SPACE EXPLORATION SYNTHETIC APERTURE RADAR - LUNAR INVESTIGATIONS TARGETED EXPERIMENT (SESAR-LITE)

R. F. Rincon, L. M. Carter[*], D. Hollibaugh-Baker; C. F. du Toit, M. Perrine, P. Steigner; B. Farrokh, M. Choi, S. Van Nostrand, N. Cao, E. Shoemaker

NASA Goddard Space Flight Center, [*]University of Arizona

Abstract

The SESAR-LITE (Space Exploration Synthetic Aperture Radar - Lunar Investigations Targeted Experiment) instrument is a compact P-band (70 cm wavelength) polarimetric synthetic aperture radar under development at the NASA Goddard Space Flight Center (GSFC) to measure the surface and upper subsurface of the Moon at full polarimetry and at meter-scale resolution. The radar will use a compact deployable antenna, distributed RF electronics, and multi-channel digital processing system to enable a set of focused mission goals for small payload opportunities. The instrument development leverages proven technology advancements recently developed and demonstrated at NASA GSFC for SESAR (Space Exploration Synthetic Aperture Radar), a flagship version of the instrument that was tailored for larger orbital missions. The development of SESAR-LITE addresses accommodation flexibility on multiple launch vehicle families that require small packages while providing unprecedented surface and subsurface imaging of the Moon as required by NASA's Artemis program. The goal of this effort is to mature the technology readiness level and to demonstrate the unique features and capabilities of this radar in preparation for upcoming mission opportunities.

***Index Terms*—** Radar, SAR, sounder, P-band, Moon, lunar, Artemis, subsurface, imaging, beamforming.

1. INTRODUCTION

SESAR-LITE is a P-band (435 MHz) orbital radar instrument capable of imaging up to several meters below the lunar surface at meter-scale spatial resolution and at full polarimetry. The radar's multi-channel and programmable architecture permits the implementation of advanced radar acquisition modes that can improve science while dynamically adjust to mission requirements.

The radar measurements can reveal the structure and stratigraphy of the upper lunar subsurface (upper 10 meters), helping identify and map buried features and resources that address a number of scientific goals of NASA's Artemis program [1]. For example, these measurements can be used

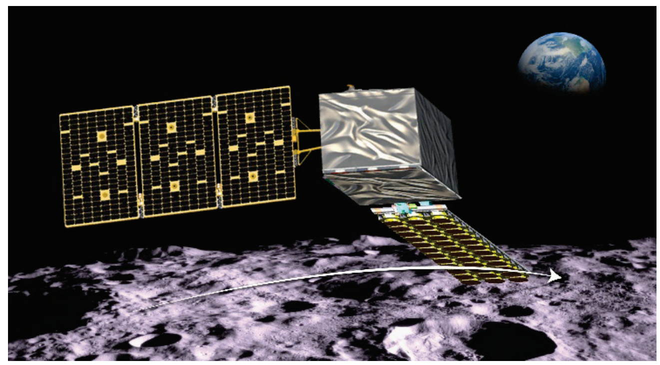

Fig. 1. SESAR-LITE's fully-polarimetric P-band (70 cm) signals penetrate several meters below the surface to detect subsurface features. Designed to fly on a smallsat, such as a NASA SIMPLEx mission, this radar can provide meter-scale spatial resolution imaging that addresses multiple Artemis, LEAG, and Decadal Survey science and exploration goals.

to characterize the physical properties of regolith and buried water ice and identify human-habitable regions of scientific interest, including lava tubes that can potentially serve as shelters for future human explorers. The upper lunar subsurface region is also close enough to the surface to be accessible to future human or robotic explorers. Therefore, characterizing its structure and mapping its stratigraphy will provide important context for understanding science and evaluating resources at lunar landing sites [2][3].

The near-term goal of the ongoing SESAR-LITE development effort is to design a compact deployable radar instrument, mature its technology readiness level (TRL6 goal), and demonstrate the unique features and capabilities of this radar through testing it in relevant lunar environmental conditions. This instrument will be a significant improvement over prior and current lunar orbital SARs since it is designed to acquire higher resolution (meter-scale) measurements at full polarimetry (the first time on the Moon), probe deeper into the surface (several meters), and implement programmable operational modes technology for dynamically customized data collections.

2. INTRUMENT OPERATIONAL MODES

The SESAR-LITE radar instrument design employs a programmable beamforming architecture consisting of “smart panels” that enable beam agile SAR imaging, sounding, or scatterometry, without slewing the antenna [4][5]. A split phase center mode that enables interferometric processing is also possible [6]. The programmable capability allows the selection of hybrid - transmit left- or right-hand circular (LC or RC) and receive horizontal (H) and vertical (V), full (HH,VV,VH,HV), single (HH or VV), or dual (HH, HV or VV,VH) polarizations depending on measurement requirements or data volume constraints. The transmit and receive beam’s look-angle is also selectable and the beam side-lobe structure can be formed to meet specific science and engineering requirements. Other programable parameters include the radar bandwidth (or range resolution), pulse repetition frequency (PRF), pulse length, and the number of transmit and receive beams. Table 1 lists general SESAR-LITE radar parameters.

Table 1. SESAR-LITE’s Parameters for Lunar Orbit.

Parameter	Value
Radar Orbit Altitude	50 km
Spacecraft Velocity	1,610 m/s
Look Angle (deg.)	± 45 deg
Center Frequency	435 MHz
Bandwidth	Variable (100 MHz max)
Polarization	HH, HV, VH, VV, LC, RC
Pulse Width	Variable
Array Size	3.6 m x 1 m
Number of Antenna Panels	4
Antenna Elements per Panel	9

In SAR imaging mode, SESAR-LITE will be capable of measuring the surface or subsurface over single or multiple beams at programmable incident angles to optimize geologic analysis. Each beam 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. Left- and right-of-the-track observations will provide imaging with increased coverage without degrading spatial resolution [4]. Table 2 lists nominal performance parameters for SESAR-LITE’s high resolution, full pol SAR imaging mode.

Table 2. SESAR-LITE’s Nominal Parameters for the High Resolution, Full Polarization SAR Imaging Mode.

Parameter	Value
Pulse Width	30 µs
Bandwidth	100 MHz
Slant Range Resolution	< 1.5 m
Single Look Azimuth Resolution	0.5 m
Single Look NESO	- 25 dB
PRF	6.4 kHz
Swath	20 km
Data Rate	583 Mbps
DC Ave. Power (W)	117 W

In sounding mode, SESAR-LITE’s nadir observations will provide high resolution subsurface stratigraphy and the depths of the distinct subsurface layers, which combined with overlapping SAR observations will provide volumetric characterization of the lunar regolith. In this mode, the antenna beam is pointed at nadir and the radar measures profiles of time delay vs. along track distance, similar to ground penetrating radars. Doppler beam sharpening techniques such as the Delay/Doppler technique [6], can be performed onboard to re-duce the along-track footprint and provide better speckle reduction and precision than conventional altimeters. Table 3 lists nominal performance parameters for SESAR-LITE’s Sounder mode.

Table 3. SESAR-LITE’s Nominal Parameters for the Sounder Mode.

Parameter	Value
Pulse Width	10 µs
Bandwidth	100 MHz
Vertical Resolution	< 1.5 m
Along-Track Resolution	< 5 m
PRF	10 kHz
Measurement Precision	0.2 dB

The scatterometer mode will help characterize the physical (e.g., roughness) and electrical (complex permittivity and loss tangent) properties of the surface and shallow subsurface at larger scales. SESAR-LITE’s scatterometry can be implemented using a narrow beam or wide beam illumination techniques [4]. In the narrow beam approach, the radar will illuminate the ground - on a pulse-to-pulse basis - by generating a narrow-beamwidth transmit pattern at the selected look angles within the antenna field of view. On receive, the backscatter signals will be detected, digitized, and digitally beamformed, pulse by pulse, over the illuminated areas. In the wide beam approach, a wide beamwidth will be generated by phase spoiling techniques or by energizing only the central subarrays, fully or partially illuminating the antenna field of view on each radar pulse. The backscattered signals will then be detected with the full antenna array and digitally beamformed at selected look angles over the illuminated scene. Table 4 lists nominal performance parameters for SESAR-LITE’s scatterometer mode.

Table 4. SESAR-LITE’s Nominal Parameters for the Scatterometer Mode.

Parameter	Value
Pulse Width	10 µs
Bandwidth	10 MHz
Slant Range Resolution	< 1.5 m
Along-Track Resolution	< 5 m
PRF	10 kHz
Measurement Precision	0.2 dB

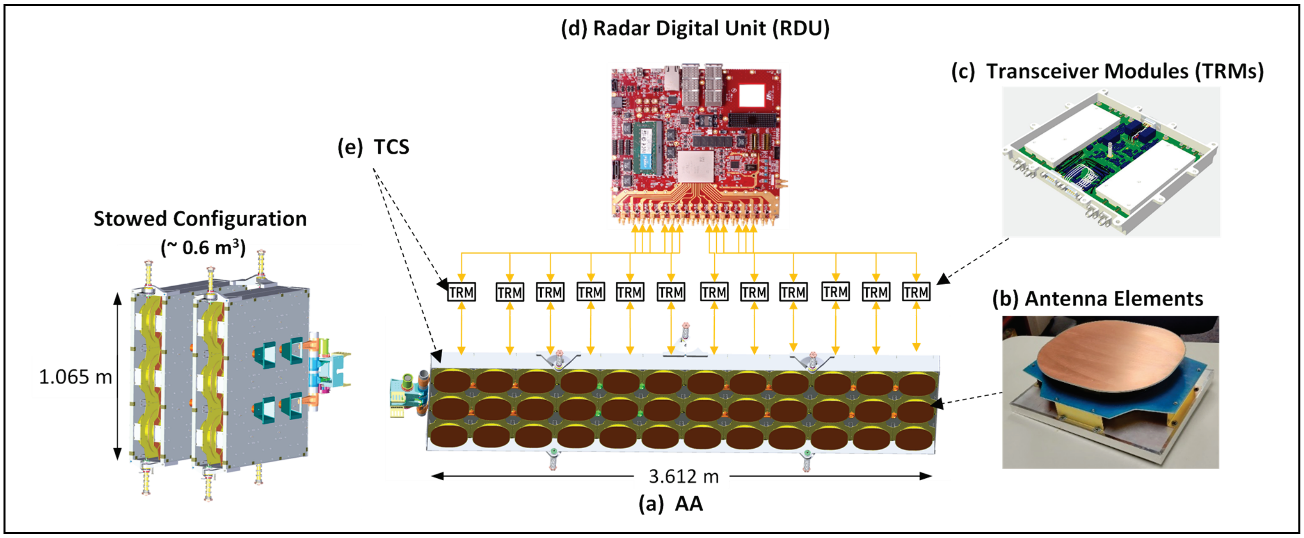

Fig. 2. SESAR-LITE's compact modular design employs four lightweight antenna panels and high efficiency distributed digital and RF electronics that enable low-cost lunar missions and compelling science.

3. INSTRUMENT ARCHITECTURE

The SESAR-LITE instrument employs a modular and lightweight architecture that can be compactly stowed for launch and easily deployed for orbital operation (Figs. 1 and 2). The instrument development leverages state-of-the-art technology advancements recently designed, built, and demonstrated (TRL 6) at NASA GSFC for SESAR (Space Exploration Synthetic Aperture Radar), a larger version of the radar instrument that was tailored for larger orbital missions (e.g., Mars mission) [5].

In contrast, SESAR-LITE is being designed for compatibility with smallsat missions (e.g., NASA SIMPLEx type of missions). Similar to other previous NASA/GSFC radar designs [8], SESAR-LITE consists of an "active" Antenna Array made up of programmable radar panels (Fig. 2). Each radar panel consists of individually controlled subarrays which are commanded by a centralized FPGA-based Radar Digital Unit (RDU). The RDU generates and receives RF signals that are conditioned at each subarray by Transmit/Receive Modules (TRMs). The TRMs in turn direct and receive the signals from the antenna subarrays. A Thermal Control System (TCS) ensures the radar system components stay well within their specified operational and survival temperature ranges for the extreme temperature environment of a lunar orbit.

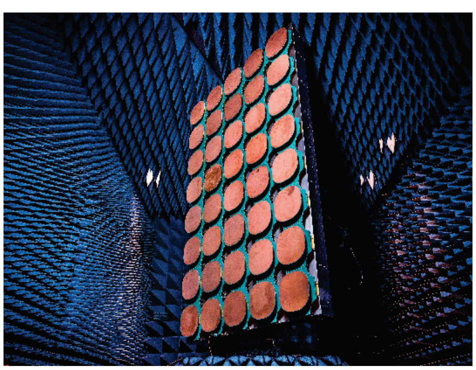

Fig. 3. The Space Exploration Synthetic Aperture Radar (SESAR), previously developed at NASA/GSFC for accommodations in larger orbital missions.

Antenna:
The SESAR-LITE Antenna Array (Fig. 2a) is made up of four antenna panels that are stowed and deployed by a custom hinge mechanism similar to the mechanisms used in solar arrays. Each antenna panel is populated with nine antenna elements (Fig. 2b) and three dual-polarization TRMs (Fig. 2c).

The antenna elements were previously developed for SESAR [5][9] and were designed with composite materials to provide high stiffness and strength while having low mass (500 g each). The predicted cross-track radiation pattern performance of the SESAR-LITE 4-panel array is shown in Fig. 3, for the 0° and 40° scan angles in the xz-plane and at the upper end of the operational frequency range. The element spacing in the across-track direction is chosen to sufficiently suppress grating lobes.

Transmit Receive Modules:
The SESAR-LITE TRMs also leverage transceiver technology previously developed (TRL 6) for SESAR [5]. These modules were designed for high power-efficiency and employed lightweight electronics. For SESAR-LITE, pairs of the original SESAR TRMs designs were combined into a single printed circuit board and enclosed by a single chassis in order to reduce overall instrument mass and power consumption. The TRM circuits were also further optimized for higher performance and improved efficiency.

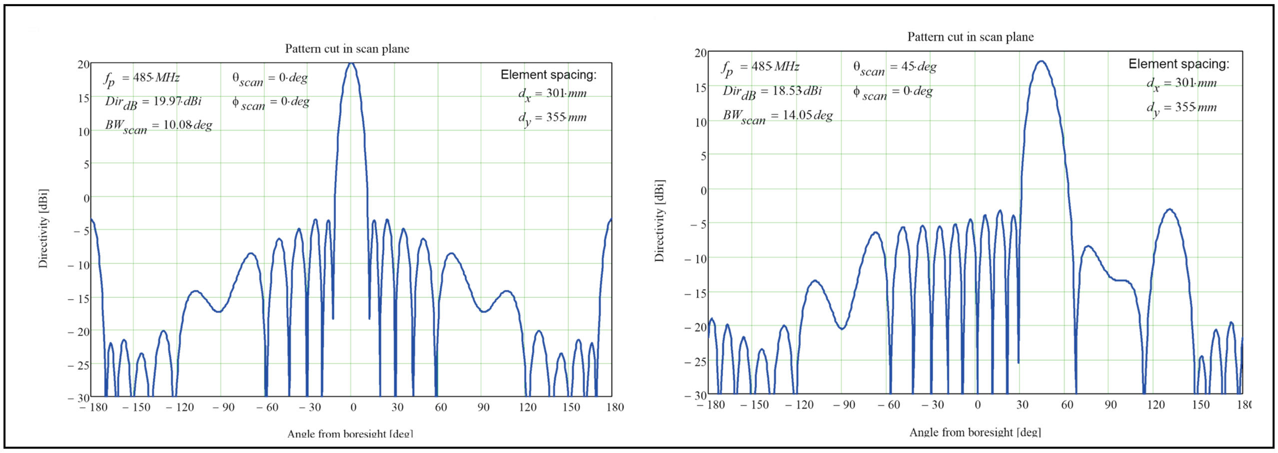

Fig. 4. SESAR-LITE's predicted cross-track radiation pattern performance for 0° and 40° scan angles at the upper end of the operational frequency range.

Radar Digital Unit (RDU):
SESAR-LITE's RDU (Fig. 2d) employs two Xilinx Zynq UltraScale RF System on Chip (RFSoC) boards [10]. Each RDU operates twelve high-efficiency Digital-to-Analog (DAC) and Analog-to-Digital (ADC) converters within the FPGA. The RDUs generate the radar transmit waveforms, acquire the radar signal returns from each subarray, perform onboard processing including beamforming and pulse compression. The RDUs also provide timing and control signals to the radar, and archive the collected data.

Thermal Control System (TCS):
SESAR-LITE's TCS (Fig. 2e) is being designed to handle the worst-case temperature scenarios based on the solar β angle range for the expected lunar orbits. The TCS utilizes the chassis of the TRMs as heatsink/radiators, with conductive optical solar reflectors to minimize the thermal effects of solar impingement. A conductive thermal coating will be used on the front of the antenna, and a multi-layer insulation (MLI) blanket on the back of the ground plane will provide thermal isolation from the orbit environment. Worst hot case (β = 0°) and worst cold case (β = 90°) prediction models were carried out, showing this approach meets the instrument's operational and survival temperature requirements for the planned lunar orbits.

4. CONCLUSION

SESAR-LITEs full polarimetry, meter-scale resolution measurements, and multimode operation will provide unprecedented information vital to future science or exploration of the Moon. The radar's advanced measurement capability coupled with its low power, lightweight, and compact design will enable a new class of smallsat-based surface and subsurface measurements currently not available for planetary investigation.

The SESAR-LITE instrument development is aimed at maturing the design technology readiness level by testing and demonstrating its unique features and capabilities in lunar mission relevant environments. Our long term goal is to prepare the instrument for upcoming Artemis mission opportunities and help pave the way for the next generation planetary radar systems.

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5. REFERENCES

[1] NASA – Artemis III Science Definition Report, Dec 2020. https://www.nasa.gov/wp-content/uploads/2015/01/artemis-iii-science-definition-report-12042020c.pdf.
[2] The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations and Priorities. Posted 2015 by the Lunar Exploration Program Analysis Group (LEAG), 2016. https://www.lpi.usra.edu/leag/roadmap/
[3] L. M. Carter, R. R. Rincon, C. F. du Toit , M. Perrine, D. Lu, R. Banting, D. M. H. Baker, P. Steigner, K. Segal, B. Farrokh, D. Caruth, M Choi, I. Ibanez, W. Aberdeen, and T. Khan, "Development of the Space Exploration SAR (SESAR) for Planetary Science Missions", presented at the *52nd Lunar and Planetary Science Conference (LPSC)*, 2021, abstract #1268
[4] R. F. Rincon, M. A. Vega, M. Buenfil, A. Geist, L. Hilliard and P. Racette, "NASA's L-Band Digital Beamforming Synthetic Aperture Radar," in IEEE Transactions on Geoscience and Remote Sensing, vol. 49, no. 10, pp. 3622-3628, Oct. 2011, doi: 10.1109/TGRS.2011.2157971.
[5] R. F. Rincon et al., "The P-Band Space Exploration Synthetic Aperture Radar (SESAR)", *2023 IEEE Radar Conference (RadarConf23)*, San Antonio, TX, USA, 2023, pp. 1-5, doi: 10.1109/RadarConf2351548.2023.10149559.
[6] K. Raney, "The delay/Doppler radar altimeter," IEEE Trans. Geosci. Remote Sens., vol. 36, no. 5, pp. 1578–1588, Sep. 1998.
[7] R. Rincon, T. Fatoyinbo, S. Lee, B. Osmanoglu, J. Ranson and G. Sun, "Digital beamforming synthetic aperture radar (DBSAR): Single-pass interferometry for forest structure estimation," 2015

IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Milan, Italy, 2015, pp. 200-202, doi: 10.1109/IGARSS.2015.7325734.
[8] R. F. Rincon et al., “Development of Next Generation Digital Beamforming Synthetic Aperture Radar architectures”, *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Beijing, China, 2016, pp. 2109-2111, doi: 10.1109/IGARSS.2016.7729544.
[9] Du Toit et al., NASA New Technology Report (NTR # 19073-1), Sept 2022, *Dual Polarized, Wide Band, Light Weight P-band Antenna Element and Array*.
[10] "Zynq UltraScale+ RFSoC Design Overview (DH219)”, docs.xilinx.com. https://docs.xilinx.com/v/u/en-US/dh0087-zynq-rfsoc-hub (accessed Jan 12, 2023).