Radar Observing: Planetary Radar Astronomy

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GBO/AO Single Dish Training Workshop, August 22, 2019

Outline

- Why use Radar? What is it good for?
- Introduction to Radar Systems
- Radar at Arecibo
- Monostatic vs Bistatic
- Science Returns – Applications

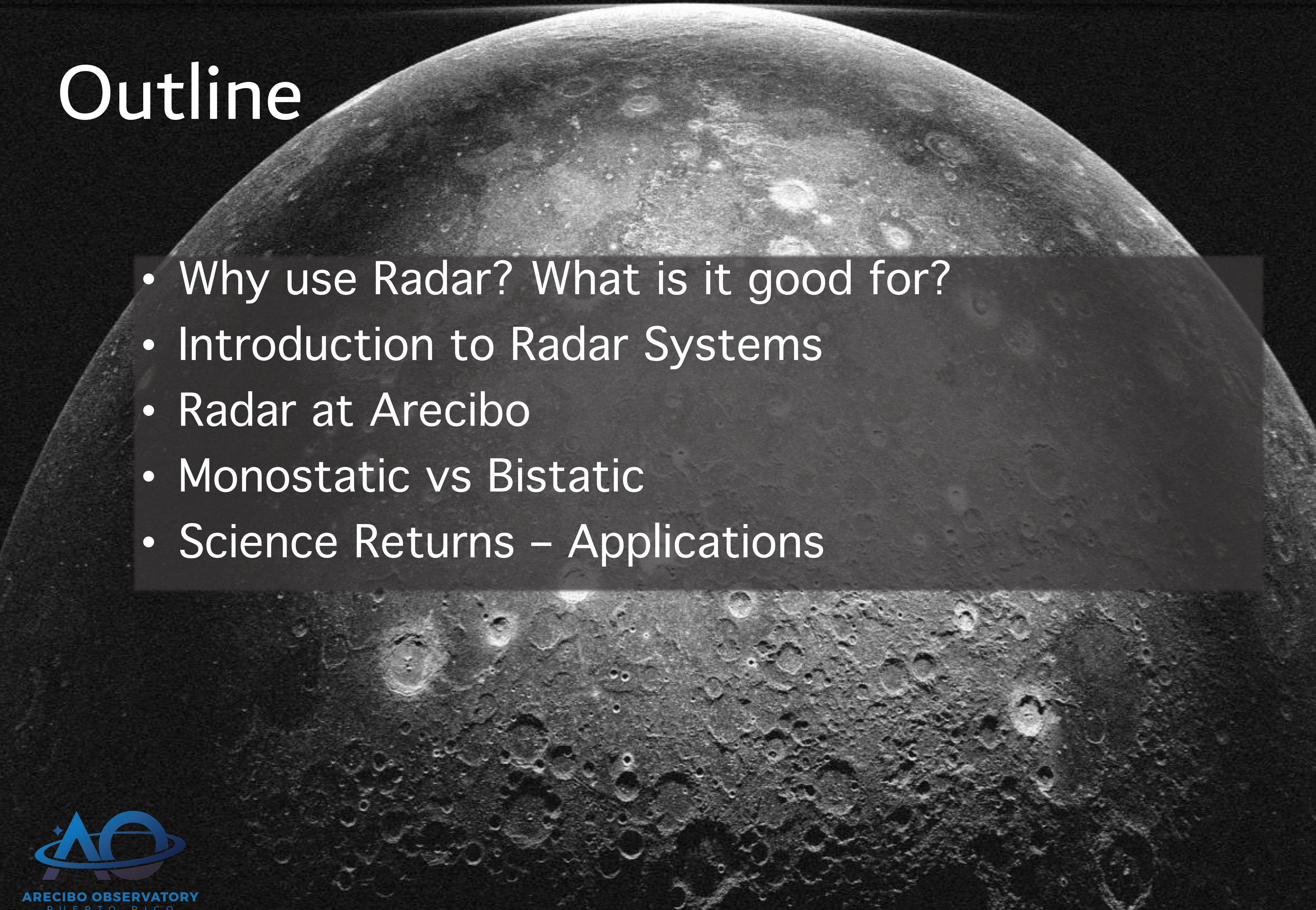

Image credit: Bruce Campbell (SI)

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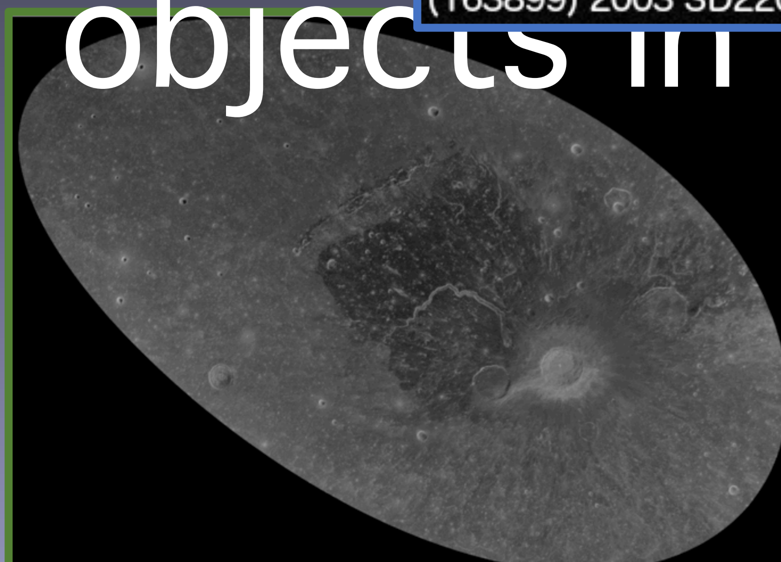
Image credit: Lynn Carter (LPL)

Image at resolutions comparable to space missions

Why use objects in spa

Penetrate through atmospheres



Reveal buried features

Use polarimetry to detect surface properties

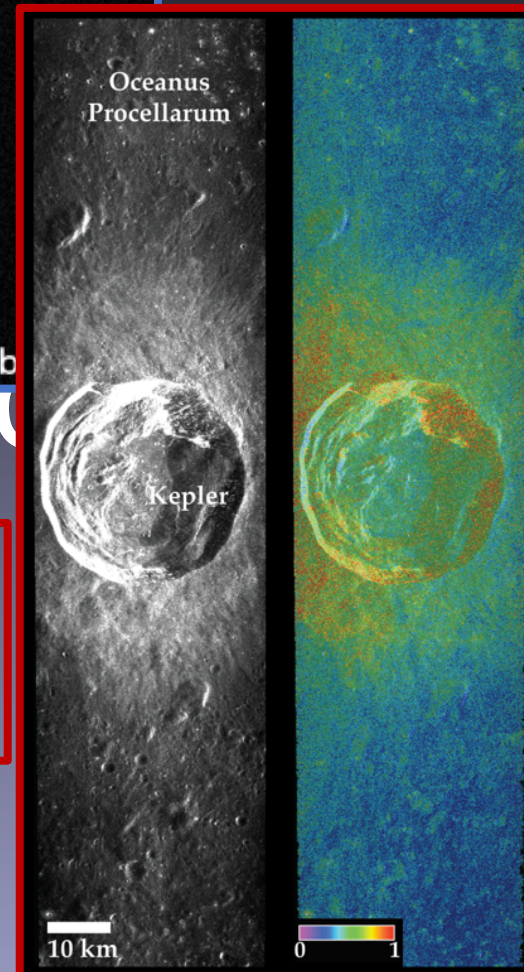


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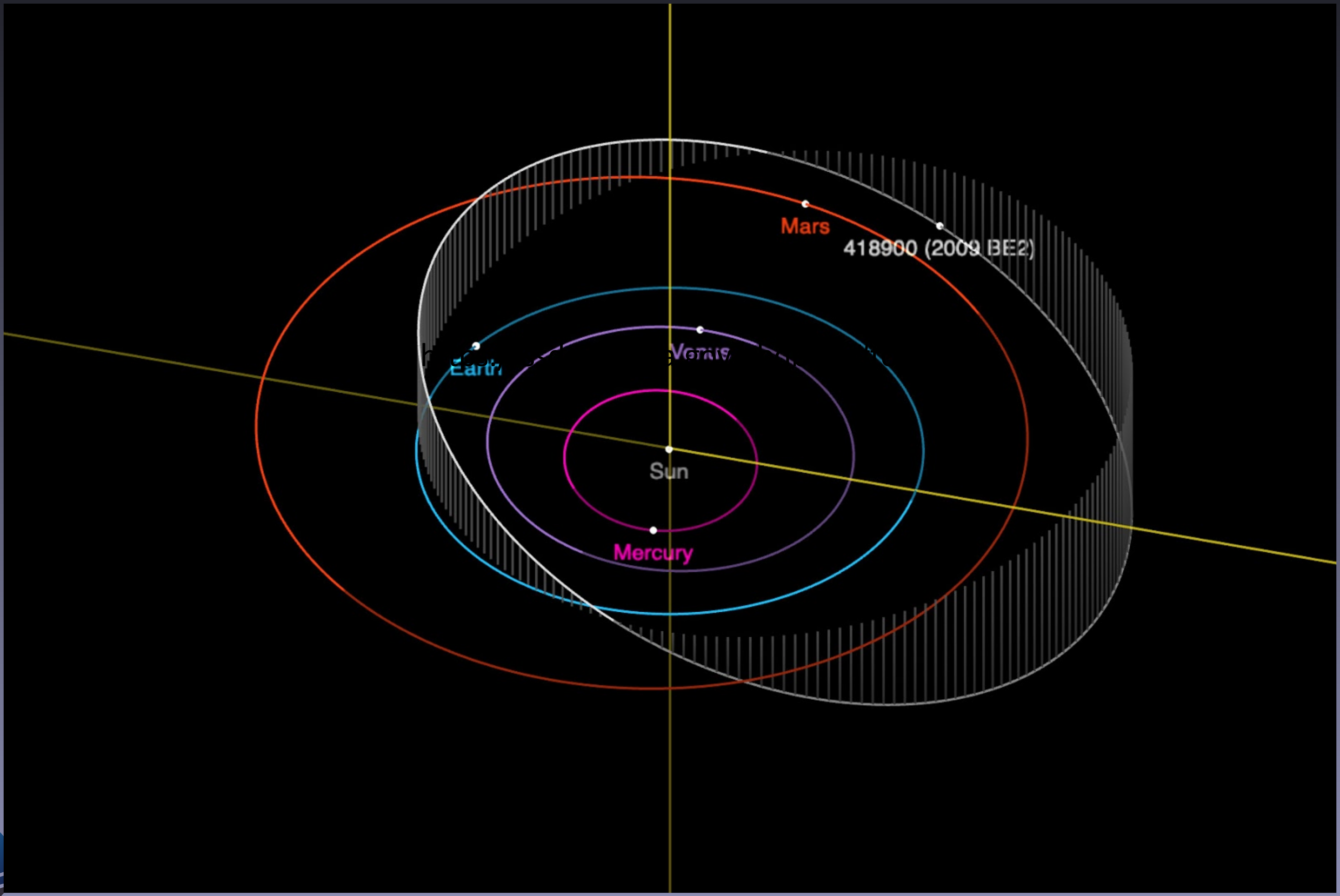
Image credit: Bruce Campbell (SI)

Image credit:
G. Wes Patterson (JHU/APL)

Astrometry: refining orbits of celestial bodies



https://ssd.jpl.nasa.gov/sbdb.cgi#top

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Astrometry: refining orbits of celestial bodies

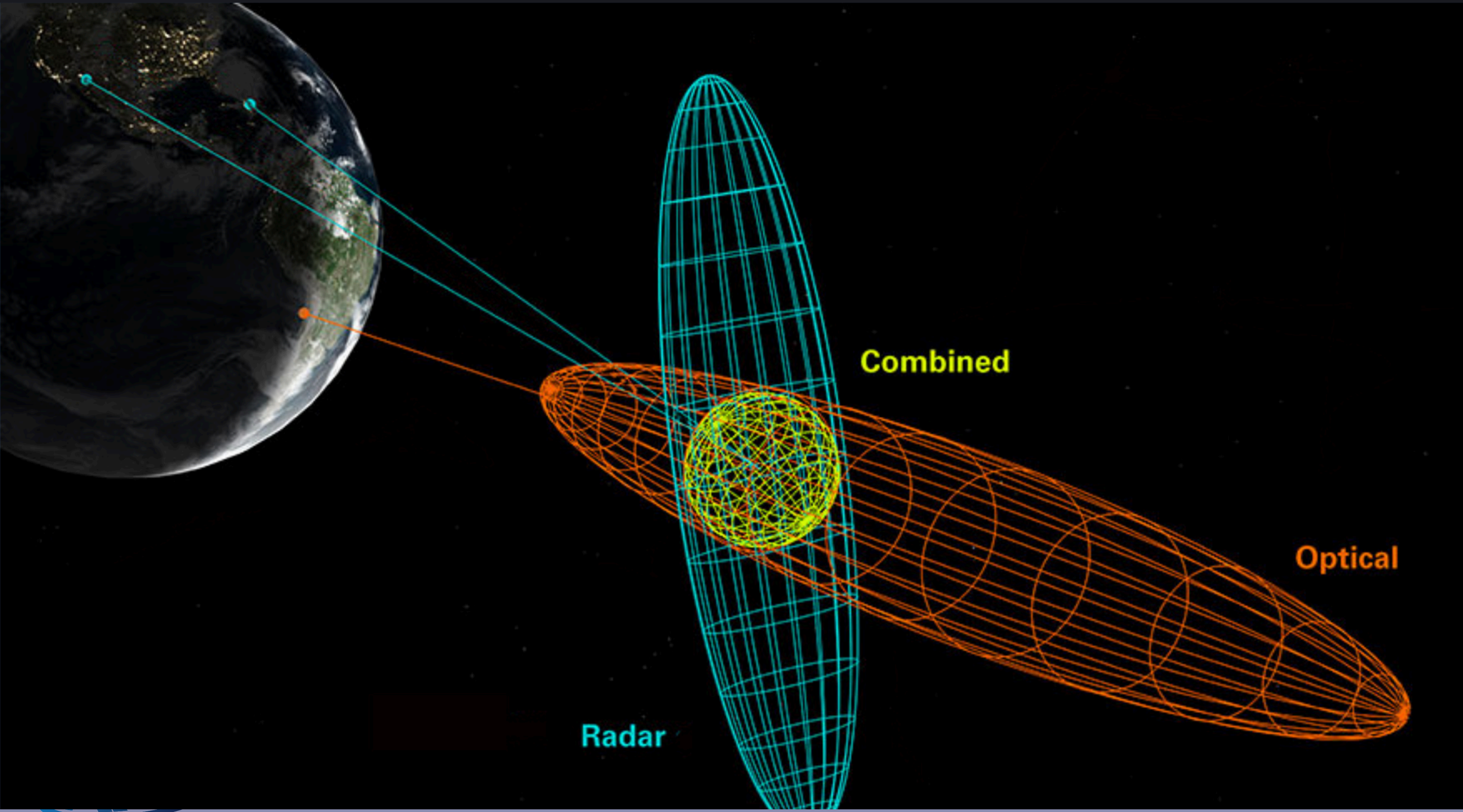
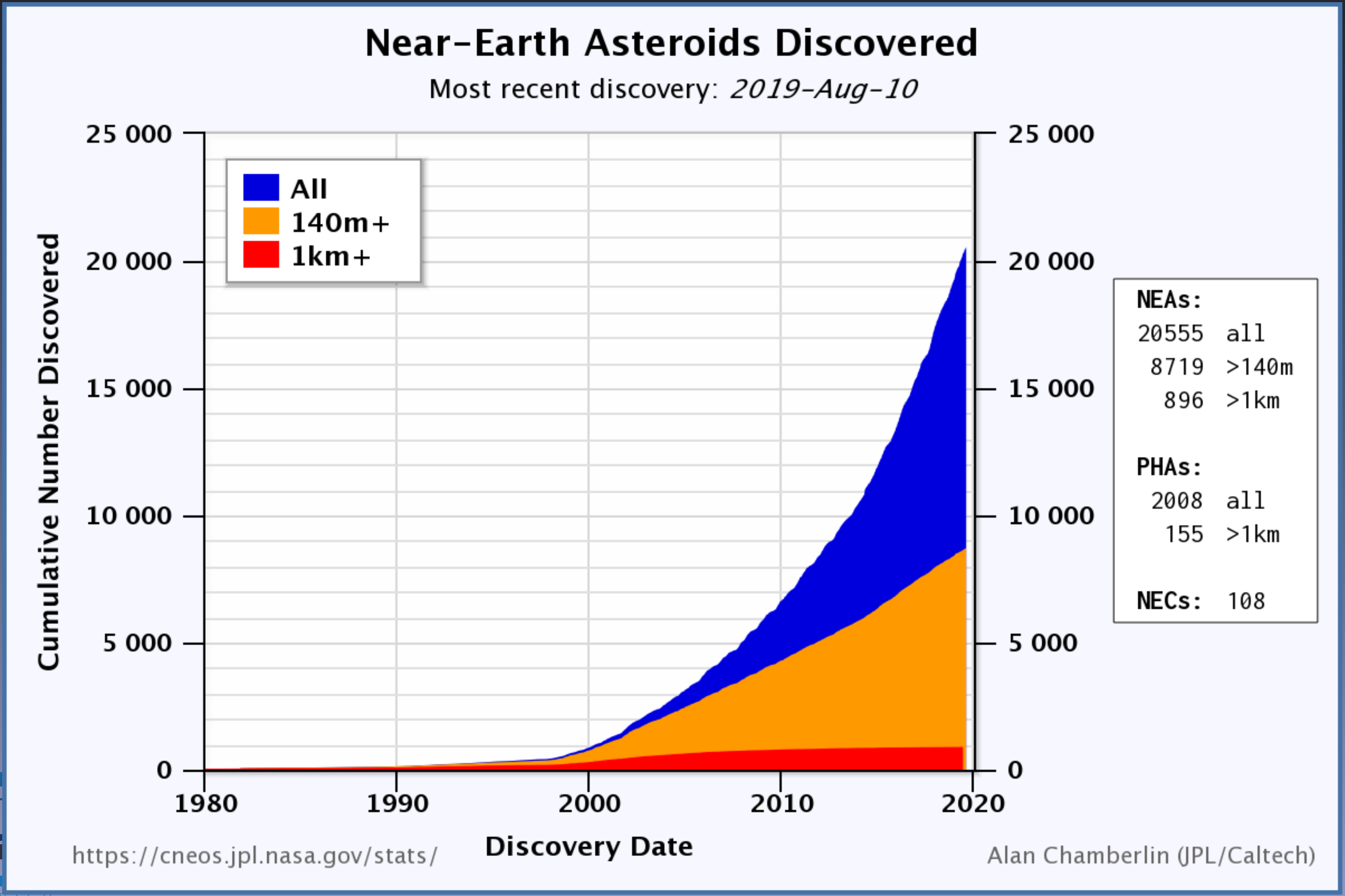


Image credit: Jon Giorgini (JPL)

NASA has congressional mandate to search and track all near-Earth asteroids (NEAs) larger than 140 m (~ 1/3 known to date)



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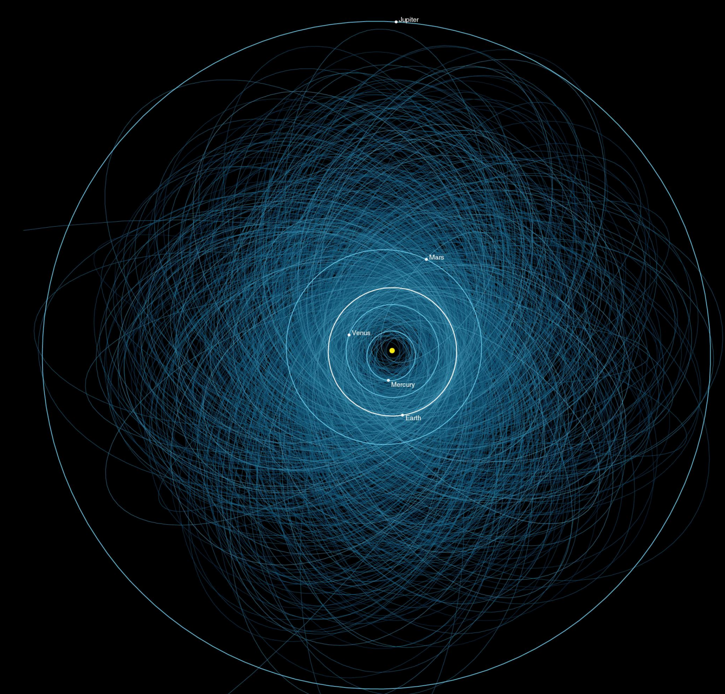
NEO priorities

- Potentially Hazardous Asteroid (PHA): asteroids >140 m (H mag = 22) in diameter and can get closer than ~ 19.5 LD (0.05 au)

- Near-Earth Object Human Space Flight Accessible Targets Study (NHATS): asteroids that are favorable targets for human space exploration [Δv < 12km/s, 450 days]



H mag = absolute magnitude (magnitude at 1 au from Sun and observer)

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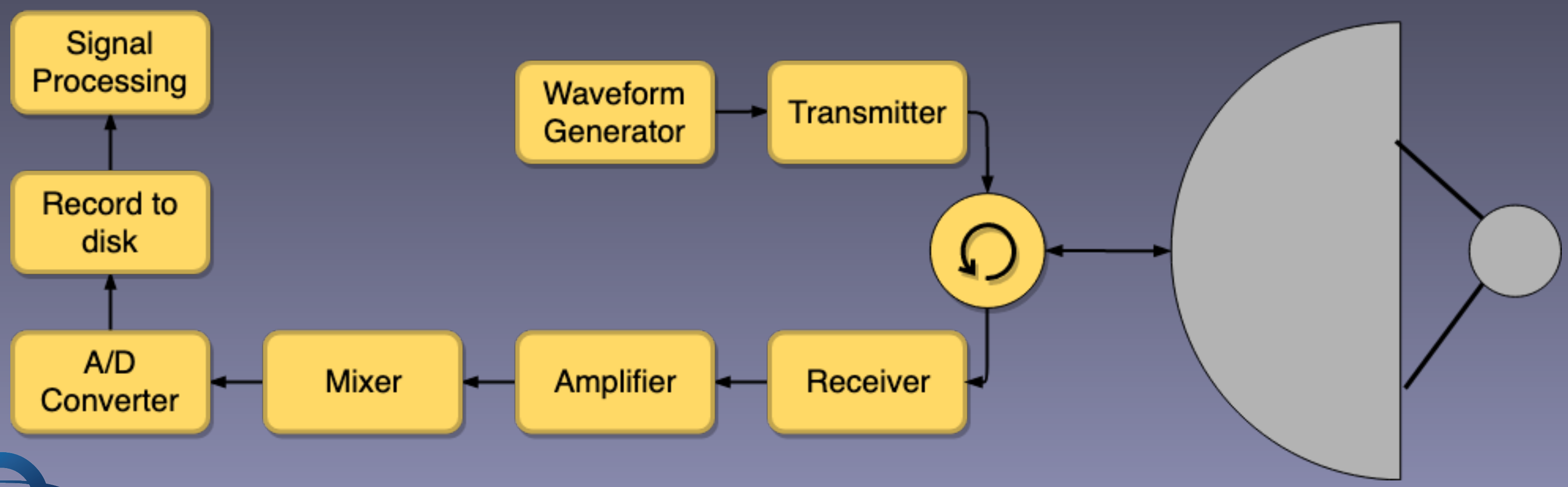
Image credit: NASA/JPL-Caltech

What is RADAR?

- RAdio Detection And Ranging
- Active remote sensing – we control the signal!
- Maximize signal properties to enhance SNR
- Measure reflected radio waves (so targets must be reflective)



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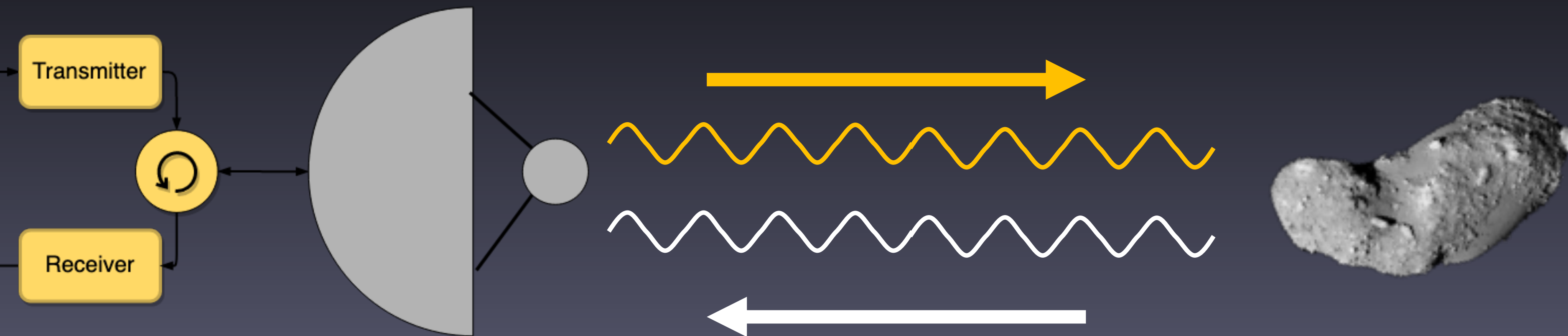
The Radar Equation



$$P_{rx} = [P_{tx}]\,[G_{tx}]\left[\frac{1}{4\pi r^2}\right][\sigma]\left[\frac{1}{4\pi r^2}\right][A_{eff}]$$

Received Power

Transmitted Power

Transmitter Gain

Radar Cross Section

Geometric Spreading

Effective Aperture

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Image credit: JAXA

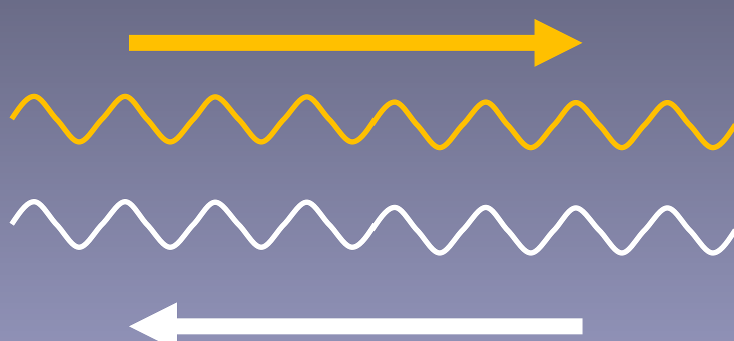
EM Reflection

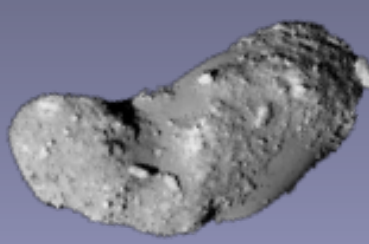
- Radar albedo is the cross section normalized by the projected area
- Derive Fresnel reflectivity from radar albedo through scattering theory
- Fresnel reflectivity dependent on constitutive parameters of near-surface material

$$\hat{\sigma} = \frac{\sigma}{A_{proj}} \qquad \hat{\sigma} \propto R_f$$

$$R_f = \left[\frac{\sqrt{n} - 1}{\sqrt{n} + 1}\right]^2$$

$$n = \sqrt{\widetilde{\varepsilon_r}\widetilde{\mu_r}}$$





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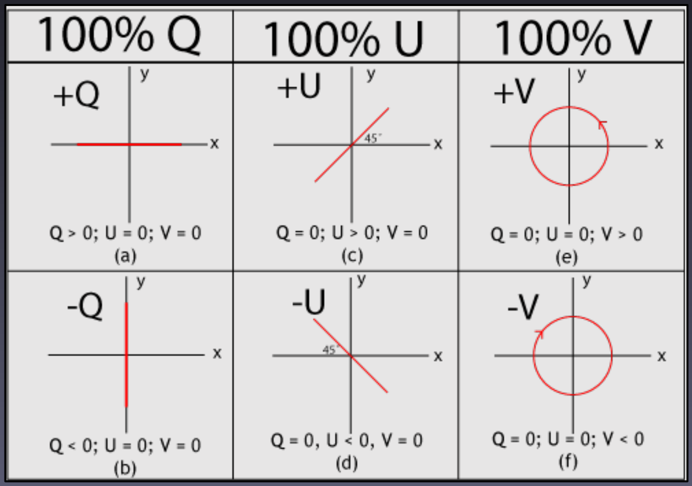
Radar Polarimetry

- Transmit a circularly polarized signal
- Receive in both handedness
  - Same sense as transmitted, SC
  - Opposite sense, OC
- Circular polarization ratio (CPR), μ_C
- Stokes vector – target decomposition



$$\mu_C = \frac{\sigma_{SC}}{\sigma_{OC}}$$

$$\vec{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle V_L^2 \rangle + \langle V_R^2 \rangle \\ 2\langle V_L V_R cos\delta \rangle \\ 2\langle V_L V_R sin\delta \rangle \\ \langle V_L^2 \rangle - \langle V_R^2 \rangle \end{bmatrix}$$

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SNR: Detectability

- Target's doppler bandwidth depends on size and spin state:

$$B = \frac{4\pi D cos\phi}{\lambda_0 P_{spin}}$$

- RMS noise power depends on bandwidth, integration time, and system temperature:

$$N_{rms} = kT_{sys}\sqrt{\frac{B}{\tau}}$$

- Need SNR of ~6 for detection, but much higher SNR for imaging

$$SNR = \frac{P_{rx}}{N_{rms}}$$

$$P_{rx} = \frac{P_{tx} G_{tx} \sigma A_{eff}}{(4\pi)^2 r^4}$$

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Continuous Wave (CW)

- Constant amplitude/frequency radio wave transmitted
- Advantages:
  - Maximizes power in reflected signal
  - Doppler shift in received signal indicates target motion and rotation
  - Good for finding binaries!
- Disadvantages:
  - Cannot provide ranging information
- Often used initially to confirm correct ephemeris in targeting NEOs

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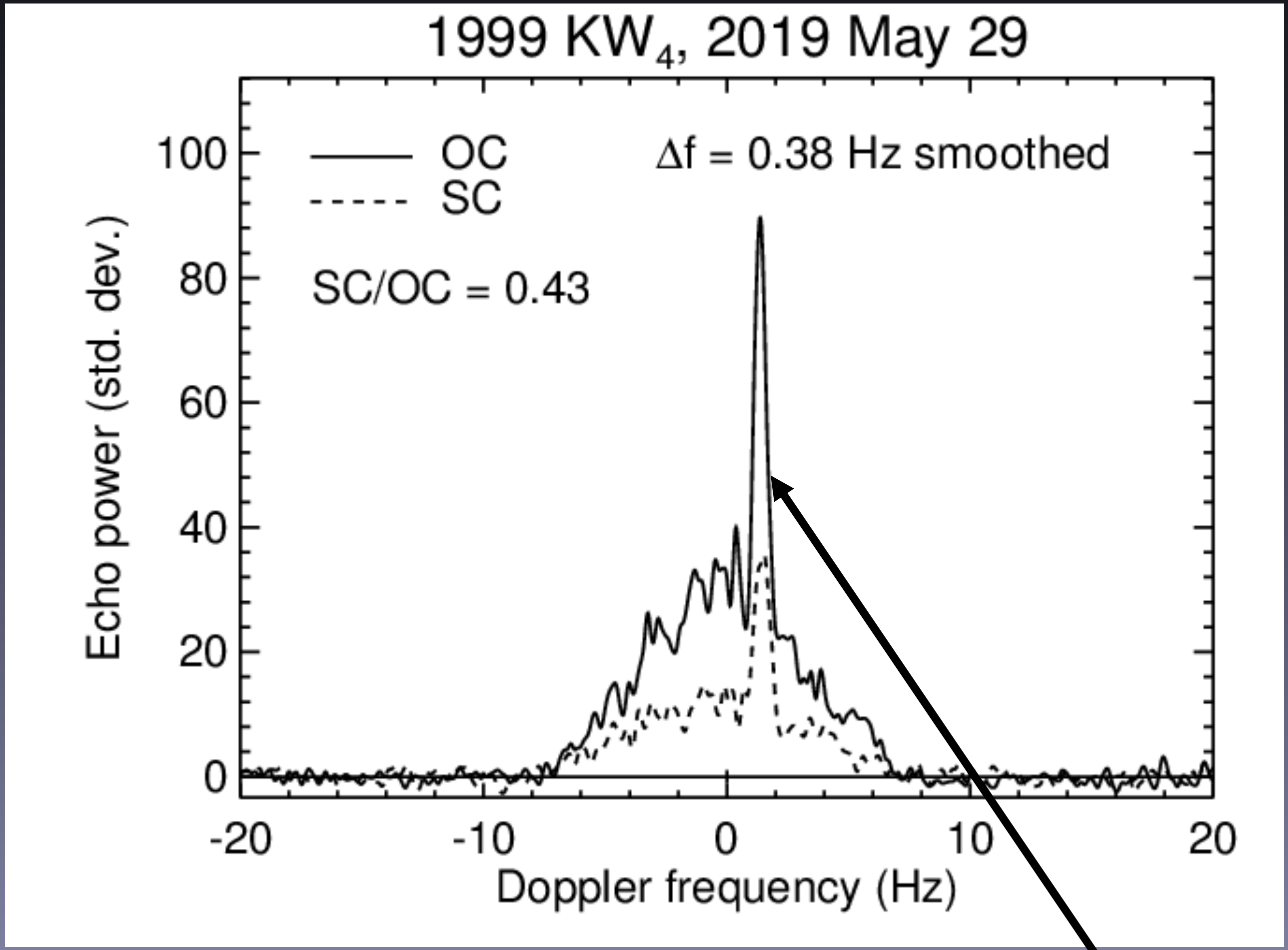
Continuous Wave (CW)



- H mag = 16.5
- r = 0.03 au

Secondary of binary system!

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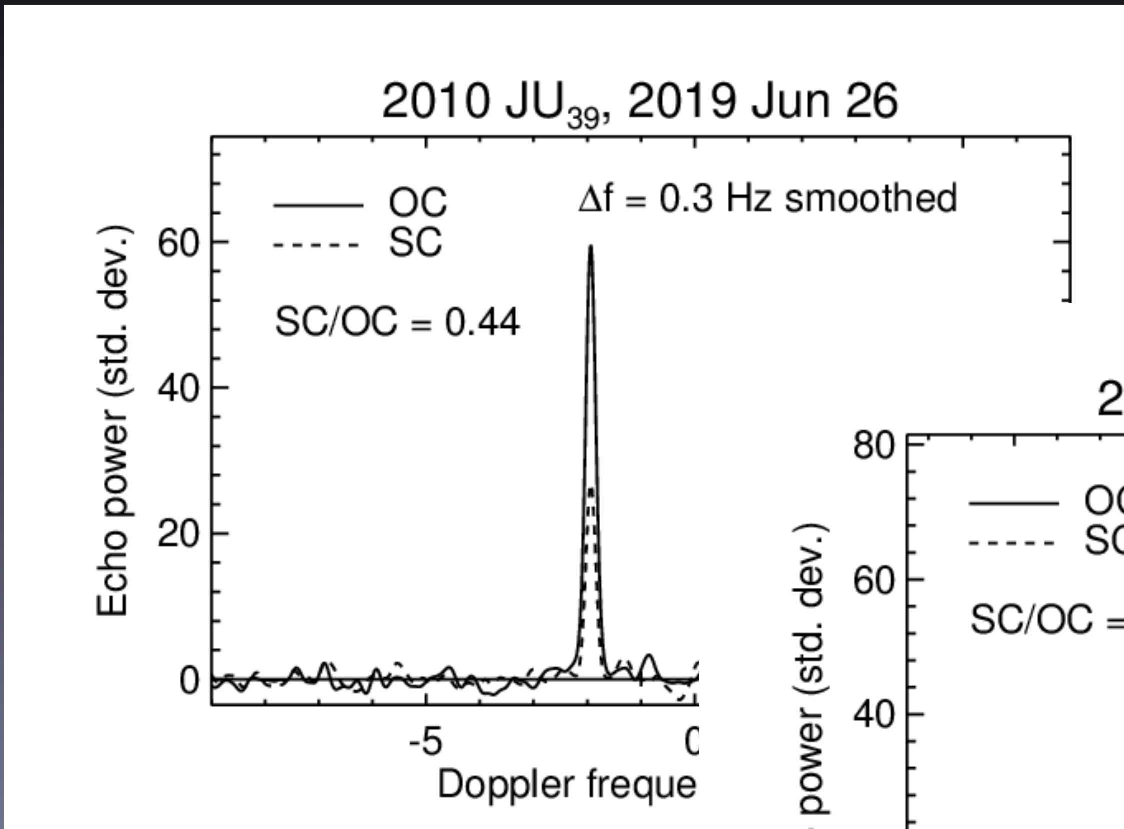
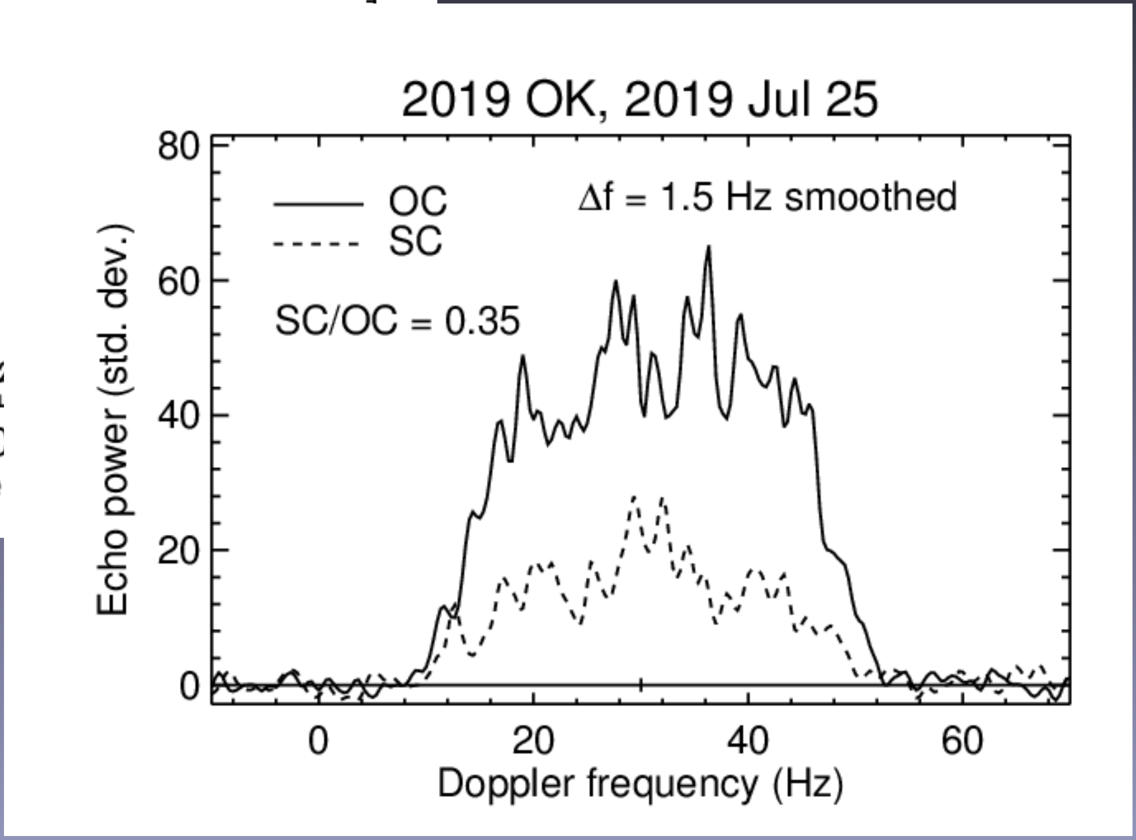
Continuous Wave (CW)



~ 5.5 Earth diameters!!!

- H mag = 23.3
- Δ = 0.00048 AU



- H mag = 19.6
- Δ = 0.06 au

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Modulated Waveforms

- Pulsing transmitted signal allows range determination
- Fine resolution requires narrow pulse width, T
- Signal bandwidth inverse of pulse width, B = 1/T
- Trade off:
  - For fine range resolution we desire short pulse width, but this decreases P_{rx}
  - For increased SNR we desire long pulse width, but this decreases range resolution
- A way around this is to modulate the signal in amplitude, frequency, or phase in order to increase B
- Range determination requires time structure in transmitted signal

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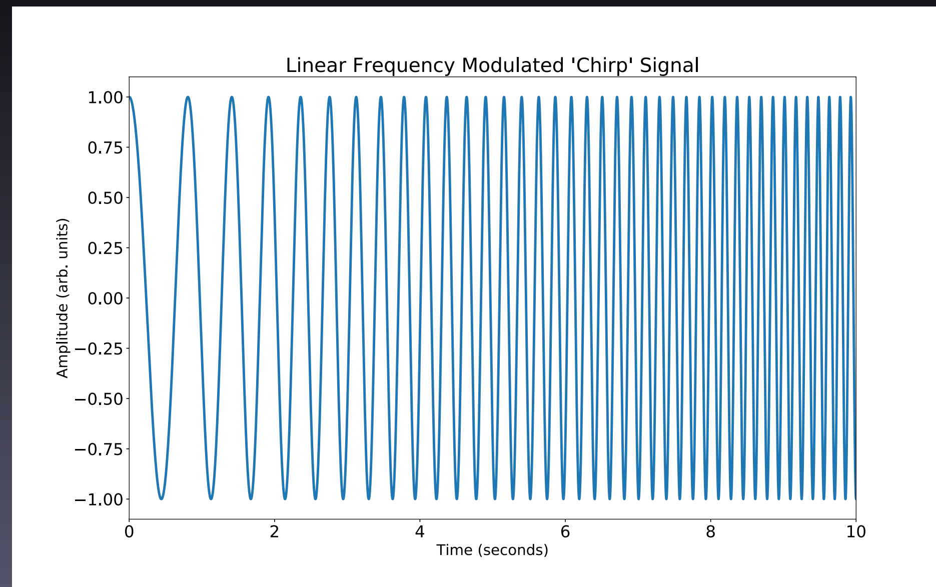
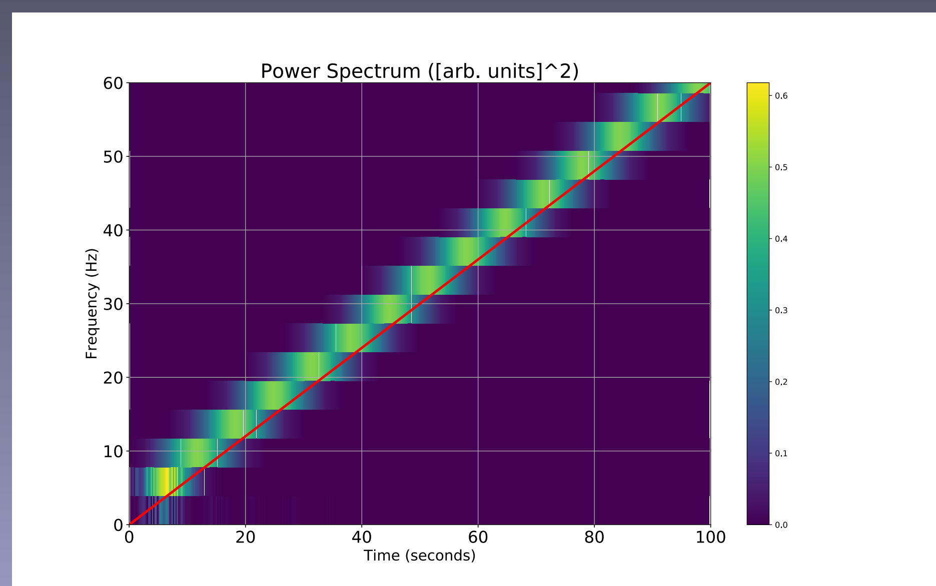
Linear Frequency Modulation

- Bandwidth = f2 – f1
- Matched filter maximizes SNR
- Convolve received signal with transmitted signal





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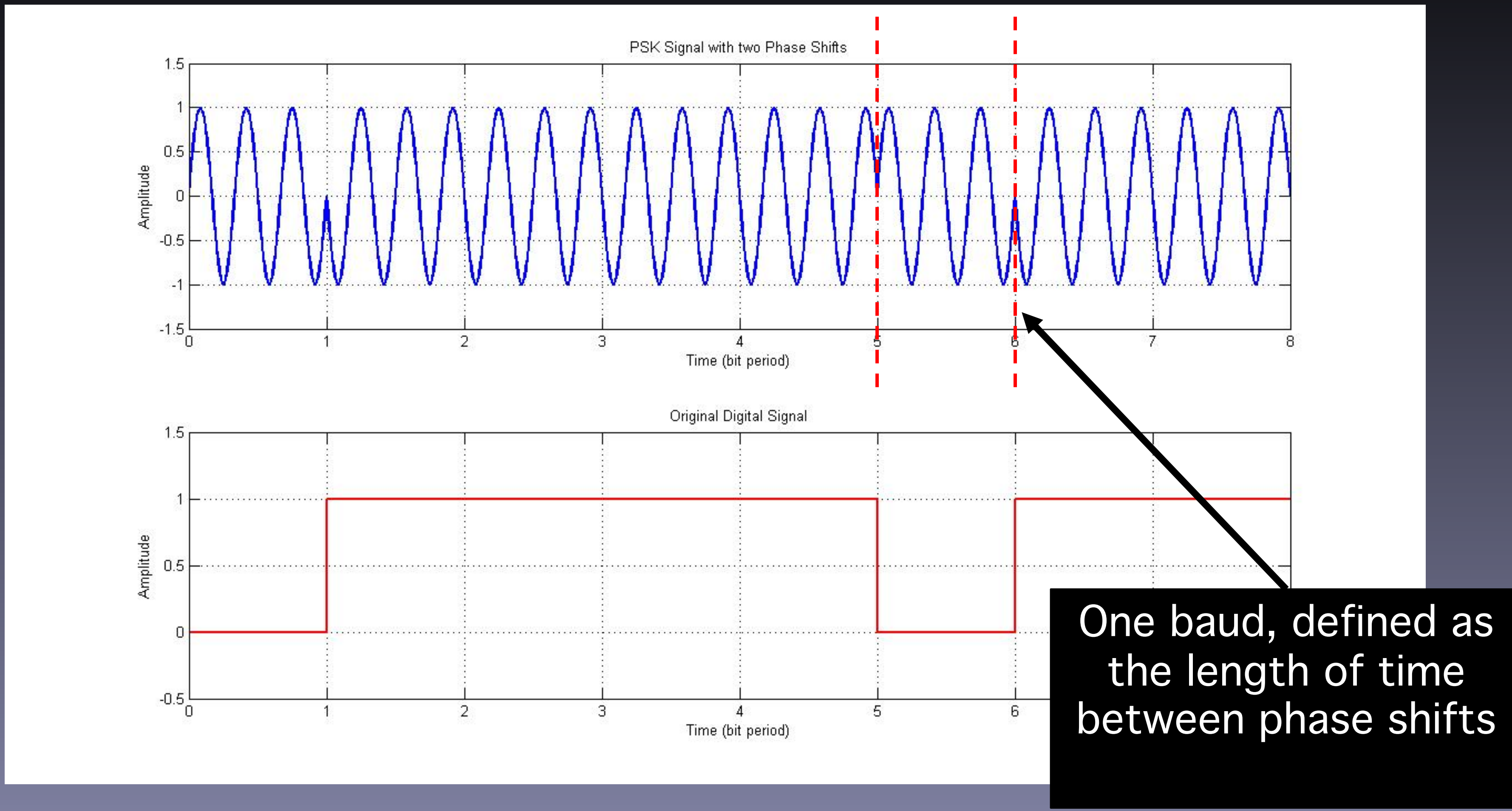
Binary Phase Coded Waveform



- Code Bandwidth = 1/[baud][codelength]

$$\Delta r = \frac{c \cdot baud}{2}$$

- Convolve received signal with transmitted signal

Planetary Radar: Goldstone (JPL)

- Declination range: -35–90 (79% of the whole sky)
- Several antennas (the largest, DSS-14: 70 m)
- Transmitter frequency: 8560 MHz (3.5 cm)
- Power up to 500 kW
- ~70 objects/year attempted, ~60 detected

Image credit: NASA/JPL-Caltech

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Planetary Radar: Arecibo

- Declination range: -1–38 (32% of the whole sky)
- 305 m antenna
- Transmitter frequency: 2380 MHz (12.6 cm)
- Power up to 1 MW
- ~100 objects/year attempted, ~80 detected

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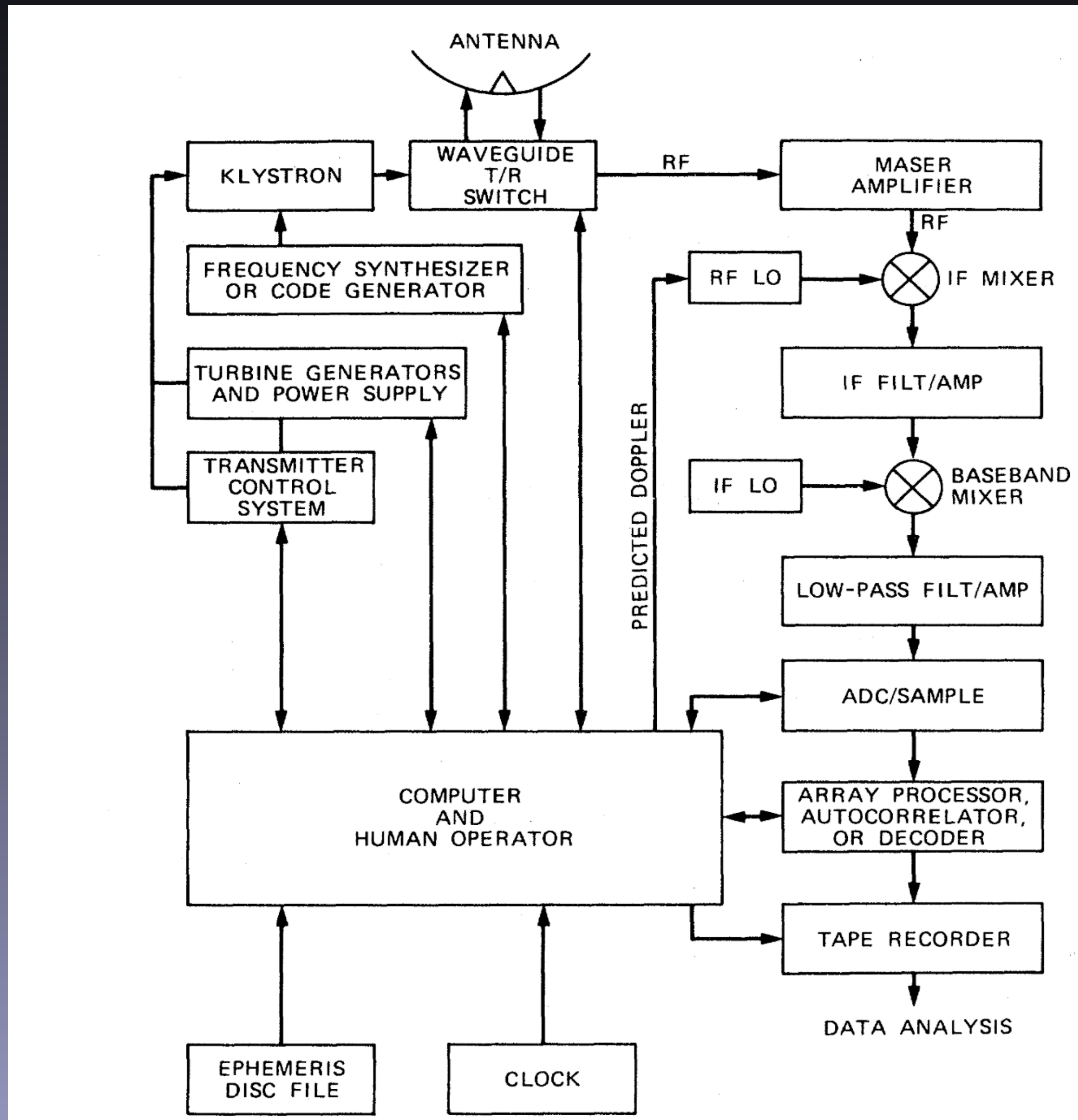
Planetary Radar: Arecibo



Ostro (1993) *Reviews of Modern Physics* 65(4) 1235-1279

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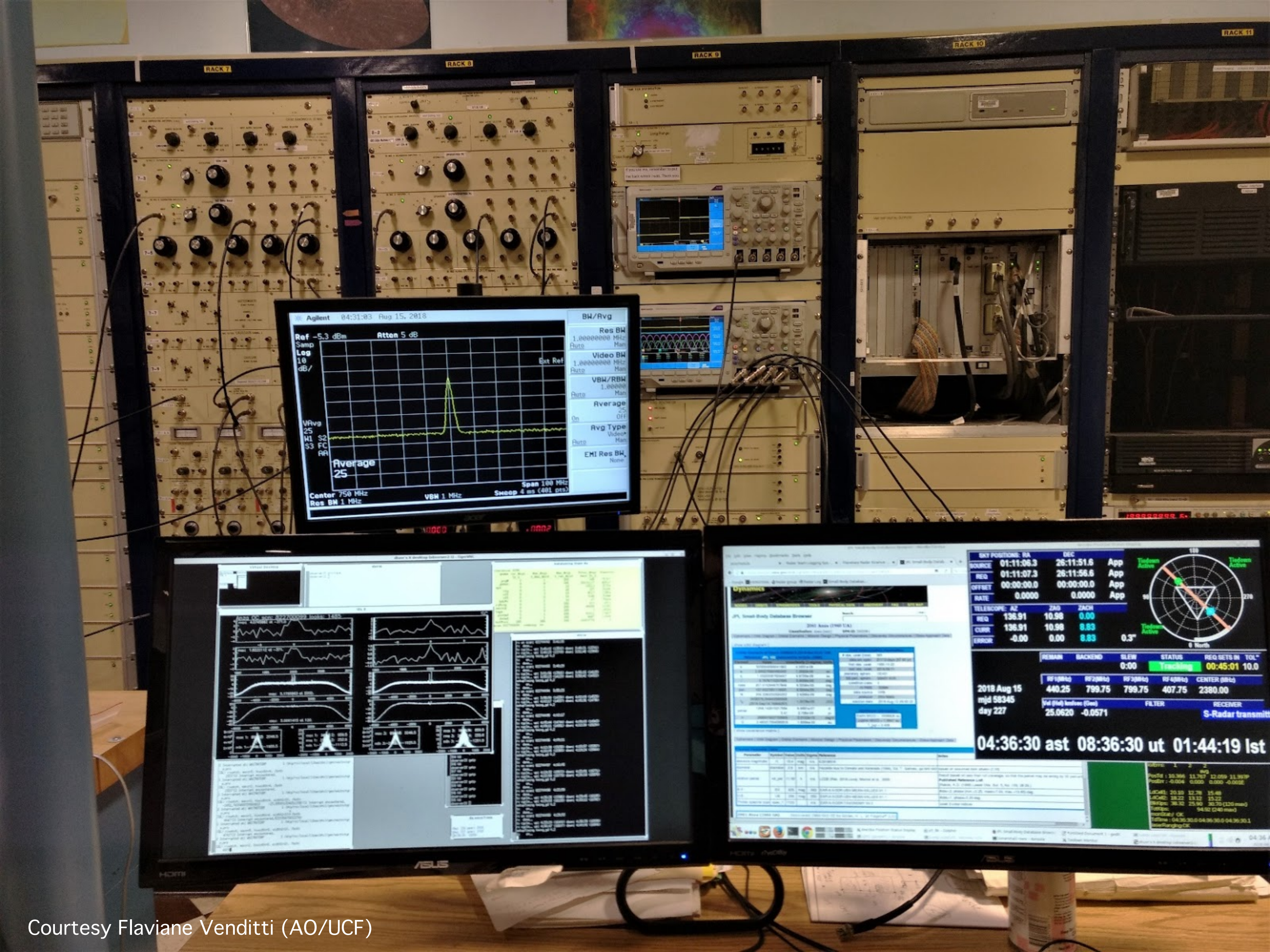
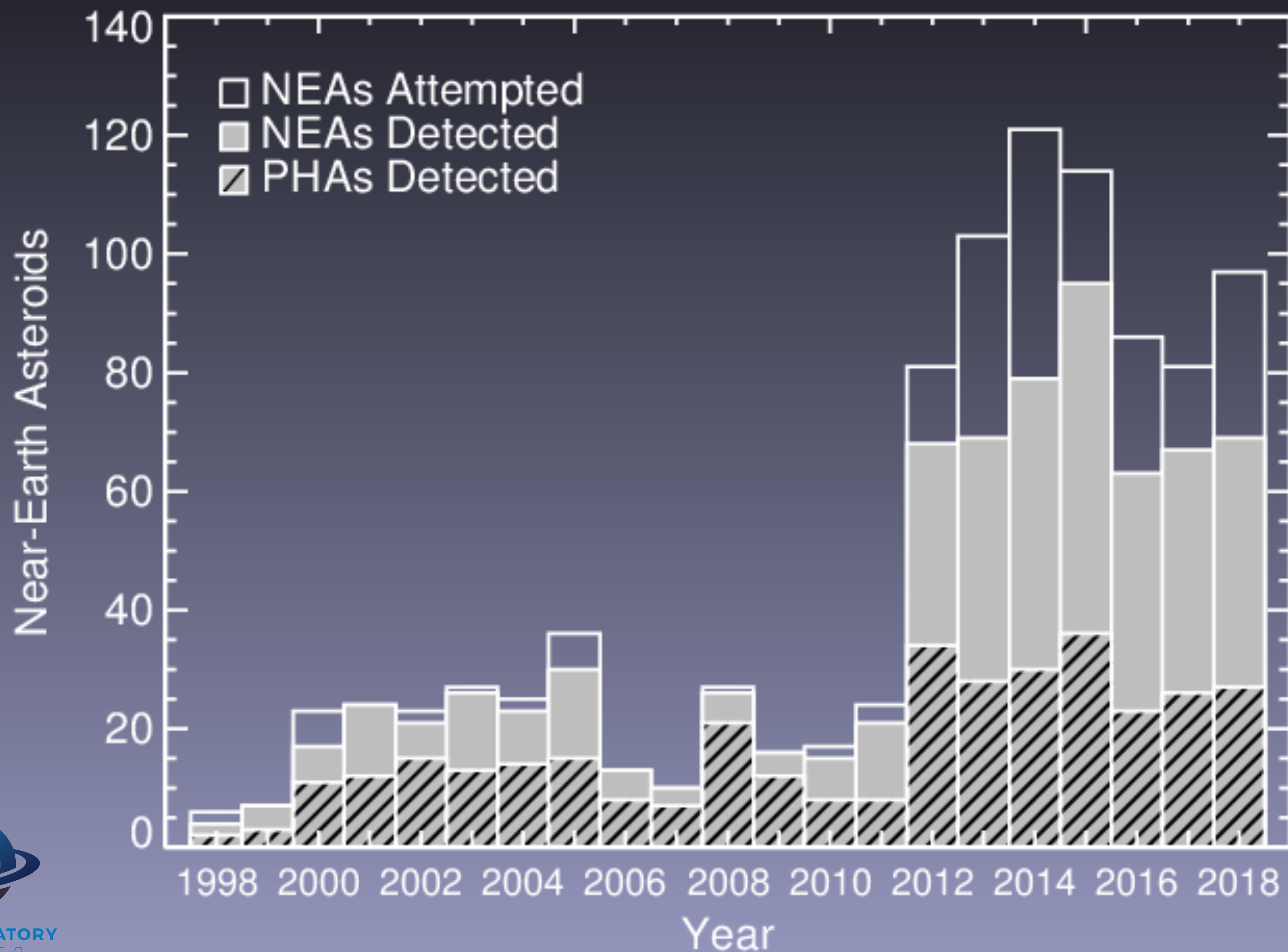


Courtesy Flaviane Venditti (AO/UCF)

Arecibo Observatory detects and characterizes ~100 near-Earth objects (NEOs) per year



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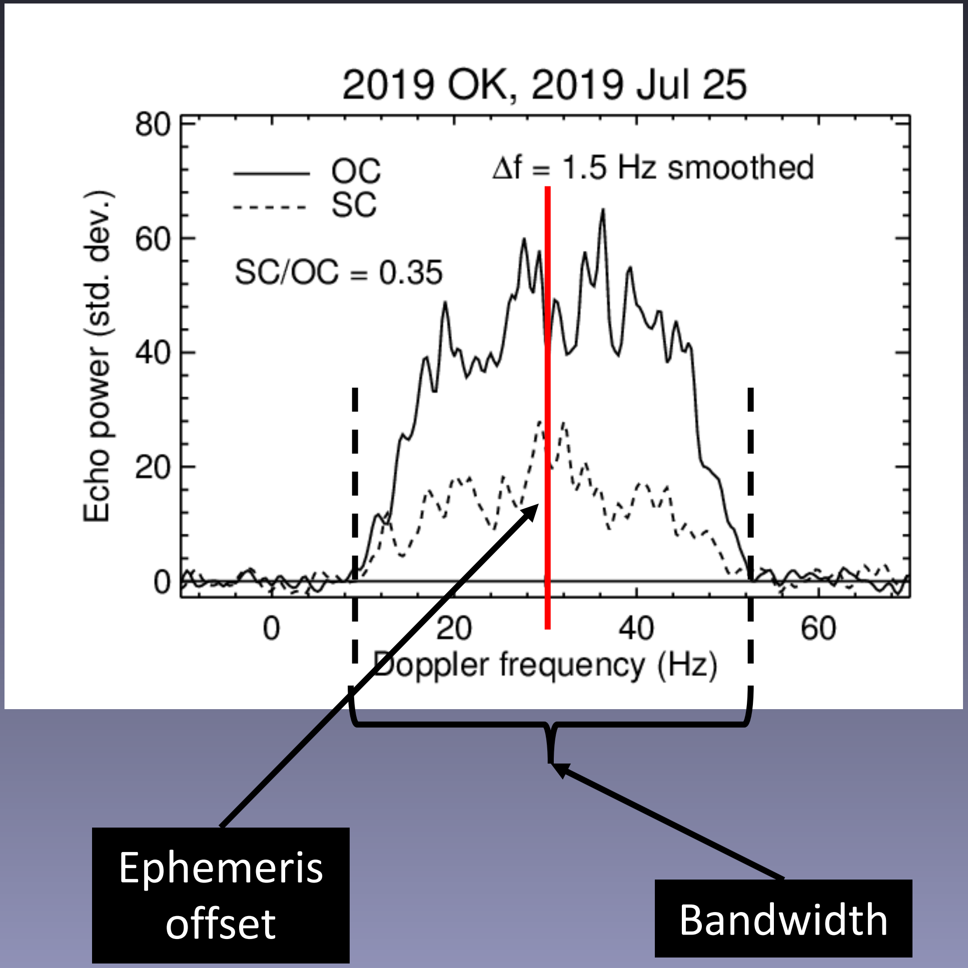
http://www.naic.edu/~pradar/PastDet.php

For every detection we learn:

- Astrometry: ~ 30 Hz offset in line-of-sight velocity of target
- Rotation rate: estimate from bandwidth and size

$$B = \frac{4\pi D cos\phi}{\lambda_0 P_{spin}}$$

- CPR: related to surface roughness and composition



Delay-Doppler Imaging

Time Delay: Distance

- Vertical axis
- Increasing downward
- Points at the top are closest to the observer

Doppler Frequency: Velocity

- Horizontal axis
- Increasing to the right
- Points on the right are approaching the observer

- Splitting signal into discrete range & frequency bins
- Requires high SNR

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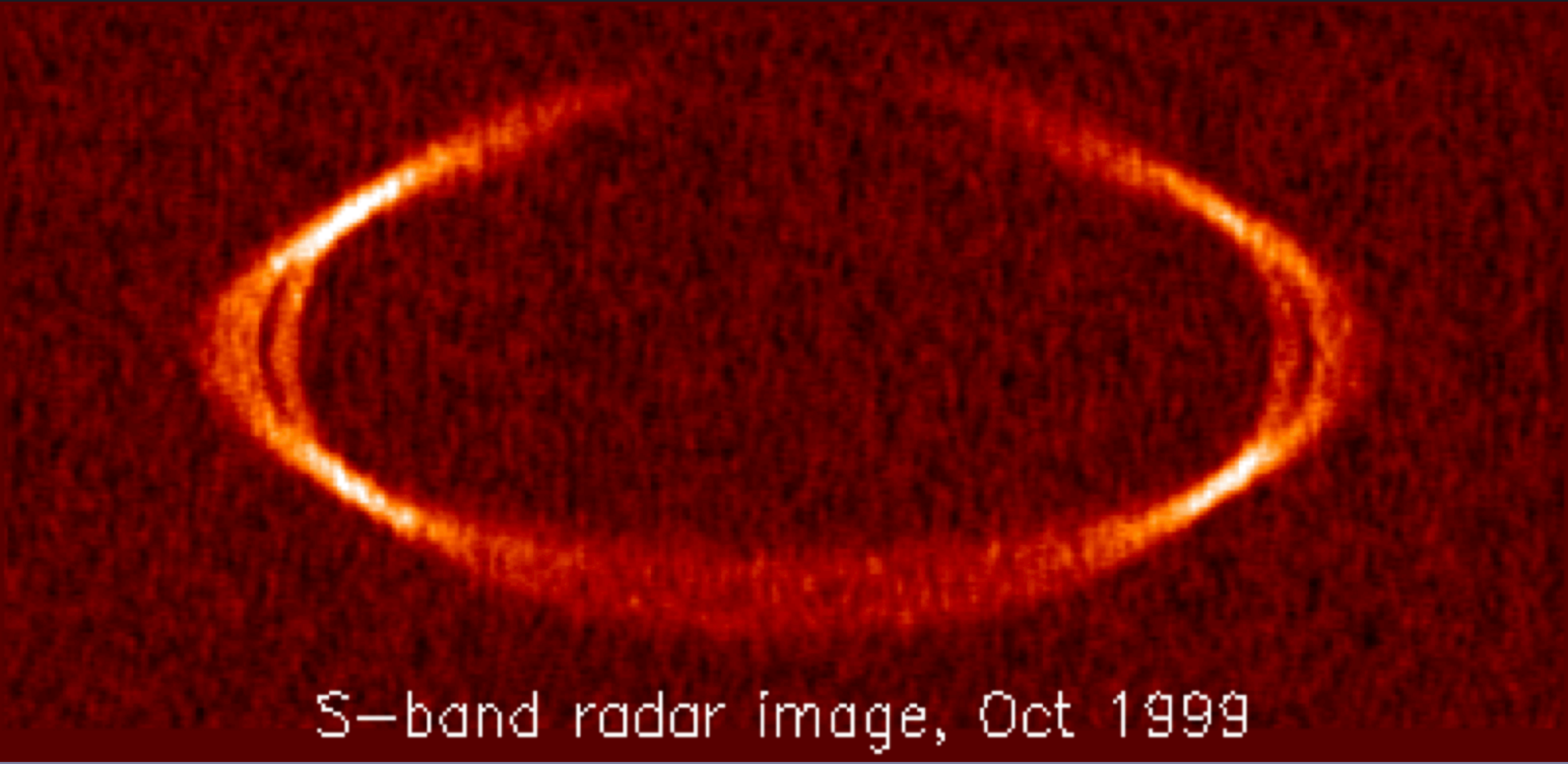
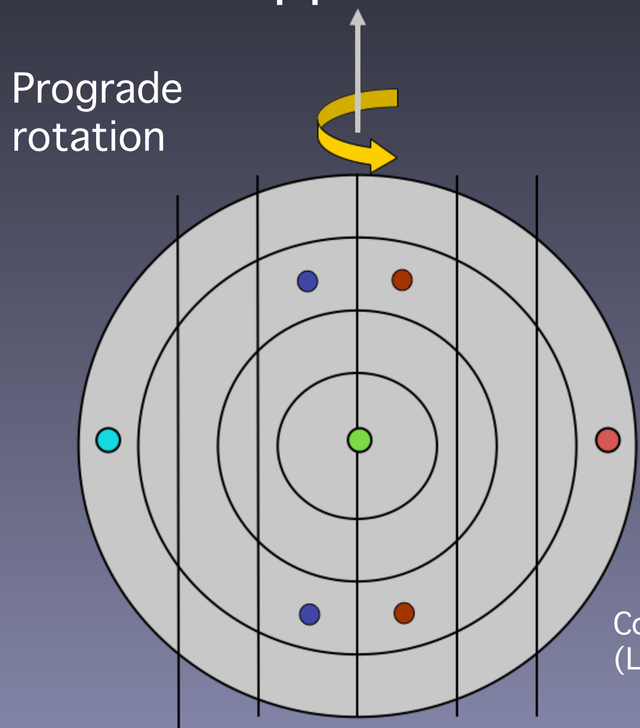
What Solar System Body is This?

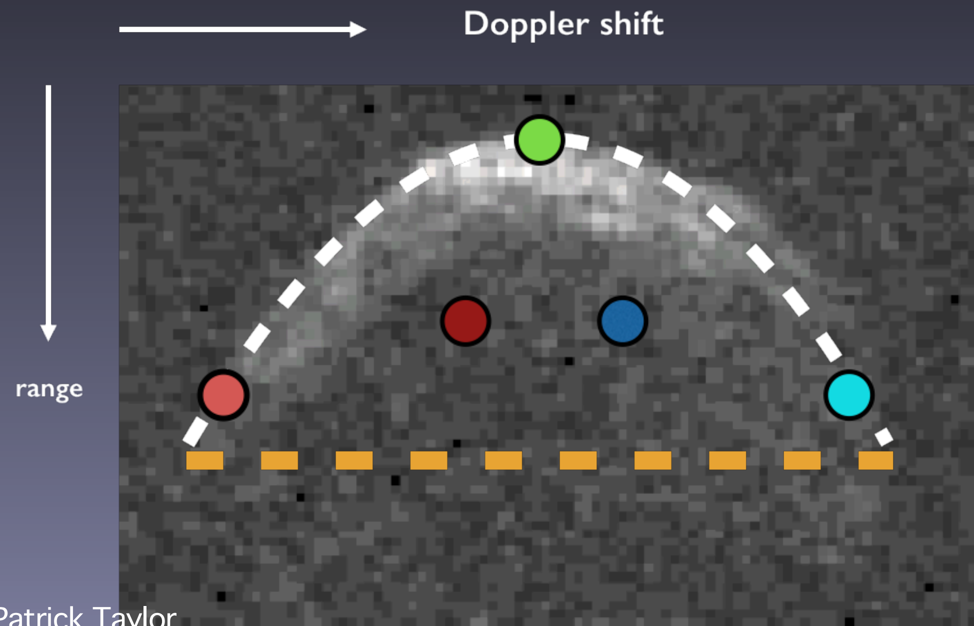


The peculiarities of radar imaging!
What two things are strange about this image?

3D – 2D ambiguity

Circles: points at the same distance (range) from observer
Vertical Lines: points of constant Doppler shift
Blue dots are blue shifted, red dots are red-shifted, green dots are not Doppler shifted





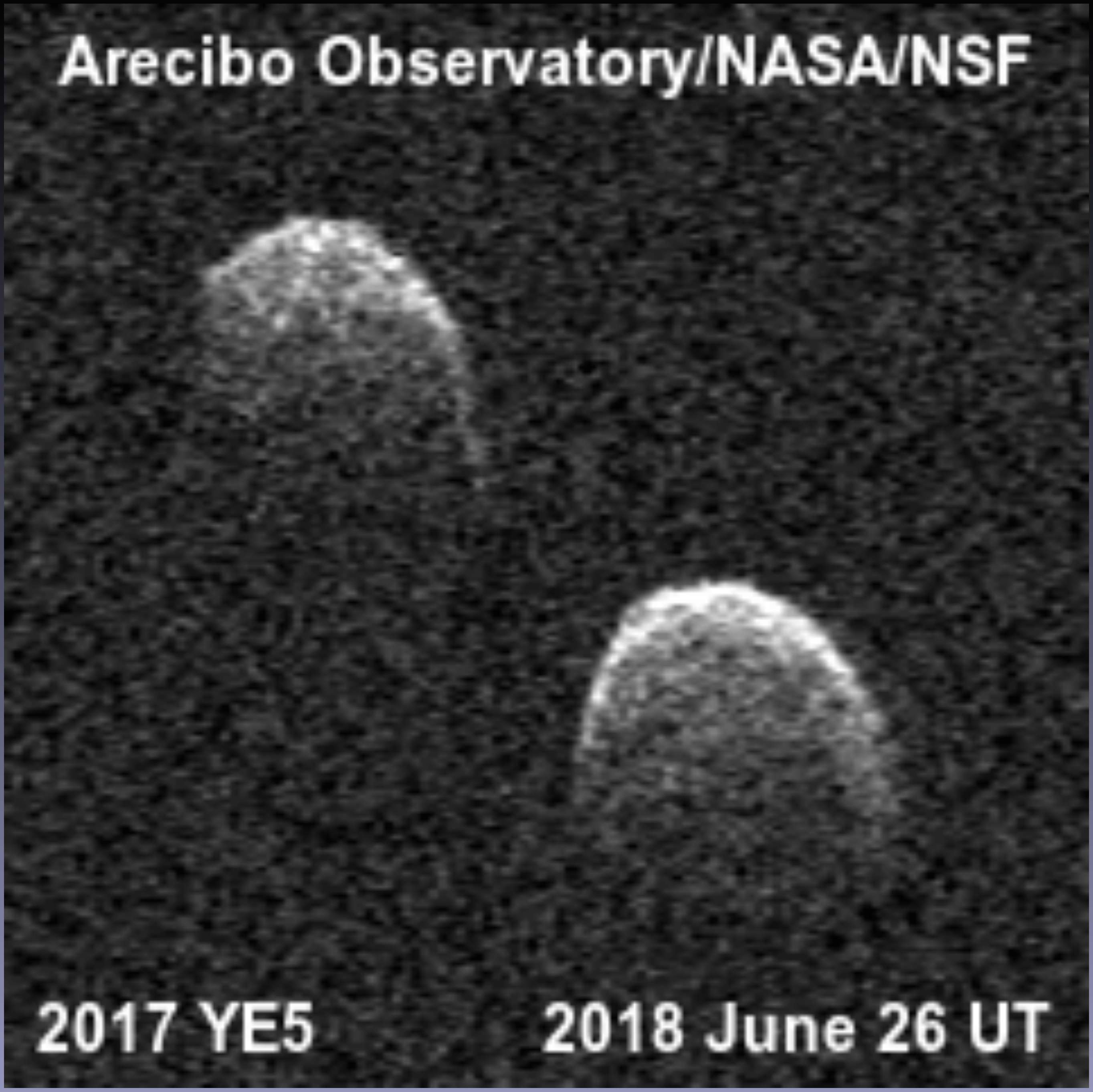
Courtesy Patrick Taylor (LPI/USRA)

The two blue and red dots map to the same point in a radar image (north/south ambiguity)

2017 YE5

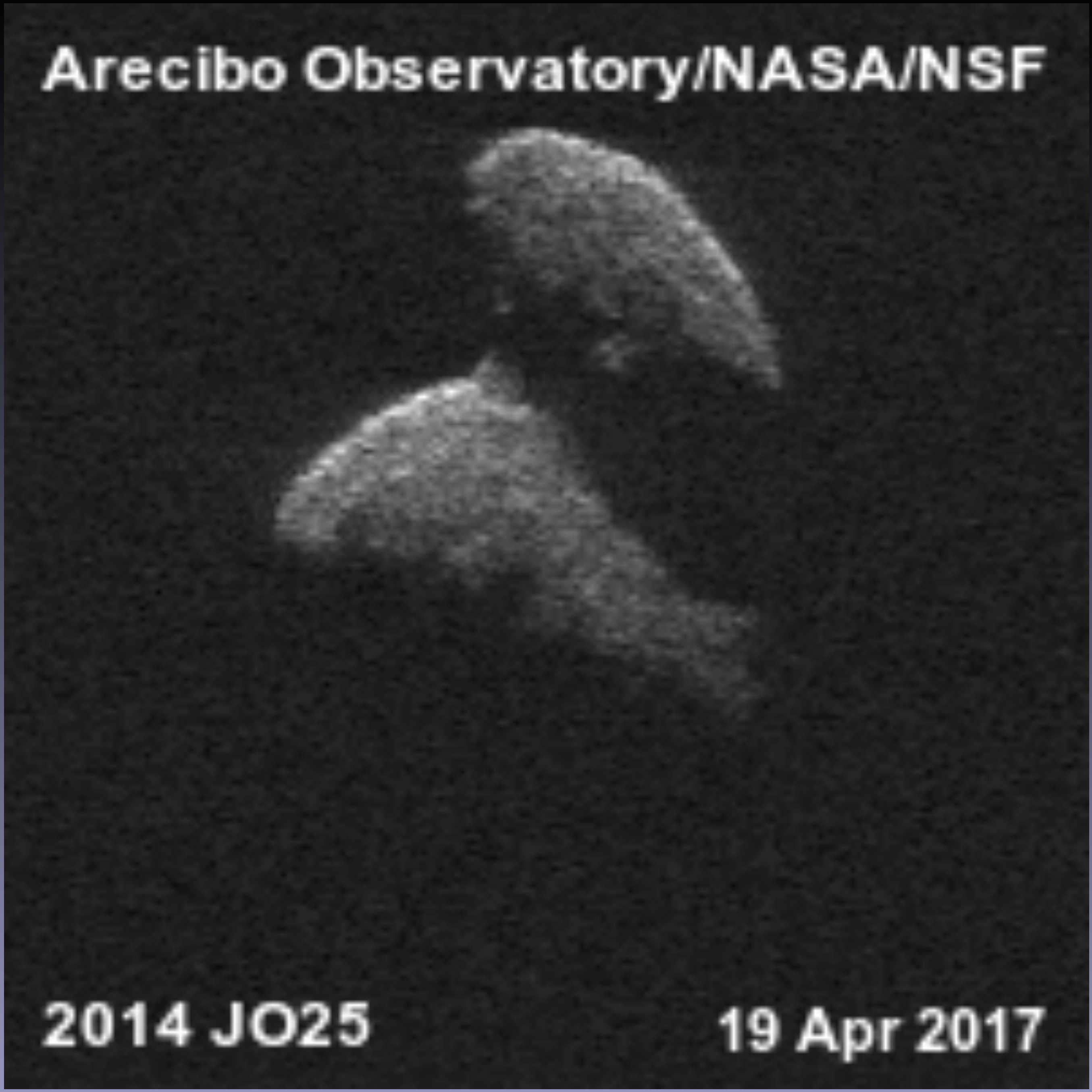
- Equal mass binary
- 7.5 m/pixel
- 20-24 hr period
- Albedo difference between bodies

Bistatic Observation between AO and GBT!



2014 JO25

- PHA
- Contact binary
- 7.5 m/pixel
- ~ 870 m
- 4.5 hr rotation period



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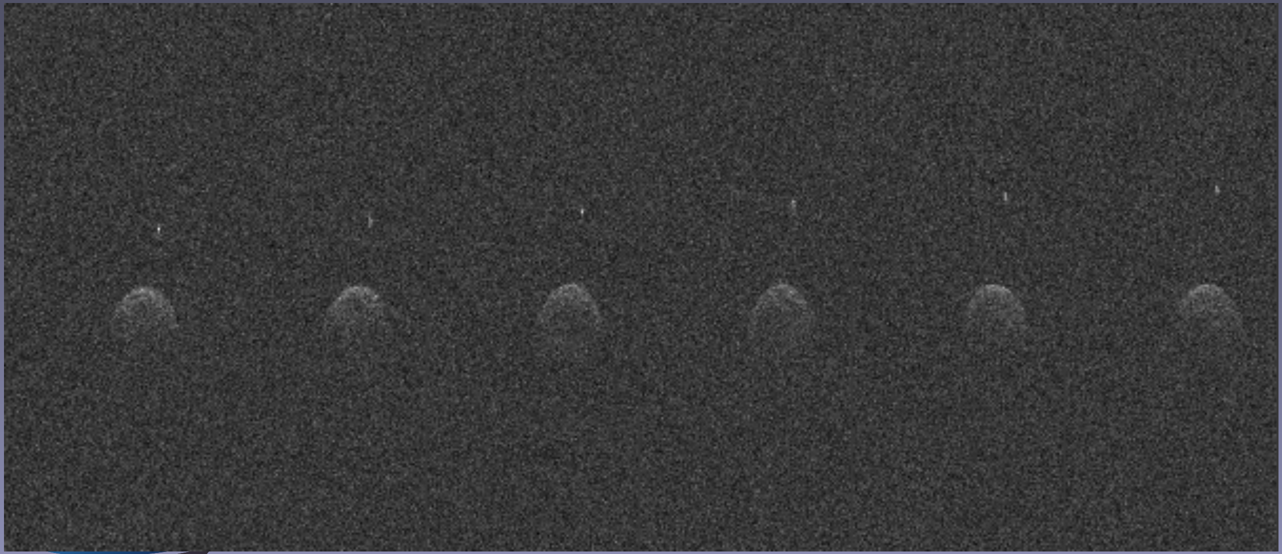
3200 Phaethon

- 2nd largest PHA known
- 75 m/pixel
- ~ 6 km
- 3.6 hr rotation period
- Surface features visible (crater or boulder?)
- Target of JAXA's Destiny+ mission set to launch 2022



Didymos

- PHA
- Binary system
- 7.5 m/pixel (2 spb)
- ~ 760 m
- 2.3 hr rotation period
- Target of NASA's DART mission
- Arecibo to play important role

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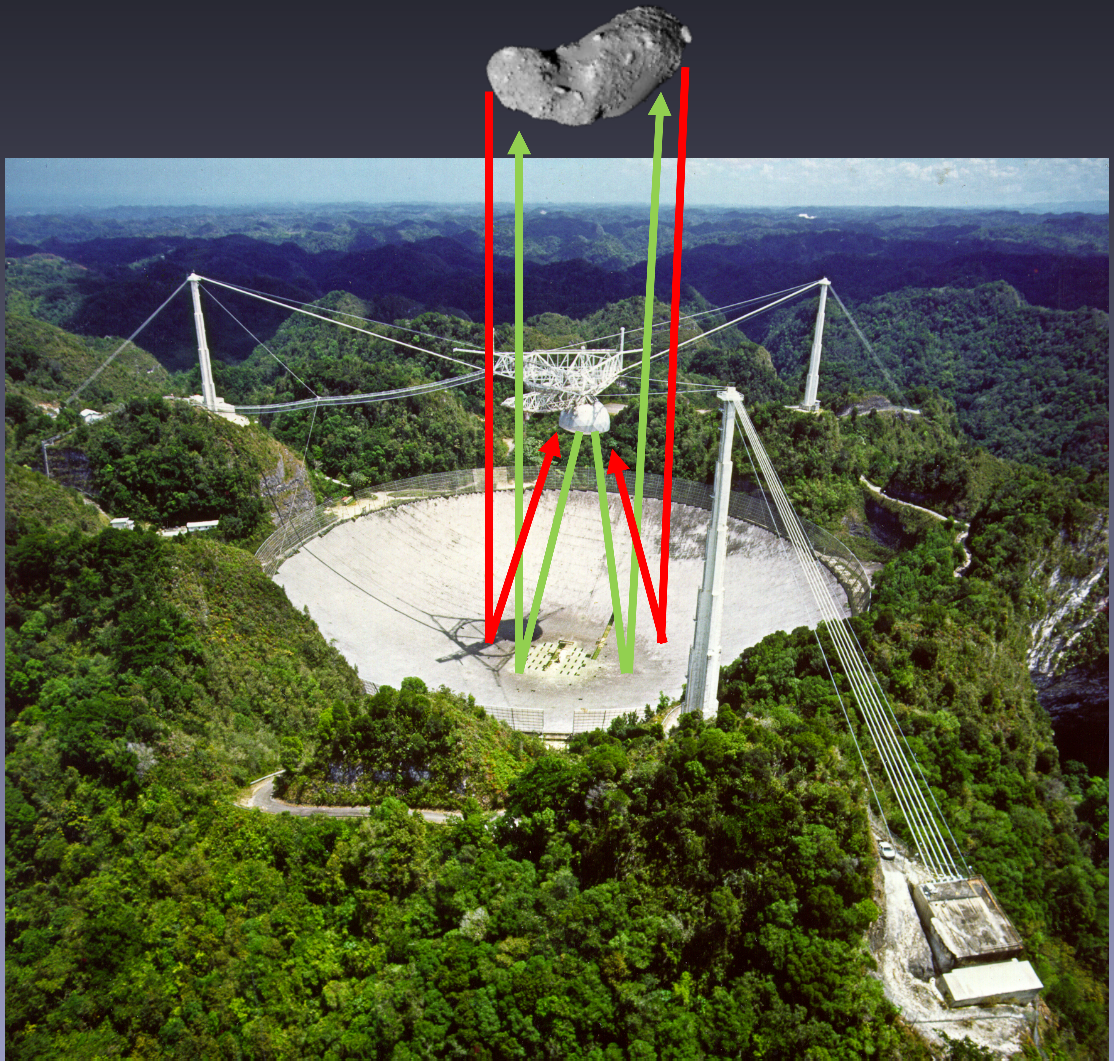
Monostatic vs. Bistatic

- Transmitter and receiver are at the same location



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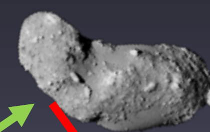
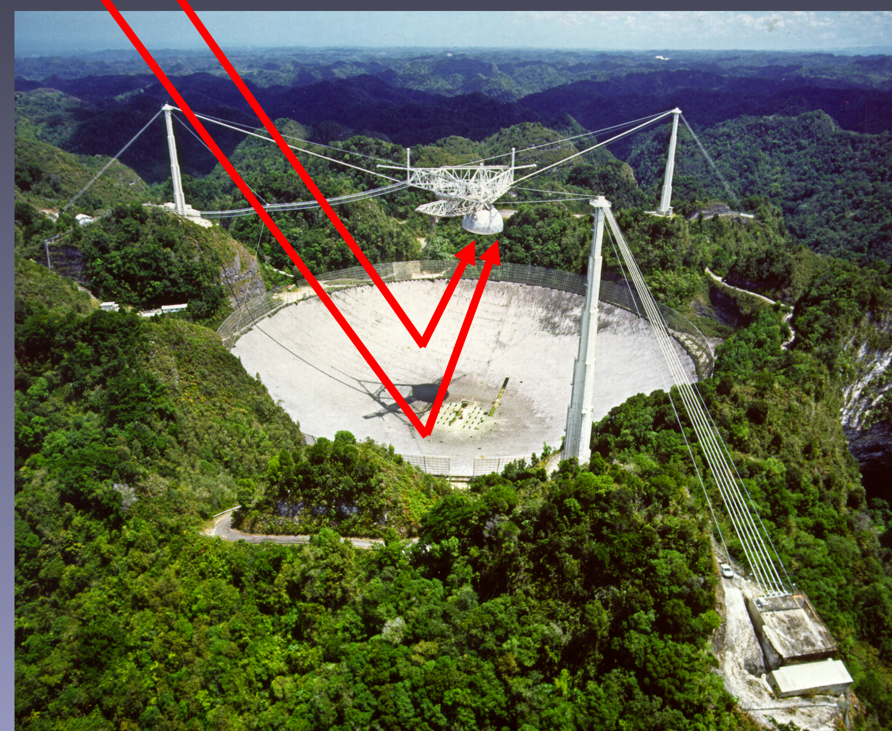
Monostatic vs. Bistatic

- Transmitter and receiver offset from one another
- Can utilize complementary aspects of different systems
- Close targets
- Speckle Interferometry





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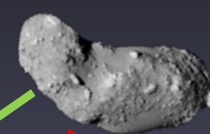


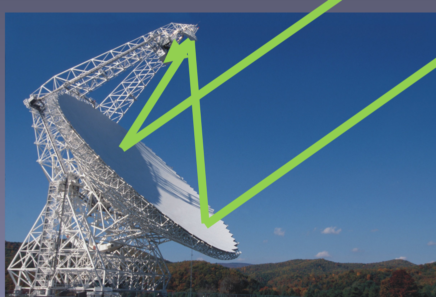
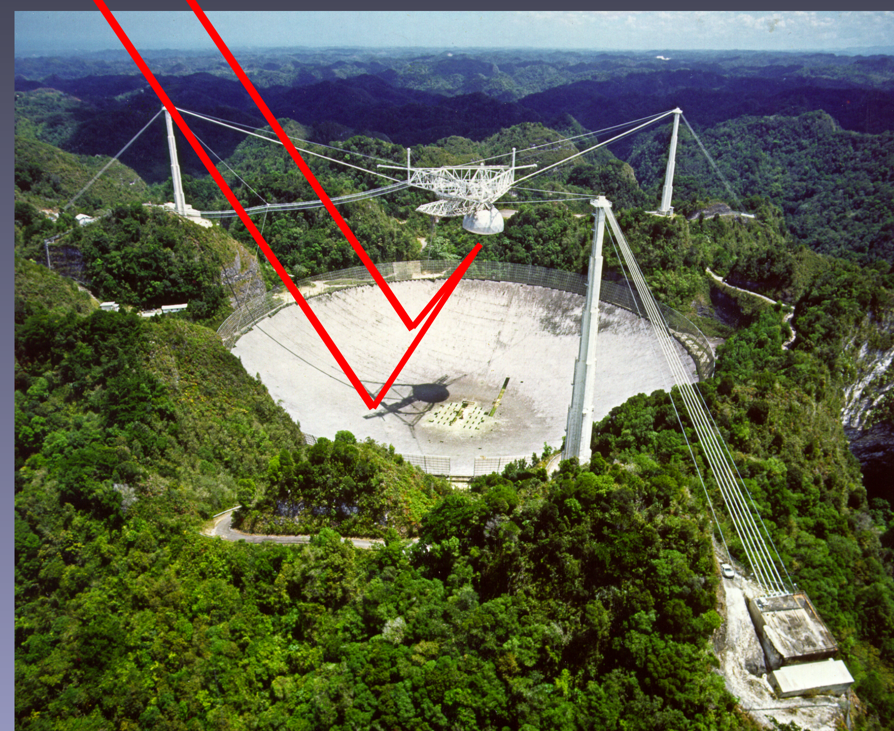


Image credit: NRAO/GBO



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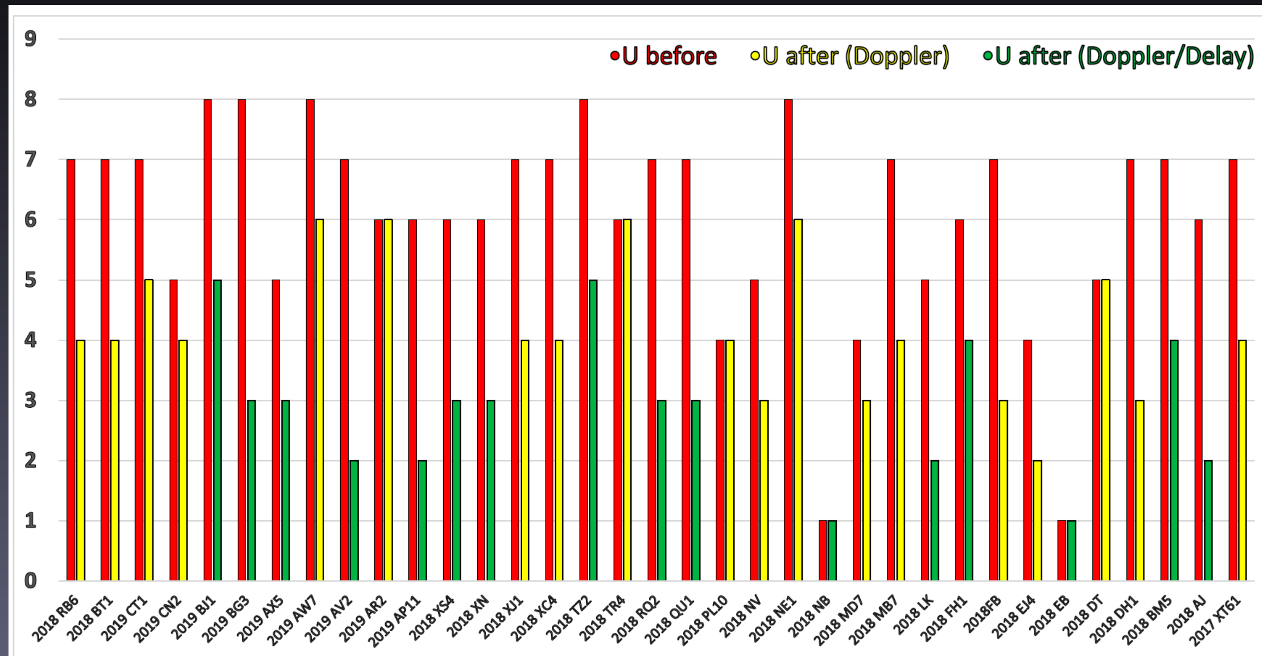
Science Return

- Refine orbits: reduce uncertainty in orbital parameters by five orders of magnitude for newly discovered objects



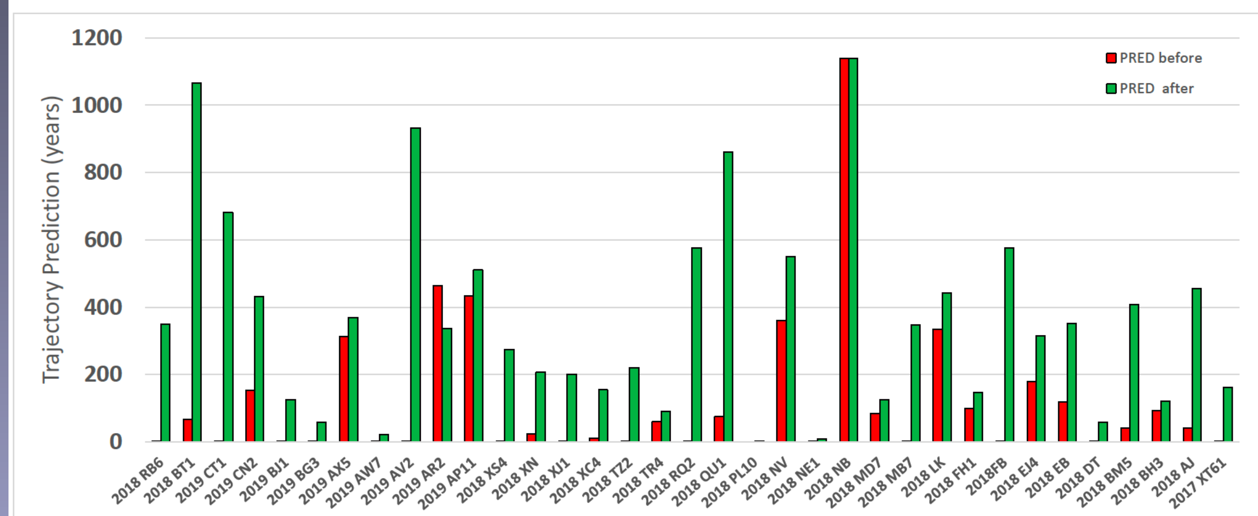


Image Credit: Flavianne Venditti (AO, UCF)

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Science Return

- Size and shape: delay-Doppler images can produce images comparable to spacecraft encounters

4719 Toutatis

Radar shape model

Chang’e spacecraft image taken during flyby

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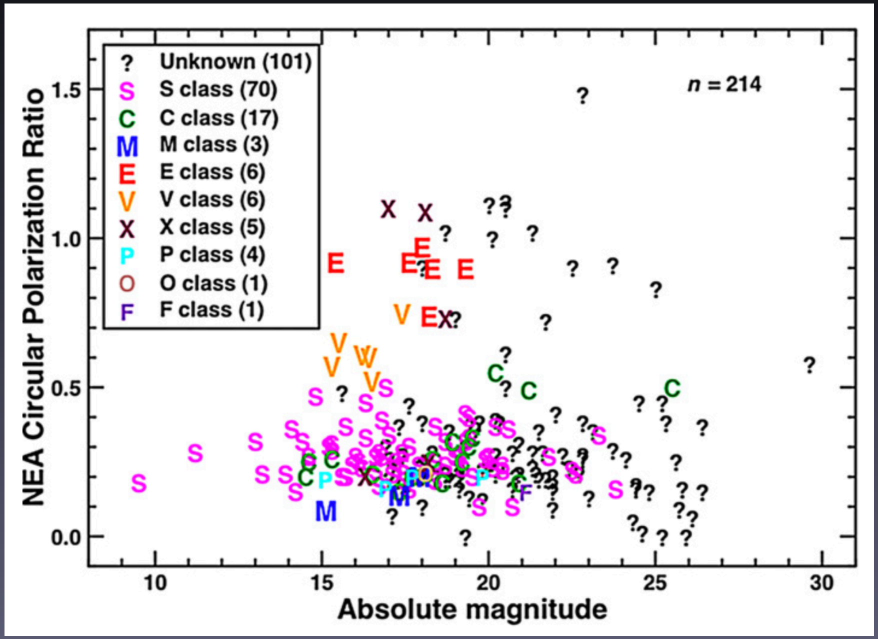
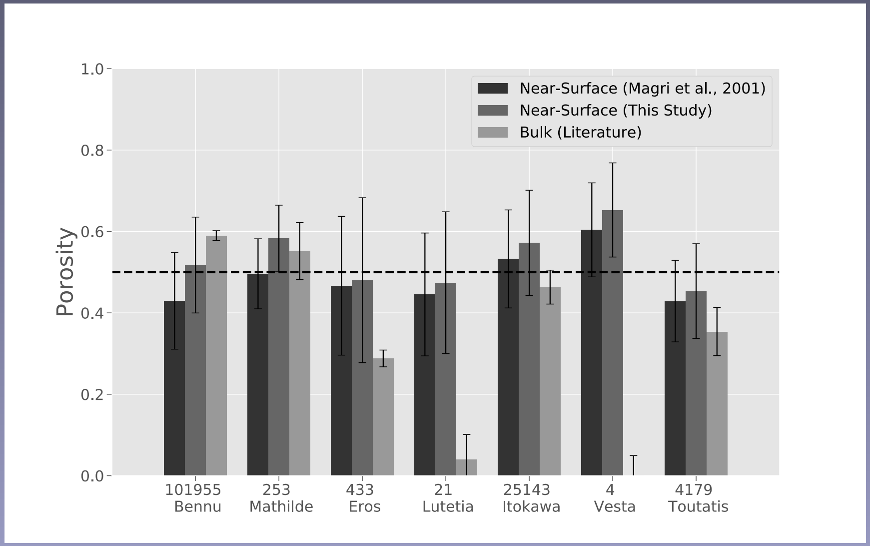
Both images: Benner et al. (2015) *Asteroids IV*, 165-182

Science Return

- Surface characterization:
  - Comparison of polarimetric properties shows correlation among taxonomic types, i.e. Benner et al. (2008)
  - Comparison with laboratory experiments constrain surface structure, i.e. Hickson et al. (2019)





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Science Return

- Solar system processes:
  - Asteroids are primitive objects that reflect the conditions of the early solar system
  - Evolutional history of asteroids sheds light on the evolution of different regions of the solar system.

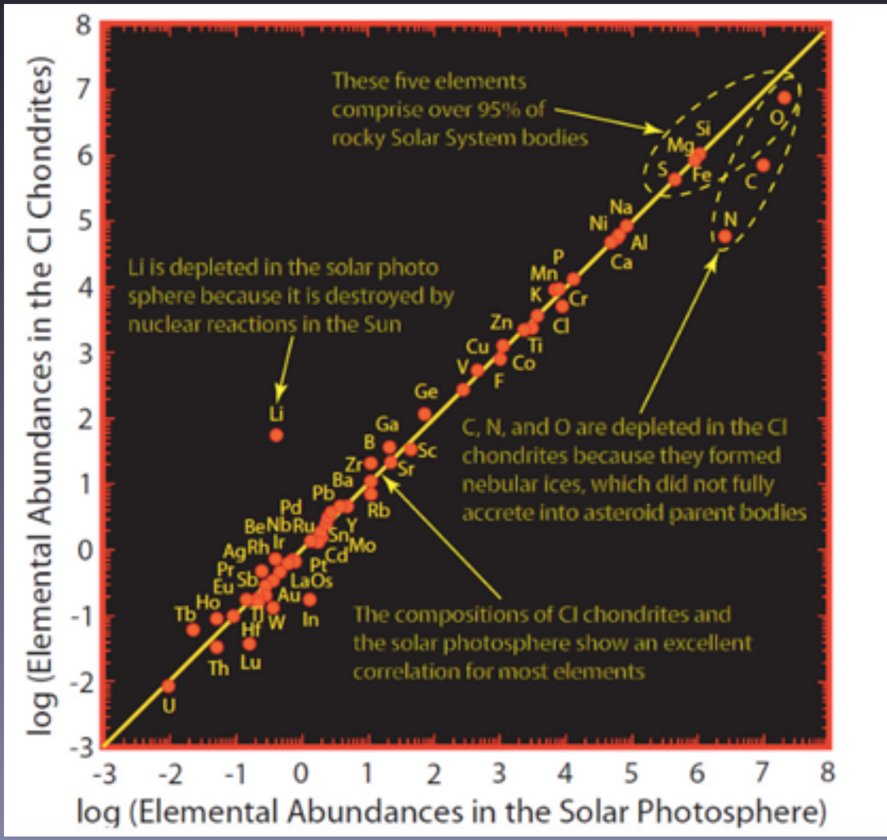

Image credit: PLANETSC 9603 Module 6 Planetary Materials Lecture, Audrey Bouvier (UWO)

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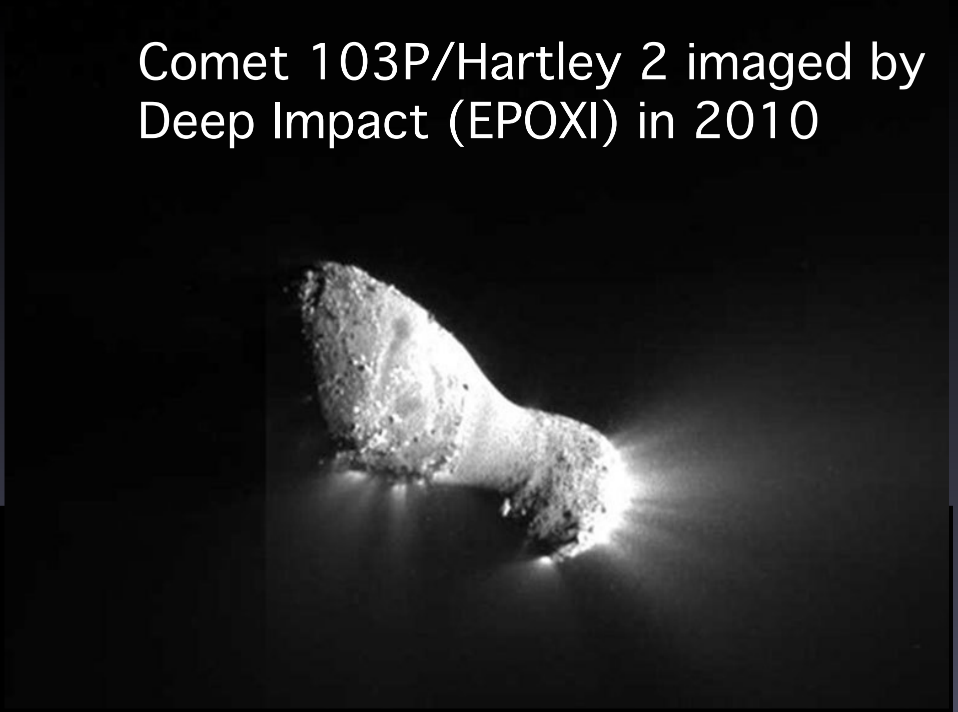
Comet 103P/Hartley 2 imaged by Deep Impact (EPOXI) in 2010



- Solar system processes:
  - Asteroids vs comets? Origins of water and organics in solar system?

101955 Bennu imaged by OSIRSI-Rex in 2019

Image credit: (Top) NASA/JPL/CalTech/UMD (Bottom) NASA/Goddard/University of Arizona/Lockheed Martin

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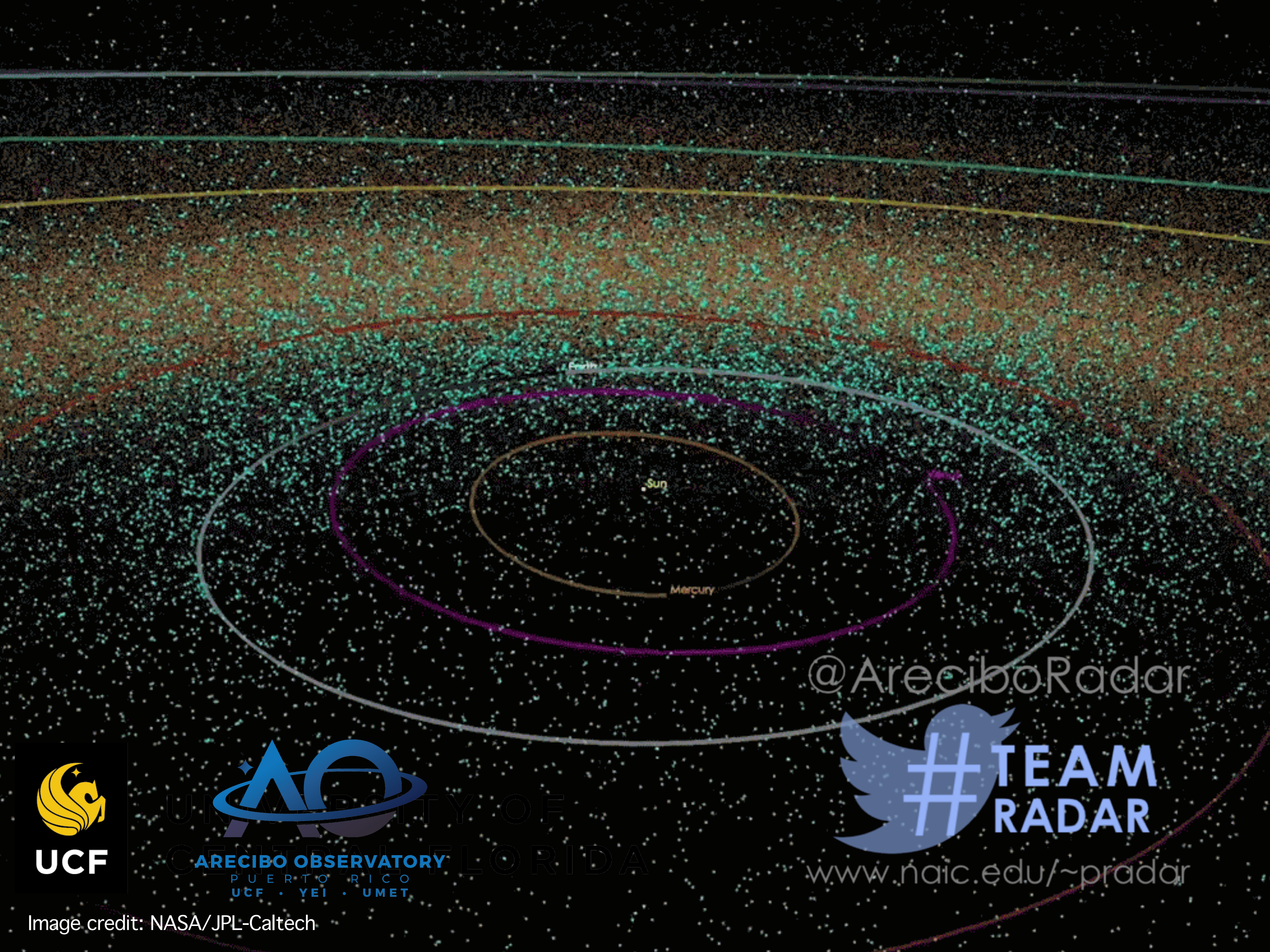
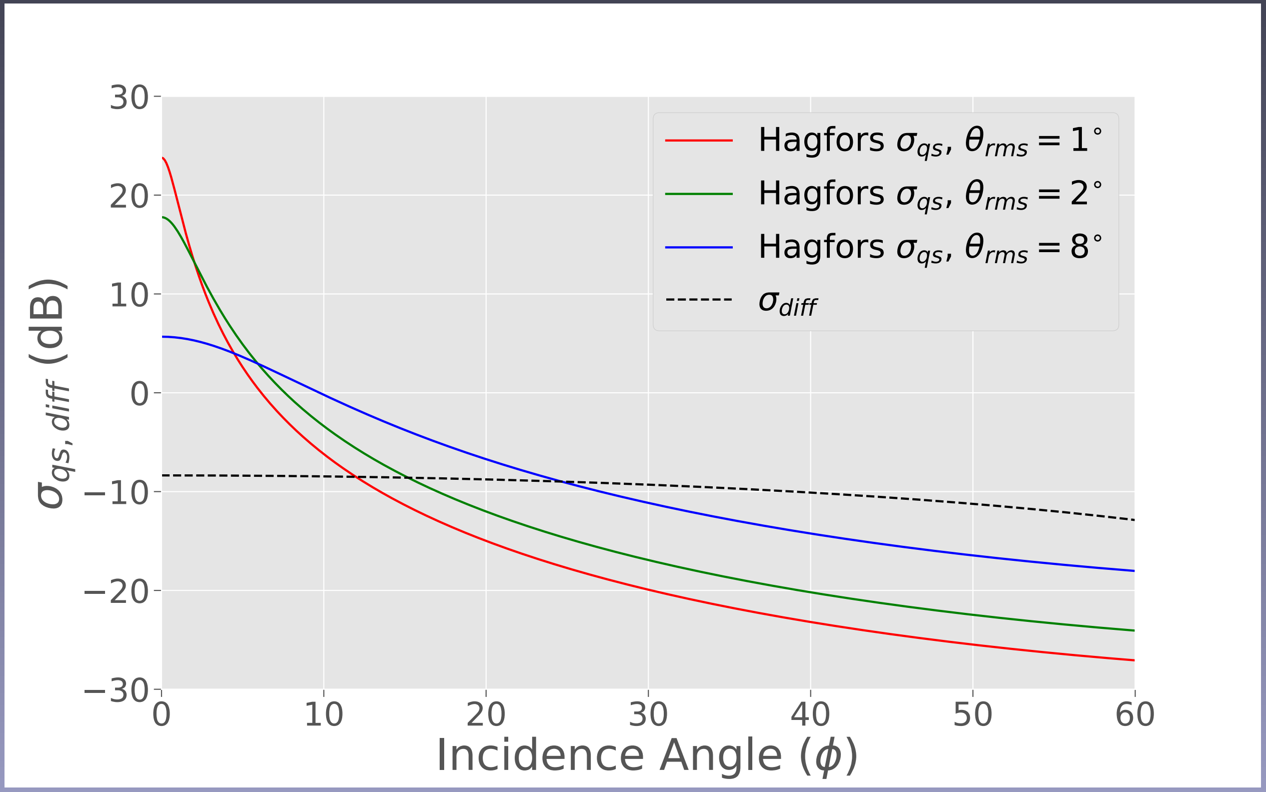


Image credit: NASA/JPL-Caltech

Backup Slides

Radar Scattering Laws

- Describe the radar cross section of a target as a function of incidence angle, ϕ, surface roughness, C, and empirical parameters
- Hagfor's Law:
  - $\sigma_{qs}(\phi) = \left(\frac{RC}{2}\right)(cos^4\phi + Csin^2\phi)^{-3/2}$
- Cosine Law:
  - $\sigma_{diff} = Rcos^n(\phi)$



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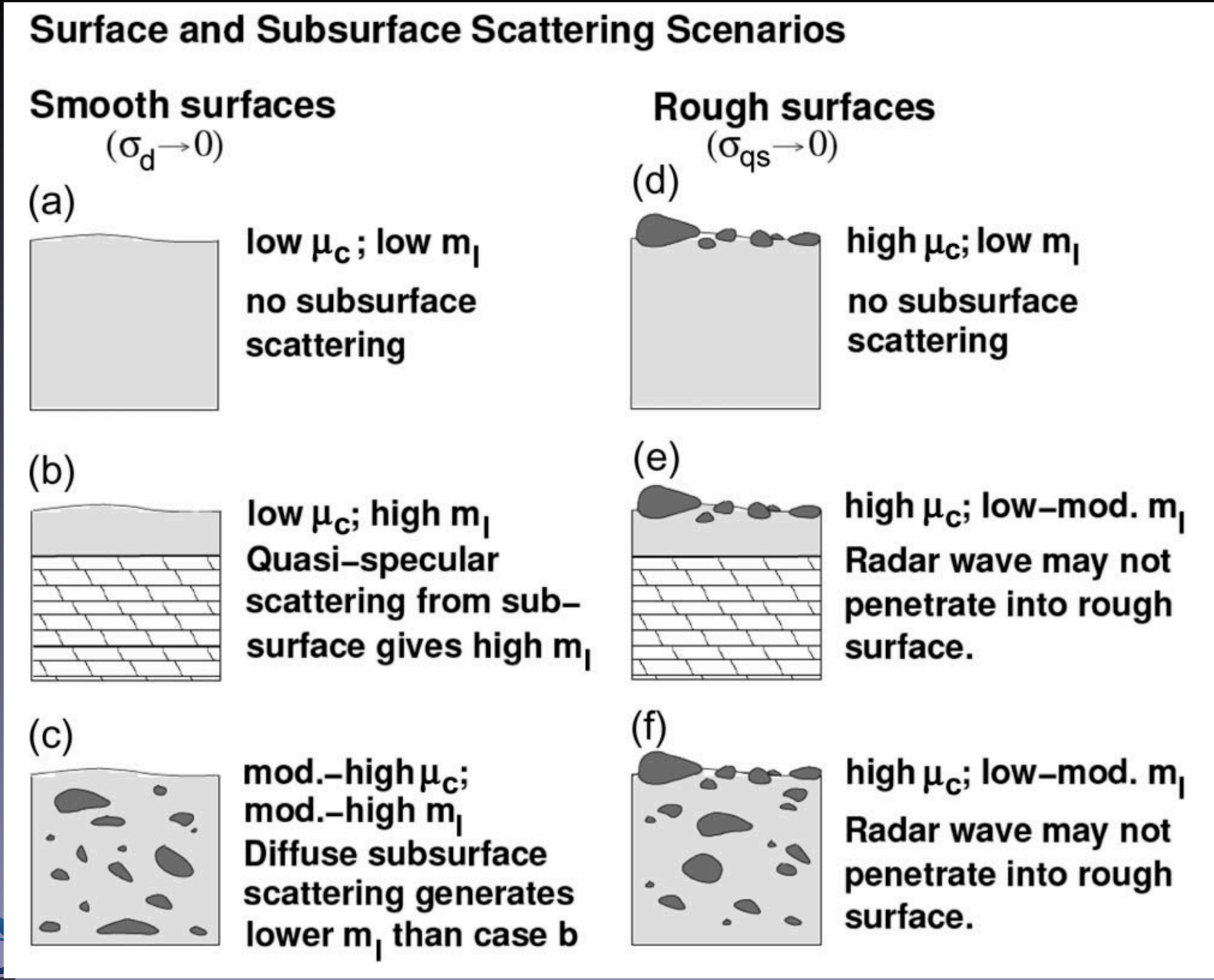

Carter, L. M., Campbell, D. B., & Campbell, B. A. 2011, Proc. IEEE, 99, 770

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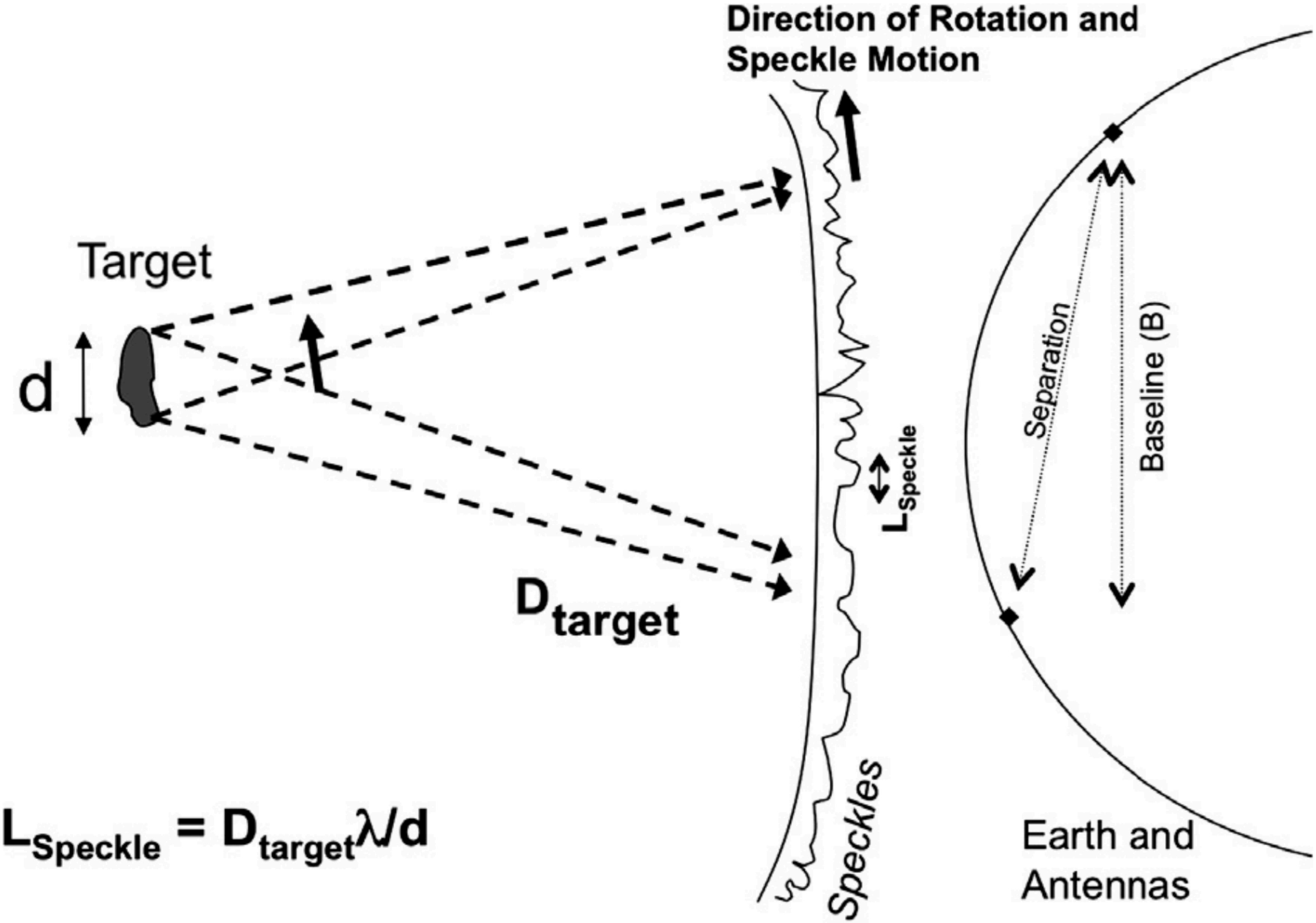

$$L_{Speckle} = D_{target}\lambda/d$$

Busch et al. (2010) *Icarus* 209, 535-541