National Aeronautics and Space Administration

DEBRIS (Distributed Element Beamformer Radar for Ice and Subsurface Sounding)

and

DOWSER (Distributed Occluded Water Sensors using Electromagnetics in Reactive Regime)

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Objectives

The objective of this research is to demostrate the feasibility of distributed systems for coherent remote sensing of ice and the subsurface. An orbital VHF (or UHF) radar system and a suborbital magneto- and electro-quasistatic system are both being developed in parallel as complementary instruments for subsurface remote sensing.

The current state-of-the-art radar beamformers are physically constrained by the size of a single spacecraft or its deployable structures. For the **Distributed Element Radar Beamformer for Ice and subsurface Sounding (DEBRIS)**, we focus on using multiple small spacecraft to synthesize antenna apertures on the order of kilometers in scale [A]. The coherent distributed array requires formation flying and position coordination of all spacecraft, and the relative position between spacecraft must be known with precision of a small fraction of the radar's wavelength.

The **Distributed Occluded Water Sensors using Electromagnetics in Reactive regime (DOWSER)** is a suborbital distributed polarimetric, MIMO (multi-input, multi-output) sounder concept. It uses quasi-static electromagnetic fields to advance detection and retrievals for deep subsurface groundwater where the high attenuation is prohibitive for remote sensing with traditional radar techniques. The distributed system improves the localization and detection of subsurface features.

Background

DEBRIS will synthesize antenna apertures that are physically large, which in turn focuses the footprint on the surface. DEBRIS uses synthetic aperture radar techniques for along-track antenna formation and the distributed array forms the aperture in the cross-track direction. By focusing the antenna's pattern in the cross-track direction, we attenuate the surface's echoes from off-nadir angles, leaving only echoes from the subsurface at nadir. The relative spacing between the elements determines the shape and power of the synthesized antenna's sidelobes (where the antenna pattern is ideally suppressed). The maximum extent of the array determines the resolution of the synthesized antenna's footprint. The number of elements determines the antenna gain, which ultimately increases the sensitivity of the radar.

DOWSER enables greater focusing, resolution of deep subsurface targets, and 3D tomographic capability when intervening lossy clutter is present. To enable this, the concept utilizes coherent, distributed multi-sensor systems (Fig. 1). The current state-of-the-art relies on a single transmitter and receiver which are moved (either together or separately) to spatially sample the environment. DOWSER introduces polarization and multiple receivers to increase the diversity of the measured subsurface response, in order to improve both the resolution and accuracy.

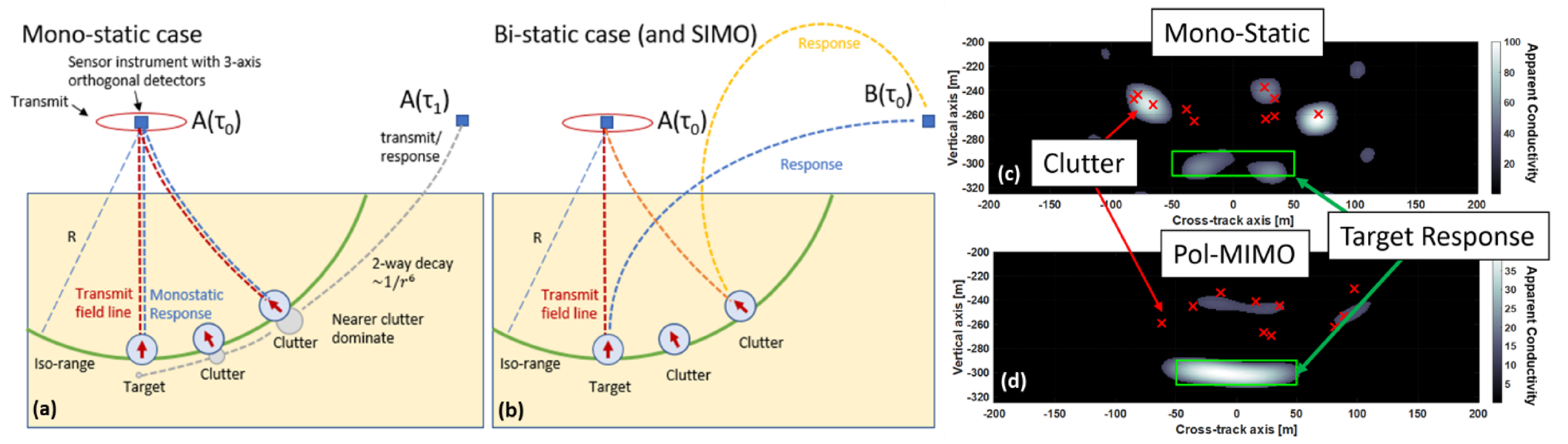

***Figure 1**: a) Current state-of-art mono-static suborbital EMQS systems uses a single transmitter and receiver. b) The DOWSER concept is a polarimetric, MIMO EMQS instrument for deep subsurface remote sensing. Sensitive exciters and detectors are configured to emit/detect quasi-static electromagnetic fields. This coherent, distributed multi-sensor system exploits spatial diversity and polarization to distinguish targets and clutter. (c-d) DOWSER provides considerable improvements in mapping, detection, retrievals of deep subsurface structure.*

Approach and Results

DEBRIS can be designed with redundant, low-cost CubeSats or SmallSats to implement one of two modes: 1) single transmitter with an array of receive-only elements or 2) a full array of transmitting/receiving elements. Formation flying is critical to DEBRIS's performance [B]. Formation members are allowed to maintain a relatively loose formation control (a fraction of the separation) but require accurate position knowledge for relative phase correction (a fraction of the wavelength). Two orbital configurations are shown in Figure 2a: a helical free-flying array [C] and a tethered array aligned along nadir [D]. Example relative positions of a helical array are shown in Figure 2b. Orbital maneuvers are periodically required to maintain the relative position of the array elements to maintain the beamformer's performance. The notional DEBRIS receive-only array with transmitting mothership is shown in Figure 2c.

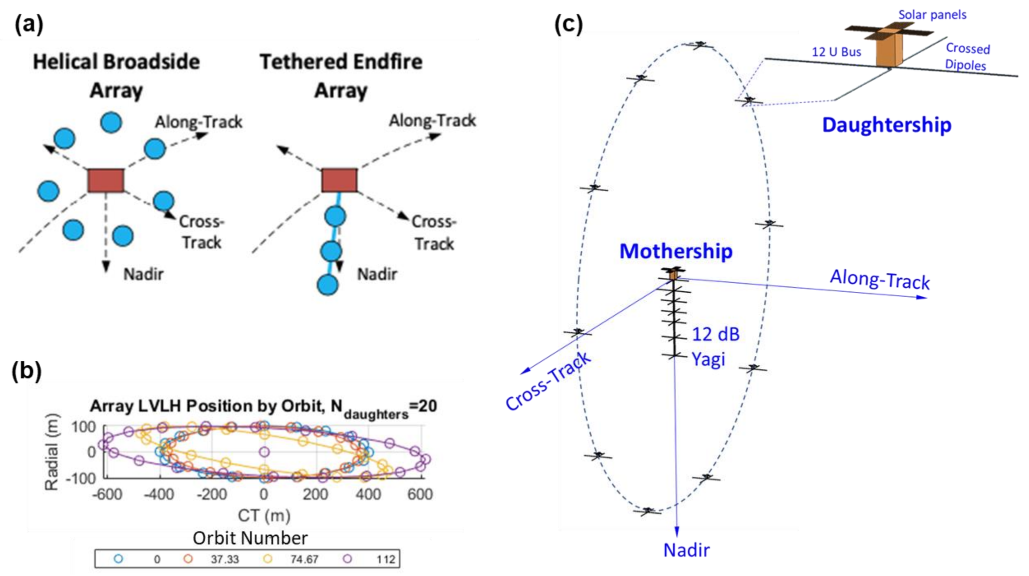

***Figure 2**: a) array configurations b) position of a 20-daughtership helix array at multiple points during its orbit. c) Diagram of DEBRIS with a receive-only helical array and the transmitting mothership at the center.*

Figure 3a illustrates the array grating lobes as the array diameter varies. Figure 3b considers the sidelobe and grating lobe variations for a helical array as it rotates through the orbit. For a full TX/RX array, the mean VHF array apertures are shown in Figure 3c for Nsc = 5, 10, and 20. The relative performance gains for VHF arrays are compared in Figure 3d. Uncertainty in relative position and timing are equivalent to 10 cm, and relative calibration error is 0.5 dB.

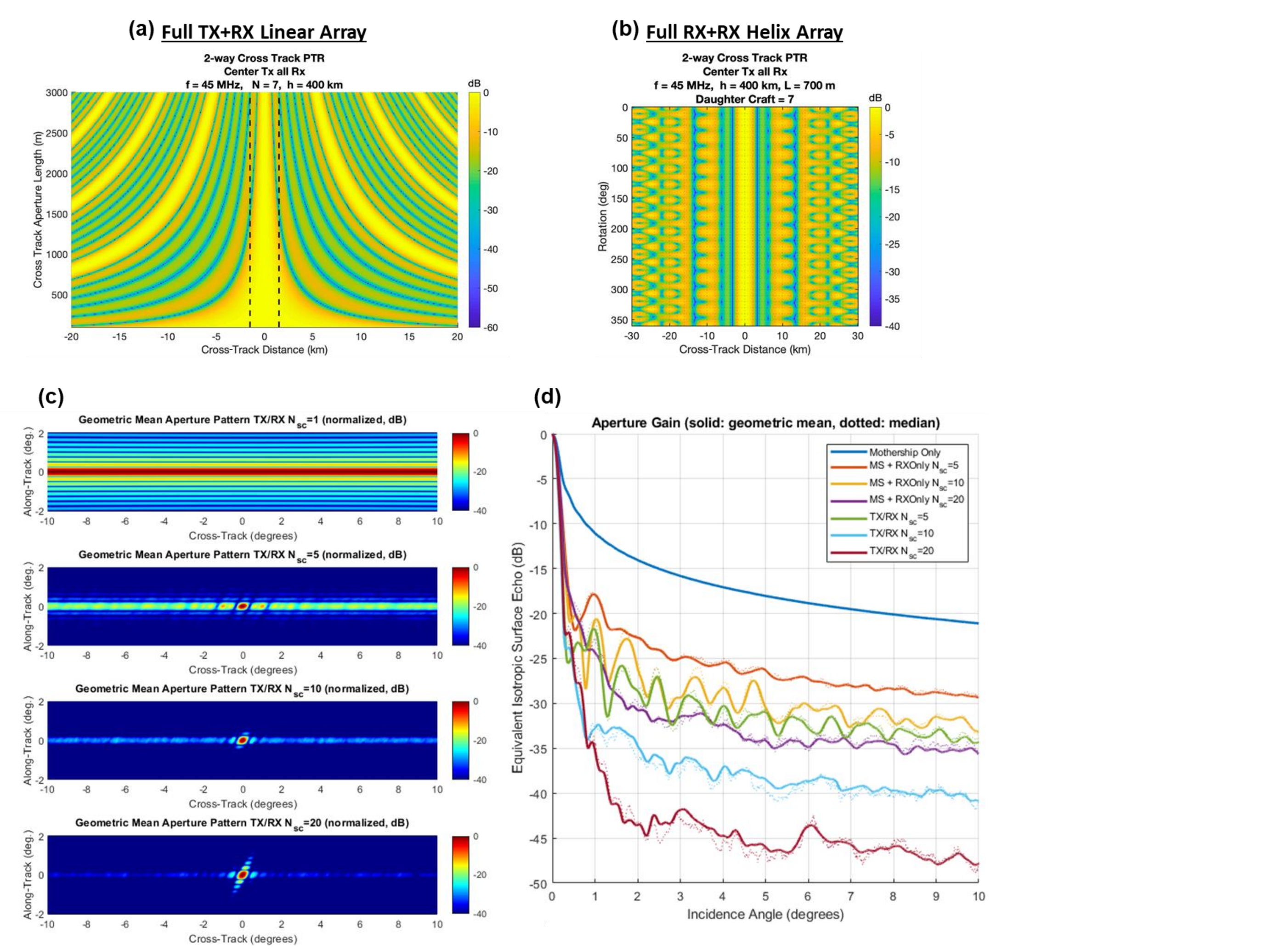

Figure 3: a) Example grating lobe pattern for a full TX+RX linear array as a function of array diameter b) Example grating lobe and sidelobe characteristics as a function of the helical array rotation through an orbit. c) the mean 2D antenna aperture for full TX/RX arrays with different number of spacecraft. d) Relative performance of the RX-only, full TX/RX array, and single spacecraft configurations.

DEBRIS is developing deployable, wideband VHF and UHF antennas for a CubeSat. Preliminary RF designs assume a baseline geometry with 12U CubeSat (Fig. 4a). The HFSS simulations were confirmed by measurements of a UHF prototype (Fig. 4b). We prototyped a deployable VHF antenna using a 40"x60" photography reflector (Fig. 4c) which folds into an 18" disk (Fig. 4d), and can be compressed into an oval for stowage. A mechanism to slow down the deployment is being investigated. Preliminary analysis of the VHF antenna's first resonant mode is 16 Hz and therefore is "rigid" enough to ensure stable spacecraft attitude control.

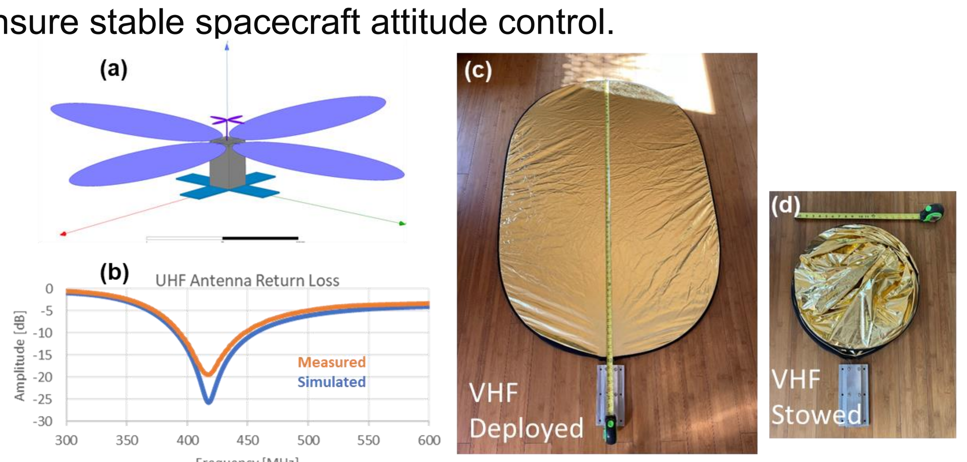

Figure 4: a) Example CubeSat with VHF and UHF antennas deployed, b) measured and simulated UHF antenna performance c) example of a deployed VHF antenna d) and the same VHF antenna in a stowed configuration.

Observables for deep radar sounding within ice are shown in Fig 5a. The array's grating lobes and ice's attenuation affect the detection of the ice bottom. As an example, Fig. 5b shows the estimated total radar signal attenuation to the bottom of the ice for areas where the bottom would not be obscured by the antenna pattern's grating lobes. (For illustration, a simple 500-m pattern of alternating detection in the vertical is used.)

(a)

Observable	Science Interest	References
Bed topography	Ice-sheet instability and future contribution to sea-level rise. This is a static field.	Schlegel et al. (2018) [1] Seroussi et al. (2020) [2]
Bed hydrology	Detection of basal hydrography and sub-ice-base aquifers, which can influence ice-sheet dynamics and evolution. Could be both static and time-variable.	Siegert et al. (2018) [3] Bessette et al. (2021) [4]
Basal units	Large structures near the bed (~100–500 m) of uncertain origin. Can effect ice flow and ice-core stratigraphy. Studied with a 150 MHz radar. This is a one-time measurement.	Goldberg et al. (2020) [5] Ross et al. (2020) [6]

(b)

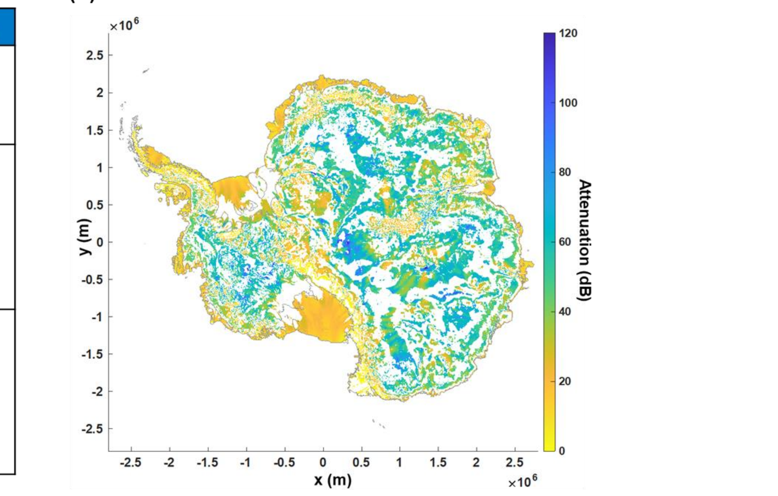

Figure 5: a) Example observables for the ice sounding application, b) an example map of attenuation to the bottom of the ice for regions that are observed with alternating 500m observable and "blind" ranges due to the mitigation or presence of surface clutter in the array grating lobes.

Simulations of the DOWSER Pol-MIMO measurements demonstrate that resistivity mapping is significantly improved compared to the mono-static system (~7x in spatial resolution and ~3x in resistivity inversion). With DOWSER, the delineation of shallow clutter from deeper targets (such as aquifers) is clearly visible. Coherently focusing the MIMO observations reduces the integrated clutter response at the target (i.e., a higher SCR). The focused images provide higher accuracy of the resistivity maps. DOWSER developed full-wave and approximate simulations to evaluate performance, which were compared to scaled laboratory experiments to validate the concept. A system trade analysis was used to define the system architecture, which we will field test in FY22.

Significance/Benefits to JPL and NASA

Several science and application disciplines can benefit greatly from an enhanced ability for subsurface remote observation. These include investigations in glaciers and ice sheets, desert aquifers, soil moisture, permafrost, and magmatic systems. Ice-sheet evolution, an area of research among the most consequential to sea level rise, requires observing dynamic changes where ice sounding is challenging because of steep topography (clutter) or the presence of melt water in or on the ice (high attenuation).

Radar ice sounders are designed to detect subsurface echoes at nadir. The radar also receives surface echoes from off-nadir angles due to the broad antenna pattern. These so-called surface clutter echoes are usually stronger than the subsurface echoes, effectively limiting the radar's maximum sounding depths and cannot be overcome by increasing the transmitter's power. DEBRIS significantly reduces surface clutter via a large antenna aperture that is formed using SAR and beamforming techniques.

DEBRIS is complemented by DOWSER, which applies magneto-quasistatic (MQS) and electro-quasistatic (EQS) techniques using frequencies (typically <100's kHz) where the wavelength are greater than the investigation range. DOWSER uses tomographic techniques to image subsurface structures in high attenuation environments where radar cannot detect.

Publications

[A] M. Haynes, R. Beauchamp, A, Khazendar, R. Mazouz, M. Quadrelli, P. Focardi, R. Hodges, W. Bertiger, N. Bienert, "DEBRIS: Distributed Element Beamformer Radar for Ice and Subsurface Sounding," IGARSS 2021.

[B] Mazouz, R., Quadrelli, M., Beauchamp, R.: Dynamics and Optimal Control for Free-Flight and Tethered Arrays in Low Earth Orbit, IEEE Aerospace Conference, March 2021,

[C] Apa, R., Quadrelli, M., Beauchamp, R.: Dynamics and Control of Helical Arrays in Low Earth Orbit, to be presented at IEEE Aerospace Conference, (submitted, March 2022).

[D] Pastori, M., Quadrelli, M., Beauchamp, R.: Dynamics and Control of Tethered Endfire Arrays in Low Earth Orbit, to be presented at IEEE Aerospace Conference, (submitted, March 2022).

[1] Schlegel, N.-J. et al. (2018), Exploration of Antarctic Ice Sheet 100-year contribution to sea level rise and associated model uncertainties using the ISSM framework, The Cryosphere, 12, 3511-3534,

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