Arecibo Radar Observations of 17 High-Priority Near-Earth Asteroids in CY2021

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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. Radar is uniquely capable of resolving the sizes and shapes of the NEA population as dedicated spacecraft are costly and the uses of stellar occultations and direct imaging of NEAs are in their infancy. With its unmatched sensitivity and resolution from the ground, radar has discovered more than 70% of known NEA binary systems, which make up $\sim$15% of the population larger than 200 m, and identified that contact binaries, two similar-size bodies resting against one another, make up a similar (or perhaps larger) fraction of the NEA population. Arecibo radar observations routinely provide astrometry with fractional precision of one part in ten million as well as images with resolution as fine as 7.5 m revealing surface features, such as boulders, concavities, and ridges. Our SHAPE software (Hudson, 1994; Magri et al., 2007) inverts radar images to obtain spin-state estimates and three-dimensional shape models limited only by echo strength and orientational coverage over several days of observation. Beyond scientific return, knowledge gained from radar can help warn of and help to mitigate a possible Earth impact.

Observing Program Status (Technical Justification)

Project R3037 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. Proposals for project R3037 have requested 277 hours of telescope time since September 2019. Of these, 232 hours (84%) have been scheduled. The discrepancy is due in part to observatory shutdowns for earthquakes, the

COVID-19 pandemic, and a broken support cable, plus planned and unplanned maintenance and oversubscription of telescope time; however, this is on par for the rate of scheduling of R3037 in past years. Overall, Arecibo has detected 106 asteroids in the past 12 months under projects R3037, companion project R3035, and urgent proposals for targets of opportunity, all while working with a single klystron rather than the optimal two. Pressworthy results[1] since last September include discovery of binary asteroid 2020 BX12, collection of high-resolution images of 52768 (1998 OR2) for shape modeling, and removal of 2020 NK1 from the list of possible Earth impactors based on precise radar astrometry that improved future trajectory prediction. All radar detections have astrometry reported to the Center for Near-Earth Object Studies at the Jet Propulsion Laboratory, and several objects are in the process of shape modeling. The remaining four months of 2020 plus early January 2021 include five high-priority targets and 108.25 hours of telescope time requested, though recovery from the broken support cable may prevent these observations.

NASA's Near Earth Object Observations program supports the Arecibo planetary radar to observe NEAs for at least 600 hours per year. We propose high-resolution radar imaging, detailed physical characterization, and orbit refinement of our 17 highest-priority NEAs during the 2021 calendar year using 299.25 hours of telescope time. A companion proposal (Virkki et al.) with a more survey-oriented approach requests 336.50 hours and concentrates on basic characterization and precise astrometry for dozens more objects bringing the total proposed time request to 635.75 hours. 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 ~60 hours. 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 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 Plan (Science Justification)

Time requests for each target in 2021 are dictated by the science goals and the estimated signal-to-noise ratio (SNR). For all targets we will: measure the circular polarization ratio and radar cross section, which are gauges of near-surface roughness and density and can provide insight into composition (Benner et al., 2008) and metal content (Shepard et al., 2015); report precise astrometry; determine binarity; and constrain the size, shape, surface features, and spin state, which when combined with photometric and/or spectroscopic measurements constrain the optical albedo and composition. We also seek to further develop polarimetric analyses (Carter et al., 2007) to infer surface properties, such as the presence of regolith, by decomposing radar scattering mechanisms without requiring additional observing time. For targets with shape models, polarimetry can be mapped to physical coordinates for more detailed analyses of surface properties. Past experience demonstrates the key factor in our ability to secure shapes and spin-state estimates is good sky and rotational coverage over several days of observations, especially when we lack prior knowledge about the target. If it is found that the complete request is not necessary, due to weaker signal than expected or completion of science goals with fewer dates, the remaining time requests can be used for targets of opportunity or relinquished for use by other projects or maintenance.

Table 1 describes our 17 targets, including 14 potentially hazardous asteroids (PHAs), and lists synergistic observations. Since PHAs are by definition large bodies that come close to Earth, bar-

[1] http://www.naic.edu/~pradar/news.php

ring other available information, they tend to populate the list of targets with the strongest predicted radar returns. The objects requested at the Goldstone radar (more maneuverable, but less sensitive than Arecibo) will have greater coverage from longer daily tracks and observations outside the Arecibo declination window, which may lead to tighter constraints on physical parameters. A subset of radar targets will be observed through a coordinated program with the NASA InfraRed Telescope Facility (IRTF) for spectral characterization and application of radar-derived shape information to thermophysical modeling (*e.g.*, Howell et al., 2018). Speckle tracking (Busch et al., 2010) with the Very Long Baseline Array (VLBA) can be used to resolve the prograde/retrograde-rotation ambiguity of radar and constrain the spin states of up to four of our brightest targets. Astrometry of previously observed NEAs and Yarkovsky-drift candidates will refine detections of non-gravitational accelerations and constrain their masses and densities given their thermal properties (*i.e.*, IRTF data). Multiple radar apparitions improve the precision of Yarkovsky-drift measurements as $\sim 2^{N-1}$ (Greenberg et al., 2020). Table 2 lists specific track requests for each target.

Only four of 17 asteroids in Table 1 have been observed before with radar. 441987 (2010 NY65) has made close approaches to Earth for the last several years, which will allow for shape modeling and strong constraints on the Yarkovsky drift of its semimajor axis. The 2021 apparition for 4660 Nereus, a historically attractive mission candidate, will provide images at 7.5-m resolution, twice as detailed as those obtained in 2002 used for shape modeling (Brozovic et al., 2009), likely revealing significantly more surface features and allowing for shape-model and spin-state refinement. The 40+ year optical baseline plus radar observations spanning almost 20 years could confirm a Yarkovsky-drift detection and place a constraint on the mass and density. Asteroids 5189 (1990 UQ) and 143649 (2003 QQ47) have very limited prior datasets, mainly radar astrometry; observations this year will drastically improve the physical characterizations of these objects.

Some targets have no previous knowledge other than their absolute magnitude, while some have only a measurement of their rotation period from optical lightcurves and/or a diameter inferred by the NEOWISE infrared spacecraft. This lack of prior information is precisely why radar is important; radar efficiently provides physical characterization for objects where knowledge is otherwise lacking. In the case of NEOWISE targets, radar provides direct size and shape estimates for comparison to the sizes inferred from thermophysical modeling. None of the targets in Table 1 are known binaries; however, statistically, discovering at least one binary among the list is likely.

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 R3035, 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 (REU) 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?	Next App	Start-End Dates	RTT [s]	SNR /day	Notes
(2020 PP)	20.6	*0.22*	*2.1*		-	Jan 15-Jan 21	49	210	P N A
363024 (1998 OK1)	19.3	0.56	*2.1*		2100	Jan 17-Jan 21	73	200	P G W
468727 (2010 JE87)	20.7	0.31	*2.1*		2107	Jan 23-Jan 25	40	850	P G W
(2016 CL136)	21.4	0.12	*2.1*		2064	Jan 29-Feb 05	35	240	P G W
(1999 RM45)	19.4	*0.39*	*2.1*		-	Mar 01-Mar 08	20	14400	P G S I
231937 (2001 FO32)	17.7	*0.86*	*2.1*		-	Mar 22-Mar 26	24	32700	P G S
(1997 GL3)	19.1	*0.45*	7.6		2034	Apr 05-Apr 12	70	360	P G
5189 (1990 UQ)	17.8	*0.82*	6.6	Y	2040	Apr 24-May 02	76	370	P G I Y
414429 (2009 DC43)	17.7	2.87	*2.1*		2178	Jun 07-Jun 16	108	520	W
450263 (2003 WD158)	18.8	*0.52*	*2.1*		2067	Jun 14-Jun 18	53	690	P G I
441987 (2010 NY65)	21.4	0.18	5.0	Y	2180	Jun 18-Jul 01	40	780	P G W Y
285571 (2000 PQ9)	18.1	*0.71*	*2.1*		2113	Jul 25-Aug 03	69	280	G I
(2016 AJ193)	18.7	1.37	*2.1*		-	Aug 22-Aug 28	27	37400	P G S W
143649 (2003 QQ47)	17.4	*0.98*	3.7	Y	2031	Sep 20-Sep 26	98	200	P G I
159857 (2004 LJ1)	15.4	3.07	2.7		2038	Nov 02-Nov 12	157	150	P I W
518678 (2008 UZ94)	17.4	*0.98*	*2.1*		2115	Nov 25-Nov 30	70	310	P G I
4660 Nereus	18.4	0.33	15.1	Y	2060	Nov 14-Dec 27	30	27600	P N G S I Y

Table 1: We propose to observe our 17 highest-priority NEAs in a combined 299.25 hours (including transmitter warm-up time; see Table 2 for detailed time requests) to collect high-resolution radar images and precise astrometry. 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 $H < 22$. Assumptions of more rapid spins and brighter albedos (smaller sizes) lead to more conservative estimates for the signal-to-noise ratio (SNR). SNR estimates assume dual-klystron mode at 800 kW and will effectively halve if only one klystron is available. "Start-End" dates bracket the acceptable tracks. The closest approach is given by the minimum round-trip time, RTT, for light to reach the target and return. Notes include potentially hazardous asteroids (P), NHATS-compliant objects (N), Goldstone radar targets (G), VLBA speckle-tracking targets (S), possible IRTF near- and thermal-infrared targets (I), objects previously observed by the NEOWISE spacecraft (W), Yarkovsky-drift detections (Y) from Chesley et al. (2016; updated at NeoDys) and Greenberg et al. (2020), and objects requiring optical astrometry prior to radar observations (A). "Next App" indicates the next comparable close approach to Earth of less than 1.2 times the RTT (within a factor of 2 in SNR) of the upcoming apparition. Almost all are not re-observable at the same proximity to Earth for several decades meaning this is our best chance to characterize them with radar.

Observing Requests

Table 2. We request 85 tracks and 299.25 hours to observe 17 asteroids to collect high-resolution radar images and precise astrometry. 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. Several days of observations spread over the observing window allow for complete rotational coverage (assuming typical rotation periods) and better constraints on the spin state. In the event observations of targets of R3037 and companion project R3035 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 $\sim$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: 4 tracks, 14.50 hours

UT Date **(2020 PP)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Jan-15	60	16.7	+28	74	12	110	12:19-14:47
2021-Jan-16	58	16.8	+24	83	15	140	12:11-14:51
+2021-Jan-17	55	16.8	+20	90	17	170	12:06-14:52
+2021-Jan-18	53	16.9	+16	93	19	190	12:05-14:49
+2021-Jan-19	51	16.9	+11	90	22	210	12:09-14:42
+2021-Jan-20	50	16.9	+06	77	24	210	12:20-14:27
2021-Jan-21	49	17.0	+00	45	22	150	12:46-13:59

Note: Optical astrometry required prior to radar observations (4 deg). In December 2020, visual magnitude <20, solar elongation >90 deg, and positional uncertainty <1 deg.

Request: 4 tracks, 14.50 hours

UT Date **363024 (1998 OK1)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+2021-Jan-17	82	23.2	+07	50	17	130	18:44-20:59
+2021-Jan-18	78	23.3	+12	61	20	160	18:37-21:15
+2021-Jan-19	76	23.5	+18	66	23	190	18:38-21:25
+2021-Jan-20	74	23.7	+24	65	25	200	18:48-21:29
2021-Jan-21	73	23.9	+31	54	16	120	19:11-21:23

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

Request: 3 tracks, 10.50 hours

UT Date **468727 (2010 JE87)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+2021-Jan-23	44	17.7	+06	88	59	550	12:55-15:05
+2021-Jan-24	42	17.5	+17	118	73	800	12:22-15:05
+2021-Jan-25	40	17.3	+28	108	81	850	12:11-14:36

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

Request: 4 tracks, 12.50 hours

UT Date **(2016 CL136)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Jan-29	50	15.3	+22	96	9	94	09:50-12:31
+2021-Jan-30	44	14.7	+26	104	15	160	09:13-11:45
+2021-Jan-31	39	13.8	+29	104	23	240	08:27-10:41
+2021-Feb-01	36	12.7	+32	95	19	190	07:27-09:20
+2021-Feb-02	35	11.4	+33	91	20	190	06:11-07:58
2021-Feb-03	38	10.2	+31	99	16	160	04:48-06:53
2021-Feb-04	42	9.3	+27	103	17	180	03:38-06:03
2021-Feb-05	49	8.6	+24	97	10	110	02:47-05:24

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

Request: 6 tracks, 18.75 hours

UT Date **(1999 RM45)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+2021-Mar-01	22	6.3	+00	82	790	7140	23:38-00:37
+2021-Mar-02	20	4.4	+05	168	1110	14400	21:14-23:03
+2021-Mar-03	23	2.5	+08	172	780	10200	19:08-21:19
+2021-Mar-04	30	1.3	+09	140	320	3780	17:46-20:06
+2021-Mar-05	39	0.6	+09	111	130	1380	16:56-19:20
+2021-Mar-06	49	0.1	+09	88	59	560	16:25-18:50
2021-Mar-07	60	23.8	+09	73	30	260	16:03-18:28
2021-Mar-08	71	23.6	+09	61	17	130	15:47-18:12

Note: Speckle tracking with the VLBA will help break the prograde/retrograde ambiguity of the high-resolution radar images and better constrain the spin state. Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.

Request: 5 tracks, 18.25 hours

UT Date **231937 (2001 FO32)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+2021-Mar-22	24	22.9	+11	207	2280	32700	13:59-16:41
+2021-Mar-23	42	23.7	+21	120	330	3650	14:43-17:31
+2021-Mar-24	61	0.1	+25	79	91	810	15:04-17:45
+2021-Mar-25	81	0.3	+26	57	35	270	15:15-17:49
+2021-Mar-26	101	0.4	+27	45	16	110	15:20-17:50

Note: Speckle tracking with the VLBA will help break the prograde/retrograde ambiguity of the high-resolution radar images and better constrain the spin state.

Request: 5 tracks, 18.75 hours

UT Date **(1997 GL3)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Apr-05	90	4.0	+17	56	17	130	18:08-20:57
2021-Apr-06	81	4.6	+20	63	25	200	18:38-21:28
+2021-Apr-07	74	5.3	+22	68	34	280	19:18-22:07
+2021-Apr-08	70	6.2	+24	71	41	350	20:08-22:54
+2021-Apr-09	70	7.1	+25	71	42	360	21:02-23:47
+2021-Apr-10	72	8.1	+24	69	37	310	21:53-00:39
+2021-Apr-11	78	8.9	+23	64	28	230	22:36-01:24
2021-Apr-12	87	9.5	+21	58	20	150	23:10-01:59

Request: 5 tracks, 17.75 hours

UT Date **5189 (1990 UQ)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Apr-24	118	15.8	+15	42	15	100	04:47-07:31
2021-Apr-25	112	15.9	+17	45	19	130	04:49-07:35
2021-Apr-26	106	16.1	+19	47	23	160	04:52-07:39
+2021-Apr-27	100	16.2	+21	50	28	200	04:57-07:43
+2021-Apr-28	94	16.4	+24	52	34	250	05:05-07:48
+2021-Apr-29	89	16.6	+26	53	42	310	05:16-07:52
+2021-Apr-30	84	16.8	+29	51	51	370	05:32-07:56
+2021-May-01	80	17.1	+32	46	39	270	05:55-07:58
2021-May-02	76	17.4	+35	34	46	270	06:29-07:54

Note: Previously detected with Goldstone in 1992, but limited to Doppler-only (line-of-sight velocity) astrometry. Radar range astrometry will refine its published Yarkovsky drift rate. Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.

Request: 5 tracks, 18.25 hours

UT Date **414429 (2009 DC43)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Jun-07	108	3.3	+36	20	50	220	14:09-15:21
2021-Jun-08	108	3.3	+31	35	51	300	13:35-15:41
+2021-Jun-09	108	3.2	+27	42	79	520	13:16-15:48
+2021-Jun-10	109	3.2	+22	45	77	520	13:04-15:48
+2021-Jun-11	111	3.2	+18	45	73	480	12:58-15:43
+2021-Jun-12	113	3.2	+14	42	67	440	12:55-15:35
+2021-Jun-13	116	3.1	+10	39	61	380	12:55-15:24
2021-Jun-14	120	3.1	+06	33	55	320	13:00-15:10
2021-Jun-15	124	3.1	+03	25	43	220	13:08-14:52
2021-Jun-16	128	3.1	-00	14	38	140	13:26-14:25

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

Request: 4 tracks, 14.00 hours

UT Date **450263 (2003 WD158)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+2021-Jun-14	53	19.8	+32	67	44	360	05:49-07:47
+2021-Jun-15	53	19.7	+24	90	72	690	05:16-07:54
+2021-Jun-16	53	19.6	+16	93	71	690	05:01-07:45
+2021-Jun-17	54	19.4	+09	79	65	570	05:01-07:23
2021-Jun-18	57	19.4	+01	47	48	330	05:18-06:46

Note: Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.

Request: 7 tracks, 26.25 hours

UT Date **441987 (2010 NY65)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Jun-18	64	7.8	+13	75	14	120	17:10-19:50
+2021-Jun-19	58	8.1	+15	85	19	180	17:23-20:07
2021-Jun-20	52	8.5	+17	96	27	270	17:41-20:28
+2021-Jun-21	48	9.0	+19	106	38	390	18:05-20:54
2021-Jun-22	44	9.6	+21	116	51	550	18:36-21:26
+2021-Jun-23	41	10.3	+23	123	63	700	19:16-22:04
+2021-Jun-24	40	11.1	+24	125	69	780	20:01-22:47
+2021-Jun-25	40	12.0	+24	124	68	760	20:47-23:33
2021-Jun-26	42	12.8	+23	119	58	640	21:29-00:16
+2021-Jun-27	45	13.4	+22	112	46	490	22:05-00:54
2021-Jun-28	49	14.0	+20	103	34	350	22:35-01:24
+2021-Jun-29	54	14.4	+19	93	24	240	22:59-01:47
2021-Jun-30	60	14.8	+17	84	17	160	23:18-02:05
2021-Jul-01	66	15.1	+15	75	12	110	23:33-02:18

Note: Previously detected with Arecibo in 2014, Arecibo and Goldstone in 2015 and 2016, Arecibo in 2017, Arecibo and Goldstone in 2018, and Arecibo in 2019. Continued monitoring will aid in understanding the evolution of its horseshoe libration about Earth as well as refine its shape, spin state, and published Yarkovsky drift rate. Time requests are spaced to improve rotational coverage.

Request: 5 tracks, 17.25 hours

UT Date **285571 (2000 PQ9)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Jul-25	69	20.1	-00	22	39	190	04:00-04:52
+2021-Jul-26	71	20.2	+03	45	36	240	03:33-05:20
+2021-Jul-27	73	20.3	+07	55	38	280	03:19-05:33
+2021-Jul-28	75	20.4	+10	60	34	260	03:11-05:41
+2021-Jul-29	78	20.4	+13	61	30	240	03:06-05:45
+2021-Jul-30	81	20.5	+16	61	27	210	03:02-05:47
2021-Jul-31	84	20.5	+19	60	23	180	03:01-05:47
2021-Aug-01	87	20.6	+21	57	20	160	03:01-05:46
2021-Aug-02	90	20.6	+24	53	18	130	03:02-05:43
2021-Aug-03	94	20.7	+26	50	16	110	03:04-05:39

Note: Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.

Request: 5 tracks, 17.75 hours

UT Date (2016 AJ193)	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+2021-Aug-22	27	7.3	+07	158	2970	37400	12:35-14:57
+2021-Aug-23	38	8.5	+19	136	980	11400	13:23-16:14
+2021-Aug-24	51	9.1	+25	94	350	3410	14:03-16:43
+2021-Aug-25	65	9.5	+28	68	150	1260	14:29-16:57
+2021-Aug-26	79	9.8	+30	52	48	350	14:46-17:04
2021-Aug-27	94	10.0	+31	42	27	170	14:57-17:08
2021-Aug-28	109	10.1	+32	34	16	94	15:04-17:09

Note: A size and shape constraint will allow for comparison with the diameter inferred from NEOWISE observations. Speckle tracking with the VLBA will help break the prograde/retrograde ambiguity of the high-resolution radar images and better constrain the spin state.

Request: 3 tracks, 11.00 hours

UT Date 143649 (2003 QQ47)	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Sep-20	118	2.1	+04	29	13	73	05:39-07:34
2021-Sep-21	109	1.7	+09	40	20	130	04:58-07:22
+2021-Sep-22	103	1.2	+15	46	25	170	04:20-06:59
+2021-Sep-23	99	0.7	+21	49	28	200	03:44-06:25
+2021-Sep-24	98	0.2	+27	45	29	200	03:11-05:39
2021-Sep-25	101	23.5	+32	35	17	100	02:44-04:42
2021-Sep-26	105	22.9	+36	19	14	62	02:28-03:33

Note: Previously detected with Arecibo in 2014, but limited to Doppler-only (line-of-sight velocity) astrometry. Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.

Request: 5 tracks, 18.50 hours

UT Date **159857 (2004 LJ1)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Nov-02	157	10.0	+32	24	17	84	10:41-12:45
2021-Nov-03	157	9.9	+29	27	27	140	10:19-12:40
+2021-Nov-04	157	9.7	+27	29	27	150	10:01-12:33
+2021-Nov-05	158	9.6	+24	30	27	150	09:45-12:24
+2021-Nov-06	159	9.4	+22	31	26	150	09:30-12:14
+2021-Nov-07	160	9.3	+19	31	25	140	09:18-12:03
+2021-Nov-08	162	9.2	+17	30	24	130	09:08-11:51
2021-Nov-09	165	9.1	+14	29	23	130	08:59-11:39
2021-Nov-10	167	9.0	+12	28	21	110	08:51-11:25
2021-Nov-11	171	8.9	+09	26	20	100	08:45-11:11
2021-Nov-12	174	8.8	+07	23	19	92	08:41-10:56

Note: A size and shape constraint will allow for comparison with the diameter inferred from NEOWISE observations. Given its size and relatively rapid 2.7-h rotation, it is a candidate binary asteroid. Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.

Request: 4 tracks, 14.00 hours

UT Date **518678 (2008 UZ94)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Nov-25	123	19.4	+23	40	10	63	18:11-20:54
2021-Nov-26	113	19.5	+21	44	13	91	18:13-20:59
+2021-Nov-27	103	19.6	+18	48	18	130	18:17-21:03
+2021-Nov-28	94	19.8	+14	52	26	190	18:24-21:07
+2021-Nov-29	85	20.0	+10	53	36	270	18:37-21:07
+2021-Nov-30	77	20.2	+05	48	44	310	19:00-21:02

Note: Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.

Request: 11 tracks, 36.75 hours

UT Date **4660 Nereus**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2021-Nov-14	115	3.2	+32	32	19	110	03:04-05:08
2021-Nov-15	110	3.2	+32	33	22	130	03:03-05:03
2021-Nov-16	106	3.2	+33	33	26	150	03:02-04:57
+2021-Nov-17	101	3.2	+33	32	30	170	03:02-04:51
+2021-Nov-18	97	3.2	+34	31	35	200	03:03-04:44
2021-Nov-19	93	3.2	+35	30	40	220	03:05-04:37
2021-Nov-20	89	3.3	+35	27	47	240	03:08-04:28
2021-Nov-21	85	3.3	+36	22	56	260	03:14-04:17
...	Target is north of the Arecibo declination window						
+2021-Dec-15	30	13.1	+35	95	1900	18400	11:10-12:45
+2021-Dec-16	32	13.3	+29	134	2390	27600	10:53-13:16
+2021-Dec-17	34	13.4	+24	140	1900	22500	10:49-13:30
+2021-Dec-18	37	13.6	+20	136	1500	17400	10:49-13:36
+2021-Dec-19	40	13.7	+17	125	1180	13200	10:52-13:37
+2021-Dec-20	43	13.7	+13	113	930	9860	10:56-13:36
+2021-Dec-21	46	13.8	+11	100	740	7360	11:01-13:32
+2021-Dec-22	49	13.9	+08	87	590	5520	11:06-13:27
+2021-Dec-23	52	13.9	+06	75	480	4120	11:11-13:20
2021-Dec-24	55	14.0	+04	62	340	2660	11:18-13:12
2021-Dec-25	58	14.0	+02	51	280	1960	11:24-13:03
2021-Dec-26	62	14.1	+01	39	230	1430	11:32-12:53
2021-Dec-27	65	14.1	+00	26	190	960	11:43-12:39

Note: Previously detected with Arecibo in 2002. Higher-resolution images will improve the shape model of Brozovic et al. (2009) and, along with possible speckle tracking with the VLBA, will refine the spin state and unambiguously determine prograde or retrograde rotation. The strong SNR and E-class taxonomy (high polarization ratio) will allow for polarimetric studies. Dates in November will provide snapshots of both sides of Nereus plus additional spin-state constraints in preparation for the best observing dates in mid-December. Nine consecutive dates will provide extensive rotational coverage over the strongest dates available. Additional radar range astrometry will refine its published Yarkovsky drift rate. Complementary infrared observations with the IRTF would constrain the composition, albedo, and thermal properties of this target.