Radar Reconnaissance of Potentially Hazardous Asteroids and Comets

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December 26, 2002

For submission to
Mitigation of Hazardous Impacts due to Asteroids and Comets
(Cambridge University Press)

3 figures
8 tables
word count including figure and table captions: 8500

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Groundbased radar is uniquely able to reduce uncertainty in trajectories and physical properties of near-earth objects. Radar can prevent the loss of a newly discovered object caused by the normal decay of orbit knowledge prior to the next optical observing opportunity, can add decades or centuries to the interval over which close Earth approaches can accurately be predicted, can significantly refine collision probability estimates that are based on optical astrometry alone, can reveal whether an object is single or binary, and can produce detailed information about potentially hazardous objects' sizes, shapes, spin states, and surface characteristics. If a small body is on course for an Earth collision in this century, then radar reconnaissance is likely to be required to distinguish the impact trajectory from a near miss and would dramatically reduce the difficulty and cost of any mitigation effort.

1. Introduction

The current Spaceguard Survey classifies each known near-Earth asteroid (NEA) as either non-threatening or deserving of additional astrometric attention. For any possibly threatening object, the dominant issues are the uncertainty in its trajectory and physical nature as well as what can be done to reduce that uncertainty. Morrison *et al.* (2002) note that, "From the standpoint of an allocator of society's resources, an uncertain threat calls for adaptive policies, delaying potentially costly action but informing later decision by investing in uncertainty-reduction measures. In the context of the NEO impact hazard, this means avoiding the costs of standing organizational structures and capital expenditures until a threat materializes...." Thus reduction in uncertainty is tantamount to ensuring that unnecessary costs are avoided and that necessary actions are undertaken with adequate warning.

Groundbased radar is a knowledge-gathering tool that is uniquely able to shrink uncertainty in NEO trajectories and physical properties. The power of radar stems largely from the precision of its measurements **(Table 1)**. The resolution of echoes in time delay (range) and Doppler frequency (radial velocity) is often of order 1/100 the extent of a km-sized target so several thousand radar image pixels can be placed on the target. Delay-Doppler positional measurements often have a fractional precision finer than 1/10,000,000, comparable to sub-milliarcsecond optical astrometry.

The single-date signal-to-noise ratio (SNR) of echoes, a measure of the number of useful imaging pixels placed on a target by a given radar data set, depends primarily on the object's distance and size. **Figure 1** shows nominal values of SNR for Arecibo and Goldstone. Notwithstanding the heroic efforts by Zaitsev and colleagues in Russia and several intercontinental asteroid radar demonstrations involving Goldstone or Arecibo transmissions with reception of asteroid echoes in Japan, Spain and Italy, the world's only effective NEO radars are at Arecibo and Goldstone. However, given the historical funding difficulties experienced by those two systems (Beatty, 2002), the future of radar astronomy cannot be taken for granted. Time will tell whether the U.S. will opt to maintain, much less improve, the current Arecibo and Goldstone radar telescopes.

In this chapter, we examine how our current radar capabilities might help at each stage of detecting and mitigating an impact hazard encountered during this century. See Ostro (1995) for a discussion of radar's role in hazard mitigation written a decade ago, Ostro *et al.* (2002) for a comprehensive review of asteroid radar astronomy, and Harmon *et al.* (1999) for a review of comet radar astronomy.

Table 1. Precision of NEA Radar Measurements[a]

	Range (m)	Radial Velocity (m/s)
Best radar resolution	~10	~0.0001
Asteroid "size"	~1,000	0.01 to 1
Asteroid "location"	~10,000,000	~10,000

[a]The optimal resolution of radar measurements of the distribution of echo power in time delay (range) and Doppler frequency (radial velocity) for observations of a large NEA is compared with the scale of the object's delay-Doppler extent and location.

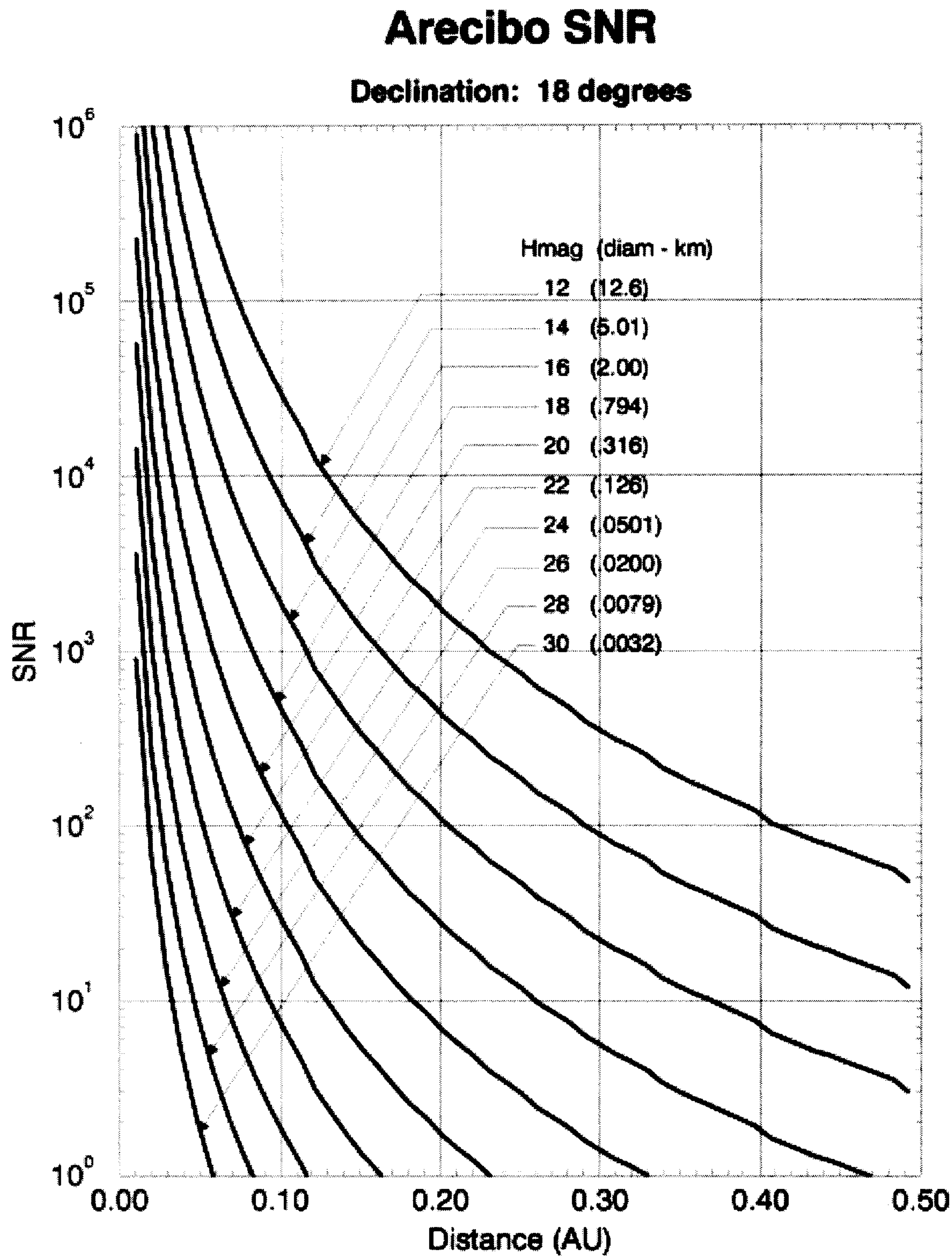

Fig.1a. Predictions of the single-date signal-to-noise ratio (SNR) for Arecibo echoes from asteroids at declination 18°, as a function of the target's distance and absolute visual magnitude (converted to diameter by assuming an S-class optical albedo). Assumptions include a 10% radar albedo, an equatorial view, a 4-hour rotation period, and optimal values for system parameters. Plots for other declinations and distances are on line (Ostro, 2003).

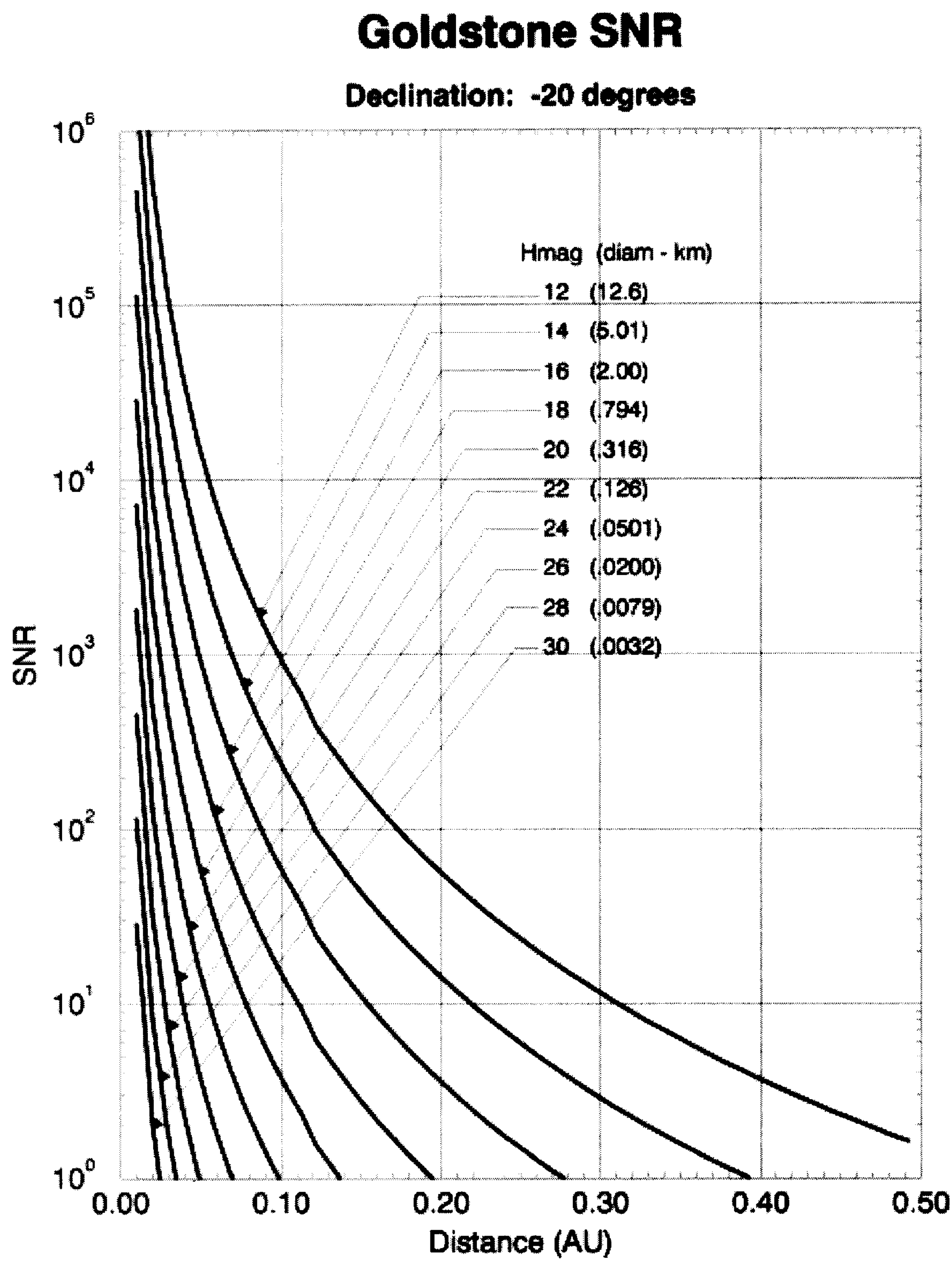

Fig.1b. Predictions of the single-date signal-to-noise ratio (SNR) for Goldstone echoes from asteroids at declination -20°, as a function of the target's distance and absolute visual magnitude (converted to diameter by assuming an S-class optical albedo). Assumptions include a 10% radar albedo, an equatorial view, a 4-hour rotation period, and optimal values for system parameters. Plots for other declinations and distances are on line (Ostro, 2003).

2. Post-discovery astrometric follow-up

The first asteroid radar astrometry was obtained in 1968 (for 1566 Icarus; Goldstein, 1968; Pettengill *et al.*, 1969), but the potential of delay-Doppler measurements for small-body orbit refinement was not examined comprehensively until a series of Monte Carlo simulations were carried out by Yeomans, Ostro and Chodas (1987). They showed that a single radar detection of a newly discovered NEA shrinks the instantaneous positional uncertainty at the object's next close approach by orders of magnitude with respect to an optical-only orbit, thereby preventing "loss" of the object. At this writing, there are 475 Potentially Hazardous Asteroids (PHAs, defined as having a Minimum Orbit Intersection Distance with the Earth $\leq$0.05 AU and absolute magnitude H $\leq$ 22), and 41% of them are lost in the sense that the three-standard deviation uncertainty in the time of the next close-approach exceeds +/- 10 days, corresponding roughly to a sky pointing angle uncertainty greater than 90°.

The Yeomans *et al.* (1987) conclusions have been substantiated quantitatively by comparison of residuals for radar+optical and optical-only positional predictions for recoveries of NEAs during the past decade (**Table 2**). Furthermore, radar astrometry can significantly reduce ephemeris uncertainties even for an object whose optical astrometry spans many decades. For example, Arecibo radar measurements of 1862 Apollo (Ostro *et al.*, 1991) showed that the object's optical-only orbit, consisting of 49 years of data, had a range error of 3750 km $\pm$ 2 km. (See also the discussion of 1950 DA below.)

The reduced uncertainties of a radar orbit can also permit recovery at fainter magnitudes. For example, 1998 ML14 was recovered (**Table 2**) at magnitude 21.2 only 0.5 arcseconds from the position predicted from a radar+optical orbit.

For NEAs observed only during their discovery apparition, one can predict the uncertainty in the location during the next opportunity for optical observation, and hence the area of the sky for a search having a given likelihood of success. **Table 3** lists the total sky area for the three-standard-deviation orbit-determination uncertainties mapped onto the sky at the next favorable Earth-based recovery date (which we define as the next time when the apparent visual magnitude exceeds 20 during reasonable sky-brightness conditions) for both an optical-only orbit and a radar+optical orbit, for seven NEAs. Radar obviously shrinks the required area, dramatically facilitating recovery. For seven other objects in the table, the optical-only and radar+optical orbits are so different that the nominal recovery dates are months or years apart. Since the radar+optical solutions would be expected to be the more accurate, reliance on an optical-only solution would be unlikely to lead to recovery.

Table 2. Residuals for Past NEA Recoveries[a]

Object	Recovery Date	O	R	O/R
1989 PB (4769 Castalia)	May 1990	24"	0.4"	60
1991 AQ	Sep 1994	57	0.1"	380
1986 DA (6178)	Oct 1994	56"	0.9"	60
1991 JX (6489 Golevka)	Mar 1995	3600"	4.6"	780
1989 JA (7335)	Oct 1996	196"	99.3"	2
1986 JK (14827)	Apr 2000	114"	0.1"	910
1998 ML14	Nov 2002	125"	0.5"	250

[a]Here O shows the residual (the observed position at recovery minus the predicted position) based on a pre-recovery orbit solution that incorporated only optical astrometry, R shows the residual for a pre-recovery orbit solution that used radar as well as optical astrometry, and O/R is the ratio of residuals for the two cases.

Table 3. Search areas for future NEA recoveries

Object	Most Favorable Earth-based Recovery Date	Optical orbit recovery	Data Span (days)	Astrometry opt	dop	dly	Gap yrs	Search area ($arcsec^2$) O	R	O/R
1990 OS	Nov 20 2003	(Jun 2003)	13	26	2	0	13	-	4.8E6	-
1996 JG	Nov 26 2003	~	20	265	3	3	7	1.5E5	310	484
2000 EH26	Jun 24 2005	~	140	47	4	2	5	47808	1055	45
2002 FD6	Sep 23 2006	~	15	556	2	4	4	3.9E5	146	2671
2002 BM26	Dec 20 2006	(2003)	87	218	2	2	4	-	294	-
2000 UG11	Oct 24 2008	(2025)	19	395	1	2	8	-	70	-
2001 AV43	Nov 03 2013	~	54	44	1	0	12	9.9E5	1.4E5	7
2002 FC	Jul 08 2021	~	137	191	3	1	19	14297	35	408
1998 KY26	May 31 2024	~	11	211	2	2	26	33534	786	43
2000 RD53	Oct 15 2031	~	102	322	5	4	31	89005	6	14834
2002 AV	Jan 25 2033	(2036)	39	210	3	2	31	-	816	-
2000 LF3	May 31 2046	(2090)	13	67	4	1	46	-	1.1E5	-
1999 TY2	Oct 03 2064	(2091)	5	115	1	0	65	-	2.3E6	-
2001 FR85	Mar 09 2081	(2082)	7	36	3	1	80	-	9.5E4	-

[a]The objects listed above were observed optically and with radar over a single apparition. We estimated optical-only and radar+optical orbit solutions and used the radar+optical orbit to determine a likely recovery date, defined as the next time when the apparent visual magnitude first exceeds 20 under reasonable sky brightness conditions. Column (R) lists the area of the three-sigma uncertainty ellipsoid projected in the plane of sky for the radar+optical orbit. Column (O) lists the optical-only orbit uncertainties at the time of recovery for the seven cases in which the optical-only solution predicted a recovery date within one month of the radar+optical prediction. The ratio O/R for those cases have a mean of 2642, providing some indication of how much larger the three-sigma search region is with just optical data. For the seven other cases, the optical-only orbit would not allow for recovery of the asteroid at all, at the time predicted;, the year of recovery indicated by such optical orbit solutions is shown.

3. Window of predictability

A goal of the Spaceguard Survey is to provide as much warning as possible of any possibly dangerous approach to Earth of NEAs as large as a kilometer. However, since an orbit estimate is based on a least-squares fit to measurements of an asteroid's position over a small portion of its orbit, knowledge of the asteroids' future trajectory generally is limited by statistical uncertainties that increase with the length of time from the interval spanned by astrometric measurements. Trajectory uncertainties are greatest and grow most rapidly during close planetary encounters, as the steeper gravity field gradient differentially affects the volume of space centered on the nominal orbit solution within which the asteroid is statistically located. Eventually the uncertainty region grows so large enough, typically within the orbit plane and along the direction of motion, that the prediction becomes meaningless.

Current ground-based optical astrometric measurements typically have angular uncertainties of between 0.2 and 1.0 arcsec (a standard deviation of 0.5 to 0.6 arcsec is common), corresponding to tens or hundreds or thousands of km uncertainty for any given measurement, depending on the asteroid's distance. Radar can provide astrometry referenced to the asteroid's center of mass, with uncertainties as small as ~10 meters in range and ~1 mm/s in range rate. Since those measurements are orthogonal to plane-of-sky angular measurements and have relatively high fractional precision, they offer substantial leverage on an orbit solution and normally extend NEO trajectory predictability intervals far beyond what is possible with optical data alone.

Let us define the window of predictability as the interval over which an object's close approaches can be reliably known at the three-sigma level of confidence. **Table 4** lists optical-only and radar+optical predictability windows for all radar-detected PHAs. For objects observed only during their discovery apparition, radar has enlarged the total window of predictability (past and future) by an average factor of six, from 137 years for solutions based only on optical data to 804 years when radar was included in the orbit solution. On average, radar has added 240 more years to the window of accurate future predictions.

When radar astrometry is excluded from the 25 single-apparition PHA radar+optical orbit solutions, 40% cannot have their next close approach predicted within the adopted confidence level using only the single apparition of optical data. This is the same percentage seen in the total population of PHAs. Radar astrometry obtained in these cases adds an average of 330 years statistical confidence to their Earth encounter predictions, preventing them from being lost. For 2000 RD53, the extension is through the end of the millennium.

We see that a discovery-apparition orbit solution containing radar astrometry can be compared favorably to a multiple-apparition solution. As an example, 1998 ML14 is listed in both single and multiple apparition categories to show the effect of including the first 6 optical observations from the November 2002 recovery, which lengthened the data arc from seven months to five years and lengthened the optical-only total knowledge window from 364 to 1721 years. By comparison, during the discovery apparition, radar astrometry combined with optical data provided an interval of 1183 years. It required the recovery of 1998 ML14 at a future apparition before an optical-only solution yielded a prediction interval comparable to the discovery apparition combined with radar.

For multiple-apparition objects, radar does not significantly extend the interval, which often is terminated centuries from the present era by one or more close planetary approaches whose detailed geometry simply cannot be discerned by any present-day data type. Nevertheless, radar improves the accuracy of multi-apparition orbits. A prime example is 1950 DA: The same gross predictability bounds of (588,2880) exist whether or not radar is included in the multiple-apparition solution. However, including radar revealed a non-negligible impact potential in 2880 not apparent in optical solutions. This was because radar astrometry eliminated a bias in the optical data and reduced the 2880 uncertainty region by about 20% as compared to the optical only solution, resulting in the potential hazard detection (section 4.2).

In five of the 38 multi-apparition cases, radar astrometry actually reduced the interval of prediction, while seven cases were slightly extended. These disparate effects arise because the different nominal orbits for the optical and optical+radar solutions have slightly altered planetary encounter circumstances, so their uncertainty regions increase in different ways. The net effect of radar is to correct the length of the optically predicted interval, suggesting that if an optical orbit were to reveal a potentially hazardous close approach, it would be highly desirable to get radar astrometry to check the prediction.

Table 4. Earth close-approach prediction intervals for radar-detected PHAs[a]

Single apparition objects

Object	Astrometry opt	dop	dly	days	Earth CA Prediction Intervals (A) Optical-only span	yrs	(B) Radar+Optical span	yrs	R-O	Re-Oe	R/O
2000 CE59	163	2	3	210	1609-2601	992	1547-2703	1156	164	102	1.2
2002 SY50	522	2	5	72	1896-2051	155	1862-2071	209	54	20	1.3
1999 RQ36	210	1	3	208	1895-2060	165	1848-2080	232	67	20	1.4
1998 KY26	211	2	2	11	1959-2024	65	1959-2099	140	75	75	2.2
2000 QW7	850	1	0	121	1902-2087	185	1755-2185	430	245	98	2.3
2000 EW70	286	6	3	16	1971-2069	98	1929-2209	280	182	140	2.9
2000 DP107	395	1	9	250	1847-2286	439	1066-2392	1326	887	106	3.0
2000 YF29	156	2	1	207	1932-2083	151	1642-2136	494	343	53	3.3
1998 ML14	243	6	6	214	1874-2238	364	1100-2283	1183	819	45	3.3#
2002 NY40	1441	5	2	35	1997-2049	52	1849-2081	232	180	32	3.5
2001 JV1	129	2	1	134	1874-2168	294	1266-2382	1116	822	214	3.8
2001 GQ2	323	2	1	15	1997-2084	87	1626-2100	474	387	16	5.5
2002 AY1	34	1	2	7	1848-2167	319	428-3034	2606	1842	867	8.2
2001 CP36	126	2	2	8	1972-2004	32	1628-2280	652	620	276	20.4
2002 VE68	196	4	0	15	1994-2010	16	448-2653	2205	2189	643	137.8
1990 OS	26	2	0	13	1990-1990	1	1966-2212	246	245	222	- (246)
2002 FD6	277	2	4	15	2002-2002	1	1862-2161	299	298	159	- (299)
2000 EH26	47	4	2	140	2000-2000	1	1806-2106	300	299	106	- (300)
1996 JG	265	3	3	20	1996-1996	1	1851-2180	329	328	184	- (329)
2000 UG11	395	1	2	19	2000-2000	1	1812-2142	330	329	142	- (330)
2000 LF3	67	6	1	14	2000-2000	1	1583-2046	463	462	46	- (463)
2002 BM26	218	2	2	87	2002-2002	1	1757-2312	555	554	310	- (555)
2002 AV	210	3	2	39	2002-2002	1	1626-2702	1076	1075	700	- (1076)
2000 RD53	322	5	4	102	2000-2000	1	1756-3023	1267	1267	1023	- (1267)
2002 FC	191	3	1	137	2002-2002	1	73bc-2415	2489	2488	413	- (2489)
Mean(25):						137		804	+649	+240	

Multiple-apparition objects

Object	Astrometry opt	dop	dly	days	Earth CA Prediction Intervals (A) Optical-only span	yrs	(B) Radar+Optical span	yrs	R-O	Re-Oe	R/O
4769 Castalia	122	7	7	13	1101-2837	1736	1043-2516	1474	-262	-321	0.8
1620 Geographos	1548	4	3	51	944-3188	2244	915-2900	1985	-259	-288	0.9
35396 (1997 XF11)	428	0	5	13	1627-2155	528	1627-2102	475	-53	-53	0.9
5604 (1992 FE)	162	0	3	17	1418-2184	766	1488-2156	668	-98	-28	0.9
6489 Golevka	686	30	26	9	1518-2706	1188	1621-2706	1085	-103	0	0.9
1998 ST27	287	1	3	3	1713-3775	2062	1690-3680	1990	-72	-95	1.0
25143 (1998 SF36)	628	6	10	3	1852-2170	318	1852-2170	318	0	0	1.0
4660 Nereus	371	2	11	21	1827-2166	339	1827-2166	339	0	0	1.0
7482 (1994 PC1)	268	2	0	28	1842-2361	519	1842-2361	519	0	0	1.0
2000 EE104	319	3	0	3	1638-2351	713	1638-2351	713	0	0	1.0
2201 Oljato	187	4	0	70	1666-2392	726	1666-2392	726	0	0	1.0
2002 HK12	516	1	0	17	1504-2299	795	1504-2299	795	0	0	1.0
33342 (1998 WT24)	736	1	6	3	1751-2675	924	1751-2675	924	0	0	1.0
1991 AQ	84	3	5	10	1786-2731	945	1786-2731	945	0	0	1.0
13651 (1997 BR)	439	1	0	20	1693-2768	1075	1693-2768	1075	0	0	1.0
4183 Cuno	495	0	1	16	>1403-2481	1078	>1403-2481	1078	0	0	1.0
23187 (2000 PN9)	295	2	1	12	>993-2325	1332	>993-2325	1332	0	0	1.0
6037 (1988 EG)	266	4	4	13	1412-2771	1359	1377-2771	1394	35	0	1.0
2101 Adonis	54	5	0	66	1244-2609	1365	1209-2609	1400	35	0	1.0
1998 ML14	249	6	6	4	562-2283	1721	562-2283	1721	0	0	1.0#

10115 (1992 SK)	217	2	8	46	932-2683	1751	932-2683	1751	0	0	1.0
9856 (1991 EE)	103	1	3	10	781-2567	1780	781-2567	1780	0	0	1.0
1999 KW4	1624	0	2	3	1145-2929	1784	1127-2929	1802	18	0	1.0
7335 (1989 JA)	137	5	0	12	1362-3219	1857	1362-3219	1857	0	0	1.0
29075 (1950 DA)	223	5	8	51	>588-2880	2292	>588-2880	2292	0	0	1.0*
22753 (1998 WT)	209	1	3	47	116-2562	2446	116-2565	2449	3	3	1.0
26663 (2000 XK47)	149	2	2	27	>71bc-2397	2469	>71bc-2397	2469	0	0	1.0
1566 Icarus	624	11	0	53	1206-3803	2597	1206-3803	2597	0	0	1.0
14827 (1986 JK)	159	11	0	14	249-2959	2710	249-2959	2710	0	0	1.0
1999 JM8	408	5	3	13	811-3988	3177	811-3988	3177	0	0	1.0
7822 (1991 CS)	212	4	0	11	305bc-2840	3146	305bc-2884	3191	45	44	1.0
7341 (1991 VK)	398	1	1	11	501-3797	3296	398-3797	3399	103	0	1.0
1862 Apollo	283	8	4	71	1848-2351	503	1788-2362	574	71	11	1.1
8014 (1990 MF)	60	10	6	8	1568-2313	745	1568-2371	803	58	58	1.1
4179 Toutatis	1105	27	19	68	1221-2069	848	1117-2069	952	104	0	1.1
4953 (1990 MU)	95	2	0	27	>1519-3123	1604	>1519-3271	1752	148	148	1.1
3757 (1982 XB)	85	2	0	20	1184-2673	1489	1005-2673	1668	179	0	1.1
1981 Midas	96	1	0	26	1237-3122	1885	1011-3122	2111	226	0	1.1
Mean (38)						1529		1534	+5	-14	

[a]For each PHA we give the time-span over which a numerically integrated orbit solution (along with its variational partial derivatives) based only on optical data can predict Earth close-approaches when compared to an independent solution that also includes radar astrometry. Prediction intervals are bounded *either* by the first Earth approach ≤ 0.1 AU for which the three-sigma linearized uncertainty in the time of closest approach epoch exceeds ± 10 days *or* by the first Earth approach for which the three-sigma approach distance uncertainty at the nominal encounter time exceeds 0.1 AU, whichever occurs first. These uncertainties are based on a mapping of the measurement covariance matrix in which the higher-order non-linear terms in the integrated variational partials are neglected. Thus, in a few cases, nonlinearities due to a particularly close approach may not be immediately detected. The first four columns give the numbers of optical, Doppler, and delay measurements, and the span of time they cover. Optical-only (O) and radar+optical (R) reliable prediction date intervals are given (the actual date range as well as the number of years spanned). R-O is the difference between the radar+optical and optical-only intervals. Re-Oe is the difference in the final year of the interval; it indicates how many additional years into the future radar can predict close approaches accurately. R/O is the ratio of the total span of years for the two solutions. Integrations were performed using the DE406/408 planetary ephemeris and include relativistic perturbations due to the Sun, planets, and Moon as well as asteroids Ceres, Pallas and Vesta. Whereas this table indicates the relative effect of radar astrometry, the limits of predictability for objects having multiple planetary encounters over centuries will normally be affected by additional factors such as radiation pressure, Yarkovsky acceleration, planetary mass uncertainties and asteroid perturbations will normally determine. These factors are not included here, since the precise models are unknown and key parameters are unmeasured.

4. Radar and collision probability prediction

For newly discovered NEOs, a collision probability is now routinely estimated (Milani *et al.*, 2002) for close Earth approaches. This probability is combined with the asteroid's estimated diameter and the time until the approach to rate the relative degree of hazard using the Palermo Technical Scale (Chesley *et al.*, 2002). JPL's Sentry program maintains a "risk page" (Chesley, 2003) that lists objects found to have an impact probability > 10^{-6} within the next 100 years. For newly discovered objects, the limited number of initial astrometric observations typically do not permit accurate trajectory prediction. Often, when an object's optical astrometric arc is only days or weeks long, the orbit is so uncertain that a potentially hazardous close approach cannot be distinguished from a harmless one or even a non-existent one. The object is placed on the Sentry page, then removed later, when more optical data are obtained. However, almost as a rule, objects on the Sentry page have not been observed with radar. The sole exception, 2001 AV43, has a single Doppler measurement and presents an extremely favorable radar opportunity in 2013, long before the 2066 close approach that Sentry assigns an impact probability of 6×10^{-7}.

4.1. A simulated impact scenario

It is highly likely that if an asteroid is on collision course with Earth, this fact will be recognized much sooner with radar data than without it. To examine the possible progression of optical-only and radar+optical impact probability estimates prior to a collision, we constructed a simulation as follows.

First, from the set of statistically possible trajectories for 2002 SM, we selected an Earth-approaching orbit that had a possible approach to about two Earth radii from Earth in 2028, a 1994 approach to Earth when it could have been discovered, and two post-discovery periods of visibility. We altered that orbit to change the 2028 close approach into an impact. We adopted an absolute magnitude, H = 19, corresponding to a diameter between 420 and 940 meters and yielding a discovery-apparition peak brightness of magnitude 14. Thirteen years after discovery, the asteroid brightens to magnitude 19, so recovery would be possible. Subsequent additional observing opportunities exist, but are less favorable since the object does not again get brighter than 20th magnitude until nine weeks before impact. Radar observations would be possible during the discovery apparition, but then not again until two weeks days prior to impact. **Table 5** gives the impacting orbit and **Table 6** lists observing opportunities.

We then simulated optical astrometry using the impacting reference trajectory and a Gaussian residual noise model in which the residual mean and standard deviation for each reporting site's astrometry was based on the actual observing results for 1994 AW7. We simulated radar data for Arecibo and Goldstone using the predicted SNRs to determine observing windows and potential measurement accuracy, adjusting the astrometry to emulate the residual statistics for previous radar campaigns.

Table 7 shows the impact probability that would be predicted for each of several cases with different amounts of discovery-apparition radar astrometry. A typical optical campaign at discovery (case B) does not show an unusual impact risk after 50 days of observations. However, if just two radar measurements are made ten days after discovery (case C), the likelihood of a very close approach immediately becomes evident, along with a non-negligible impact probability. Comparison of cases A and C reveals that after the first two radar measurements, the volume of the uncertainty region is nine orders of magnitude smaller with the radar+optical orbit than with the optical-only orbit.

At the conclusion of case B's 50-day observing window, a 0.027% impact probability is indicated by the optical-only solution. This is noteworthy, but not unusual for single-apparition objects -- there currently are four objects on the Sentry Risk Page with a comparable impact probability. However, with the radar astrometry (case F), a 19% impact probability is indicated at the same point in time. Radar reduces the volume of the uncertainty region at the encounter by five orders of magnitude compared to the optical-only case B. A 19% impact probability would attract additional resources and would extend the window of optical observability several months, down to at least magnitude 22 (case G). Ironically, in that case, the additional optical data moves the solution's nominal close-approach slightly further away from the Earth, decreasing the impact probability estimate.

If instead there is no radar data at the discovery apparition, recovery would probably still occur during the optically favorable apparition 13 years after discovery. If so, two such apparitions of optical data conclusively identify the impact event whether or not radar data is available (cases H and I), although the radar data reduces the volume of the uncertainty region by a factor of 29 compared to a solution based only on two apparitions of optical data. However, if the recovery does not occur, the next good opportunity to recover the object and clarify the impact risk, or perhaps to first become aware of it, would be two months prior to impact. Radar data during the discovery apparition guarantees the recovery by clearly indicating a high impact risk immediately, providing 34 years of warning instead of 21 years (or possibly only a few weeks).

Table 5. Simulated impacting orbit

```
ORBIT (heliocentric J2000.0 ecliptic elements):

 Impacts Earth surface: 2028-Mar-30 15:51:38.5000 (CT)
 Impact relative speed: 17.26 km/s

EPOCH = 1994-Mar-05 00:00:00.0000 = 2449416.5 JD (CT)
   EC =       0.50990174495185
   QR =       0.93177704136264
   IN =      15.587556441422
   OM =      10.5543473199928
    W =     215.77334777809
   TP = 2449468.8313169

    H =      19.0
    G =       0.15
```

Table 6. Observing opportunities for the simulation

Years Since Discovery	Date		Visual Brightness (mag)	Radar SNR	Comments
0	1994	Mar 10	16.7	-	Optical discovery
		Mar 20	15.1	532	Arecibo start
		Mar 27	14.0	17791	Last day in Arecibo window
		Mar 28	14.3	1064	Goldstone start
		Mar 30	15.2	455	Goldstone stop
		Apr 30	19.5	-	Last optical data (no impact detection)
		Oct 14	22.0	-	Last optical data (if impact detection)
13	2007	Apr 19	20.0	-	Optical recovery
		Jul 17	19.0	-	Peak brightness
		Oct 15	22.0	-	Last optical data (impact detection)
20	2014	Dec 21	21.6	-	
21	2015	Feb 21	20.0	-	Peak brightness
		Oct 14	22.0	-	
34	2028	Jan 22	20.0	-	Optical recovery
		Mar 16	16.0	15	Goldstone detection possible
		Mar 30	9.5		
		12:49:56	6.0		Dark-sky naked eye visibility
		14:01:13	5.0		
		14:45:55	4.0		
		15:12:39	3.0		
		15:29:47	2.0		
		15:40:14	1.0		
		15:46:32	0.0		
		15:50:16	-1.0		
		15:51:38	-		Surface impact

Table- 7. Simulation cases and results[a]

Cases

Discovery apparition only

Description	Data span 1994 – 1994	Optical	Delay	Doppler	n-RMS
A) Optical data only	Mar 10 - Mar 21	57	0	0	0.65
B) Optical data only	Mar 10 - Apr 30	158	0	0	0.74
C) Optical & initial radar	Mar 10 - Mar 21	57	1	1	0.65
D) Optical & initial radar	Mar 10 - Apr 30	158	1	1	0.73
E) Optical & all radar	Mar 10 - Apr 01	127	11	7	0.70
F) Optical & all radar	Mar 10 - Apr 30	158	11	7	0.73
G) Optical & all radar	Mar 10 - Oct 16	229	11	7	0.75

Discovery apparition plus recovery apparition 13 years later

Description	Data span 1994 – 2007	Optical	Delay	Doppler	n-RMS
H) 2 appar optical only	Mar 10 - Oct 15	313	0	0	0.65
I) 2 appar optical & radar	Mar 10 - Oct 15	313	11	7	0.66

Results

Nominal Date (Disc. + 34 y)	± minutes	NomDist AU	MinDist AU	MaxDist AU	N-sigs	Volume (km^3)	Prj Area (km^2)	Impact Probability Linear	Impact Probability Nonlinear
A) May 23.57393	± 1.0E6	0.237217	0.203725	2.771532	15902	1.3E+17	6.0E+13	0.00000	0.00002
B) Apr 10.07787	± 86217	0.081599	0.010467	1.364941	266000	1.8E+10	1.1E+09	0.00000	0.00027
C) Mar 30.40767	± 671	0.002550	0.000000	0.007037	1.6707	9.6E+08	6.0E+07	0.00694	0.00679
D) Mar 30.73868	± 172	0.000620	0.000001	0.001759	1.5278	1.6E+07	2.0E+06	0.02919	0.02763
E) Mar 30.61238	± 107	0.000554	0.000001	0.001267	2.1537	1.2E+06	1.6E+06	0.01130	0.01113
F) Mar 30.65632	± 87	0.000104	0.000001	0.000679	0.3228	6.2E+05	9.1E+05	0.19110	0.19430
G) Mar 30.64146	± 60	0.000261	0.000001	0.000659	1.6603	3.2E+05	6.1E+05	0.04231	0.03781
H) Mar 30.66428	± 0.22	0.000001	0.000001	0.000001	0.0000	26301	1750	1.00000	-
I) Mar 30.66426	± 0.20	0.000001	0.000001	0.000001	0.0000	894	1433	1.00000	-

[a]For each case in our simulation, the top part of the table indicates the number of optical and radar astrometric measurements and their date span, and the normalized r.m.s. residual. In the "results" section at the bottom, the first columns give the encounter time and its three-sigma uncertainty. NomDist is the solution's nominal (highest probability), numerically integrated Earth approach distance on the given date. MinDist and MaxDist are the minimum and maximum (three-sigma) approach distances from the linearized covariance mapping. N-sigs is the number of standard deviations required for the mapped covariance ellipsoid to intersect the surface of the Earth. The next columns give the volume of the three-sigma uncertainty region and the area it projects into a plane perpendicular to the impactor's velocity vector at encounter. The last columns give the impact probabilities computed by the linearized mapping method by the nonlinear method used by Sentry, JPL's automated hazard monitoring system. For probabilities greater than about 10^{-3}, linear and nonlinear calculations agree fairly closely.

4.3. Negative predictions, positive predictions, and warning time

To a great extent, the dominance of PHA trajectory uncertainties is a temporary one, an artifact of the current discovery phase. Predictions are made for single-apparition objects having a few days or weeks of measurements. The uncertainty region in such cases can encompass a large portion of the inner solar system, thereby generating small but finite impact probabilities that change rapidly as the data arc lengthens, or if high-precision radar delay and Doppler measurements can be made. Impact probabilities in such cases are effectively a statement that the motion of the asteroid is so poorly known that the Earth cannot avoid passing through the asteroid's large uncertainty region -- hence the apparent impact "risk". As optical measurements are made, the region shrinks. The resulting change in impact probability, up or down, is effectively a statement about where the asteroid won't be -- a "negative prediction" -- rather than a "positive prediction" of where it will be. This is due to the modest positional precision of optical measurements.

In contrast, radar measurements naturally provide strong constraints on the motion and hence "positive predictions" about where an asteroid will be decades and often centuries into the future. *Thus radar measurements substantially open the time-window of positive predictability.* However, within a couple decades, asteroids being found now (but unobserved by radar) will themselves have multiple optical apparitions and similarly be predictable in a positive way over centuries, as radar cases are now. In this way, orbit uncertainties for present-day radar cases illustrate what the situation will be by mid-century for most of the asteroids known today, and presumably for almost all PHAs as large as a kilometer.

Warning time is the key to mitigation, and long-term, positive prediction of close approaches enables low-energy deflection techniques. Depending on the interval between discovery and collision, radar might reduce a risk assessment from one of "urgent concern" to a leisurely, multi-generation engineering exercise. With centuries of warning, mitigation really would be indistinguishable from curiosity-driven science, becoming the driver for small-body exploration and eventually for human activity in space (Ostro and Sagan, 1998).

4.3. 1950 DA

At this writing, there is only one known NEO with a potentially significant possibility of collision. For 29075 (1950 DA), integration of the radar-refined orbit by Giorgini *et al.* (2001) revealed that in 2880 there could be a hazardous approach not indicated in the half-century arc of pre-radar optical data. The current nominal orbit represents a risk as large as 50% greater than that of the average background hazard due to all other asteroids from now through 2880, as defined by the Palermo Technical Scale (PTS value = +0.17). 1950 DA is the only known asteroid whose danger could be above the background level. During the observations, a radar time-delay measurement corrected the optical ephemeris's prediction by 7.9 km, changing an optical-only prediction of a 2880 close approach to a nominal distance of 20 Earth radii into a radar-refined prediction of a nominal distance of 0.9 Earth radii.

The uncertainty in the closeness of 1950 DA's 2880 approach and hence in the probability of a collision (which could be as low as zero or as high as 1/300) is due to a combination of the factors in **Table 8**. The dominant factor is the Yarkovsky acceleration, which is due to the anisotropic reradiation of absorbed sunlight as thermal energy and depends on the object's mass, size, shape, spin state, and global distribution of optical and thermal properties. Thus, unlike previous cases, predicting a potential 1950 DA impact with the Earth depends mostly on the asteroid's physical characteristics, not initial trajectory measurement. The accelerations are all small, but add up over time and are amplified by 15 close encounters with the Earth or Mars prior to 2880.

The 1950 DA example underscores the fundamental inseparability of the physical properties of NEAs and long-term prediction of their trajectories. The urgency of physically characterizing a threatening object naturally would increase as estimates of the collision probability rise and mitigation is transformed from a hypothetical possibility to an engineering requirement. If we take the hazard seriously, physical characterization of these objects deserves high priority.

Table 8. Sources of uncertainty in 1950 DA's position during the 2880 close approach[a]

Phenomenon	Relative max.along-track effect	
Galilean satellites	1.0	(3360 km, 4 min)
Galactic tide	2.5	
Numerical integration error	3.0	
Solar mass loss	4.0	
Poynting-Robertson drag	7.2	
Solar oblateness	12	
61 most perturbing "other" asteroids	447	
Planetary mass uncertainty	460	
Solar radiation pressure	3332	
Yarkovsky effect	21130	

[a]These factors normally are neglected in asteroid trajectory prediction. From Giorgini *et al.* (2002).

5. Physical characterization

5.1. Images and Physical Models

With adequate orientational coverage, delay-Doppler images can be used to construct three-dimensional models (e.g., Hudson *et al.*, 2000), to define the rotation state, and to constrain the internal density distribution. Even a single echo spectrum jointly constrains the target's size, rotation period, and subradar latitude. A series of Doppler-only echo spectra as a function of rotation phase can constrain the location of the center of mass with respect to a pole-on projection of the asteroid's convex envelope (e.g., Benner *et al.*, 1999). For objects in a non-principal-axis spin state, the hypothesis of uniform internal density can be tested directly (Hudson and Ostro, 1995). Given a radar-derived model and the associated constraints on an object's internal density distribution, one can use a shape model to estimate the object's gravity field and hence its dynamical environment, as well as the distribution of gravitational slopes on the surface, which can constrain regolith depth and interior configuration.

For most NEAs, radar is the only Earthbased technique that can make images with useful spatial resolution. Therefore, although a sufficiently long, multi-apparition optical astrometric timebase might provide about as much advance warning of a possibly dangerous close approach as a radar+optical data set, the only way to compensate for a lack of radar images is with a space mission.

5.2. Extreme Diversity

As reviewed by Ostro *et al.* (2002), NEA radar has revealed both stony and metallic objects, principal-axis and complex rotators, very smooth and extraordinarily rough surfaces, objects that must be monolithic and objects that almost certainly are not, spheroids and highly elongated shapes, objects with complex topography and convex objects virtually devoid of topography. **Figure 2** illustrates some of the diversity of NEAs. Obviously it is useless to talk about the physical characteristics of a "typical" PHA.

Fig. 2. Radar delay-Doppler images and shape models. The top collage shows radar images of (left to right) 1999 JM8 (Benner *et al.*, 2002a), Geographos (Ostro *et al.*, 1996), the binary 1999 KW4 (Ostro *et al.*, 2002), 1950 DA (Giorgini *et al.*, 2002), and Golevka (Hudson *et al.*, 2000). In the bottom collage of shape models, Toutatis (Hudson *et al.*, 2003) is at left and Bacchus (Benner *et al.*, 1999) is above the triptych that has (left to right) Castalia (Hudson and Ostro, 1994), the 1-km-diameter Nyx (Benner *et al.*, 2002b), and Golevka (Hudson *et al.*, 2000). The relative scale of the images and models is approximately correct.

5.3. Surface roughness and bulk density

Porous, low-strength materials are very effective at absorbing energy (Asphaug *et al.*, 1998). The apparently considerable macroporosity of many asteroids (Britt *et al.*, 2002) leads Holsapple to claim that impact or explosive deflection methods may be ineffective, even for a non-porous asteroid if it has a low-porosity regolith only a few cm deep: "That leaves the low force, long time methods. However, even in those cases the problems of anchoring devices to the surface may make them very difficult."

The severity of surface roughness would be of concern to any reconnaissance mission designed to land or gather samples. The wavelengths used for NEAs at Arecibo (13 cm) and Goldstone (3.5 cm), along with the observer's control of the transmitted and received polarizations, make radar experiments sensitive to the surface's bulk density and to its roughness at cm-to-m scales (e.g., Magri *et al.*, 2001). An estimate of the surface bulk density bounds estimates of the object's mass and can be taken as a safe lower bound on the subsurface bulk density, which provides a joint constraint on porosity and grain density. If an asteroid can confidently be associated with a meteorite type, then the average porosity of the surface can be estimated. Values of porosity estimated by Magri *et al.* (2001) for nine NEAs range from 0.28 to 0.78, with a mean and standard deviation of 0.53 ± 0.15. The current results suggest that most NEAs are covered by at least several centimeters of porous regolith, and therefore the above warning by Holsapple may be valid for virtually any object likely to threaten collision with Earth.

The fact that NEAs' circular polarization ratios (SC/OC) range from near zero to near unity (**Fig. 3**) means that the cm-to-m structure on these objects ranges from negligible to much more complex than any seen by the spacecraft that have landed on Eros (whose SC/OC is about 0.3, near the NEA average), the Moon, Venus, or Mars. 2101 Adonis and 1992 QN (Benner *et al.*, 1997) and 2000 EE104 (Howell *et al.*, 2001) are the extreme examples, with SC/OC near unity.

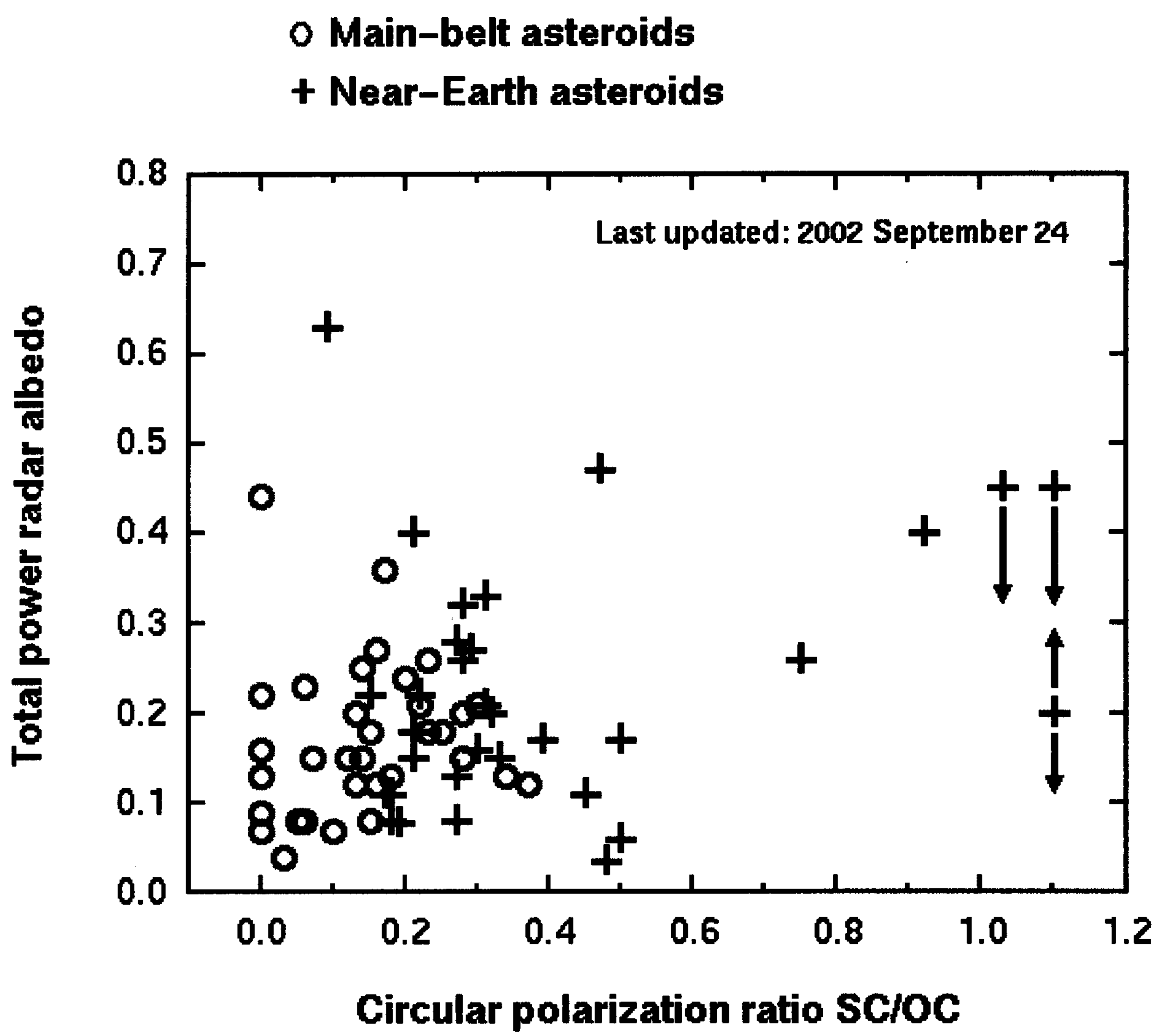

Fig. 3. Radar properties of NEAs and mainbelt asteroids.

Ostro *et al.* (2002) claim that an asteroid's SC/OC can be taken as a crude estimate of its rock coverage, that is, the fraction of the surface area covered by roughly wavelength-sized rocks. To what extent might the surface rock coverage be representative of the structural configuration inside the object? NEA surfaces apparently can have rock coverages anywhere from negligible to total, and NEA interiors apparently can lie anywhere in the Richardson *et al.* (2002) relative-tensile-strength-vs.-porosity parameter space. Is there any relation between the two? If so, then an object's radar properties may indicate possibilities for its interior and hence for mitigation options. If not, then those properties still constrain options for spacecraft surface operations.

5.4. Binary NEAs: mass and density

The most basic physical properties of an asteroid are its mass, its size and shape, its spin state, and whether it is one object or two. The current Arecibo and Goldstone systems are uniquely able to identify binary NEAs, and at this writing have revealed six (Margot *et al.*, 2002, and references therein; Nolan *et al.*, 2002), all of which are designated PHAs. Current detection statistics, including evidence from optical lightcurves (Pravec, 2003) suggest that between 10% and 20% of PHAs are binary systems.

Analysis of echoes from these binaries is yielding our first measurements of the PHA densities. Delay-Doppler images of 2000 DP107 (Margot *et al.*, 2002) reveal a 800-m primary and a 300-m secondary. The orbital period of 1.767 d and semimajor axis of 2620 $\pm$ 160 m yield a bulk density of 1.7 $\pm$ 1.1 g cm^{-3} for the primary. DP107 and the five other radar binaries have spheroidal primaries spinning near the breakup point for strengthless bodies. Whether binaries' components were mutually captured following a highly dispersive impact into a much larger body (Richardson *et al.*, 2002, and references therein) or formed by tidal disruption of an object passing too close to an inner planet (Margot *et al.*, 2002), it seems likely that the primaries are unconsolidated, gravitationally bound aggregates, so Holsapple's warning applies to them.

5.5. Radar investigations, mission design, and spacecraft navigation

Whether a PHA is single or binary, mitigation will involve spacecraft operations close to the object. Maneuvering near a small object is a nontrivial challenge, because of the weakness and complexity of the gravitational environment (Scheeres, Williams, and Miller, 2000). Maneuvering inside a binary system would be especially harrowing.

The instability of close orbits looms as a such a serious unknown that unless we have detailed information about the object's shape and spin state, it is virtually impossible to design a mission capable of autonomous navigation close to the object. If it turns out to be necessary to have a sequence of missions beginning with physical reconnaissance and ending with a deflection, then a radar-derived physical model would speed up this process, reduce its cost, decrease complexity in the design and construction of the spacecraft, and improve the odds of successful mitigation.

Ironically, although PHAs include the lowest-delta-V rendezvous targets in the solar system, a PHA rendezvous mission has yet to be launched. Japan's MUSES-C sample-return mission to 1998 SF36 is scheduled to become the first, with launch in mid 2003. Results of Arecibo and Goldstone imaging of that asteroid (Ostro *et al.*, 2001) are being used by the Japanese Institute of Space and Astronautical Science in planning for the late 2005 rendezvous, and radar observations during the asteroid's mid-2004 close approach will be used for navigational assistance and to refine the model derived from the 2001 images. Radar-derived shape models of small NEAs have made it possible to explore the evolution and stability of close orbits (e.g., Scheeres *et al.*, 1996, 1998), and this experience is currently being applied to SF36 and MUSES-C.

Control of a spacecraft operating in the vicinity of an asteroid requires knowledge of the asteroid's location, spin state, gravity field, size, shape and mass, as well as knowledge of any satellite bodies which could pose a risk to the spacecraft. Radar can provide information on all these parameters, enabling more complex missions. A reduced need for contingency fuel could be significant enough to allow a smaller launch vehicle for the mission. The result could save $100 million via a switch from a Titan III launch vehicle to a Titan IIS, or $200 million for a switch from a Titan IV to a Titan III.

Knowledge of the target's spin state as well as its shape (and hence nominal gravity harmonics under the assumption of uniform density; Miller *et al.*, 1999) would permit design of stable orbits immune to escape or unintended surface impact. Upon its arrival at Eros, the NEAR-Shoemaker spacecraft required almost two months to refine its estimate of the gravity field enough to ensure reliable close-approach operations.

Radar refinement of physical properties and radar refinement of orbits are fundamentally coupled -- shape modeling necessarily involves estimation of the delay-Doppler trajectory of the center of mass through the observing ephemerides. With adequate radar astrometry, a spacecraft lacking onboard optical navigation could be guided into orbit around, or collision course with, an asteroid. For example, consider how Goldstone observations shrunk the positional error ellipsoid of Geographos, an object already heavily observed by optical telescopes, just prior to a Clementine flyby of that target on Aug. 31, 1994 (Ostro, 1996). Before Goldstone ranging observations carried out during Aug. 28-29, the overall dimension of the positional error ellipsoid was ~11 km. The radar astrometry collapsed the ellipsoid's size along the line of sight to several hundred meters, so its projection toward Clementine on its inbound leg would have been 11 x 2 km. Goldstone-VLA radar aperture synthesis angular astrometry (see discussions by de Pater *et al.*, 1994, and Hudson *et al.*, 2000), could have shrunk the error ellipsoid's longest dimension to about 1 km, about half of Geographos' shortest overall dimension. For less well-observed objects, the gains could be substantially more, as with 1862 Apollo's 3750 km radar range correction.

A motivation for the Arlington meeting and these proceedings (Belton, 2003) is that it will take considerable learning time and practice to do mitigation effectively and reliably, and that it is strategically desirable to implement as soon as feasible a series of medium cost, competitively selected, NEO missions whose goals are to satisfy the scientific requirements for impact mitigation techniques. The ability of prior radar reconnaissance to reduce mission cost, complexity and risk was embraced by the Department of Defense in their design of the Clementine II multiple-flyby mission (Hope *et al.*, 1997), all of whose candidate targets either had already been observed with radar (Toutatis, Golevka) or were radar observable prior to encounter (1987 OA, 1989 UR).

5.6. Modeling the efficiency of explosive deflection

Mitigation scenarios include the use of explosives to deflect the projectile (Ahrens and Harris, 1992). However, as demonstrated by Asphaug *et al.* (1998), the outcome of explosive energy transfer to an asteroid or comet (via a bomb or a hypervelocity impact) is extremely sensitive to the pre-existing configuration of fractures and voids, and also to impact velocity. Just as porosity damps shock propagation, sheltering distant regions from impact effects while enhancing energy deposition at the impact point, parts of multi-component asteroids are preserved, because shock waves cannot bridge inter-lobe discontinuities. A radar-derived shape model would allow realistic investigation (Asphaug *et al.*, 1998) of the potential effectiveness of nuclear explosions in deflecting or destroying a hazardous asteroid.

5.7. Comets

The risk of a civilization-ending impact during this century is about the same as the risk of a civilization-ending impact by a long-period comet (LPC) during this millennium. At present, the maximum possible warning time for an LPC impact probably is between a few months and a few years. Comet trajectory prediction is hampered by optical obscuration of the nucleus and by uncertainties about nongravitational forces. Comets are likely to be very porous aggregates, so concern about the ineffectiveness of explosive deflection is underscored in the case of comets.

Radar reconnaissance of an incoming comet would be the most reliable way to estimate the size of the nucleus (Harmon *et al.*, 1999), could reveal the prevalence of centimeter-and-larger particles in the coma (Harmon *et al.*, 1989, 1997) and would be valuable for determining the likelihood of a collision. Readers can speculate about the course of developments once the possibility of an LPC impact is announced if radar observations can be conducted, and if they cannot.

6. Concluding remarks and recommendations

How much effort should be made to make radar observations of NEAs? For newly discovered objects, it is desirable to guarantee recovery and to ensure accurate prediction of close approaches well into the future, and at least throughout this century. Moreover, a target's discovery apparition often provides the most favorable radar opportunity for decades and hence a unique chance for physical characterization that otherwise would require a space mission. Similarly, even for NEAs that have already been detected, any opportunity offering a significant increment in echo strength and hence imaging resolution should be exploited. Binaries and NPA rotators, for which determination of dynamical and geophysical properties requires a long, preferably multi-apparition time base, should be observed extensively during any radar opportunity.

Construction of the proposed Large Synoptic Survey Telescope (LSST) has been endorsed (Belton *et al.*, 2002), in part as a means to extend the Spaceguard Survey's 90% completeness goal for km-sized objects down to 300-m objects. However, both Arecibo and Goldstone are already heavily oversubscribed, with only several percent of their time available for asteroid radar. Over the coming decades, it may become increasingly clear that most of the NEO radar reconnaissance that is technically achievable with Arecibo and Goldstone is precluded by the limited accessibility of those instruments, and that a dedicated NEO radar instrument is desirable.

An ideal NEO radar system (Ostro, 1997) might consist of two antennas like the 100-m NRAO Greenbank Telescope (GBT, in West Virginia), one with a megawatt transmitter and one just for receiving, separated by a few tens of kilometers, operating at a wavelength between 0.9 and 3.5 cm (Ka and X band). A two-antenna (bistatic) configuration would eliminate the frequent transmit/receive alternation and klystron power cycling required in single-antenna observations of NEOs. This dedicated NEO radar could be an order of magnitude more sensitive than the upgraded Arecibo telescope and, unlike Arecibo, would be fully steerable. The capital cost of building this system now, as calibrated by the GBT experience, would be within 10% of $180M, comparable to the cost of a small Discovery mission and very close to the estimated cost of the LSST.

Acknowledgment. This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).

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