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

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Observing Program

Radar is arguably the most powerful Earth-based technique for post-discovery orbit refinement and physical characterization of near-Earth asteroids (NEAs). Line-of-sight radar astrometry substantially improves our knowledge of asteroid trajectories (Ostro & Giorgini, 2004) owing to the fractional precision of radar, about one part in ten million, and its orthogonality to optical plane-of-sky astrometry. As such, NASA's Near-Earth Object Observations program supports the Arecibo planetary radar for at least 600 hours per year to observe up to 125 NEAs.

We propose to continue our survey-oriented approach 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 several dozen NEAs in a relatively short amount of telescope time, *i.e.*, one or two tracks per target. A companion proposal (Taylor et al.) concentrates on those 19 objects with the highest expected signal strengths and/or desired to have 3+ days of observations, which will provide more detailed physical characterizations using significantly more telescope time per object. In the last 12 months, the Arecibo planetary radar program has detected 100 NEAs under these companion projects.

Our observing program consists of three parts: moderate resolution imaging, where we request two tracks per target to determine its basic shape (14 NEAs, 28 tracks, 93.75 hours; see Table 1), astrometry, where we request one track per target to obtain the precise line-of-sight velocity of and distance to the target (3/4 of the suggested 23 NEAs, $\sim$18 tracks, $\sim$60 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 will concentrate on objects discovered by optical survey programs as the moon wanes. Typically about half of our annual detections are newly discovered objects one cannot explicitly plan for in advance, many of which are detected on such survey nights. In all, we request at least 248.25 hours of telescope time (including transmitter warm up) for this survey-oriented observing program.

In 2017 (project R3035), we proposed similarly for 241 hours of telescope time for this program. Thus far, in 8 months, 77.25 hours have been scheduled for this project. This is partly due to the two-month planetary radar shutdown (July and August) to replace the S-band heat exchangers, competition for telescope time around new moon with atmospheric world day and HF campaigns, and opportunities to combine observing tracks with our companion project R3037. Four (of eight) survey nights were scheduled, resulting in 13 detections of mostly newly discovered objects, which is on par with our historical average per night. We have detected 4 of 5 moderate-imaging targets and 7 of 11 astrometry targets (on par with our request of two-thirds of those objects). Among the astrometry targets was (163693) Atira, which was found to be a binary system (Rivera-Valentin et al., 2017) with much stronger echoes than expected. We note that the signal-to-noise ratios (SNR) presented here are often lower bounds due to conservative assumptions about the 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.

Combining this proposal, 14 moderate imaging targets and ~18 astrometry targets, with the 19 high-priority imaging targets in our companion proposal totals ~50 likely detections of previously known NEAs. Newly discovered asteroids observed during survey nights and as targets of opportunity during other scheduled tracks could double the number of detections to ~100 or more using ~570 hours of telescope time. Additional observations may be requested via urgent proposals for newly discovered objects not observable during previously scheduled tracks (or survey nights) or for additional time on targets found to be of particular scientific interest. Proposals to observe NEAs not included in these companion proposals accounted for ~15% of time requests in the last two years such that we expect to surpass 600 hours requested in 2018.

Student Participation

Graduate student Luisa Zambrano-Marin (Granada), member of the local Arecibo team, is using radar scattering models to constrain the surface properties of asteroids and comets. Graduate student Sean Marshall (Cornell) works on shape and thermal modeling of asteroids observed with radar and NASA's InfraRed Telescope Facility (IRTF; Marshall et al., 2017) and will join the local Arecibo team in late 2017. Graduate student Jenna Crowell (Central Florida) used radar in the shape and thermal modeling of asteroid 1627 Ivar (R2831; Crowell et al., 2017) and will lead observations of Ivar in 2018. Graduate student Adam Greenberg (UCLA) led observations of asteroids (1566) Icarus (R2960; Greenberg et al., 2017a) and (441987) 2010 NY65 (R3037) and is publishing Yarkovsky-drift measurements based partly on radar astrometry (Greenberg et al., 2017b). Graduate student Cassandra Lejoly (Arizona) observed Comet 45P (R3142) and is analyzing radar cross sections of Arecibo asteroid data. Benjamin Sharkey (now a graduate student at Arizona) was part of the Research Experience for Undergraduates (REU) program in 2015 and a summer research assistant at Arecibo in 2016 shape modeling asteroid (52760) 1998 ML14 (R1172 and R2831) and participated in radar observations. Undergraduate Andy Lopez-Oquendo (UPR Humacao) regularly participated in observations in 2017. Other undergraduate and graduate students are welcome to gain observing and research experience through this proposed work.

References

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Object	H mag	Diam [m]	P_{spin} [h]	Start-End Dates	Preferred Dates	RTT [s]	SNR /day	Notes
306383 (1993 VD)	21.5	*150*	*2.1*	Jan 21-25	Jan 22-23	37	370	P G Y
276033 (2002 AJ129)	18.7	*540*	*2.1*	Feb 06-09	Feb 06-07	39	2290	P G I
363599 (2004 FG11)	21.0	150	4.0	Apr 08-09	Apr 08-09	64	60	B P G Y
2016 JP	21.2	*170*	*2.1*	Apr 14-17	Apr 16-17	39	330	P
1999 FN19	22.5	*90*	3.5	May 16-23	May 17-18	40	160	N G A
2014 WG365	19.9	*310*	*2.1*	May 24-27	May 26-27	63	140	P G A
467309 (1996 AW1)	20.0	*300*	*2.1*	Jun 16-19	Jun 17-18	61	150	P G
13553 Masaakikoyama	16.4	*1600*	38.0	Jul 09-Aug 15	Jul 11, Aug 12	208	65	G
1998 SD9	24.2	*40*	*0.5*	Aug 29-31	Aug 29-30	12	1640	G
2013 UG1	22.4	*100*	*0.5*	Oct 15-21	Oct 17-18	27	330	G A
475534 (2006 TS7)	21.2	*710*	*2.1*	Oct 30-01	Oct 30-31	23	3200	P G
410088 (2007 EJ)	18.1	750	2.4	Nov 29-04	Nov 30-01	80	190	G
2003 NW1	18.7	*540*	*2.1*	Dec 04-16	Dec 09-10	69	260	P G I
2012 MS4	18.7	*540*	*2.1*	Dec 20-21	Dec 20-21	82	130	P G A

Table 1: We request two (2) tracks for each object totaling 28 tracks and 93.75 hours of telescope time (including transmitter warm up time; see Table 3 for detailed time requests). ”Start-End” dates bracket the acceptable dates for observations, while ”Preferred” are the two preferred tracks. Absolute magnitudes H are taken from the JPL Small-Body Database. Rotation periods P_{spin} are taken from the asteroid Lightcurve Database [Warner et al., 2009] or previous radar observations when available. Italicized periods are assumed very rapid at 2.1 h for H < 22, which gives a more conservative signal-to-noise ratio (SNR), and 0.5 h for H > 22. Diameters are taken from previous radar observations if available; otherwise italicized diameters are estimates based on H assuming an optical albedo of 0.2. The closest approach is given by the round-trip time, RTT, for light to reach the target and return. Notes include known binary asteroids (B), potentially hazardous asteroids (P), NHATS objects (N), Goldstone radar targets (G), possible IRTF near- and thermal-infrared targets (I), Yarkovsky-drift candidates (Y) from Greenberg et al. (2017b), and objects that would benefit from optical astrometry prior to radar observations (A).

Object	H mag	Diam [km]	P_{spin} [h]	Start-End Dates	Preferred Date	RTT [s]	SNR /day	Rise-Set UT	Notes
2006 WE4	18.9	*490*	*2.1*	Jan 23-29	Jan 26	107	40	15:58-18:25	
162882 (2001 FD58)	18.8	*520*	*2.1*	Feb 10-15	Feb 13	94	60	18:23-20:42	P G
311554 (2006 BQ147)	18.7	*540*	9.2	Feb 13-24	Feb 19	114	75	00:53-03:38	I
2013 RZ73	20.9	*200*	*2.1*	Mar 13-15	Mar 13	58	95	15:45-17:57	P G
96950 (1998 XB)	16.2	1700	520	Mar 26-11	Mar 29	286	65	14:04-15:58	
85953 (1999 FK21)	18.1	*710*	17.6	Apr 01-09	Apr 05	128	90	02:08-04:43	I Y
242708 (2005 UK1)	18.1	540	50	Apr 12-22	Apr 18	149	50	13:56-15:41	P
194126 (2001 SG276)	17.7	*860*	*2.1*	Apr 17-22	Apr 21	99	100	04:33-06:22	G I
2002 JR100	24.3	*40*	*0.5*	Apr 26-03	Apr 29	28	90	08:46-11:21	N G A
469737 (2005 NW44)	20.4	*250*	*2.1*	Jun 21-24	Jun 21	64	90	01:14-03:12	G
439313 (2012 VE82)	17.0	*370*	*2.1*	Jul 16-20	Jul 18	93	35	19:11-20:45	P
420591 (2012 HF31)	19.4	*390*	*2.1*	Aug 08-12	Aug 09	89	50	14:43-16:42	
2061 Anza	16.6	*1400*	11.5	Aug 13-29	Aug 20	201	35	07:13-09:38	I Y
163899 (2003 SD220)	17.3	1000	285	Aug 16-29	Aug 25	241	40	16:10-18:06	P N
2015 QM3	20.4	*250*	*2.1*	Aug 25-29	Aug 26	69	70	18:20-20:39	A
54660 (2000 UJ1)	18.0	*750*	5.4	Nov 01-05	Nov 03	122	70	05:57-08:31	I
2015 NU2	20.9	*200*	*2.1*	Nov 06-10	Nov 08	69	55	19:40-22:16	P A
65733 (1993 PC)	18.4	*620*	4.2	Nov 01-19	Nov 08	104	90	20:53-23:32	Y
2011 WA	21.6	*140*	*2.1*	Nov 10-14	Nov 12	67	40	05:29-08:04	
2009 WB105	23.5	*60*	*0.5*	Nov 25-26	Nov 25	39	40	02:35-05:13	
2012 MM11	20.3	300	19.0	Dec 04-11	Dec 07	99	60	08:42-10:18	P
2014 JU54	19.8	*320*	*2.1*	Dec 15-20	Dec 18	87	50	05:38-08:22	
2007 YQ56	19.9	*310*	*2.1*	Dec 28-02	Dec 30	81	60	01:42-04:27	

Table 2: Assuming each track is 3.25 h (including transmitter warm up), we request at least 58.5 hours of telescope time to observe at least 3/4 of the objects listed above. "Start-End" dates bracket the acceptable dates for observations, while "Preferred" is the preferred track. Priority, if necessary, should be given to potentially hazardous asteroids (P), NHATS objects (N), Yarkovsky-drift candidates (Y), and possible IRTF near- and thermal-infrared targets (I). Some objects would benefit from optical astrometry prior to radar observations (A). Column descriptions are otherwise the same as in Table 1.

Observing Requests

Table 3. We request 28 tracks and 93.75 hours to observe the 14 moderate-imaging targets in Table 1. 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. Calculations assume the physical parameters from Table 1 and a radar albedo of 0.1. When unknown, the sizes and spin rates used tend to give conservative estimates of the signal-to-noise ratio. Nominal system parameters are assumed: transmitter power = 450 kW (single-klystron mode), sensitivity = 10 K/Jy, and system temperature = 24 K.

Request: 2 tracks, 6.00 hours

UT Date **306383 (1993 VD)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Jan-21	39	15.0	+37	24	30	190	11:13-11:44
+ 2018-Jan-22	37	16.3	+34	83	37	330	11:50-13:32
+ 2018-Jan-23	38	17.5	+28	121	34	370	12:32-15:04
2018-Jan-24	41	18.4	+21	124	26	280	13:14-16:04
2018-Jan-25	47	19.1	+15	108	16	170	13:51-16:38

Request: 2 tracks, 7.00 hours

UT Date **276033 (2002 AJ129)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+ 2018-Feb-06	39	10.3	+08	102	222	2290	04:39-06:50
+ 2018-Feb-07	53	9.4	+15	89	73	690	03:28-06:06
2018-Feb-08	70	8.9	+19	69	28	240	02:51-05:34
2018-Feb-09	89	8.6	+21	55	12	95	02:28-05:11

Request: 2 tracks, 6.75 hours

UT Date **363599 (2004 FG11)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+ 2018-Apr-08	74	15.7	+25	65	5	40	05:45-08:25
+ 2018-Apr-09	64	16.1	+32	60	8	60	06:22-08:30

Request: 2 tracks, 6.25 hours

UT Date **(2016 JP)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Apr-14	56	1.6	+15	88	11	110	15:16-17:59
2018-Apr-15	50	1.6	+20	101	16	170	15:09-17:55
+ 2018-Apr-16	44	1.6	+26	105	25	250	15:09-17:43
+ 2018-Apr-17	39	1.6	+34	80	37	330	15:27-17:11

Request: 2 tracks, 6.00 hours

UT Date **(1999 FN19)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Apr-21	56	9.2	+29	77	5	50	22:32-00:56
2018-Apr-22	53	9.2	+30	76	6	60	22:33-00:48
2018-Apr-23	51	9.2	+32	73	8	70	22:35-00:38
2018-Apr-24	48	9.3	+34	65	10	80	22:41-00:24
2018-Apr-25	45	9.3	+36	46	12	85	22:54-00:03
...	Target is north of the Arecibo declination window						
2018-May-16	38	21.2	+36	54	21	160	09:34-10:42
+ 2018-May-17	40	21.2	+33	83	17	160	09:08-11:00
+ 2018-May-18	43	21.2	+30	93	14	140	08:53-11:07
2018-May-19	46	21.3	+28	97	11	110	08:43-11:10
2018-May-20	48	21.3	+26	97	9	90	08:35-11:11
2018-May-21	51	21.3	+24	94	8	75	08:29-11:09
2018-May-22	54	21.3	+22	91	6	60	08:24-11:07
2018-May-23	57	21.3	+21	87	5	50	08:19-11:04

Request: 2 tracks, 6.50 hours

UT Date **(2014 WG365)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-May-24	74	22.2	+24	65	10	85	09:11-11:52
2018-May-25	69	22.1	+18	71	13	110	09:01-11:46
+ 2018-May-26	66	22.1	+12	70	15	130	08:59-11:33
+ 2018-May-27	63	22.0	+05	56	18	140	09:09-11:07

Request: 2 tracks, 7.00 hours

UT Date **467309 (1996 AW1)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Jun-16	72	16.2	+23	67	10	85	01:42-04:24
+ 2018-Jun-17	66	16.0	+27	69	14	120	01:33-04:05
+ 2018-Jun-18	61	15.8	+31	63	19	150	01:29-03:36
2018-Jun-19	56	15.6	+36	32	25	160	01:41-02:41

Request: 2 tracks, 7.50 hours

UT Date **13553 Masaakikoyama (1992 JE)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Jul-09	213	20.4	+16	23	12	60	04:20-07:04
2018-Jul-10	211	20.4	+16	23	13	60	04:19-07:03
+ 2018-Jul-11	210	20.4	+16	23	13	65	04:18-07:02
2018-Jul-12	209	20.5	+17	24	13	65	04:17-07:02
2018-Jul-13	208	20.6	+17	24	14	65	04:15-07:01
2018-Jul-14	207	20.6	+17	24	14	70	04:14-07:00
2018-Jul-15	206	20.7	+17	24	14	70	04:13-06:59
2018-Jul-16	205	20.7	+18	24	14	70	04:13-06:58
2018-Jul-17	204	20.8	+18	24	14	70	04:12-06:58
2018-Jul-18	203	20.8	+18	24	15	70	04:11-06:57
2018-Jul-19	203	20.9	+18	25	15	75	04:10-06:56
2018-Jul-20	202	20.9	+18	25	15	75	04:09-06:55
2018-Jul-21	202	21.0	+18	25	15	75	04:08-06:54
2018-Jul-22	201	21.0	+19	25	15	75	04:07-06:53
2018-Jul-23	201	21.1	+19	25	15	75	04:06-06:52
2018-Jul-24	200	21.1	+19	25	15	75	04:05-06:51
2018-Jul-25	200	21.2	+19	25	15	75	04:04-06:50
2018-Jul-26	200	21.2	+19	25	16	75	04:03-06:50
2018-Jul-27	200	21.3	+19	25	16	75	04:02-06:49
2018-Jul-28	200	21.3	+19	25	16	75	04:01-06:48
2018-Jul-29	200	21.4	+19	25	16	75	04:00-06:47
2018-Jul-30	200	21.4	+19	25	15	75	03:59-06:45
2018-Jul-31	200	21.5	+19	25	15	75	03:58-06:44
2018-Aug-01	201	21.5	+19	25	15	75	03:57-06:43
2018-Aug-02	201	21.6	+19	25	15	75	03:56-06:42
2018-Aug-03	201	21.6	+18	25	15	75	03:55-06:41
2018-Aug-04	202	21.6	+18	25	15	75	03:54-06:40
2018-Aug-05	202	21.7	+18	25	15	70	03:52-06:38
2018-Aug-06	203	21.7	+18	25	15	70	03:51-06:37
2018-Aug-07	204	21.8	+18	24	15	70	03:50-06:36
2018-Aug-08	204	21.8	+18	24	14	70	03:48-06:34
2018-Aug-09	205	21.9	+17	24	14	70	03:47-06:33
2018-Aug-10	206	21.9	+17	24	14	70	03:46-06:31
2018-Aug-11	207	21.9	+17	24	14	65	03:44-06:29
+ 2018-Aug-12	208	22.0	+16	24	13	65	03:43-06:28
2018-Aug-13	209	22.0	+16	24	13	65	03:41-06:26
2018-Aug-14	211	22.1	+16	23	13	60	03:40-06:24
2018-Aug-15	212	22.1	+16	23	13	60	03:38-06:22

Request: 2 tracks, 6.50 hours

UT Date **(1998 SD9)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+ 2018-Aug-29	12	17.0	+34	279	103	1640	22:06-23:53
+ 2018-Aug-30	15	17.8	+13	326	51	910	22:17-00:59
2018-Aug-31	20	18.2	+01	129	21	230	23:14-00:39

Request: 2 tracks, 6.50 hours

UT Date **(2013 UG1)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Oct-15	34	8.0	+15	142	13	160	09:36-12:15
2018-Oct-16	30	7.3	+21	161	20	250	08:50-11:29
+ 2018-Oct-17	27	6.4	+28	156	26	330	07:58-10:20
+ 2018-Oct-18	27	5.2	+32	124	28	320	07:01-08:52
2018-Oct-19	28	4.0	+35	90	23	230	05:59-07:24
2018-Oct-20	31	3.0	+35	83	16	150	04:51-06:18
2018-Oct-21	36	2.2	+33	90	10	100	03:48-05:36

Request: 2 tracks, 7.25 hours

UT Date **475534 (2006 TS7)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+ 2018-Oct-30	23	13.8	+25	213	227	3200	14:25-17:06
+ 2018-Oct-31	30	14.3	+09	148	93	1110	14:56-17:23
2018-Nov-01	39	14.6	+00	49	39	270	15:50-16:53

Request: 2 tracks, 5.75 hours

UT Date **410088 (2007 EJ)**	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Nov-29	77	14.4	+00	25	37	180	13:47-14:52
+ 2018-Nov-30	80	14.2	+03	37	31	190	13:17-14:56
+ 2018-Dec-01	85	14.1	+05	43	37	170	12:55-14:55
2018-Dec-02	89	14.0	+07	45	22	150	12:37-14:50
2018-Dec-03	93	13.9	+09	46	19	130	12:22-14:45
2018-Dec-04	98	13.8	+11	46	16	110	12:09-14:39

Request: 2 tracks, 7.50 hours

UT Date (2003 NW1)	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
2018-Dec-04	84	21.6	+08	52	15	110	20:00-22:24
2018-Dec-05	79	22.0	+10	58	19	140	20:13-22:45
2018-Dec-06	75	22.4	+12	64	23	180	20:29-23:08
2018-Dec-07	72	22.8	+14	69	26	220	20:49-23:33
2018-Dec-08	70	23.3	+16	72	29	240	21:13-00:00
+ 2018-Dec-09	69	23.8	+18	74	30	260	21:39-00:28
+ 2018-Dec-10	69	0.3	+19	74	30	250	22:06-00:56
2018-Dec-11	71	0.9	+20	72	28	230	22:34-01:23
2018-Dec-12	73	1.4	+21	69	24	200	23:01-01:49
2018-Dec-13	77	1.8	+21	65	20	160	23:25-02:13
2018-Dec-14	82	2.2	+21	62	17	130	23:46-02:34
2018-Dec-16	87	2.6	+21	58	13	100	00:04-02:52

Request: 2 tracks, 7.25 hours

UT Date (2012 MS4)	RTT [s]	RA [h]	Dec [deg]	Runs	SNR /run	SNR /day	UT rise-set
+ 2018-Dec-20	82	22.3	+26	57	17	130	19:33-22:09
+ 2018-Dec-21	85	22.4	+10	54	15	110	19:33-22:04