Improved Impact Hazard Assessment with Existing Radar Sites and a New 70-m Southern Hemisphere Radar Installation

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1. Summary of Proposal

Add radar capability to the existing southern hemisphere 70-m Deep Space Network (DSN) site at Canberra, Australia, thereby increasing by 1.5-2x the observing time available for high-precision NEO trajectory refinement and characterization. Estimated cost: ~$16 million over 3 years, $2.5 million/year for operations (FY09).

1.1 Introduction

The two existing ground-based planetary radar transmitter sites (70-meter 500 kW Goldstone DSS-14 and 305-meter 1000 kW Arecibo) have historically been found to:

(A) Extend by a factor of five the interval over which 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 only on optical astrometry, reducing the unknowns (thus cost) of any mitigation effort [2,3,4],

(D) Physically characterize potentially hazardous asteroids (PHAs), in some cases at levels comparable to a spacecraft mission, providing shape, surface roughness, binary status, and constraints on composition and internal structure [5,6,7,8,9].

Such radar reconnaissance can allow one to more quickly distinguish between an impact trajectory and a near miss, reducing the need for a mitigation effort, or better informing such an attempt, by dramatically reducing uncertainties prior to mission development.

Goldstone Solar System Radar (GSSR) and Arecibo are complementary in obtaining such radar data. Goldstone's steerable dish provides higher range and frequency resolution coverage of 3 times the sky declination extent, over tracking periods 3 to 8 times longer, while 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 shared facilities are heavily subscribed for purposes other than NEO observations, such as spacecraft communication and other science endeavors. Historically, only about 2% of the time at each site has been made available for NEO observations.

Analyses described below were undertaken to further quantify radar performance and evaluate improvements to NEO operations possible with three potential upgrade scenarios: (1) Adding a third site in the southern hemisphere (70-m at 430 kW); (2) increasing DSS-14 transmit power from 430 kW to 900 kW; (3) increasing delay measurement accuracy from 0.125 μs to 0.026 μs.

The primary finding was that existing radar capabilities are grossly under-utilized for the NEO problem. The most effective upgrades would be those that enable more observing time at existing sites, or addition of a new radar capability at the existing 70-m DSN site in Canberra, Australia.

1.2 Analysis

1.2.1 Background

For the 239 radar-detected NEO's, delay-Doppler astrometry has been obtained for the following population fractions:

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

These results show radar naturally tends to access those cases of greatest interest: large objects that most closely approach the Earth.

However, radar is a follow-up tool that requires targets be discovered optically. This is due to the narrow beam-width (~1 arc-minute), 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 the frequency spectrum with changing radar-to-target relative motion.

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 pointing uncertainties are small enough for the radar beam-width.

During a radar experiment, delay-Doppler measurements along the line-of-sight (with time-delay typically accurate to ~150-300 m and radial velocity to ~8 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.

Impact probability is computed by extrapolating orbit solution position and uncertainties from a solution epoch to future times using numerical integration. Accuracy of such predictions depends on dynamics over the time interval, properties of the measurement dataset, and associated uncertainties of both.

1.2.2 Simulation

To explore all these issues, a simulation was developed [4] using a representative, de-biased population of 989 simulated PHA orbits [10] intended to cover the range of possible orbits. All simulated objects were designed to impact the Earth at a known date. Figure #1 compares the synthesized impacting PHA population with the observed PHA population (no known impactors).

Starting 80 years prior to each object's impact, three diameters (i.e., objects) for each dynamical orbit were numerically integrated to impact: 700-m, 140-m, 70-m. 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.

Fit statistics (covariance matrix), impact probability and SNR were computed as simulated optical and radar observations were added. 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.

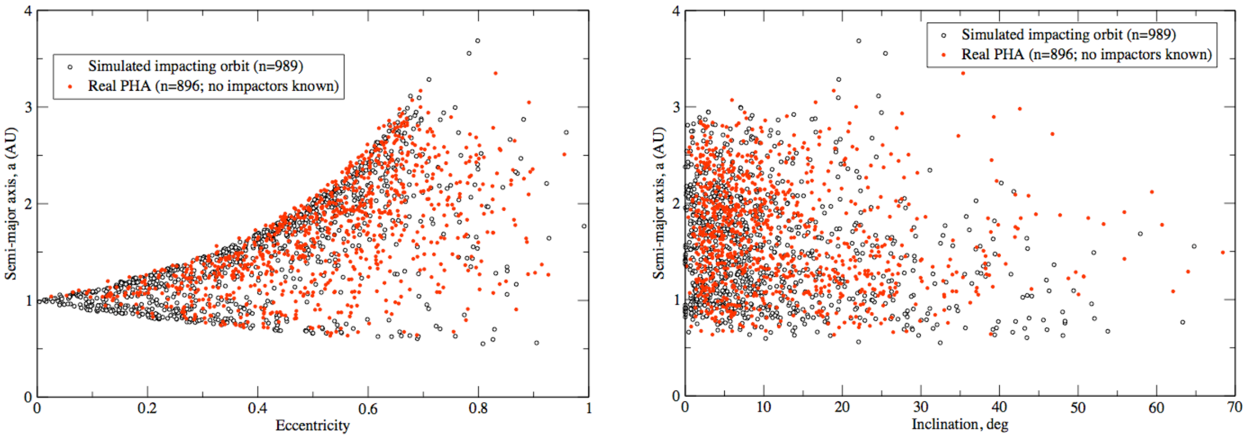

Figure #1: Comparing synthesized PHA impacting population to observed-PHA population.

<u>1.2.3 Study Results</u>

Detectability

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.

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 small 70-m objects, 98% the detection level for larger 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 +5%.

A new southern hemisphere radar site could also detect 69-92% of PHAs within 79 years. 1-5% of PHAs are uniquely detectable from a radar site in one hemisphere but not the other.

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

A new southern site therefore does *not* greatly increase the detectable fraction of total NEO population, but *increases 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 would have a high potential for producing ambiguous estimated impact probabilities that could not 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 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 over the next 80 years to detect all detectable NEOs >140-m (~7500 objects). Current radar systems operating at the present "2% allocation" 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 discovery and fully assess NEO hazards.

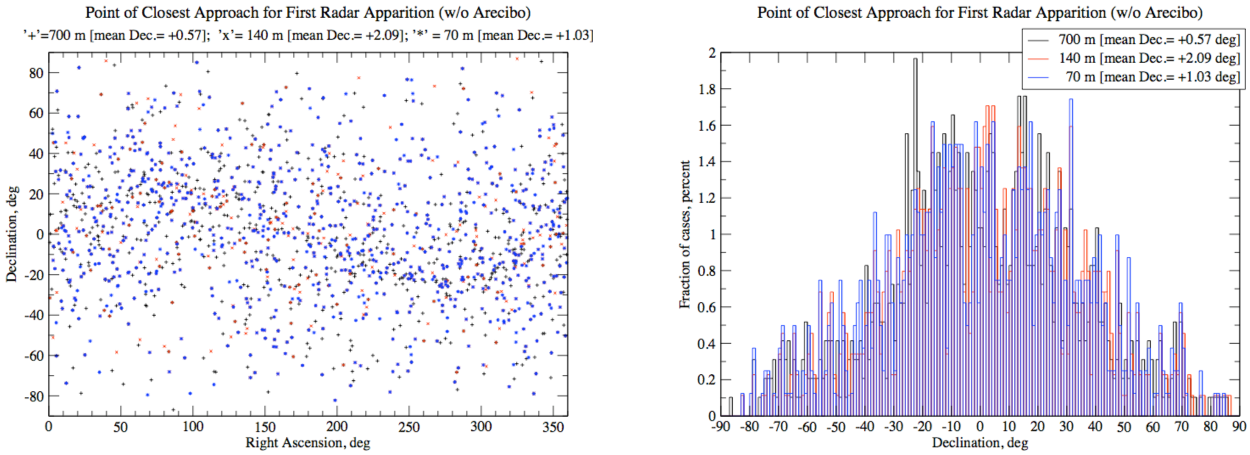

Figure #2: Plane-of-sky location at point of closest approach (maximum SNR)

Impact Warning Time

If "warning time' is defined to be the point where 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. The 50% warning level is usually reached during the NEO's second apparition.

If radar astrometry is obtained, 30% of 140-m cases have a definitive impact warning within 6 months of discovery, compared to 4% if only optical astrometry is available.

Without Arecibo, warning time for 700-m objects is increased only 0.5 years by GSSR data alone, indicating Arecibo provides 66% of the impact warning improvement relative to optical data in the current system. In the absence of Arecibo, warning time for smaller 140-m objects increases 1-2 years, indicating GSSR contributes 50-70% of the impact warning improvement for the more numerous smaller objects, the focus of future surveys.

Physical Characterization

Generally, Arecibo provides more high-resolution 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 >140-m diameter, 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 radar targets achievable. If all

GSSR upgrades were then implemented, including a southern hemisphere site, there would still be a -33% decrease in high-resolution targets. By contrast, if Arecibo remains and all DSN upgrades are made, only a 0.3% increase in gross quantity of high-resolution 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.

2. Cost Estimate

The cost of developing a new 500 kW, 3.5-cm radar capability analogous to GSSR at Canberra (DSS-43, Figure #3) would be mitigated through use of existing DSN transmitter assets already at the site:

(1) Existing equipment for power generation and cooling of the 400 kW DSS-43 S-band transmitter (now used for spacecraft communications) would be used in a switched-shared arrangement with the new X-band radar, as is done at DSS-14.

(2) Replication of GSSR capability would involve developing a new XKR cone to house the two primary active radar klystrons that would be combined to generate a 500 kW transmit signal. This new housing would be based on the existing cone.

For the transmitter and feed system, a total of 5 klystrons and 3 magnet assemblies would be procured in the first 18 months of the three-year task. Hardware would include all associated electronics, plumbing automation, advanced exciter, cabling, spares, RF and quasi-optical switching assemblies and polarizers. The cone would be brought to JPL for design and integration activities and tested at the Goldstone high-power transmitter test facility in the second half of Year 2, then shipped to Canberra for final integration

Figure #3: Existing 70-m DSS-43 at Canberra

activities in Year 3. Cost accounted values for this task, in accordance with JPL institutional costing tools, are shown in Table #1 in FY09 dollars: $10.085 million.

Procurement and assembly of a delay-Doppler data acquisition infrastructure system (front and back end, including primary and spare X-band HEMT packaged with closed-cycle DSN standard Sumitomo refrigerator) are estimated to be $5.6 million.

The total preliminary cost estimated for developing the new radar capability at DSS-43 is thus ~$16 million over three years, with subsequent operating costs estimated to be $2.5 million/year. Considering the early state of the estimate, development costs ~25% higher are not improbable.

	Project ID: 102688 (Oblg) Grand Total of WP in CA #: 1.0	FY2010 YEAR	FY2011 YEAR	FY2012 YEAR	Total Oblg
1	Total Labor	1,984.86	1,501.74	482.08	3,968.68
2	Total Procurement and Services	5,096.92	864.83	155.40	6,116.96
3	Total (K$)	7,081.78	2366.57	637.48	10,085.64

Table #1: Preliminary cost estimate, 500 kW X-band radar transmitter + feed at DSS-43 site

3. Conclusions: advantages/disadvantages

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

(1) Invest in maintenance and reliability of the existing radar capability. This retains at lowest cost the longer impact warning times and ability to characterize some NEOs at levels comparable to a spacecraft. The disadvantage would be yearly operating expenses. However, if radar eliminates the need for a future billion-dollar reconnaissance or mitigation mission, or identifies exceptionally interesting targets that *warrant* a dedicated mission, this relatively low yearly cost could provide substantial long-term benefit and cost-savings.

(2) Obtain more observing time on the two existing radar facilities. This is potentially the most effective *improvement*, but is difficult to achieve given the current time-share and funding arrangements. 15%+ time at existing facilities could in principle keep up with the optical NEO discovery rate, if automated.

(3) If (1) is implemented and (2) explored to the extent possible, addition of a radar capability to the existing 70-m DSN site at Canberra, Australia would be the most practical “new” development. It increases available NEO observing time, thus increases the number of targets that can be pursued by a factor of 1.5-2x, even if only "2% allocation" levels similar to DSS-14 and Arecibo are obtained. It also increases the tracking time during a given apparition (improving physical characterization), and accesses the ~1-5% of PHAs visible to radar only in southern hemisphere prior to impact. The disadvantage is the initial installation cost of at least ~$16 million with $2.5 million/year operating cost. It might also require changes in observing approach; for example, increased pursuit of low-SNR targets that aren't otherwise of interest to obtain delay-Doppler astrometry for improved orbit solutions.

(4) Double DSS-14 transmitter power to 900 kW. This increases the detectable NEO population by 5% and improves characterization for already high SNR cases. The disadvantage is higher cost relative to the performance improvement obtained; a new 1000 kW 70-m transmitter at Canberra is estimated to cost more than twice that of the new 500 kW capability described here.

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