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CAPABILITIES OF EARTH-BASED RADAR FACILITIES FOR NEAR-EARTH ASTEROID OBSERVATIONS

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ABSTRACT

We evaluated the planetary radar capabilities at Arecibo, the Goldstone 70 m DSS-14 and 34 m DSS-13 antennas, the 70 m DSS-43 antenna at Canberra, the Green Bank Telescope (GBT), and the Parkes Radio Telescope in terms of their relative sensitivities and the number of known near-Earth asteroids (NEAs) detectable per year in monostatic and bistatic configurations. In the 2015 calendar year, monostatic observations with Arecibo and DSS-14 were capable of detecting 253 and 131 NEAs respectively, with signal-to-noise ratios (SNRs) greater than 30/track. Combined, the two observatories were capable of detecting 276 NEAs. Of these, Arecibo detected 77 and Goldstone detected 32, or 30% and 24% of the numbers that were possible. The two observatories detected an additional 18 and 7 NEAs respectively, with SNRs of less than 30/track. This indicates that a substantial number of potential targets are not being observed. The bistatic configuration with DSS-14 transmitting and the GBT receiving was capable of detecting about 195 NEAs, or ~50% more than with monostatic observations at DSS-14. Most of the detectable asteroids were targets of opportunity that were discovered less than 15 days before the end of their observing windows. About 50% of the detectable asteroids have absolute magnitudes >25, which corresponds to diameters <~30 m.

Key words: minor planets, asteroids: general – techniques: radar astronomy – telescopes

1. INTRODUCTION

Ground-based radar is an invaluable tool for improving the orbits and characterizing the physical properties of near-Earth asteroids (NEAs). Such characterization is essential for identifying and mitigating impact threats, planning robotic and human space missions, and for advancing our scientific understanding of asteroids. Radar range and Doppler measurements of NEAs often have fractional precision better than 1 in 10^7, which can provide dramatic improvements to asteroid orbits, prevent loss of newly discovered objects, and increase the window of reliable predictions of trajectories by decades to centuries (Ostro & Giorgini 2004). In some cases, signal-to-noise ratios (SNRs) are high enough to obtain delay-Doppler images of the objects with range resolutions as fine as 1.875 m. Delay-Doppler images provide a powerful technique to see surface features, obtain shape models (e.g., Naidu et al. 2013), discover natural satellites (e.g., Margot et al. 2002), and estimate masses and densities from binary systems (e.g., Ostro et al. 2006; Margot et al. 2015; Naidu et al. 2015) and from non-gravitational accelerations due to the Yarkovsky effect (e.g., Benner et al. 2015; Vokrouhlicky et al. 2015). Radar observations also help support spacecraft missions such as *NEAR-Shoemaker, Hayabusa, Chang'e 2, EPOXI, OSIRIS-REx*, and the proposed *Asteroid Redirect Mission* and the Asteroid Impact and Deflection Assessment mission.

In 2005, the United States Congress passed the George E. Brown, Jr. Act that directed NASA to detect, track, and characterize near-Earth objects larger than 140 m in diameter. The objectives were based on a NASA report (Near-Earth Object Science Definition Team 2003) which concluded that such objects are capable of penetrating through Earth's atmosphere and causing regional destruction on impact. In 2010, the goals of the George E. Brown, Jr. Act were incorporated in the National Space Policy of the USA (https://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10. pdf) that guides the NASA administrator to pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalog, and characterize near-Earth objects to reduce the risk of harm to humans from an unexpected impact on our planet and to identify potentially resource-rich planetary objects.

The 305 m Arecibo Observatory in Puerto Rico (2380 MHz, 12.6 cm) and the 70 m DSS-14 antenna at the Goldstone Deep Space Communications Complex in California (8560 MHz, 3.5 cm) are the only telescopes with radar transmitters that are regularly used to observe NEAs. Arecibo and DSS-14 have observed hundreds of NEAs since the 1970s (Figure 1).

In 2014, the 34 m DSS-13 antenna at Goldstone was equipped with an 80 kW transmitter that operates at a frequency of 7190 MHz (4.2 cm wavelength). This transmitter allows delay-Doppler imaging with range resolutions up to 1.875 m, which is twice as fine as the finest range resolution available at DSS-14 and four times finer than the finest resolution available at Arecibo. The transmitter at DSS-13 was used to image two NEAs in 2015.

The 100 m Green Bank Telescope (GBT) is occasionally used in a bistatic configuration to receive radar echoes from NEAs, with DSS-14, DSS-13, or Arecibo transmitting. The GBT does not have a radar transmitter.

In 2015 November, the 70 m DSS-43 antenna in Canberra (2290 MHz, 13.1 cm) and the 64 m Parkes Radio Telescope obtained the first radar detection of an NEA in Australia with (413577) 2005 UL5. This is an important capability because these telescopes are located in the southern hemisphere and can point to high southern declinations that cannot be seen by Arecibo, Goldstone, or the GBT. The bistatic DSS-43 to Parkes

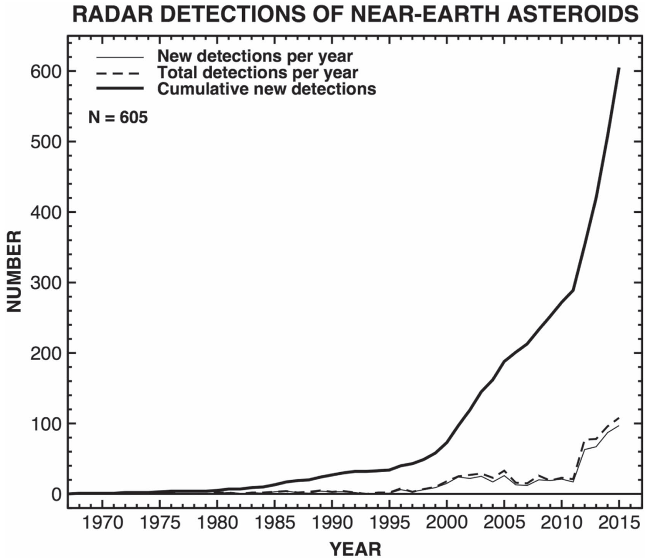

Figure 1. Total number of near-Earth asteroids detected by ground-based radar facilities each year until 2015. The cumulative number of radar detections as a function of time is shown using a solid bold line.

configuration is currently the most sensitive option for radar observations of NEAs at high southern declinations. Because DSS-43 and Parkes are offset substantially in longitude from Arecibo and Goldstone, they can also allow observations of asteroids at times when targets are below the horizon at the other radar facilities, which could extend rotational coverage for some objects and allow radar observations in Australia that are not possible elsewhere due to scheduling conflicts.

Delay-Doppler images are important data products of radar observations and resolve the target in time delay and Doppler frequency (see Ostro 1993 for details). The resolution along the delay axis depends on the transmitted signal and cannot be changed once the data are recorded. The finest possible delay resolution is limited by the maximum transmitter bandwidth.

The choice of Doppler resolution is more flexible as it depends on the Fourier transform length, which is selected when processing the data. The finest possible Doppler resolution is given by the inverse of the total integration time. For monostatic observations this is approximately equal to the round-trip light time to the target (minus the time required to switch from transmitter to receiver). With bistatic observations, it is limited by the length of continuously recorded data. During observations, the delay and Doppler resolutions are subjectively chosen such that the corresponding spatial scales along each axis are roughly equal. Other factors are also considered but are outside the scope of this discussion.

In this paper, we explore the capabilities of these ground-based radars in terms of their relative sensitivities and the number of NEAs detectable per year in various monostatic and bistatic configurations. We seek to answer the question: if resources were not an issue, how many NEAs could be observed with current radar facilities per year? This study is important for strategic planning of observations, implementing policies, and future upgrades.

The first study into this topic was by Jurgens & Bender (1977), who found that 60 out of the 1984 then-known asteroids (near-Earth and main belt) were detectable at either Goldstone or Arecibo between 1977 and 1987. The number of known asteroids has grown tremendously since then and the number of objects detectable by these facilities is now dramatically higher. 605 NEAs and 138 main belt asteroids have been detected through the end of 2015 (Figure 1).

Giorgini et al. (2008) performed a study to determine the improvements in number of detectable asteroids, trajectory predictions, and physical characterization of asteroids achieved by doubling the transmitter power at DSS-14, adding a southern hemisphere planetary radar, and increasing the bandwidth of the transmitter. The study used a simulated NEA population to estimate the improvements.

In 2010, the National Research Council, at the request of NASA, conducted a study that found that planetary radar plays a crucial role for achieving the goals of the George E. Brown, Jr. Act (Shapiro et al. 2010). The report estimated that about 410 near-Earth objects could be observed by radar (Arecibo and Goldstone) in a one year interval starting in 2008 May. Out of these, 140 had been discovered before 2008 May and 270 were found during the time interval considered in the report.

During calendar year 2015, more than 1500 NEAs were discovered (http://minorplanetcenter.net/iau/lists/YearlyBreakdown.html), the largest number of NEA discoveries in a single year to date. The NEA discovery rate is expected to rise in the next few years as new survey telescopes such as Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) 2 and ATLAS become fully operational and new wider-field cameras are installed at the Catalina Sky Survey (CSS) telescopes (Christensen et al. 2015). Because many NEAs are detectable by radar during their discovery apparition (Ostro & Giorgini 2004), 2015 provides the most accurate indication of the number of radar-detectable NEAs under current circumstances. Often the discovery apparition provides the best opportunity for radar observations for decades (Ostro & Giorgini 2004) and considerable effort is devoted to observe such targets of opportunity (TOOs). For example, in 2015, 45 TOOs were observed with Arecibo and 15 TOOs were observed with DSS-14.

2. METHODS

We performed an automated search of all NEAs listed on the minor planet center (MPC) website (http://www.minorplanetcenter.net/iau/mpc.html) that were discovered before the end of 2015 to identify all radar observing opportunities in that year. We downloaded trajectories of the NEAs from the Jet Propulsion Laboratory's Horizons Ephemeris Service (http://ssd.jpl.nasa.gov/?horizons_doc). We estimated radar SNRs for transmission/reception at Arecibo, DSS-13, DSS-14, DSS-43, Parkes, and the GBT for this study. For each telescope, we created a short list of objects that came within 1 astronomical unit (au) of Earth and passed through the declination window of the telescope (Table 1). In this step, we computed the positions of the objects at 1 hour intervals throughout 2015. For each object in the short-list, detailed observing windows, or radar track durations, were computed by finding the time intervals in which the asteroid was above the minimum viewable elevation of the telescope (Table 1).

For each observing window we computed the minimum range to the target and estimated the SNR of its radar echo as $P_{rx}/\Delta P_{\rm noise}$, where P_{rx} is the power of the received echo and $\Delta P_{\rm noise}$ is the standard deviation of the receiver noise. P_{rx} can

Table 1
Telescope Parameter Assumptions

	DSS-13	DSS-14	DSS-43	Arecibo	GBT	Parkes
Declination range	$-35°$ to $+90°$	$-35°$ to $+90°$	$-90°$ to $+34.°5$	$-1°$ to $+38°$	$-46°$ to $+90°$	$-90°$ to $+26.°5$
Min. elevation (degrees)	20	20	20	70	5	30.5
Accessible sky fraction (%)	79	79	78	32	86	72
Diameter (m)	34	70	70	305	100	64
Aperture efficiency	0.71	0.64	0.64	0.38	0.71	0.45
				0.17 (X-band)		
Transmitter frequency (MHz)	7190	8560	2290	2380	NA	NA
Transmitter power (kW)	80	450	100	900	NA	NA
System temperature (K)	20	18	NA	23	25	28
Transmit-receive switch time (s)	NA	5	NA	5	NA	NA

be estimated using the radar equation (e.g., Ostro 1993),

$$P_{rx} = \frac{P_{tx} G_{tx} G_{rx} \lambda^2 \sigma}{(4\pi)^3 R^4}. \quad (1)$$

Here, P_{tx} is the transmitter power, G_{tx} and G_{rx} are the gain of the transmitting and receiving antennae, λ is the radar wavelength, σ is the radar cross-section of the target, and R is the distance between the target and the reference point of the antenna. For monostatic radar observations, the receiving and transmitting antennae are the same so $G_{tx} = G_{rx}$. Antenna gain, G, is given by $4\pi\eta A_{\rm ant}/\lambda^2$, where η is the aperture efficiency of the antenna and $A_{\rm ant}$ is the geometric area of the antenna. $\Delta P_{\rm noise}$ is given by

$$\Delta P_{\rm noise} = \frac{k T_{\rm sys} \Delta f}{(\Delta t \Delta f)^{\frac{1}{2}}}. \quad (2)$$

Here k is Boltzmann's constant, $T_{\rm sys}$ is the receiver temperature, Δf is the frequency resolution, and Δt is the total integration time of the received signal. The SNR is maximized if Δf is equal to the bandwidth (B) of the echo. Because receiver noise is stochastic in nature, the standard deviation of noise power falls off as the square root of the integration time.

The radar cross-section and echo bandwidth depend on the physical properties of the target and are often unknown. The radar cross section is given by $\sigma = \hat{\sigma} A$, where $\hat{\sigma}$ is the radar albedo and A is the projected area of the target. For a spherical object, the echo's bandwidth is given by $B = 4\pi D \cos\delta / \lambda P$, where D is the diameter, δ is the sub-radar latitude of the object, λ is the radar wavelength, and P is the spin period of the object. The telescope parameters used for the calculations are provided in Table 1. The relative sensitivities per round-trip light time (RTT), the time for the transmitted signal to reach, reflect off of, and return from the target, are given in Table 2 for various combinations of transmitters and receivers.

We used the European Asteroid Research Node (earn.dlr.de) database, which is the most thorough and up-to-date database of NEA physical properties, to obtain estimates of D and P. When a diameter estimate was not available, we computed a value for D from the absolute magnitude of the object by assuming a typical S-class optical albedo of 0.18. For objects with unknown rotation periods, we assumed a rotation period of 2.1 h if the object was larger than 140 m in diameter and 0.5 h for smaller objects. Spin periods for the vast majority of asteroids greater than 140 m exceed 2.1 h (Pravec et al. 2002, pp. 113–22), so this threshold places a conservative lower bound on the SNRs. Smaller asteroids exhibit a wide range of

Table 2
Relative Sensitivities of Various Transmitter–Receiver Combinations

Transmitter	Receiver	Relative sensitivity
DSS-14	DSS-14	1
	Arecibo	5.1
	GBT	2.3
	DSS-13	0.3
Arecibo	Arecibo	15
	GBT	5
	DSS-13	0.6
	DSS-14	2.2
DSS-43	Parkes	0.007
DSS-43 (400 kW)	Parkes	0.03
DSS-13	Arecibo	0.2
	GBT	0.08

Note. The first column indicates transmitting telescope, the second column indicates receiving telescope, and the third column indicates S/N/RTT values normalized to those at DSS-14. Transmitter and receiver parameters are provided in Table 1.

spin periods, both faster and slower than 2.1, and 0.5 h is close to the median (see Figure 5 in Harris et al. 2015).

For bistatic observations, the radar signal can be transmitted for the entire duration of the observing window (100% duty cycle). For monostatic observations, the same antenna transmits and receives so the duty cycle of transmission cannot exceed 50% and the total integration time of the radar echo cannot be more than one half of the observing window. Our calculations also took into consideration the finite time required to switch between the transmitter and receiver, which makes the integration time several seconds less than 50% of the observing window.

We adopted an SNR cutoff of $\geqslant$30/track for the final list of radar-detectable NEAs. Objects are detectable at lower estimated SNRs but the rate of successful detection is close to 100% above this threshold.

Monthly "survey nights" are scheduled at Arecibo to observe as many NEAs (mostly TOOs) as possible in a nominally 8 hr block of observing time. During these nights the observers often target NEAs with SNRs weaker than 30/track. This is tractable because Arecibo radar tracks for single objects are usually short (less than 3 hr) because the telescope can only point within 20° of zenith. If a target is not detected rapidly, a new target, if available, is selected.

Asteroids with SNRs <30/track are infrequently scheduled at Goldstone because the telescope is heavily subscribed with

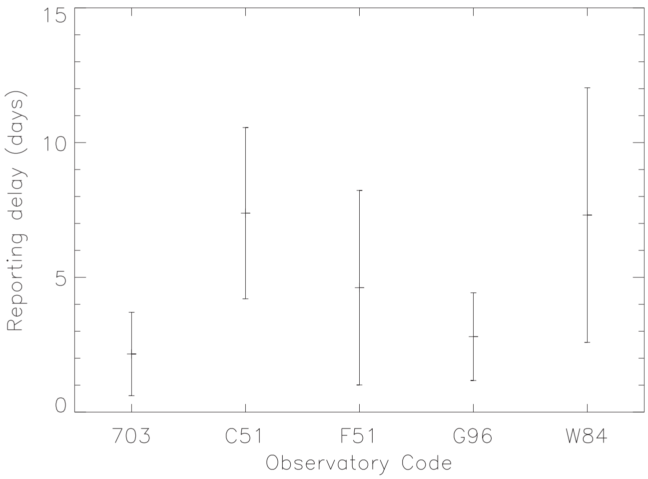

Figure 2. Means and standard deviations of discovery report delays for the top 5 observatories in terms of the number of NEAs discovered. Observatory codes designated by the MPC and sample sizes for each observatory are as follows: 703 Catalina Sky Survey (142), C51 NEOWISE mission (30), F51 PanSTARRS I (320), G96 Mt. Lemmon Survey (263), and W84 Dark Energy Cam (35).

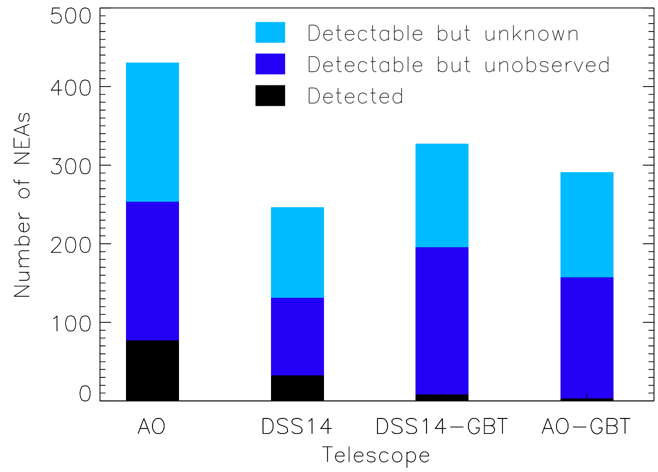

Figure 3. Histogram of currently known NEAs detectable and detected by various configurations of radar telescopes in 2015. AO stands for Arecibo Observatory and DSS-14 is the 70 m antenna at Goldstone. Each bar is divided into three parts: black indicates the asteroids that were observed by radar whereas light and dark blue colors represent asteroids that were not observed by radar. Asteroids in light blue were unknown during their radar observing windows. Dark blue represents asteroids that were known during their radar windows but not observed by radar.

spacecraft communications and only asteroids with high probabilities of success are scheduled. Radar tracks at Goldstone are usually much longer than at Arecibo and can, at least in principle, last more than 24 hours for objects at high northern declinations. This implies that it may take an unreasonably long time to achieve low SNRs at Goldstone for some objects and it is not practical to schedule such long tracks.

We assumed that Canberra and Parkes would only be used for crucial targets that are not visible at other radar facilities so we used a lower threshold of SNR $\geqslant 15/\mathrm{track}$ for these telescopes.

Our calculations account for the discovery announcement dates of the radar-observable NEAs and excluded targets that were detectable by radar only before their discoveries were announced. For targets discovered by the CSS and Mt. Lemmon Survey we added a typical reporting lag time of 2 days between discovery observation and discovery announcements. For the Pan-STARRS we added 4 days, and for all other observatories we adopted reporting lag times of 10 days. These typical reporting lag times were estimated by averaging over 790 randomly selected asteroid discovery announcements from 2014 from the MPC website. Figure 2 shows the means and standard deviations of the reporting lag times for various observatories. In this paper, we refer to asteroids that were detectable by radar irrespective of their discovery dates as "potentially detectable." We use the term "detectable" to refer to potentially detectable asteroids whose discoveries were announced before the radar view periods ended.

Radar beam sizes, approximately given by λ/D_{ant}, where D_{ant} is the antenna diameter, are on the order of 1 arcmin, so pointing uncertainties should ideally be significantly smaller than that prior to a radar observation. In practice, we prefer 3σ pointing uncertainties <20 arcsec. Radar is not an efficient method for blindly searching for asteroids due to its narrow beam width, the potentially enormous Doppler shifts caused by the object's translational motion, and the cost of the observations. Some known NEAs have large plane-of-sky pointing, Doppler, and time delay uncertainties. For these objects we ignored the uncertainties and adopted the nominal orbit. We often request optical astrometry for such objects so only a few scheduled objects are not detected annually due to large pointing uncertainties. For some of the observable objects there is insufficient time for scheduling and planning observations before the objects exit the radar windows. More time is required to schedule a target at Goldstone than at Arecibo because obtaining transmit authorization from various government agencies is necessary due to airspace restrictions. Other limitations to schedule NEAs for radar observations include scheduling conflicts with other observing projects, spacecraft communication, equipment problems, and insufficient budget for staffing telescopes to observe all detectable NEAs. DSS-43 and Parkes are currently not configured to observe TOOs on short notice. These limitations make the number of observed targets much lower than the number of detectable asteroids listed in this paper. For Arecibo, DSS-14, and GBT we compared the numbers of observable NEAs with the number of NEAs actually observed.

3. RESULTS

3.1. Arecibo Monostatic

We found 430 known and new objects that were potentially detectable at Arecibo in 2015 with SNRs greater than 30/track (Figure 3). There were 253 discoveries ($\sim$59% of the potentially detectable NEAs) that were announced by the Minor Planet Center before radar view periods with SNR/track $\geqslant$30 ended. The fraction of discoveries announced in time for radar observations varies as a function of the absolute magnitudes of the asteroids and is shown in Figure 4. Discoveries of all potentially detectable asteroids brighter than absolute magnitude of 19 (corresponding to diameters $>\sim$500 m) were announced before their radar view periods ended. Arecibo detected 77 NEAs in 2015 with estimated SNRs greater than 30/track, or about 30% of the NEAs considered as detectable in this study. An additional 18 NEAs were detected with weaker SNRs.

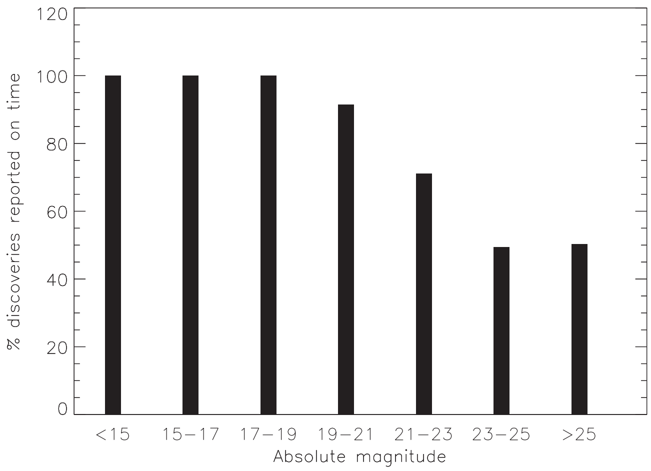

Figure 4. Fraction of potentially detectable asteroids at Arecibo for which discoveries were announced before their radar view periods with SNRs/track >30 ended.

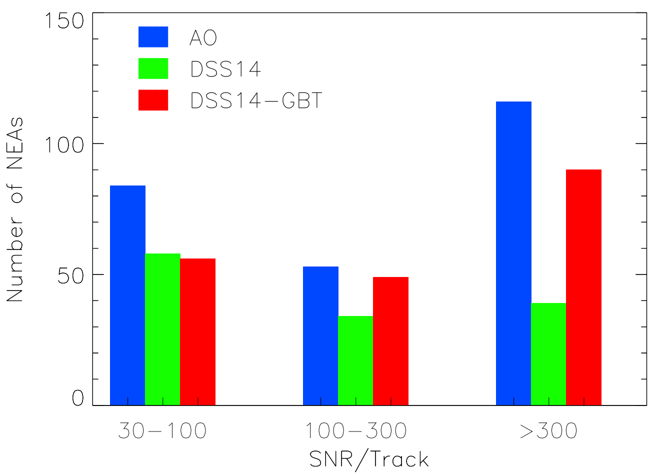

Figure 5. Number of radar-detectable asteroids in the low-, medium-, and high-SNR categories for monostatic observations at Arecibo and DSS-14, and bistatic observations with DSS-14 and GBT.

We divided the population of asteroids detectable by Arecibo into three categories depending on the SNRs/track (Figure 5). The first category consists of asteroids with SNRs/track between 30 and 100 for which we can typically obtain ranging observations and echo power spectra that resolve them in Doppler frequency. There are 84 detectable asteroids in this category (18 were detected). The second category consists of targets with SNRs/track between 100 and 300 that can typically yield delay-Doppler images with coarse to medium resolutions (a few to a few tens of delay pixels over the object). There are 53 detectable asteroids in this category (23 were detected). The third category of targets have SNRs/track >300. These are imaging targets that can be resolved with range resolutions as fine as 7.5 m pixel^{-1}, the highest range resolution available at Arecibo. There are 116 detectable asteroids in this category (36 were detected).

For TOOs that were discovered within 100 days of their radar view periods, Figure 6 shows a histogram of the number of days between discovery announcements and the ends of the observing windows for the corresponding objects. Almost all of new discoveries are detectable by radar only within 15 days of the discovery announcement. If the delay in reporting NEA discoveries from optical surveys were 2 days for all observatories, then about 270 NEAs would have been detectable at Arecibo, or 17 more than with the current reporting delays. Of the 17 additional targets, 10 are in the highest SNR category.

Arecibo sometimes targets NEAs with SNRs <30/track during survey nights. If we adopt a threshold of SNR/track ⩾20, then 290 NEAs become detectable at Arecibo, i.e., a 12% increase over the number of detectable asteroids with SNRs ⩽30/track.

3.2. DSS-14 Monostatic

We found 246 objects that were potentially detectable at DSS-14 with SNRs/track ⩾30 in the year 2015 (Figure 3). There were 131 discoveries that were announced on the MPC website before the radar view periods ended. DSS-14 observed 32 NEAs or about 24% of these objects. An additional seven NEAs with weaker SNRs were also observed. The targets are roughly evenly spread among the three categories defined in the previous section: 58 targets had SNRs/track between 30 and 100 (10 were detected), 34 had SNRs/track between 100 and 300 (two were detected), and 39 had SNRs/track greater than 300 that were suitable for high-resolution imaging (Figure 5) (20 were detected). As we found with Arecibo targets, the time between the discovery announcement and the end of the radar window was less than 15 days for most.

Recently an engineering study (L. Teitelbaum 2016, personal communication) was conducted to examine the efficacy of designing and building new klystron amplifiers that would double the transmitter power at DSS-14 from 450 to 900 kW. If this upgrade occurred, then the number of detectable NEAs would have been 165, which is a 26% increase from the current capability. Doubling the transmitter power will also increase the effective range of DSS-14 by 19%, double the SNRs, and allow us to image targets with ∼2 times finer resolution than is possible with current SNRs.

3.3. Bistatic DSS-14 to GBT

The number of NEAs detectable by using DSS-14 to transmit and GBT to receive is greater than the NEAs detectable by monostatic DSS-14 observations but less than the number of NEAs detectable with monostatic observations at Arecibo. This is correlated to the collecting area of the receiving telescopes. There were 327 objects that were potentially observable using DSS-14 and GBT in 2015 (Figure 3), and of these, 195 were discoveries that were announced before the end of their radar view periods. This is an increase of 64 radar-detectable asteroids, or about 50%, compared to monostatic observations at DSS-14. The number of NEAs in the highest SNR category was more than double relative to DSS-14 monostatic observations (Figure 5), indicating that many of the low- and medium-SNR objects were promoted to the high-SNR category. In 2015, we observed eight NEAs using DSS-14 and GBT. This bistatic configuration was only rarely used for observing NEAs before 2015.

All the objects detectable by DSS-14 monostatically were also detectable using the DSS-14–GBT bistatic configuration mainly due to the similar declination ranges covered by the telescopes. The estimated SNRs were higher in the bistatic configuration because the GBT has a larger effective aperture

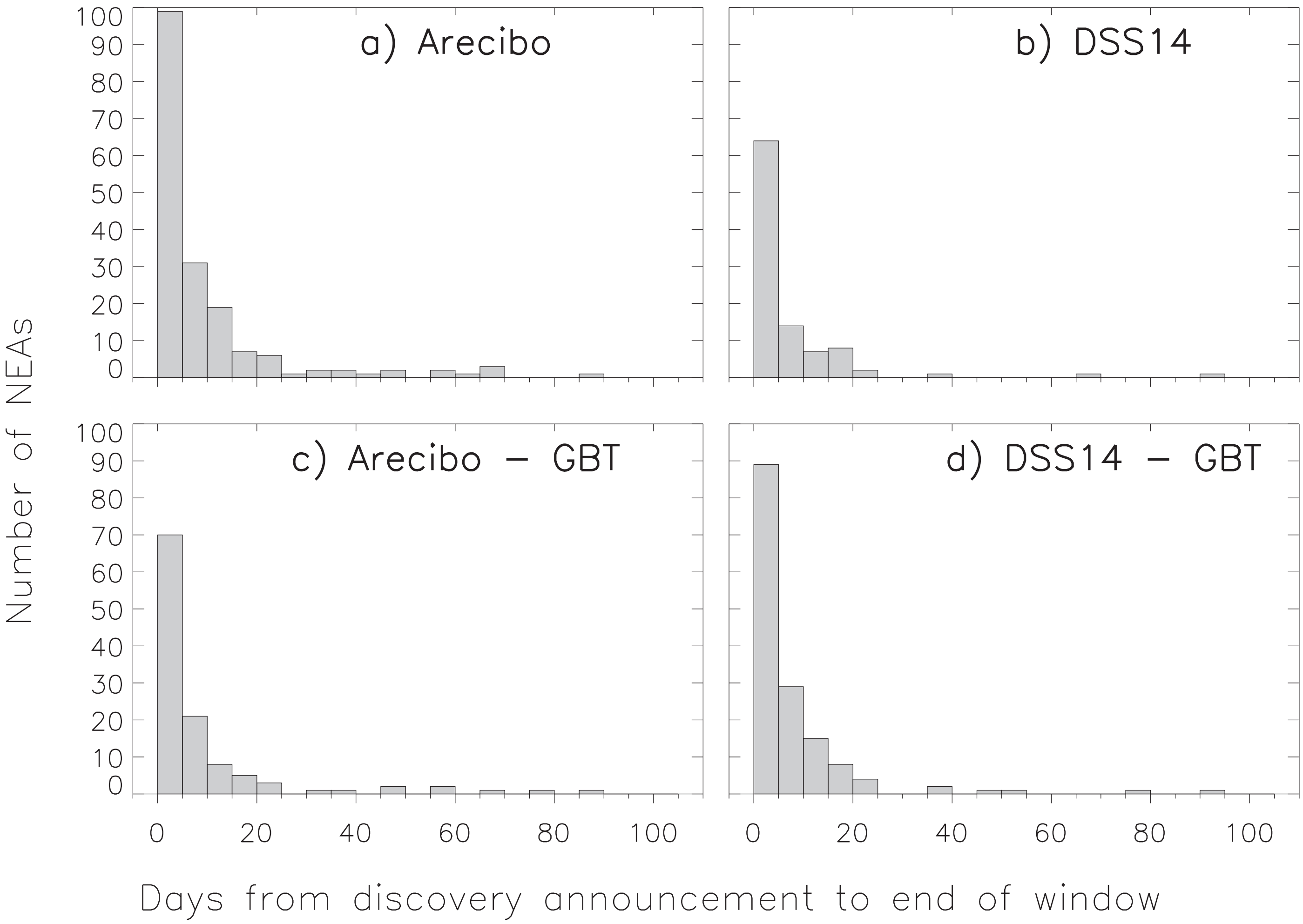

Figure 6. Histograms showing the number of detectable NEAs as a function of the time between discovery announcement to the end of observing window for Arecibo, DSS-14, Arecibo-GBT and DSS-14-GBT.

(100 m versus 70 m) and the total integration time is about two times greater. On average, the Goldstone (DSS-14)–GBT bistatic configuration provides SNRs/track about three times greater than the Goldstone monostatic configuration. Note that this factor compares SNRs/track and is different from the relative sensitivity listed in Table 2, which compares SNRs/RTT.

Lowering T_{sys} at GBT would further increase the relative sensitivity and enable more NEA detections. For example, if T_{sys} were 18 K at GBT, then DSS-14 and GBT would have been able to detect 230 NEAs, an 18% increase relative to the current capability with $T_{sys} = 25$ K. A preliminary study shows that lowering T_{sys} to 18 K at GBT is feasible (J. Ford 2016, personal communication). No such upgrade is currently planned.

There are some limitations to using the DSS-14-GBT bistatic configuration: the GBT is not always available, the latitude and longitude differences means that overlapping time is short for targets at southern declinations, and weather in the winter at the GBT can preclude observations.

3.4. Bistatic Arecibo to GBT

We found 291 NEAs that were potentially observable with SNRs/track $\geqslant$30 in 2015 using the Arecibo–GBT bistatic configuration (Figure 3). The discoveries of 157 of these were reported before the end of their radar view periods. This is fewer than those detectable using DSS-14 and GBT because that configuration provides longer observing windows and results in higher SNRs/track compared to the Arecibo–GBT bistatic configuration for some targets. The number of detectable asteroids is also lower than that for monostatic observations at Arecibo because the GBT has a smaller collecting area than Arecibo. However, the Arecibo–GBT bistatic configuration is very useful because it provides longer integration times and allows for finer Doppler resolution of the data. This is ideal for very close targets with RTT < 10 s and/or very slow rotators with intrinsically narrow bandwidths. Three asteroids (2015 HM10, 2015 SZ, and 2003 SD220) were observed in this configuration in 2015.

3.5. Bistatic DSS-13 to GBT

We found 57 NEAs that were potentially detectable with SNRs/track $\geqslant$30 in 2015 using this configuration, and of these, the discoveries of 33 were reported before the end of their radar view periods. Four asteroids were probably strong enough for delay-Doppler imaging with the finest possible range resolution of 1.875 m, namely (357439) 2004 BL86, 2015 HD1, 2015 HM10, and 2015 JF1. We observed 2004 BL86 and 2015 HM10 using this bistatic configuration but we were not able to

Table 3
NEAs Detectable in 2015 Using DSS-43 and Parkes

Object	Absolute Magnitude	Distance (au)	SNRs/Track
(33342) 1998 WT24	17.9	0.0280	16
(357439) 2004 BL86	19.3	0.0080	1700
(413577) 2005 UL5	20.3	0.0153	87
(436724) 2011 UW158*	19.9	0.0199	62
2014 YD15	26.8	0.0049	20
2014 YE42	23.4	0.0110	16
2015 BC	24.0	0.0050	300
2015 CL13	25.7	0.0054	44
2015 DS53	24.2	0.0081	37
2015 DY198	26.6	0.0056	30
2015 EF	26.8	0.0065	16
2015 FW117	22.7	0.0092	72
2015 FM118	28.7	0.0031	70
2015 GU	28.4	0.0037	39
2015 GL13	28.8	0.0041	23
2015 HD1	27.4	0.0004	380000
2015 HM10	23.6	0.0039	590
2015 HQ11	27.1	0.0053	20
2015 HO116	25.5	0.0045	150
2015 HQ171*	26.9	0.0052	26
2015 HA177*	27.7	0.0048	24
2015 KW120	26.0	0.0035	300
2015 KA122	23.2	0.0085	63
2015 LF	26.6	0.0014	6000
2015 OQ21*	27.9	0.0040	32
2015 SZ2*	25.4	0.0034	700
2015 TC25*	29.5	0.0013	1600
2015 TB145	20.0	0.0078	4400
2015 VO142*	29.0	0.0026	130
2015 XP	25.8	0.0038	210
2015 XX128*	26.0	0.0062	24
2015 XR169*	28.7	0.0035	35
2015 XY261	27.2	0.0019	2100
2015 YQ1*	28.1	0.0038	39

Note. Distance indicates the minimum distance of the asteroid from Earth within the radar observing window. Objects in bold were observed by DSS-43 and Parkes. Asterisk (*) indicates that the asteroid is on the NHATS list.

achieve the maximum range resolution of 1.875 m due to technical difficulties.

NEA (85989) 1999 JD6 was the largest detectable asteroid with a diameter of about 1.8 km and an SNR/track of ~400. It was detected using DSS-14, Arecibo, and the GBT in 2015 July. The smallest detectable asteroid was 2015 FM118 (SNRs ≈700) with an inferred diameter of 5 m based on an absolute magnitude of 28.7. This asteroid approached Earth within 0.002 au in March. At this distance the round-trip light time to the asteroid would have been shorter than the transmit-receive switching time at Arecibo and DSS-14, so bistatic observations would have been the only way to detect 2015 FM118 with radar at the closest approach. The median of the absolute magnitudes of the detectable asteroids was 25.5, which corresponds to a diameter of ~24 m.

3.6. Bistatic DSS-43 to Parkes

About 70 NEAs were potentially detectable with SNRs/track ⩾15 in 2015 using the bistatic DSS-43–Parkes configuration and the discoveries of 34 were reported before the end of their radar view periods. Table 3 lists all the NEAs that were observable using this configuration in 2015. One of these asteroids, 2015 BP509, was not observable by any other radar-capable telescope considered in this paper because its close approach was at a southern latitude of −36° that was beyond the reach of telescopes located in the northern hemisphere.

(33342) 1998 WT24 was the largest detectable asteroid in this configuration with a diameter of ~400 m (Busch et al. 2008). The maximum SNRs/track for this object was about 10–20 in 2015 December, when it approached Earth at a distance of 0.03 au. It was the second asteroid detected by DSS-43 and Parkes. The smallest detectable asteroid was 2015 TC25, with a diameter of 3 m inferred from its absolute magnitude of 29.5. It approached within 0.001 au and its maximum SNRs/track was about 1500. This asteroid was detected by Arecibo in 2015 October, when it was 0.01 au from Earth or about 10 times its distance at closest approach. The median of the absolute magnitudes of all detectable asteroids by DSS-43 and Parkes was 26.6, corresponding to a diameter of 14 m.

Currently the transmitter power at DSS-43 is restricted to less than 100 kW; however it could potentially be raised to 400 kW in the future. With the higher power 62 NEAs (an increase of 82%) would have been detectable using DSS-43 and Parkes. Transmission at higher power would require radiation clearance from government authorities such as local air traffic control, which will increase the lead time required for scheduling radar observations at DSS-43.

3.7. Absolute Magnitude and Size Distribution of Radar-detectable Asteroids

Figure 7 shows the distribution of absolute magnitudes of the radar-detectable asteroids for each transmitter–receiver configuration. It includes only those objects whose discoveries were announced before their radar view periods ended. For a typical S-class asteroid optical albedo of 0.18, magnitudes of 15, 20, and 25 correspond to diameters of about 3000 m, 300 m, and 30 m, but the size of a given object may vary by a factor of two due to albedo assumptions.

The smallest radar-detectable asteroid was 2015 VU64, with an absolute magnitude of 30.6 and a diameter of ~2 m. It approached within 0.0007 au (16.4 Earth radii) and was observable only with a bistatic configuration because the round-trip light time to the asteroid during the radar tracks was less than the transmit–receive switching time at all telescopes. The maximum SNRs/track was over 10^6. The largest detectable asteroid was (152679) 1998 KU2, which is ~4.6 km in diameter and approached within 0.25 au. It was detectable only at Arecibo.

The median of the absolute magnitudes of all radar detectable asteroids is 25.4, which corresponds to a diameter of ~25 m. For Arecibo, most of the asteroids fainter than 25 mag are in the high-SNR category, but for Goldstone, medium- and low-SNR targets constitute the majority of the small asteroids. Figure 7 shows that using the GBT as a receiver with DSS-14 promotes all small targets from the medium- to the high-SNR category.

Objects ~25 m in diameter are worth tracking with radar due to the impact risk such as the Chelyabinsk airburst in 2013 (Popova et al. 2013), because some will be mission targets, and due to scientific interest in their physical properties.

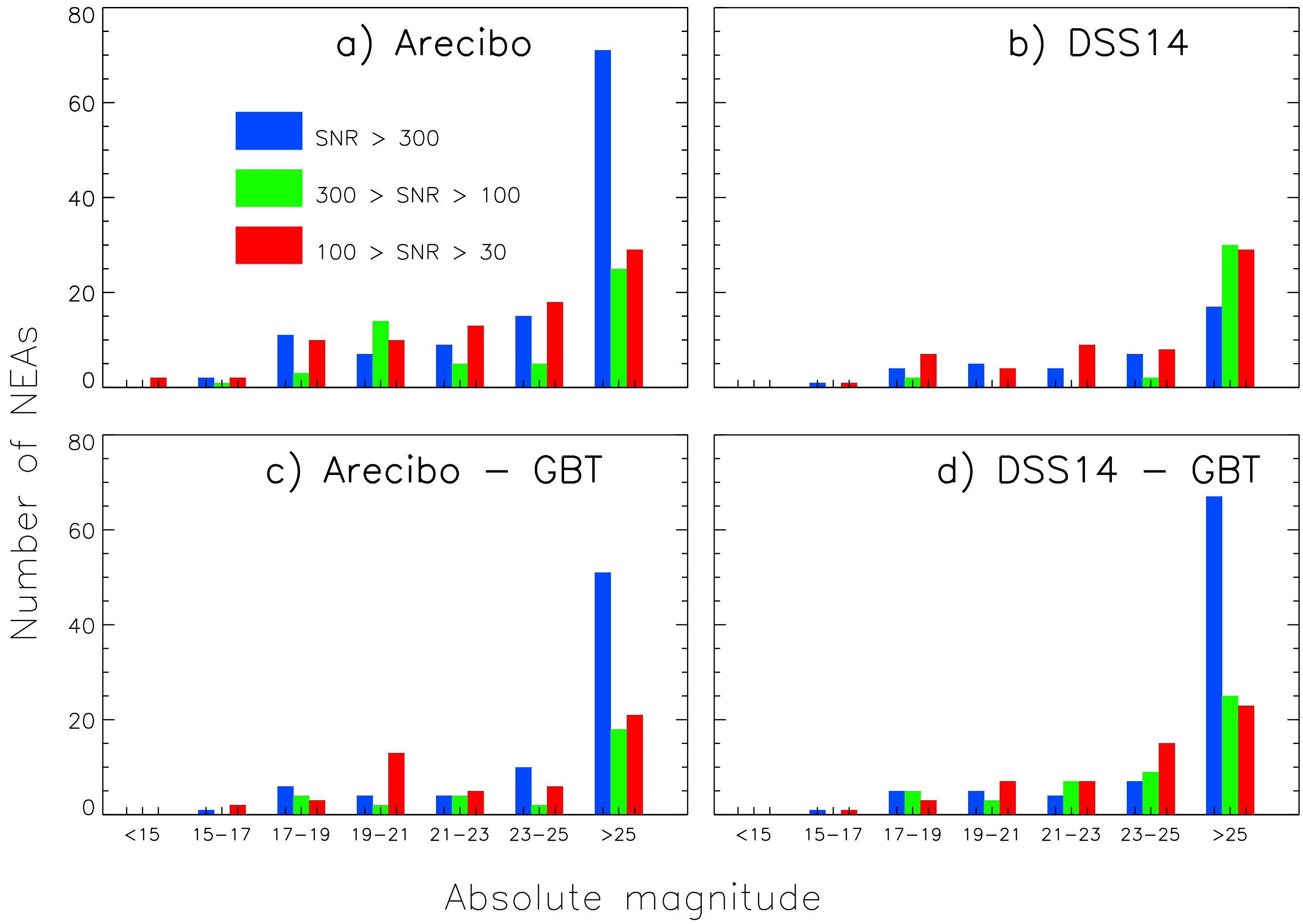

Figure 7. Histogram of the number of radar-detectable NEAs as a function of absolute magnitude for Arecibo (top left), Goldstone (top right), Arecibo–GBT (bottom left) and Goldstone–GBT (bottom right). The targets are divided into high-SNR (blue), medium-SNR (green), and low-SNR (red) categories.

Out of 1562 NEAs discovered in 2015, ∼66% had absolute magnitudes >22 (diameter <140 m). This explains the high fraction of small radar-detectable asteroids. The means ± standard deviations of the absolute magnitudes of the asteroids observed by Arecibo and DSS-14 are 21.1 ± 3.2 and 20.9 ± 3.3 respectively. This implies that radar detections are biased toward observing optically brighter asteroids. This bias is partly due to the brighter/larger targets being prioritized as a result of limited resources, such as telescope time and observing staff, but also due to time available to prepare for the observations.

4. DISCUSSION

Out of the 13,513 known NEAs at the end of 2015, 430 and 246 had SNRs high enough to be detected by Arecibo and Goldstone, respectively, during the calendar year. About 40%–50% of these were not observable because the discoveries were reported after the end of their radar observing windows, leaving 253 and 131 targets that were actually detectable at Arecibo and Goldstone. Of these, Arecibo and Goldstone observed 30% (77 out of 253) and 24% (32 out of 131). Combined, the two observatories were capable of observing 276 NEAs in 2015. This number is different from the corresponding value of 410 reported in Shapiro et al. (2010) because we adopted an SNR threshold of 30/track versus 5/track in the earlier study. The analysis in the current study is much more rigorous because we computed detailed SNRs for each object based on the actual close approach circumstances.

Shortening the delay in reporting NEA discoveries from optical surveys would increase the potential of radar observatories. If all the optical surveys reported discoveries within 2 days, then about 17 additional objects, including 10 high-SNR objects, become detectable at Arecibo.

The bistatic DSS-14 to GBT configuration increases the number of radar-detectable targets by about 50% compared to the monostatic DSS-14 configuration. Most of the low-and medium-SNR targets in the monostatic case are promoted to the high-SNR category with reception at the GBT. Some of these high-SNR targets that were not observed could have been imaged with resolutions as fine as 3.75 m.

Doubling the transmitter power at DSS-14 increases the number of detectable NEAs by about 26%. In an earlier study, Giorgini et al. (2008) reported that a 5% increase in detectable NEAs would be achieved by doubling the transmitter power at DSS-14. The two studies used different approaches in the sense that we looked at known NEAs whereas Giorgini et al. (2008) looked at a simulated NEA population. The two studies adopted different SNR thresholds: 30/track in this study versus 10/track in Giorgini et al. (2008). The methodology was different in the two studies because they had different goals but their results are consistent.

This study clearly shows that Arecibo and Goldstone are observing less than one-half of potentially detectable NEAs. The number of NEAs observed by radar could be increased by at least several tens of percent by obtaining more telescope time without changing protocols to respond more rapidly. Most of the radar-detectable asteroids leave the detectability window within 5 days of their discovery announcement and have absolute magnitudes >25. For Arecibo and Goldstone to observe these targets, a more rapid response time is necessary at both telescopes and a higher level of dynamic scheduling and staffing is needed that would allow switching quickly from previously scheduled observations to active radar observations. More rapid discovery announcements would allow more lead time to prepare for radar observations, thereby enabling radar detection of more asteroids.

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