GREEN BANK OBSERVATORY - ESTABLISHING NEW SCIENTIFIC AND OPERATIONAL GOALS FOR PLANETARY RADAR APPLICATIONS

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Theme	Advancements in Near Earth Object (NEO) Discovery
Sub Theme	Prospects for future NEO survey systems and efforts (e.g. LSST).

Significant and growing constraints on what the U.S. radar infrastructure can deliver in coming decades

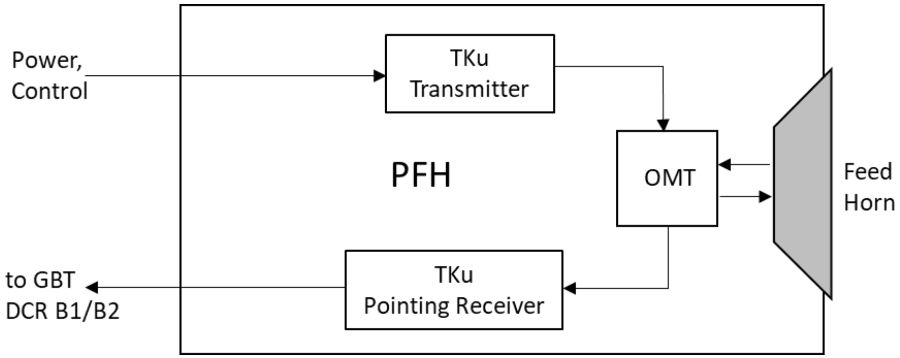
- **Availability** – the field is based on the use of U.S. federal facility investments in radio astronomy and deep-space communications, i.e. facilities focused on other missions, and therefore constrained in the total amount of observing time that can be assigned to radar work. These constraints have grown due to the recent loss of the Arecibo 305-m instrument, and increasing demands on the DSN to service the increasing interplanetary and near-Earth space mission roster
- **Technology** – the current technologies used to produce high-power radar transmit signals (klystrons, travelling wave tubes) are expensive, difficult to use and maintain, with large form factors and difficult cooling requirements. NASA's recent loss of GSSR capabilities for an extended period between 2019 and 2020, due to klystron repairs, indicates the operational difficulties and maintenance arising from these old technologies
- **Planetary radar defense awareness** – the planetary radar community have been long advocating for expansion of ground-based radar capabilities, and with the loss of Arecibo Observatory (AO), this need has been emphasized and object of several planetary science panels and decadal discussion involving key players such as NASA and NSF
- **Capacity building, processing pipelines, and data** – expansion of ground-based radar capabilities for scientific and planetary defense awareness will require building and strengthen human and technical capabilities, adequate pipelines for data processing, and data archival accessible to the science radar community

New technical directions and operational approaches

- **New technical directions and operational approaches** have been identified in recent years, and discussed as part of the ongoing Planetary Science and Astrobiology Decadal Survey – including the use of more powerful transmitters and flexible phased-array transmit hardware systems, and utilizing arrays of antennas both as transmitting sources and as mono/bi/multi-static receiving elements
- **Recent studies and developments at Green Bank Telescope (GBT)** have seen a low-power prototype transmitter at prime focus being successfully tested on November 2020, and March 2021 paving the way for a more powerful system design
- **A new high-power high-frequency transmitter at GBT at Gregorian** focus will increase the volume of our radar research capabilities in the solar system by an order of magnitude relative to recent capabilities, and powerful antenna array-based transmit/receive radar functionality promises increased sensitivity and operational readiness for solar system and near-Earth studies significantly
- **These new observational capabilities will be transformational** for the US research and space domain awareness communities across multiple scientific disciplines

New technical directions and operational approaches at GBO

- **Phase 1** – observation goals for Moon and space debris
  - testing of low-power (~1kW) Ku-band radar transmitter prototype at GBT Prime Focus to establish new radar capabilities with Raytheon partnership
  - work on future plans for GBO and Raytheon to achieve technical capabilities with a high-power radar system (Phase 2, and Phase 3)
  - Phase 2, and Phase 3 contingent to initial funding through the NSF's Mid-scale Research Infrastructure (MSRI) proposal step 2, which is in progress and to be submitted by the end of April 2021



- General instrument diagram of the Prime Focus Housing (PFH) containing the TKu transmitter and TKu pointing receiver system. The TKu transmitter and receiver were using the same feed horn (Prodelin 0800-3369 Ku Earth Terminal Feed) closely matching the GBT optics.
- Feed equipped with an orthomode transducer (OMT) to separate two orthogonally polarized microwave signal paths, and receive low pass filter that allow for full duplex links - uplink up to 3 kW at 13.75-14.5 GHz (transmit) and simultaneously downlink at 10.95-12.75 GHz (receive), which was critical for observations.

- **Phase 2** - observation goals for Mars/Asteroids by 2023
  - <= 0.2-1.5 AU
- **Phase 3** - observation goals for Jovian moons by 2026
  - > 1.5 AU

Testing the low-power Ku-band radar prototype at GBT Prime Focus on November 2020

- First phase and pilot study with GBT and VLBA bistatic observations
- Cooperation with industry partner Raytheon (RTX) for a low-power radar transmitter prototype and data processing
- Testing the low-power Ku-band radar transmitter (TKu) prototype at GBT Prime Focus on November 2020 to explore
  - Operational feasibility

    - required GBT pipeline operation chances for auxiliary Ku-band pointing receiver
  - Solid-state technology

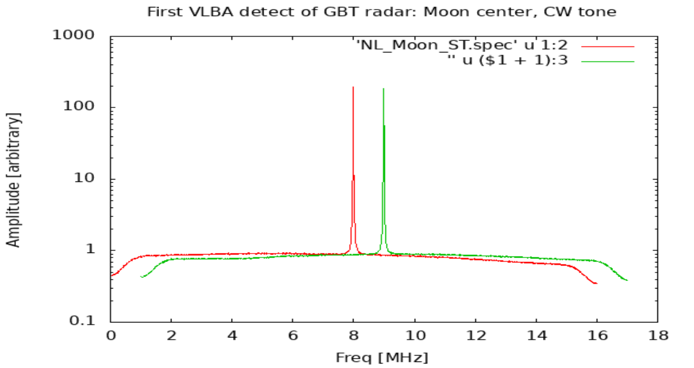
    - Raytheon pilot transmitter system (700W - 13.9 GHz; effectively operating at 650W)
    - simple tone CW and few LFM SAR basic modes
  - GBT-VLBA bistatic

    - main selected target: Moon and space debris
    - Moon successful
    - space debris - uncertainty on detection - data being analyzed by Raytheon

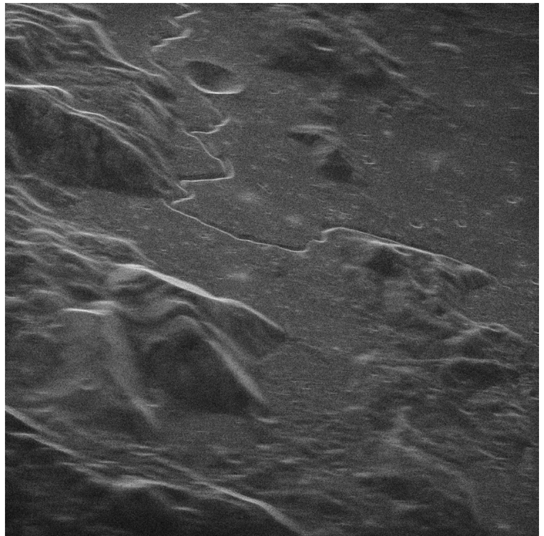
Testing the low-power Ku-band radar prototype at GBT Prime Focus on November 2020

- successful Phase 1 commissioning and first light observations took place less than 11 months later (November 2020), and Phase 1 forward in March 2021 - the transmitter seen in a standard GBT prime focus housing box is shown

- example of the received signal at the VLBA Hancock, NH site after a Moon bounce is shown



- an image of the Apollo 15 landing area on the Moon generated From the VLBA data is shown – this stunning image has 5-m x 5-m linear resolution on the surface! Additional observations of the lunar surface and a number of orbiting targets remain under analysis by Raytheon (press release- https://greenbankobservatory.org/successful-test-paves-way-for-new-planetary-radar/)



Credit: Raytheon Technologies

Testing the low-power Ku-band radar prototype at GBT Prime Focus on March 2021

- Phase 1 forward and pilot study with GBT and VLBA bistatic observations
- Testing the low-power Ku-band radar prototype at GBT Prime Focus on March 2021 to further explore
  - Operational feasibility
    - required GBT pipeline operation chances for auxiliary Ku-band pointing receiver
    - ephemerides used a GSSR predicts format (topocentric) modified using center frequency 13.9 GHz of the TKu transmitter to account for light-delay time in attempt at Mars and Asteroid observations (predicts provided by Jon Giorgini - JPL)
  - Solid-state technology
    - Raytheon pilot transmitter system (700W - 13.9 GHz; effectively operating at 650W)
    - simple tone CW, and expanded to 17 LFM SAR modes
  - GBT-VLBA bistatic
    - main selected target: Moon, Mars, space debris, and asteroid 231937 (201 FO32)
    - attempt of Mars detection (1.3 AU) - insufficient SNR in initial processing
    - space debris detected, used as calibrator
    - asteroid 231937 (201 FO32) at 0.113 AU - data being analyzed by Raytheon

Testing the low-power Ku-band radar prototype at GBT Prime Focus on March 2021

- VLBA received modes

VLBA Receive Modes

Mode	Thread ID	Frequency [MHz]	Sideband	BW [MHz]	Polarization
U16	0	13892	U	16	RHCP
	1	13892	U	16	LHCP

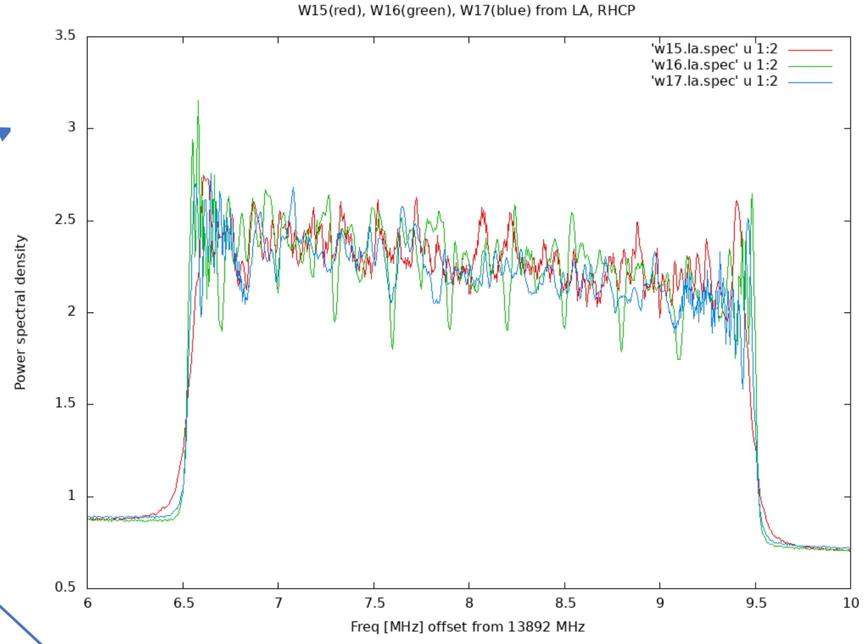
Mode	Thread ID	Frequency [MHz]	Sideband	BW [MHz]	Polarization
U32	0	13884	U	32	RHCP
	1	13884	U	32	LHCP

Mode	Thread ID	Frequency [MHz]	Sideband	BW [MHz]	Polarization
U128	0	13868	U	128	RHCP
	1	13868	U	128	LHCP

Mode	Thread ID	Frequency [MHz]	Sideband	BW [MHz]	Polarization
U256	0	13740	U	128	RHCP
	1	13740	U	128	LHCP
	2	13868	U	128	RHCP
	3	13868	U	128	LHCP

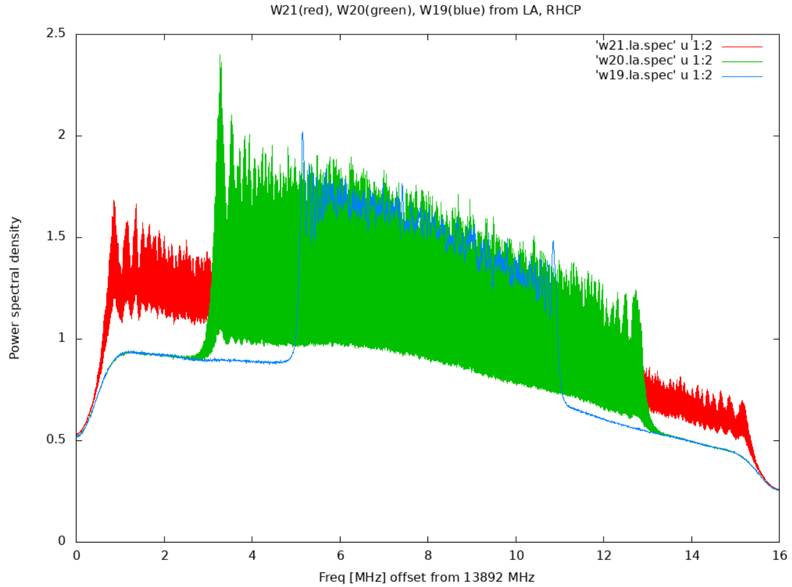
Testing the low-power Ku-band radar prototype at GBT Prime Focus on March 2021

- Moon sub-radar point sequence of transmit waveforms
  - 12 waveforms with bandwidth < 16 MHz were transmitted
    - VLBA detected all of them
    – example of W15, W16 & W17 as seen at LA, RHCP
    – example of W19, W20 & W21 as seen at LA, RHCP
    - signal bandwidth generally as expected
  - 5 waveforms with bandwidth > 16 MHz - not captured in real-time.



- Additional observations of the lunar surface and a number of orbiting targets remain under analysis as i.e. higher resolution (1.25 m) of the Apollo 15 landing site, and asteroid 201 FO32
  - Asteroid 2001FO32

  - the changing Doppler shift (50 Hz per second) prevented existing VLBA software from performing a real-time detection
  - a method to shift the spectrum accumulator on receive side was created; highest resolution possible was 8 Hz.
  - WFB's calculations show that 1 hour of CW at this resolution would not produce SNR greater than about 3
  - no real-time detection capabilities
  - data processing on going by Raytheon



Testing the low-power Ku-band radar prototype at GBT Prime Focus on March 2021

- Asteroid 2001FO32 - waveform transition W001 to W002 at 14:30-14:32 UTC, after restart of GBT track

Expanding Operational goals for planetary radar capabilities

- The Phase 1 highly successful pilot program has demonstrated the capabilities of NRAO/GBO/Raytheon collaboration, and established a new field of radio astronomy at NRAO/GBO moving forward
- A second phase towards establishing new scientific and operational goals for planetary radar applications involves GBT, VLA, VLBA and planned ngVLA capabilities
- Cooperation with industry partner Raytheon for a high-power radar transmitter and high-frequency prototype at 18 or 35 GHz
- GBT high-power radar prototype would be at Gregorian Focus and will present new requirements:
  - Operational feasibility
    - will require structural analysis of GBT to host new instrument at Gregorian
    - will require GBT transmitter dedicated focusing model
  - Solid-state technology at higher-power and high-frequency
    - will require higher power input studies and cooling system capabilities at GBT
  - GBT-VLA/VLBA bistatic
    - will require new backend data capabilities
    - new processing pipeline

Expanding Operational goals for planetary radar capabilities

- high-frequency 18 or 35 GHz considerations and trade-off

  - main considerations are in view of capabilities such as beam and related precision, power and achievable resolution, skin depth capabilities at different wavelength needed to detect and characterize space debris in Earth's orbit, NEAs, and other planetary objects at AU ranges

  - power and SNR requirements

  - pointing stability requirements

Frequency		**18 GHz - K** **1.13-1.67 cm**	**35 GHz - Ka** **0.5-1.13 cm**
Beam/precision		wider beam / less pointing precision	narrower beam (~1/2 of 35GHz beam) / higher pointing precision
Power/resolution		at equal power / good resolution	at equal power / higher resolution
Skin-depth capability at target/λ penetration		higher penetration at surface target / ~several λ equivalent to ~ 15 cm ~ within few layers in icy bodies ? rocky bodies ? metallic objects	higher penetration at surface target / ~ few λ equivalent to ~ 5 cm ~ within one layer in icy bodies ? rocky bodies ? metallic objects
Surface RMS vs λ		at cm scale RMS return can differentiate surface characteristics	at cm scale RMS return will be mainly specular and might not allow to differentiate surface characteristics
Power & SNR	**GEO orbit**	at equal power / good SNR and higher coverage over time	at equal power /higher SNR and lower coverage over time
	NEAs orbit	at equal power / good SNR with higher coverage over time	at equal power /higher SNR with less coverage over time
	Planetary bodies > 1AU	at equal power / reduced SNR strictly depends on 1/R^4 / higher coverage over time	at equal power / reduced SNR strictly depends on 1/R^4 / less coverage over time
Pointing requirements	**GEO orbit**	align with WGS84 pointing highly relevant	align with WGS84 pointing extremely relevant due to narrower beam
	NEAs orbit	align with WGS84 pointing highly relevant	align with WGS84 pointing extremely relevant due to narrower beam
	Planetary bodies > 1AU	align with WGS84 pointing highly relevant	align with WGS84 pointing extremely relevant due to narrower beam

Conceptual studies examining technical options and configurations at GBO

- Conceptual studies examining technical options and configurations are now underway, and general designs and trade-offs under consideration, along with venues to gather input from the planetary radar community will be key
- Short term activities will concentrate on:

  - seeking funding for project development and exploring partnerships

  - NRAO/GBO workshops developing community-based technical & operating requirements, and explore conceptual designs

  - Design/development phase (12-15 months), technology prototyping and construction

- Long term capabilities would aim for up to 40-50% of GBT time available to radar science/planetary defense/surveillance?

- Radar Science-ready Data Products will require:
  - initial integrated proposal through science data delivery (pipeline processing)
  - broaden participation and open up interest to new user communities data products types and access

AUI/NRAO/GBO/RTX future vision

- AUI-NRAO/GBO Radar Initiative is underway leading to capabilities for Phase 2 and Phase 3

  - GBO high power system, AO-8/ngVLA transmit unit (ngVLA site at AO already planned; have proposed early activation as a leading/edge science capability on site)

  - Technical prototyping, construction – begin FY2022 and 3-4 years to science

- AUI/NRAO/GBO – strongly support continuation of scientific legacy/STEM activities at AO

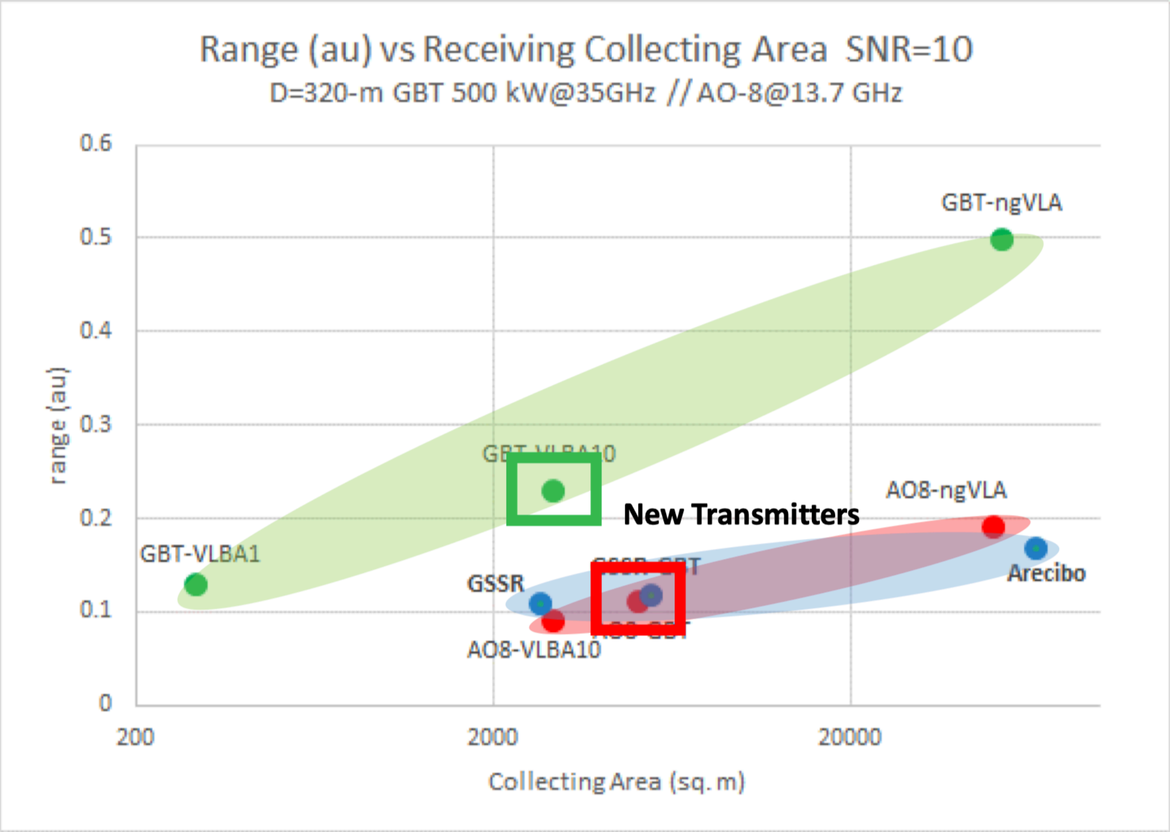
  - Primary focus: ngVLA site at AO – concept getting underway (not in conflict with the Next Generation Arecibo Telescope (NGAT) UCF/AO)

- Idea of larger array (~8) capable of enhanced long-baseline ngVLA interferometric science – plus possible phased-antenna radar transmitter?

  - Proposal: AO-8 – sensitive receive/transmit facility for AO (UPRM, NRAO, UCF/AO + other organizations)

AUI/NRAO/GBO/RTX future vision

Progression in transmitter capabilities to detect an hypothetical 320-m diameter object with 0.1 reflectivity to a SNR of 10 in 100-s presented to the PSDS2020 – March31st, 2021 (Tony Beasley, AUI/NRAO)



Preliminary estimates + numerous assumptions Requirements capture and conceptual design effort needed.

- GBT transmit example using 35 GHz
- range distance in au
- VLBA1 indicates a single VLBA antenna receive
- VLBA10 indicates all VLBA antennas (resolution effects will complicate adding of VLBA voltage data)
- AO8-ngVLA indicates a transmitting cluster of 8 ngVLA antennas with 236 remaining 18-m antennas receiving

Acknowledgments

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