PLANETARY RADAR
AND NEAR-EARTH OBJECTS

Lance Benner
Jet Propulsion Laboratory
California Institute of Technology

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?

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Number</th>
<th>Impact Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 km</td>
<td>940</td>
<td>1 million years</td>
</tr>
<tr>
<td>100 m</td>
<td>20,000</td>
<td>10,000 years</td>
</tr>
<tr>
<td>10 m</td>
<td>millions</td>
<td>10 years</td>
</tr>
</tbody>
</table>
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

Updated: 2014 Oct 22
N = 489

Year: 1970-2015
Number: 0-500
Near-Earth Asteroids Detected by Radar

### Diagram

- **Title**: Near-Earth Asteroids Detected by Radar
- **Axes**:
  - X-axis: Absolute Magnitude (AU)
  - Y-axis: Semimajor Axis (AU)
  - Z-axis: Diameter (KM)
- **Data Points**:
  - Red dots: All NEAs (N = 11501)
  - Black circles: Radar NEAs (N = 489)
- **Legend**:
  - Red dots: All NEAs (N = 11501)
  - Black circles: Radar NEAs (N = 489)
- **Source**:
  - Updated: 2014 Oct 22
  - Source for orbital elements: Minor Planet Center
For newly-discovered asteroids, radar can enable computation of trajectories for \textit{centuries} farther into the future than is possible otherwise.

Figure credit: Jon Giorgini, JPL
NOT the same as images from digital cameras!
3-D Shapes: Toutatis

~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 = $2.7 \pm 0.6 \times 10^{-4}$ g/cm$^3$

Close Orbits Using Shape Models

Castalia

Scheeres et al. (1996)

Toutatis Return Orbits

1.2 days

2.9 days

168 days

Toutatis-fixed frame

Inertial frame

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

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/cm³ (Chesley et al. 2014)

Physical properties and orbital evolution are coupled.
2005 YU55: Nov. 2011, Goldstone
Evidence for a rounded shape \( \sim 360 \) 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: \(\sim 15\%\) of NEA Population

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

Long axis: \(\sim 7\) km

\(P \sim 26\) h

(Nolan et al., in prep.)
Binaries...and Triples!

~1/6 of NEA population > 200 m in diameter
Provides masses and densities

Binary 1999 KW4

Ostro et al. 2006

Triple 2001 SN263

Becker et al.
Oblate Shapes: They’re Common

2004 DC

2008 EV5

1994 CC

Taylor et al., in prep.

Busch et al. 2011

Brozovic et al. 2011
For More Information:
Asteroid Radar Research Website:

http://echo.jpl.nasa.gov/
### Asteroid and Comet Spacecraft Missions Supported by Radar

<table>
<thead>
<tr>
<th>Mission</th>
<th>Agency</th>
<th>Object(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEAR</td>
<td>NASA</td>
<td>Mathilde, Eros</td>
</tr>
<tr>
<td>Hayabusa</td>
<td>JAXA</td>
<td>Itokawa</td>
</tr>
<tr>
<td>Rosetta</td>
<td>ESA</td>
<td>Lutetia</td>
</tr>
<tr>
<td>EPOXI</td>
<td>NASA</td>
<td>Comet Hartley 2</td>
</tr>
<tr>
<td>Dawn</td>
<td>NASA</td>
<td>Vesta</td>
</tr>
<tr>
<td>Chang’e 2</td>
<td>China</td>
<td>Toutatis</td>
</tr>
<tr>
<td>Dawn</td>
<td>NASA</td>
<td>Ceres (2015)</td>
</tr>
<tr>
<td>OSIRIS-REx</td>
<td>NASA</td>
<td>Bennu (2018-2023)</td>
</tr>
<tr>
<td>AIM/DART</td>
<td>ESA/NASA</td>
<td>Didymos (proposed)</td>
</tr>
<tr>
<td>Asteroid Retrieval Mission</td>
<td>NASA</td>
<td>Target not yet selected</td>
</tr>
</tbody>
</table>

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
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