# Radar Characterization of NEAs: Moderate Resolution Imaging, Astrometry, and a Systematic Survey

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## Background

Radar is arguably the most powerful Earth-based technique for post-discovery physical and dynamical characterization of near-Earth asteroids (NEAs) and plays a crucial role in the nation's planetary defense initiatives led through the NASA Planetary Defense Coordination Office. Recent efforts of ground- (and space-) based observations are driven by the *George E. Brown, Jr. Near-Earth Object Survey Act*, which tasked NASA to detect, track, and characterize 90% of all NEAs larger than 140 meters. The *National Near-Earth Object Preparedness Strategy and Action Plan*, a report by the National Science & Technology Council, and *Finding Hazardous Asteroids Using Infrared and Optical Wavelength Telescopes*, a report by the National Academies of Sciences, Engineering, and Medicine, emphasize radar's unique role in tracking and characterization as critical to fulfilling the goals of the George E. Brown Act and for attaining a complete understanding of the Earth impact hazard including preparation for impact mitigation, if necessary.

To date, radar has detected 966 NEAs, providing astrometry and physical characterizations and effectively sampling the NEA population. Ultra-precise radar measurements have fractional precision of one part in ten million corresponding to measurements of line-of-sight velocity to millimeters per second and line-of-sight distance to less than one kilometer for objects (tens of) millions of kilometers away. Radar astrometry, which is orthogonal to optical plane-of-sky astrometry, substantially improves our knowledge of asteroid trajectories (Ostro & Giorgini, 2004) by reducing uncertainties in orbital elements by orders of magnitude and increasing the range of Earth-encounter predictability by decades, if not centuries. This is especially important for preventing newly discovered NEAs from being lost and requiring re-discovery in the future. With increasing signal strength, radar is uniquely capable of directly measuring the sizes of NEAs and can provide basic shape descriptions for a number of the objects targeted by this proposed work.

## Observing Program Status (Technical Justification)

Project R3035 uses well-established radar-observing techniques and data analysis developed, in part, by the proposing team with many decades of combined relevant experience with the Arecibo planetary radar system. Data management will follow the plan prescribed in NASA Grant No. 80NSSC19K0523 that funds the Arecibo planetary radar system. We requested 294.50 hours of telescope time for R3035 for the 2020 calendar year, including monthly 8-hour "survey nights." Through eight months, 206.25 hours of the request were possible and 91 hours (44%) were scheduled. This discrepancy is due in part to telescope shutdowns for earthquakes, the COVID-19 pandemic, and a broken support cable as well as planned and unplanned maintenance, the lack of viable targets throughout survey nights, targets not requiring as much telescope time as requested to meet science goals, and opportunities to combine observing tracks with our companion project R3037. Only three (of eight) survey nights were utilized for the above reasons. During these survey nights, nine objects were detected, consistent with our historical average of $\sim$3 detections per survey night. Twelve urgent proposals to observe newly discovered objects that did not fit the typical scheduling of survey nights or overlap with other scheduled tracks were submitted outside the R3035/R3037 framework. Through August, despite limited time scheduled, we have detected 7 of 10 possible moderate-imaging targets and 6 of 19 astrometry targets (those most expendable in reaction to the above issues). So far this calendar year, the Arecibo planetary radar has detected 56 NEAs and 106 NEAs in the past 12 months via companion projects R3035 and R3037 plus urgent proposals, all while working with a single klystron rather than the optimal two.

NASA's Near Earth Object Observations program supports the Arecibo planetary radar to observe NEAs for at least 600 hours per year. We propose to continue our survey-oriented approach using 336.50 hours of telescope time to collect precise astrometry and basic characterizations: circular polarization ratios and radar cross sections, plus size, shape, and spin-state constraints as signal strength allows, on dozens of NEAs with a relatively short amount of telescope time, *i.e.*, one or two tracks, per target. A companion proposal (Taylor et al.) concentrates on those 17 objects with the highest expected signal strengths, which will provide more detailed physical characterizations using significantly more telescope time per object and totaling 299.25 hours. Combining the target lists of our proposals totals more than 60 likely detections of known NEAs. Newly discovered or recovered asteroids observed during survey nights or as targets of opportunity during other scheduled tracks, *i.e.*, no additional telescope time, historically add a few dozen detections per year using our proposed 635.75 hours of telescope time. We note that Brozovic et al. will submit a separate proposal at this deadline for extensive radar observations of 99942 Apophis in Spring 2021 totaling $\sim$60 hours. Urgent proposals to observe NEAs not included in these proposals: newly discovered or recovered objects whose detectability could not be predicted in advance, historically account for an additional 15 to 20% of time requests such that we may surpass 800 total hours requested in 2021 with the understanding that not all can be realistically scheduled.

## Proposed Observing Program (Science Justification)

This proposal consists of three parts: moderate-resolution imaging and objects of dynamical interest, where we request two tracks per target to determine sizes and basic shapes and collect astrometry (20 NEAs, 39 tracks, 139 hours; see Table 1); astrometry only, where we request one track per target to obtain the precise line-of-sight velocity of and distance to the target (29 NEAs/tracks, 101.5 hours; see Table 2); and a monthly ”survey night” scheduled within $\pm$3 days of New Moon (12 tracks, 96 hours). Survey nights do not have a predetermined target list and concentrate on objects discovered just days before by optical surveys as the Moon wanes. In all, we request 336.50 hours of telescope time (including transmitter warm up) in this survey-oriented proposal.

Often, very little is known in advance about the proposed targets other than their absolute magnitudes. This lack of prior information is precisely why radar is important; radar efficiently provides physical characterization for objects where knowledge is otherwise lacking. Some targets in Tables 1 and 2 have rotation periods estimated from lightcurves and some have sizes estimated by the NEOWISE infrared spacecraft. Radar provides spin-state constraints for confirming lightcurve results and direct size and shape estimates for comparison to the sizes inferred from thermophysical modeling by NEOWISE. For those objects previously detected with radar, we will further constrain their dynamical and physical properties, including refining measurements of non-gravitational accelerations, *e.g.*, Yarkovsky drift. Multiple radar apparitions improve the precision of Yarkovsky-drift measurements as $\sim 2^{N-1}$ (Greenberg et al., 2020).

We highlight a few targets in the limited space available: 5143 Heracles and 363027 (1998 ST27), both binary systems discovered with radar, are returning. While their predicted signal strengths preclude detailed characterization, satellite detection would constrain the properties of the system while constraints on Yarkovsky drift can help provide independent estimates of their system masses to compare with those previously determined from the satellites' motions. 138127 (2000 EE14) is part of a long-term astrometric monitoring campaign led by team member Jean-Luc Margot to use ultra-precise radar astrometry to separate the orbital perturbations of Yarkovsky-orbital drift, solar oblateness, and General Relativity on objects with low perihelia (Margot and Giorgini, 2010; Verma et al. 2017). The 2021 apparition would mark the third radar detection of 2000 EE14 after 2007 and 2008, extending the observational arc to more than 20 years and the arc of radar observations by more than a decade ($>$ 20 heliocentric orbits).

We note that the signal-to-noise ratios (SNRs) presented here are often lower bounds due to conservative assumptions about the size, rotation period, and viewing geometry of many of the targets, which means some could be an order of magnitude brighter than predicted. Attempting observations of objects predicted to have low SNRs can only increase the scientific return of the program. Past astrometry-only tracks (*i.e.*, akin to Table 2) resulted in the discovery of binary asteroid (163693) Atira (Rivera-Valentín et al., 2017) and rare equal-mass binary 1994 CJ1 (Taylor et al., 2014), possibly the smallest known binary. The binary nature of each would not have been determined without this program pushing to observe more asteroids with lower predicted SNRs.

Some potential targets require optical astrometry to reduce the plane-of-sky pointing uncertainties sufficiently for the arcminute-scale Arecibo radar beam. These targets typically attain visual magnitudes $<$ 22 at solar elongations of $\sim$90 degrees prior to their expected flybys of Earth such that optical astrometry is likely to materialize from the extensive community of professional and amateur astronomers who prioritize recovery of possible radar targets. In cases where the current uncertainties are several degrees, the revised orbit once these objects are recovered might change the timing (scheduling) and distance from Earth (signal strength) significantly. Such cases would be handled in consultation with the telescope scheduler to ensure efficient use of telescope time.

## Student Participation

Graduate student Luisa Zambrano-Marin (U. Granada), member of the local Arecibo team, is using radar scattering models to constrain the surface properties of small bodies. Graduate student Sanjana Prebhu Desai (UCLA) has conducted observations under this program and R3037, including leading observations of 441987 (2010 NY65). Graduate students Mary Hinkle (UCF) and Kiana McFadden (U. Arizona) are combining infrared and radar observations of 433 Eros and 2100 Ra-Shalom, respectively, based on data from project R3037. Research Experience for Undergraduates students working with the proposing team have traditionally participated in radar observations, data analysis, and shape modeling under this program. Team members Taylor, Virkki, Venditti, Marshall, Becker, Naidu, and Rożek all used radar data or data products from Arecibo as part of their graduate studies. Other students not specifically named among the proposing team are welcome to gain observing and research experience through this proposed work.

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| Object | H mag | Diam [km] | $P_{spin}$ [h] | Prev Obs? | Start-End Dates | RTT [s] | SNR /day | Notes |
|---|---|---|---|---|---|---|---|---|
| (2019 QW2) | 24.8 | *0.03* | *0.25* | | Jan 02-Jan 05 | 22 | 100 | N A |
| 505657 (2014 SR339) | 18.5 | 1.50 | 8.7 | Y | Feb 02-Feb 11 | 195 | 76 | P W |
| 311554 (2006 BQ147) | 18.7 | 0.38 | 9.2 | Y | Feb 15-Feb 20 | 89 | 96 | W |
| (2020 CX1) | 24.1 | *0.05* | *0.25* | | Feb 17-Feb 18 | 12 | 1090 | N A |
| 138127 (2000 EE14) | 17.1 | 0.75 | 2.6 | Y | Feb 26-Mar 05 | 168 | 21 | P W J |
| 462550 (2009 CB3) | 19.4 | *0.39* | *2.1* | | Mar 01-Mar 04 | 75 | 120 | P |
| 483656 (2005 ES70) | 23.8 | 0.07 | 1.7 | Y | Mar 10-Mar 15 | 56 | 65 | Y |
| 271480 (2004 FX31) | 17.6 | 0.71 | *2.1* | | Mar 10-Mar 16 | 93 | 110 | G W |
| 351545 (2005 TE15) | 19.7 | *0.34* | *2.1* | | Mar 26-Mar 31 | 70 | 100 | G Y |
| (2012 BA35) | 23.8 | *0.05* | *0.25* | | Aug 14-Aug 19 | 19 | 270 | N G A |
| (2019 NC1) | 21.4 | *0.16* | 9.0 | | Aug 16-Aug 26 | 62 | 120 | N |
| (2011 UC292) | 22.8 | *0.08* | *0.25* | | Aug 21-Aug 29 | 23 | 360 | N |
| 152664 (1998 FW4) | 19.7 | 0.30 | 17.4 | Y | Sep 19-Sep 27 | 115 | 44 | P |
| 363027 (1998 ST27) | 19.5 | 0.80 | 3.0 | Y | Sep 27-Oct 09 | 187 | 32 | B P W Y |
| (1999 FJ21) | 20.3 | *0.26* | *2.1* | | Oct 15-Oct 19 | 65 | 110 | |
| (2015 FF37) | 18.7 | *0.54* | *2.1* | | Nov 04-Nov 08 | 89 | 95 | |
| (2004 UE) | 21.0 | *0.19* | 5.6 | | Nov 04-Nov 09 | 45 | 320 | P G A |
| (2010 VK139) | 23.7 | 0.06 | 0.03 | | Nov 15 | 17 | 220 | G W A |
| 5143 Heracles | 14.0 | 4.40 | 2.7 | Y | Nov 17-Nov 23 | 306 | 14 | B I W |
| 7341 (1991 VK) | 16.7 | 1.20 | 4.2 | Y | Dec 28-Jan 06 | 116 | 83 | P G W Y |

Table 1: We request one or two tracks for each of 20 objects totaling 39 tracks and 139 hours of telescope time (including transmitter warm up time; see Table 3 for detailed time requests) to collect precise astrometry, radar scattering properties, spin-state constraints, size estimates, and basic shape information as signal strength allows. ”Start-End” dates bracket the acceptable dates for observations. Absolute magnitudes H are taken from the JPL Small-Body Database. Diameters are taken from previous radar observations or infrared observations by NEOWISE (Mainzer et al., 2019) when available; otherwise, italicized diameters are estimates based on H assuming a brighter-than-average optical albedo of 0.2. Rotation periods $P_{spin}$ are taken from the asteroid Lightcurve Database (Warner et al., 2009, and updates) when available. Previously observed objects (”Prev Obs?” column) have radar-estimated spin periods consistent with $P_{spin}$. When unknown, rotation periods are italicized and assumed very rapid at 2.1 h for $H < 22$ and 0.25 h for $H > 22$. Assumptions of more rapid spins and brighter albedos (smaller sizes) lead to more conservative estimates for the signal-to-noise (SNR) ratio. SNR estimates assume dual-klystron mode at 800 kW and will effectively halve if only one klystron is available. The closest approach is given by the minimum round-trip time, RTT, for light to reach the target and return. Notes include known binary asteroids (B), potentially hazardous asteroids (P), NHATS-compliant objects (N), Goldstone radar targets (G), possible IRTF near- and thermal-infrared targets (I), objects previously observed by the NEOWISE spacecraft (W), objects with low perihelia usable for constraints on solar oblateness and General Relativity (J; Margot and Giorgini, 2010; Verma et al., 2017), Yarkovsky-drift detections (Y) from Chesley et al. (2016; updated on NeoDys) and Greenberg et al. (2020), and objects requiring optical astrometry prior to radar observations (A).

| Object | H mag | Diam [km] | $P_{spin}$ [h] | Prev Obs | Start-End Dates | Preferred Date | RTT [s] | SNR /day | Notes |
|---|---|---|---|---|---|---|---|---|---|
| (2015 NU13) | 19.7 | *0.34* | *2.1* | | Jan 19-Jan 20 | Jan 19 | 86 | 25 | P G |
| 535844 (2015 BY310) | 21.7 | *0.14* | 0.1 | | Feb 28-Mar 02 | Mar 02 | 45 | 19 | P N G |
| 456537 (2007 BG) | 19.5 | 0.31 | *2.1* | | Mar 09-Mar 12 | Mar 09 | 84 | 28 | G |
| (2017 SG14) | 20.3 | *0.26* | *2.1* | | Mar 20-Mar 22 | Mar 20 | 87 | 30 | P |
| (2004 TP1) | 20.6 | *0.23* | *2.1* | | Apr 12-Apr 16 | Apr 14 | 61 | 86 | P G |
| 140158 (2001 SX169) | 18.4 | 0.57 | 3.1 | | May 20-Jun 01 | May 23 | 103 | 68 | P W |
| 87024 (2000 JS66) | 18.7 | 0.27 | 18.0 | Y | May 24-May 30 | May 26 | 145 | 30 | |
| 494690 (2004 JQ1) | 20.0 | *0.30* | *2.1* | | May 31-Jun 04 | Jun 02 | 73 | 84 | P |
| (2014 XJ3) | 20.1 | 0.21 | 32.0 | Y | Jun 11-Jun 14 | Jun 13 | 111 | 37 | P |
| (2015 DP155) | 21.5 | 0.14 | 3.1 | Y | Jun 12-Jun 19 | Jun 16 | 107 | 20 | P N |
| (2014 WF497) | 20.1 | *0.28* | *2.1* | | Jul 04-Jul 07 | Jul 05 | 84 | 41 | |
| 3103 Eger | 15.2 | 1.73 | 5.7 | Y | Jul 14-Jul 22 | Jul 20 | 240 | 18 | Y |
| 523664 (2012 OD1) | 18.6 | *0.57* | 12.6 | | Jul 18-Jul 22 | Jul 21 | 108 | 77 | P |
| 326732 (2003 HB6) | 17.6 | 0.90 | 9.4 | Y | Jul 18-Aug 11 | Jul 27 | 169 | 32 | |
| (2018 LM4) | 18.9 | *0.49* | *2.1* | | Jul 28-Jul 31 | Jul 30 | 100 | 35 | |
| 506459 (2002 AL14) | 17.8 | *0.82* | 2.3 | | Jul 30-Aug 04 | Aug 01 | 128 | 35 | |
| 199003 (2005 WJ56) | 18.1 | 0.45 | 4.4 | Y | Aug 01-Aug 09 | Aug 01 | 229 | 5 | P |
| (2020 PN1) | 25.5 | *0.02* | *0.25* | | Aug 05-Aug 09 | Aug 06 | 25 | 39 | N |
| 37655 Illapa | 17.8 | 1.20 | 2.7 | Y | Aug 04-Aug 11 | Aug 07 | 191 | 16 | P Y |
| (2019 UD4) | 23.1 | *0.07* | *0.25* | | Aug 18-Aug 22 | Aug 21 | 36 | 50 | N A |
| 7822 (1991 CS) | 17.4 | 0.71 | 2.4 | Y | Aug 19-Aug 25 | Aug 22 | 145 | 49 | P W Y |
| 4034 Vishnu | 18.4 | *0.62* | 44.4 | Y | Aug 22-Sep 02 | Aug 28 | 220 | 14 | P Y |
| 3361 Orpheus | 19.0 | 0.35 | 3.5 | | Oct 30-Nov 02 | Nov 02 | 93 | 22 | P N G W Y |
| (2017 TS3) | 22.1 | *0.11* | *0.25* | | Nov 07-Nov 09 | Nov 08 | 47 | 25 | G |
| (2008 XQ2) | 20.3 | *0.26* | *2.1* | | Nov 07-Nov 11 | Nov 08 | 72 | 70 | P |
| (2016 JG12) | 22.5 | *0.09* | *0.25* | | Nov 13-Nov 17 | Nov 15 | 38 | 46 | N |
| (1994 WR12) | 22.3 | *0.10* | *0.25* | | Nov 24-Nov 26 | Nov 24 | 41 | 42 | |
| (2009 WB105) | 23.5 | *0.06* | *0.25* | | Nov 24-Nov 26 | Nov 25 | 39 | 31 | |
| 1862 Apollo | 16.2 | 1.52 | 3.1 | Y | Nov 28-Dec 03 | Nov 30 | 223 | 9 | B P W Y |

Table 2: Assuming each track is 3.5 h (including transmitter warm up), we request 29 tracks and 101.5 hours of telescope time to collect precise astrometry, radar scattering properties, and spin-state constraints on the 29 objects listed above. "Start-End" dates bracket the acceptable dates for observations, while "Preferred" is the desired track. Priority, if necessary, should be given to potentially hazardous asteroids (P), NHATS-compliant objects (N), objects previously observed by the NEOWISE spacecraft (W), and Yarkovsky-drift detections (Y) from Chesley et al. (2016; updated on NeoDys) and Greenberg et al. (2020). Some objects require optical astrometry prior to radar observations (A). Column descriptions are otherwise the same as in Table 1. SNR estimates assume dual-klystron mode at 800 kW and will effectively halve if only one klystron is available. 199003 (2005 WJ56) is included despite its low predicted SNR because previous radar observations suggest either the rotation period is much longer than estimated from lightcurves or it was viewed fortuitously along its spin axis; a second apparition with a stronger-than-expected SNR would suggest a long rotation period as the orientation should not be pole-on in 2021. Its viewing times overlap with those of 506459 (2002 AL14).

# Observing Requests

Table 3. We request 39 tracks and 139 hours to observe the 20 targets in Table 1 to collect precise astrometry, radar scattering properties, spin-state constraints, size estimates, and basic shape information as signal strength allows. Requested tracks are marked with a +; unmarked tracks are acceptable alternatives. The rise/set times do NOT include one hour of transmitter warm-up time prior to the source rising. In the event observations of targets of R3035 and companion project R3037 overlap, the proposing team will work with the telescope scheduler to find a solution that attains the goals of both projects, if possible. Calculations assume the physical parameters from Table 1 and a radar albedo of 0.1 unless estimated from previous radar observations. When unknown, the sizes and spin rates used tend to give conservative estimates of the SNR. Nominal system parameters are assumed: transmitter power = 800 kW (dual-klystron mode), sensitivity ~7 K/Jy (post-Maria, also a function of declination), and system temperature = 24 K. SNRs will effectively halve if only one klystron is available.

**Request:** 2 tracks, 7.50 hours

| UT Date<br>**(2019 QW2)** | RTT<br>[s] | RA<br>[h] | Dec<br>[deg] | Runs | SNR<br>/run | SNR<br>/day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Jan-02 | 23 | 18.3 | +29 | 185 | 6 | 88 | 14:46-17:06 |
| +2021-Jan-03 | 22 | 18.4 | +23 | 220 | 6 | 100 | 14:37-17:21 |
| +2021-Jan-04 | 23 | 18.5 | +15 | 217 | 6 | 98 | 14:39-17:22 |
| 2021-Jan-05 | 23 | 18.6 | +09 | 187 | 6 | 85 | 14:50-17:13 |

**Note:** Optical astrometry required prior to radar observations (5 deg). In December 2020, visual magnitude <22, solar elongation >90 deg, and positional uncertainty ~1 deg.

**Request:** 2 tracks, 7.25 hours

| UT Date<br>**505657 (2014 SR339)** | RTT<br>[s] | RA<br>[h] | Dec<br>[deg] | Runs | SNR<br>/run | SNR<br>/day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Feb-02 | 196 | 14.2 | +02 | 15 | 15 | 58 | 08:59-10:36 |
| 2021-Feb-03 | 197 | 14.2 | +05 | 18 | 15 | 64 | 08:46-10:46 |
| 2021-Feb-04 | 199 | 14.2 | +07 | 21 | 17 | 75 | 08:35-10:52 |
| +2021-Feb-05 | 201 | 14.2 | +10 | 22 | 16 | 76 | 08:27-10:56 |
| +2021-Feb-06 | 203 | 14.3 | +12 | 23 | 15 | 75 | 08:21-10:58 |
| 2021-Feb-07 | 206 | 14.3 | +15 | 24 | 15 | 71 | 08:16-10:59 |
| 2021-Feb-08 | 209 | 14.3 | +17 | 24 | 14 | 68 | 08:12-10:58 |
| 2021-Feb-09 | 212 | 14.4 | +19 | 23 | 13 | 64 | 08:10-10:56 |
| 2021-Feb-10 | 216 | 14.4 | +22 | 23 | 12 | 59 | 08:08-10:53 |
| 2021-Feb-11 | 220 | 14.4 | +24 | 22 | 11 | 54 | 08:07-10:48 |

**Note:** Previously detected at Arecibo and Goldstone in 2018 revealing a larger-than-expected elongated shape. Observations will further constrain the spin state and provide additional ranging astrometry.

**Request:** 2 tracks, 7.25 hours

| UT Date **311554 (2006 BQ147)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Feb-15 | 111 | 13.8 | +09 | 40 | 7 | 46 | 07:23-09:50 |
| 2021-Feb-16 | 105 | 14.0 | +13 | 45 | 8 | 59 | 07:23-10:02 |
| 2021-Feb-17 | 100 | 14.2 | +17 | 50 | 10 | 73 | 07:27-10:13 |
| +2021-Feb-18 | 96 | 14.4 | +21 | 52 | 12 | 87 | 07:35-10:22 |
| +2021-Feb-19 | 93 | 14.7 | +25 | 51 | 13 | 96 | 07:50-10:29 |
| 2021-Feb-20 | 91 | 14.9 | +30 | 46 | 9 | 63 | 08:13-10:31 |

**Note:** Previously detected at Arecibo in 2018, but limited to Doppler-only (line-of-sight velocity) astrometry. Observations will constrain its size for comparison with NEOWISE and provide additional ranging astrometry.

**Request:** 2 tracks, 6.50 hours

| UT Date **(2020 CX1)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| +2021-Feb-17 | 12 | 3.8 | +31 | 302 | 42 | 740 | 21:25-23:30 |
| +2021-Feb-18 | 13 | 3.2 | +12 | 348 | 58 | 1090 | 20:30-23:01 |

**Note:** Optical astrometry required prior to radar observations (3 deg). In January 2021, visual magnitude $<$22, solar elongation $>$90 deg, and positional uncertainty $\sim$1 deg.

**Request:** 2 tracks, 7.50 hours

| UT Date **138127 (2000 EE14)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Feb-26 | 181 | 16.7 | +09 | 24 | 3 | 15 | 09:31-11:56 |
| 2021-Feb-27 | 178 | 16.7 | +11 | 26 | 3 | 16 | 09:25-11:59 |
| 2021-Feb-28 | 176 | 16.8 | +14 | 27 | 3 | 18 | 09:21-12:02 |
| 2021-Mar-01 | 174 | 16.8 | +17 | 29 | 3 | 19 | 09:18-12:03 |
| +2021-Mar-02 | 172 | 16.9 | +19 | 29 | 3 | 20 | 09:16-12:03 |
| +2021-Mar-03 | 170 | 16.9 | +22 | 29 | 3 | 20 | 09:17-12:01 |
| 2021-Mar-04 | 169 | 17.0 | +25 | 28 | 4 | 21 | 09:19-11:58 |
| 2021-Mar-05 | 168 | 17.1 | +28 | 27 | 4 | 20 | 09:24-11:53 |

**Note:** Previously detected with Arecibo in 2007 and 2008. This is a target for studies of Yarkovsky drift plus the effects of solar oblateness and General Relativity. Radar astrometry from a third apparition is necessary to begin disentangling these effects.

**Request:** 2 tracks, 7.5 hours

| UT Date<br>**462550 (2009 CB3)** | RTT<br>[s] | RA<br>[h] | Dec<br>[deg] | Runs | SNR<br>/run | SNR<br>/day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Mar-01 | 81 | 1.8 | +05 | 47 | 9 | 64 | 18:35-20:41 |
| +2021-Mar-02 | 76 | 2.4 | +12 | 63 | 13 | 110 | 18:50-21:30 |
| +2021-Mar-03 | 75 | 3.1 | +19 | 68 | 14 | 120 | 19:23-22:14 |
| 2021-Mar-04 | 78 | 3.9 | +25 | 63 | 12 | 99 | 20:08-22:50 |

**Request:** 2 tracks, 6.75 hours

| UT Date<br>**483656 (2005 ES70)** | RTT<br>[s] | RA<br>[h] | Dec<br>[deg] | Runs | SNR<br>/run | SNR<br>/day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Mar-10 | 65 | 12.6 | +12 | 72 | 5 | 43 | 04:37-07:11 |
| 2021-Mar-11 | 61 | 12.3 | +10 | 72 | 6 | 52 | 04:15-06:42 |
| +2021-Mar-12 | 59 | 11.9 | +09 | 72 | 7 | 60 | 03:51-06:11 |
| +2021-Mar-13 | 57 | 11.5 | +06 | 67 | 7 | 65 | 03:28-05:36 |
| 2021-Mar-14 | 56 | 11.0 | +04 | 60 | 7 | 57 | 03:06-04:58 |
| 2021-Mar-15 | 56 | 10.6 | +02 | 47 | 7 | 51 | 02:48-04:16 |

**Note:** Previously detected with Arecibo in 2017. Additional radar range astrometry will refine its published Yarkovsky drift rate.

**Request:** 2 tracks, 7.50 hours

| UT Date<br>**271480 (2004 FX31)** | RTT<br>[s] | RA<br>[h] | Dec<br>[deg] | Runs | SNR<br>/run | SNR<br>/day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Mar-10 | 93 | 20.0 | +01 | 29 | 14 | 76 | 12:33-14:01 |
| 2021-Mar-11 | 93 | 19.8 | +06 | 42 | 16 | 110 | 11:53-14:02 |
| 2021-Mar-12 | 93 | 19.5 | +11 | 48 | 16 | 110 | 11:24-13:54 |
| +2021-Mar-13 | 95 | 19.3 | +15 | 51 | 15 | 110 | 10:59-13:41 |
| +2021-Mar-14 | 98 | 19.0 | +20 | 50 | 13 | 97 | 10:40-13:24 |
| 2021-Mar-15 | 101 | 18.8 | +24 | 47 | 12 | 83 | 10:23-13:03 |
| 2021-Mar-16 | 106 | 18.6 | +27 | 43 | 10 | 68 | 10:10-12:40 |

**Note:** A size constraint will allow for comparison with the diameter inferred from NEOWISE observations.

**Request:** 2 tracks, 7.25 hours

| UT Date<br>**351545 (2005 TE15)** | RTT<br>[s] | RA<br>[h] | Dec<br>[deg] | Runs | SNR<br>/run | SNR<br>/day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Mar-26 | 70 | 1.7 | +34 | 45 | 9 | 61 | 17:01-18:45 |
| +2021-Mar-27 | 72 | 1.6 | +29 | 60 | 13 | 100 | 16:33-18:56 |
| +2021-Mar-28 | 75 | 1.6 | +24 | 65 | 11 | 93 | 16:16-18:57 |
| 2021-Mar-29 | 78 | 1.5 | +19 | 64 | 10 | 81 | 16:06-18:52 |
| 2021-Mar-30 | 81 | 1.4 | +15 | 60 | 8 | 67 | 16:01-18:44 |
| 2021-Mar-31 | 85 | 1.4 | +11 | 55 | 7 | 54 | 15:58-18:33 |

**Note:** Radar range astrometry will refine its published Yarkovsky drift rate.

**Request:** 2 tracks, 7.25 hours

| UT Date **(2012 BA35)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Aug-14 | 19 | 9.2 | +33 | 176 | 14 | 190 | 15:14-17:07 |
| +2021-Aug-15 | 21 | 9.0 | +27 | 217 | 18 | 270 | 14:39-17:07 |
| +2021-Aug-16 | 22 | 8.8 | +23 | 222 | 14 | 220 | 14:17-16:59 |
| 2021-Aug-17 | 23 | 8.7 | +18 | 210 | 11 | 170 | 14:03-16:47 |
| 2021-Aug-18 | 25 | 8.6 | +14 | 190 | 9 | 130 | 13:54-16:34 |
| 2021-Aug-19 | 27 | 8.5 | +11 | 169 | 7 | 95 | 13:48-16:20 |

**Note:** Optical astrometry required prior to radar observations (10 deg). In July 2021, visual magnitude <21, solar elongation >90 deg, and positional uncertainty 2 deg.

**Request:** 2 tracks, 7.00 hours

| UT Date **(2019 NC1)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Aug-16 | 62 | 20.5 | +06 | 63 | 14 | 110 | 02:16-04:26 |
| +2021-Aug-17 | 62 | 20.4 | +08 | 67 | 14 | 120 | 02:01-04:19 |
| +2021-Aug-18 | 62 | 20.3 | +09 | 70 | 14 | 120 | 01:46-04:11 |
| 2021-Aug-19 | 62 | 20.1 | +11 | 73 | 14 | 120 | 01:32-04:03 |
| 2021-Aug-20 | 62 | 20.0 | +12 | 75 | 14 | 120 | 01:19-03:54 |
| 2021-Aug-21 | 62 | 19.9 | +13 | 76 | 13 | 120 | 01:06-03:45 |
| 2021-Aug-22 | 63 | 19.8 | +15 | 77 | 13 | 120 | 00:54-03:36 |
| 2021-Aug-23 | 63 | 19.7 | +16 | 78 | 13 | 120 | 00:42-03:26 |
| 2021-Aug-24 | 64 | 19.6 | +17 | 77 | 12 | 110 | 00:31-03:16 |
| 2021-Aug-25 | 65 | 19.5 | +19 | 77 | 12 | 110 | 00:20-03:05 |
| 2021-Aug-26 | 65 | 19.4 | +20 | 76 | 11 | 100 | 00:10-02:55 |

**Request:** 2 tracks, 7.25 hours

| UT Date **(2011 UC292)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Aug-21 | 27 | 14.3 | +32 | 143 | 9 | 110 | 19:41-21:51 |
| 2021-Aug-22 | 25 | 15.1 | +31 | 158 | 12 | 150 | 20:23-22:34 |
| 2021-Aug-23 | 23 | 16.0 | +30 | 181 | 15 | 200 | 21:08-23:29 |
| +2021-Aug-24 | 23 | 16.9 | +27 | 206 | 25 | 360 | 21:52-00:29 |
| +2021-Aug-25 | 24 | 17.8 | +23 | 214 | 22 | 330 | 22:34-01:22 |
| 2021-Aug-26 | 25 | 18.5 | +18 | 202 | 18 | 260 | 23:12-02:02 |
| 2021-Aug-27 | 28 | 19.1 | +14 | 177 | 13 | 180 | 23:47-02:30 |
| 2021-Aug-29 | 31 | 19.6 | +10 | 147 | 9 | 120 | 00:16-02:47 |

**Request:** 2 tracks, 7.00 hours

| UT Date **152664 (1998 FW4)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Sep-19 | 127 | 4.0 | +25 | 38 | 5 | 32 | 07:13-09:54 |
| 2021-Sep-20 | 122 | 4.3 | +26 | 39 | 6 | 37 | 07:34-10:11 |
| +2021-Sep-21 | 118 | 4.8 | +28 | 38 | 6 | 41 | 07:58-10:29 |
| +2021-Sep-22 | 116 | 5.2 | +29 | 38 | 7 | 44 | 08:23-10:49 |
| 2021-Sep-23 | 115 | 5.7 | +30 | 37 | 4 | 28 | 08:50-11:11 |
| 2021-Sep-24 | 115 | 6.2 | +30 | 36 | 4 | 28 | 09:17-11:34 |
| 2021-Sep-25 | 117 | 6.6 | +30 | 35 | 4 | 27 | 09:42-11:58 |
| 2021-Sep-26 | 119 | 7.1 | +30 | 35 | 4 | 24 | 10:04-12:23 |
| 2021-Sep-27 | 123 | 7.5 | +30 | 35 | 3 | 21 | 10:24-12:46 |

**Note:** Previously detected with Arecibo and Goldstone in 2009 and 2013 and found to have a contact-binary shape. Additional radar observations will further constrain the spin state and provide ranging astrometry for a possible Yarkovsky drift detection.

**Request:** 2 tracks, 7.50 hours

| UT Date **363027 (1998 ST27)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Sep-27 | 205 | 22.2 | +28 | 21 | 4 | 22 | 01:08-03:33 |
| 2021-Sep-28 | 202 | 22.1 | +27 | 23 | 5 | 23 | 00:54-03:26 |
| 2021-Sep-29 | 199 | 22.1 | +25 | 24 | 5 | 25 | 00:41-03:18 |
| 2021-Sep-30 | 196 | 21.9 | +23 | 25 | 5 | 27 | 00:29-03:10 |
| 2021-Oct-01 | 194 | 21.8 | +21 | 25 | 5 | 29 | 00:17-03:01 |
| 2021-Oct-02 | 192 | 21.7 | +20 | 26 | 6 | 30 | 00:07-02:52 |
| 2021-Oct-02 | 190 | 21.6 | +18 | 26 | 6 | 32 | 23:57-02:42 |
| +2021-Oct-03 | 189 | 21.5 | +16 | 26 | 6 | 32 | 23:48-02:31 |
| +2021-Oct-04 | 188 | 21.4 | +14 | 26 | 6 | 32 | 23:40-02:20 |
| 2021-Oct-05 | 188 | 21.4 | +12 | 25 | 6 | 32 | 23:33-02:08 |
| 2021-Oct-06 | 187 | 21.3 | +10 | 24 | 6 | 31 | 23:28-01:55 |
| 2021-Oct-07 | 187 | 21.2 | +07 | 22 | 6 | 31 | 23:23-01:41 |
| 2021-Oct-08 | 188 | 21.1 | +05 | 20 | 5 | 24 | 23:20-01:25 |
| 2021-Oct-09 | 189 | 21.0 | +03 | 17 | 5 | 23 | 23:19-01:09 |

**Note:** Binary asteroid discovered with radar at Arecibo in 2001 and detected again in 2004. Additional radar range astrometry will refine its published Yarkovsky drift rate.

**Request:** 2 tracks, 7.25 hours

| UT Date **(1999 FJ21)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Oct-15 | 68 | 0.1 | +08 | 63 | 10 | 85 | 01:49-04:10 |
| +2021-Oct-16 | 66 | 23.8 | +13 | 72 | 11 | 100 | 01:22-03:59 |
| +2021-Oct-17 | 65 | 23.6 | +18 | 76 | 12 | 110 | 00:57-03:41 |
| 2021-Oct-18 | 65 | 23.2 | +23 | 74 | 12 | 110 | 00:37-03:17 |
| 2021-Oct-19 | 65 | 22.9 | +28 | 67 | 12 | 99 | 00:20-02:47 |

**Request:** 2 tracks, 6.75 hours

| UT Date **(2015 FF37)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| +2021-Nov-04 | 91 | 17.3 | +07 | 44 | 12 | 79 | 17:42-19:56 |
| +2021-Nov-05 | 89 | 17.3 | +11 | 52 | 12 | 89 | 17:30-20:04 |
| 2021-Nov-06 | 89 | 17.4 | +16 | 56 | 12 | 94 | 17:23-20:08 |
| 2021-Nov-07 | 89 | 17.4 | +21 | 56 | 12 | 95 | 17:21-20:07 |
| 2021-Nov-08 | 90 | 17.4 | +25 | 53 | 12 | 89 | 17:24-20:01 |

**Request:** 2 tracks, 7.25 hours

| UT Date **(2004 UE)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Nov-04 | 71 | 23.6 | +19 | 70 | 9 | 77 | 23:46-02:32 |
| 2021-Nov-05 | 64 | 23.6 | +17 | 77 | 13 | 120 | 23:43-02:28 |
| +2021-Nov-06 | 58 | 23.7 | +13 | 83 | 19 | 170 | 23:44-02:23 |
| +2021-Nov-07 | 51 | 23.7 | +09 | 85 | 28 | 260 | 23:49-02:13 |
| 2021-Nov-09 | 45 | 23.8 | +03 | 72 | 37 | 320 | 00:05-01:53 |

**Note:** Optical astrometry required prior to radar observations (10 deg). In October 2021, visual magnitude $<$20, solar elongation $>$90 deg, and positional uncertainty 3 deg.

**Request:** 1 tracks, 3.75 hours

| UT Date **(2010 VK139)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| +2021-Nov-15 | 17 | 22.6 | +13 | 291 | 13 | 220 | 21:59-00:41 |

**Note:** Optical astrometry required prior to radar observations (5 deg). In November 2021, visual magnitude $<$22, solar elongation $\sim$90 deg, and positional uncertainty 3 deg.

**Request:** 2 tracks, 7.50 hours

| UT Date **5143 Heracles** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Nov-17 | 306 | 11.8 | +28 | 15 | 3 | 13 | 11:11-13:42 |
| 2021-Nov-18 | 306 | 12.0 | +25 | 16 | 3 | 14 | 11:17-13:56 |
| +2021-Nov-19 | 306 | 12.2 | +23 | 16 | 3 | 14 | 11:23-14:07 |
| +2021-Nov-20 | 308 | 12.4 | +21 | 16 | 3 | 14 | 11:31-14:17 |
| 2021-Nov-21 | 310 | 12.6 | +19 | 16 | 3 | 14 | 11:38-14:25 |
| 2021-Nov-22 | 314 | 12.8 | +16 | 16 | 3 | 12 | 11:47-14:32 |
| 2021-Nov-23 | 320 | 13.0 | +14 | 15 | 3 | 12 | 11:55-14:37 |

**Note:** Binary asteroid discovered with radar at Arecibo in 2011 and detected again with Arecibo and Goldstone in 2016. Additional radar range astrometry could provide a Yarkovsky drift detection.

**Request:** 2 tracks, 5.50 hours

| UT Date **7341 (1991 VK)** | RTT [s] | RA [h] | Dec [deg] | Runs | SNR /run | SNR /day | UT rise-set |
|---|---|---|---|---|---|---|---|
| 2021-Dec-28 | 161 | 22.5 | +06 | 23 | 8 | 40 | 19:28-21:34 |
| 2021-Dec-29 | 156 | 22.5 | +05 | 24 | 8 | 38 | 19:24-21:28 |
| 2021-Dec-30 | 152 | 22.5 | +05 | 24 | 8 | 43 | 19:21-21:21 |
| 2021-Dec-31 | 147 | 22.5 | +04 | 24 | 9 | 47 | 19:18-21:14 |
| 2022-Jan-01 | 143 | 22.4 | +04 | 23 | 11 | 53 | 19:15-21:06 |
| 2022-Jan-02 | 138 | 22.4 | +03 | 23 | 12 | 59 | 19:12-20:58 |
| +2022-Jan-03 | 134 | 22.4 | +02 | 22 | 14 | 65 | 19:10-20:50 |
| +2022-Jan-04 | 129 | 22.4 | +02 | 21 | 15 | 72 | 19:08-20:40 |
| 2022-Jan-05 | 124 | 22.3 | +01 | 20 | 17 | 77 | 19:07-20:29 |
| 2022-Jan-06 | 120 | 22.3 | +00 | 17 | 20 | 83 | 19:07-20:16 |

**Note:** Previously detected with radar at Goldstone in 1997, Arecibo in 2007, Arecibo and Goldstone in 2012, and Arecibo and Goldstone in 2016/2017. Additional radar range astrometry will refine its published Yarkovsky drift rate.