GROUND-BASED LOW-FREQUENCY RADAR FOR ASSESSING NEAR-EARTH ASTEROID INTERIORS. M. S. Haynes[1], C. Elachi[2], L. Benner[1], G. Hallinan[2], and I. Fenni[1], [1]Jet Propulsion Laboratory, California Institute of Technology (4800 Oak Grove Dr. M/S 300-235, Pasadena, CA. mark.s.haynes@jpl.nasa.gov), [2]California Institute of Technology, Pasadena, CA.

Introduction: Characterizing the interior structure and composition of near-Earth asteroids (NEAs) is critical for advancing our understanding of solar system evolution and aiding planetary defense. Multiple lines of evidence indicate that many, if not most, NEA interiors are rubble piles, with a subset that are monolithic solids. Definitive answers will influence the response to potentially hazardous objects. The proximity and frequency of NEA flybys creates opportunities to repeatedly probe and study the interiors of NEAs using ground-based radar systems and to fill a strategic knowledge gap in our understanding of these objects, [1]. Investigating the use of low frequency (HF/VHF/UHF) ground-based radar as a means for interior imaging is relatively new, [2,3,4]. We present initial results on the feasibility of this method and planning for future proofs-of-concept.

NEA Occurrence for Tomography: Although Apophis is the best-known example for a future very close flyby, and will present an outstanding opportunity for radar tomography in 2029, other NEAs > 100 m in diameter will approach very closely this decade that could provide signal-to-noise ratios suitable for tomography: 1999 AN10 in 2027; 2001 WN5 and 1997 XF11 in 2028; and possibly 2006 SU49 in 2029.

Arguably the most frequent opportunities for radar tomography will be with significantly smaller NEAs <100 m in diameter that approach within roughly one Earth-Moon distance. During 2021, 12 NEAs per month on average were discovered that approached within one lunar distance, most of them <10 m in diameter, and one per month was >15 m in diameter.

Most asteroids making very close encounters are found with less than one week notice and about 50% of these are discovered after the flyby. Among flybys within one lunar distance in the last four years, seven objects were >50 m in diameter, and two objects, 2018 AH and 2020 LD, were probably larger than 100 meters.

The number of known very close NEA flybys increased from 81 in 2019 to 107 in 2020 and finally to 142 in 2021, presumably due to improvements in the efficiency, sky coverage, and perhaps sensitivity of NEA search efforts. The rate seems poised to increase when the Vera Rubin Observatory begins operations in 2023 and after NASA's Near-Earth Object Surveyor mission launches in 2026. To date, the lowest frequency facility that has considered routine detection of NEOs and investigation of mini-moons is EISCAT3D in Norway which will operate at 233 MHz, [5].

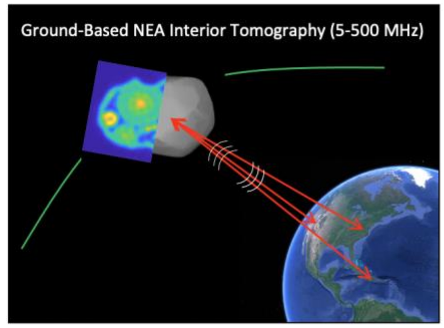

Figure 1: Illustration of ground-based radar tomography.

Requirements for Ground-Based NEA Interior Tomography: Ground-based interior imaging has two goals: 1) general assessment of the backscatter from the interiors of NEAs, 2) interior imaging using 3D Tomographic SAR or inverse scattering methods [6]. Low frequencies (long wavelengths) are required to penetrate the interior, specifically in HF/VHF/UHF bands, where several dB/m absorption are expected for frequencies <100MHz, [7]. Good SNR, coherent integration, ionospheric compensation, and multiple viewing angles are also required. One major limitation of low frequencies, compared to e.g., X-band, is far lower antenna gain for the same sized dish antennas

Ground-based Low-frequency Radio/Radar Observatories: We have compiled a list of ground-based low-frequency radio/radar observatories in an effort of understand what facilities and capabilities are available for ground-based NEA imaging in the HF/VHF/UHF bands. Figure 2 shows the locations of the observatories listed in Table 1. Parameters are compiled from publicly available sources. Most observatories are for radio astronomy and therefore are receive-only. We plan to added many of these to the JPL HORIZONS database to aid future studies.

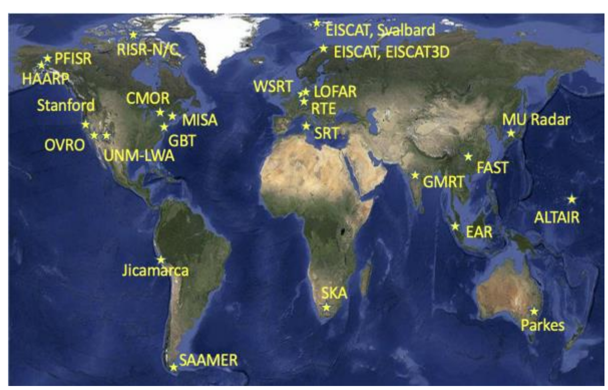

Figure 2: Location of low-frequency radar/radio facilities.

Observatory	Frequency (MHz)	Mode	Aperture Type
OVRO-LWA	12-85	Rx	*PA, Dish 40m
Jicamarca	50	Tx/Rx	PA (6 MW)
HAARP	2.8-10	Tx/Rx	PA (3 MW)
CMOR	17, 30, 38	Tx/Rx	PA (6 kW)
MU Radar	47	Tx/Rx	PA (1 MW)
EAR	47	Tx/Rx	PA (100 kW)
EISCAT	224	Tx/Rx	Dish 32m
EISCAT 3D	233	Tx/Rx	PA, Dish 70m
EISCAT, Svalbard	500	Tx/Rx	Dish
ALTAIR	158	Tx/Rx	Dish (5 MW)
UNM-LWA	10-88	Rx	PA
Parkes	≥704	Rx	Dish 64m
MISA	440	Tx/Rx	Dish 46m (2.5 MW)
Stanford	≥20	Tx/Rx	Dish 46m
Green Bank	≥290	Rx	Dish 100m
FAST	≥70	Rx	Dish 500m
Westerbork	≥120	Rx	Dish array: 14x24m
GMRT	50	Rx	Dish 45m
Effelsberg (RTE)	408	Rx	Dish 100m
Sardinia (SRT)	≥300	Rx	Dish 64m
LOFAR (core)	10-240	Rx	PA
SKA	≥50	Rx	PA
SAAMER	32.5	Tx/Rx	PA (60 kW)
PFISR, RISR-N/C	440	Tx/Rx	PA (2 MW)

*Table 1: List of radio/radar facilities. *PA = Phased array*

Link Budget for OVRO-LWA at 60 MHz: We have developed a basic link budget using parameters of the Owens Valley Radio Observatory-Long Wavelength Array (OVRO-LWA). We assess a hypothetical example where OVRO-LWA receives and the OVRO 40 m dish is used as transmitter at 60 MHz. Figure 3 shows the link budget for a 100kW Tx power, 352 LWA elements, and 20 dBm^2 radar backscatter vs coherent integration time. Figure 3 shows that 10s of dB of SNR may be possible for cislunar NEAs and reasonable integration times. The key limitation is the low gain of the dish at 60 MHz.

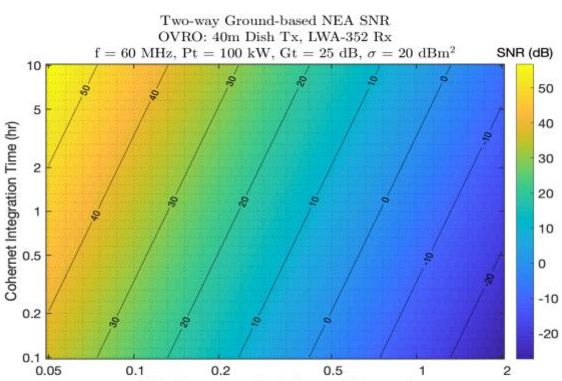

Figure 3: OVRO SNR link budget vs coherent integration time for 100 m^2 radar backscatter target.

Potential NEA targets in 2022 and 2023: We aim for a proof-of-concept test in the next two years. To that end, we have searched for close passing NEAs that are estimated to have an SNR>10,000 for the Goldstone 70m dish, Table 2. This provides a proxy for targets with usable close approach ranges and sizes to attempt with lower frequencies. We found NEA 2010 XC15 will pass at ~2 lunar distances (LD) in late 2022. Figure 4 shows the elevation angle and range at OVRO-LWA on 2022 Dec 27. The most frequent opportunities will be newly-discovered NEAs with only a few days of notice to their closest approaches. These will require active coordination with optical observers to obtain astrometry to reduce plane-of-sky pointing uncertainties sufficiently to point the radio/radar telescopes.

Date	Target	DIA	LD	DSS-14 SNR
2022 Jan	1994 PC1	1.1	5.06	110000
2022 Nov	2005 LW3	0.17	2.96	29000
2022 Dec	2015 RN35	0.08	1.79	22000
2022 Dec	**2010 XC15**	**0.19**	**2.02**	**290000**
2023 Oct	1998 HH49	0.19	3.11	25000

Table 2: Potential close NEAs in 2021-2023. SNRs are for entire daily view period. DIA in km. LD = Lunar Distance.

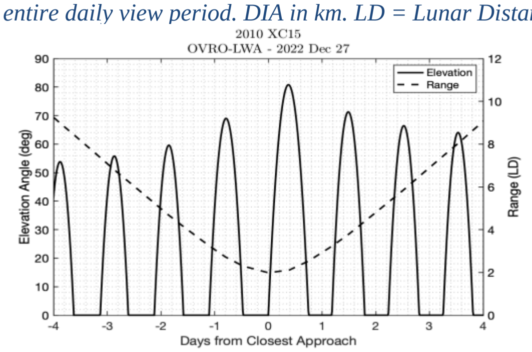

Figure 4: Elevation angle and closest approach range of NEA 2010 XC15 in Dec 2022 as viewed from OVRO.

Next Steps: 1) Assessing whether these facilities can detect asteroids and/or needed capabilities, 2) detailed understanding of digital processing capabilities for coherent SAR, 3) expanding the search space of possible targets, 4) improved methods for estimating SNR and using these for rapid response, 5) testing the idea on a real asteroid in 2022/2023.

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References: [1] Haynes, M., et al., (2020) *NASEM* PSDS. [2] Nolan, M., et al (2020) *Apophis T-9*, 2242. [3] Herique, A., et al. (2020) *AT-9*, 2029. [4] Virkki, A., et al. (2020) *AT-9*, 2013. [5] Kastinen, D., et al (2020) *AGP*, 38, 861-879. [6] Haynes, M., et al. (2021) *LPSC* 2548. [7] Herique, A., et al (2018) *ASR*, 62, 2141-2162.