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CAPABILITIES OF PAST, PRESENT, AND FUTURE RADAR SYSTEMS FOR
OBSERVATIONS OF NEAR-EARTH OBJECTS

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Introduction:

Ground-based radar systems have unique capabilities for physical and dynamical characterization of near-Earth asteroids and comets. With a planetary radar system, it is possible to measure a near-Earth object's radial velocity and distance with great accuracy (as fine as 1 cm/s and 100 m, respectively), through observations that take less than one hour. Radar astrometry from a single observation is usually sufficient to prevent a newly discovered object from becoming lost (due to growing uncertainties) after its first apparition and requiring later rediscovery. With fast and accurate determination of an NEO's orbital parameters and future trajectory, it is possible to rule out the vast majority of potential impacts, or otherwise to provide strong constraints on the time and location of a potential impact.

Radar is also very useful for physical characterization of NEOs, providing information on size, shape, surface properties, rotation state, and binarity, which aids planning of potential impact mitigation missions [1]. With radar, the observers control the transmitted signal and can change the properties of that signal (within the technical limitations of the system) to return the most useful information. The brightest radar targets can be resolved into sets of delay-Doppler images, revealing details almost as fine as in images from a spacecraft flyby, for much less cost.

Building upon the work of [2,3,4], we investigate how many near-Earth asteroids and potentially hazardous asteroids could be detected with past, present, and potential future planetary radar systems. We consider radar transmissions from Arecibo Observatory, Goldstone Deep Space Communications Complex, and two radar facility concepts that have been proposed for the future.

Radar facilities:

In this work, we consider four planetary radar systems: Arecibo Observatory (305 m diameter; collapsed in December 2020 but still a useful point of comparison; we

assume system parameters from before the telescope was damaged by Hurricane Maria in September 2017), Goldstone Deep Space Communications Complex DSS-14 (70 m), and two radar facility concepts that have been proposed for the future: the Next Generation Arecibo Telescope (NGAT) array concept (slightly modified from [3]), and a bistatic configuration with the Green Bank Telescope (GBT) transmitting [5] and the Next-Generation Very Large Array (ngVLA) [6] receiving the echoes. For DSS-14, Arecibo, and NGAT, we assume monostatic observations, in which that facility switches between transmitting and receiving. We use the following system parameters:

Facility	Transmitter frequency (GHz)	Transmitter power (MW)	Transmitter gain	Maximum zenith angle	Receiver sensitivity (m ² /K)
Goldstone DSS-14	8.56	0.45	74.0 dB	70°	140
Arecibo	2.38	0.90	73.4 dB	20°	1150
NGAT	5.00	2.00	82.7 dB	48°	1900
GBT to ngVLA	13.70	0.50	81.4 dB	78°	2050

Table 1: System parameters for the radar transmitters and receivers considered in this work. Gain is proportional to the transmitter's effective area. A radio receiver's sensitivity is its effective area divided by its system temperature.

Detectability of asteroid with $D = 140$ m

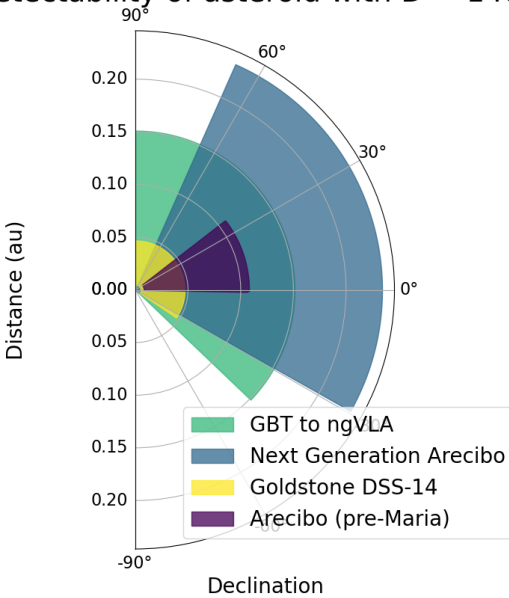


Figure 1: Distances and declinations at which a potentially hazardous asteroid (140 meters in diameter) would be detectable ($\text{SNR} > 5$ in 30 minutes of observations) with the various radar systems. This asteroid is assumed to have a radar albedo of 0.10 and a rotation period of 2.1 hours.

Methods: counting potential radar detections

We used the Minor Planet Center’s database of NEA orbital elements [7] (version of 2023 March 19) to calculate all NEAs’ positions at one-day intervals during the one-year period from 2022 March 1 through 2023 February 28. For each NEA and each radar facility, we calculated the NEA’s signal-to-noise ratio (SNR) for hypothetical radar observations [8], during the dates at which the NEA would appear within the facility’s range of observable declinations.

The MPC database gives every known NEA’s orbital elements and absolute magnitude. For radar SNR calculations, we converted that absolute magnitude to a diameter and a radar cross section by assuming an optical albedo of 0.18 and a radar albedo of 0.10. Radar SNR also depends (weakly) on the target’s rotation period. We assumed that objects with a calculated diameter of more than 140 meters have a rotation period of 2.1 hours, and that smaller objects have a rotation period of 0.25 hours.

On a given date, we define an NEA to be detectable if its SNR after 30 minutes of observations would be at least 5. We use 30 minutes based on past experience, since radar observers rarely would spend more than 30 minutes trying to observe an object if there is no clear signal. In such cases, we normally would move on after about 30 minutes and try to observe another object instead.

However, some potential detections (theoretically with sufficient SNR) had to be filtered out. In many cases, an NEA was only observed for a few days or a few weeks, at the time of its discovery. Without additional observations at later apparitions, such NEAs are effectively lost, since a short arc of observations gives poorly constrained orbital parameters, leading due to large and growing uncertainties in the NEA’s future sky position. If the uncertainty in its right ascension and declination is greater than the width of the radar beam (typically of order one arcminute), radar observations cannot be done. We consider an NEA to be lost and unobservable if its arc of observations is less than one year, and length of time between the last optical observation and the potential radar observation is greater than the arc of observation times. Thus, for example, an NEA with a ten-day arc is considered potentially observable for up to ten more days after the last optical observation, then lost after that. This simple rule does not account for all the complexities of orbit determination, but it gives adequate agreement with some manually inspected cases of how an NEA’s plane-of-sky uncertainty typically grows over time.

We also had to filter out objects that were only detectable (by radar) before they were actually discovered. For example, an object that was discovered in February could not have been observed with radar in January, no matter how close to Earth it may have been. We consider an NEA to be observable 24 hours after the time of its discovery observation (as reported in the corresponding Minor Planet Electronic Circular). Note that [2] assumed greater delays between discovery and reporting, but reporting seems to have gotten faster since then. During Arcibo’s final years of operation, we occasionally attempted to observe objects that were listed on the Minor Planet Center’s NEO confirmation page, with only about one day of observations.

We kept track of lost and not-yet-discovered objects when doing the calculations, and they are shown in some figures for comparison purposes, but such objects are not counted as potential detections.

We also divided the simulated detections into groups, based on their estimated SNR. $\text{SNR} > 50$ is typically bright enough to get spatially resolved delay-Doppler images of a target. $10 < \text{SNR} < 50$ is enough for a range measurement but usually not enough for well-resolved images. $5 < \text{SNR} < 10$ is a weak detection in which the target could be resolved only in Doppler frequency (called continuous-wave or CW observations).

Results: counts of detectable NEAs and PHAs

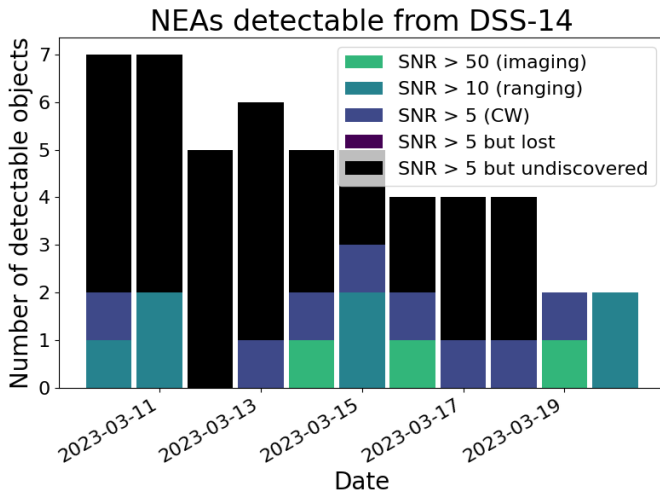


Figure 2: Counts of NEAs that could have been detected by Goldstone DSS-14 on each of 11 days in March 2023. On the first date (March 10), there was one NEA bright enough for ranging, one more NEA that was only bright enough for CW, and five others that would have been detectable but had not yet been discovered. On March 11, there were two known NEAs that were bright enough for ranging.

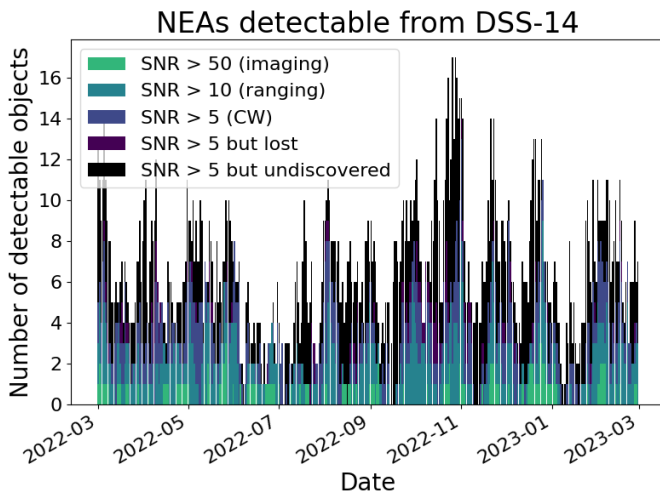


Figure 3: Similar to Figure 2, but showing how many NEAs could have been detected by DSS-14 on each day during the twelve-month period from March 2022 through February 2023.

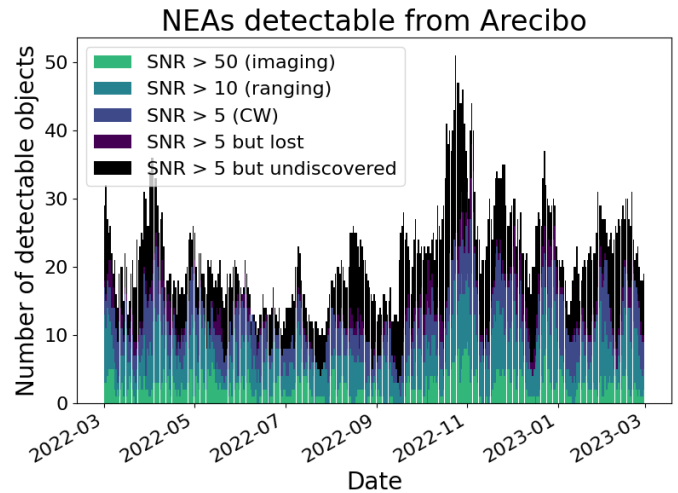


Figure 4: Like Figure 3, showing how many NEAs could have been detected by Arecibo Observatory during the same twelve months.

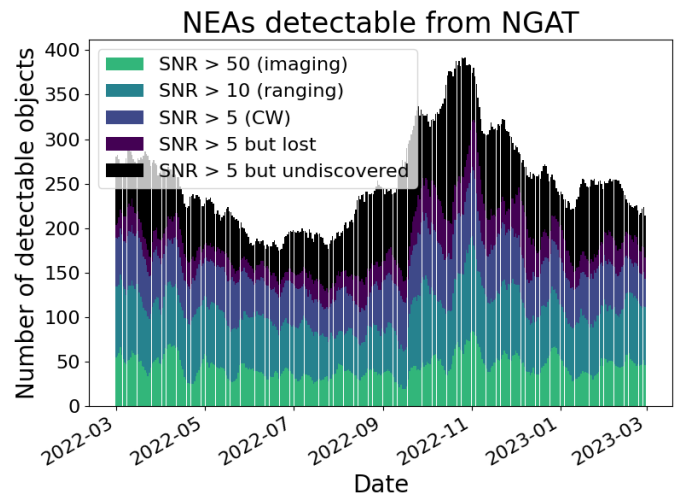


Figure 5: Like Figures 3 and 4, showing how many NEAs could have been detected by the Next Generation Arecibo Telescope during the same twelve months.

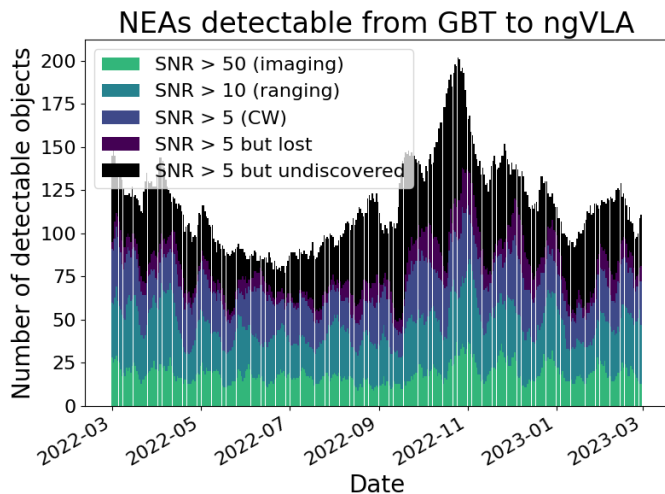


Figure 6: Like Figures 3 through 5, showing how many NEAs could have been detected with GBT transmitting and ngVLA receiving during the same twelve months.

Finally, we have tabulated and plotted how many unique NEAs could have been detected by each of these four radar facilities during this twelve-month period:

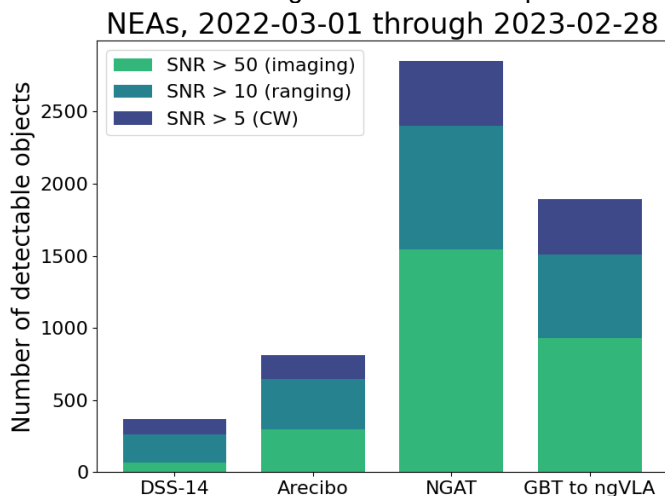


Figure 7: Counts of potential detections by each facility over the entire twelve-month period, for all NEAs: 368 for Goldstone DSS-14, 810 for Arcibo, 2849 for NGAT, and 1892 for GBT to ngVLA. An observatory's annual total (shown here) is considerably less than the sum of its daily potential detections, because an NEA is typically observable for multiple consecutive days.

We note that the NEA counts in Figure 7 include many small objects. For instance, the median estimated diameter for the potential Arcibo detections is just 23 m. For planetary defense, we are more concerned about larger objects. Figure 8 shows the counts for potentially hazardous asteroids (PHAs), which by definition have absolute magnitude less than 22.0 (diameter greater than about 140 m) and also can approach within 0.05 au of Earth's orbit.

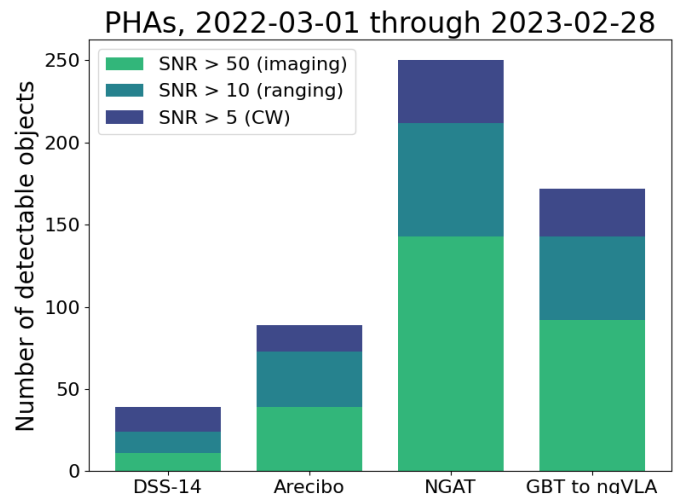


Figure 8: Counts of potential detections of PHAs by each facility over the entire twelve-month period. DSS-14 could detect 39, Arcibo 89, NGAT 250, and GBT-ngVLA 172.

Future work:

The scripts that do these radar SNR calculations can easily be modified to analyze potential detections for additional existing or planned planetary radar facilities.

There are a number of potential improvements that could be made to these scripts. For instance, instead of estimating each asteroid's diameter and rotation period from (only) its absolute magnitude, it would be better to use published values for diameter or rotation period, for objects for which they are available. Additionally, it may be worthwhile to refine criteria such as the script's definition of when an asteroid is lost.

In addition to counting radar-detectable PHAs, we also could count detectable objects in other categories of interest, such as NHATS (potential spacecraft targets) or potential impactors listed by JPL (Sentry) and NEODyS. Furthermore, we can look at other ways of subdividing and plotting the detected objects, based on size, MOID, SNR, or other attributes.

We are interested in analyzing how many of the asteroids expected to be discovered by Vera C. Rubin Observatory (LSST) and NEO Surveyor would be detectable by radar. If you are involved with either of those programs, the first author would like to discuss this with you!

Acknowledgments

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