRATUS concept [4]). Such a formation-flying satellite configuration allows for the synthesis of a large antenna array, offering several advantages over traditional radar sounding configurations: i) suppression of surface clutter through beamforming techniques, ii) increased signal-to-noise ratio (SNR), iii) possibility of exploiting interferometric and tomograohic techniques. Compared to an Earth observation scenario, Enceladus offers several unique observational characteristics that make the use of an HF-band sounder favorable. These include a negligible ionized atmosphere content and very low temperatures, resulting in minimal signal attenuation in the ice crust. In addition, orbiting at lower orbit altitudes, e.g, below 100 km from the surface, is possible at Enceladus. However, various aspects of the Enceladus environment and the large distance to Earth lead to increased system and mission complexity, necessitating careful study and consideration in system design.

Table 1 Preliminary radar system parameters

Parameter	**Value**	**Comment**
Centre frequency	9 MHz (cf. RIME)	Compromise between penetration capability and implementable bandwidth
Average transmit power	0.5 W (cf. RIME)	Variable within the study
Chirp Bandwidth	3 MHz (cf. RIME)	Variable within the study
Pulse duration	100 μs (cf. RIME)	Variable within the study
PRF	500 Hz (cf. RIME)	Variable within the study. Can be optimized to maximize the transmit duty cycle
System losses	3 dB	Assumption
Noise figure	3 dB	Assumption
Dipole length	$0.48 \cdot \lambda$	$0.48 \cdot \lambda$, for matching. Equals 16 m at 9 MHz
Antenna gain	2.13 dBi	Reduced from nominal 2.15
Range spectral weighting loss	1.8 dB	Range spectral tapering for side-lobe suppression

3 Preliminary System and Instrument Assumptions

The satellite system comprises one complex master satellite (in the 1.5-ton class) and several relatively simple deputy satellites (in the 200-kilogram class). The master satellite hosts most of the power-, mass-, and space-demanding functionalities of the system, including transfer to Enceladus, telecommunication, radar transmitter, data storage and processing, as well as additional payload. After orbit insertion around Enceladus, the deputy satellites are detached from the master satellite to form the across-track formation and serve as radar receivers. They forward the echoes to the master satellite in a MirrorSAR-like [5] configuration (further discussed below). Each satellite is powered by Radioisotope Thermoelectric Generators (RTGs) and heated by Radioisotope Heating Units (RHUs) due to their potentially higher power-to-mass ratio compared to solar arrays in the Saturn system (at approximately 10 AU from the Sun). Based on preliminary analyses, using an Ariane 64-like launcher, it is estimated that one master satellite and up to 7 deputy satellites could potentially be placed into Enceladus orbit, assuming a rather favorable launch window including multiple gravity assists by Earth, Venus, and Jupiter.

The preliminary radar system assumptions are mainly based on the RIME instrument [3] of ESA's Juice mission. An HF-band center frequency of 9 MHz is chosen as

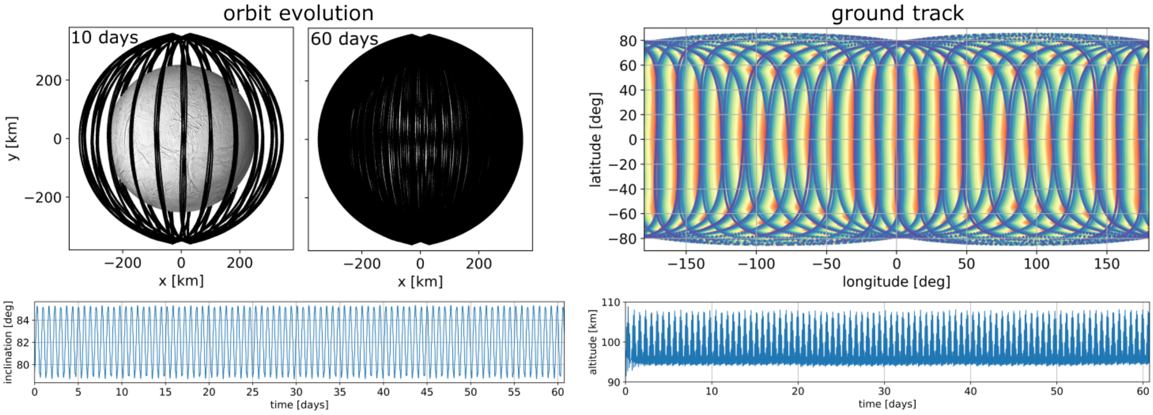

Figure 3 Characteristics of the high-inclined candidate orbit. The orbit evolution is shown in a body-fixed frame. The color variation of the ground track indicates the drift over time.

a compromise between minimizing scattering losses and clutter, which facilitates penetration to larger depths, while also enabling the utilization of bandwidths extending to several MHz, thereby allowing for achieving vertical resolution in the tens of meters range. The most relevant system parameters are depicted and discussed in Table 1.

4 Orbit and Formation Considerations

The orbit characteristics around Enceladus represent one of the most constraining factors for the system. The orbit must offer nearly global access, especially to the intriguing south polar region, without necessitating an unreasonable amount of delta-v (i.e., propellant) for station-keeping. Satellite orbits around Enceladus are severely influenced by the third-body force of Saturn and the non-spherical gravity field of Enceladus [6]. Without significant station-keeping efforts, polar orbits degrade into impacts with Enceladus after just a few days. Long-term stable solutions exist for moderate inclinations. In [7], several orbits with natural lifetimes beyond ten years and inclinations up to 60° have been proposed. While these orbits do not offer nadir-looking access to the polar regions, they remain reasonable candidates for mapping the regions between −60° and 60° latitude, and are thus considered in the study. Small short-term stability regions can be found for orbits with inclinations beyond 60°, with lifetimes ranging from several days to a few tens of days. These high-inclined solutions can potentially be controlled with moderate delta-v expenses. Our current control strategy involves maintaining the orbit by applying only along-track maneuvers (i.e., slowing down or accelerating the satellite) every few days. This approach allows for relatively simple yet effective orbit maintenance. **Figure 3** shows the evolution of one candidate orbit over the course of 60 days in a body-fixed frame. Along-track maneuvers are implemented every four days, accumulating to a total delta-v of less than few meters per second, depending on the simulated orbit determination accuracy. It is noteworthy that the satellite's velocity is approximately 140 $\mathrm{m\,s^{-1}}$. Both the orbit plots and the ground track show that the orbit is drifting over the course of the 60 days and covers latitudes between −85° and 85°. The inclination varies between 79° and 85°, while the altitude fluctuates between 94 km and 108 km. This orbit may be a suitable candidate for the system since it allows access to substantial portions of the interesting south polar region, while maintaining a suitable altitude for safety considerations. Moreover, the orbit can be sustained over the mission duration with moderate delta-v requirements.

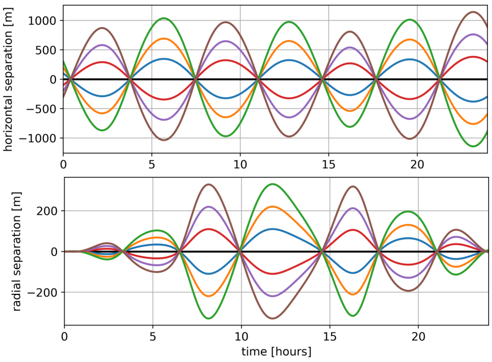

Figure 4 Separation of the satellites with respect to the primary satellite (black line) without relative orbit control: (top) horizontal baseline and (bottom) radial baseline.

In addition to the nominal orbit, the relative orbits within the formation experience significant perturbations in the Enceladus gravity environment. For the fractionated sounder, the desired formation is to be separated in the horizontal across-track direction (i.e., parallel to the surface) to achieve baselines suitable for beamforming in the nadir-pointing sounder acquisition geometry. Horizontal baselines ranging from several tens to hundreds of meters are required for the HF band system. Maintaining a constant horizontal separation of the formation would require forcing the relative orbits against their natural evolution in the gravity field. Such forced formations are known to demand a high amount of delta-v for continuous station-keeping compared to natural formations. Therefore, we focus on natural solutions that lead to varying across-track and along-track separations over the course of one orbit pe-

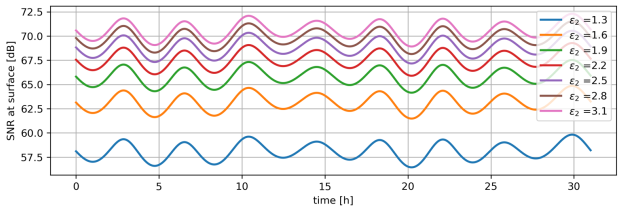

Figure 5 Surface SNR for the system outlined in Table 1, based on the orbit in Figure 3, various values of surface layer permittivity (ε_2), and a noise contribution dominated by galactic noise.

riod. In particular, we assess the suitability of a HELIX-like formation, which has been utilized for TamDEM-X [8]. The HELIX combines an out-of-plane (horizontal) orbital displacement, using different ascending nodes, with a radial separation, using different eccentricity vectors, resulting in a helix-like relative movement of the satellites along the orbit. In the perturbed Enceladus gravity, the ascending node displacement results in a strong relative along-track drift that separates the formation over the course of days. This drift can be partially compensated by introducing an additional separation of the inclination. The resulting natural evolution of the baselines over 24 hours is depicted in **Figure 4** for a formation of 7 satellites. The horizontal and radial baselines are shown, both in reference to the central satellite of the formation (black line). The natural movement results in varying baselines of a few hundred meters, with noticeable perturbations compared to an unperturbed HELIX. Similar to the nominal orbit, control of the formation for safe operation and optimized baselines is expected to be possible at the expense of a moderate delta-v.

5 Sensitivity and Attenuation Assessment

As part of the study, a comprehensive sensitivity and attenuation modeling has been conducted, and some key findings from the analysis are presented herein.

Considering the system parameters outlined in Table 1, the SNR at the surface of the ice crust is shown in **Figure 5** over a period of 32 hours along the orbit illustrated in Figure 3. The SNR values are shown for various surface layer permittivity values, ranging from fine snow to solid ice. The variation along the orbit arises from the changing altitude. The surface SNR provides a rough indication of the tolerable attenuation within the ice crust for detecting subsurface interfaces. It is important to note that in the HF band and within the Saturn system, the noise is primarily dominated by galactic noise. Assuming the noise is uncorrelated for the different receivers on the deputies, the SNR increases by a factor equal to the number of receive channels. To further improve the SNR, the average transmit power needs to be increased (note the initial value of 0.5 W in Table 1).

The attenuation of signals within the ice crust, and hence the penetration capability, is expected to be primarily governed by dielectric absorption losses in the HF band, with scattering losses having a secondary effect. The attenuation is considered frequency-independent below several hundred MHz and increases with rising ice temperature and impurity content. Among attenuation-enhancing impurities, only chloride is expected to be present in the ice crust with a relevant concentration, as analyzed in [9]. The temperature within the Enceladus ice crust varies significantly, ranging from surface temperatures of approximately 60 K to temperatures near the melting point of ice at the ice-ocean interface, i.e., 0 °C. The vertical temperature distribution within these extremes is expected to heavily depend on the thickness and composition of the snow (i.e., regolith) layer atop the ice crust, originating from the plumes in the south polar region and the E-ring of Saturn. **Figure 6** (left) displays the modeled temperature distribution for an ice crust of 21 km (assuming a conductive heat transport) for different values of regolith thickness, in the range predicted by [10]. Note the strong dependence on the regolith thickness. The center and right panel of Figure 6 show the corresponding accumulated 2-way attenuation. In the center, for a minimum chloride (low loss case) concentration, and on the right, for the maximum theoretically possible chloride concentration within the ice (high loss case). The color scale saturates at an attenuation of 100 dB. It is important to note that within the potential parameter space range, scenarios may arise where the entire ice crust can be penetrated, as well as scenarios allowing penetration only to a few kilometers. Additionally, strong regional variability is anticipated, such as a varying ice crust thickness ranging from 4 km at the South Pole to 35 km at equatorial latitudes. Surface temperature and heat transport characteristics are also expected to vary significantly spatially. The presented analysis depicts both worst and best-case scenarios in terms of potential penetration capability. It is worth noting that conditions predicting minimal penetration (i.e., high temperatures in the upper layers) are also conducive to the formation of near-surface brine reservoirs, which are of high interest.

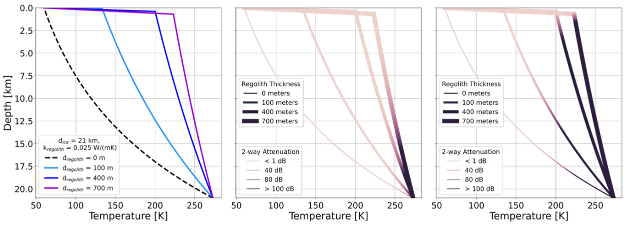

Figure 6 (Left) ice shell temperature profiles and corresponding accumulated radar attenuation values using (center) low loss and (right) high loss scenarios. The profiles correspond to different values of regolith thickness. The ice crust thickness and regolith thermal conductivity are fixed to 21 km and 0.025 W/mK, respectively.

6 Radar Operational Concept

The performance and overall feasibility of beamforming, interferometric, and tomographic techniques tend to increase with the number of channels, which is equivalent to the number of satellites for the HF-band sounder. However, the amount of dry mass and volume that can be deployed into Enceladus orbit is severely limited. Thus, we propose a radar concept aimed at achieving the highest degree of simplification of the satellite system, thereby reducing the mass of individual satellites and allowing for an increase in the number of satellites. We propose to achieve this simplification by operating in a MirrorSAR configuration [5], wherein a single transmit satellite (the more complex master satellite) is paired with all other satellites (low-complexity deputy satellites) implemented solely as receive-only space transponders. This configuration corresponds to a fractionated radar concept. A notable advantage of the MirrorSAR configuration is the simplification of the receiver satellites [5]. Their main functionality is reduced to routing the radar signals from passive receivers to the transmitter, acting essentially as space relays. Consequently, they no longer require expensive data storage and downlink systems, resulting in reduced mass, power, and accommodation demands, which supports the use of small, low-cost satellite buses. It is important to note that one complex satellite (i.e., the master satellite) with relatively high mass and power generation capabilities is required anyhow to realize other power- and mass-demanding functionalities, such as transfer from and telecommunication with Earth. Therefore, the MirrorSAR concept is highly suitable for multi-satellite radar systems at distant planets and moons, such as Enceladus. The MirrorSAR concept is illustrated in **Figure 7** for the case in which a simple amplitude modulation strategy is employed for the inter-satellite link.

Another key benefit of MirrorSAR is the opportunity to overcome the necessity of a bidirectional phase synchronization link between the transmitter and receiver satellites as typically required in systems like TanDEM-X, leading to a significant reduction in system complexity [5]. For this, we require that the signal routing from the receiver to the master satellite preserves the phase of the radar signal up to a constant internal delay. This may be achieved by using amplitude modulation of the radar echoes on a carrier signal. An incoherent demodulation on the transmitter (master satellite) will then recover the time-delayed radar echo without phase disturbance from the carrier. Following this initial stage of down-conversion, the RF radar signal is demodulated to baseband using a coherent I/Q demodulator driven by the local oscillator in the transmitter. Radar echoes from multiple channels of the various deputy satellites can be accommodated through frequency multiplexing within the inter-satellite link band. Currently, we are exploring two options for the inter-satellite link and modulation: i) radio frequency (RF) link, and ii) optical link, where the sounder echoes are modulated on an optical carrier.

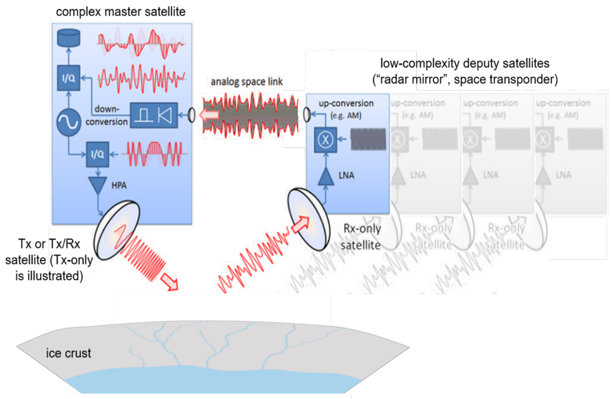

Figure 7 Illustration of the MirrorSAR concept for the sounder constellation (modified from [5]).

7 Clutter Mitigation Example

Various multi-phase center sounder techniques have been already proposed to enhance the performance beyond the limitations of a monostatic (single-channel) system. Those approaches can be grouped as follows: i) interferometric approaches for surface clutter discrimination and subsurface layer elevation measurement, ii) beamforming approaches for clutter suppression, iii) tomographic approaches for 3-D subsurface imaging. The feasibility and potential of the approaches primarily depend on the number of satellites, the available baselines (i.e., the natural evolution of the formation and the formation control), the baseline determination accuracy (should be better than e.g., $\frac{\lambda}{30}$, i.e., ≈ 1 m at 9 MHz), and the signal integrity of the receive signals routed over the inter-satellite links.

As an example, we show here a performance simulation for a surface clutter suppression technique using an adaptive null-steering of the antenna pattern, as suggested in [11]. Assuming that we have a rough estimate of the topography (note that digital elevation models of Enceladus are available with a resolution of few hundreds of meters [12]), the slant range to a nadir target of interest can be related to an equivalent off-nadir look angle from where surface clutter is collected (see Figure 2). By employing complex weighting and coherent combination of the receive channels from an across-track formation, we can, for each range (i.e., depth), steer nulls of the combined antenna pattern to the equivalent off-nadir look angles, thereby suppressing surface clutter. **Figure 8** shows a simulation of surface clutter nulling for the Enceladus geometry and the system in Table 1. A formation with 5 receive satellites is assumed and the baseline distribution is a snapshot from the formation simulation in Figure 4. Note that no topography has been assumed beyond the Enceladus ellipsoid. The left panel in Figure 8 shows, as an example case, the synthesized Rx antenna pattern for a target depth of 6 km. The red, dashed lines show the equivalent target depth on the off-nadir look angle axis. We note that dedicated nulls are steered to the corresponding look angles. The center and right panels compare the received surface clutter power after beamforming to the one of a single channel system. The effect of the clutter is evaluated in terms of a clutter SNR, i.e., the power of the clutter with respect to the noise floor. A clutter SNR < 0 dB is desirable. The clutter is modeled as angular independent up to 30° with a backscatter of -15 dB, mainly resulting from quasi-specular scattering

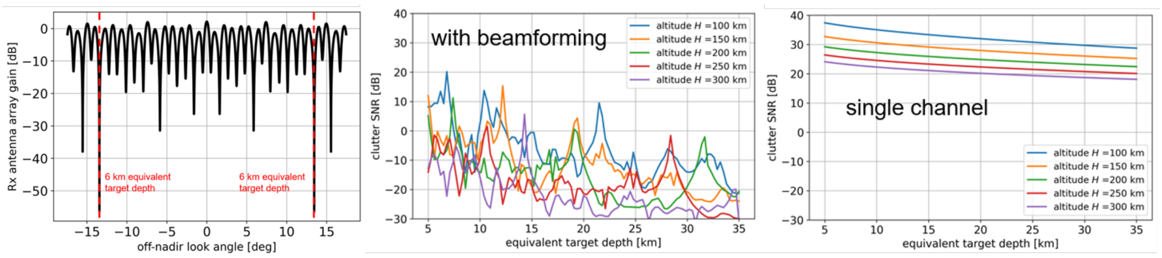

Figure 8 Simulation of surface clutter nulling, comparing the surface clutter SNR of a 9 MHz monostatic sounder with almost no directivity to a fractionated sounder with 5 receive satellites in an across-track formation. (Left) synthesized Rx gain pattern of the fractionated sounder with nulls steered to a look angle equivalent to a 6 km deep target, (center) surface clutter SNR for the fractionated sounder with surface clutter nulling for each depth, and (right) for an equivalent single channel system.

from smooth interfaces [13]. We note that the clutter could be suppressed significantly by the nulling process with respect to the SNR of the monostatic system and results for most areas in a clutter SNR < 0 dB (i.e., the clutter is beneath the noise floor). It is important to note that perfect baseline and topography knowledge is assumed here. This simulation provides a glimpse into the potential of surface clutter suppression techniques for the Enceladus scenario.

8 Conclusion

We have presented a preliminary assessment of the feasibility and potential of a fractionated HF-band radar sounder for the exploration of the Enceladus ice crust. The orbit and the geophysical properties of Enceladus introduce unique characteristics that need to be accounted for in the system and mission design. We showed that the fractionated sounder satellite constellation can potentially overcome the limitations of conventional low-frequency sounders based on a single satellite in terms of clutter suppression and flexibility for advanced imaging modes like interferometry or tomography.

9 Acknowledgment

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