# Improved Impact Hazard Assessment:

Existing Radar Sites
and
a New 70-m Southern Hemisphere Radar Installation

1. Current Situation
2. Performance Analysis
3. Summary of Results
4. Conclusions

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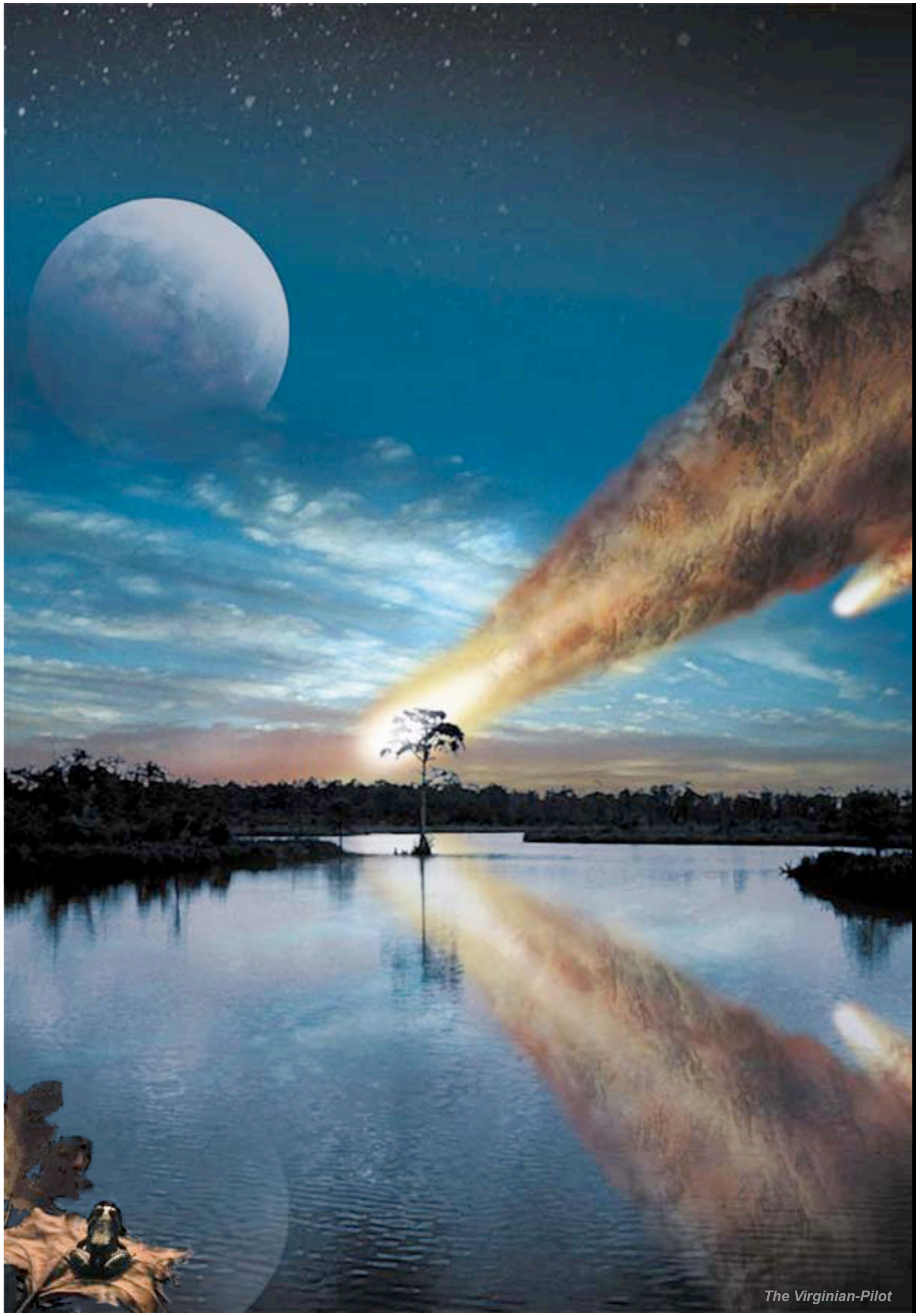
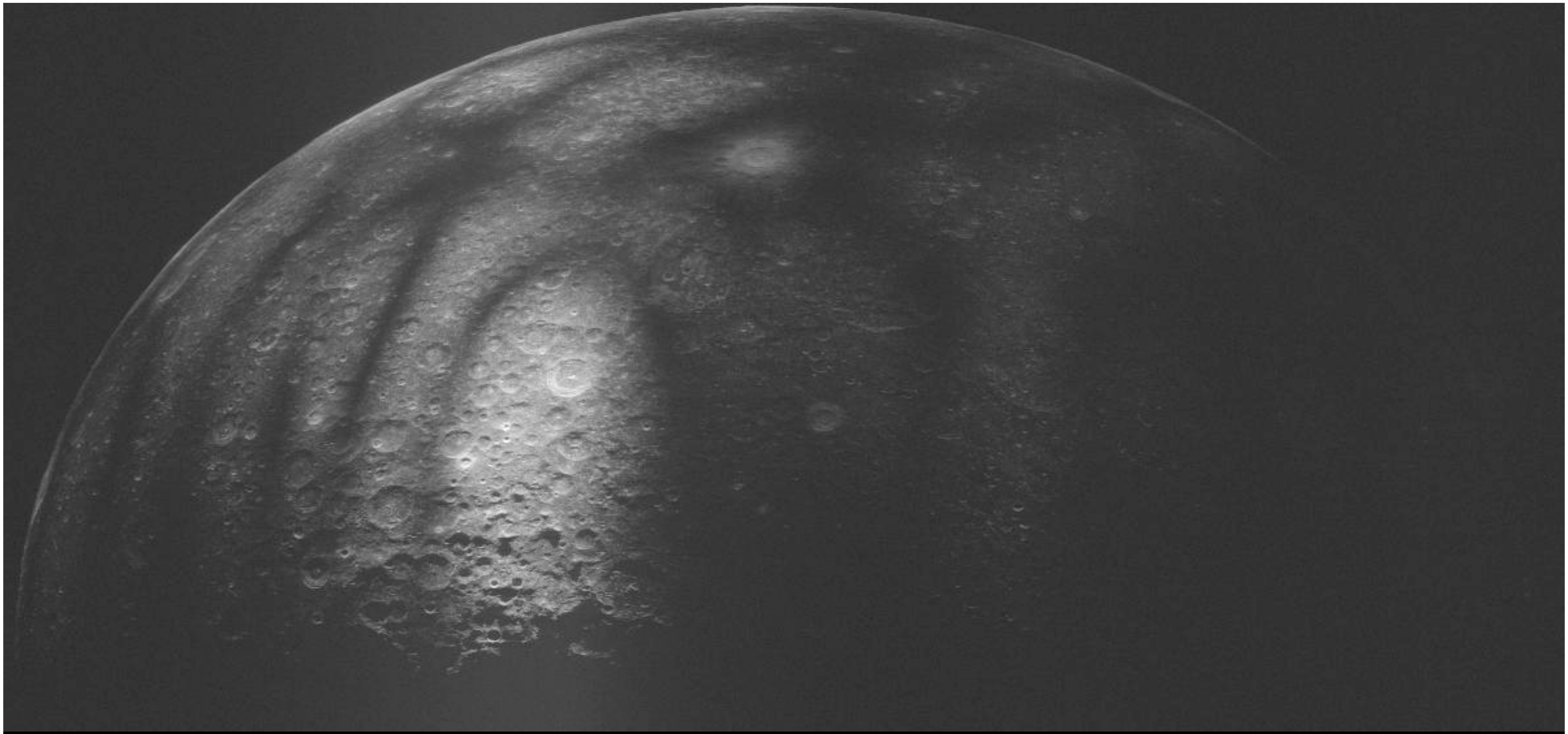



## How Much Warning?

- 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 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.

# Radar Systems

- Two adequately sized & powered RADAR transmitters:
  - DSS-14: 70 meter, ~430 kw (X-band), steerable (horizon to horizon)
  - 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 the objects of greatest interest: those that encounter Earth
- Historically, ~2% of system time available/used for asteroid targets



The Moon, illuminated by Arecibo S-band (2380 MHz) 2001-Nov-11 12:55 (27-second data sum, 3.5 km resolution. PI & image: J.L. Margot)

- Narrow-beam, time-delayed, microwave “flash-light”
- Echoes must be integrated over time
- Accurate a-priori pointing knowledge required
- Search impractical; radar is follow-up tool (after optical discovery)

# Prediction Improvement Using Radar

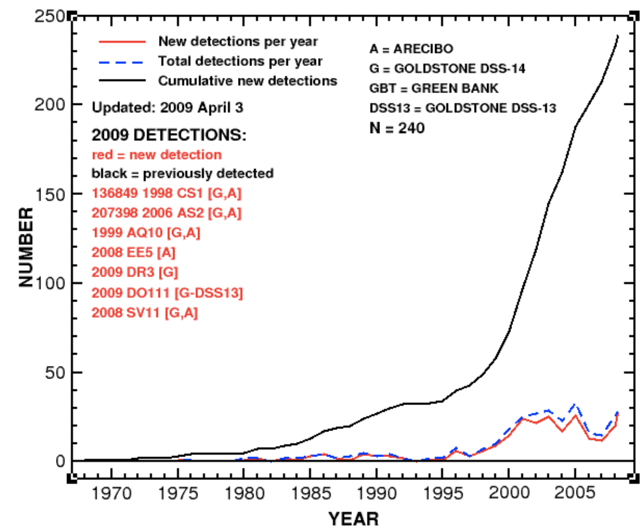
<u>Of 240 radar-detected NEOs:</u>

- 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 DETECTIONS OF NEAR-EARTH ASTEROIDS




- Radar astrometry has been obtained for:

| | | |
|---|---|---|
| 3.8% of | 6258 known **NEOs** | Interesting |
| 8.9% of | 821 known **NEOs > 1 km** | ↓ |
| 13.0% of | 1050 known **PHAs** | |
| 28.0% of | 143 known **PHAs > 1 km** | More interesting |

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

Figures: L. Benner

1999 JM8

For PHAs, historical average <u>prediction extent</u> is …

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

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

**Radar extends prediction window at discovery 5x, on average**

# Radar Performance Study

**Purpose**:

Provide data relevant to decisions on future NEO radar

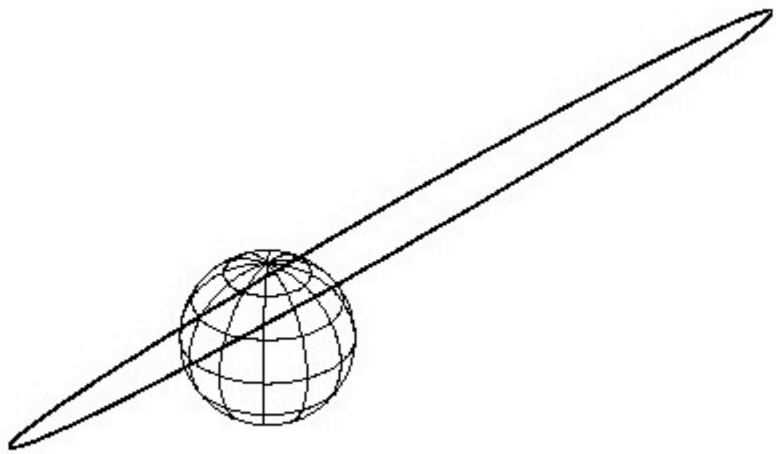
**Goal:** Simulate three radar upgrade variations, in combinations:

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 μs)

... with respect to:

- Detectability
- Trajectory predictability
- Physical characterization

# Why a Simulation?



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?

- 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.

# Underlying Issues

1) **Radar detectability & characterization depend on echo strength:**

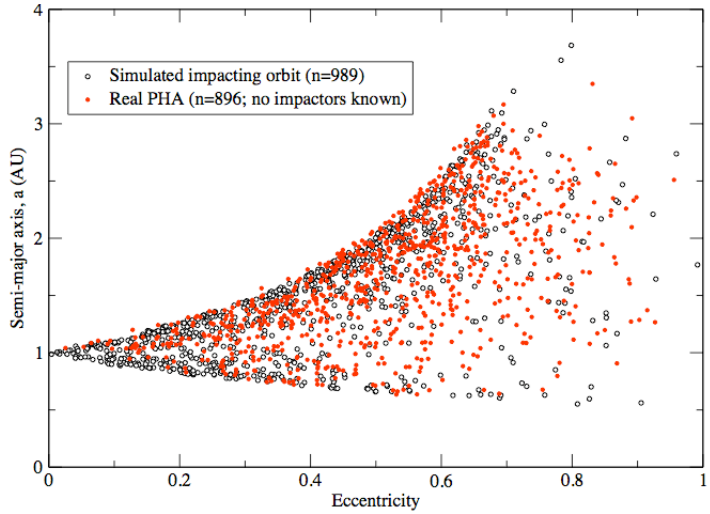
- Signal-to-Noise Ratio (SNR); a function of ...
  - Observatory parameters: transmitter power, receiver performance
  - $1 / (\text{range})^4$ [gets weak fast with distance; main-belt limit]
  - $(\text{diameter})^{1.5}$ [bigger target, stronger echo]
  - $(\text{rotational period})^{0.5}$ [slower spin,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

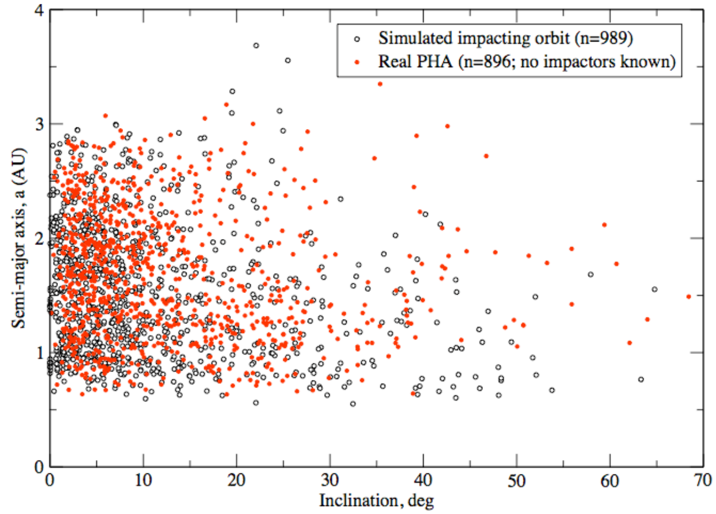
2) **Trajectory predictability depends on ...**

- 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:

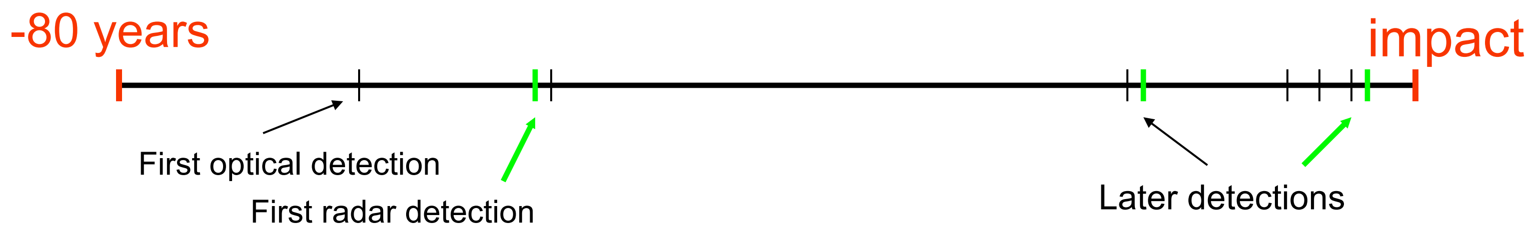



- Representative population of 989 <u>simulated</u> PHA orbits [Chesley & Spahr, 2003 (Bottke)]
- All objects impact Earth ... by design

- 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

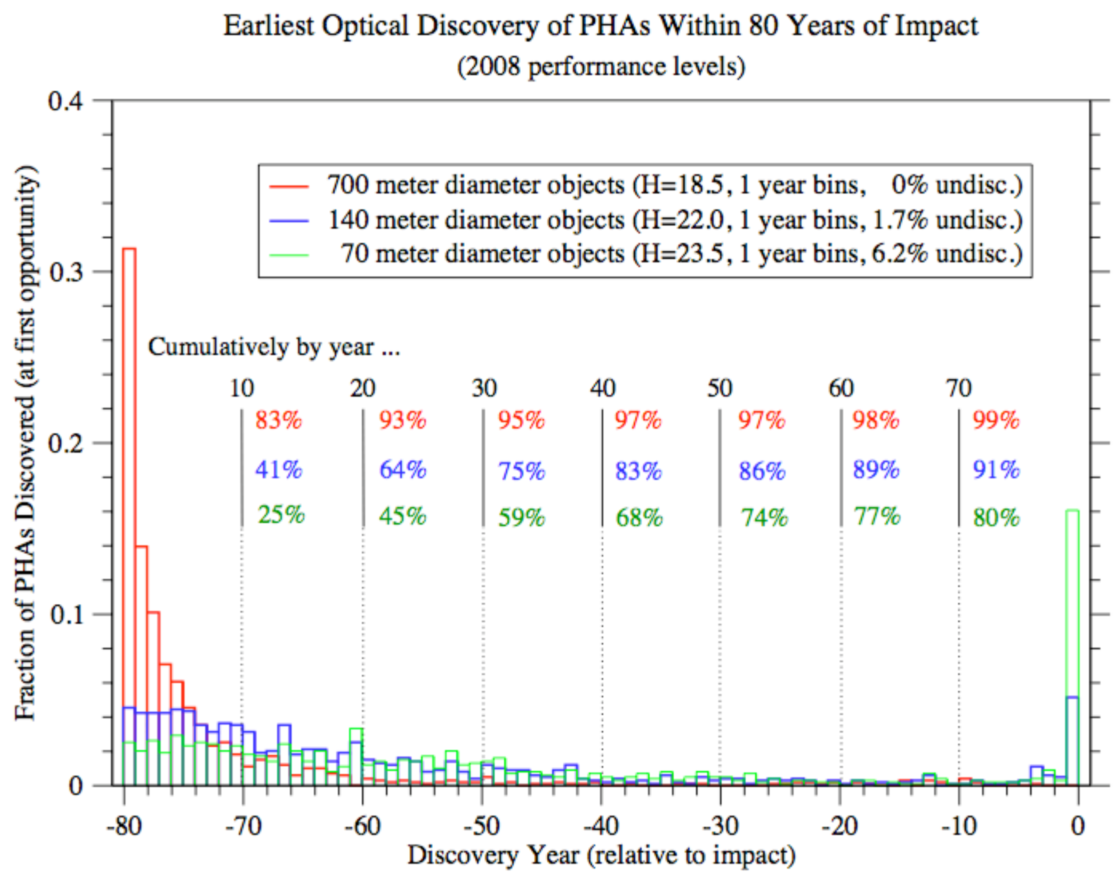
| Optical rules | Radar rules: |
|---|---|
| Standard (H,G) magnitude model | GSSR/CSSR/Arecibo: |
| Solar elongation cut-off at 55 deg | - Dec. limits, xmit power & freq., |
| No observations within 20 deg of Moon | antenna size & performance, |
| or within 3 days of full moon. | Integration time (3.5 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)

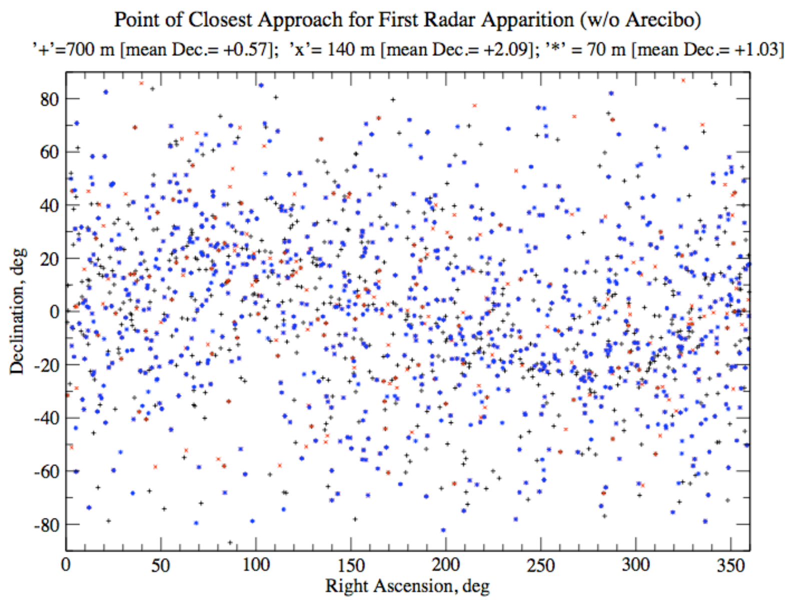
- **Doubling GSSR transmit power**:
  - ✓ Increases detectable population +5% (> 1 year prior to impact)

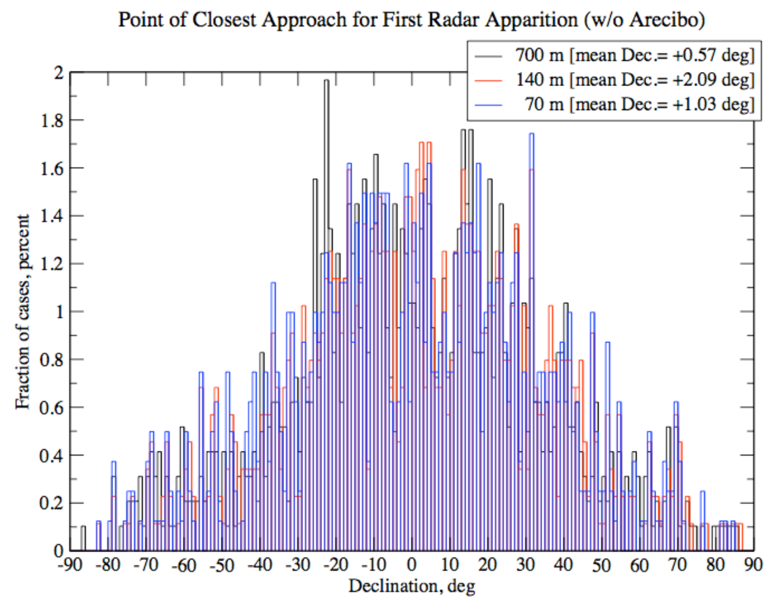
- **New southern site**, 70 m @ 900 kw
  - ✓ Could detect 73-95% of PHA's (increase +4% over current DSN)
  - ✓ 2 - 7% of PHA's are detectable ONLY by southern DSN site
  - ✓ 1 - 5% of PHA's are detectable ONLY by northern DSN site

- 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:

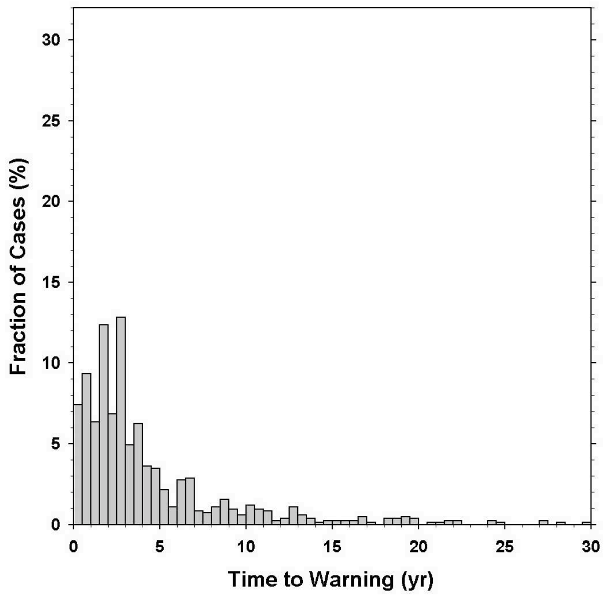
  ... 6+ years of cumulative transmit/receive cycles, over next 80 years, to detect all detectable objects > 140 m (~7500 objects)

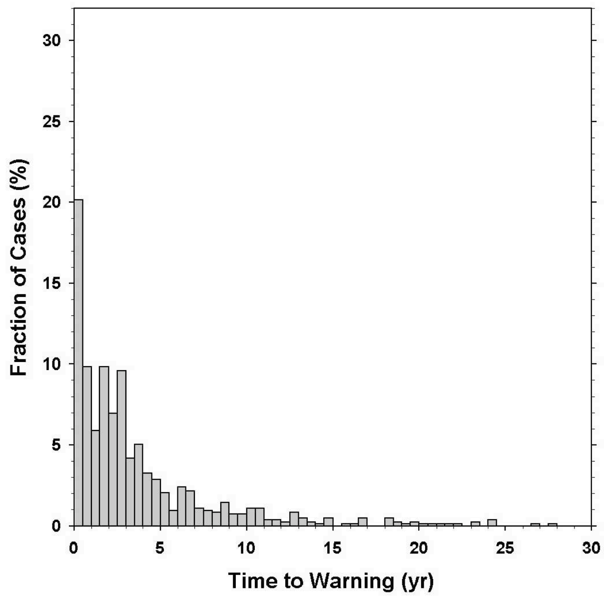
  ... 29+ years xmit/receive to detect all detectable objects 70 -140 m (~37,000 objects)

- 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

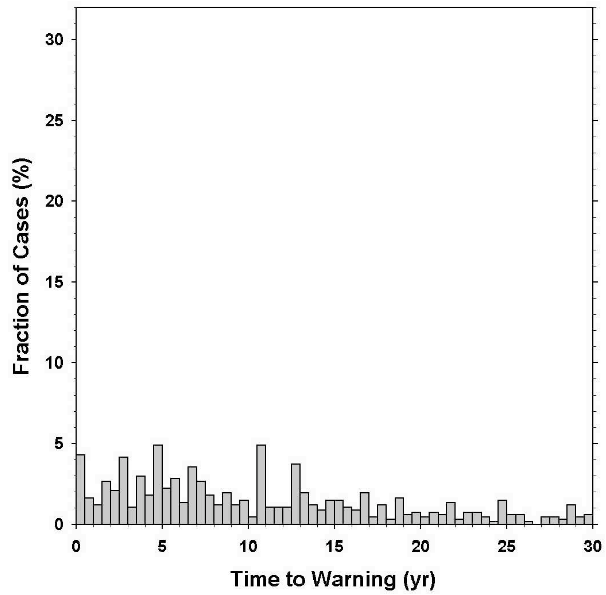
Optical + radar:

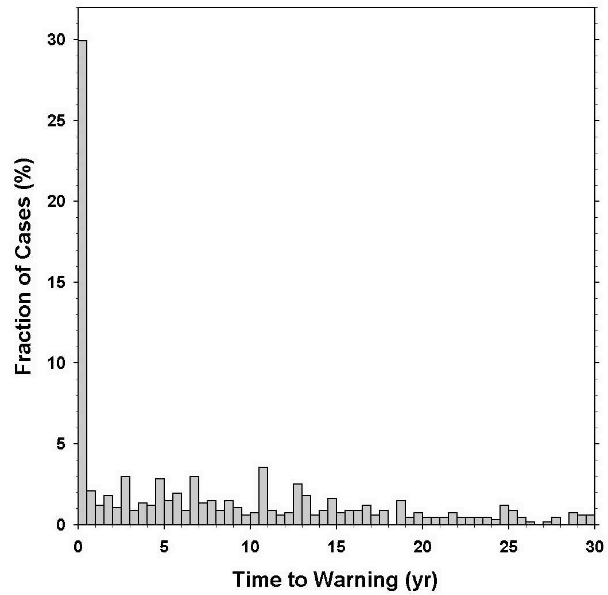
- Median warning within 2.3 yrs discovery
- 75% of cases reach warning < 4.2 yrs

- 50% warning usually reached in second apparition
- Radar advances warning time ~9 months for 700 m objects, averaged over population (i.e., includes undetectables)

# 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 (i.e., includes undetectables)

# Impact Warning Time by Site

- Without Arecibo –

  700-m objects: GSSR increases warning time 0.5/0.75 yrs
  (Arecibo provides 66% of improvement)

  140-m objects: GSSR increases warning time 1-2/4 years
  (GSSR provides 50-70% of improvement)

  … compared to optical-only warning.

- Arecibo warns better for large object (more range depth)
- GSSR warns better for small objects (bigger window)

# 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 of Analyses

- 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: resource sharing & "2%" scheduling
  - ➢ 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


# Existing Facility -- 70-m DSS-43 at Canberra, Australia

- Used now for spacecraft up/down-link
- Add switched-shared radar capability

| Project ID: 102688 (Oblg) Grand Total of WP in CA #: 1.0 | | FY2010 YEAR | FY2011 YEAR | FY2012 YEAR | Total Oblg |
|---|---|---|---|---|---|
| 1 | JPL FTE | 7.8 | 5.8 | 1.8 | |
| 2 | JPL Hours | 13,996.0 | 10,251.5 | 3254.9 | 15.4 27,502.4 |
| 3 | CatA FTE | | | | |
| 4 | CatA Hours | | | | |
| 5 | NonQuota FTE | | | | |
| 6 | NonQuota Hours | | | | |
| 7 | Total Labor | 1,984.86 | 1,501.74 | 482.08 | |
| 8 | Chargeback | 72.66 | 68.65 | 21.44 | 3,968.68 |
| 9 | Procurement (Subcontract) | 4,173.07 | | | |
| 10 | Procurement (Materials) | 639.06 | 536.72 | 34.73 | 162.76 |
| 11 | Research Support Agreement (RSA) | | | | 4,173.07 |
| 12 | Service | 175.21 | 215.42 | 18.57 | |
| 13 | Travel | 36.92 | 44.05 | 80.46 | 1,210.51 |
| 14 | Interdivisional Authorization | | | | |
| 15 | CT Transfers | | | | |
| 16 | BOWS Sub-Total | 7,081.77 | 2366.57 | 637.48 | 409.19 |
| 17 | By Pass | | | | 161.43 |
| 18 | Reserves | | | | 10,085.63 |
| top | Total (K$) | 7,081.77 | 2366.57 | 637.48 | 10,085.63 |

Preliminary cost estimate (transmitter & feed only), 500 kW @ DSS-43

- Use existing power generation, cooling, & structure
- Develop new cone (housing 2 klystrons → 500 kW, X-band transmit signal)
- Over three years (preliminary estimate):

  Transmitter and feed system : ~ $10.1 million
  Data acquisition system : ~ $ 5.6 million
  Total : ~ $16.0 million (+ 25%?)
- Operating costs: ~ $2.5 million/year (FY09 dollars)

# Conclusions

**(1) Invest in maintenance and reliability of existing radar**

*pro*: Retains longer warning times and Characterization of NEOs comparable to spacecraft

*con*: On-going operating expenses

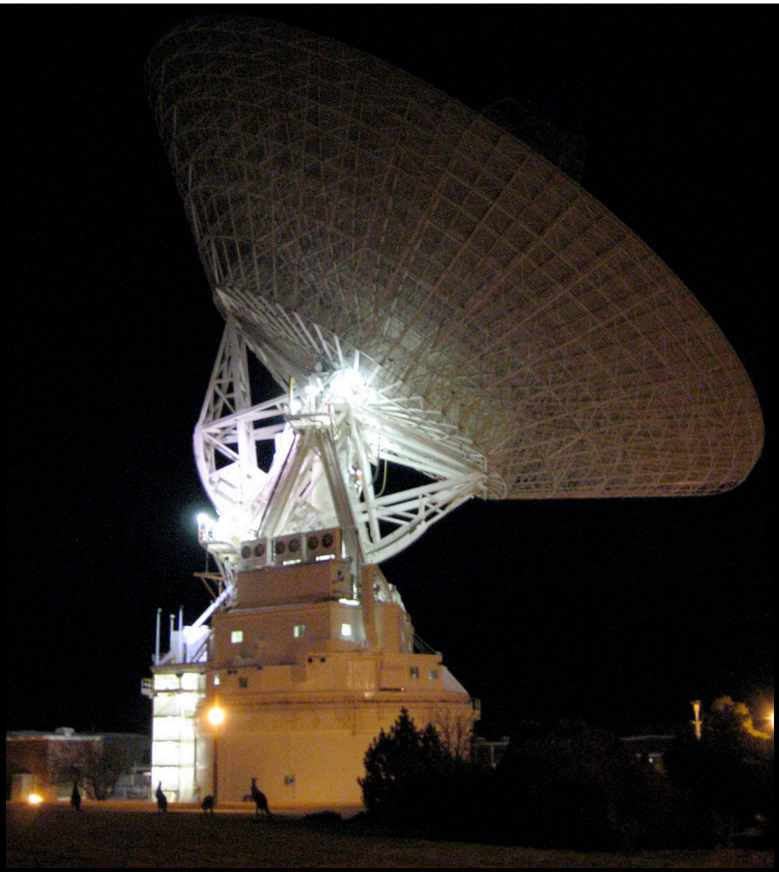
**(2) Obtain more observing time at two existing radar sites**

*pro*: Most effective *improvement* at lowest cost

*con*: How to achieve with current manpower, funding, time-share situation? 15% time at existing facilities could (in principle) “keep up” with expected 140-m discovery rate, accurately assessing hazard.

……….

**IF (1) is implemented and (2) explored to extent possible …**



## (3) Add radar capability to existing 70-m Australian site

*pro*: Increases available observing time by 1.5-2x
Increases tracking time (characterization) during apparition
Accesses ~1-5% of PHAs visible only in southern hemisphere

*con*: Initial cost of ~$16 million, yearly operations of $2.5 million
Changes in observing approach (pursuit of low SNR targets)