

HF Bistatic Radar Experiments with HAARP, UNM-LWA and OVRO-LWA for Planetary and Near-Earth Asteroid Science

Mark S. Haynes⁽¹⁾, Paul A. Bernhardt^{*(2)}, Lance A. M. Benner⁽¹⁾, Jessica Matthews⁽²⁾, Mike McCarrick⁽²⁾, Whitham D. Reeve⁽²⁾, Evans Callis⁽²⁾, Tracy Coon⁽²⁾, Jayce Dowell⁽³⁾, Greg. B. Taylor⁽³⁾, Charles Elachi⁽⁴⁾, Gregg Hallinan⁽⁴⁾, Ivey Davis⁽⁴⁾, Larry D'Addario⁽⁴⁾, Joseph Lazio⁽¹⁾

(1) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; e-mail: mark.s.haynes@jpl.nasa.gov, benner@jpl.nasa.gov, joseph.lazio@jpl.nasa.gov

(2) University of Alaska – HAARP, Fairbanks, AK; e-mail: pabernhardt@alaska.edu, jamatthews02@alaska.edu, mike.mccarrick@gmail.com, whitreeve@gmail.com, ehcallis@alaska.edu, tcoon2@alaska.edu

(3) University of New Mexico, Albuquerque, NM; e-mail: jdowell@unm.edu, gbtaylor@unm.edu

(4) California Institute of Technology, Pasadena, CA; e-mail: celachi@caltech.edu, hallinan@caltech.edu, idavis@astro.caltech.edu, ldaddario@caltech.edu

Abstract

We describe three HF (9.6 MHz) bistatic radar experiments that were conducted in 2022 with the High-frequency Active Auroral Research Program (HAARP) facility and the University of New Mexico Long Wavelength Array (UNM-LWA) and the Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA). The purpose of these experiments was to understand the potential for using these facilities in a bistatic radar mode for planetary science investigations, specifically, near-Earth asteroid interior sensing (cislunar and Apophis 2029 flyby). We conducted two Moon-bounce experiments as well as the first asteroid detection experiment at 9.6 MHz using ~1.25 GW EIRP transmissions of FMCW radar chirps. We attempted to detect asteroid 2010 XC15 at 2 Lunar distances for which several hours of coherent processing are required for a positive signal to noise ratio. Data are still under analysis but future experiments at these wavelengths may have to target asteroids that approach closer than 2 Lunar distances. In addition, the processing of received waveforms revealed ionosphere effects that suggest the potential for using these facilities for future ionospheric research.

1 Introduction

The primary objectives of this project are to complete the first feasibility study and experiments toward demonstrating near-Earth asteroid (NEA) interior tomography with ground-based radar systems [1]. The goals are to assess infrastructure and conduct proof-of-concept experiments in advance of the 2029 Apophis flyby [2] and to initiate future ground-based population studies of NEA interiors. The study will recommend facilities/missions that should or need to be developed to accomplish ground-based NEA tomography in the future.

Long-wavelengths (HF/VHF/UHF) offer the best potential for penetrating and sensing the interiors of small bodies. HAARP is the highest-power, lowest-frequency

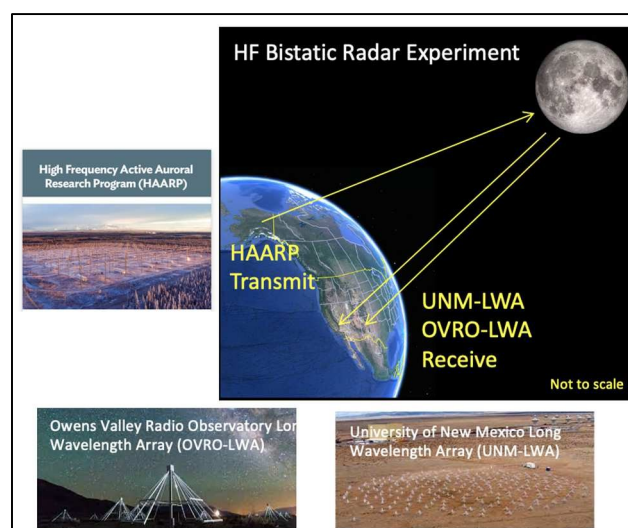


Figure 1. Bistatic radar experiment at 9.6 MHz between HAARP (transmitting) and UNM-LWA (receiving) and OVRO-LWA (receiving).

transmitter that exists while VHF radio astronomy arrays offer the best sensitivity though large-scale coherent beamforming. A Moon-bounce experiment was previously conducted in 2008 at 7 MHz between HAARP and a dipole array temporarily constructed near the first New Mexico LWA station, [3-5], which successfully detected of the Lunar echo with minimal processing. Our approach was to repeat the Moon-bounce experiment employing full beam steering capability of both HAARP and the radio observations and test matched filter processing before attempting an asteroid detection experiment. Table 1 presents the observing log for the experiments.

This paper's copyright is held by the author(s). It is published in these proceedings and included in any archive such as IEEE Xplore under the license granted by the "Agreement Granting URSI and IEICE Rights Related to Publication of Scholarly Work."

Table 1. Observing Log

Epoch	Experiment	Status
2022 January 14	Moon-bounce	Successful
2022 October 19–21	Moon-bounce	No detection Ionospheric effects?
2022 December 27	near-Earth asteroid 2010 XC15	Data under analysis

In each experiment HAARP transmitted a 2-second repeating chirp centered at 9.6 MHz with a bandwidth of 30 kHz (9.585 – 9.615 MHz), with approximately 1.25 GW EIRP, while UNM-LWA and OVRO-LWA observatories received. Both HAARP and the radio observatories actively steered their arrays at the targets. Dual polarization data were received at UNM-LWA and OVRO-LWA. Note the UNM-LWA consists of two stations: LWA1 and LWA-SV; the data shown below were collected at the Sevilleta station (LWA-SV). Raw voltage waveforms were demodulated and matched filtered using a reference waveform measured at HAARP. Despite the low bandwidth, the theoretical time-bandwidth product of the 2 second matched filtered chirp is ~48 dB.

2 Jan. 14, 2022 Moon-bounce

On Jan. 14, 2022, HAARP transmitted right-circular polarization (O-mode) for 1.5 hours starting at 0600 UTC. The Moon's elevation angle at HAARP was approximately 50°. Data from the UNM-SV array was sampled at 9.8 MHz complex baseband centered at 10.6 MHz. The data were digitally down-converted to be centered at 9.6 MHz and then subsampled at 76.5625 kHz to reduce data volume. The entire 1.5 hr record was then matched filtered and wrapped at 2-second intervals to produce a radargram (a radargram is an image that aligns echoes at the pulse repetition interval (PRI)). OVRO-LWA power data also showed detection of a 2-second repeating chirp.

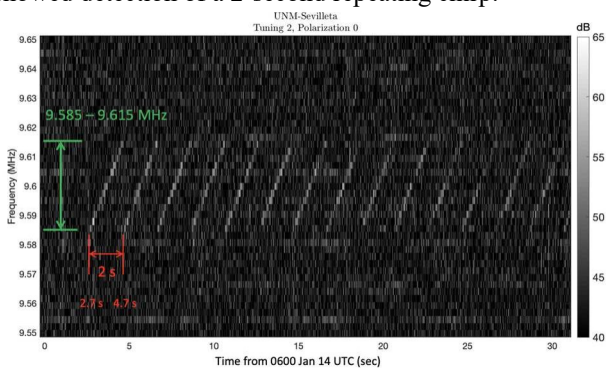


Figure 1. Spectrogram of the HAARP chirp received at UNM-SV. The first chirp arrives approximately 2.7 s after transmission, consistent with the round-trip time to the Moon.

The spectrogram is shown in Figure 2. The matched filtered radargram is shown in Figure 3. The single-pulse signal to noise ratio (SNR) of the primary Lunar echo is as high as

35 dB. The red line shows the predicted round-trip time delay of about 2.7 seconds which is computed using outputs from the JPL Horizons online ephemeris tool. The primary echo is slightly delayed relative to the prediction which may be a result of imperfect matched filter response or ionospheric group delay. Ghost images appear at 4 ms intervals before and after the primary echo. These artifacts are known to be due to the transmit waveform. The Moon is tidally locked to Earth and the look angles from the observatories to the Lunar surface change slowly, therefore, we expect the speckle pattern to be nearly constant or slowly varying. Amplitude fading that is observed might then be attributable to the ionosphere. Simple polarization combination of the UNM-SV dual-pol data showed strong preference for one circular handedness over the other, which is consistent with the single-handed circular polarization of the transmitted waveform and further suggests the potential for using these facilities in a polarimetric bistatic mode.

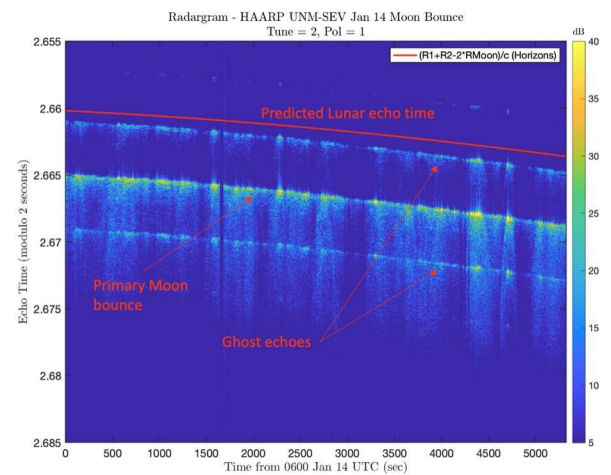


Figure 2. Matched filtered radargram of HAARP to UNM-SV bistatic Moon-bounce echo. Red line is the predicted two-way echo time of the lunar surface from JPL Horizons. Ghost echoes (attenuated copies of the primary) that appear before and after the primary are processing artifacts.

3 Oct. 19-21, 2022 Moon-bounce

A second Moon bounce experiment was conducted in three parts: Oct 19 16:30-1800 UTC, Oct 20 17:30-18:30 UTC, and Oct 21 18:30-19:00. The local elevation angles of the Moon at HAARP were 47°, 43°, and 38°, respectively. On all three occasions the transmitted signal was received at both OVRO-LWA and UNM-SV immediately after transmission on repeated 2-second intervals and persisted for the durations of the tests. The equivalent range delay of the echoes was approximately 4000 km, which is roughly the distance between the observatories. No echoes were evident at the predicted Lunar delays. This suggests that the ionosphere was completely opaque, which is consistent for the time of day. The received signal power decreased from day to day suggesting a dependence on ionospheric conditions or beam pointing.

4 Dec. 27, 2022 near-Earth asteroid 2010 XC15

We attempted to detect asteroid 2010 XC15 on Dec 27, 2022. The asteroid orbit is depicted in Figures 4 and 5 as generated by the JPL Small-body Database Lookup online tool. This asteroid made it close approach at approximately 2 Lunar distances ($\sim 800,000$ km), which corresponds to a two-way time delay of about 5.4 seconds. This asteroid was selected because 1) its ephemeris was well-known allowing time to plan the experiment, 2) its diameter was estimated as 150 m and therefore presents are reasonably sized target, 3) it was the only asteroid of this size and distance known within the project study period. Concurrent Goldstone DSS-14 observations confirmed the diameter to be approximately 140 m.

HAARP transmitted for 12 hours starting at 1100 UTC. Its beam direction was updated every 5 minutes. The first 3-4 hours were expected to have quieter ionosphere before the Sun rose at the radio observatories. Figure 6 shows the range to target and local elevation angles as a function time. Figures 7 show the radargram for the first 9 hours and first 0.06 seconds of the 2 second PRI. Several slowly varying ionospheric signals at various delays are evident in addition to strong radio frequency interference (RFI). The absence of a direct signal at ~ 0.02 seconds indicates windows during which the transmission through the ionosphere was more likely.

Given the far distance from Earth of 2010 XC15 at its closest approach, the bistatic link budget indicated that several hours of coherent processing would be required to detect the asteroid with positive SNR. This is in principle possible, but it requires that the phase of each matched filter pulse be known before combining pulses. Phase terms that were identified include: geometric propagation phase to target vs time, pulse-to-pulse phase of the transmitter, progressive phase shift of the steered HAARP beam, unknown random ionospheric phase, unknown polarization state, speckle phase from rotating asteroid, as well as a random phase offset every hour due to a scheduled transmitter restart. In light of these, incoherent processing is easiest but hampered by the presence of RFI. As of this submission, processing for asteroid detection is ongoing. Future experiments may have to target asteroids that make their closest approach to Earth closer than 2 Lunar distances.

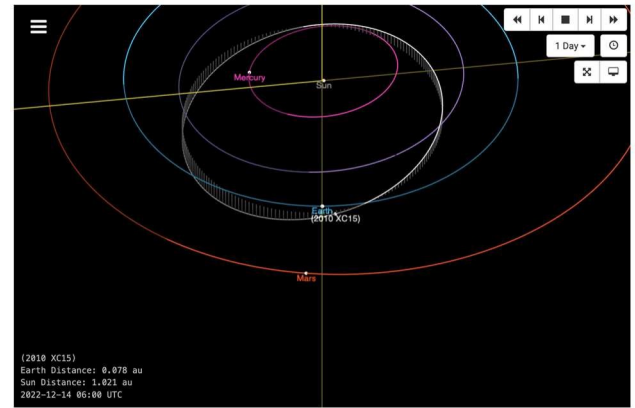


Figure 3. Illustration of the orbit of asteroid 2010 XC15.

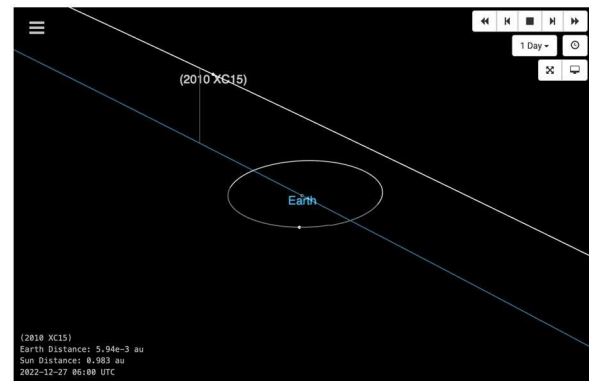


Figure 4. Zoom-in illustration of the orbit of asteroid 2010 XC15 on Dec 27, 2022.

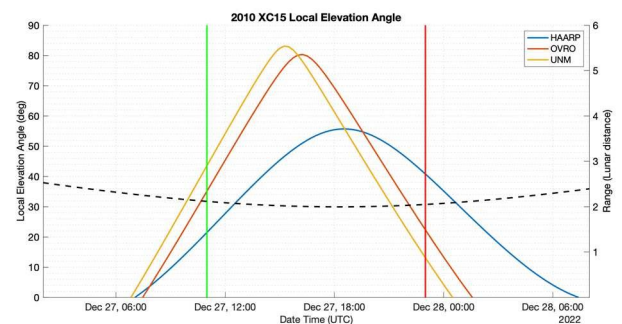


Figure 5. Local elevation angles of asteroid 2010 XC15 on Dec 27 from HAARP, OVRO-LWA, and UNM-LWA. Range is plotted as the dashed line. Transmission lasted from 1100 (green line) to 2300 (red line) UTC.

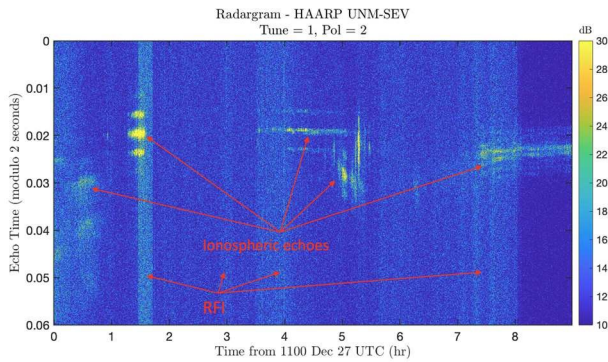


Figure 6. Processed HAARP/UNM-SV bistatic radargram for the first 0.06 seconds of the PRI for the first 9 hours of the Dec 27 observation. Different ionospheric echoes are present. Strong RFI is also present.

5 Discussion

These experiments demonstrate attempts to use HAARP and UNM-LWA and OVRO-LWA as an HF bistatic radar. It was the first time a near-Earth asteroid detection was attempted at 9.6 MHz. Coherent matched filter processing proved reasonably successful in the Moon bounce and asteroid experiments. Ghost artifacts due to the transmit waveform can be improved. Levels of ionospheric interference and blockage were mixed across the three experiments. The variety of short-time echoes during the Dec 27 experiment shows potential for future ionospheric studies. Finally, the Dec 27 experiment generated strong public interest because hundreds of HAM radio reception reports were submitted from around the world.

Acknowledgements

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA (80NM0018D0004). © 2023. All rights reserved. HAARP operations and University of Alaska staff were supported by NSF award #2054361, Establishing a Subauroral Geophysical Observatory for Space Physics and Radio Science at Gakona, Alaska.

References

- [1] M. S. Haynes, C. Elachi, L. Benner, G. Hallinan, I. Fenni, "Ground-Based Low-Frequency Radar for Assessing Near-Earth Asteroid Interiors," *53rd Lunar and Planetary Society Conference, LPI Contributions* 2678, March 2022.
- [2] M. S. Haynes, C. Elachi, L.A.M. Benner, G. Hallinan, I. Fenni, B. Davidsson, M. Brozovic, P. A. Bernhardt, J. Matthews, J. Lazio, "Potential use of Ground-Based Long-Wavelength Radar for Interior Sensing of Apophis in 2029", *Apophis T-7 Workshop, LPI Contributions* 2681, May 2022.
- [3] W. D. Reeve, "Lunar Echo Experiment – Reflections of an Observer", *RadioUser Magazine*, [Whitepaper], 2008. (<http://www.radiouser.co.uk/>)
- [4] P. Rodriguez, K. P. Stewart, B. C. Hicks, N. Paravastu, E. J. Kennedy, P. A. Kossey, L. J. Rickard, "Lunar Echo Experiments at Long Wavelength using HAARP and LWA," *URSI General Assembly and Scientific Symposium*, JP05.5, Chicago, IL, 2008.
- [5] K. P. Stewart, P. Rodriguez, B. C. Hicks, N. Paravastu, N. E. Kassim, E. J. Kennedy, P. A. Kossey, L. J. Rickard, "Instrumentation for Lunar Echo Measurements with HAARP and LWA," *URSI General Assembly and Scientific Symposium*, JP05.3, Chicago, IL, 2008.