

PHYSICAL PROPERTIES OF NEAR-EARTH OBJECTS FROM RADAR OBSERVATIONS

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Arecibo Radar Images of 2000 ET70 (S. P. Naidu et al., submitted)

NEO Radar Community

Founder of the field: Steve Ostro

Lance Benner	JPL/Caltech
Marina Brozovic	JPL/Caltech
Michael Busch	NRAO-Socorro
Jon Giorgini	JPL/Caltech
John Harmon	Arecibo
Observatory	
Ellen Howell	Arecibo Observatory
Chris Magri	Univ. Maine at Farmington
Jean-Luc Margot	UCLA
Mike Nolan	Arecibo Observatory
Shantanu Naidu	UCLA
Dan Scheeres	Univ. of Colorado
Mike Shepard	Bloomsburg Univ.
Martin Slade	JPL/Caltech
Sondy Springmann	Arecibo Observatory
Patrick Taylor	Arecibo Observatory

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, sizes, surface features, spin states, surface roughness and density, regolith, constrain composition; gravitational environments

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

Improve orbits: Very precise. Shrink uncertainties drastically for newly-discovered NEOs. Predict motion for decades to centuries. Radar observations of previously-known NEOs can reduce uncertainties by several tens of percent.



Arecibo: 305 m

Capabilities are complementary



Goldstone
70 m

Status of Arecibo

NASA funding: ~\$2M annually started in 2010

NEO radar program expanded SIGNIFICANTLY:
67 NEA radar detections in 2012

Radar offline from Nov. 2012-Feb. 2013 due to
equipment problems

New radar observer: Alessondra Springmann

New digital receiver to receive 3.75 m chirp
transmissions from Goldstone. First test soon.

NSF Portfolio Review (2012) recommended re-
evaluation of the observatory in five years.

Status of Goldstone

Three-fold increase in NEA observations in 2012

4-m-resolution chirp imaging system has been upgraded and is in routine use

Major refurbishment of DSS-14 in 2010 to extend lifetime by ~20 years

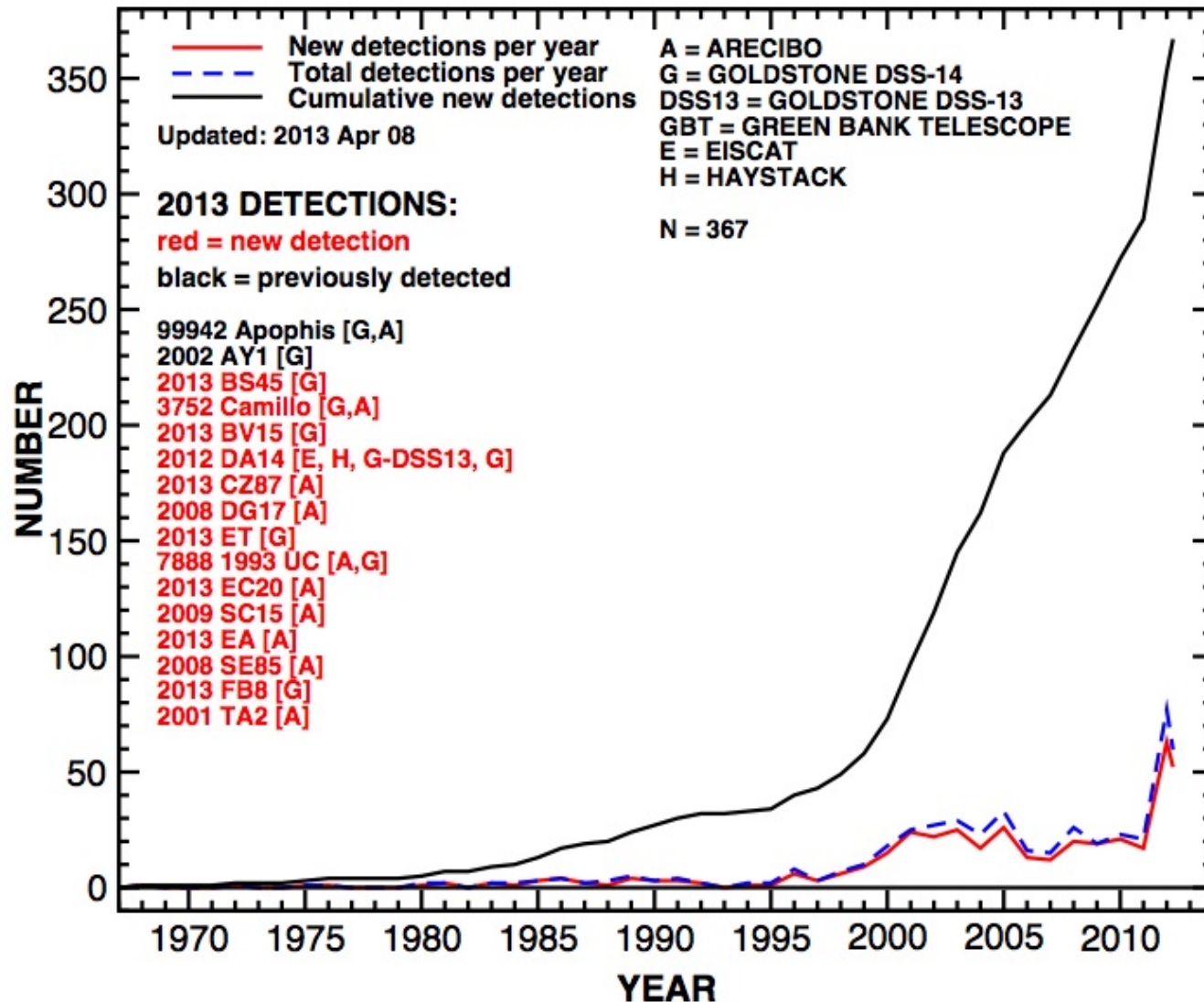
New radar coming later this year to DSS-13: 80 kW, 80 MHz (1.875 meter resolution). Receive at DSS-28 or Arecibo. Niche capability.

Study into building 120 MHz klystrons (1.25 m resolution) for DSS-14: looks feasible

Near-Earth Asteroid Radar Detection History

Big increase starting in late 2011

RADAR DETECTIONS OF NEAR-EARTH ASTEROIDS



2011: 22

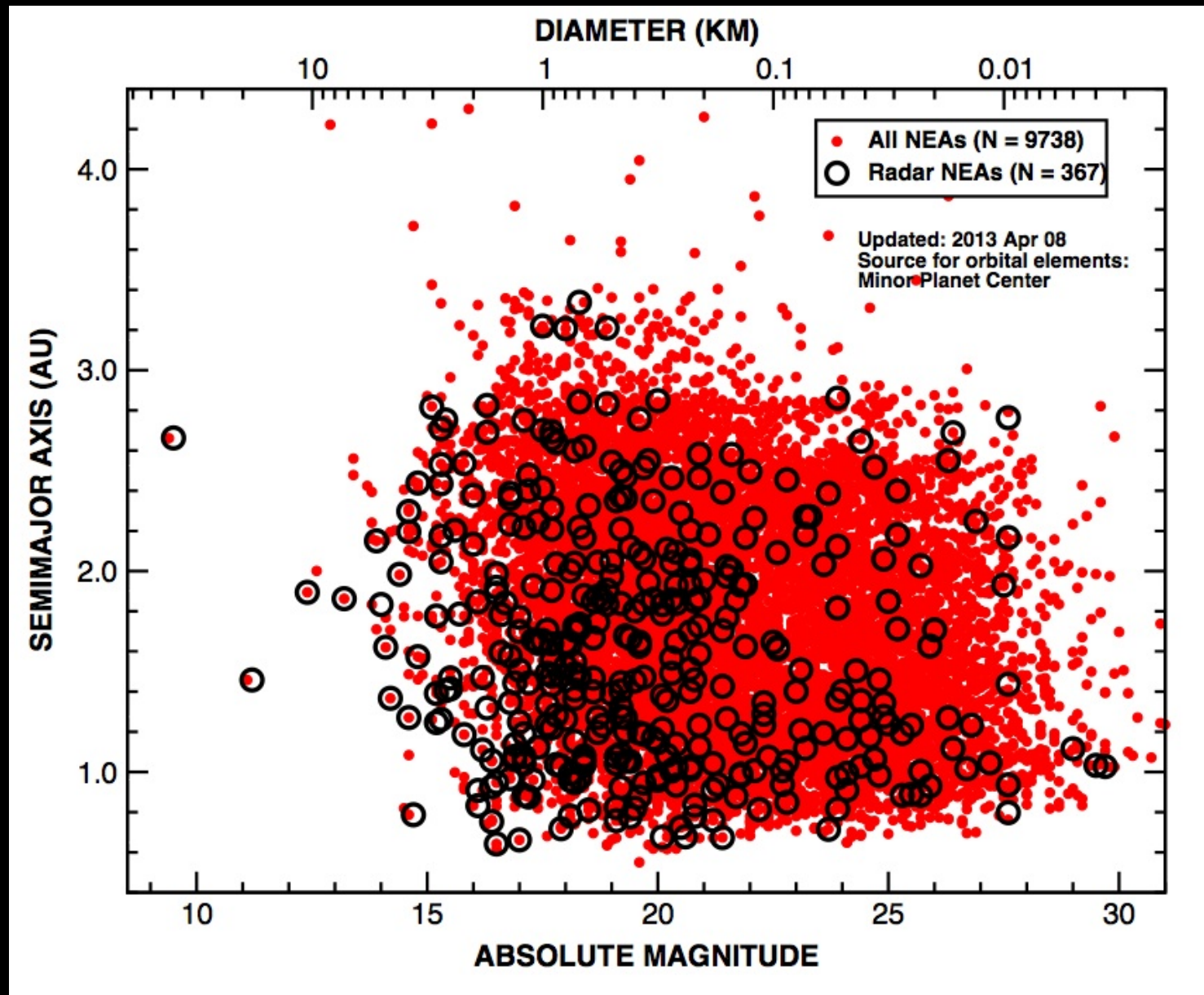
2012: 77

2013: 16

Total:
367

Near-Earth Asteroids Observed by Radar

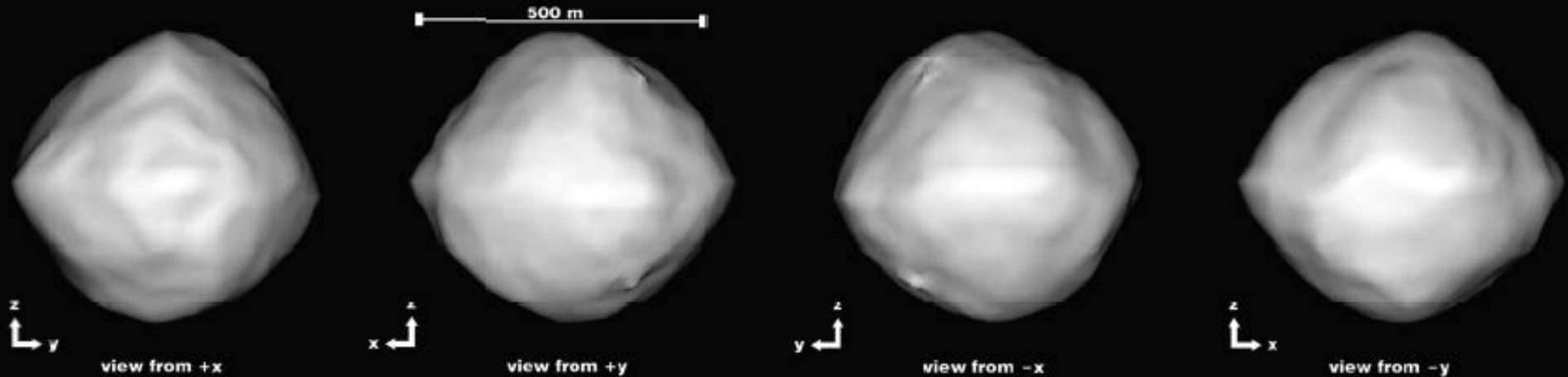
$N = 367$: 199 PHAs, 52 NHATS objects, 37 binaries/triples



$H > 21$: $N = 107$; 29% of all NEAs detected by radar

OSIRIS-REx Mission Target: 1999 RQ36

Equatorial bulge, rounded shape, evidence for a boulder
(Nolan et al., in press)



Yarkovsky effect detection in 2011: $\rightarrow \rho = 0.97 \pm 0.15 \text{ g/cm}^3$
(Chesley et al. 2012)

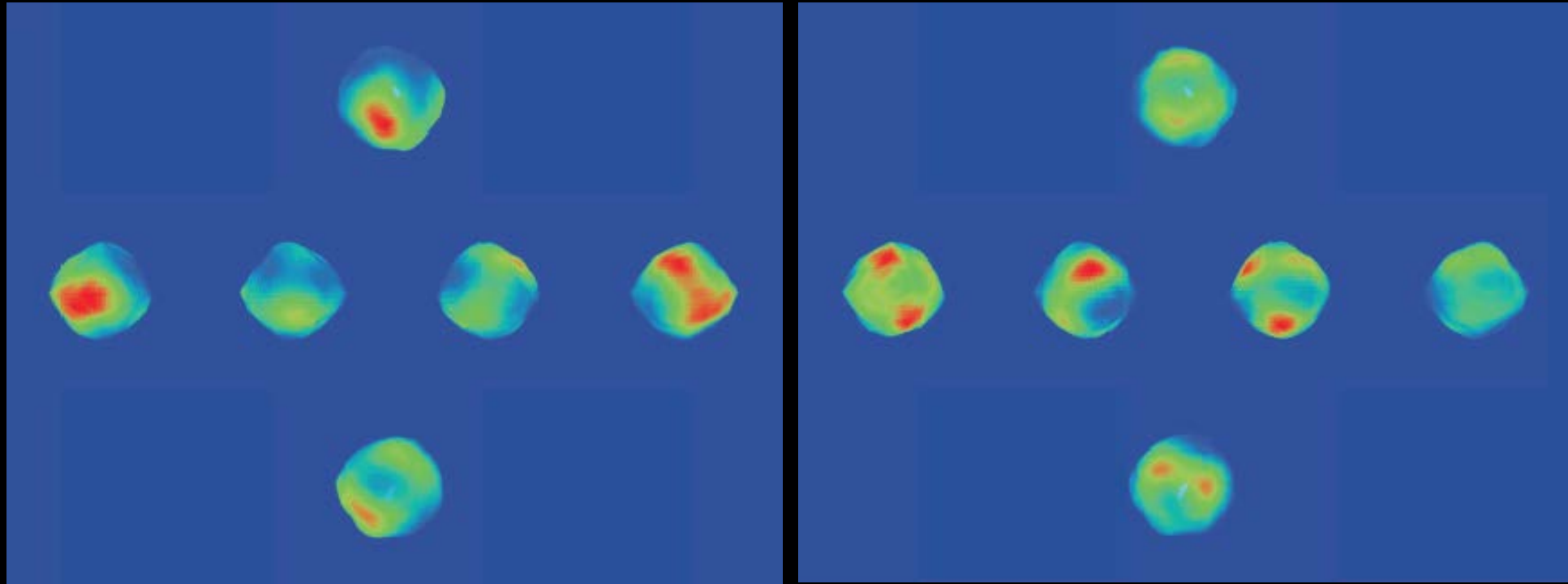
~40 asteroid shape models are available

(101955) 1999 RQ36

Principal axis views

OC Radar Albedo

Circular Polarization Ratio

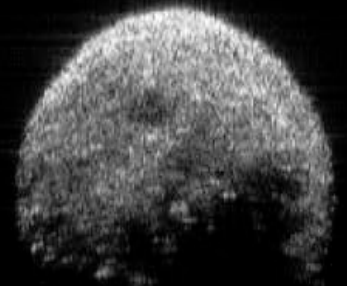
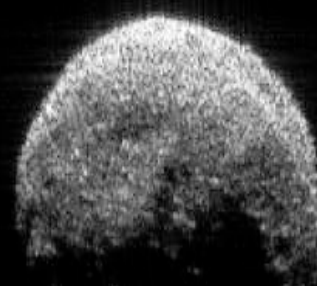
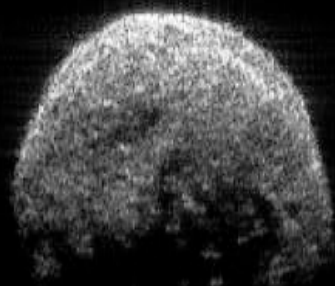
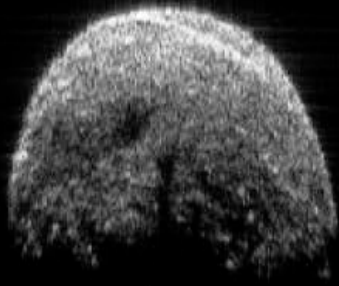
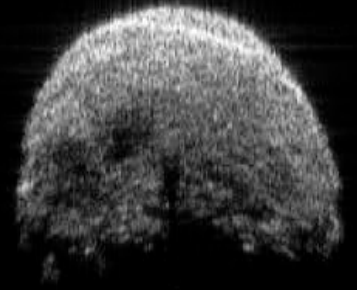
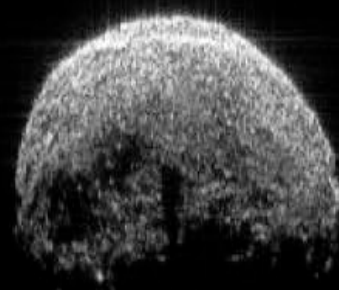
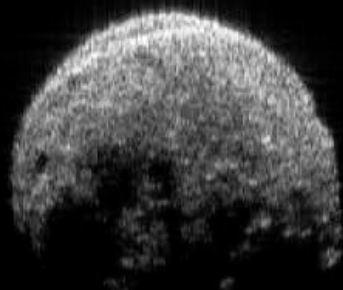
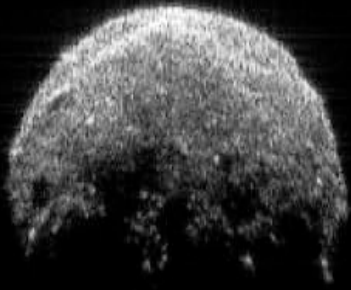


Nolan et al., in press

2005 YU55: 2011 Nov. 9, Goldstone

Evidence for boulders, an equatorial bulge, an craters

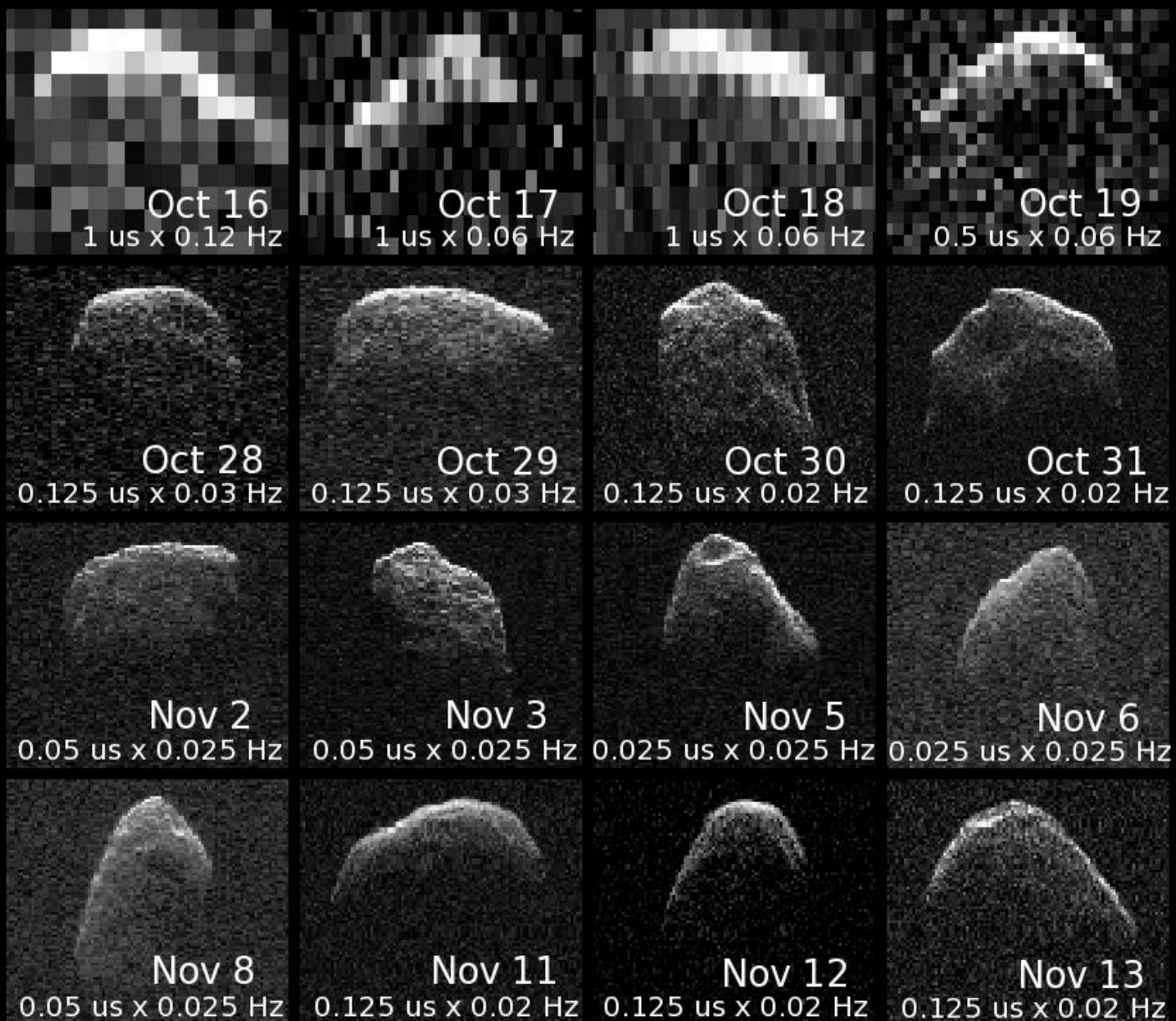
1.875 m x 0.005 Hz



Busch et al., in prep.

(214869) 2007 PA8

Goldstone Radar Images



Brozovic et al., in prep.

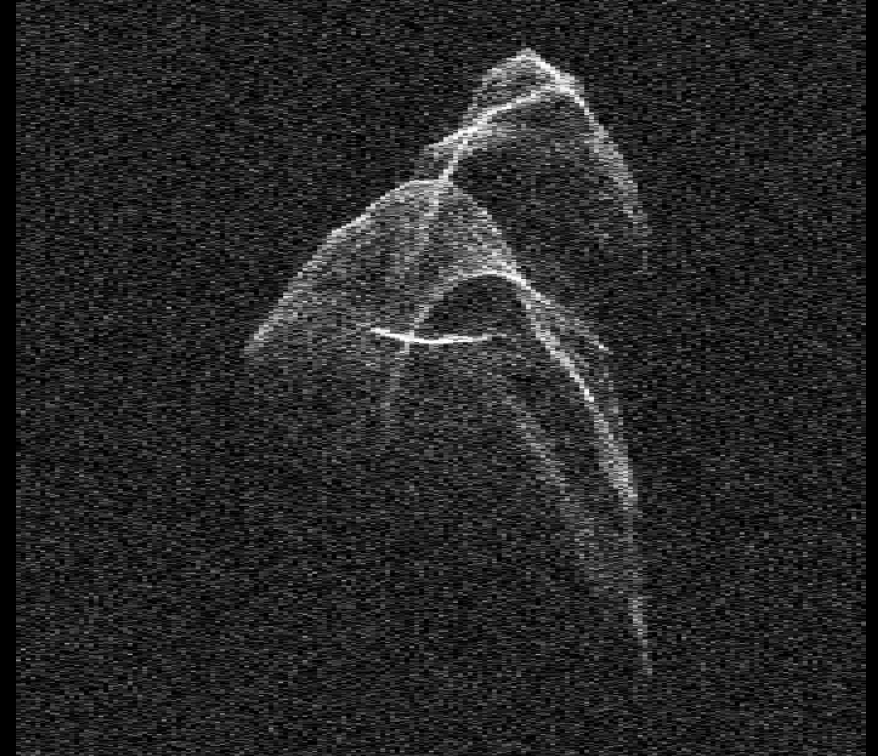
Goldstone Images of 4179 Toutatis, Dec. 2012

Resolution: 3.75 m x 0.025 Hz

Dec. 12



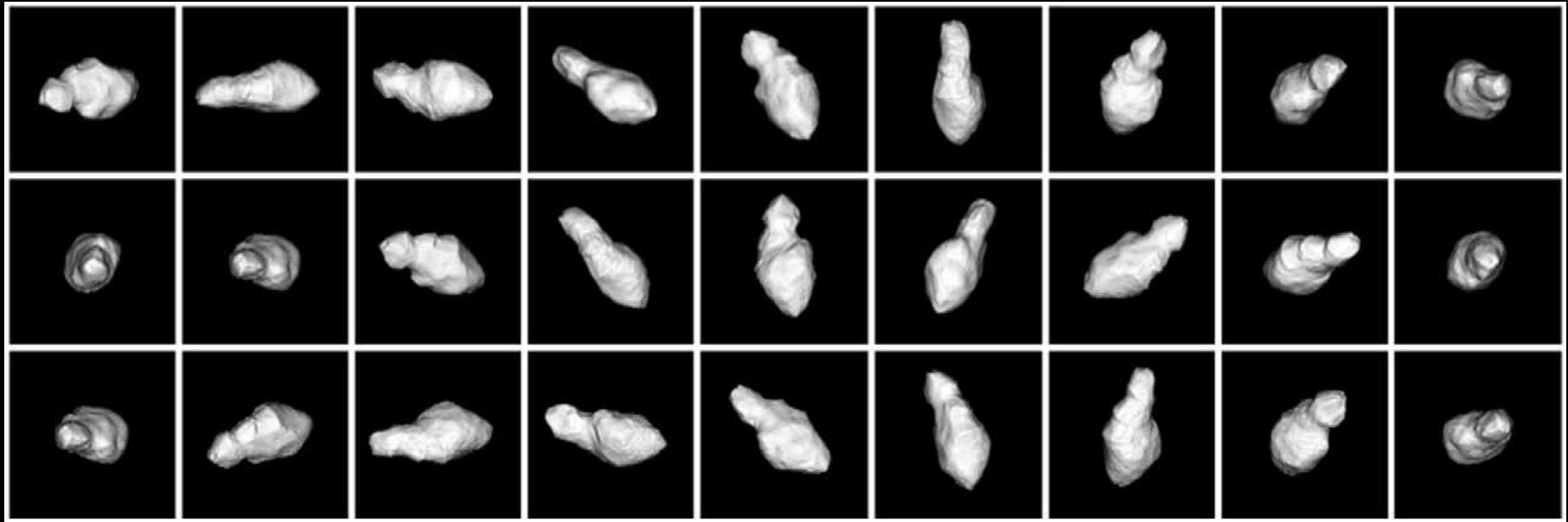
Dec. 13



Spin state changed due to close Earth flybys
(Takahashi et al., Busch et al.)

Ground-truth for Shape models & Non-Principal Axis Rotation

4179 Toutatis (Hudson et al. 2003)



Chang'e 2
spacecraft
images



Toutatis
小行星间隔成像照片

CE-2卫星拍摄

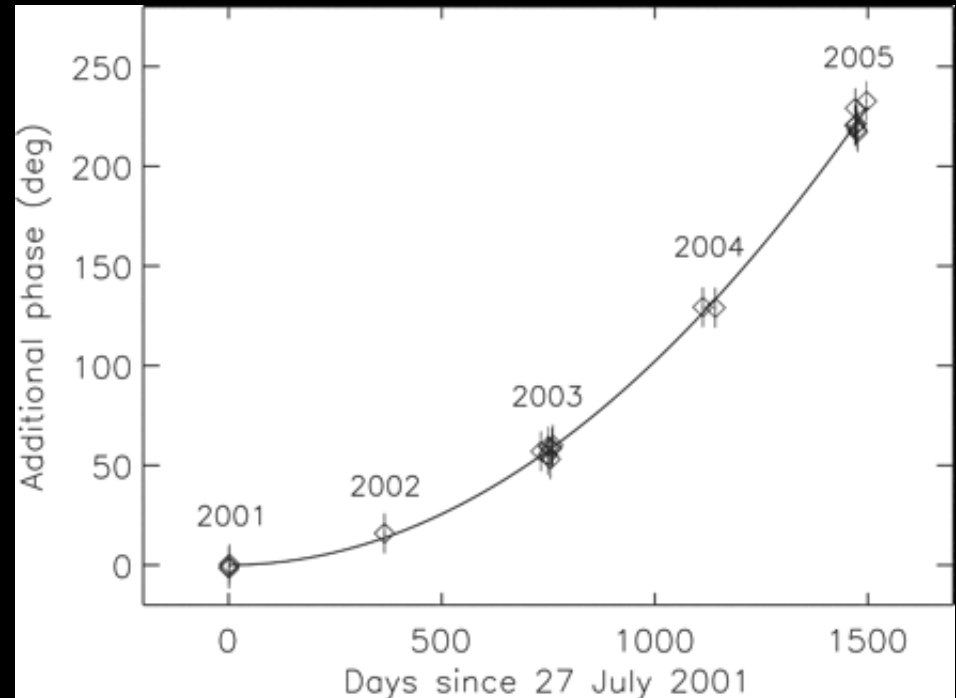
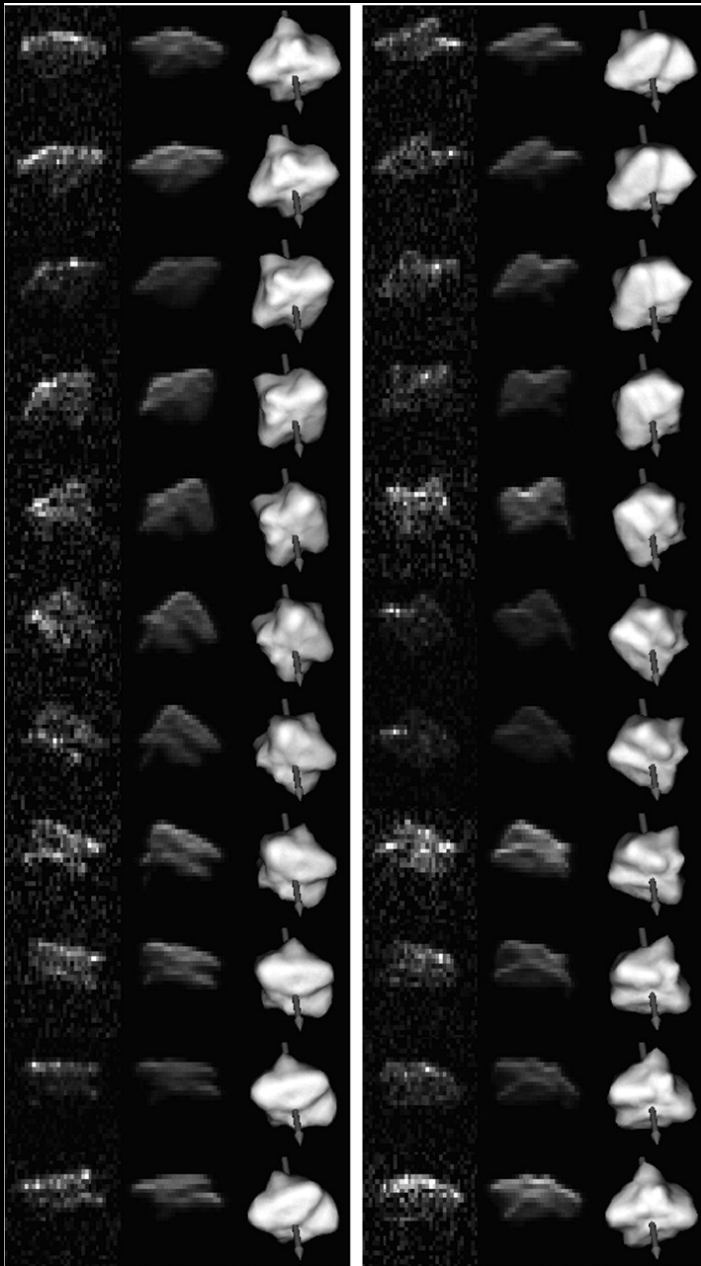
北京时间
2012年12月13日16时30分09秒-24秒
成像距离 93km-240km

■最高分辨率: 10m ■相对速度: 10.73km/s ■交会距离: 3.2km ■到地球: 7,000,000km

@新华视点
weibo.com/xinhuashidian

Accelerating Spin: YORP Effect

54509 YORP



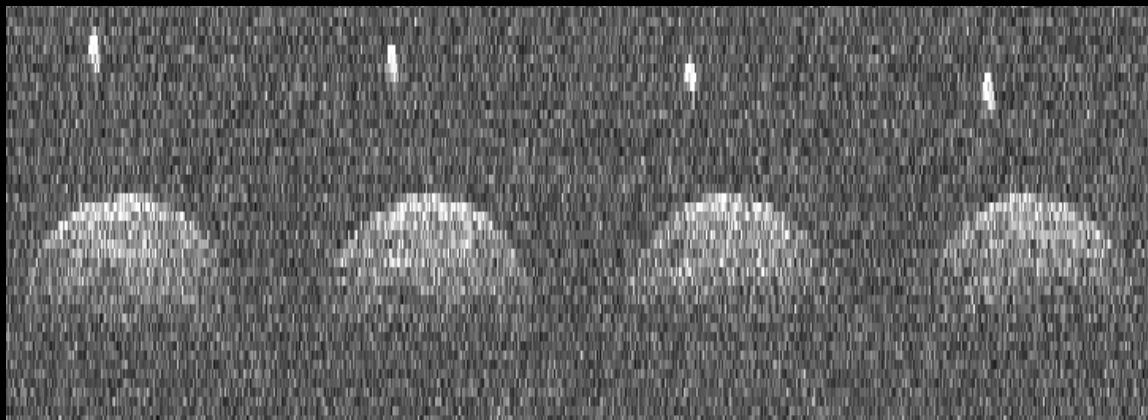
Taylor et al., Lowry et al., *Science* **316**, (2007)

Binaries and Triples

~15% of NEA population >200 m in diameter (Margot et al. 2002)

Binary 1996 FG3

Arecibo, Nov 2011

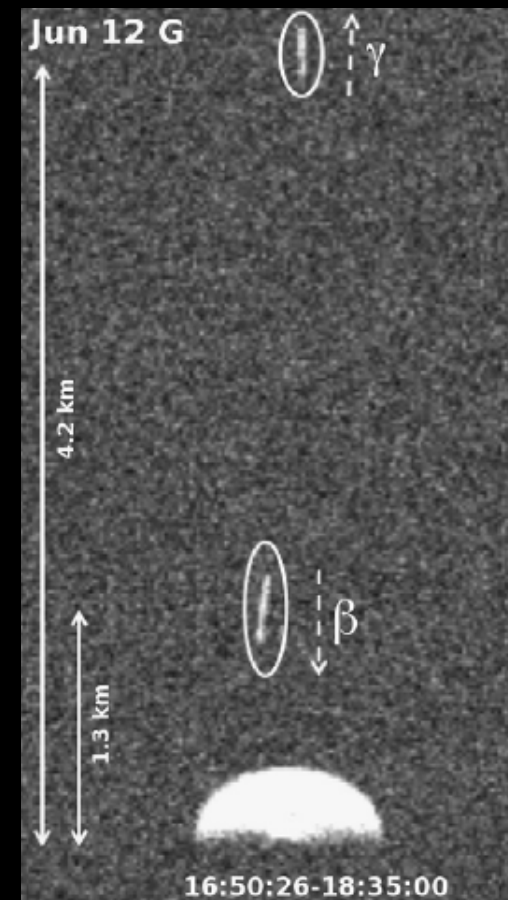


Benner et al., in prep.

Binaries and triples provide masses and bulk densities; some show complex dynamics

Triple 1994 CC

Goldstone, Jun 2009



Brozovic et al. 2011

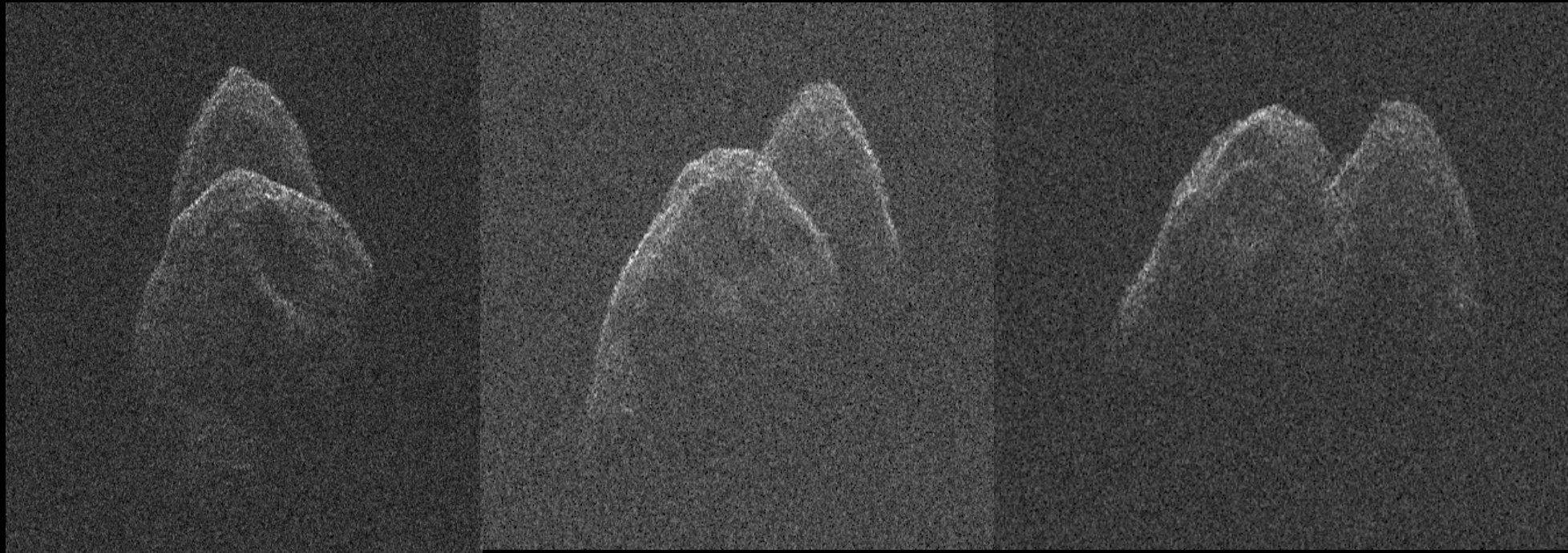
Contact Binaries: ~10-15% of NEA Population

1999 RD32, Arecibo, February 2012, range resolution = 7.5 m

March 6

March 7

March 8



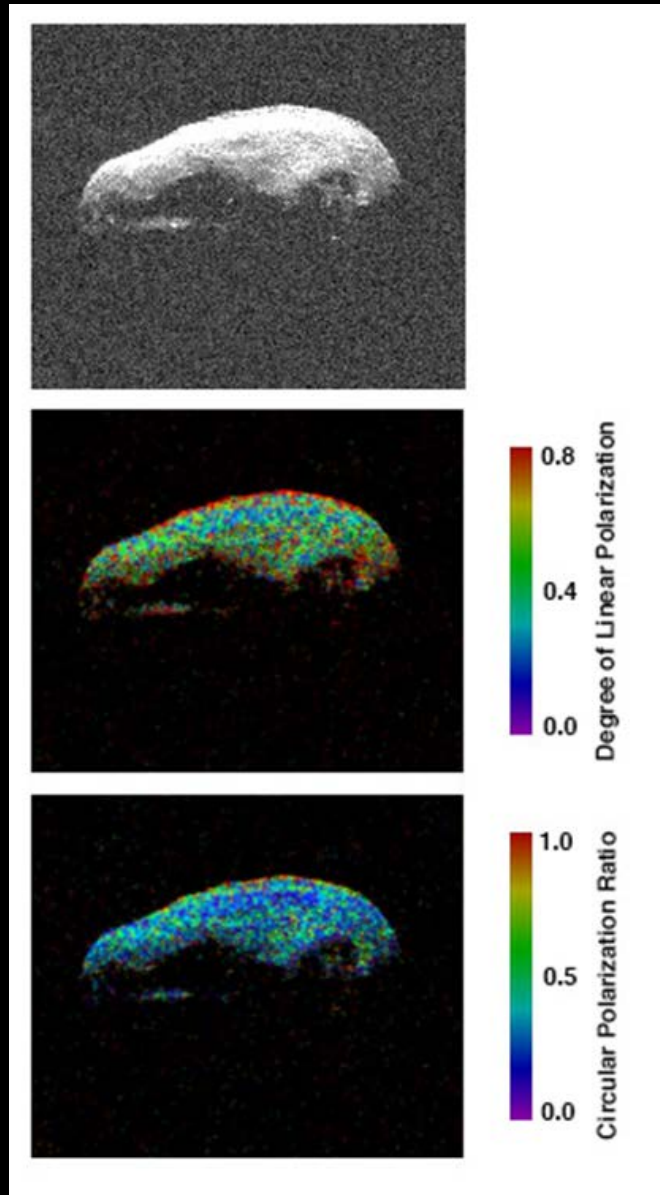
Long axis: ~ 7 km

P ~ 26 h

(Nolan et al., in prep.)

Regolith Distribution from Polarimetry

2006 VV2 (Arecibo-Green Bank data), range resolution = 15 m



OC Delay-Doppler image

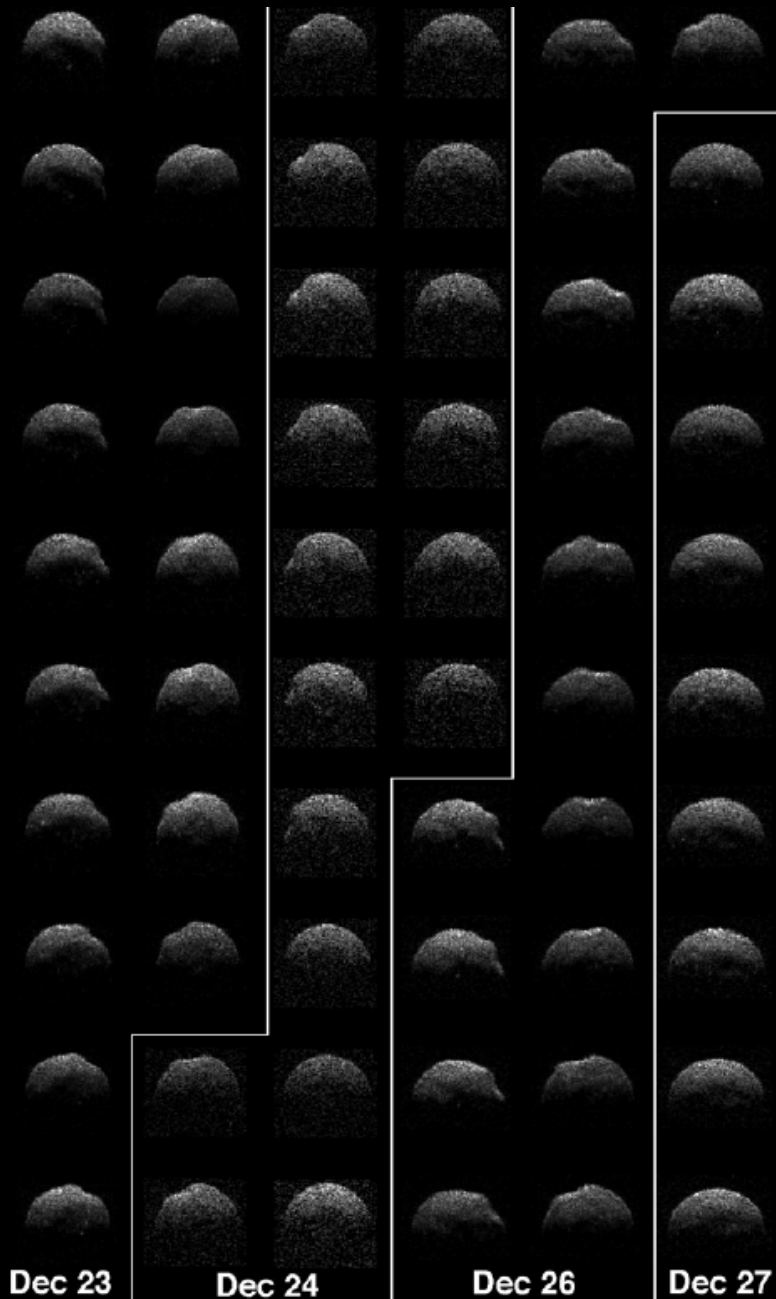
Degree of linear polarization

Circular polarization ratio

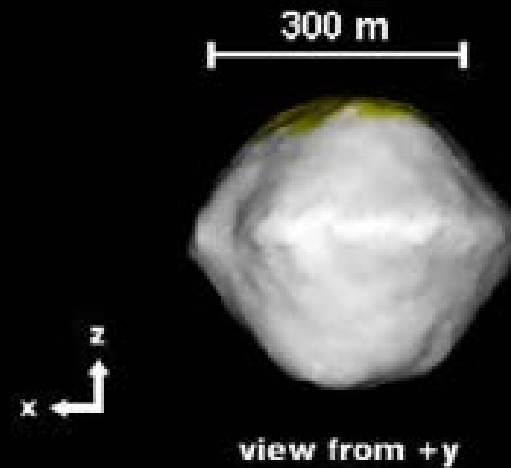
(Carter et al., in prep.)

2008 EV5: *Marco Polo-R* Mission Target

Arecibo Images



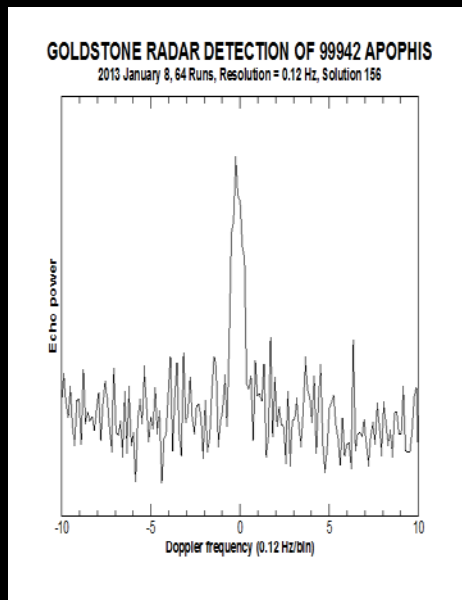
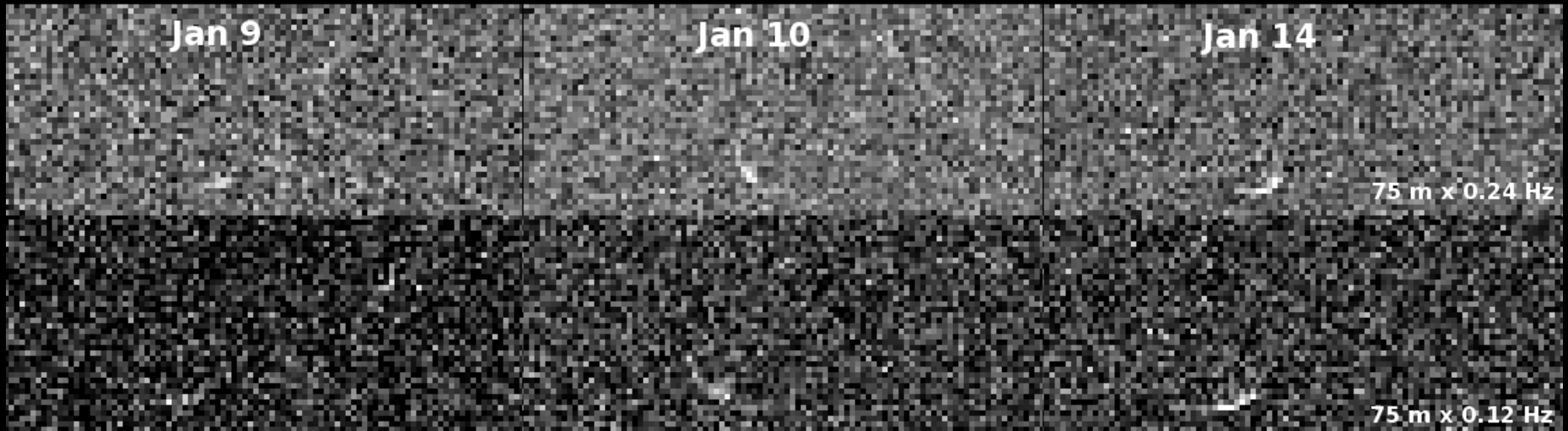
Pole estimated with
Radar Speckles



Busch et al. 2011

99942 Apophis

99942 Apophis, Goldstone Radar Images



Goldstone radar astrometry ruled out any chance of an Earth impact in 2036.

Reliable orbit estimation into the 2060s

More radar observations are planned in June, 2013 at Arecibo.

Non-principal axis rotator: Pravec et al.

Asteroid 2012 DA14

Close Approach = 34,400 km (0.09 lunar distances) on Feb. 15

D ~ 50 meters

Closest approach known in advance by something this large

Goldstone radar observations: Feb. 16, 18, and 19

Asteroid 2012 DA14: Earth Close Approach,
Feb. 15, 2013

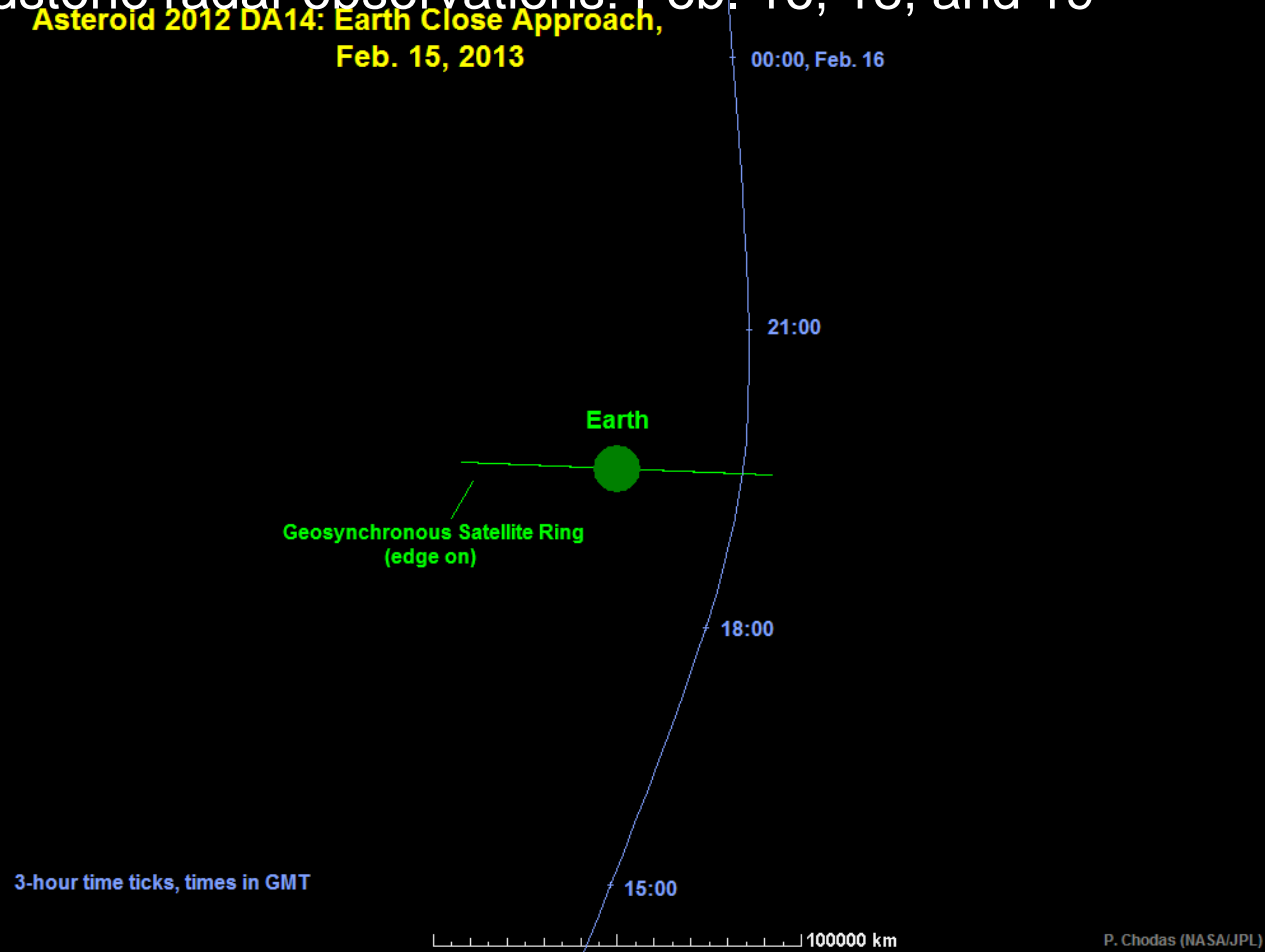
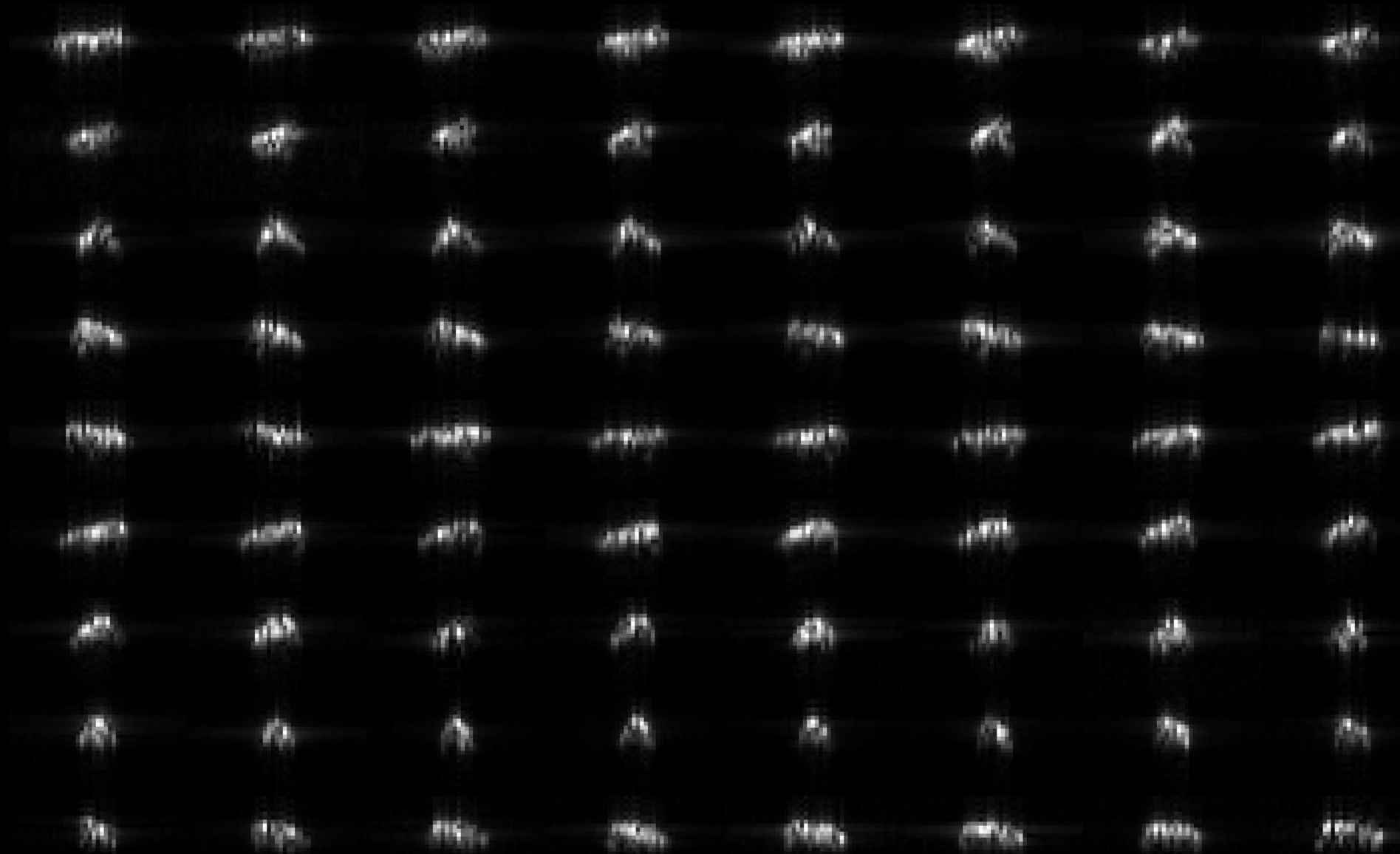


Figure credit: Paul Chodas

Goldstone Radar Images of 2012 DA14

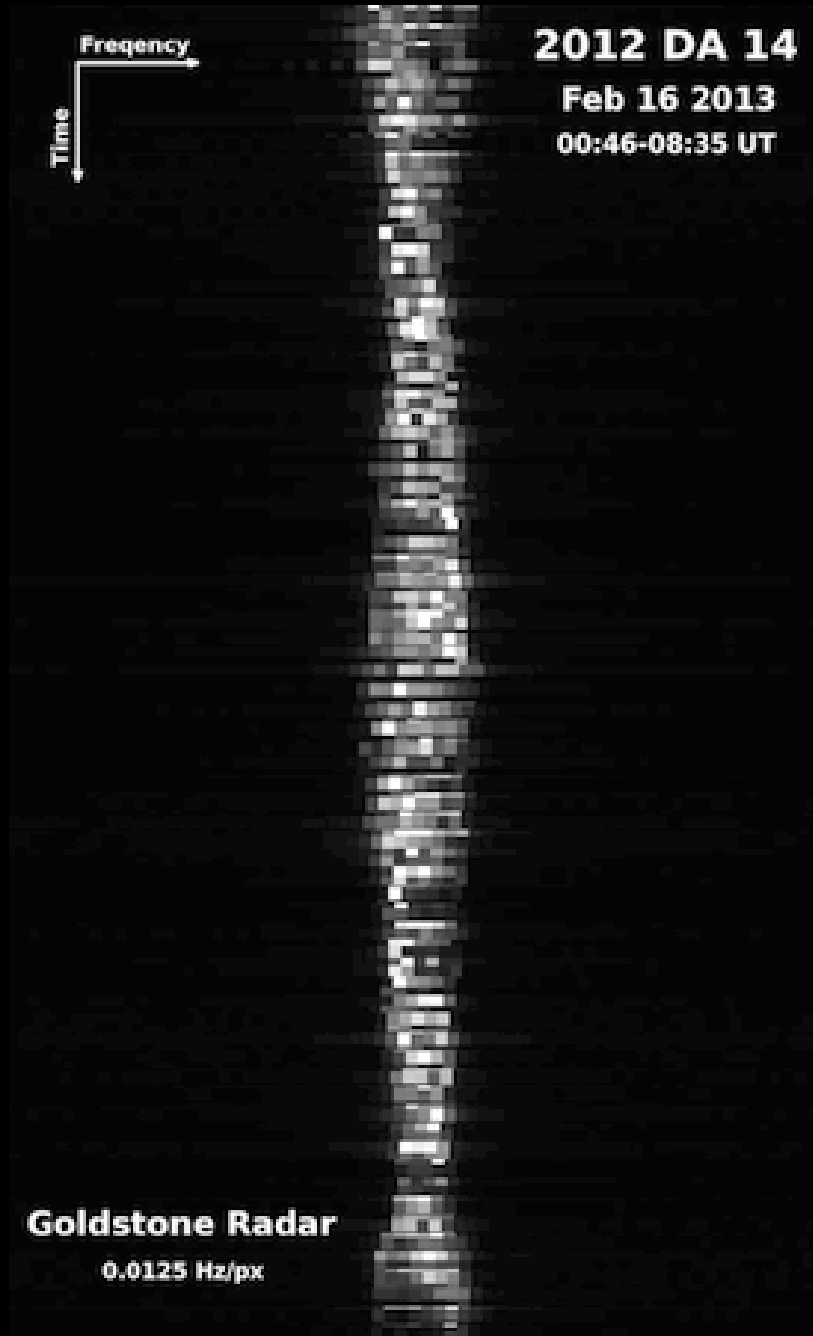
2013 Feb. 16, 1.875 m x 0.0125 Hz



Elongated, angular object: roughly 40 m x 20 m

$P_{>} = 8$ h

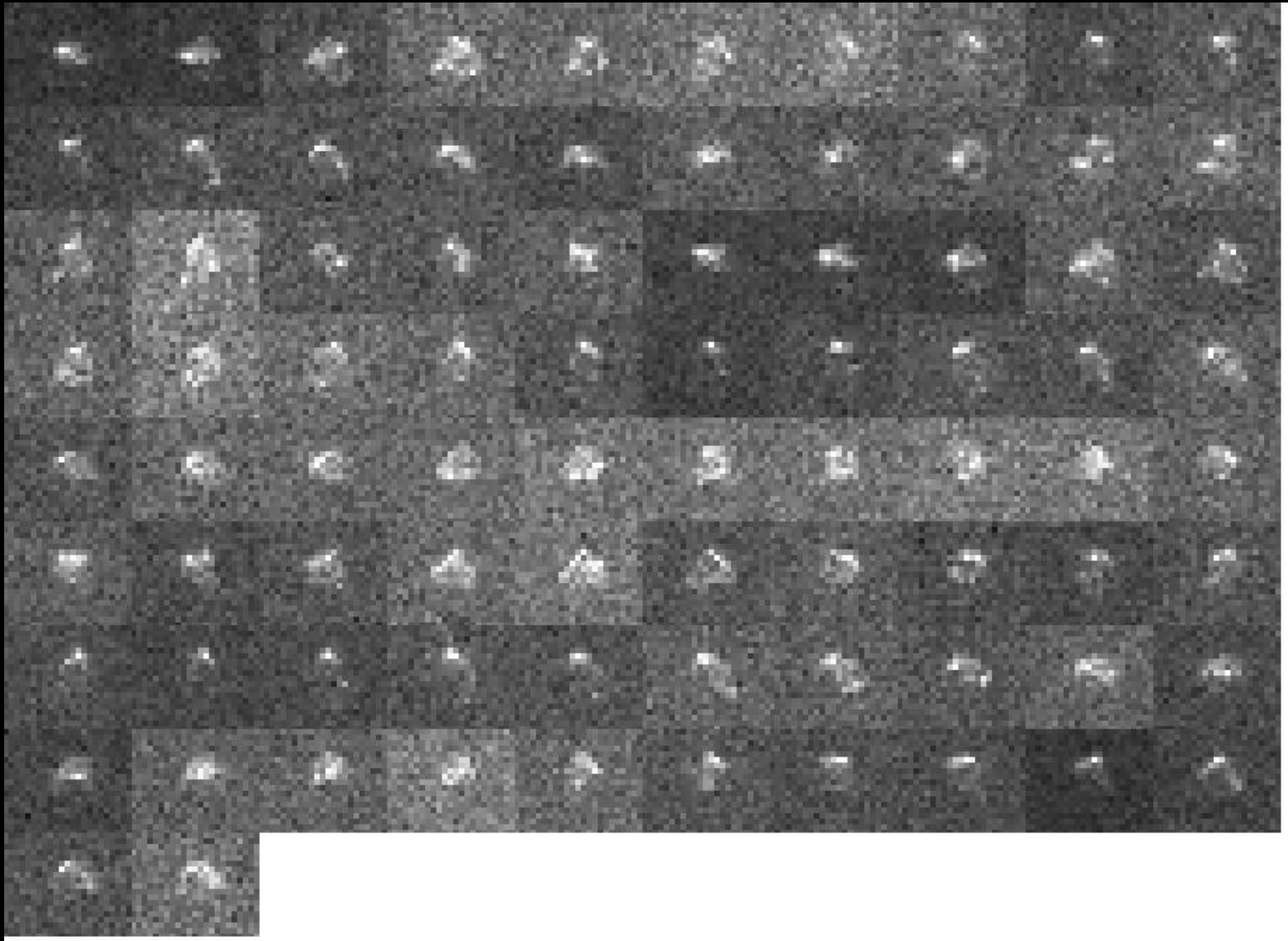
2012 DA14 Images Stacked Vertically



Also detected by radar at:
EISCAT(Norway)
Haystack (Massachusetts)

Goldstone Radar Images of 2013 BV15

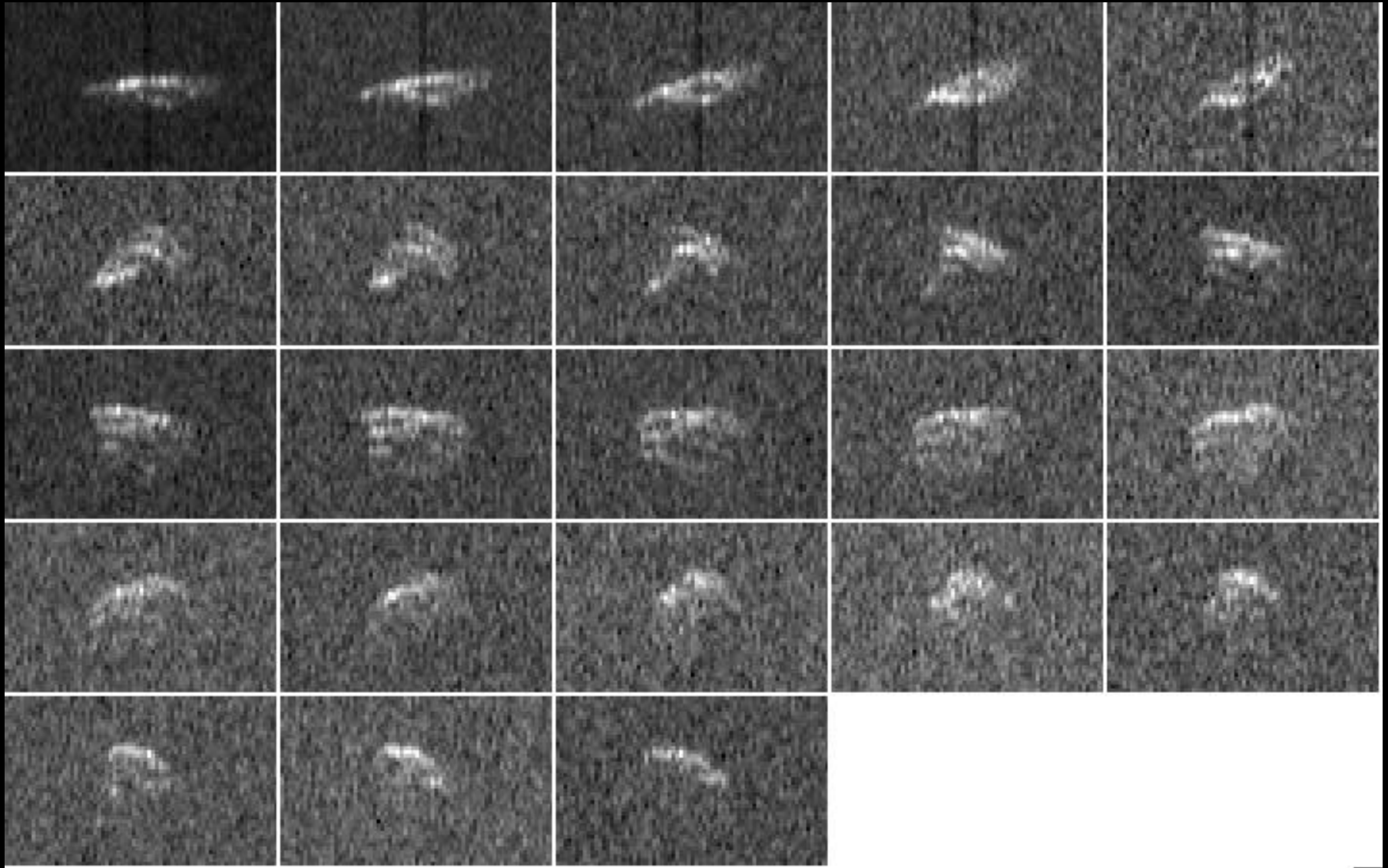
2013 Feb. 12, resolution = 3.75 meters x 1.0 Hz



$P = 0.49$ h (Bill Ryan, pers. comm.)

2013 ET: 2013 March 10, Goldstone

1.875 m x 0.015 Hz



Upcoming NEA Radar Targets

Apr	2005 NZ6	A G	Sep	2002 NV16	A G
May	1988 TA	A G	Sep	1998 FW4	A G
Jun	2002 OD20	A G	Sep	2002 OA22	A G
Jun	1998 QE2	A G	Nov	2001 AV43	A G
Jun	1999 JV3	A	Nov	2000 DK79	A
Jun	2004 KH17	A	Nov	1998 UT18	A
Jun	2006 RO36	A	Dec	1997 WQ23	A
Jun	1999 WC2	A	Dec	2006 CT	A
Jun	Aten	A	Dec	2000 WZ104	A
Jun	2002 GT	A			
Jun	Apophis	A			
Jul	2010 AF30	A			
Jul	Ivar	A			
Jul	2001 PJ9	A G			
Jul	1988 XB	A			
Aug	2005 WK4	A G			
Aug	1999 CF9	A G			
Aug	1998 ML14	A G			
Aug	2007 CN26	A G			
Aug	2004 AR1	A G			

Plus targets-of-opportunity

More Information:

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Asteroid Radar Research Website:

<http://echo.jpl.nasa.gov/>

Asteroid and Comet Missions

Supported by Radar Observations

NEAR 433 Eros, 253 Mathilde, 4660 Nereus

Hayabusa 25143 Itokawa, 4660 Nereus

EPOXI Comet Hartley 2

Clementine 1620 Geographos

Dawn 4 Vesta, 1 Ceres

Rosetta 21 Lutetia

Chang'e 2 4179 Toutatis

OSIRIS-REx 1999 RQ36

Deep Impact 2002 GT (Arecibo, June 2013)

Proposed Missions: *Marco Polo-R* (2008 EV5, 1996 FG3), *AIDA* (Didymos),
BASiX (Didymos), *Amor* (2001 SN263), *Deep Interior*
(Nyx),