DSN Radar Upgrade Study

1. Current Situation
2. Study Goals & Execution
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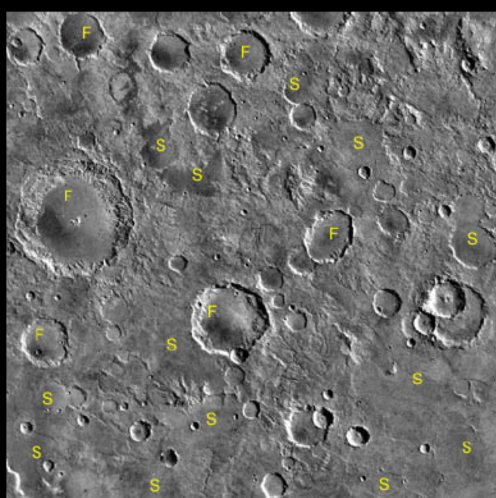
Most solid objects in solar system are covered with craters:

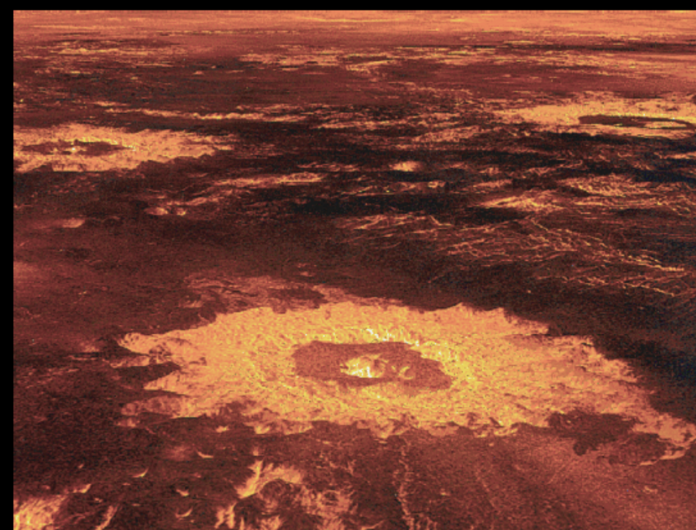
Moon

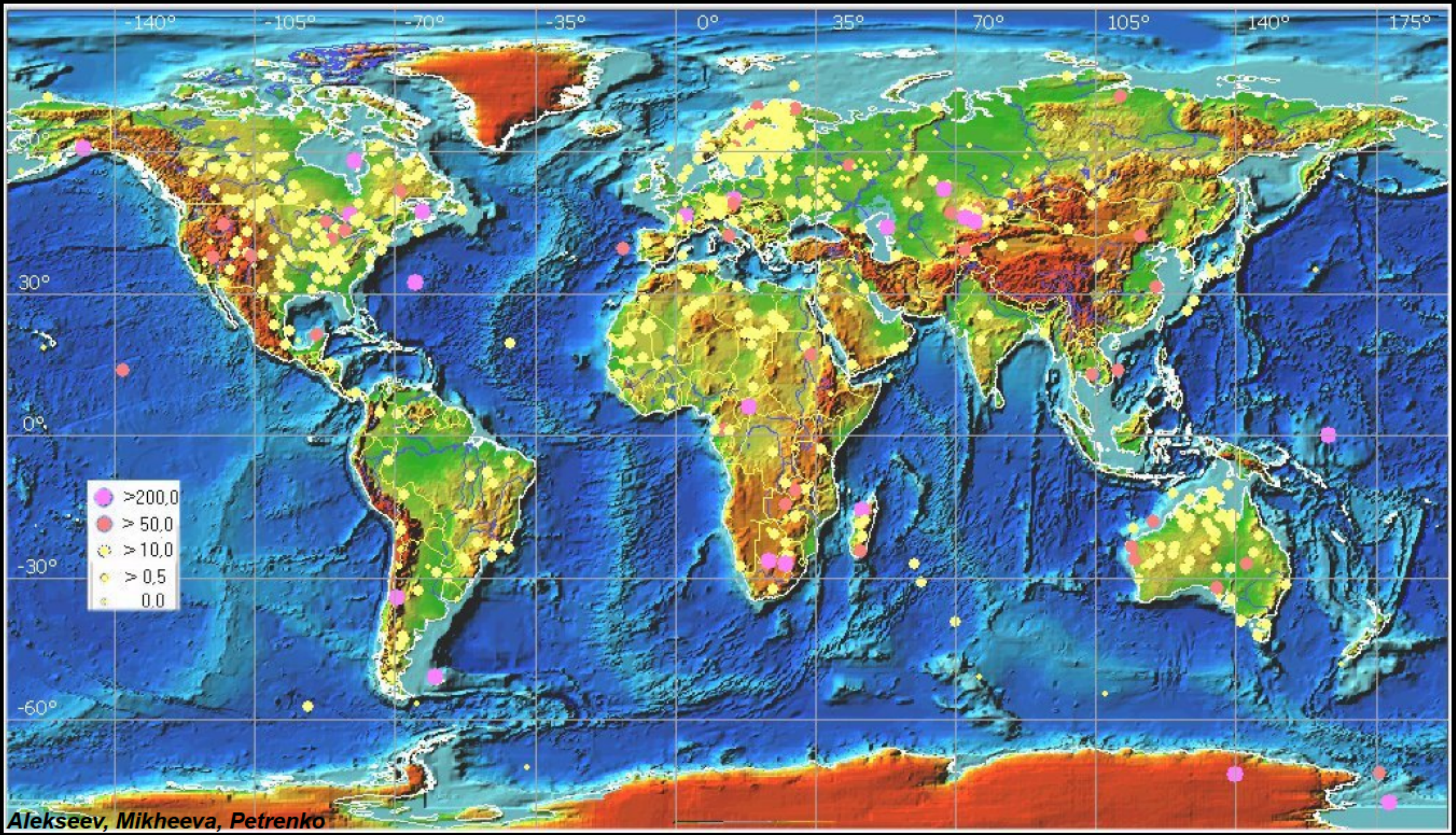
Asteroid 433 Eros

Mars



Venus





Tectonics, weathering & sedimentation erase craters on Earth, BUT …

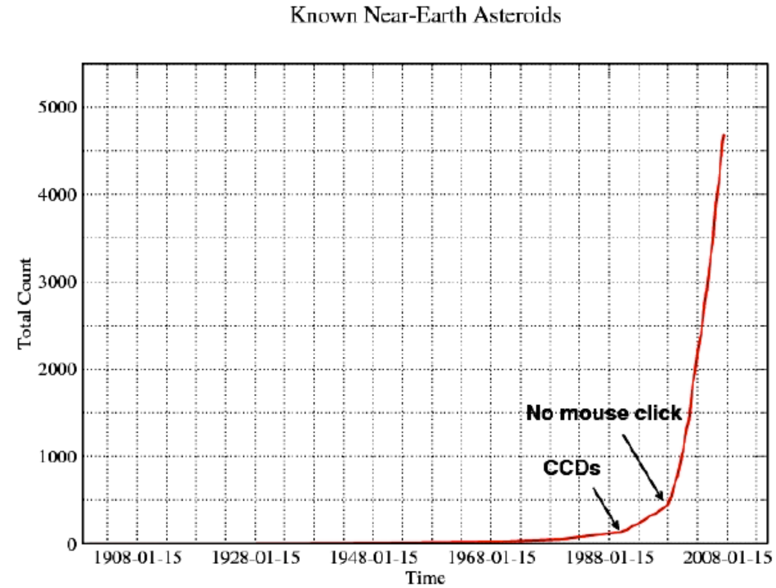
- 175+ confirmed impact craters (PASSC, 2008)
- A few hundred other potential sites (Rajmon, 2008)

How Much Warning?

- If an asteroid is on a collision course, when will we know impact is likely?
- NASA supports spacecraft missions and ground-based optical efforts to find and assess potentially hazardous objects.
- How do DSN radar observations relate to this effort, and what role do they have in assessing risk?
- A study to statistically assess ground-based radar capabilities was performed.

JPL/NASA Near-Earth Object Program Office

LINEAR telescope, Socorro NM



Goal: Discover 90% of near-Earth objects >1 km by 2009 ... assess risk

- Size-limit for impact to have global effects
- Formal start in 1998
- Currently: ~82% discovery level (757 of ~920)
- $4.1 million / year budget

Next: "Potentially Hazardous Asteroids" within 0.05 AU of Earth's orbit
Discover 90% of PHAs > 140 m diameter by end of 2020
Pan-STARRS to increase discovery rate ~10x (2009+)

Radar Systems

- Two adequately sized & powered RADAR transmitters:
  - DSS-14: 70 meter, ~430 kw (X-band), steerable (~all sky)
  - Arecibo: 305 meter, ~900 kw (S-band), pointing within 20 deg of zenith
- Optical discovery as "pixel" ... narrow beam-width radar follow-up resolves
- Radar can provide imaging & trajectory data comparable to spacecraft, for objects of greatest interest: those that encounter Earth
- Historically, ~2% of system time available/used for asteroid targets

Prediction Improvement Using Radar

Of 230 radar-detected NEOs:

- 80% detected in last 10 years ...

Radar delay-Doppler measurements:

- Time-delay to 8 m (150-300 m typical)
- Doppler to 1.6 mm/s (8 mm/s typical)
- Used with optical RA/DEC angles in orbit soln.

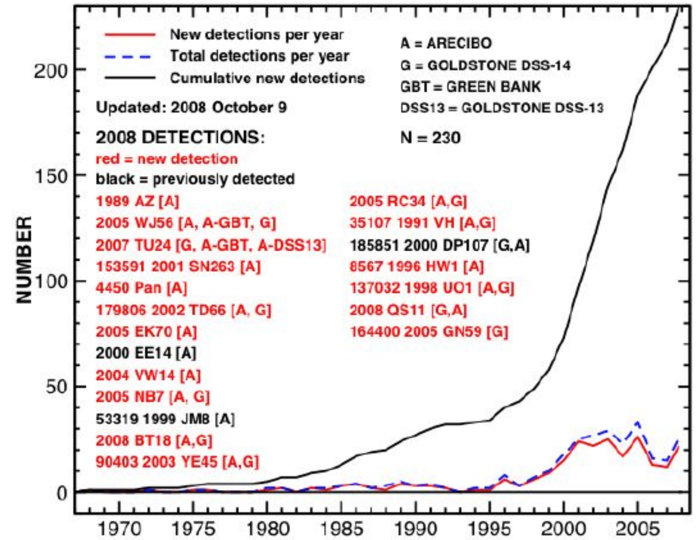
- Radar astrometry has been obtained for:

3.5% of	5718 known	**NEOs**
7.7% of	810 known	**NEOs > 1 km**
12.6% of	981 known	**PHAs**
25.5% of	145 known	**PHAs > 1 km**

Interesting ↓ More interesting

- Reduces orbit uncertainties ~10^5 (at discovery)

RADAR DETECTIONS OF NEAR-EARTH ASTEROIDS



Figures: L. Benner

1999 JM8

For PHAs, historical average prediction extent is …

1st apparition : +400 years w/radar, +80 years without radar

2nd apparition: +800 years with or w/o radar (radar can still cut uncertainties 50%)

Radar extends prediction window at discovery 5x, on average

Radar Performance Upgrade Study

Purpose:

Provide data relevant to DSN decisions on future NEO radar capability

Goal: Simulate three radar upgrade variations, in combinations:

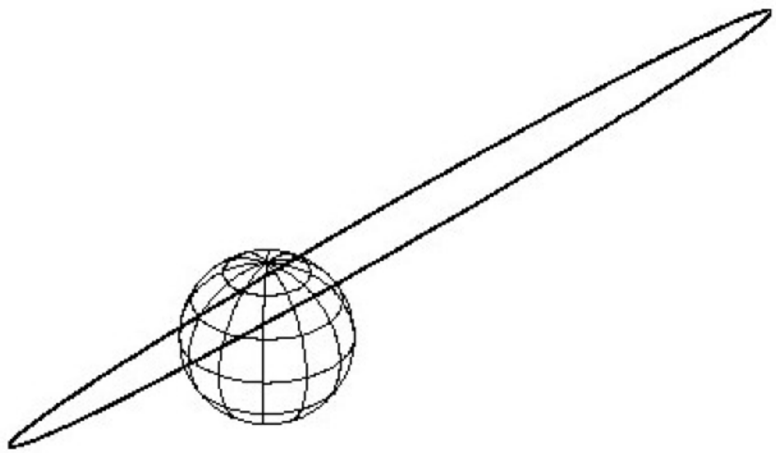
1. Doubling GSSR radar transmit power (430 → 900 kw)
2. New southern hemisphere site 70 m @ 900 kw (Canberra)
3. Increasing delay accuracy (0.125 → 0.026 usec)

... with respect to:

- Detectability
- Trajectory predictability
- Physical characterization

Implementation, logistics & observational goals **NOT** part of study

Why a Simulation?



- Impact probability is computed using the predicted position and predicted position uncertainties.
- Such predictions of the future depend on an orbit solution and its uncertainties.
- Orbit solution uncertainties depend on measurements of the object and their uncertainties.
- Therefore, a simulation was used to capture the full range of measurements and orbits for the impact problem.

Current Process:

1. Optical discovery
2. Assess: good radar target?
   (visibility, SNR, scheduling)
3. Orbit refinement (more optical);
   can take days or weeks
4. Pointing uncertainties small
   enough for radar?

Underlying Issues

1) **Radar detectability & characterization depend on <u>echo strength</u>:**

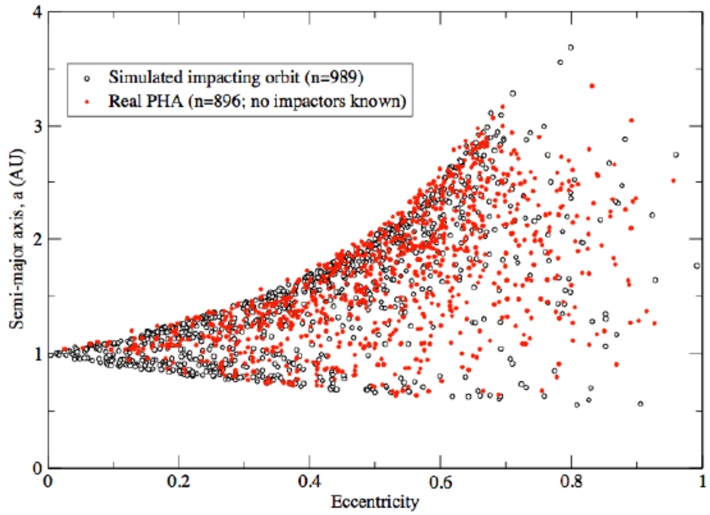
- <u>Signal-to-Noise Ratio (SNR)</u>; a function of ...
  - Observatory parameters: transmit power, receiver performance
  - 1 / (range)^{4} [gets weak fast with distance; main-belt limit]
  - (diameter)$^{1.5}$ [bigger target, stronger echo]
  - (rotational period)$^{0.5}$ [slower spin, stronger echo]
  - cos(sub-radar latitude) $^{-0.5}$ [stronger echo as view → pole]
- Echoes must be summed ("integrated") over time

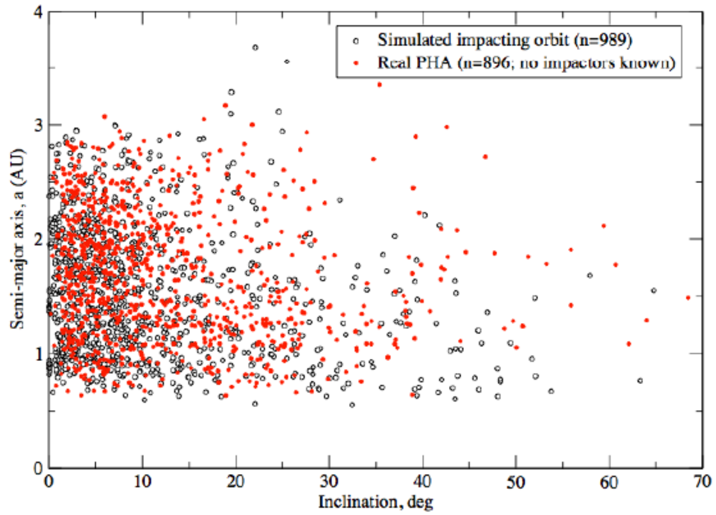
2) **Trajectory predictability depends on ...**

- Fraction of orbit sampled by measurements
- Accuracy and precision of measurements
- Interval between measurement & time of prediction
- Forces acting on object

Study Approach

To capture these issues, a full simulation was developed:

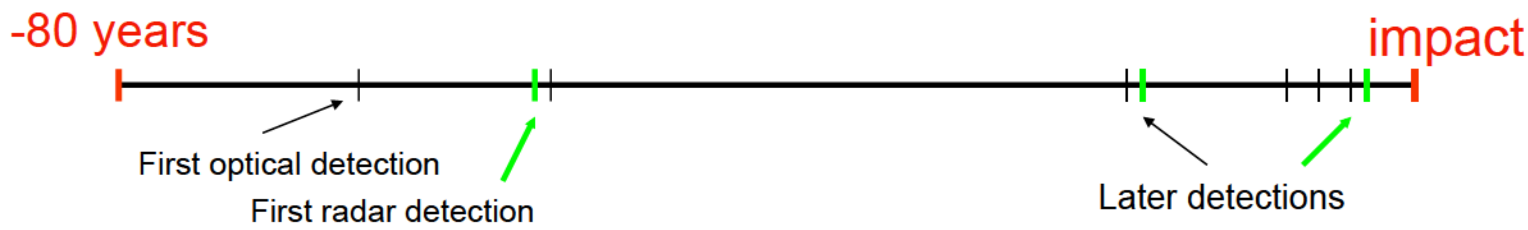




- Representative population of 989 <u>simulated</u> PHA orbits [Chesley & Spahr, 2003]
- All objects impact Earth ... by design

- Start with position 80 years prior to impact
- Numerically integrate three object sizes *per orbit* to impact:
  large (diam.= 700 m), medium (d= 140 m), small (d= 70 m)
- Find all times during 80 year interval when optically observable
  (after optical discovery), or radar detectable

Study Approach



- Simulate reasonable optical & radar measurements

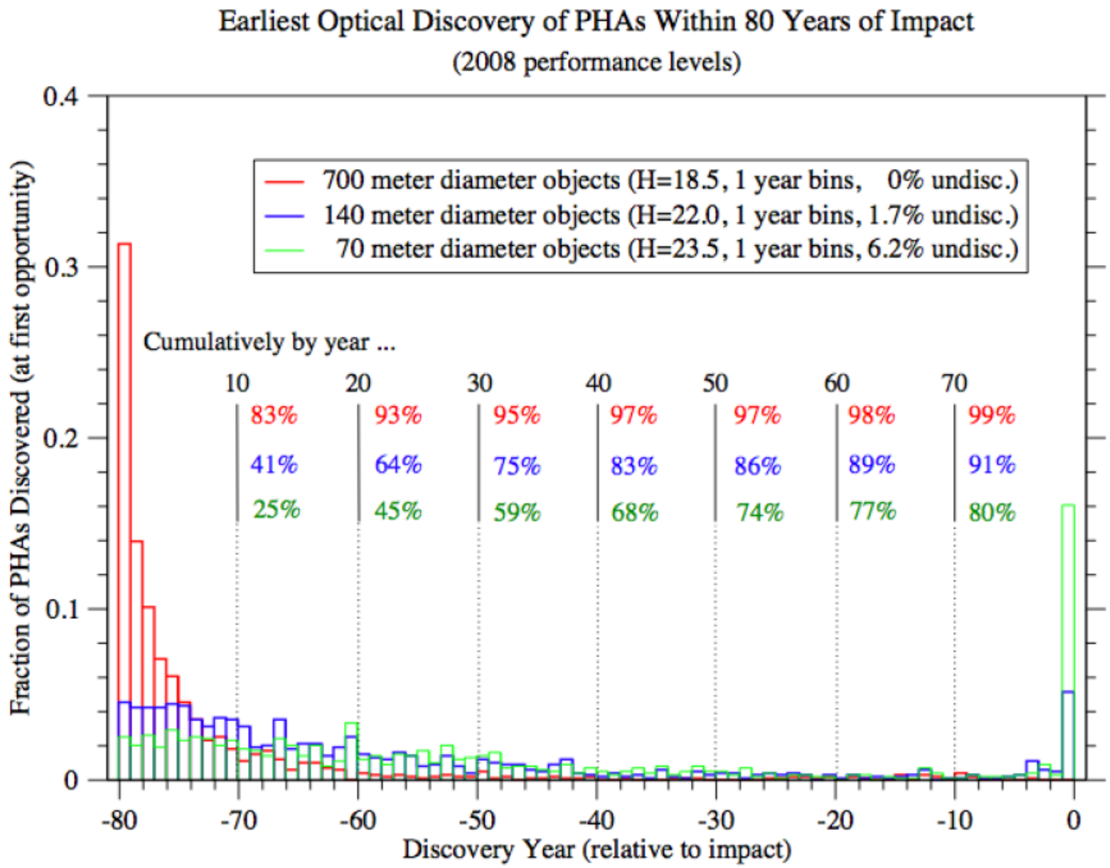
Optical rules	Radar rules:
Standard (H,G) magnitude model	GSSR/CSSR/Arecibo:
Solar elongation cut-off at 55 deg	- Dec. limits, xmit power & freq.,
No observations within 20 deg of Moon	antenna size & performance,
or within 3 days of full moon.	Integration time (3.5 hr, 1.5hr)
Discovery at V_{lim}= 20, follow-up to V_{lim}=22	SNR > 10
One obs. every 4 days (V= 21), to 4 per day (V= 18)	+/- 8 days around max. SNR
No observation errors	One delay, Doppler per day

- Compute impact probability & SNR as observations are added
- Operational software used for simulation

- Considered:
  - ✓ 9 radar/upgrade configurations (including current config.)
  - ✓ 1 optical-only control case

- Total of 118,680 cases
- Simulation run on 26-node CPU cluster (11 GB output)

Results: Detectability (1)



Optical discovery:

700 m: All objects discovered prior to impact

140 m: 1.7% ***not*** discovered before impact

70 m: 6.2% ***not*** discovered before impact

Results: Detectability (2)

- Arecibo
  Capable of detecting 76-98% of discovered PHAs (>1 year prior to impact)

- Current GSSR:
  Capable of detecting 69-92% of discovered PHAs (>1 year prior to impact)

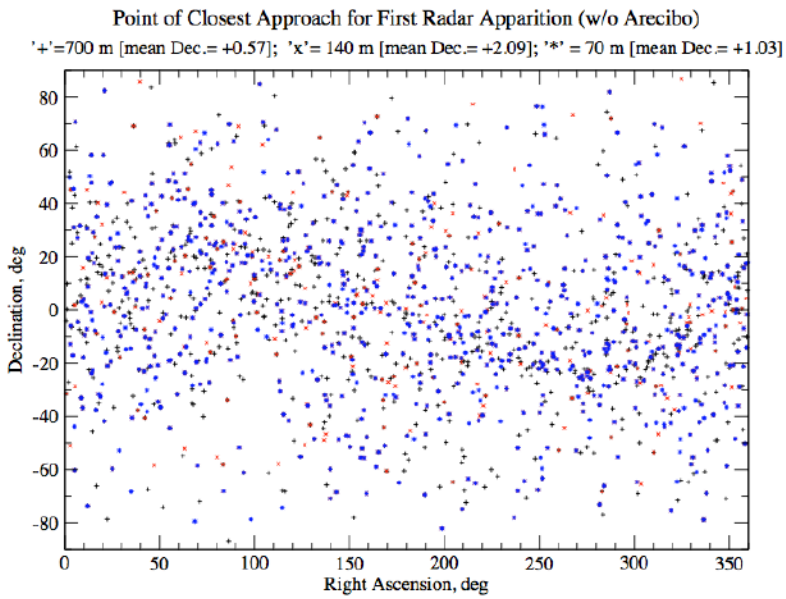
- **Doubling GSSR transmit power**:
  - ✓ Increases detectable population +5% (> 1 year prior to impact)

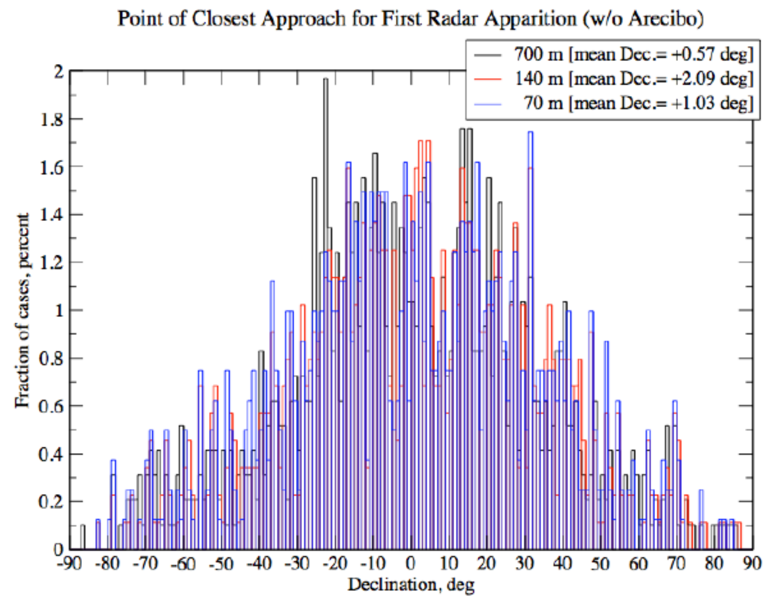
- **New southern site**, 70 m @ 900 kw
  - ✓ Could detect 73-95% of PHA's (increase +4% over current DSN)
  - ✓ 2 - 7% of PHA's are detectable ONLY by southern DSN site
  - ✓ 1 - 5% of PHA's are detectable ONLY by northern DSN site

- Loss of radar: reduces or eliminates warning, especially for 7-23% of impactors having "one-time-only" optical observing opportunities >1 year prior to impact (high potential for "unresolved impact uncertainty")

- Hypothetical "aggressive" radar program ("detect all detectable objects") with current systems could clarify impact prediction for 1-5% of detectable impactors (those with single apparition optical **AND** radar visibility)

Results: Detectability & Observing Time





- No significant north/south radar visibility distinction (max. SNR evenly distributed)
- Northern & southern sites each detect 1-7% of population other hemisphere cannot
- A hypothetical ***aggressive*** DSN radar program ("detect all objects possible") requires:

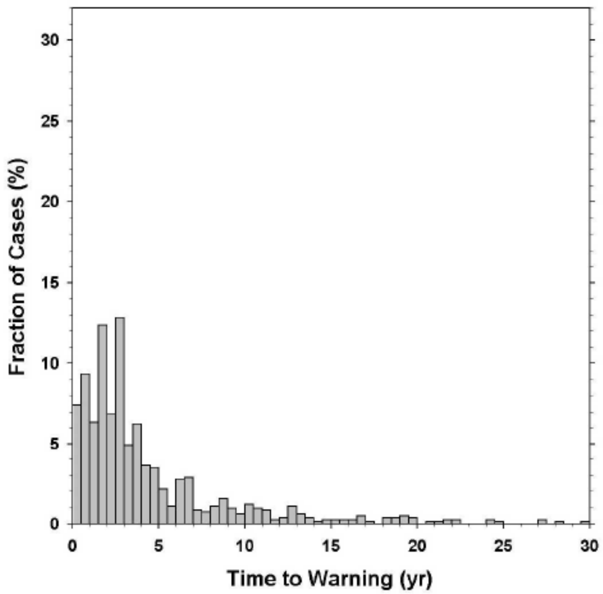
  ... 6+ years of cumulative transmit/receive cycles, over next 80 years, to detect all detectable objects > 140 m (~7500 objects)

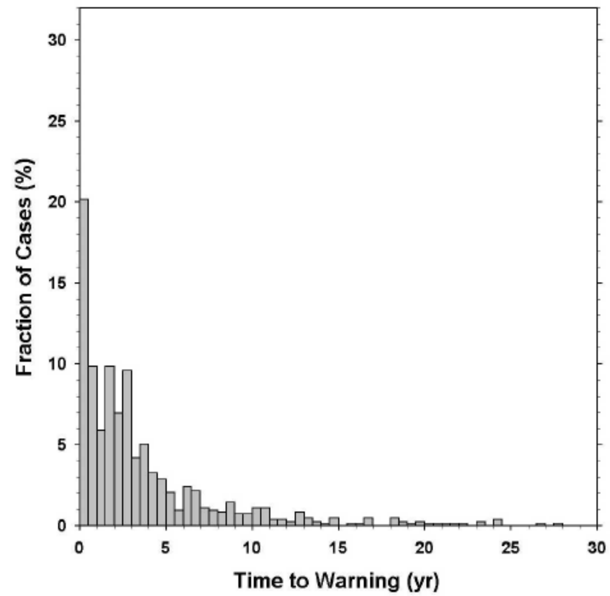
  ... 29+ years xmit/receive to detect all detectable objects 70 -140 m (~37,000 objects)

- Current rate: ~140+ calendar yrs for DSN to cover next 20 yrs of new 140 m+ discoveries
- Southern site can increase scheduled time (share load) + increase track length to improve physical characterization. *Still "falls behind" if only 2% time scheduling.*

Impact Warning Time (700 m)

"Warning time" ... when impact probability reaches 50%





Optical only:

- Median warning within 2.9 yrs discovery
- 75% of cases reach warning < 5 yrs

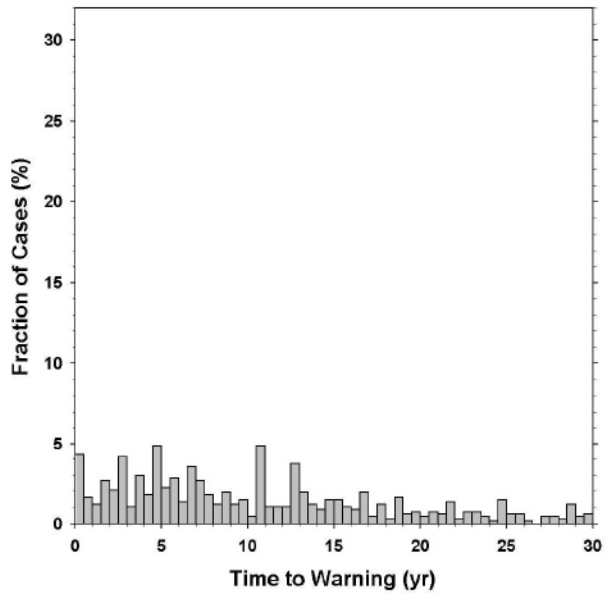
Optical + radar:

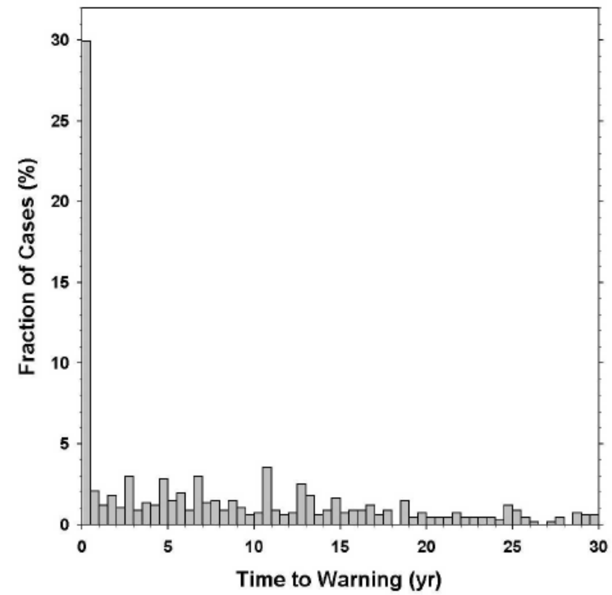
- Median warning within 2.3 yrs discovery
- 75% of cases reach warning < 4.2 yrs

- 50% warning usually reached in second apparition
- Radar advances warning time ~9 months for 700 m objects, averaged over population

Impact Warning Time (140 m)

"Warning time" ... when impact probability reaches 50%





Optical only:
- Median warning within 10.5 yrs discovery
- 75% of cases reach warning < 18 yrs

Optical + radar:
- Median warning within 6 yrs discovery
- 75% of cases reach warning < 15 yrs
- *30% warn in 6 months*

- 50% warning usually reached in second apparition
- Radar advances warning time ~4 years for 140 m objects, averaged over population

Physical Characterization

- Physical characterization (science) ... categorized by maximum SNR:
  - ✓ Minimal detection, polarization ratio = 10 < SNR < 20
  - ✓ Low-resolution shape = 20 < SNR < 100
  - ✓ Moderate-resolution shape = 100 < SNR < 1000
  - ✓ High-resolution shape (& CHIRP) = SNR > 1000

PHAs for which high-resolution physical characterization could be obtained:

	Est. No. Objects* >70 m	% pop.>70 m	% pop.>140 m
Arecibo + DSN upgrades	11400	18.1%	22.1%
Current (GSSR @ 430 kw + Arecibo)	11149	17.7%	21.8%
Arecibo alone	10703	17.0%	21.0%
DSN upgrades, no Arecibo	7480	11.9%	15.9%
GSSR @ 430 kw alone	5798	9.2%	13.4%
	(Werner, 2002)		

- An Arecibo shut-down, leaving …
  Current GSSR: -46% reduction in high-resolution radar targets
  +All upgrades : -33% reduction in high-resolution radar targets

- All upgrades (w/Arecibo): +2% increase in high-resolution radar targets

- Arecibo: more high-resolution characterization cases (> receiver collecting area)
- GSSR : finer spatial resolution for high-SNR targets (CHIRP + Doppler)

Summary & Conclusions

- Goldstone and Arecibo radars provide essential data relevant to protecting the Earth from impact hazards. They ...
  - ✓ Increase Earth encounter gross predictability 5x (from 80 to 400 years)
  - ✓ Increase impact warning time up to an average of 4 years
  - ✓ Provide physical characterization comparable to a spacecraft mission for cases of greatest interest (objects that come close)
  - ✓ Identify targets of interest for future spacecraft missions
- Existing radar capability is grossly under-utilized for small-bodies
  - ➢ Primary limitation: "2%" scheduling & resource sharing
  - ➢ Most effective upgrade to existing systems: additional observing time
  - ➢ Current DSN radar observation rate ~7-60x less than pace to "keep up" with potential optical discoveries, fully assess impact hazard in ~2 decades
- Increasing GSSR transmitter power would ***not*** greatly improve risk reduction (detectability +5%) or population characterization (high-res. SNR cases +0.3%)
- A new southern hemisphere radar site can significantly accelerate risk reduction and physical characterization:
  - ✓ Effectively increases available observing time 1.5 - 2x + by sharing load
  - ✓ Provides longer tracking passes for better characterization of many PHAs
  - ✓ Detects the 2 - 7% of targets uniquely visible in southern hemisphere