SESAR: A DIGITAL BEAMFORMING POLARIMETRIC SAR FOR NEAR-SURFACE IMAGING.

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Introduction: Many important questions in planetary science are dependent on our ability to detect and map surface and subsurface layers of planetary bodies. These objectives include mapping the surfaces of the planets to determine how they are shaped through different processes (volcanism, cratering, fluvial activity, etc.), comparing the development and evolution of cryospheres across planets, determining how regoliths develop through time, and locating regions that are (or were) hospitable to life., It is critical to be able to search for buried features that hold clues about the planet's geologic history, particularly in dust-covered environments. In addition, identification of subsurface layers will be critical for in-situ resource utilization needed for the manned exploration of the solar system.

Synthetic aperture radar (SAR) is the only remote sensing technique capable of imaging buried surfaces at meter-scale spatial resolution. Current and past Solar System orbital radars operate at fairly short wavelengths (4-13 cm), capable of penetrating only about a meter, or at very long wavelengths (15-100 m), capable of detecting layers greater than ~30 m below the surface. These wavelengths are either too short to penetrate through thick layers of dust and regolith, or too long to be relevant to depths that could be explored via robotic or human missions. In addition, they cannot detect important components of near-surface geology such as potential ice layers and volcanic layering several meters below the surface. Moreover, most planetary radars are not polarimetric and none have the capability to acquire data at the range of incidence angles and resolutions needed for quantitative modeling.

To provide a new capability to address near-surface science questions, we are developing a P-band (70 cm wavelength) digital beamforming radar, called Space Exploration SAR (SESAR), capable of providing the measurement flexibility needed to address multiple types of science goals. SESAR will provide high spatial resolution imaging, full polarimetry, multi-beam scatterometry and altimetry of planetary targets such as the Moon and Mars by using beamforming technology that can adjust the radar experiment to meet the specific science goals of each target.

SESAR Science: We are focusing on development of an orbital radar system for the Moon and Mars, because they both have compelling science goals that would be met by a regolith-penetrating imaging radar. However, the SESAR instrument will be modular and can be easily adapted for Discovery (or New Frontiers) missions to Mercury, Venus, and asteroids (including Ceres and Mars' moons).

Lunar Science: Lunar volcanic deposits provide a window into the Moon's early evolution with ages of up to 3.8 Gyr. However, the surface is covered in a ~2-10 m of regolith (dust and small rock mixture) that hides many aspects of this geology. SESAR will be able to image through the regolith to characterize the near-surface stratigraphy of the Moon in unprecedented detail not available to any other instrument. P-band radar data acquired with Earth-based systems have revealed rough buried flows in mare regions that are not visible to any other type of instrument [1,2]. High-resolution (few m) morphologic mapping and polarimetry with SESAR would reveal details about the volcanic processes that built the mare (e.g. size of flows, emplacement scenarios, channels). SESAR will also be able to image buried channels [2] and possibly detect near-surface lava tubes. Mapping these features is important for both science and future exploration purposes, because tubes could be "safe haven" shelters for astronauts or a path to obtaining less weathered lava samples.

Mars Science: Locating habitable regions, finding water, and determining the evolution of the Martian cryosphere are primary goals of Mars exploration. Because water and all ice outside of the polar regions is buried, radar is a key technology for cryosphere studies. SESAR could detect and image ice or brine under the regolith, and be used to map the extent of these deposits. Other instruments capable of detecting water, such as neutron and gamma ray detectors, have much lower spatial resolution from orbit (km-scale) and cannot penetrate tens of meters under the surface. Radar also has a long history of detecting buried fluvial channels on the Earth and Mars (Fig. 1), and could be

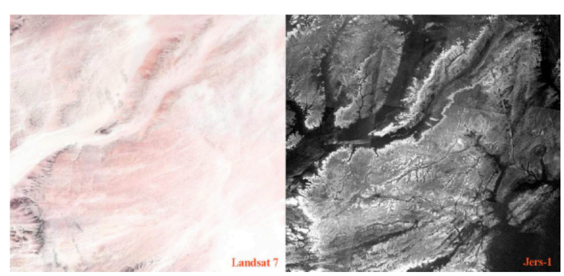

Fig. 1: Radar (right) reveals buried fluvial networks in southern Sudan that are not visible in Landsat imagery (left). SESAR would provide meter-scale imaging of buried channels on Mars. Image from [3].

used to search for these features in the upper tens of meters of the Martian surface. Radar polarimetric data would also allow mapping of dust-covered volcanic units, which would address the questions of how the plains of Mars were formed and what types of volcanism and volcanic flows occurred near both large and small volcanoes.

Key radar parameters: Using a P-band wavelength will ensure that SESAR will image features below 2-3 m (and as much as 10-15 m) of surface cover on the Moon and Mars, and many tens of meters into water ice on Mars. P-band is an ideal wavelength because 1.) it penetrates to a depth that is reachable by human and robotic explorers, 2.) it provides high-resolution, meter-scale imaging, and 3.) it will not reflect from centimeter-sized rocks that are prevalent in near-surface regolith.

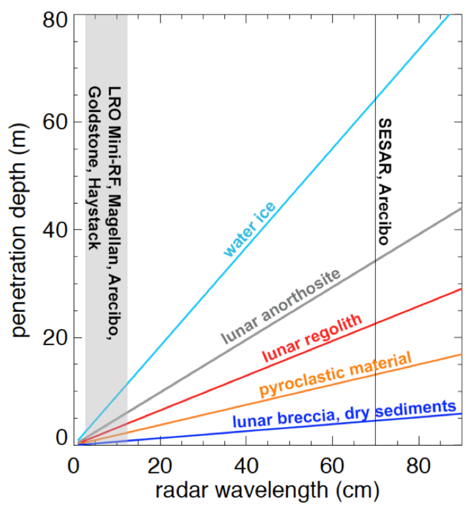

Fig. 2: SESAR will have a greater penetration depth than most prior radars (orbital and Earth-based). Penetration depth is defined as the point at which the wave power has been reduced by 1/e relative to the original power.

Polarimetric data products provide important information about the nature of the surface and subsurface that cannot be obtained solely with backscatter power images (e.g. [4],[5],[6]). Polarimetry data are critical for distinguishing mantling deposits from smooth uncovered surfaces (Fig. 3), and for determining the roughness and continuity of geologic units. The added quantitative information that comes from polarimetry provides the only means to distinguish between surface models.

An imaging SAR with high-resolution, full-polarimetry and flexible look-angle can most effectively be achieved using the digital beamforming approach that will be implemented in SESAR.

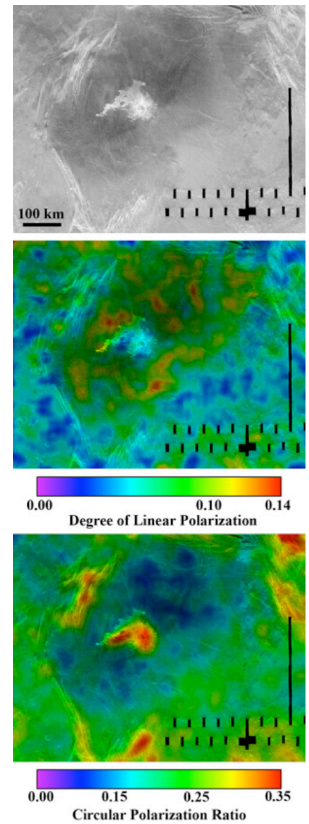

Fig 3: Radar polarimetry from Arecibo Observatory demonstrates that a radar-dark region surrounding the crater Galina on Venus is covered in fine-grained mantling material [6]. Increased DLP values (middle) reveal that the radar wave penetrates into a surficial deposit, while low CPR values (bottom) demonstrate that the deposit is rock-poor. This dark area in Magellan radar imagery (top) is therefore a smooth deposit of cm-sized or smaller material generated by the impact.

The SESAR Instrument Concept: SESAR is an advanced digital beamforming radar instrument concept that will enable a new class of observations suitable to meet Decadal Survey science goals for planetary exploration. The instrument design will employ a modular approach which allows for the customization of the instrument architecture to meet scientific mission requirements for a specific planetary body. The modular approach distributes the radar systems into instrument panels composed of active subarrays, as illustrated in Fig 4. This architecture will be capable of providing surface and subsurface imaging of planetary bodies using advanced multi-mode radar operations, enhancing the scientific observations and enabling new measurements.

SESAR's architecture will be fully programmable and capable of multi-mode radar operation including unprecedented polarimetric SAR imaging, nadir SAR altimetry, and scatterometry. Some of its advanced programmable features include single, dual, or full

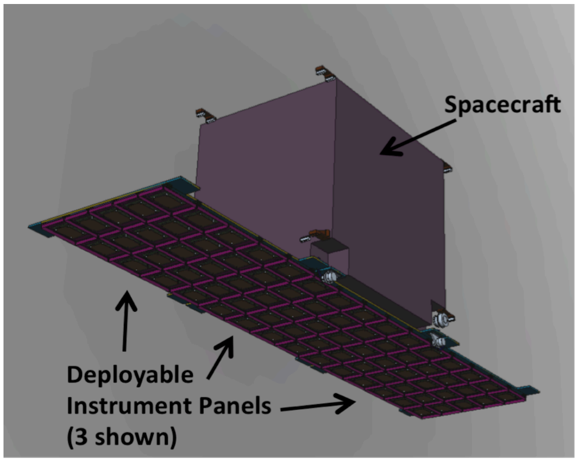

Fig. 4: SESAR employs a modular approach that permits customizing the architectures for a given planetary mission. SESAR's distributed architecture enables advanced operational modes.

polarimetry; multi-look angle data collection: simultaneous left and right of the track imaging; selectable resolution and swath width; digital beam steering (no moving parts); and beam pattern control; among others.

One of SESAR's main features will be its operation using electronic beamforming on transmit, and digital beamforming on receive [7]. Both beamforming techniques employ interference among the signals from each of the radar antenna subarrays to generate far-field beam patterns with predefined and selectable look angles, beamwidths and sidelobe levels, and without the use of moving parts.

Using beamforming, SESAR will be able to synthesize multiple antenna beams, simultaneously or interleaved, permitting the implementation of non-conventional imaging that can overcome fundamental limitations of conventional radar systems [7,8,9]. Some of its benefits include an increase in the measurement swath without reducing the received antenna gain, and the suppression of ambiguities or localized interference in the receiver signal by appropriate null-steering of the antenna pattern. The antenna gain, beam pointing angle, and sidelobe structure can be programmed in real-time for specific tasks. Furthermore, multiple beams can be synthesized on both sides of the flight-track, as well as nadir, using a single nadir-looking antenna, thus increasing the coverage area.

In the SAR imaging mode, SESAR will image the ground with fine resolution pixels in the order of up to 2 m over one or multiple beams to permit geologic analysis. Each of the beams will measure up to four polarizations to facilitate retrieval of the Stokes parameters, from which a broad suite of scattering mechanisms associated with particular geological processes can be assessed. A high-gain single beam on either side of the flight track will image areas that require increased subsurface penetration or higher signal-to-noise ratio (SNR). Simultaneous left- and right-of-the-track beams will provide imaging with increased coverage without degrading the spatial resolution. These techniques have been successfully demonstrated by sirborne radars such as DBSAR [7] and more recently by EcoSAR [10]. Raw data archiving, onboard real-time beam-forming, and onboard SAR focusing will be available. These capabilities will provide a very flexible radar system that can be used to tailor radar experiments to the science questions for a given target.

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