Radar Astrometry of Small Bodies: Detection, Characterization, Trajectory Prediction, and Hazard Assessment

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1. Summary

Existing ground-based planetary radar sites provide unique centimeter and few-meter level measurements of the state and nature of small-bodies. Positional radar astrometry can reduce trajectory uncertainties several orders of magnitude, improving prediction, targeting, and impact probability estimates. Radar data can identify destinations of interest for future spacecraft missions, improving resource use. Commitment to maintain existing radar sites and increase the time used for small-body observations offers substantial, cost-effective science return, enhancing ground and flight investigations of small-bodies. This paper summarizes actual and potential planetary radar capabilities for small-body positional astrometry.

1.1 Introduction

The two existing ground-based planetary radar systems (the 430 kW, 70-m dish at Goldstone and the 900 kW, 305-m Arecibo site) have historically been found to:

(A) Extend by a factor of five the interval over which near-Earth object (NEO) motion and future close Earth approaches can accurately be predicted; from 80 years to 400 years, on average [1],

(B) Reduce NEO orbit solution uncertainties by five orders of magnitude for newly discovered objects (0.001% of pre-radar) [1],

(C) Significantly improve impact probability estimates relative to those based on optical astrometry only [2,3,4], generally identifying non-impacting objects given one radar measurement (the most recent example being 2009 DO111),

(D) Physically characterize potentially hazardous asteroids (PHAs), in some cases at levels comparable to a spacecraft flyby mission. In particular, radar can provide shape, spin-state, surface roughness, binary status (hence mass), taxonomic type, trajectory drift due to thermal re-radiation ("Yarkovsky effect"), and constraints on composition and internal structure [5,6,7,8,9,10]. Comets and large main-belt objects may also be characterized [11,12,13,14], although weaker echo strength due to distance can limit shape determination.

Radar reconnaissance can more quickly identify non-impacting cases, reducing the need for a mitigation effort, or better inform such an attempt, by dramatically reducing uncertainties prior to mission development. Spin-pole determinations possible with radar can be necessary for valid impact hazard estimation and long-term trajectory prediction for sub-km objects due to trajectory drift caused by radiation momentum transfer [2,3]. Radar is the only technique capable of directly imaging NEOs from the Earth or nearby space. The largest ground-based optical telescopes can, at best, barely resolve any NEO and this situation will continue for the foreseeable future.

Despite efforts by Zaitsev and colleagues in Russia, and several intercontinental asteroid radar demonstrations involving Goldstone or Arecibo transmitting for reception of echoes in Japan, Spain, and Italy, the world's only effective NEO radars are at Arecibo and Goldstone.

Having somewhat different capabilities, the Goldstone Solar System Radar (GSSR) and Arecibo Planetary Radar provide complementary data. Goldstone's steerable dish can provide higher range and frequency resolution coverage spanning 3 times the sky declination extent, over tracking periods 3 to 8 times longer than Arecibo. Arecibo's fixed dish, 20x larger in collecting area and radiating twice the power, can produce and receive fainter echoes from more distant objects, providing about twice the range depth of GSSR.

Both facilities are shared and heavily subscribed for purposes other than NEO radar observations, such as spacecraft communication and other science endeavors. This places limits on time available for radar targets. Historically, about 2% of the time at each site has been used for NEO observations.

Despite substantial and wide-ranging published results, a NSF sponsored Senior Review of current NSF astronomical facilities recommended a very significant reduction in the funding for the Arecibo Observatory starting in FY2011 [15]. The Review largely ignored the Observatory's unique radar capabilities. The recommendation will potentially result in the shut down of the planetary radar system unless alternative funding can be obtained.

JPL and on-site personnel who support GSSR's specialized antenna and transmitter operations have also been reduced from a staff of 17 (twenty years ago) to 7, having multiple single-point failures. Inadequate support and resulting equipment problems have led to cancellation of numerous radar observations at both sites even as interest in small-bodies grows rapidly. Robust, high-level prioritization by the planetary science community is necessary to inform institutional planning.

Analyses described below quantify the performance of existing radar systems and potential upgrades. The primary finding is that existing radar capabilities are grossly under-utilized for the NEO problem. This is the result of other priorities limiting observation time coupled with an over-all decline in funding for both sites. The most effective actions would be those that preserve existing sites and support the scheduling of more NEO observing time.

2. Analysis

2.1 Background

366 small-bodies have been detected by radar. Within this set, delay-Doppler astrometry has been obtained for 244 NEOs and PHAs as follows:

3.5%	…	of known NEOs
7.7%	...	of known NEOs > 1 km
12.6%	...	of known PHAs
25.5%	...	of known PHAs > 1 km

This history illustrates how radar naturally tends to access those cases of greatest general interest: large objects that most closely approach the Earth.

However, for objects at interplanetary distances, radar is a follow-up tool that requires targets be discovered optically. This is due to the narrow beam-width (~2 arc-minutes), rapid decrease in return echo-strength with range ($1/r^4$), and the time-delay of received echoes. Accurate a-priori tracking predictions (ephemerides) based on optical astrometry are required to integrate and detect the echo as it moves through frequency with the changing radar-to-target relative motion. Hence *searching* for new objects using radar is impractical.

After an object is discovered optically, it is assessed as a potential radar target based on visibility window, estimated echo signal-to-noise ratio (SNR), and site scheduling. Optical astrometry is accumulated and the orbit solution refined until plane-of-sky position uncertainties are small enough to assure antenna pointing can place the radar beam on the target.

During a radar experiment, delay-Doppler measurements along the line-of-sight (with

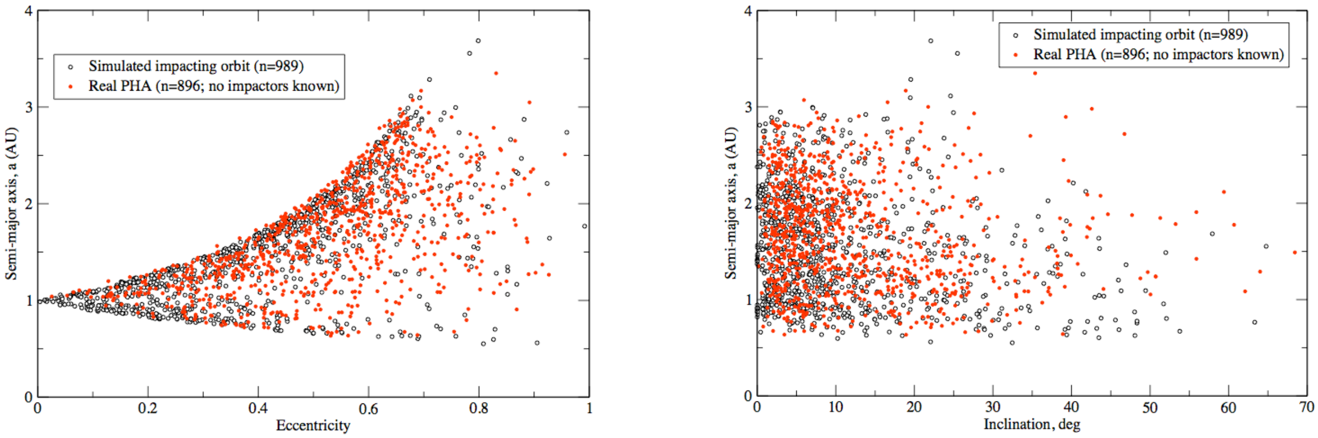

Figure #1: Comparing the synthesized PHA impacting orbits to known PHA orbits.

time-delay typically accurate to ~150-300 m and radial velocity to ~8 mm/s, but in some situations up to ~3.5 m and ~1 mm/s) are combined with *orthogonal* plane-of-sky optical angle measurements (right ascension and declination) reported by other observatories to refine the target's orbit solution.

Future trajectory and impact probability are estimated by extrapolating orbit solution position and uncertainties from a solution epoch to future times using numerical integration [16,17]. The accuracy of the estimates depends on dynamics over the time interval, properties of the measurement dataset, and associated uncertainties of both.

2.2 Simulation

To fully explore the capabilities of current and potential radar systems, a simulation was developed [4] using a representative, de-biased population of 989 simulated PHA orbits [18] intended to cover the range of possible orbits. A PHA orbit is defined as one that comes within 0.05 AU of the Earth's orbit.

All simulated objects were designed to impact the Earth at a known date. Figure #1 compares the synthesized impacting PHA orbits with the observed PHA orbits (which include no known impactors).

Starting 80 years prior to impact, each orbit was numerically integrated to impact. Objects having three diameters (700-m, 140-m, 70-m) were considered for each trajectory. Times during the 80-year interval when the object was detectable optically or by radar (after optical discovery) were identified, with the different size cases creating different visibility and detection scenarios for each orbit.

Optical and radar measurements were simulated according to rules (for radar) based on declination limits, site transmit power and frequency, antenna size, performance, and integration time, with radar detection being indicated if an SNR > 10 integrated over a single track was obtained. An object was deemed optically discovered when its apparent magnitude exceeded H_v=20 (given favorable sky-brightness circumstances at the time), with optical follow-up to H_v=22.

Fit statistics (orbit uncertainties), impact probability and SNR were computed as simulated optical and radar observations were added. The normal operations software was used for these calculations. Nine radar-upgrade configurations were considered, along with the current configuration and an optical-only control case for a total of 118,680 cases.

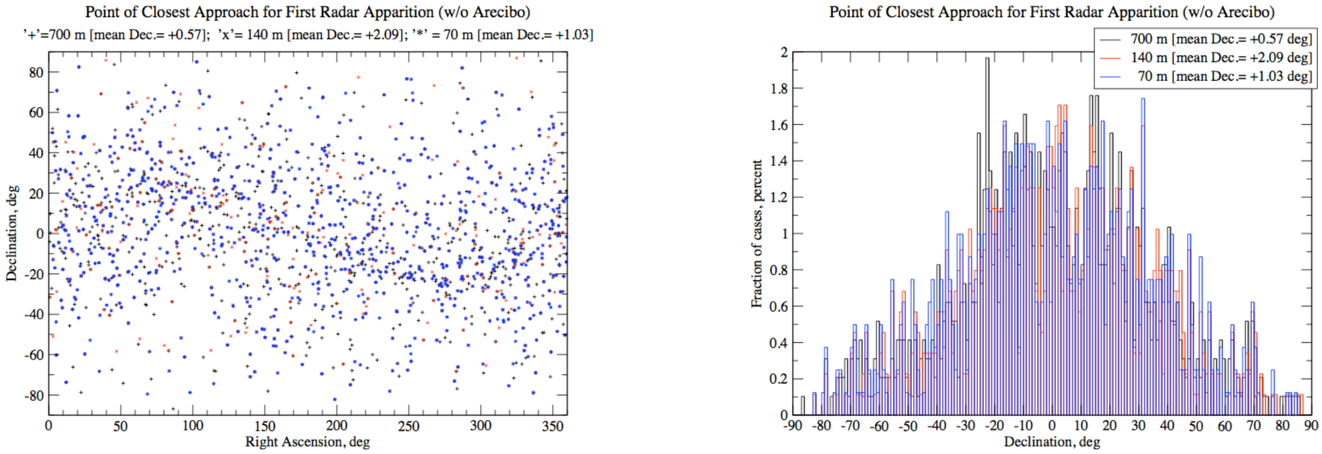

Figure #2: Plane-of-sky location at point of closest approach (maximum SNR)

2.3 <u>Study Results</u>

<u>Detectability</u>

All 700-m objects were optically discovered in the 80 years prior to impact. 1.7% of 140-m and 6.2% of 70-m objects were *not* discoverable prior to impact.

The Arecibo radar is capable of detecting 76-98% of discovered PHAs more than one year prior to impact. (The range is related to object-size, with the lower limit of 76% being the detection level for 70-m objects, 98% the detection level for 700-m objects, with 140-m objects being within the interval).

The current GSSR can detect 69-92% of discovered PHAs more than one year prior to impact, 99% prior to impact, if terminal approach is included. Doubling GSSR transmit power from 430 to 900 kW increases the detectable population by only 5%.

A hypothetical 70-m southern hemisphere radar site could also detect 69-92% of PHAs within 79 years. 1-5% of PHAs are detectable from a radar site in only one hemisphere during that time-span.

There is no significant north/south bias in Earth encounters, with right ascension and declination at the point of closest approach (maximum SNR) evenly distributed between the hemispheres, as shown in Figure #2.

An additional southern hemisphere site therefore does *not* greatly increase the detectable fraction of total NEO population, but does increase available observing time to 1.5-2x that of the current configuration, increases track length across an apparition (improving physical characterization), and provides access to a percentage of NEOs that are radar-visible prior to impact only in the southern hemisphere.

Loss of all radar capability reduces or eliminates warning, especially for the 7-23% of impactors that have only one optical observing opportunity more than a year prior to impact. Without radar, these cases have high potential for producing ambiguous estimated impact probabilities that cannot be clarified until just days prior to impact if at all.

A hypothetical "aggressive" radar program that sought to detect all detectable objects using current systems could uniquely clarify impact prediction for the 1-5% of detectable impactors that have just one optical and radar apparition.

Such a program would require 6 years of *cumulative* transmit-receive cycles ("equipment on time") over the next 80 years to detect all detectable NEOs with diameters greater than 140-m (assuming ~7500 objects). Current radar systems, operating at the present 2% usage rate, would require ~140 *calendar years* to assess the expected >140-m discoveries over the next 20 years. Current systems are thus operating at a rate ~7-60x less than the pace to keep up with predicted discoveries and fully assess NEO hazards.

Impact Warning Time

If "warning time' is defined to be the interval after discovery until impact probability first exceeds 50% (more likely to impact than not), radar astrometry from the present systems provides an average of 0.75 years earlier warning for 700-m objects, and 4 years earlier warning for 140-m objects, compared to predictions based only optical astrometry. The 50% warning level is usually reached during the NEO's second apparition. 30% of 140-m radar cases have a definitive impact warning within 6 months of discovery, compared to 4% if only optical astrometry is available.

Without Arecibo, time-to-warn for 700-m objects is increased 0.5 years on average (from 0.75 to 1.25 years), indicating Arecibo (due to greater range depth) provides ~67% of the impact warning improvement relative to optical data in the current system. For the smaller 140-m objects, time-to-warn increases 1-2 years without Arecibo. Thus GSSR (due to larger tracking window) contributes 50-75% of the impact warning time improvement for the more numerous smaller objects, the focus of future surveys.

Physical Characterization

Generally, Arecibo provides more high-resolution imaging cases due to greater receiver collecting area and transmitter power, while GSSR can provide finer spatial resolution for already high-SNR targets due to its higher Doppler frequency resolution and finer "chirp" delay resolution.

To quantitatively assess the ability of radar to characterize the physical properties of NEOs (valuable information for missions targeting an object and for assessing impact probability for smaller objects), science quality was rated based on maximum SNR in these categories:

Maximum SNR	Expected science
10 - 20	Minimal detection; delay-Doppler astrometry; surface polarization ratio,
20 - 100	+ low resolution shape
100 - 1000	+ moderate resolution shape
>1000	+ high resolution shape

Given these criteria, high-resolution physical characterization could be obtained for the NEO population having diameters greater than 140-m as tabulated below:

Scenario	Hi-res. cases % of pop.
Arecibo+DSN upgrades	22.1%
Current (GSSR@430kW+Arecibo)	21.8%
Arecibo alone	21.0%
DSN upgrades, no Arecibo	15.9%
GSSR@430 kW alone	13.4%

From this, it can be seen that an Arecibo shut-down, leaving the current GSSR system, would reduce by 46% the number of high-resolution imaging radar targets achievable. If all GSSR upgrades considered were then implemented, including a southern hemisphere site, there would remain a 33% decrease in high-resolution targets. That is, a new 70-m facility, funded by a different source, could not substantially compensate for the loss of high-resolution characterization capabilities at the NSF's Arecibo.

By contrast, if Arecibo remains and all DSN upgrades are made, only a 0.3% increase in the gross quantity of *high-resolution imaging* cases might be expected, although within that set, higher-power 900 kW DSN transmitters would provide somewhat improved quality of results, given the higher SNR obtained.

3. Conclusions:

From these analyses, recommendations are ranked below in order of priority, based on cost-effectiveness and performance:

(1) Ensure the maintenance and increased reliability of existing planetary radar sites. This retains the compelling ability to characterize some NEOs at levels comparable to a spacecraft flyby while improving trajectory prediction and hazard assessment. Radar may eliminate the need for future billion-dollar reconnaissance or mitigation missions, *or* identify exceptionally interesting targets that *warrant* a dedicated manned or unmanned mission. Either result improves use of resources. Maintaining a robust radar capability is cost effective and provides substantial science benefits.

(2) Increase small-body observing time at the two existing radar facilities. 15% or more time at existing sites could in principle keep up with the estimated future optical discovery rate of NEOs having a diameter greater than 140-m. This is the most effective improvement, but would require changes in institutional support. An increased level of activity would also likely require changes in observing approach. For example, increased and automated operations for targets having echo SNRs low enough that only minimal delay-Doppler astrometry could be obtained for improved orbit solution and hazard assessment.

(3) If (1) is implemented and (2) explored to the extent possible, a southern hemisphere 70-m radar site could further increase available NEO observing time, thus the number of pursuable targets by a factor of 1.5-2x. It would also increase the tracking time during a given apparition, thereby improving physical characterization, and access the ~1-5% of PHAs visible to radar only in the southern hemisphere prior to impact. The disadvantage is the high initial installation cost relative to actions (1) and (2); equipping the existing NASA DSN 70-meter facility at Canberra, Australia with radar is estimated to cost ~$16.5 million (FY2009) with $2.5 million/year operating costs [4].

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