# Arecibo and Goldstone Radar Observations of Near-Earth Objects

Lance Benner
Jet Propulsion Laboratory
California Institute of Technology

# What Can Radar Do?

**Spatially resolve objects with up to 4-meter resolution:** Greatly exceeds any ground- or space-based optical telescope; 3-D shapes, convex hulls, sizes, surface features, spin states, surface roughness and density, regolith distrubutions, constrain composition; gravitational environments.

**Identify binary and ternary objects:** orbital parameters, masses and bulk densities, orbital dynamics, constrain bulk porosity.

**Improve orbits:** Very precise: for ARM targets, measure distances to < 10 meters. Shrink uncertainties by many orders-of-magnitude for newly-discovered NEOs. Prevent loss of objects. Predict motion for decades to centuries. Radar observations of previously-known NEOs can reduce uncertainties by several tens of percent.

Goldstone
70 m

Arecibo: 305 m

Capabilities are complementary

| | Arecibo | Goldstone |
|---|---|---|
| Diameter | 305 m | 70 m |
| Transmitter power | 900 kW | 450 kW |
| Transmitter frequency | 2380 MHz | 8560 MHz |
| System temperature | 25 K | 18 K |
| Declination coverage | -1 to +38 | > -35 deg |
| Sky coverage | ~1/3 | ~80% |
| Finest range resolution | 7.5 m | 3.75 m |
| Monostatic obs'ns limit | ~0.008 AU | ~0.005 AU |

Arecibo is ~20x more sensitive and can detect NEAs to about double the distance at Goldstone. Arecibo can track for 2.9 hours/day; Goldstone can track up to 24 h. Arecibo is easier to schedule on short notice. Goldstone resolves slow rotators 3.6x more finely. Airspace coordination is necessary at Goldstone but not at Arecibo.

# Less Sensitive Radar Facilities

(partial list; there could be others)

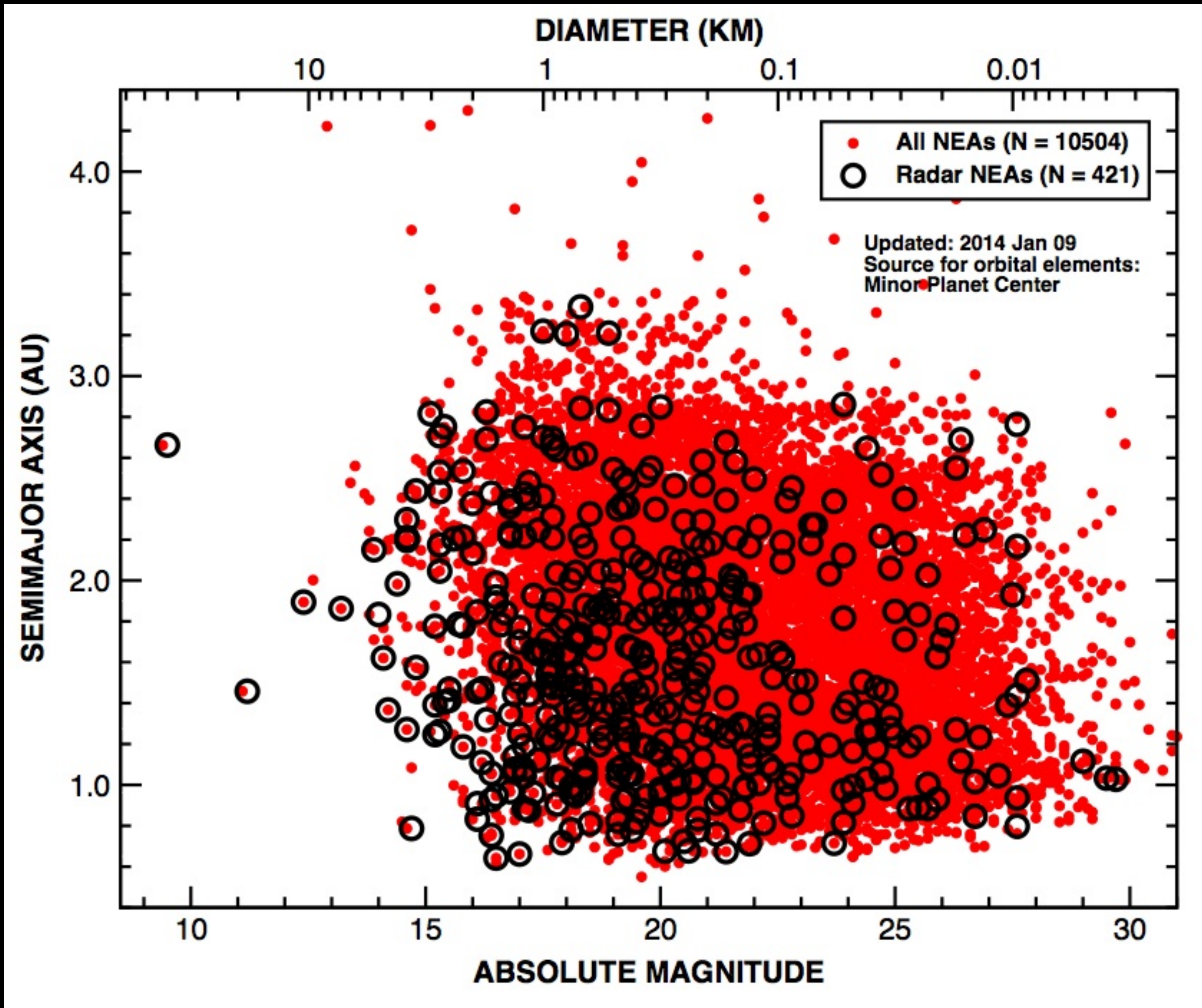
## Telescopes that have detected NEAs

| | |
|---|---|
| Evpatoria | Ukraine |
| Haystack 46m | Massachusetts, USA |
| Haystack 37m | Massachusetts, USA |
| EISCAT | Tromso, Norway |

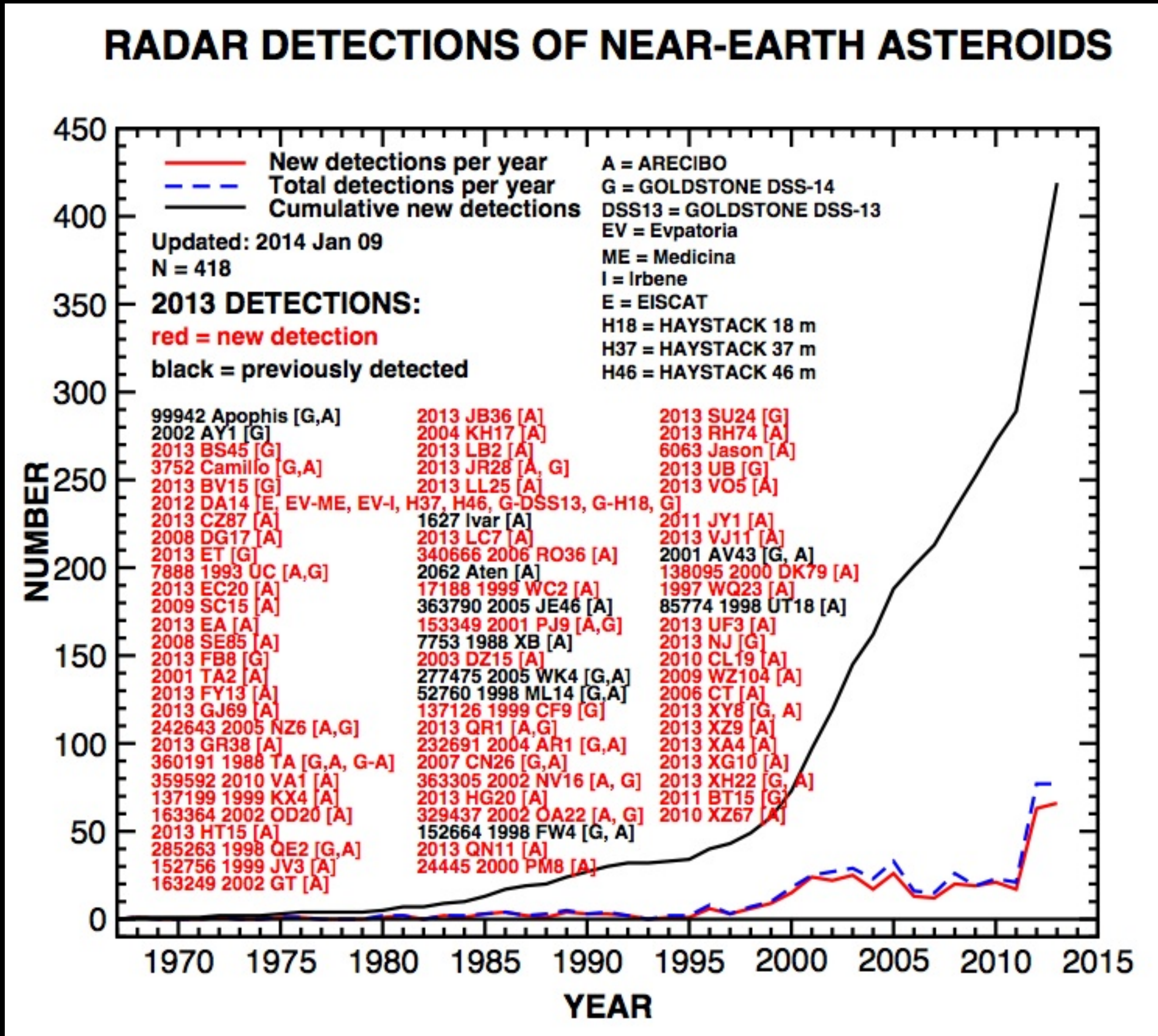
## Others with the potential to detect NEAs

| | |
|---|---|
| TIRA | Germany |
| EISCAT | Svalbard, Norway |
| DSS-13 | Goldstone (34 m, 80 kW) |
| ALTAIR | Kwajalein, Marshall Islands |

# Near-Earth Asteroids Observed by Radar



# NEA Radar Detections Through 2013



# Post-Arecibo Upgrade Radar Detections in Detail

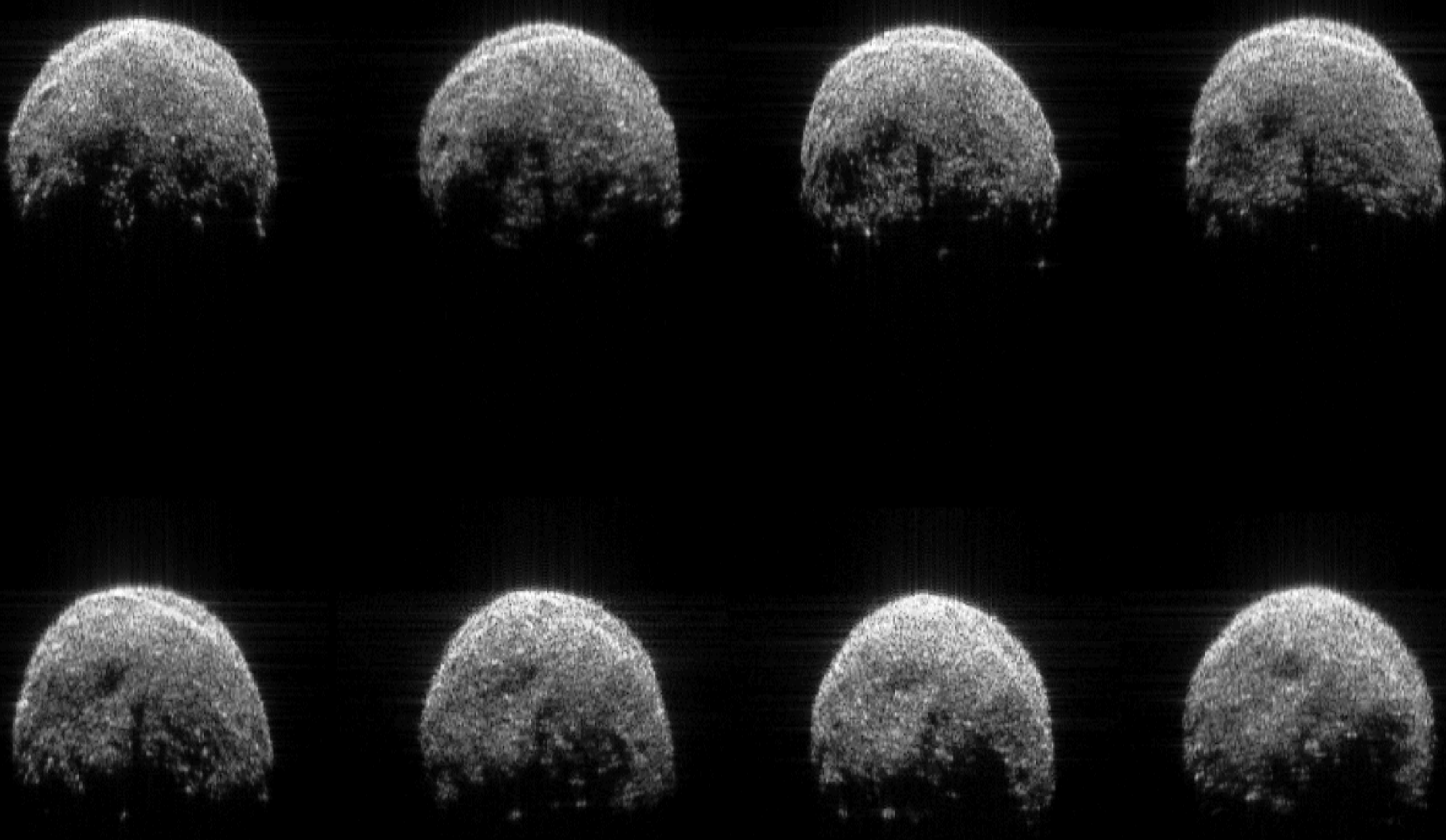
| Year | Arecibo | Goldstone | Both | Total |
|---|---|---|---|---|
| 1998 | 4 | 4 | 1 | 7 |
| 1999 | 7 | 7 | 4 | 10 |
| 2000 | 16 | 7 | 5 | 18 |
| 2001 | 24 | 8 | 7 | 25 |
| 2002 | 22 | 9 | 4 | 27 |
| 2003 | 25 | 10 | 5 | 29 |
| 2004 | 21 | 4 | 3 | 23 |
| 2005 | 29 | 10 | 7 | 33 |
| 2006 | 13 | 7 | 4 | 16 |
| 2007 | 10 | 6 | 2 | 15 |
| 2008 | 25 | 13 | 13 | 26 |
| 2009 | 16 | 14 | 11 | 19 |
| 2010 | 15 | 7 | 0 | 22 |
| 2011 | 21 | 6 | 5 | 22 |
| 2012 | 67 | 26 | 15 | 77 |
| 2013 | 65 | 32 | 20 | 77 |
| 2014 | 3 | 0 | 0 | 3 |

2000-2011 Average: 25

# 2005 YU55: 2011 Nov. 9, Goldstone

Rounded shape, evidence for boulders, an equatorial bulge, and craters

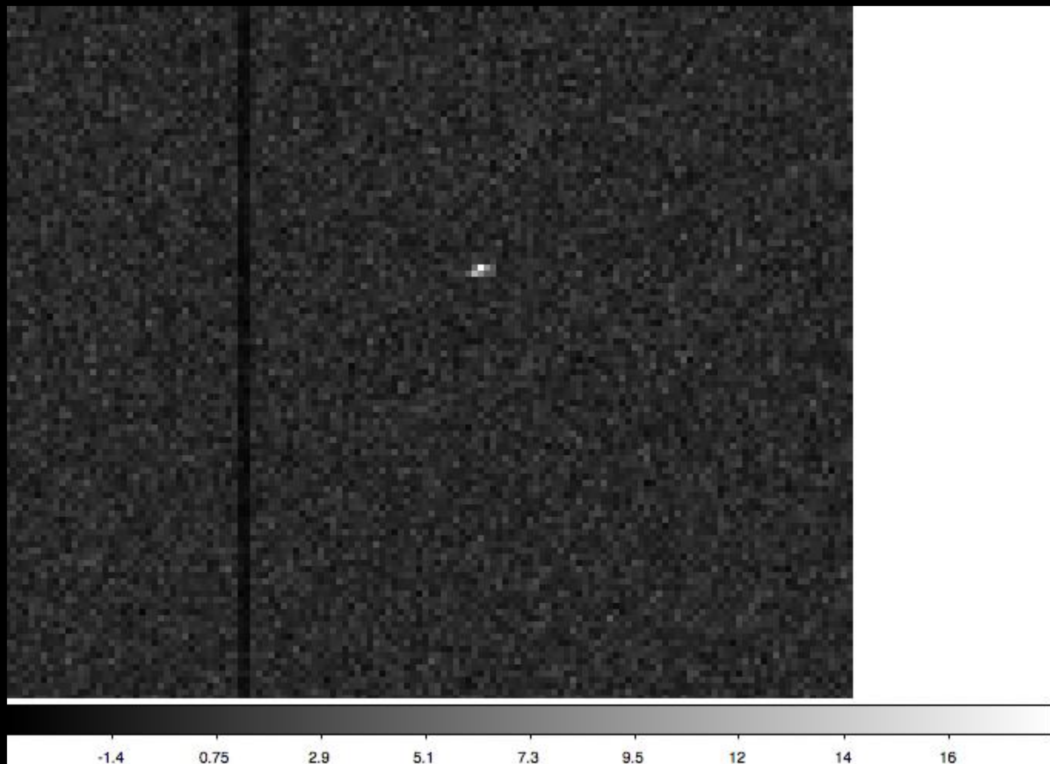
Diameter ~ 360 meters, 1.875 m x 0.005 Hz



Busch et al., in prep.

# Goldstone Detection of 2013 XH22: 2013 Dec. 18

## Resolution = 7.5 meters x 5 Hz




Goldstone chirp radar image of target-of-opportunity 2013 XH22 from December 18. This object is roughly 20 meters in diameter. We observed 2013 XH22 only ~10 hours after we requested telescope time: this was the most rapid time between request to start of observations for any asteroid at Goldstone. The round-trip light travel time to the asteroid was between 5-6 seconds, but even so, the observations were monostatic, and we got three seconds of data with each transmit/receive cycle (as was the case with 2013 XY8 one week earlier).

# Obstacles for Scheduling Radar Observations on Short Notice

1: Is the asteroid in the declination window?

2: Are the SNRs strong enough for a detection?

3: Are the 3$\sigma$ pointing uncertainties small enough (< 20 arcsec)? If not, can optical astrometry improve them sufficiently before the radar observations?

4: Can we schedule telescope time and observing personnel?

5: Goldstone: To transmit full power (450 kW), can we get radiation clearance in time? We can't get it on Saturday or Sunday and it usually takes at least two days. NOTE: this has recently improved.

6: If $\Delta < 0.005$ AU, then we need to receive with a different telescope. Can we schedule DSS-13 or Green Bank?

# Other Thoughts:

How do we select targets?

a. Known objects: mostly from future close approach tables
b. Targets-of-opportunity
    a. MPECs
    b. Future close approach tables
    c. Mike Nolan's script for AO
    d. Alerts from Paul Chodas, Paul Abell, Lindley Johnson
    e. NHATS website

We use detailed ephemerides to estimate SNR/RTT and SNR/day. We prescreen for the strongest targets in general except for ARRM targets and anything particularly important.

Arecibo: Observe targets with SNR/day >10
Goldstone: Observe targets with SNR/day > 30
OCC threshold: varies, but often about 4 or 5 unless prospects for astrometry are OK

TOOs in 2012 (29) & 2013 (29)

Bistatic GSSR->Arecibo X-band observations: already feasible; 4-m imaging in development

# Other Issues

Goldstone can observe at 115 kW without radiation clearance, enabling rapid response, but still need telescope time, observing personnel, small pointing uncertainties, and strong SNRs.

Goldstone schedules fixed months in advance are difficult to change on short notice.

For tiny targets <20 m in diameter, short notice is the biggest problem for scheduling radar observations because most targets will be close enough to detect for only a few days at best.

Maintenance at Arecibo is suffering due to NSF budget cuts.

The VLBA (radar speckle tracking: NEA spin states) and Green Bank (bistatic receiver for very close targets) might close due to NSF budget cuts.

The NSF will probably conduct another review of Arecibo in the next few years.

Goldstone currently has only one functional spare klystron.