The next generation planetary radar system on the Green Bank Telescope

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ABSTRACT

The National Radio Astronomy Observatory (NRAO), Green Bank Observatory (GBO), and Raytheon Intelligence & Space (RIS) are designing a high-power, next generation planetary radar system for the Green Bank Telescope (GBT). As a pilot project, a low-power, Ku-band transmitter (up to 700 W at 13.9 GHz) designed by RIS was integrated on the 100-meter GBT at GBO, and radar echoes were received at NRAO's ten 25-meter Very Long Baseline Array (VLBA) antennas. These observations generated the highest resolution, ground-based, synthetic aperture radar images of select locations on the Moon ever collected, provided size and spin-state characterizations of defunct satellites, and detected a near-Earth asteroid at a distance of 2.1 billion meters (~5.5 lunar distances) from Earth. Design work continues on the final objective of a 500 kW, Ku-band planetary radar system for GBT using the VLBA and the future Next Generation Very Large Array (ngVLA) as receivers with capabilities of target characterization and imaging for space situational/domain awareness and planetary science/defense. As a next step in the near term, integration of a medium-power, Ku-band transmitter (of at least 10 kW) would develop the end-to-end system at GBO/NRAO for real-time radar observations.

1. INTRODUCTION

Space situational awareness, the predictive knowledge and characterization of natural and/or man-made objects in space, is a critical capability for United States (US) space activities. High-power radar infrastructure in the US for radar astronomy and planetary defense has generally relied on assets of the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) to perform this mission. Since the 2020 collapse of the 305-m William E. Gordon Telescope at Arecibo Observatory in Puerto Rico, access to high-power radar observations by the US scientific community has been severely diminished, leaving the 70-m Goldstone telescope (DSS-14) in California, part of the Deep Space Network, as the only remaining high-power planetary radar system in the US. At the time of the Arecibo collapse, Associated Universities Inc. (AUI), who manage the National Radio Astronomy Observatory (NRAO) and Green Bank Observatory (GBO), and partner Raytheon Intelligence & Space (RIS) had just completed a pilot demonstration using the 100-m Robert C. Byrd Green Bank Telescope (GBT) in West Virginia, shown in Fig. 1, as a radar transmitter and ten 25-m antennas of the Very Long Baseline Array (VLBA) as receivers.

While the GBT has often acted as a radar receiver for transmissions from Arecibo and Goldstone due to its large aperture and maneuverability, this was the first time the GBT was used as a radar transmitter. During two observing campaigns conducted using the GBT/VLBA system, we obtained synthetic aperture radar (SAR) images of the Moon, collected against space debris in the form of two defunct satellites, and detected a near-Earth asteroid. Details are provided in [1]. Here, we discuss the experiments and results of the GBT/VLBA radar observations conducted in November 2020 and March 2021 as well as plans for a high-power, next generation planetary radar system.

The new technology and techniques currently under development by the NRAO/GBO/RIS team have the potential, in the near term, to directly address and overcome the science capability gap created by the loss of the Arecibo telescope. In addition to enabling unprecedented science, our next generation planetary radar system has the potential to add an entirely new, high-availability tool to the nation's space situational awareness capabilities that supports radar observations into the cis-lunar region.

Fig. 1. At 100 m in diameter, the Green Bank Telescope in West Virginia is the largest fully steerable antenna in the world. The pilot transmitter was mounted on the prime-focus boom, which extends from the feed arm into position between the receiver house and the concave subreflector at the top-center of the image. Image Credit: NSF/GBO/Mike Holstine[1].

2. PILOT TRANSMITTER DEVELOPMENT

As the world's largest fully steerable radio telescope (Fig. 1), the GBT has been a leader in radio astronomy for over 20 years. Its mission has included studying pulsars, mapping our own galaxy and others, and searching for signs of life, among many other ventures. We now aim to add radar transmitting to the GBT portfolio. There are two focal points on the GBT, one in the receiver cabin called the Gregorian focus, where many of the receivers for astronomical observations are mounted, and one in front of the concave subreflector called the prime focus. Initially, the team discussed developing a Ka-band transmitter placed at the prime focus; however, the operational frequency was ultimately determined by the available receiver bands at the VLBA that were aligned with the radar bands allocated by the Federal Communications Commission. We reviewed the VLBA receiving bands, focusing on the highest frequencies between X band and Ka band, and our analysis determined the best frequency to use was in the Ku band from 13.75 GHz to 14.0 GHz. For the experiments described here, our transmitter license covered a 200 MHz bandwidth from 13.8 GHz to 14.0 GHz.

The GBT uses standard receiver housings for mounting equipment at the prime focus. For ease of installation and removal, the RIS Ku-band transmitter was integrated inside one of these prime-focus housings. Fig. 2 shows the transmitter under development at RIS in El Segundo, California, where work began in April 2020. These housings consist of a rectangular box measuring approximately 28x28x60 cubic inches with brackets for hoisting and attaching to the mounting cage at the prime focus. One 28x28-inch panel of the box carries the feed horn, while the opposite 28x28-inch panel carries connectors and fittings for the RF, power, and cooling. An aggressive schedule and budget constraints mandated the use of commercial off-the-shelf hardware, and, after a thorough analysis, the Qorvo Spatium solid-state power amplifier was selected as it met all the technical requirements as well as the schedule. Integrating a

[1] https://flic.kr/p/2hwuEQz

Keysight 8195 arbitrary waveform generator allowed us to transmit more than a simple tone at 13.9 GHz, including the waveforms required to produce high-resolution images of the lunar surface. A duplexer allowed the transmitter and a pointing receiver to be connected to the same feed horn and enabled development of a pointing model for the transmitter. The transmitter was designed to be compatible with existing GBT interfaces and to be controlled and monitored remotely via a secure internet link. Upon completion in late October 2020, the transmitter in its prime-focus housing was shipped to Green Bank, West Virginia.

Fig. 2. Partial integration of the pilot-transmitter hardware into a prime-focus housing for mounting on the GBT. Image Credit: Raytheon Technologies

3. TRANSMITTER INTEGRATION AND CALIBRATION

Once the transmitter was at GBO, we conducted a successful remote test of the transmitter's nominal output, including generation of narrowband tones and chirp (linear frequency modulation) waveforms, where the transmitter in a GBO lab was controlled from Los Angeles, California. The transmitter was subsequently installed on the GBT at the prime-focus position shown in Fig. 3 and operated in campaign mode, where the transmitter was only mounted for specific test observations and then removed. Typically, receivers at the prime focus of the GBT operate at much lower frequencies than the pilot transmitter. As such, the existing pointing model for the prime focus was only accurate for observing frequencies below 2 GHz meaning that one could potentially miss the target when operating at 13.9 GHz. By duplexing a pointing receiver with the transmitter using the same feed horn, on-the-fly updates of the GBT pointing model were possible. Furthermore, the mounting of the prime-focus housing allows for position adjustments in the plane parallel to the primary 100-m reflecting surface, forward or backward along the focal line, and in rotation about the receiver axis. The pointing model was updated by fitting beam patterns to cross-scans in azimuth and elevation about known astronomical calibrators, i.e., Ku-band quasars, with well-known positions and intensities. Pointing and focus corrections were also made against geostationary satellites acting as Ku-band beacons.

Fig. 3. The transmitter, within its housing (rectangular box at center), was mounted on a boom that extends from the feed arm (left) into position at the prime focus of the GBT. Image Credit: NSF/GBO

4. OPERATIONAL CONFIGURATION AND DATA COLLECTION

Given the successful remote lab test and being amid the COVID-19 pandemic, it was decided that the GBO staff could take care of on-site issues should they arise. Thus, for both experimental runs in November 2020 and March 2021, the transmitter was controlled remotely from California, while GBO staff controlled the GBT itself, and NRAO staff controlled the VLBA receive sites. The observations and data collection were coordinated between GBT and VLBA through planned observation blocks with detailed time sequences. Transmissions ranged from narrowband (Doppler-only) tones to high-bandwidth chirped waveforms for fine range resolution. Target range and elevation above the horizon with respect to the transmit and receive sites were based on ephemerides from the NASA Jet Propulsion Laboratory's (JPL) Horizons ephemeris service[2]. For instance, the GBT operated at elevations between 10º and 80º. The VLBA participated as a set of ten single-dish receiving antennas as target visibility at each of the geographically diverse VLBA sites allowed. Pointing was done in the blind, from a radar perspective, based on pre-observation positional knowledge. There was no active feedback for pointing adjustments, Doppler compensation, or range corrections during the experiments themselves. Despite this, the repeatability of performing blind pointing on our targets was satisfactory to within a fraction of the 54-arcsecond beamwidth in azimuth and elevation.

Baseband signals were recorded with the VLBA backend system and recorder at each site at a Nyquist rate for 16, 32, 128 and 256 MHz bandwidths in both circular polarizations. Data were stored in the VLBI Data Interchange Format with two-bits-per-sample quantization. A portion of the lower-bandwidth data acquired at 16 and 32 MHz was transferred in real time to computers at the VLBA operations center for rapid diagnostic evaluation. The complete set of recordings was later shipped on hard disk from each site for further analysis. Determination of target detection occurred in post processing approximately 30 days after the experiments because the radar data were on hard drives also used for other astronomical observations. Once a hard drive was full it was shipped back to Socorro, New Mexico, where the radar data was transferred to RIS hard drives for further analysis.

5. EXPERIMENTAL RESULTS

The GBT radar experiments from November 10-12, 2020, and March 15-21, 2021, gave NRAO, GBO, and RIS an opportunity to investigate ways to process long-range radar data collected for high-resolution lunar SAR images, against two defunct Molniya satellites, and against a near-Earth asteroid. For reference, there is more power in a conventional microwave oven than was transmitted by the GBT during these experiments. Some analysis is presented in [1] and expanded upon here.

[2] https://ssd.jpl.nasa.gov/horizons/app.html#/

5.1. SPACE DEBRIS

During the November 2020 and March 2021 experiments, we collected against two Molniya satellites (3-10 and 2-9). We show the collection geometry at midstream during one of the collection experiments in Fig. 4. Using the data collected from the Hancock VLBA site after removal of the Doppler shift due to orbital velocity, we found, as shown in Fig. 5, that the Molniya 2-9 satellite is rotating with a period of approximately one minute with a Doppler magnitude of ±50 Hz. There are several scatterers in the figure, but two reach the 50 Hz maximum, where the positive term indicates a component of the rotating body approaching our antenna, and a negative term indicates a component receding. From Fig. 5, we can use the rotational period and the maximum Doppler shift to estimate the size of the satellite as approximately 5.1 meters in projected length, similar to optical studies [2] and radar results from one year earlier using Arecibo Observatory to transmit and VLBA to receive. In essence, the Arecibo experiment had incredible signal levels owing to its ~300 kW output power but, at 20 MHz, lacked sufficient waveform bandwidth to effectively translate that signal to fine range resolution for physical characterization of the targets. Meanwhile, the GBT experiment had up to an order of magnitude more bandwidth (200 MHz) but lacked the output power at a maximum of 700 W (a factor of ~500 less than Arecibo) to have enough signal at that resolution for detailed characterization of the targets. Thus, a medium-power system, similar in design to the pilot system described here, but capable of 10 kW in output power, would provide both the power and bandwidth needed for more detailed characterization of space debris.

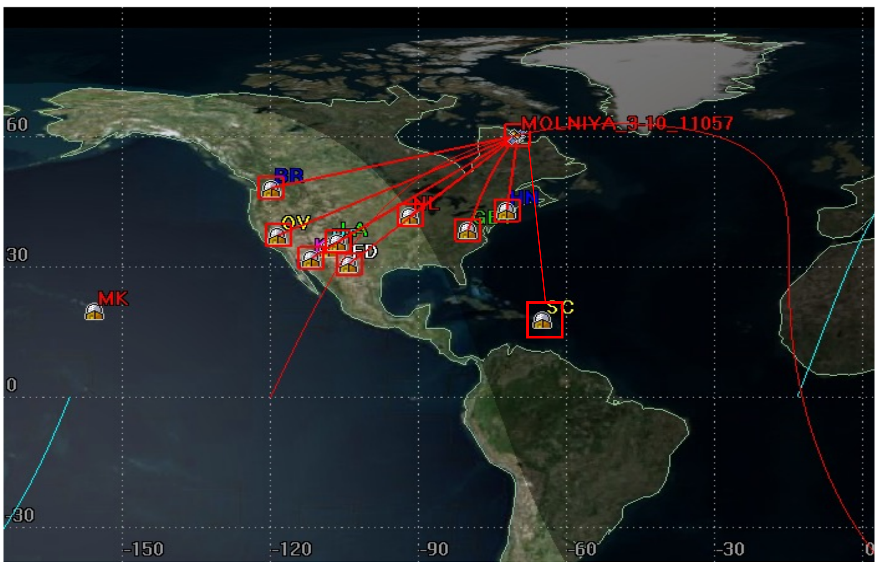

Fig. 4. Snapshot of the position of Molniya 3-10 during data collection on November 11, 2020, along with locations of Green Bank (GB) and the VLBA antennas (see Table 1) that had the satellite in view. Image Credit: Raytheon Technologies

Table 1. Locations of the ten 25-m antennas that are part of the Very Long Baseline Array along with their common abbreviations used in Fig. 4.

VLBA Sites (West to East)
MK = Mauna Kea, HI
BR = Brewster, WA
OV = Owens Valley, CA
KP = Kitt Peak, AZ
PT = Pie Town, NM
LA = Los Alamos, NM
FD = Fort Davis, TX
NL = North Liberty, IA
HN = Hancock, NH
SC = St. Croix, USVI

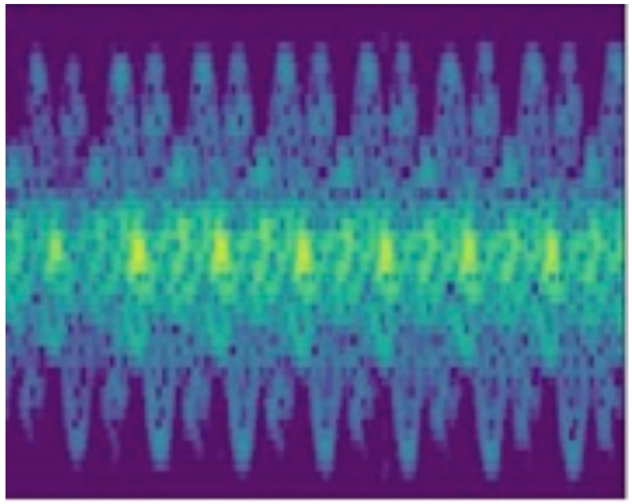

Fig. 5. Doppler frequency as a function of time for the echo from defunct satellite Molniya 2-9 as received at the Hancock VLBA site. The timespan along the horizontal axis is 8 minutes and spans several rotations of the target. The vertical axis is Doppler frequency, where the largest values are ±50 Hz, which constrains the size of the satellite. Image Credit: Raytheon Technologies

5.2. NEAR-EARTH ASTEROID (231937) 2001 FO32

Near-Earth asteroid (231937) 2001 FO32 made a close approach to Earth of 0.01348 au (2.1 billion meters or ~5.5 lunar distances) on March 21, 2021, and observations of the asteroid were included in the second campaign of the pilot transmitter. Due to the fast motion of the asteroid across the sky during its close approach and the geographic separation between the transmitting and the receiving sites, the predicted angular difference between the transmit and receive ephemerides using JPL's Horizons was 52 arcseconds. Therefore, given our 54-arcsecond beamwidth, observations required we lead the moving target to maximize the returned signal-to-noise ratio (SNR). Jon Giorgini at JPL generated the necessary radar predicts to make these observations. The asteroid's position in the sky was mainly in the south, reaching an elevation of only 21° above the horizon at GBT, and making the southern VLBA sites in St. Croix and Fort Davis the best opportunities for a detection.

As the asteroid crossed Earth's orbit, its large line-of-sight acceleration caused its Doppler shift to change too rapidly for coherent integration on an uncompensated Doppler spectrum. Fig. 6 shows the geometry of the closest approach obtained from JPL's Small Body Database orbit viewer[3]. At five hours before closest approach, the range rate was -10.3 km/s compared to its total velocity magnitude of 34 km/s. Therefore, the Doppler shift at a carrier frequency of 13.9 GHz was approximately 1 MHz, and the rate of change of Doppler was roughly 50 Hz per second. The fine-grained prediction of range rate in the ephemeris was applied as a phase to the radar return using a sliding Doppler window and coherent integration for 1073.74 seconds. The detection, shown in Fig. 7, is within 100 Hz of the expected frequency location. Detection of such a Doppler offset, in practice, can constrain the orbit of an asteroid and determine (ideally eliminate) its impact hazard to Earth. While the signal is only a factor of 1.12 above the mean noise in this data received at the St. Croix VLBA site, a similar corroborating detection was made at the Fort Davis VLBA site. Zooming in on the echo revealed a broadening of the tone corresponding to a rotation period of ~45 hours, only ~15% larger than the rotation period of 39.9 hours measured optically[4] and confirmed by Goldstone radar observations[5] using the GBT as a receiver. During the close approach of 2001 FO32, a variety of waveforms were tested, but only the echo of the narrowband tone was strong enough to detect. All integration times of chirped waveforms were too short to extract a signal distinguishable from noise.

[3] https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=2001%20FO32&view=VOP
[4] https://www.asu.cas.cz/~ppravec/newres.txt
[5] https://www.jpl.nasa.gov/images/pia24561-goldstone-radar-observations-of-asteroid-2001-fo32

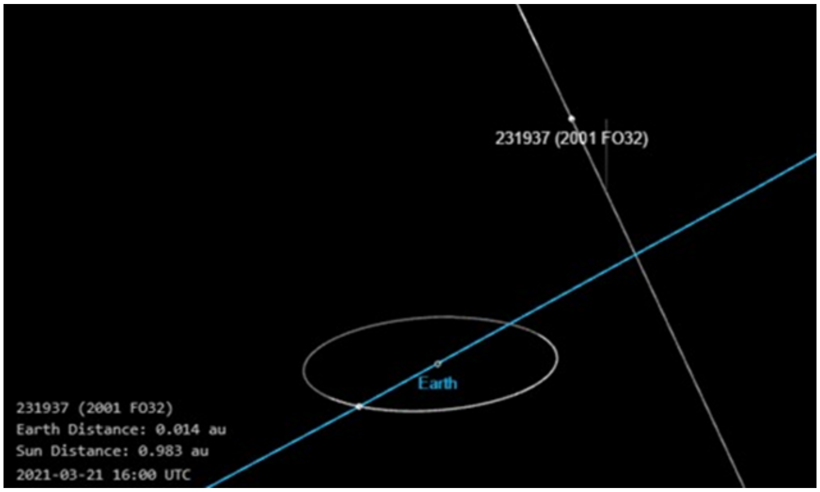

Fig. 6. Close-approach geometry of near-Earth asteroid (231937) 2001 FO32 at the time of the GBT experiments as illustrated in the JPL Small-Body Database. The blue line is Earth's orbit about the Sun, the white ellipse is the Moon's orbit about Earth, and the white line is the trajectory of the asteroid. Image Credit: NASA/JPL

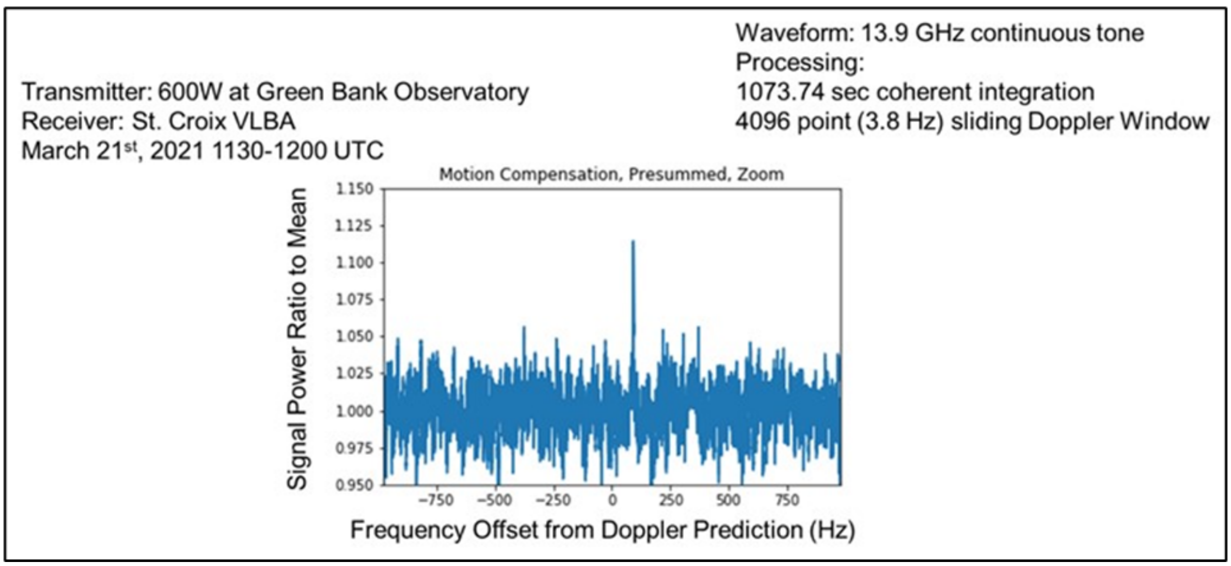

Fig. 7. Doppler spectrum of the echo from near-Earth asteroid (231937) 2001 FO32 received at the St. Croix VLBA site from a narrowband tone transmitted from the GBT. Image Credit: Raytheon Technologies

5.3. LUNAR IMAGERY

The goal of the lunar experiments was to collect high-resolution SAR data, and we collected resolutions of 50 m, 5 m, and 1.25 m (determined by integration time) that we are still processing. Because of the Earth's rotation and the relative translational motion of the Moon in its orbit (and the Moon's own rotation), the Doppler shifts vary as a function of position on the Moon. When imaging regions of the Moon away from the equator, we can exploit the synthetic aperture created by the rotation of Earth to form images. During a 40-minute SAR collection to produce 5-m resolution using a 30 MHz bandwidth transmitted waveform, the GBT moves approximately 874 km and the Pie Town VLBA site moves 922 km. Using digital processing, we can form an image equivalent to a real aperture of the size of the distance that Pie Town moved during the collection. To do so, we had to develop a new method of motion compensation since our process for tactical SAR was inadequate, especially for the long integration times for target locations not on Earth. We used the dynamical models available through JPL's Horizons to initially stabilize the image enough for autofocus algorithms to bring out the surface detail. The 50-m data required just over 4 minutes of integration time and were used to tune the signal processing for the 5-m data since the phase errors are much more forgiving at 50-m resolution than at a factor of ten finer. Using the Pie Town VBLA site, we formed detailed SAR images, as shown in Fig. 8 of the Apollo 15 site with resolution of 5 m by 5 m. This image was made public in an NRAO press release[6] that was translated to at least seven different languages globally. This is the highest resolution SAR image ever taken of the Moon from Earth.

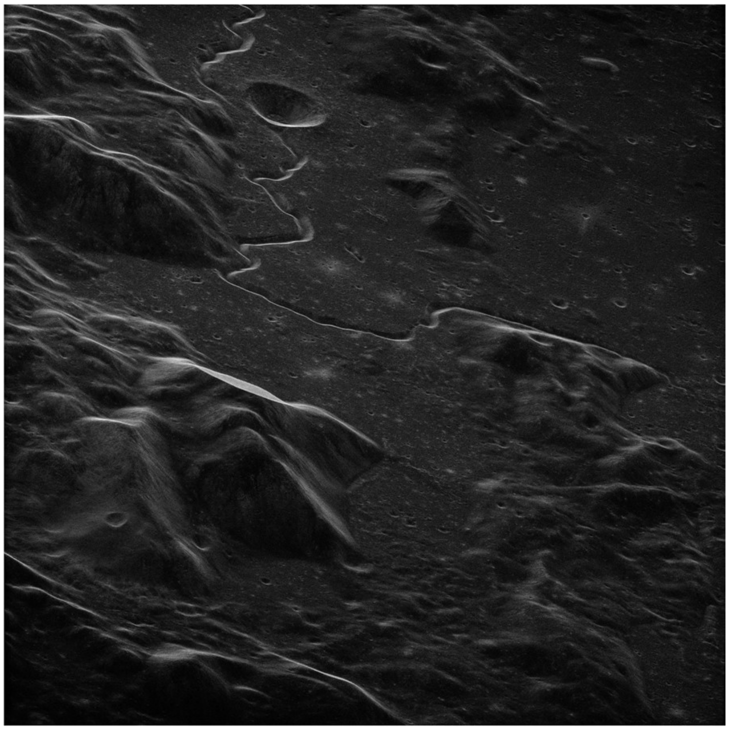

Fig. 8. A 5-m resolution SAR image of the area around the Apollo 15 landing site (below the sinuous rille Rima Hadley) on the Moon. For reference, the crater at the top of the image, Hadley C, is about 6 km in diameter. This is an improved version of the image released by NRAO. Image Credit: Raytheon Technologies

The 1.25-m resolution image, on the other hand, has presented more issues. At such high resolution, the image quality is sensitive to motion comparable to (or exceeding) the fidelity of models used for ephemeris prediction. To produce 1.25-m resolution in azimuth of the region around the Apollo 15 landing site required a collection duration of two hours and 40 minutes. Currently, we present the 1.25-m data as an inverse SAR (ISAR) image, where Fig. 9 shows a single 64-second sub-aperture of the collection. By combining 100 sub-apertures we have produced an ISAR movie of this data prior to any additional formatting beyond the initial motion compensation. Performing this step provides clues to the corrections required to obtain a high-resolution SAR image at 1.25 m in azimuth resolution.

Our image of Tycho crater, shown in Fig. 10, was also made public in an NRAO press release[7] and selected by Forbes[8] as one of the top five astronomical images of 2022. It is also a 5-m resolution image, and, since the crater is in the far southern hemisphere of the Moon, the geometry was approaching more like what we have in airborne radar. We believe that this fact helped to stabilize the image using JPL's Horizons data for motion compensation, where the image did not have the same level of errors as seen in the 5-m data of the Apollo 15 landing site. Since the initial release of this image, we have greatly improved the image quality as shown in Fig. 11. Using advanced focusing algorithms, we can clearly see structure on the crater floor. Work continues to refine the image-processing techniques used on the lunar SAR data that will enable improvements in future planetary radar images.

[6] https://public.nrao.edu/news/successful-test-new-planetary-radar/
[7] https://public.nrao.edu/news/radar-tycho-crater-intricate-detail/
[8] https://www.forbes.com/sites/jamiecartereurope/2022/04/19/the-new-83-megapixel-photo-of-our-sun-is-one-of-five-astonishing-hi-rez-space-images-you-must-see-and-download/

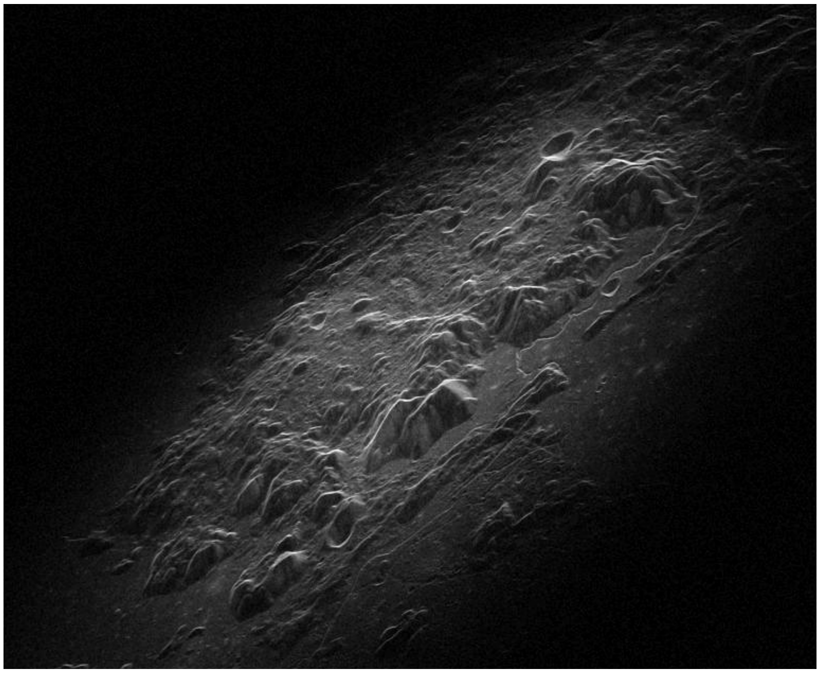

Fig. 9. ISAR image of the region around the Apollo 15 landing site with resolution of 1.25 m in range (vertical axis) and 182 m in azimuth (horizontal axis) using 64 seconds of coherent integration. The overall gradient from light to dark is due to the transmitter's beam pattern. Image Credit: Raytheon Technologies

Fig. 10. A 5-m resolution SAR image of the 85-km diameter Tycho crater on the Moon as featured in Forbes[5]. As in Fig. 9, the overall gradient from light to dark toward the corners of the image is due to the transmitter's beam pattern. Image Credit: Raytheon Technologies

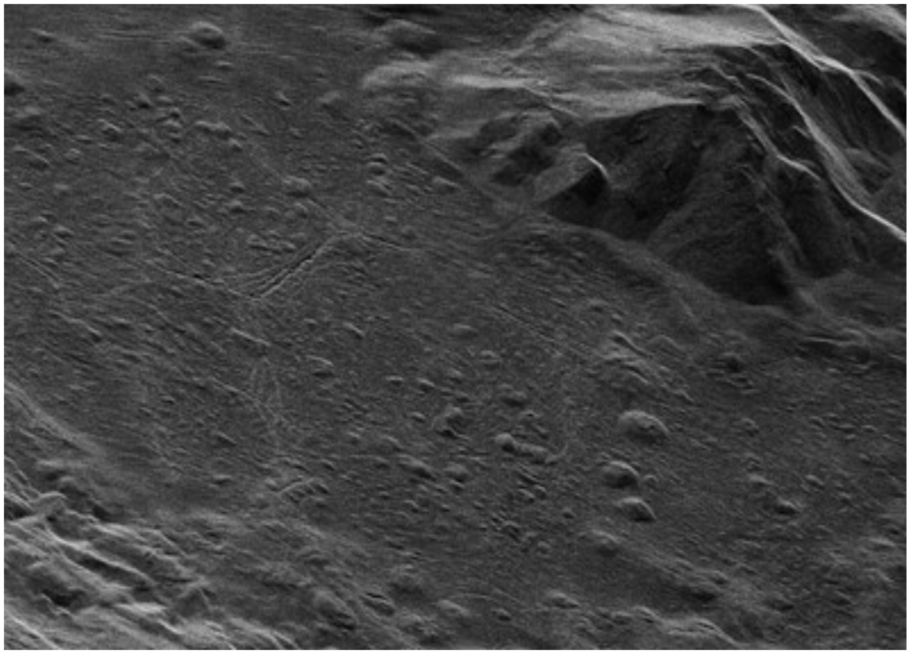

Fig. 11. Improvements in the quality of image processing of Tycho crater at 5-m resolution reveal detailed structure on the crater floor. Image Credit: Raytheon Technologies

6. SUMMARY AND NEXT STEPS

The pilot observations described here demonstrate the ability of the Green Bank Telescope and antennas of the Very Long Baseline Array to act as a bistatic planetary radar system for monitoring and characterizing artificial and natural targets in cis-lunar space and beyond. Furthermore, the pilot transmitter constructed for this work shows the potential of solid-state microwave technology for use in high-power radar systems. With only 700 W of output power, the wide bandwidth of the transmitter coupled with the gain available at the transmit and receive sites has produced the highest-resolution images of the Moon ever from the ground. We also characterized the size and rotation states of defunct satellites and detected an asteroid more than two billion meters from Earth. A more capable planetary radar system in the future can provide precision orbit determination and high-resolution images of solar system objects for planetary science and planetary defense, as well as contribute to space situational and domain awareness in the cis-lunar region.

Our goal is a multi-static planetary radar system using a 500 kW, Ku-band (between 13.4 and 14.0 GHz with up to 600 MHz bandwidth) transmitter design with the ten VLBA (25-m diameter) sites receiving with eventual use of elements of the Next Generation Very Large Array (ngVLA; up to 244 antennas each 18 m in diameter). For the transmitter, we will use solid-state microwave amplifier components that can be arranged in a modular configuration with many similar components. Using solid-state components allows for graceful degradation and simpler maintenance through module replacement. This is as opposed to vacuum-tube amplifier (klystron) systems currently used in planetary radar systems that can be less flexible to build and maintain and whose failure reduces transmitter output to 50% (or 0%) until a replacement can be procured. Because of the higher output power, the size, weight, prime input power, and cooling of the system will increase. As such, a high-power transmitter located at the prime focus of the GBT is not a realistic option. AUI, as the manager of NRAO and GBO, along with RIS currently have a Mid-Scale Research Initiative award from the NSF to develop the concept and design of this high-power planetary radar for the GBT. Once a design is in hand and construction funds acquired, the team can work toward bringing this next generation planetary radar into reality. A planetary radar on the GBT will help to fill the void left by the collapse of the Arecibo telescope and complement the Goldstone planetary radar facility. The capabilities of the GBT system will support planetary science, planetary defense, and space situational awareness in the cis-lunar domain.

While a high-power radar system is a significant infrastructure project, we note that an intermediate step of a transmitter with of order 10 kW of output power could be used for refinement of operational techniques. This includes testing of real-time detection and ephemeris correction and improvement of analysis techniques for production of science-ready data products. Such a "medium-power" system would provide enough signal to exploit the resolution attainable with high-frequency, wide-bandwidth observations of some man-made targets and to detect a subset of near-Earth asteroids for planetary science and planetary defense. This system would be similar in design to the pilot system described here and mounted in a similar way, building upon what was learned from our pilot observations. Furthermore, a medium-power system would act as a bridge between the pilot system and our objective of a high-power system such that once the high-power system is constructed, the pipeline for operations, observations, processing, and analysis are well understood and results for science and defense can be delivered promptly.

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