PLANETARY RADAR AND NEAR-EARTH OBJECTS

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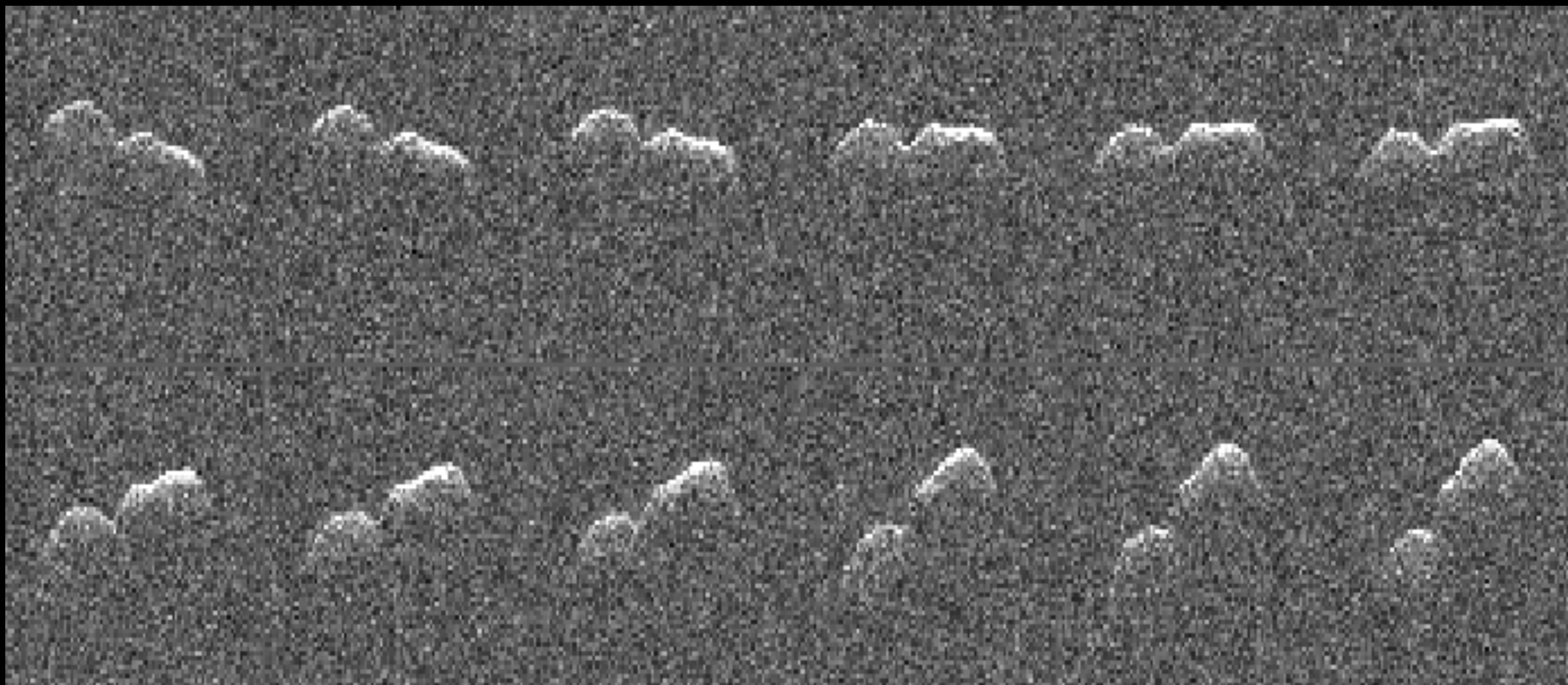


Arecibo Radar Images of Asteroid 11066 Sigurd

Why Are Near-Earth Asteroids Important?

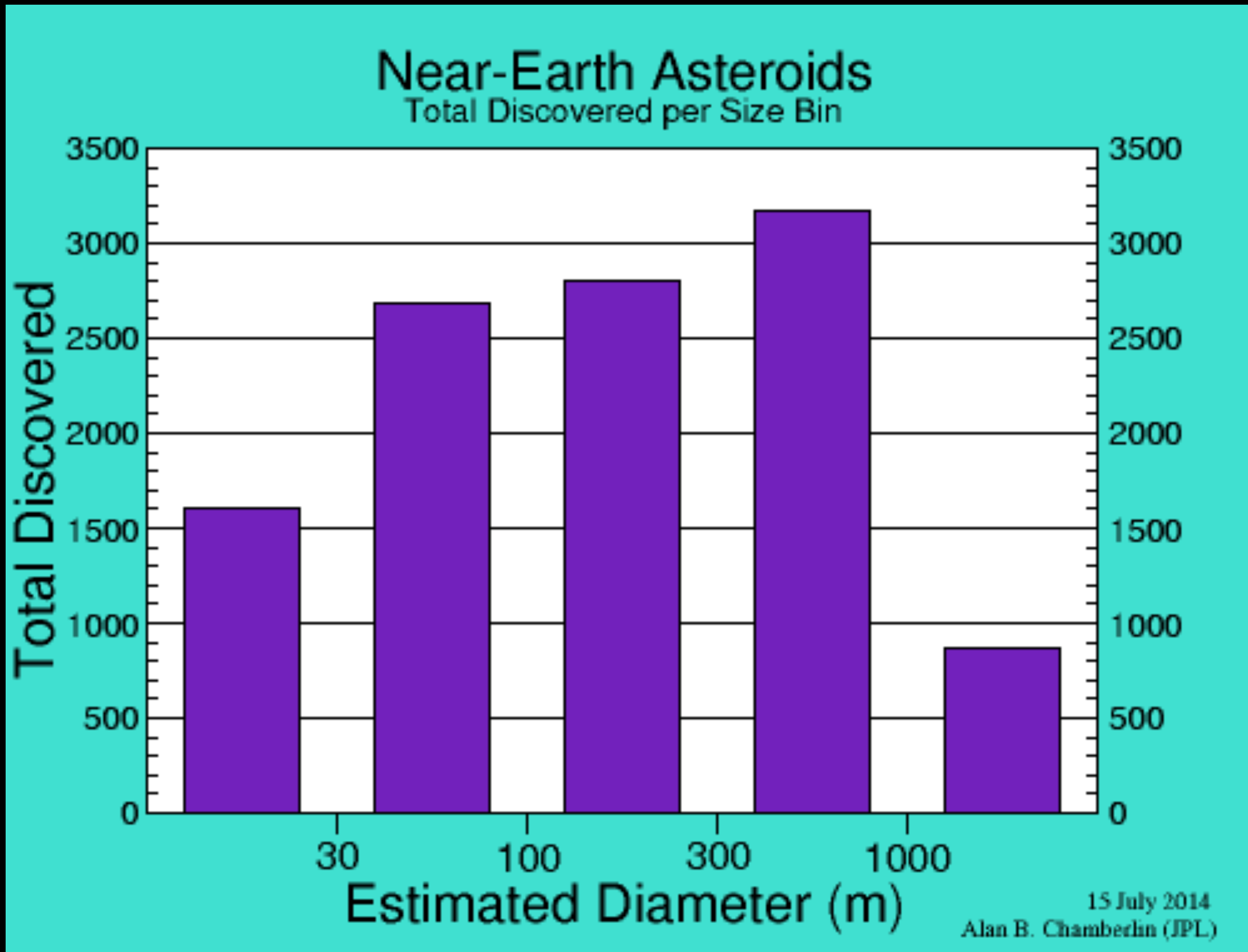
1. Earth impact hazard; key role in inner solar system geologic history
2. Long-term orbital motion and physical properties are coupled through the Yarkovsky effect
3. Source of meteorites
4. Delivery of volatiles and amino acids to Earth
5. Try to understand their formation and geologic evolution.
6. Some are dormant or dead comets
7. Resources: metals and water
8. Targets of robotic and future human missions

How Many Near-Earth Asteroids Exist?

Diameter	Number	Impact Frequency
1 km	940	1 million years
100 m	20,000	10,000 years
10 m	millions	10 years

11504 NEAs have been discovered

(as of 23 October 2014)



Why Use Radar?

Radar is a very powerful astronomical technique for characterizing near-Earth objects and for improving their orbits

What Can Radar Do?

Study physical properties: Image objects with 4-meter resolution (more detailed than the *Hubble Space Telescope*), 3-D shapes, sizes, surface features, spin states, regolith, constrain composition, and gravitational environments

Identify binary and triple objects: orbital parameters, masses and bulk densities, and orbital dynamics

Improve orbits: Very precise and accurate. Measure distances to tens of meters and velocities to cm/s. Shrink position uncertainties drastically. Predict motion for centuries. Prevent objects from being lost.

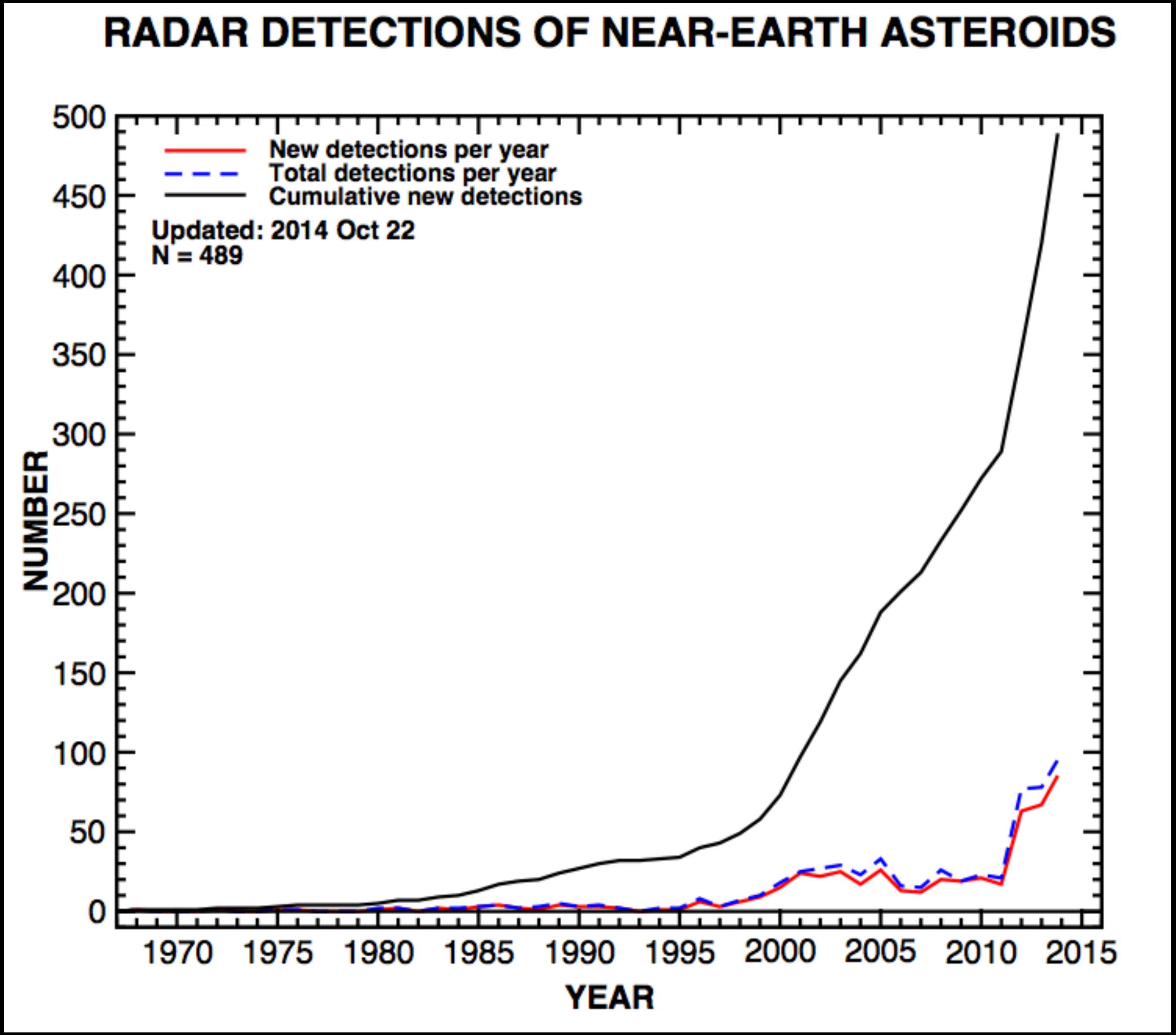
→ Radar Imaging is like a spacecraft flyby

Radar Telescopes

Arecibo
NSF, NASA
Puerto Rico
Diameter = 305 m

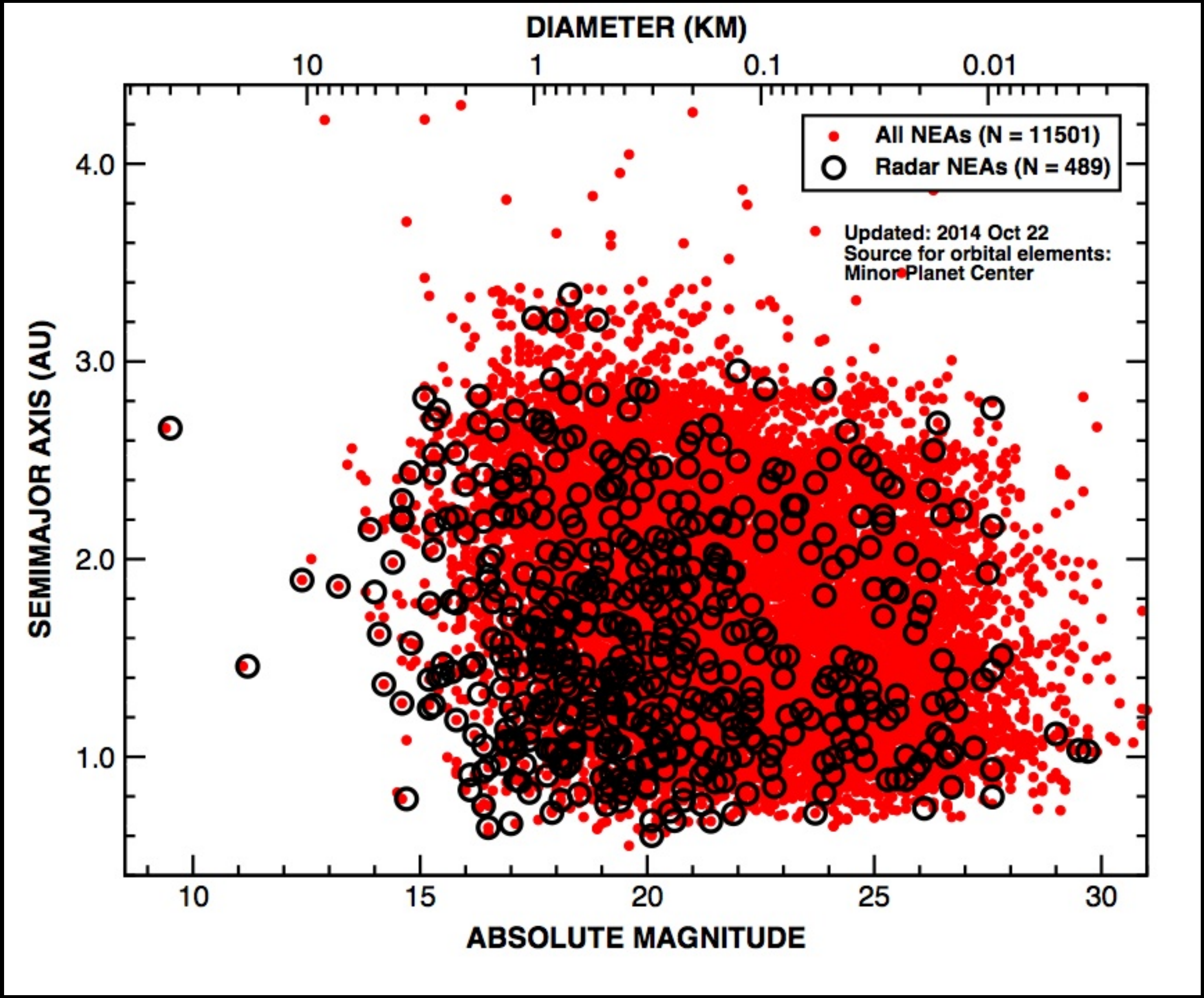
Goldstone
NASA
California
Diameter = 70 m

~20% of the sky has no coverage

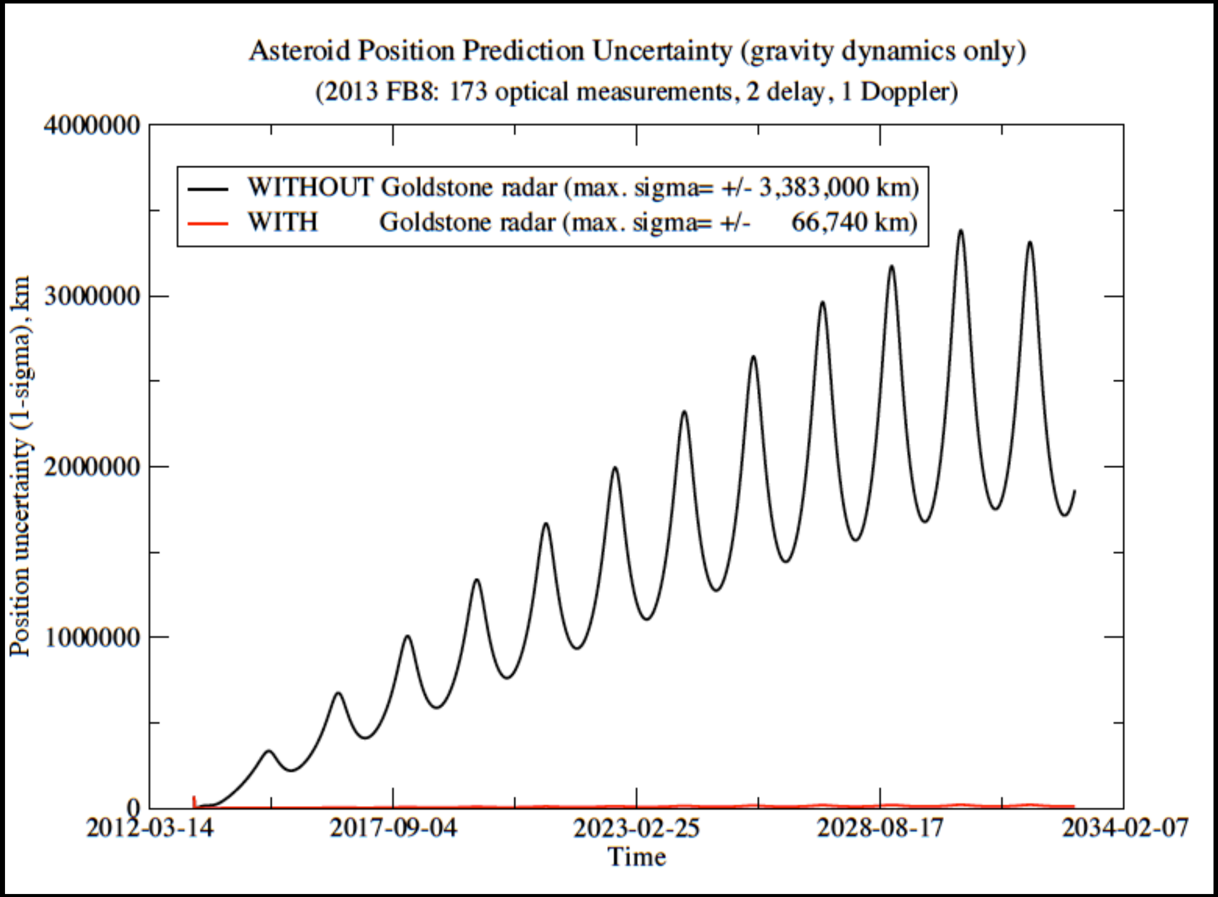


RADAR DETECTIONS OF NEAR-EARTH ASTEROIDS
New detections per year
Total detections per year
Cumulative new detections
Updated: 2014 Oct 22
N = 489
NUMBER
YEAR
0
50
100
150
200
250
300
350
400
450
500
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015

Near-Earth Asteroids Detected by Radar



Orbit Improvement Example: 2013 FB8



For newly-discovered asteroids, radar can enable computation of trajectories for centuries farther into the future than is possible otherwise

Figure credit: Jon Giorgini, JPL

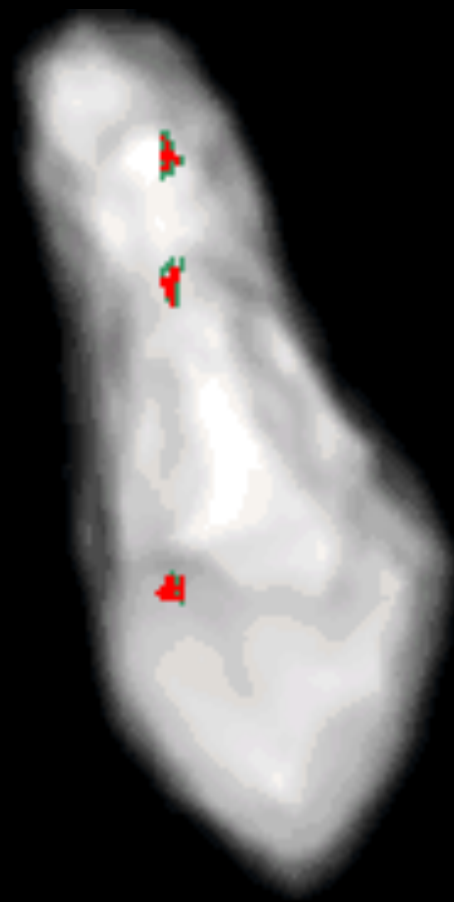
Radar Image Geometry

Radar Image

↓ Distance

Doppler frequency →

Asteroid as seen by eye

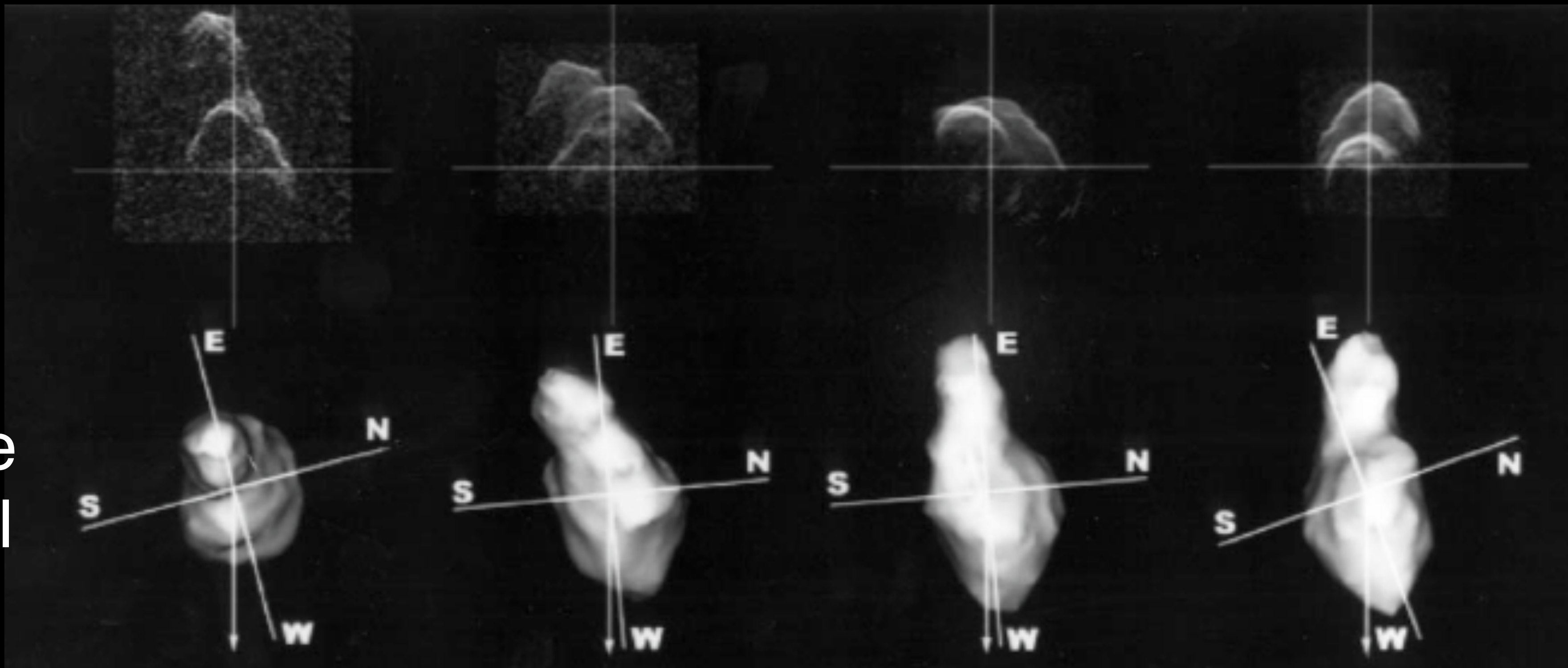


NOT the same as images from digital cameras!

3-D Shapes: Toutatis

Data

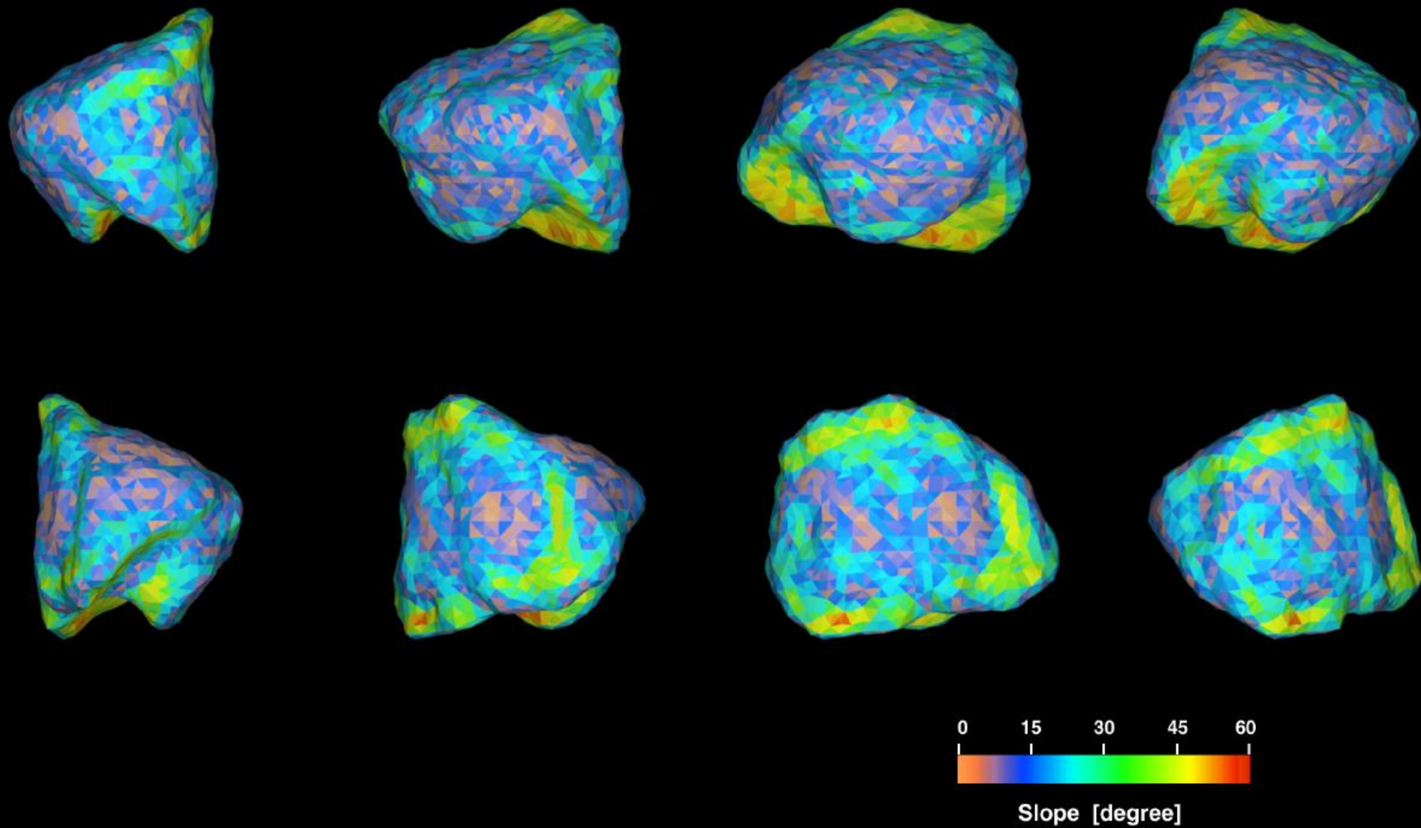
Shape Model



~45 shape models are available or in preparation

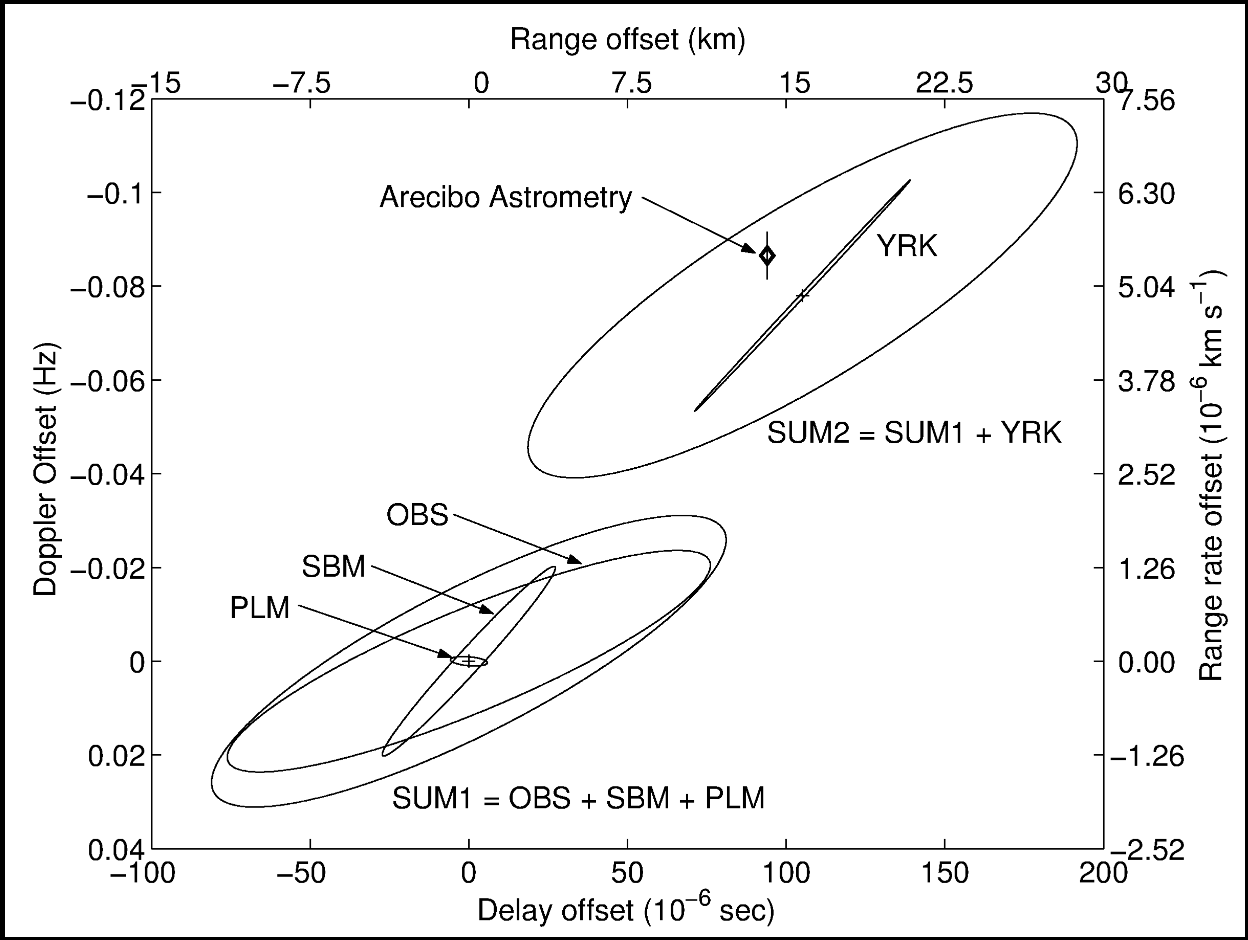
Ostro et al. 1999

Gravitational Slopes: Golevka



Hudson et al. 2000

Detection of the Yarkovsky Effect by Radar Ranging: Mass and Density of Golevka

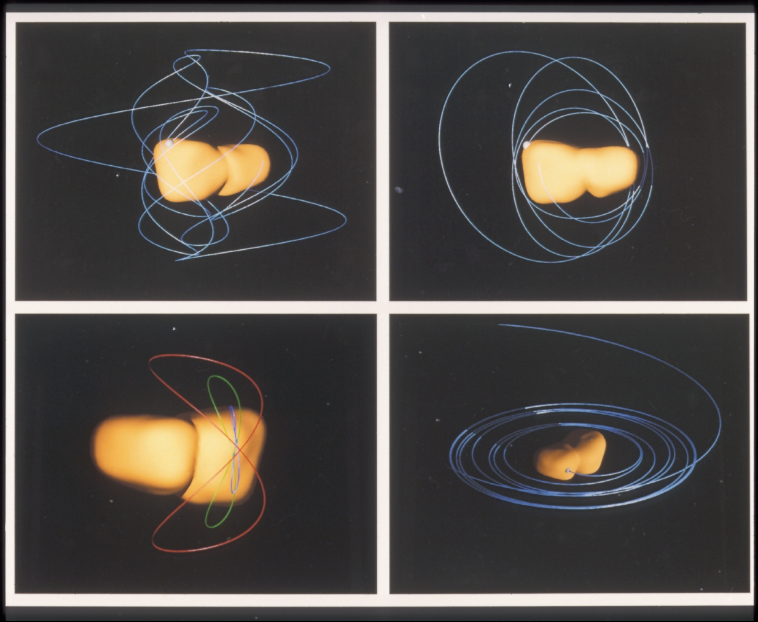


Density = 2.7 +0.6 -04 g/cm^3

Chesley et al., *Science* **302** (2003).

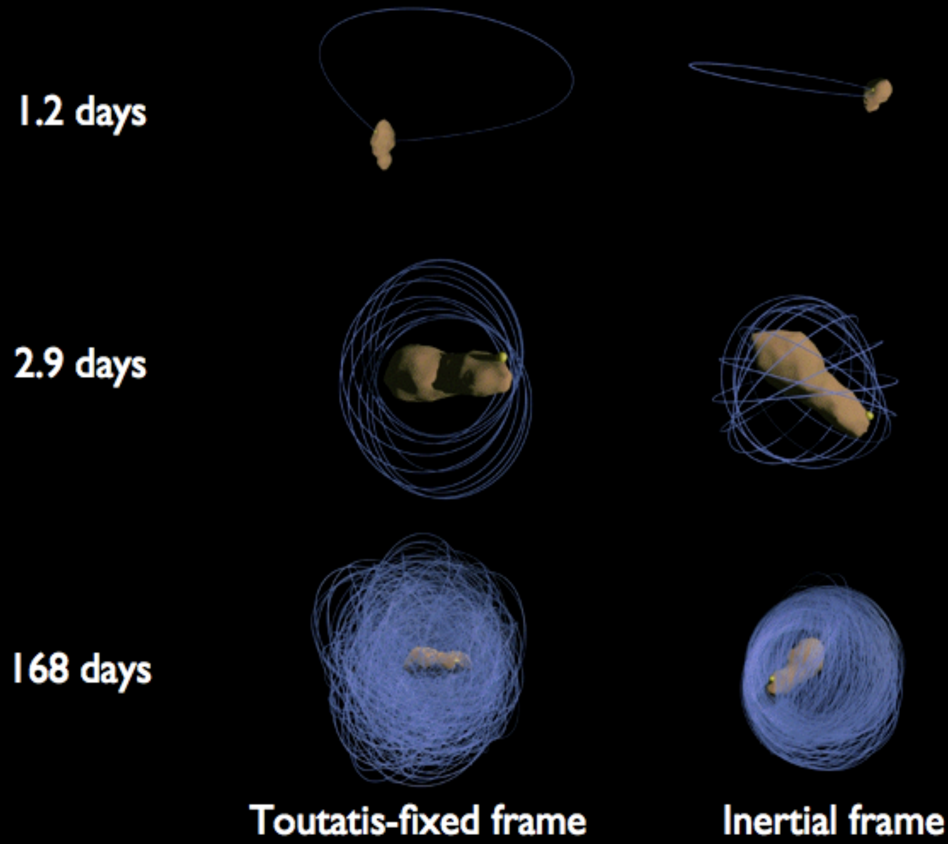
Close Orbits Using Shape Models

Castalia



Scheeres et al. (1996)

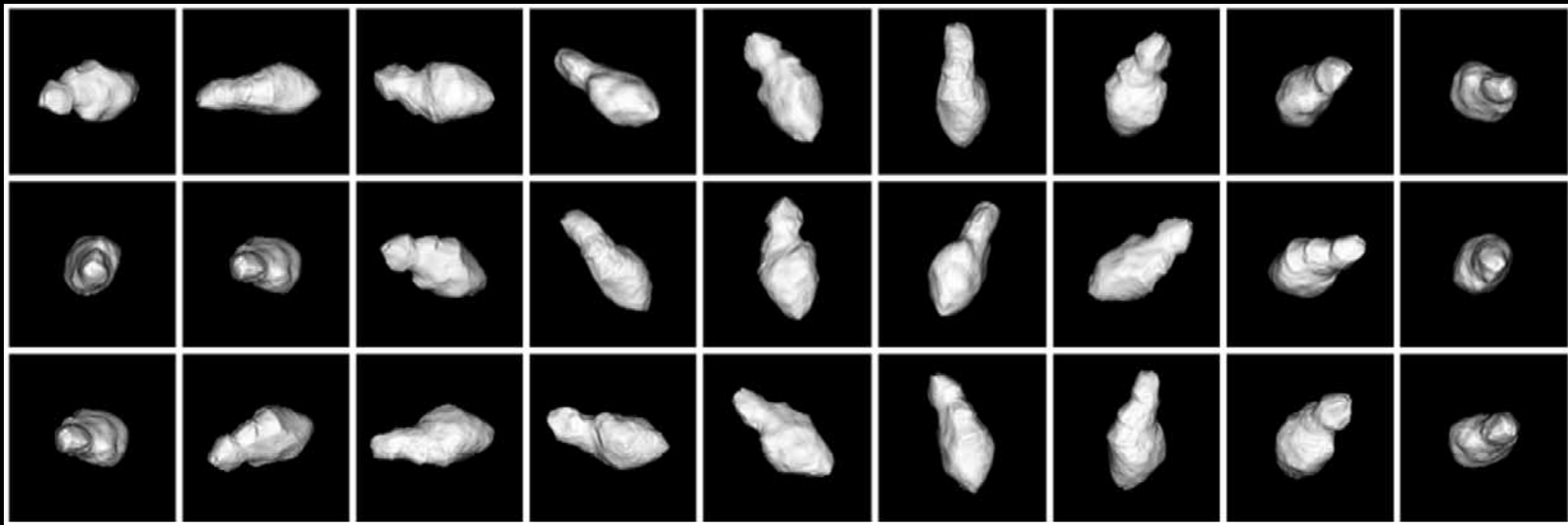
Toutatis Return Orbits



Scheeres et al. (1998), *Icarus* **132**, 53-79.

Ground-truth for Radar Shape Models: Toutatis

(Hudson et al. 2003)

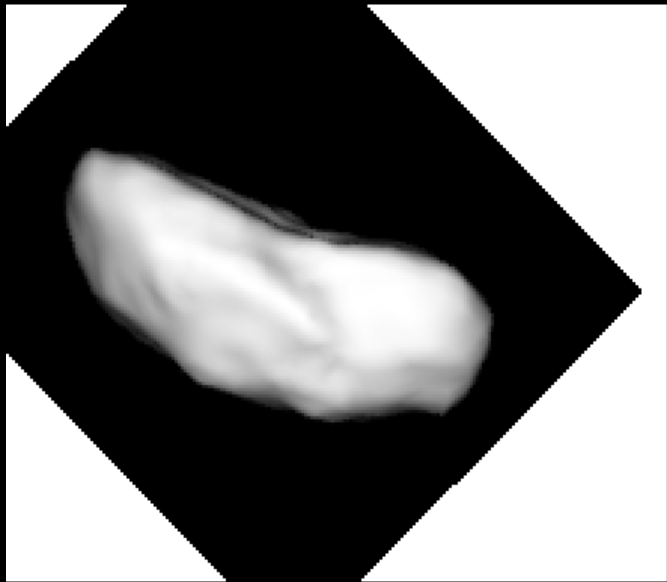


Chang'e 2 spacecraft → image

(Huang et al. 2013)

Spin state changed: seen in radar images

Spacecraft Target: Itokawa



Shape estimated from radar images

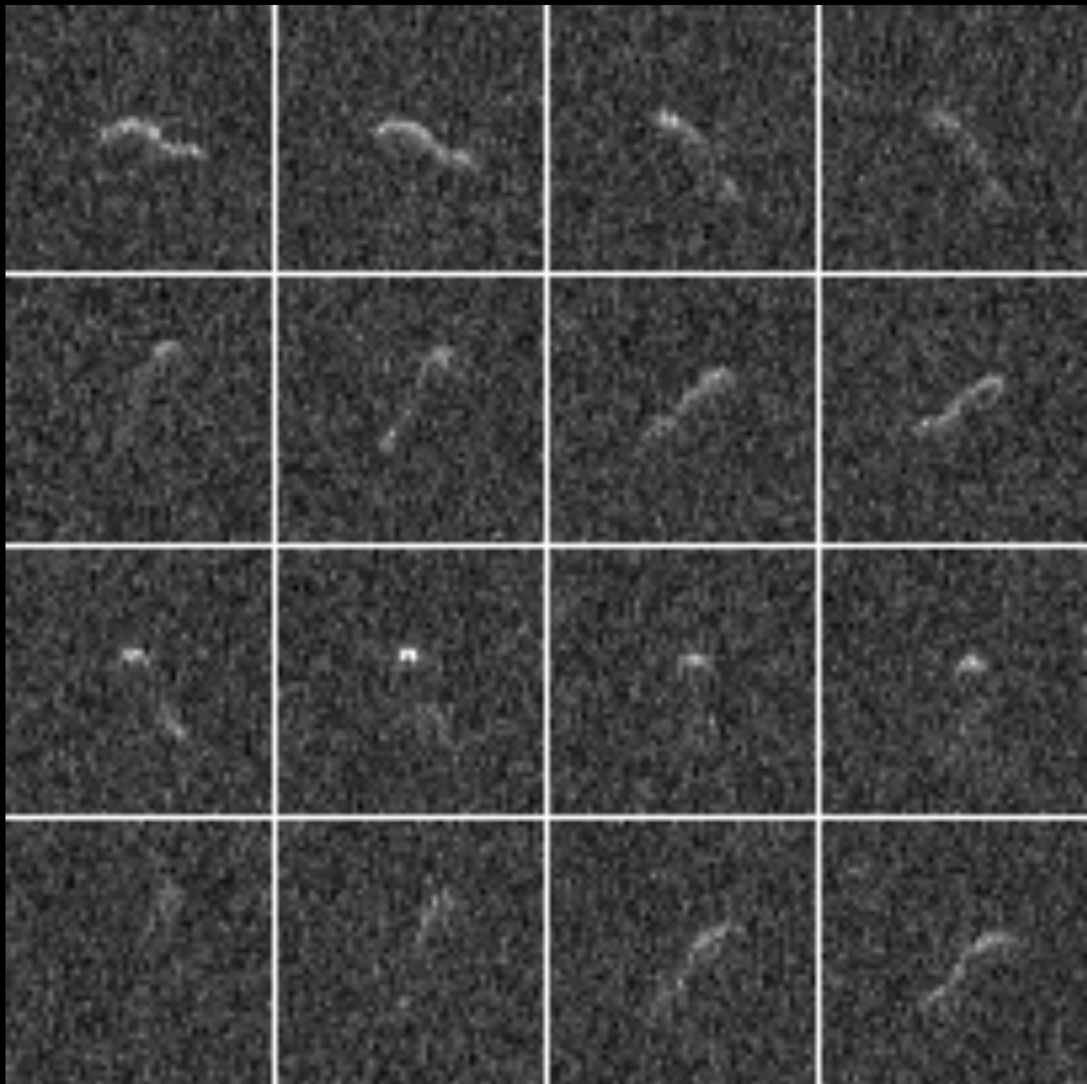
Hayabusa spacecraft images

Release 051101-1 ISAS/JAXA

HELPS MISSION PLANNING

EPOXI Spacecraft Target: Comet Hartley 2

Arecibo Radar Images

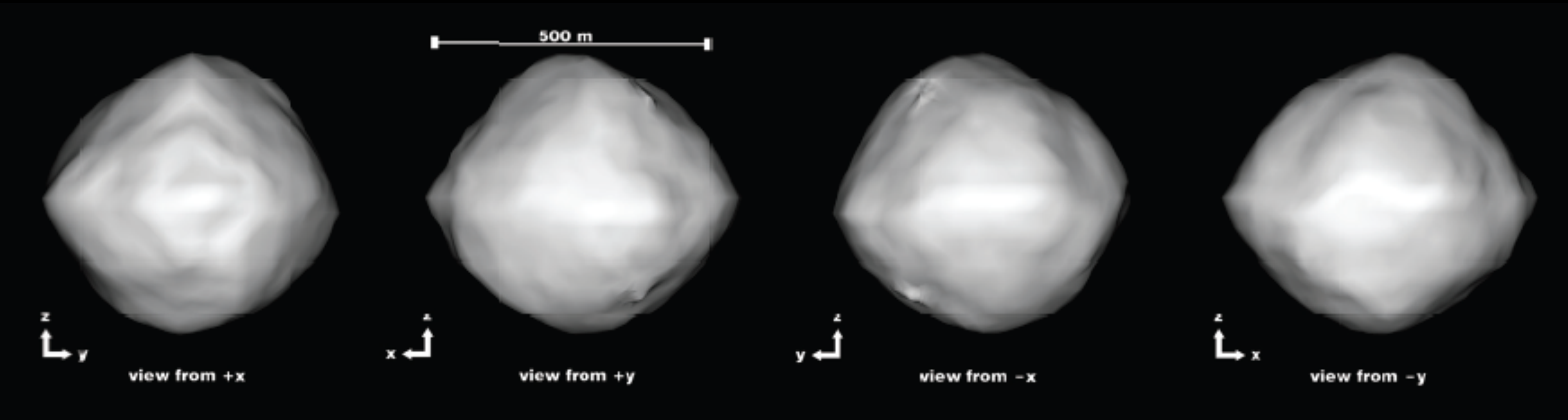


Harmon et al. 2011

Spacecraft image

OSIRIS-REx Mission Target: Bennu

(Nolan et al. 2013)

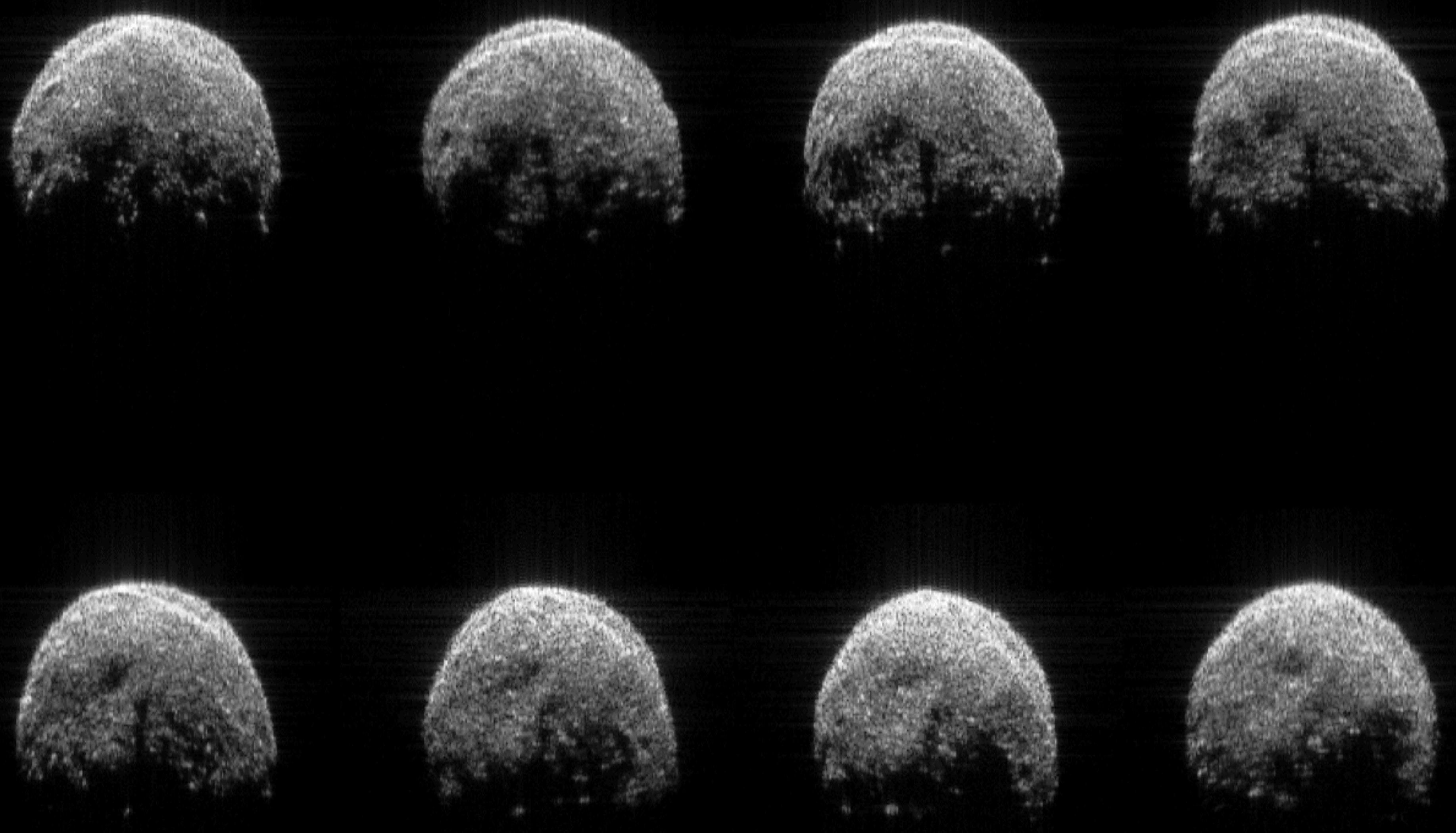


Mass estimated by detection of the Yarkovsky effect:
Bulk density = 1.3 g/cm^3 (Chesley et al. 2014)

Physical properties and orbital evolution are coupled.

2005 YU55: Nov. 2011, Goldstone

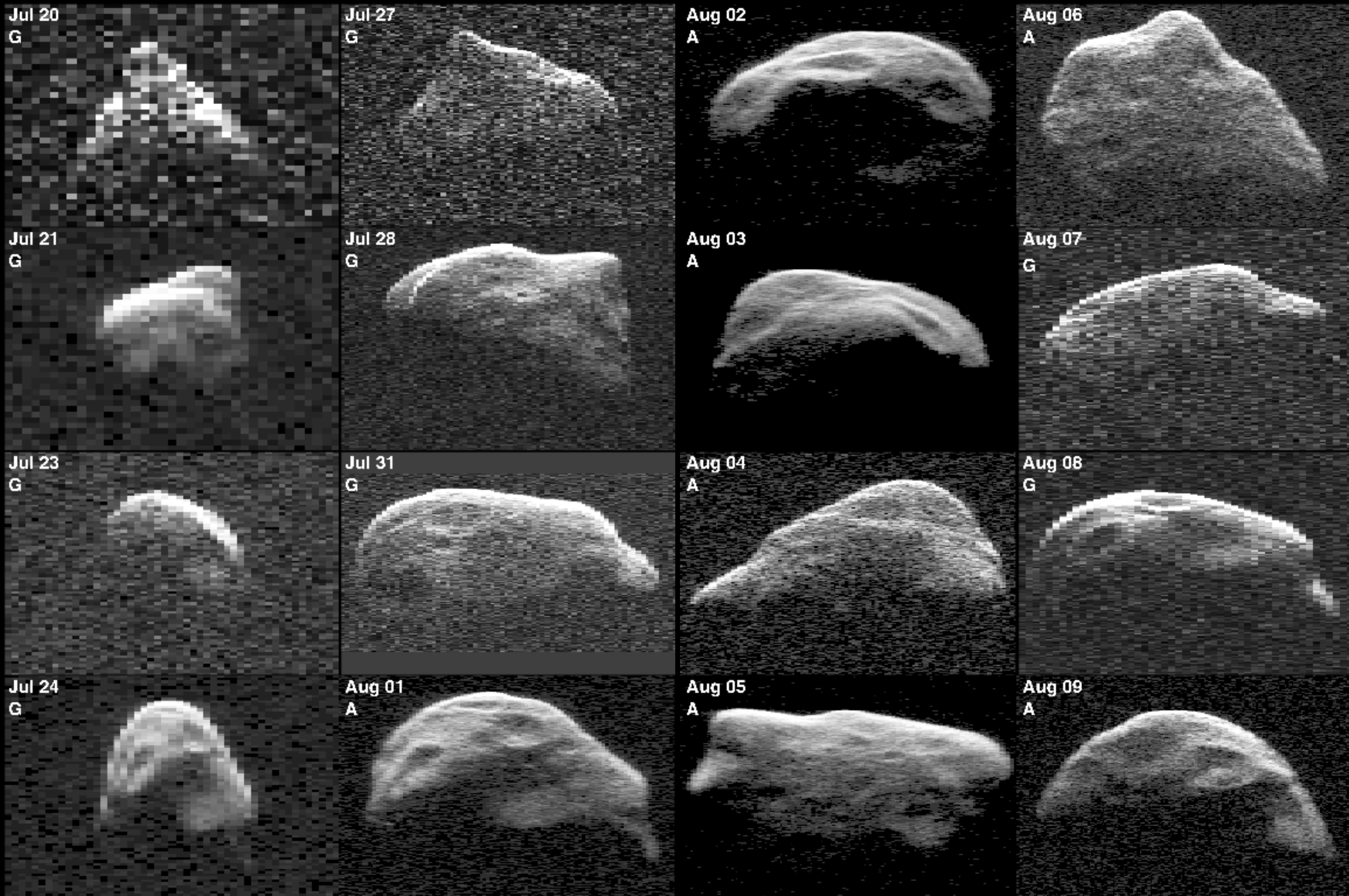
Evidence for a rounded shape ~360 m in diameter, boulders, an equatorial bulge, and craters



Busch et al., in prep.

Diverse Surface Features:1999 JM8

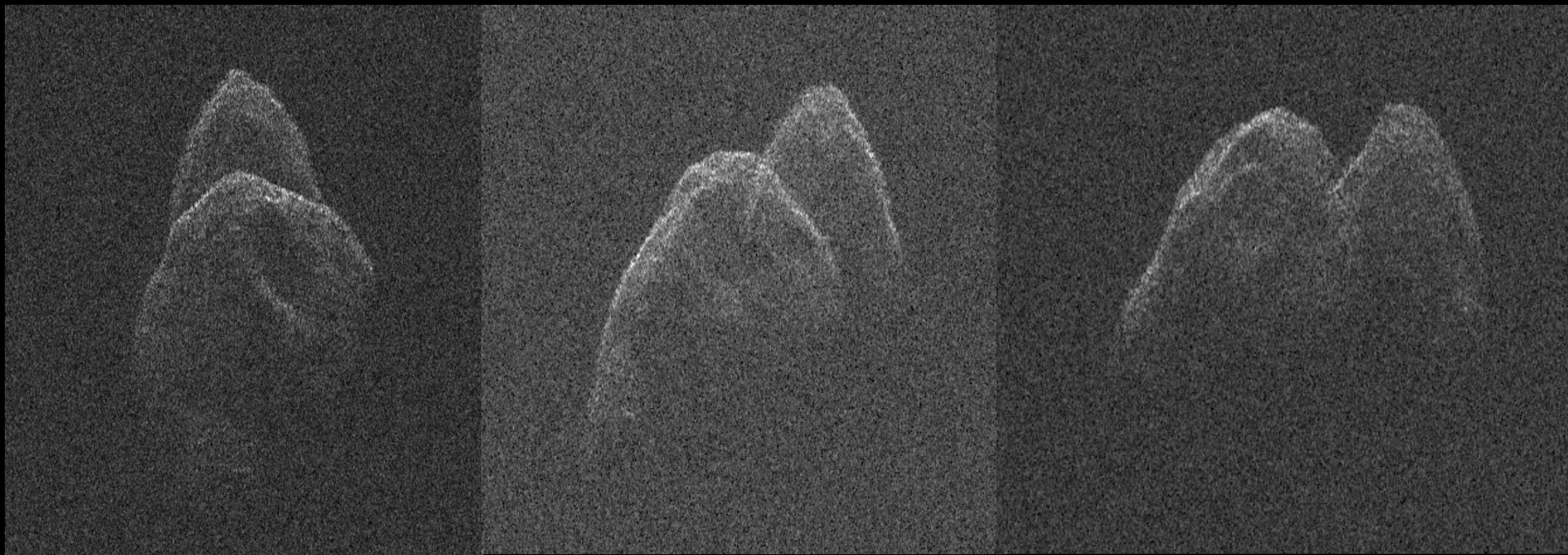
D = 7 km, Tumbling Rotation



Benner et al. 2002

Contact Binaries: ~15% of NEA Population

1999 RD32, Arecibo, March 2012, resolution = 7.5 m



Long axis: ~ 7 km
P ~ 26 h

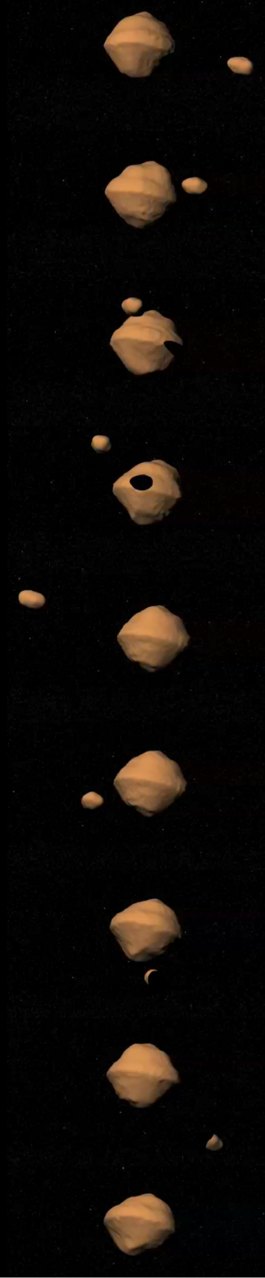
(Nolan et al., in prep.)

Binaries...and Triples!

~1/6 of NEA population > 200 m in diameter

Provides masses and densities

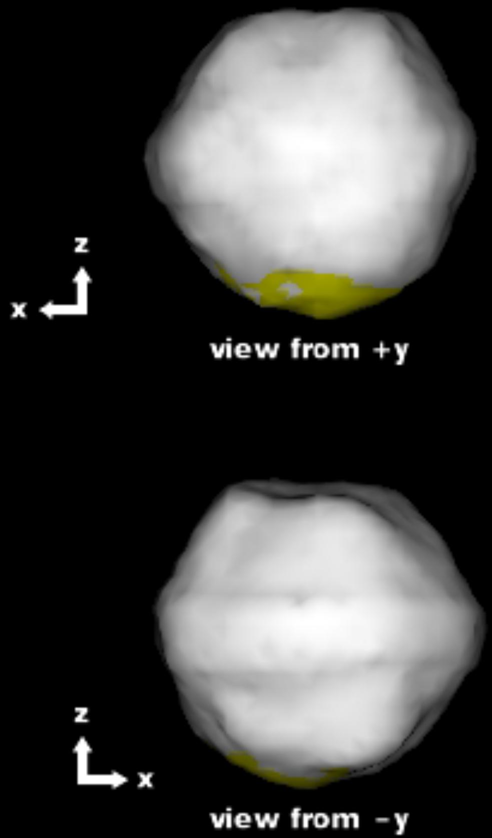
Ostro et al. 2006



Becker et al.

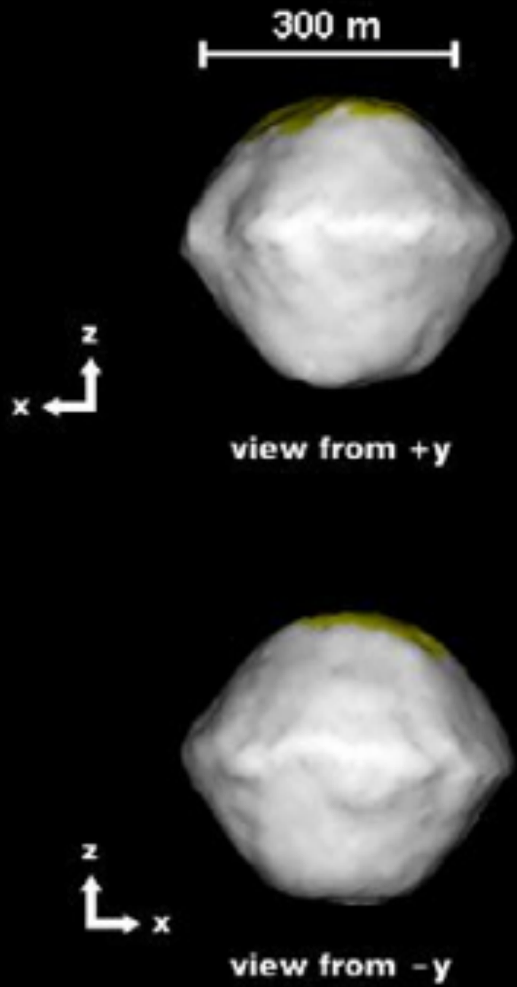
Oblate Shapes: They're Common

2004 DC



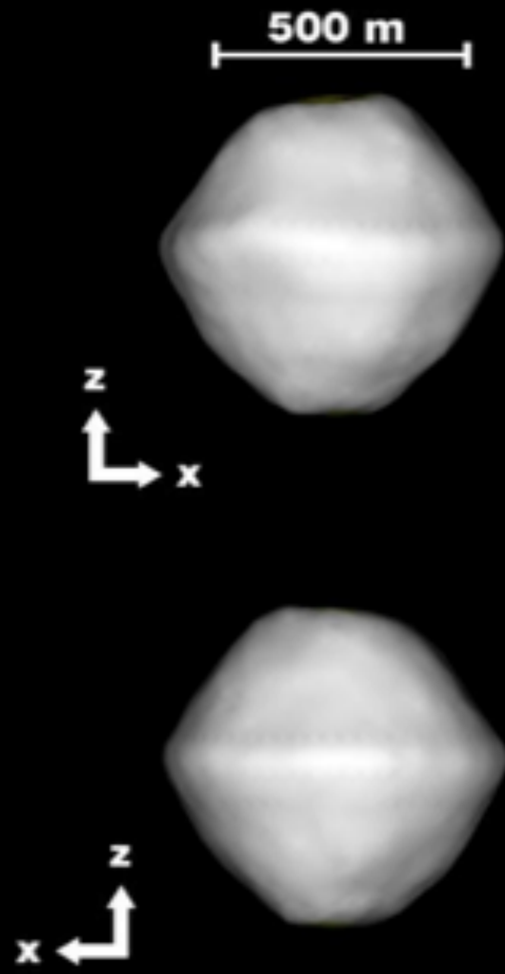
Taylor et al., in prep.

2008 EV5



Busch et al. 2011

1994 CC

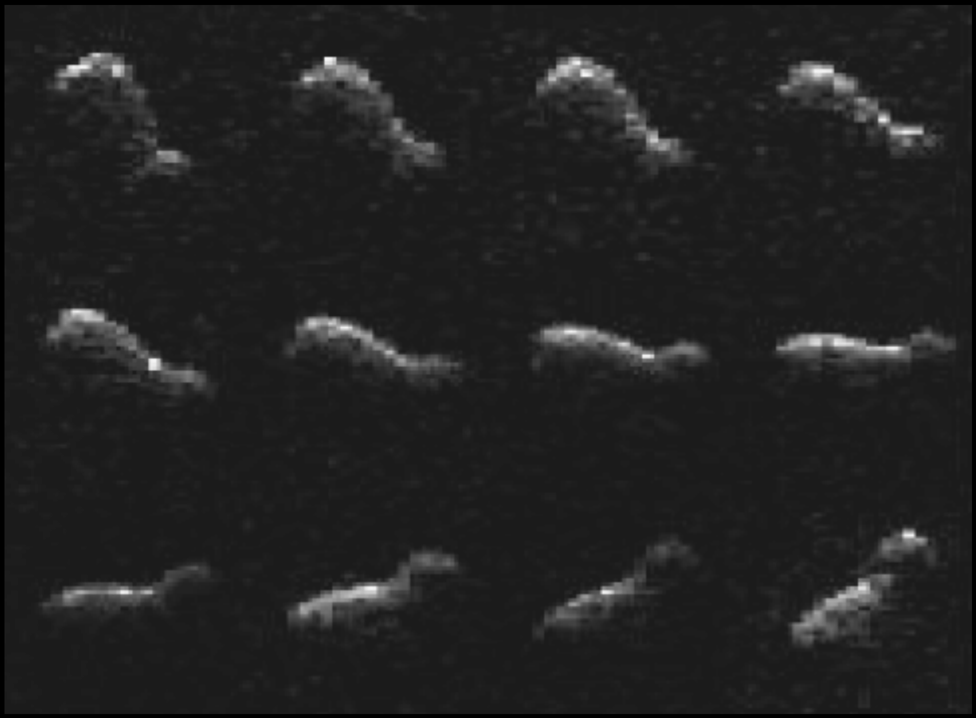


Brozovic et al. 2011

For More Information:

Asteroid Radar Research Website:

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



Asteroid and Comet Spacecraft Missions Supported by Radar

NEAR	NASA	Mathilde, Eros
Hayabusa	JAXA	Itokawa
Rosetta	ESA	Lutetia
EPOXI	NASA	Comet Hartley 2
Dawn	NASA	Vesta
Chang'e 2	China	Toutatis
Dawn	NASA	Ceres (2015)
OSIRIS-REx	NASA	Bennu (2018-2023)
AIM/DART	ESA/NASA	Didymos (proposed)
Asteroid Retrieval Mission	NASA	Target not yet selected

Plus many asteroids observed by NASA's *Spitzer Space Telescope* and *WISE* mission

Impacting Object: What Can We Do?

Discover them **EARLY!**

SEARCH EFFORTS ARE DESIGNED TO FIND ASTEROIDS DECADES TO CENTURIES IN ADVANCE, *NOT* DURING THEIR FINAL APPROACH

Study with telescopes: size, shape, composition, spin state, mass, density, multiplicity, and surface properties.

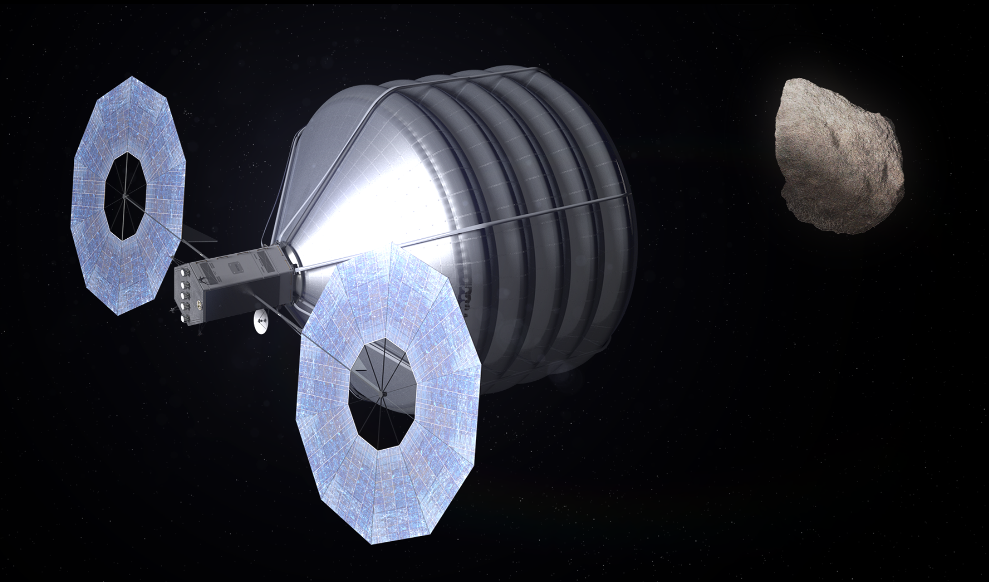
Study with robotic spacecraft

Deflection techniques:

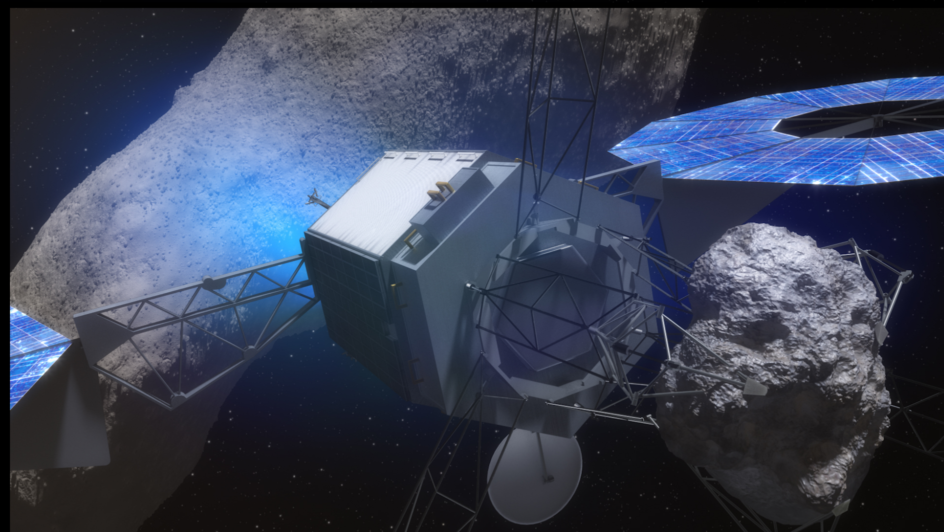
- Kinetic impact with spacecraft: hit the asteroid to nudge it
- Gravity Tractor: pull it with a massive spacecraft
- Nuclear explosion: deflect it; far easier than blowing it up

NASA'S PROPOSED
ASTEROID RETRIEVAL MISSION (ARM)

Option A:
Capture a small NEA



Option B:
Pull a boulder off
a larger NEA



Goldstone Solar System Radar Block Diagram

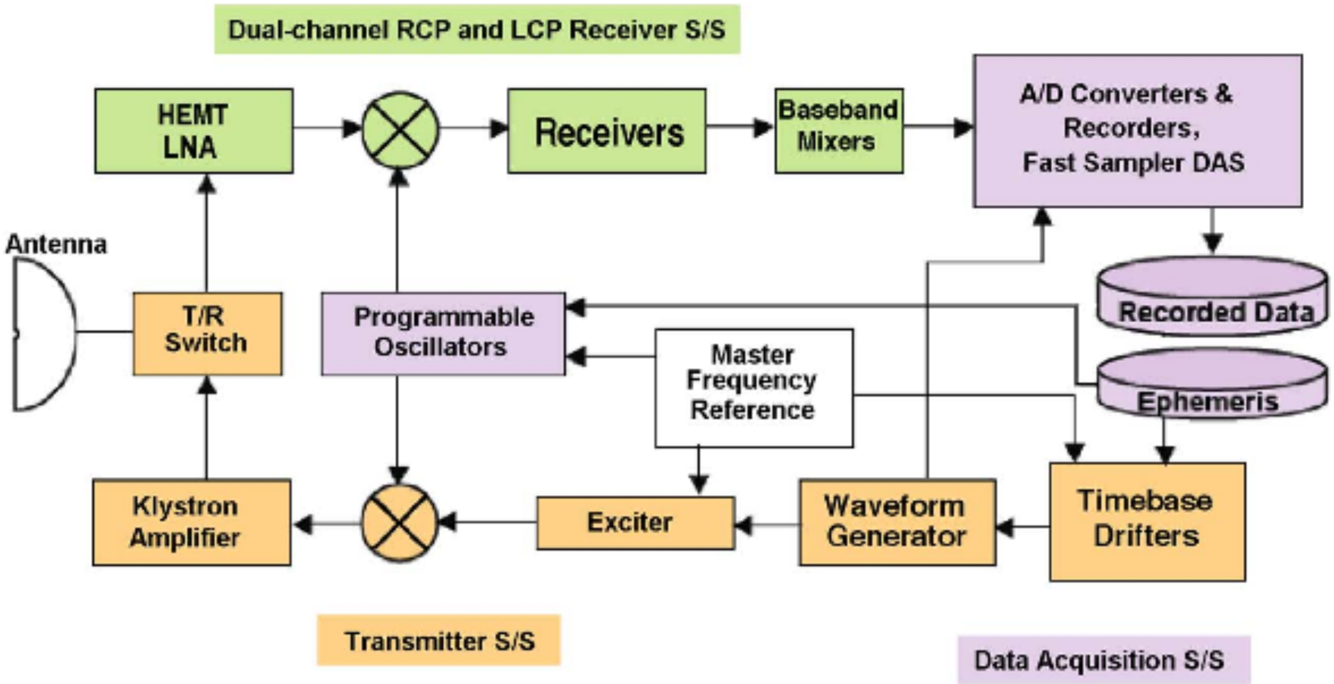


Fig. 2. *Diagram of GSSR subsystem (S/S) interfaces. The dual-channel receiving LNA and data processing chain is capable of recording right-circularly-polarized and left-circularly-polarized (RCP and LCP) signals simultaneously. The T/R switches between the two feed horns, one horn from the transmitter, the other to the LNA. (See Fig. 1.)*

Barringer Meteor Crater
Winslow, Arizona

Diameter = 1.2 km
Age = 50,000 y
Metallic impactor ~50 m in diameter