THE P-BAND SPACE EXPLORATION SYNTHETIC APERTURE RADAR (SESAR)

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***Abstract*— The Space Exploration Synthetic Aperture Radar (SESAR) is a P-band (435 MHz) radar instrument for planetary applications capable of measuring the surface and subsurface of planetary bodies at full polarimetry and at meter-scale resolution. These measurements can reveal important information about the surface evolution and geologic history of the planetary bodies, and help identify buried resources for future explorers. SESAR's architecture is based on a low power, lightweight, beamforming design, specifically developed to meet stringent requirements of planetary instruments. The SESAR developmental effort, carried out at NASA/GSFC, designed and built a prototype SAR instrument, and environmentally tested it, with the goal of maturing the SESAR technology readiness level for upcoming planetary mission opportunities.**

Keywords*—— *SAR, P-band, radar, Moon, Mars, subsurface imaging, Beamforming, MIMO.

I. INTRODUCTION

The Space Exploration Synthetic Aperture Radar (SESAR) is a "next generation" P-band Synthetic Aperture Radar instrument specifically designed for planetary exploration. SESAR's long wavelength (70 cm) signals can penetrate through meters of planetary surface cover and image the near-subsurface at meter-class spatial resolution and full polarimetry. These measurements can provide information that is vital to planetary science and exploration [1], [2].

The SESAR instrument is particularly useful for orbital missions to the Moon and Mars (Fig. 1). The upper subsurface – the upper ten meters – of these planetary bodies consists of a layer of dust and regolith which is nearly transparent at P-band wavelengths. This layer contains buried features and materials that hold clues about the surface evolution and geologic history of these planetary bodies. The layer is also close enough to the surface to be accessible to human or robotic explorers and thus serve as a source of resources for future planetary exploration.

Orbiting Mars or the Moon, SESAR would provide global high-resolution polarimetric measurements of the upper subsurface in unprecedented detail not available to any other instrument, thus allowing accurate identification of buried features and resources. For example, SESAR's measurements would characterize the structure and stratigraphy of buried fluvial channels, lava tubes, and ancient lakes; locate buried ice water; and identify habitable regions.

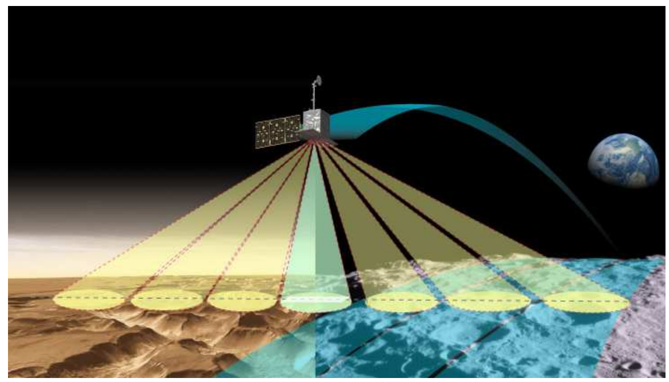

Fig. 1 The Space Exploration Synthetic Aperture Radar (SESAR) is a "next generation" P-band Synthetic Aperture Radar designed to measure high resolution polarimetric measurements of the subsurface for the identification of buried features and resources.

Current sounding radars in orbit at Mars and at the Moon have wavelengths that are too long (e.g., SHARAD [3] and MARSIS [4]), or to short (Mini-SAR [5] and DFSAR [6]) to accurately and unambiguously detect the entire near-subsurface. On the other hand, SESAR's 70 cm wavelength signals will penetrate through up to 10 meters of mantle deposits and their smaller illumination footprint would permit the detection of near-surface features.

Furthermore, SESAR can operate in several modes, including imaging or sounding (altimetry) without slewing the spacecraft by digitally synthesizing custom antenna beams with prescribed pointing and side lobe structure. In imaging mode, the antenna beam is pointed to either side of the flight-track and the radar maps large swaths of the surface and subsurface with unprecedent detail (meter class resolution and high sensitivity). In sounding mode, the antenna beam is pointed to nadir and the radar measures profiles of time delay vs. along track distance, similar to ground penetrating radars like SHARAD.

Our team at the NASA Goddard Space Flight Center (GSFC) recently completed the development of a prototype radar instrument as part of the NASA's MATISSE (Maturation of Instruments for Solar System Exploration) program. Our goal was to build and demonstrate a fully functional radar prototype, test it under critical environmental conditions relevant to missions to Mars and the Moon, and ready the SESAR technology for future mission opportunities.

II. INSTRUMENT DESCRIPTION

SESAR employs a lightweight and low power, multi-channel beamforming architecture that enables capabilities beyond current planetary remote sensing methods, and makes it highly suitable for planetary exploration. Furthermore, the instrument architecture distributes the radar subsystems into instrument panels composed of "smart" active subarrays. Thus, the radar panel, the basic building block of the SESAR 'active' array (Fig. 2), is a self-contained radar that operates in full synchronicity with other panels. This modularity permits configuring the number and arrangement of the radar panels to facilitate meeting a variety of science and mission requirements.

SESAR's beamforming architecture is based on proven P-band (EcoSAR) and L-band (DBSAR) airborne radars [10], [11], and spaceborne radar concepts developed at GSFC [7], [8], [9]. The beamforming architecture is fully programable and capable of several advanced features. For example, the radar can be programmed to operate at different polarizations (full linear, full circular, compact polarization, dual, or single) and bandwidths; or perform measurements at different incident angles and beamwidths. This architecture also enables full beam agility in transmit and receive independently, this permitting the decoupling the transmit and receive antenna patterns. All these unique features can be used to enhance science information, increase coverage, improve sensitivity, and reduce power consumption.

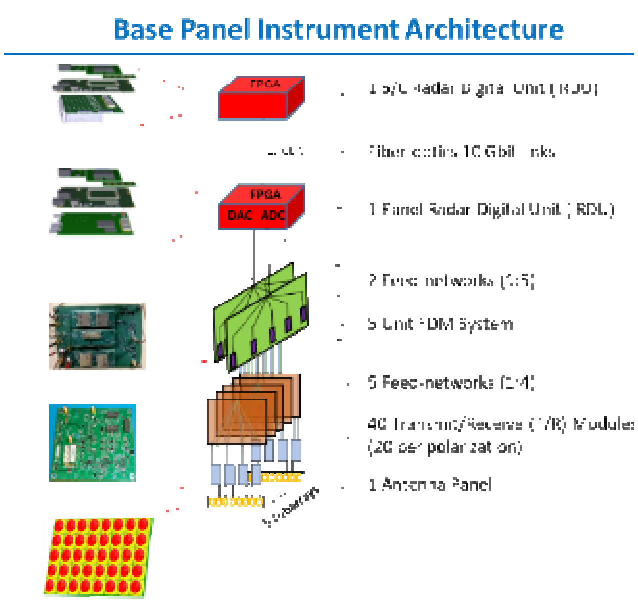

Fig. 2 SESAR's architecture is based on a modular design that employs active programmable panels as the basic building blocks of the beamforming radar. SESAR's architecture consists multiple antenna elements, multiple radar Transmit/Receive (T/R) Modules, a Frequency Domain Multiplexing (FDM) subsystem, and a Radar Digital Unit (RDU).

Table 1. SESAR's performance metrics for missions to the Moon and Mars.

Parameter		Moon	Mars
Center Frequency	(MHz)	435	435
PRF (full pol)	(kHz)	2.4	2.55
Pulse Width	(μs)	50	50
Bandwidth	(MHz)	100	100
Polarization		Full, Hybrid	Full, Hybrid
Slant Range Resolution	(m)	1.5	1.5
NESO (high res. case)	(dB)	< - 23	< -23
Swath (full pol)	(km)	54	70
RF Peak Output Power	(W)	72	432
DC power (avg)	(W)	61	375
Beam Steering	(deg)	± 50	± 50
Antenna Size (L×W)	(m)	2.84 x 1.5	8.52 x 3.01
Panel Configuration	(units)	1 x 1	3 x 2

SESAR's panels are made up of 'smart active' subarrays that are each controlled at the panel level by a programmable Radar Digital Unit. A number of radar parameters can be configured in real-time to meet the specific requirements. Therefore, the architecture can be 'tuned' to meet the science and engineering goals of a specific planetary mission. Furthermore, our architecture design employs advanced processes and techniques to reduce significantly the mass and power of the radar, and to meet the stringent requirements of planetary instruments. Table 1 lists the radar performance metrics for two possible configurations and mission scenarios: A single panel for a Moon mission, and a six panel array for a Mars mission.

The description of each of the SEAR main subsystems is as follows:

A. Antenna:

The SESAR antenna array operates at 435MHz in two linear polarizations (H &V) over a 100 MHz bandwidth to support the high-resolution full-polarimetric imaging, and beam steering agility. The antenna array (Fig. 3) consists of a panel of forty antenna elements (5 subarrays of 8 elements).

Our element design (Fig. 3) is based on a dual-layer slot-coupled patch approach that provides high bandwidth (> 100 MHz) and high cross-polarization isolation (> 30 dB), and enables beam steering over a wide range of angles (±45°). The antenna element construction employs a composite material structure that exhibits high stiffness and low mass (~0.5 kg per antenna element), while allowing optimum RF performance. Eelectromagnetic and structural analyses of the antenna element and the antenna array were performed to ensure the design met the instrument and launch requirements with margins.

We investigated two types of composite materials - Kevlar reinforced cyanate ester, and woven glass-reinforced epoxy (FR4) – for use in the final design. Prototype antenna elements of each the designs were fabricated and environmentally tested.

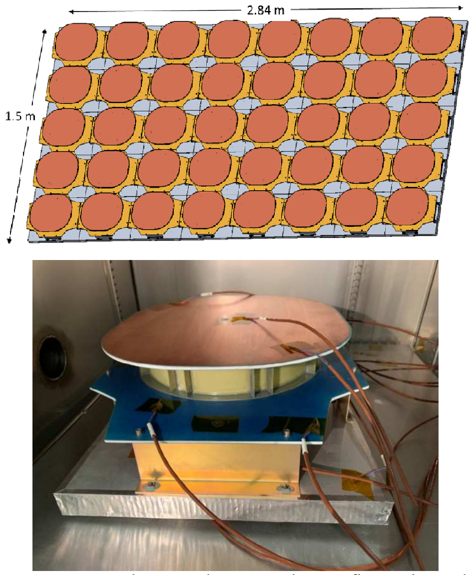

Fig. 3 The SESAR panel, CAD shown on the top figure, is made up of 40 dual-polarization antenna elements. The antenna elements (bottom figure) were designed for lightweight and high stiffness.

After evaluation of test results, the FR4 design was selected for the final build as its structural and RF performance was very similar to the Kevlar prototype, but it exhibited significant advantages in the fabrication process, the mass difference between the two prototypes was not significant (< 10%), and it had a lower cost.

Once the mechanical and the RF aspects of the prototype antenna element design were rigorously evaluated, forty antenna elements were fabricated, thermally stressed, and individually tested for RF performance. In addition, before beginning the assembly of the full-size array, we assembled 5 elements into a subarray (5 x 1 elements) and measured its far-field radiation patterns in the anechoic chamber. The results showed a very good agreement with our predictions from simulations using HFSS. The 40-element array (Fig. 3 and 6) assembly consisted in installing the individual antenna elements on a light-weight aluminum honeycomb backplane that serves as the instrument ground plane and main structural frame. Signals to and from each of the antenna elements are routed through the honeycomb for connections to the instrument's electronics units (described below) were on the back of the panel.

B. Radar Digital Unit (RDU) and The Frequency Division (FDM) Operation:

SESAR achieves reduction in mass and power consumption by employing a novel FDM technique [12],[13] to steer the array. The FDM approach reduces the number of DACs and ADCs required in the RDU for beam steering, and enables centralized waveform generation and data acquisition that preserves full array steering functionality. Only a single DAQ and a single ADC are required to steer the transmit and receive beams of the SESAR radar panel. The FDM approach was developed for SESAR [12] a fully demonstrated by our team as described in section *D*.

SESAR's RDUs (Fig. 4) consists of FPGA-based programmable digital electronics custom designed for SESAR. On transmit, a panel RDU generates five modulated (e.g., chirp) signals using a single DAC. The signals are spread across five frequency bands over the bandwidth of the DAC (~2 GHz). The signals are synthesized with appropriate phase and amplitude weights to drive the array and steer beam with a predetermined antenna pattern. The multi-band signal is then routed to the FDM subsystem. The FDM frequency-translates each of the bands to the radar operational band (centered at 435 MHz) and outputs them as separate RF channels that, after amplification by the REU, drive each of the panel subarrays.

On receive, signals from each subarrays are conditioned by the REU and then routed to the FDM where they are translated back to their initial bands (i.e., the reverse process used for transmitting), and fed back to the RDU as single multi-band signal. In the RDU, the multi-band signal is then coherently sampled by a single ADC and passed to the FPGA for onboard processing.

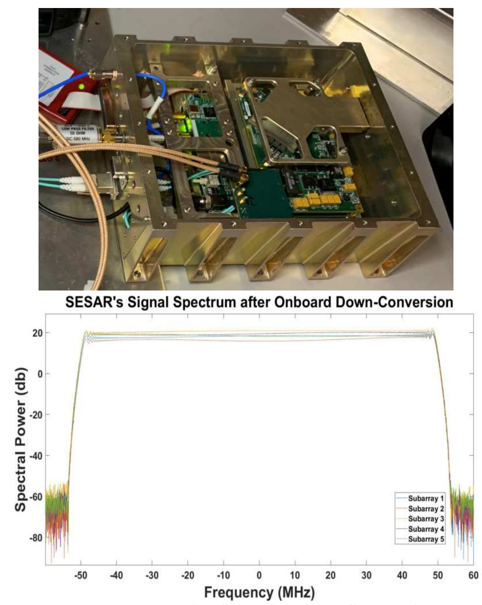

Fig. 4 SESAR's RDU (one unit shown on top figure) is responsible for waveform generation, data acquisition, down-conversion, filtering, and decimation, as well as timing and control, and onboard data processing. The firmware and hardware functionality generating and acquiring five frequency multiplexed 100-MHz bandwidth waveforms (bottom plot) was demonstrated in the lab, and later in the anechoic chamber.

The units employ power efficient components, including Kintex Ultrascale FPGAs, and power efficient Digital-to-Analog (DAC) and Analog-to-Digital (ADC) converters. The firmware running on the RDUs is responsible for performing the FDM waveform generation, data acquisition, down-conversion, filtering, and decimation, as well as timing and control, onboard data processing. Two identical RDUs were fabricated thermally tested over the operational temperature ranges the SESAR instrument electronics would be exposed to at the Moon and Mars (-20° to 40° C). The RDU's firmware and hardware functionality was tested in the laboratory, and later demonstrated in the anechoic chamber with full SESAR system beamforming tests.

Fig. 5 SESAR's T/R modules were designed for high efficiency, robust performance, compactness and reduced weight while exhibiting optimum system performance. Each module is paired with an antenna subarray to support beamforming operation. The modules also included independent loop back calibration paths.

C. *RF Transceiver (T/R) Modules:*

SESAR's T/R modules (Fig. 5) build on the heritage of Goddard's DBSAR and EcoSAR radar systems which miniaturized radar transceivers while exhibiting optimum system performance [14]. The primary function of the transceivers is to amplify the transmit signal to the necessary power level to feed the antenna, and to amplify and conditioned the very low power signal returns form the surface. Each module transmits into and receive from a single antenna subarray.

The design of the modules employs an innovative approach based on surface-mount components on compact printed circuit boards that effectively reduce mass and power consumption, and increase reliability. The transmit section of each module employ solid state power amplifier (SSPA) that operates at efficiency (60%). Power consumption is further reduced by the instrument duty factor using a fast-switching capability The T/R receiver section was designed for low noise figure to yield high SAR imaging signal to noise ratio (SNR). The module also includes loop back paths to calibrate the transmitter and receiver independently, thus permitting measurements with high accuracy and precision.

D. *Environmetal Testing:*

The goal of the environmental tests was to validate the SESAR instrument under relevant Mars and Moon environmental conditions. Achieving the "acceptance performance" level in these tests raised SESAR's Technology Readiness Level (TRL) to a level 6. The tests performed included radar operation in the anechoic chamber, radar subsystems testing in thermal chambers (in vacuum and at standard pressure), and subsystems and full system testing on vibration tables.

SESAR's main subsystems were thermally stressed in order to prepare them to vibration testing. The antenna's forty elements were exposed to the temperatures relevant to the Moon's environment (more stringent temperature requirements than Mars) in a TVAC chamber at a pressure of 0.04 Torr. The RF electronics (RDU, T/R, and FDM units) were also thermally stressed at the relevant temperatures (at standard pressure).

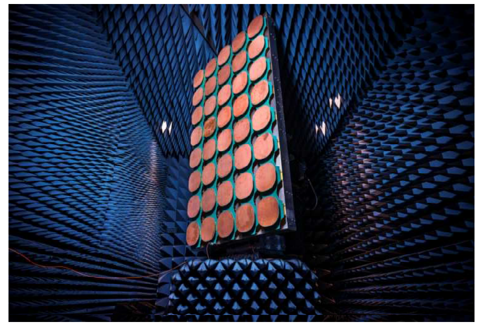

Fig. 6. SESAR at GSFC's anechoic chamber during the systems RF characterization, beamforming demonstration, and antenna pattern measurements.

All SESAR's subsystems were then integrated into the final radar instrument configuration where all electronics, RF cables, and thermal control were installed on the back of the honeycomb ground plane. The radar's RF functionality was fully evaluated in the laboratory, and upon verification of radar performance, the instrument was taken to the RF anechoic chamber (Fig. 6).

The anechoic chamber tests consisted in the characterization of each of the radar's transmit and receive channels, and the generation of a beamforming coefficients matrix required to steer the beam to any arbitrary angle within the radar's field of view (± 45°). Then, the radar's beamforming operation was successfully demonstrated by generating panels with prescribed look angles and side-lobe structure, and antenna patterns were measured at each of the steering angles. Fig. 7 shows the measurements of boresight gain and phase patterns for each of the individual subarrays (top plots), and the beamformed gain pattern for the entire antenna panel (bottom plot).

Next, the SESAR instrument was tested for vibration at GSFC's Integration and Test (I&T) facilities (Fig. 8). Lateral and vertical vibration loads, representative of the loads the radar would be exposed during launch, were applied. Sine, random and burst waveforms at levels specified by GSFC's General Environmental Verification Specification (GEVS) were used in the tests. Accelerometers, deployed at various locations of the array, measured the array response to the applied waveform. All the GEVS acceptance levels were met during the tests.

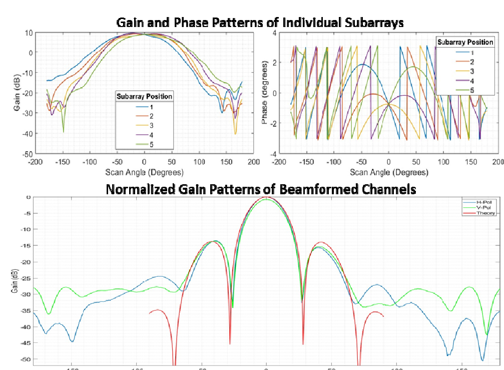

Fig. 7. SESA's boresight gain and phase patterns of the individual subarrays after calibration are shown on the two top plots. The resulting beamformed far-field pattern is shown at the bottom.

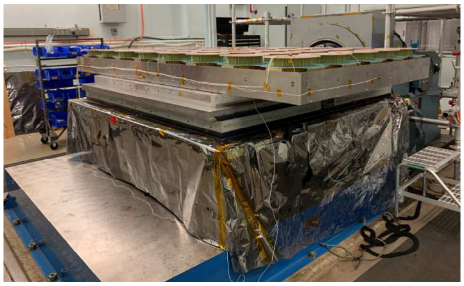

Fig. 8. SESAR during vibration tests at GSFC's I&T facility.

CONCLUDING REMARKS

SESAR's innovative technology and techniques enable a new class of surface and subsurface measurements of planets and asteroids terrains currently not available for planetary science and exploration. The instrument's development and environmental testing performed at NASA GSFC were aimed at demonstrating a unique kind of planetary radar, and at maturing the technology readiness level for upcoming planetary mission opportunities. The radar's full polarimetry, meter-scale resolution measurements, low power and lightweight design, and multimode operation will provide unprecedented information vital to future Moon and Mars orbital missions, and help pave the way for the next generation planetary radar systems.

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