Virtual Research Presentation Conference

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

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Program: Strategic Initiative

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Tutorial Introduction

Localizing the source of signals is critical to meaningful remote sensing measurements. Spatial ambiguity leads to uncertainty in geophysical interpretation. For spaceborne radar sounders, which provide information on the 3D structure of the environments they probe, the radar's footprint is a function of the size of the antenna and the vertical resolution is tied to the radar's bandwidth. Ice sounders, which observe ice sheets that are kilometers deep, use frequencies in the VHF and UHF bands to reduce the signal attenuation through ice. To achieve horizontal resolution on the order of kilometers, VHF antenna apertures need to be on the order of kilometers.

DEBRIS aims to improve the spatial resolution and detection sensitivity of orbital radar sounders by using a distributed beamforming array to synthesize a larger antenna aperture. This reduces the radar footprint, increases the radar's sounding depth, and suppresses off-nadir surface clutter. Each of these effects improves the radar's ability to detect and resolve subsurface features. With increased spatial resolution of radar observations from orbit, DEBRIS can be applied to multiple applications including: ice sheets, aquifers, soil moisture, and permafrost.

DEBRIS Array in LEO

The following team members also contributed to DEBRIS: Vijay Venkatesh (334), Thaddaeus Voss (337), Paolo Focardi (337), Jack Bush (334), William Bertiger (335), Rayan Mazouz (347 / CU Boulder), Nicole Bienert (334 / Stanford)

Problem Description

a) Low frequencies are required for deep radar sounding in ice. Long wavelength radars typically use dipole-like antennas which have broad antenna patterns with poor spatial localization.

  a) Increasing the antenna aperture narrows the antenna beam pattern and spatially constrain the region of observation

b) Regions with topography result in significant “clutter” echoes from the surface that can be stronger than the subsurface echoes.

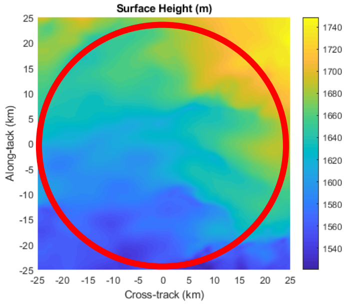
  a) Increasing the antenna aperture narrows the antenna beam pattern which and suppress surface clutter from regions outside of the target area of interest (e.g., at nadir).

c) Synthetic aperture radar (SAR) techniques focus the along-track antenna pattern but still have a broad view in the cross-track direction.

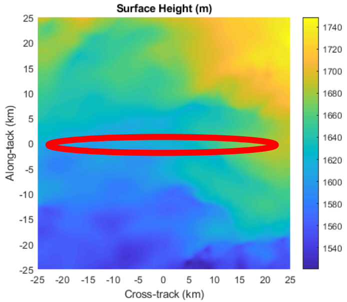
  a) Combining SAR and a cross-track array of distributed radar elements effectively forms a large 2D antenna aperture.

Relevance: A distributed observing system has a broad relevance to NASA and JPL. While our driving application is ice sheet sounding, high-resolution sounders and imaging radars can be applied to characterizing dense forests, root zone soil moisture, permafrost and sea ice, and desert hydrology. The applications for a high resolution distributed sounder system also extends to asteroid tomography and exploration of ice moons.

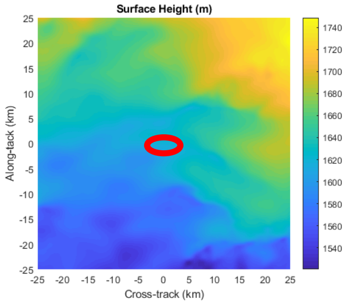
Physical Antenna’s Footprint (No Focusing)



SAR Footprint (Along-track Focusing)



DEBRIS Footprint (Along-track and cross-track Focusing)



Potential Applications

Referencing the Earth Science/Applications objectives identified in the 2017 Earth Science Decadal Survey (DS)

ICE SHEETS/GLACIES [DS2017: C-1c]

Determine the **changes in total ice sheet mass balance**… for decades to come. Measurements include: **ice sheet bed elevation**, ice shelf cavity shape, **ice thickness,** *ice shelf/basal melting*

AQUIFERS/GROUNDWATER/DESERT [DS2017: H-2c, S-6a, S-6c, H-3a]

Quantify how anthropogenic activity affect water quality and ***especially groundwater*** recharge. Determine the transport and storage properties of aquifers.

SOIL MOISTURE [DS2017: H-2c, E-3a, W-2a, S-4b, S-6b, E-1d]

Measure all significant fluxes in and out of the groundwater system across the recharge area. Quantify **moisture** status of **soils**. ***(Also relevant to Aquifers above)***

PERMAFROST [DS2017: C-8f, S-1c]

Measure permafrost thaw which drives land cover changes that affect turbulent heat fluxes, above and below ground carbon pools, resulting greenhouse gas fluxes (carbon dioxide, methane) in the Arctic, as well as their impact on Arctic amplification.

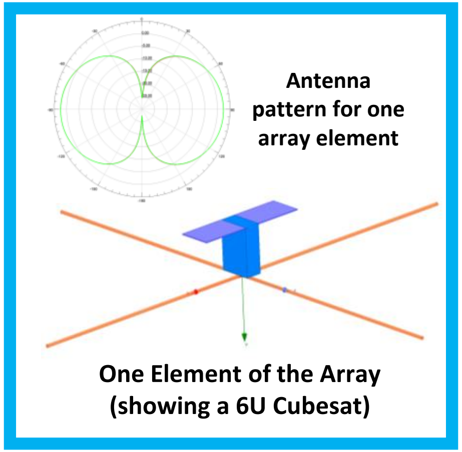
Methodology

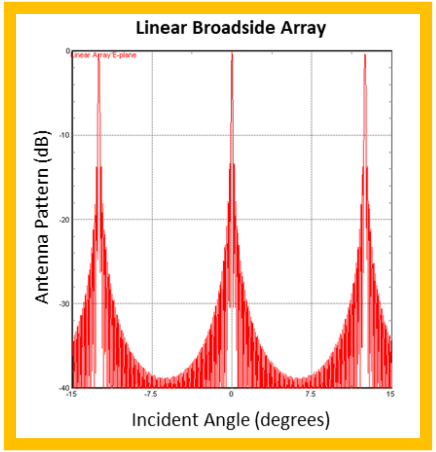
a) The distributed radar system can be implemented using a swarm of satellites (green box). Each individual satellite is an element of the beamforming array (blue box). Each element receives the echoes from the surface and subsurface.

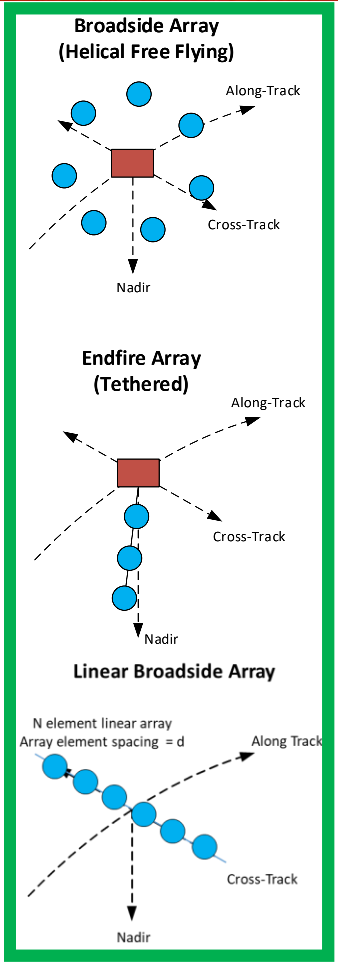
b) By time-shifting the received echoes from each element and then adding the signals from all receivers, we can implement the synthesized antenna pattern (orange box).

c) The distributed array is used to sparsely sample the aperture space. While sparse sampling introduces aperture grating lobes, the grating lobes can be designed to avoid overlapping with the sounding depths of interest (for Antarctica ice sounding, depth <5 km).

d) Electromagnetic sounding using the quasistatic fields are used for deep remote sensing investigations, beyond the reach of radar. Like the orbital sounder, these methods are limited in their spatial resolving power. Extending these methods to form distributed apertures can enhance the spatial resolution and detection capabilities for subsurface sounding beyond the reach of conventional radar systems (see Slide 7).

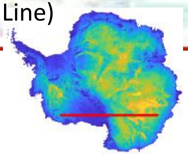




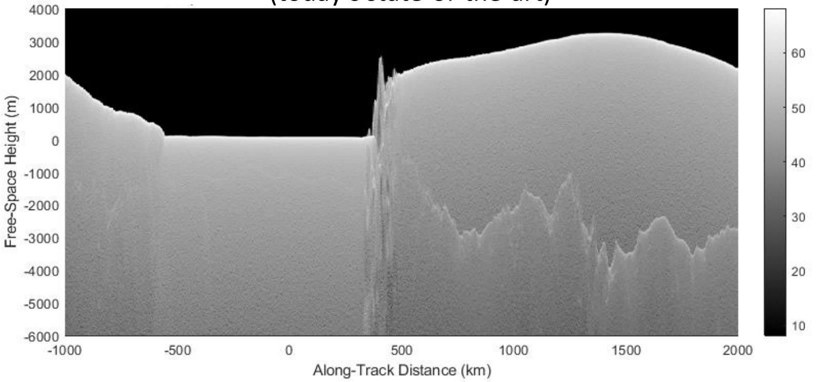


Radar Beamformer Results

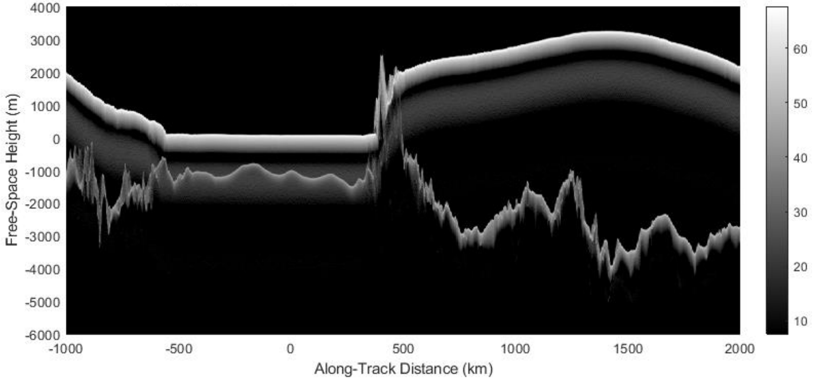
Simulated Overpass
(Red Line)



Monolithic Radar
(today's state-of-the-art)



Notional DEBRIS



In this study, we have determined that several key technologies/methods exist that are required to implement a distributed VHF (45 MHz) DEBRIS system:

a) Combining beamforming with SAR techniques to form a two-dimensional antenna aperture. (confirmed in simulation)

b) GPS can provide the required relative timing and relative positions of elements within an array. (uncertainty ~5 cm RMS, confirmed in simulation)

c) Passive relative orbits (with daily to weekly maintenance) or tethered configurations are available. (confirmed in simulation)

Future Work:

a) Consolidate hardware functionality to reduced the size, weight, power and cost of instrument implementation and operations

b) Evaluate array and ADCS requirements to optimize array sidelobes

c) Design, build and test a wideband VHF/UHF deployable antenna suitable for cubesat/smallsat.

d) Study the trade between a single centralized transmitter vs. a distributed transmitter, evaluating design performance and spacecraft requirements

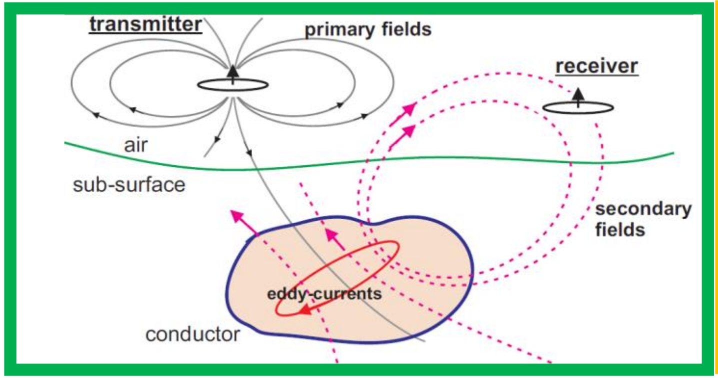
e) In-depth exploration of potential science applications and the imposed system requirements.

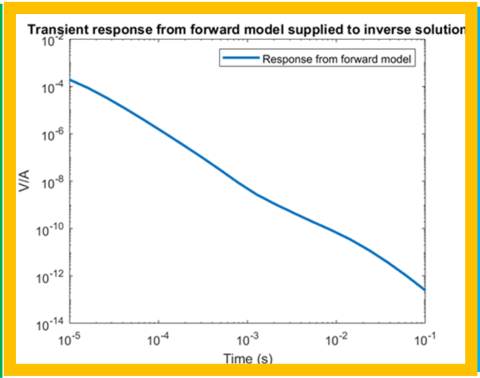
Magnetic Quasistatic (MQS) Remote Sensing

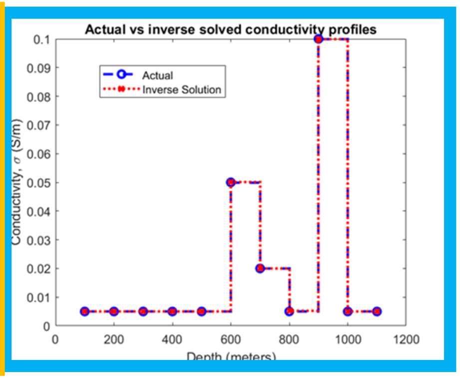
Overview: In the quasistatic regime (within a wavelength of the source/receiver), the electric and magnetic field are decoupled. Transient electromagnetic (TEM) techniques generate a magnetic field that is periodically switched on and off (or alternates polarity). The changing magnetic field induces a current in the subsurface related to its permeability and conductivity. The induced current generates its own secondary magnetic field which is measured by the receiver (green box). Compared to radar, the attenuation is significantly small for MQS allowing deeper investigation depths.

The magnitude and shape of the secondary magnetic field measured at the receiver (orange box) is related to the properties and structure of the subsurface. Measurements of the secondary fields as a function of time delay from the switched field can be related (inverted) to estimate conductivity as a function of depth (blue box).

Next Step: Apply high-resolution synthetic aperture magnetic (SAM) imaging to sounding warm ice to profile thermal state and aquifer detection and ground water monitoring in arid regions.







Publications and References

Carrer, L., Gerekos, C., Bovolo, F., & Bruzzone, L. (2019). Distributed Radar Sounder: A Novel Concept for Subsurface Investigations Using Sensors in Formation Flight. *IEEE Transactions on Geoscience and Remote Sensing*, *57*(12), 9791–9809. https://doi.org/10.1109/TGRS.2019.2929422

Dall, J., Kusk, A., Kristensen, S. S., Nielsen, U., Forsberg, R., Lin, C. C., … Buck, C. (2012). P-band radar ice sounding in Antarctica. *International Geoscience and Remote Sensing Symposium (IGARSS)*, 1561–1564. https://doi.org/10.1109/IGARSS.2012.6351098

National Academies of Sciences, Engineering, and Medicine 2018. Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space. Washington, DC: The National Academies Press. https://doi.org/10.17226/24938.

Mazouz, R., Quadrelli, M., Beauchamp, R. (abstract submitted, 2021) Dynamics and Optimal Control for Free-Flight and Tethered Arrays in Low Earth Orbit. *IEEE Aerospace Conference*.

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