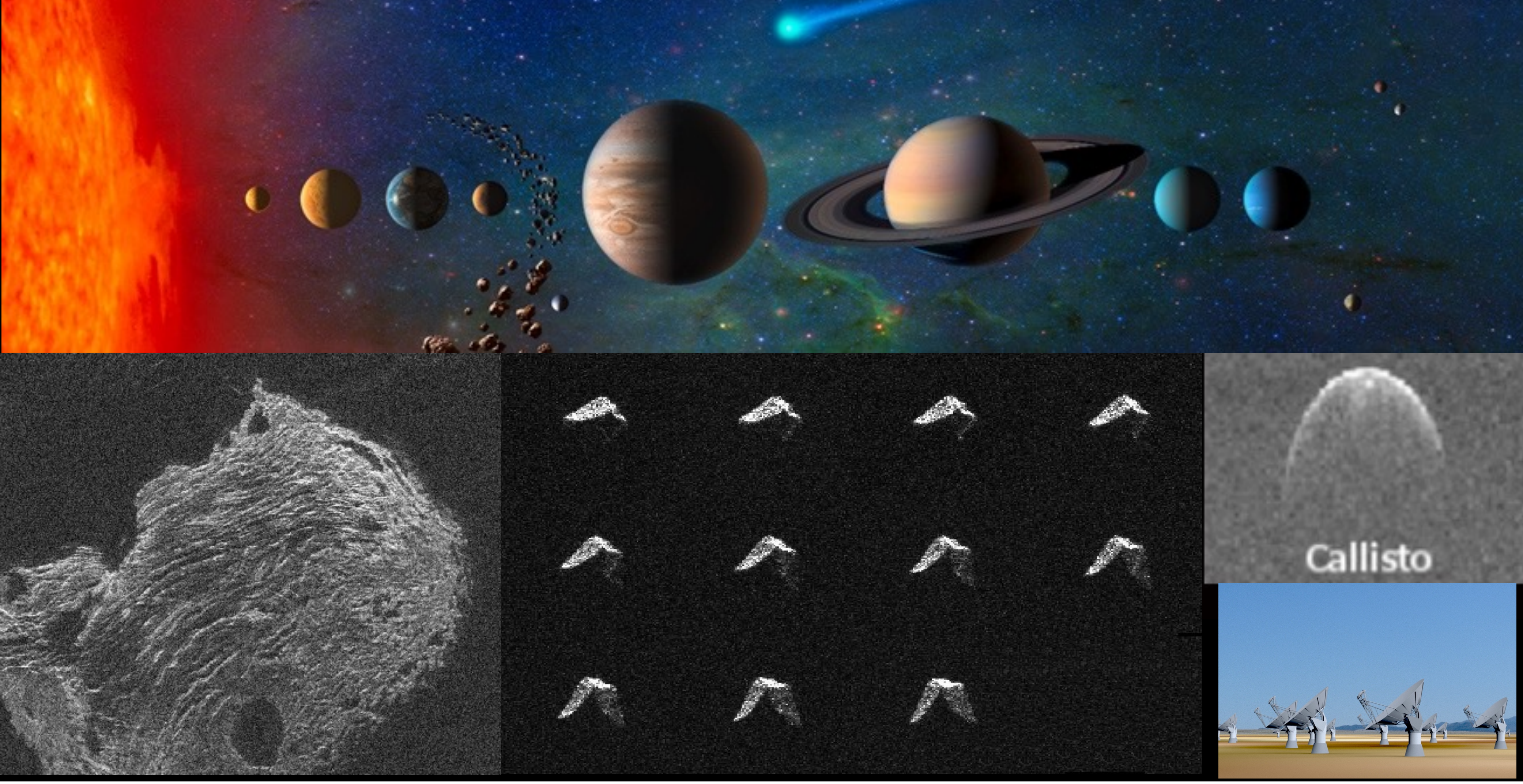


Next-Generation Ground-Based Planetary Radar

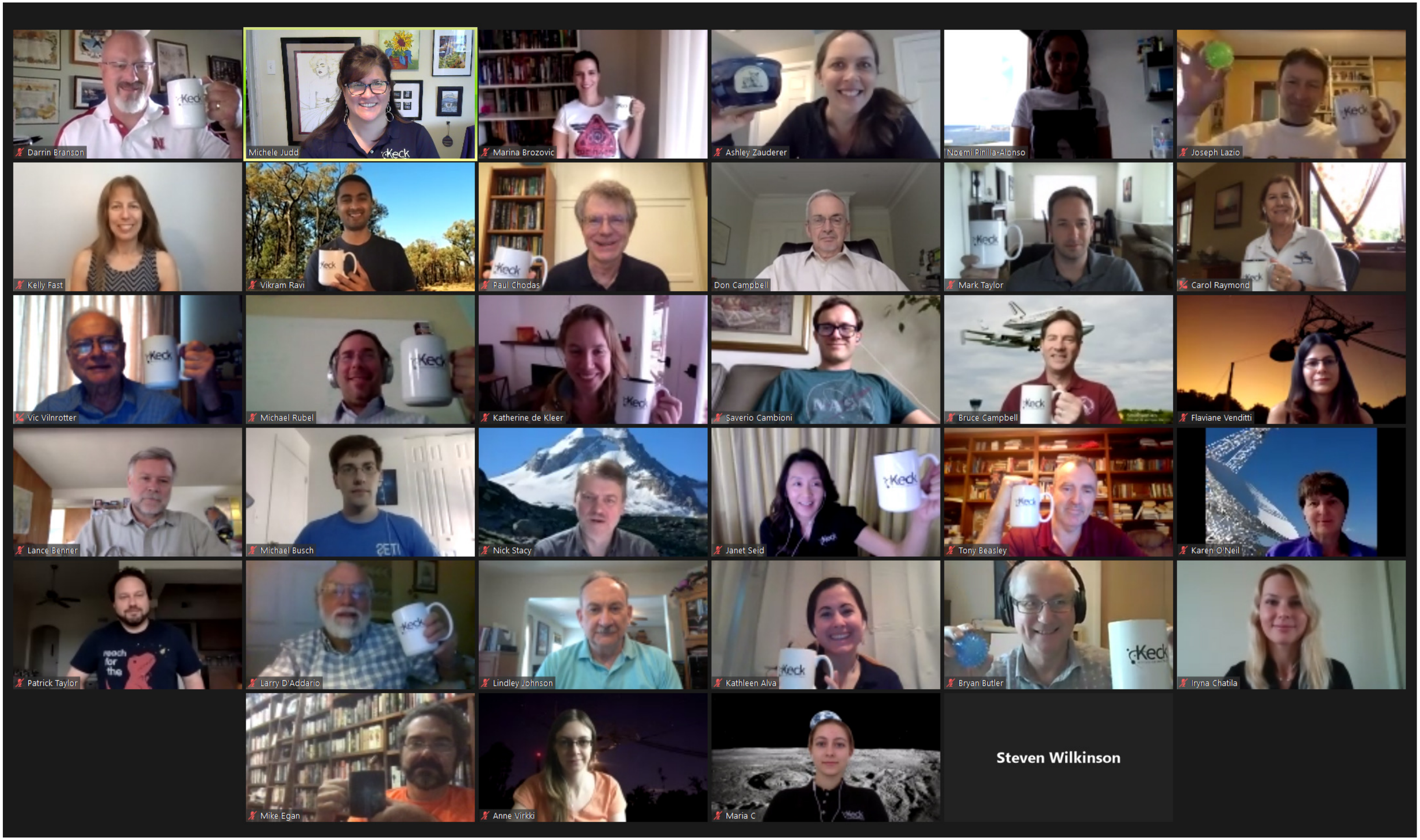
Small Solar System Bodies Panel

Jet Propulsion Laboratory
California Institute of Technology

Joseph Lazio

Thanks to M. Sanchez-Net, K. Andrews, M. Brozovic, B. Butler, B. Campbell, E. Murphy, M. Taylor, V. Vilnrotter, M. Judd, KISS Study Participants

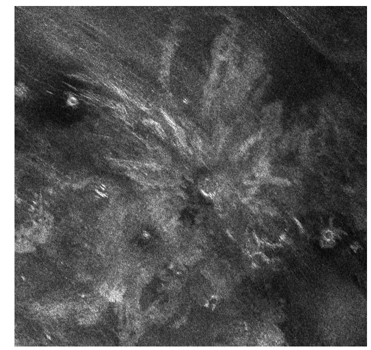
W. M. Keck Institute for Space Studies
Next-Generation Planetary Radar Study



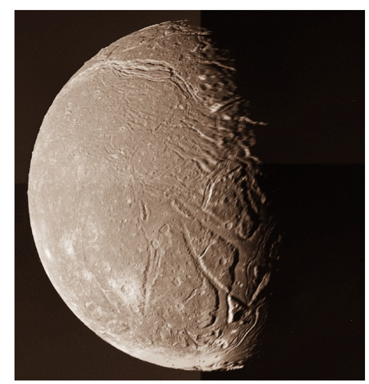
Science Case – Next-Generation Planetary Radar

Driving use cases identified at KISS Workshop

- **Near-Earth Asteroids and Planetary Defense**
- Venus
- Outer Solar System satellites



Venus / Sif Mons



Ariel

Other potential targets

- Mini-moons
- Interstellar objects
- Earth Trojans
- …

Science Case - Near-Earth Asteroids and Planetary Defense

Radar delivers size, rotation, shape, density, surface features, precise orbit, non-gravitational forces, presence of satellites, mass, …

- **Science:** Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere
- **Robotic missions:** Navigation, orbit planning, observations
- **Planetary defense:** Precise orbit determination, size, shape for hazard assessment

International Radar Assets

Goldstone Solar System Radar (DSN)

70 m antenna, 450 kW transmitter, 4 cm wavelength (X band)

Arecibo (NAIC)

Green Bank Telescope (GBO)

100 m antenna, no transmitter *(yet!)*

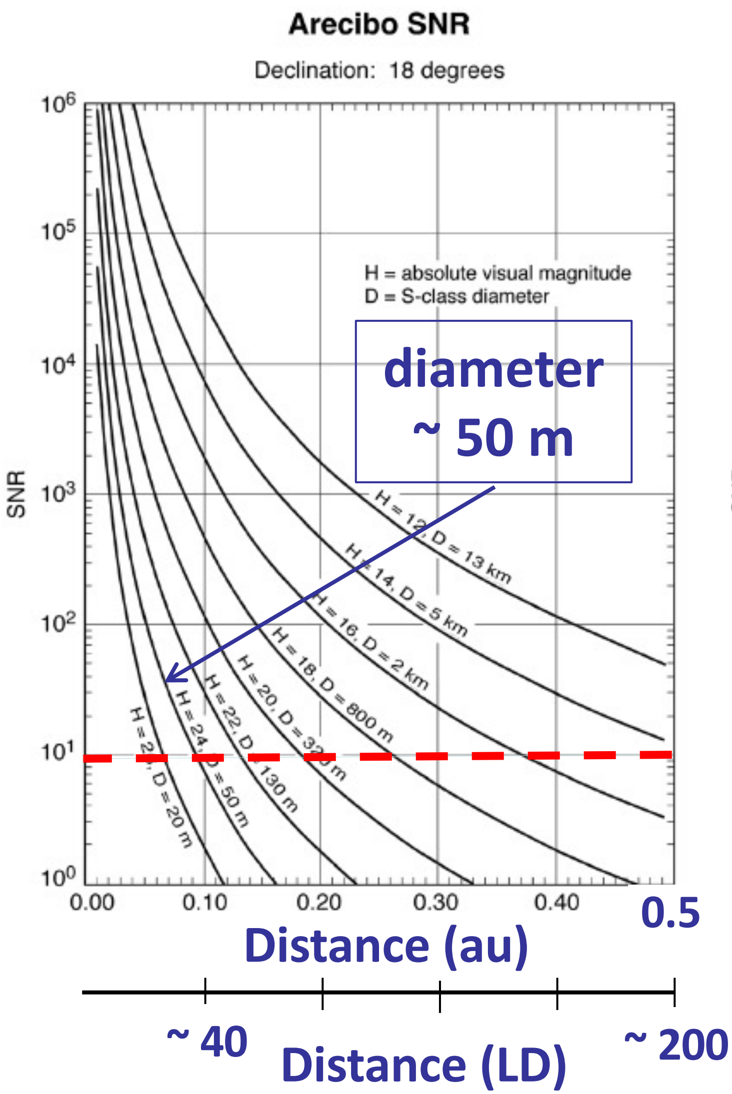
Canberra DSS-43 (DSN)

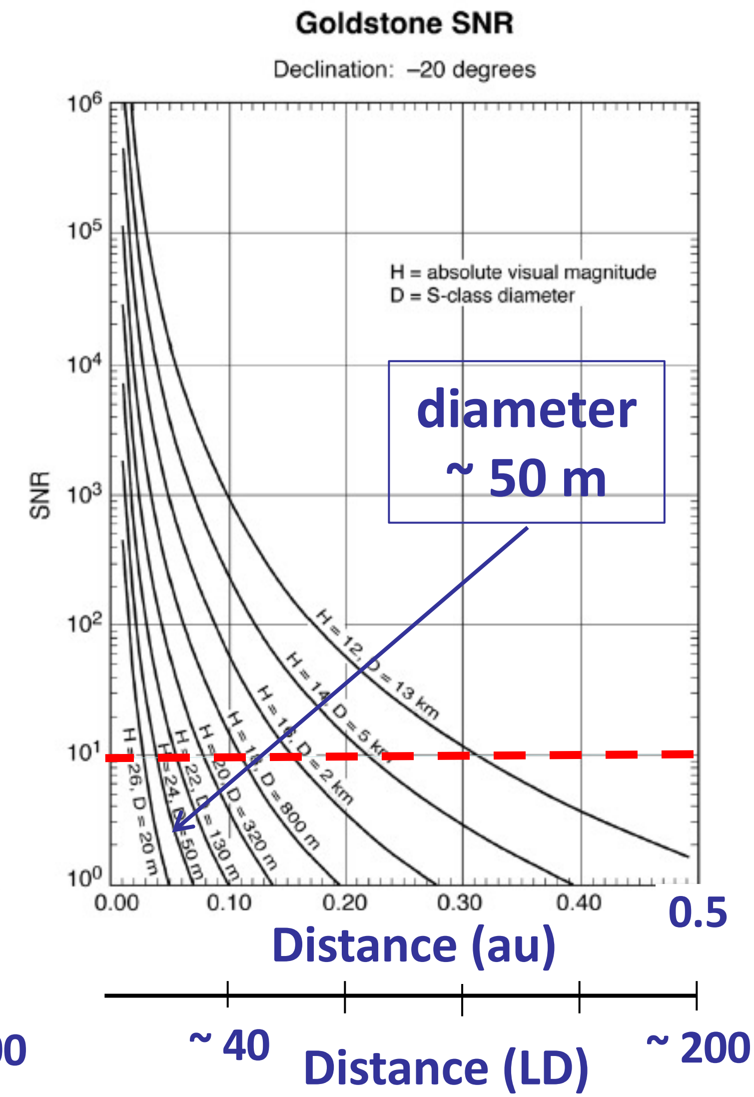
70 m antenna, 80 kW transmitter, 4 cm wavelength (C band)

+ Australia Telescope Compact Array

+

Radar and NEA Detectability





Ostro & Giorgini

Planetary Radar Trade Space

Received Power (a.k.a. Radar Equation)

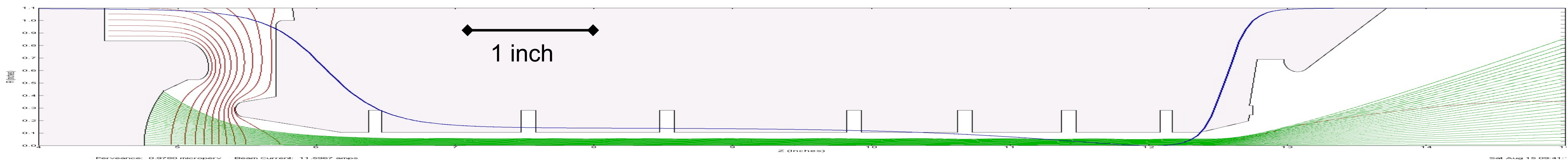
$$P_{RX} = \frac{1}{(4\pi)^3}\boxed{\underbrace{G_{RX}}_{\text{Receiver Gain}}\underbrace{(P_{TX}G_{TX})}_{\text{Effective Isotropic Radiated Power}}\lambda^2}\,\boxed{\underbrace{\frac{\sigma}{R^4}}_{\textit{Asteroid Characteristics}}}$$

Over the next decade, a variety of technologies

- **arrays of transmitting antennas;**
- **modular, solid-state microwave amplifiers; and**
- **improved data acquisition, processing, data fusion, and archiving**

will mature and could be deployed to produce a much more capable and reliable ground-based radar for planetary science and planetary defense.

Future I: Modular, Solid-State Amplifiers

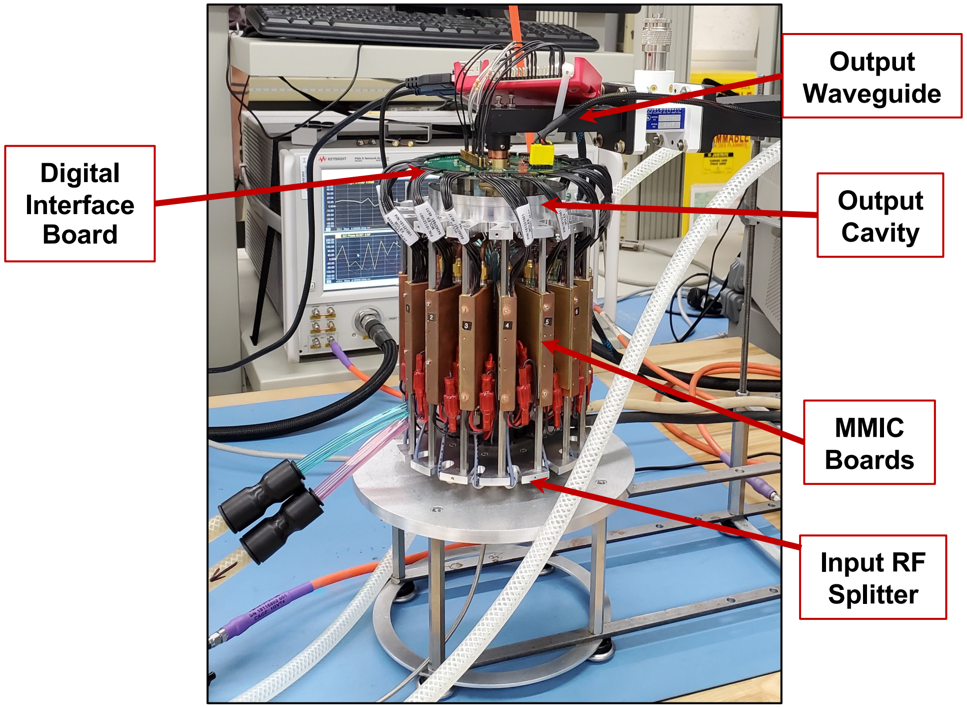


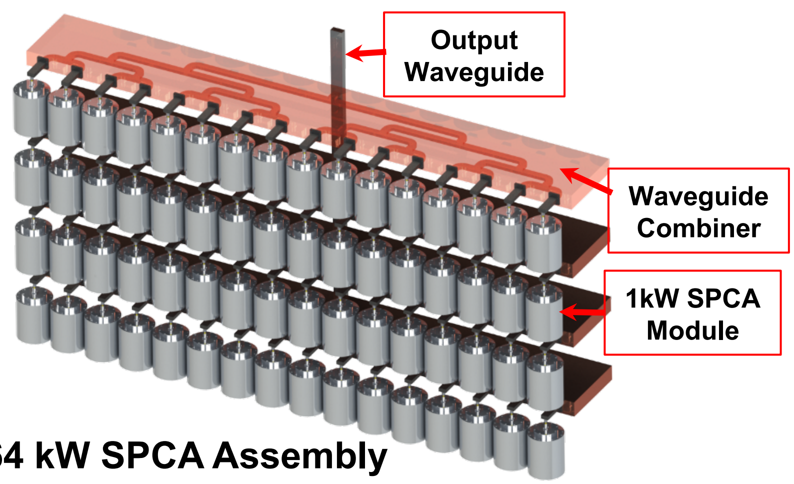
State of the Art: high-power amplification via klystrons (vacuum tubes)

- **Planetary radar klystrons have challenging power densities and manufacturing tolerances (~ 1 MW/mm^2)**
  - **Only 50% efficient**
  - **Even small beam deviations lead to potentially damaging heat dissipation**

Future I: Modular, Solid-State Amplifiers

1 kW Spatial Power Combining Amplifier (SPCA)





64 kW SPCA Assembly

- Klystrons have challenging power densities and manufacturing tolerances (~ 1 MW/mm²)
- **Solid-state amplifiers**
  - Modular / scalable, a.k.a. graceful degradation
  - Reliable: Device lifetimes > 100 yr in optimal operating conditions
  - Used in commercial and military communications/radar systems
- **Technology Development**
  - JPL: 16 × 80 W (commercial) MMICs, 90% combining efficiency → 1 kW output @ 8.56 GHz
  - JAXA: 30 kW solid-state system transmitter

➢ **Need to scale to ~ 1 MW**

Planetary Radar Trade Space

Received Power (a.k.a. Radar Equation)

$$P_{RX} = \frac{1}{(4\pi)^3}\boxed{G_{RX}\underbrace{(P_{TX}G_{TX})}\lambda^2}\boxed{\frac{\sigma}{R^4}}$$

Receiver Gain

Effective Isotropic Radiated Power

Asteroid Characteristics

Over the next decade, a variety of technologies

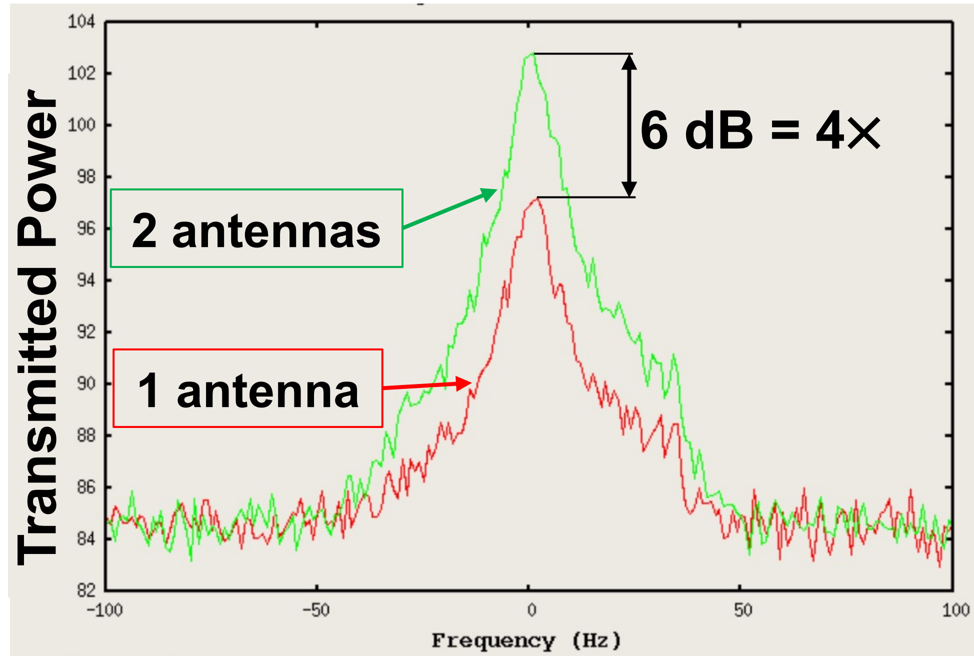
- **arrays of transmitting antennas;**

✓ **modular, solid-state microwave amplifiers (*P_{TX}*); and**

- **improved data acquisition, processing, data fusion, and archiving**

will mature and could be deployed to produce a much more capable and reliable ground-based radar for planetary science and planetary defense.

Future II: Arrays of Transmitting Antennas



✓ **Arrays of receiving antennas are well-developed**
  Both for radio astronomy (1974 Nobel Prize) and DSN

- **Arrays of transmitting antennas**
  - **Array gain $G_{TX} \propto N^2$ for *N*-antenna array**
  - ✓ **Demonstrated in context of communication for up to 3 antennas**
    - ➢ **See backup**
  - ➢ **Need to show ranging performance expected for planetary radar**
    On-going work at JPL and elsewhere to do so

Vilnrotter et al.;
D'Addario et al.

Planetary Radar Trade Space

Received Power (a.k.a. Radar Equation)

$$P_{RX} = \frac{1}{(4\pi)^3} \boxed{\underbrace{G_{RX}}_{\text{Receiver Gain}} \underbrace{(P_{TX} G_{TX})}_{\text{Effective Isotropic Radiated Power}} \lambda^2} \underbrace{\boxed{\frac{\sigma}{R^4}}}_{\textit{Asteroid Characteristics}}$$

Over the next decade, a variety of technologies

- ✓ **arrays of transmitting antennas (G_{TX});**
- ✓ **modular, solid-state microwave amplifiers (P_{TX}); and**
- **improved data acquisition, processing, data fusion, and archiving**

will mature and could be deployed to produce a much more capable and reliable ground-based radar for planetary science and planetary defense.

Planetary Radar Trade Space

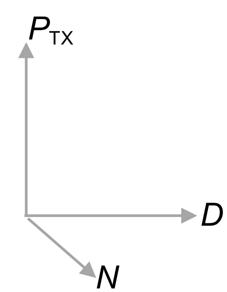
Received Power (a.k.a. Radar Equation)

$$P_{RX} = \frac{1}{(4\pi)^3} \boxed{G_{RX}(\underbrace{P_{TX}G_{TX}}_{\text{EIRP}})\lambda^2} \boxed{\frac{\sigma}{R^4}}$$

Effective Isotropic Radiated Power (EIRP)

EIRP $\propto N^2 D^2 P_{\text{TX}}$

Number of Antennas | **Antenna Diameter** | **Transmitter Power per Antenna**

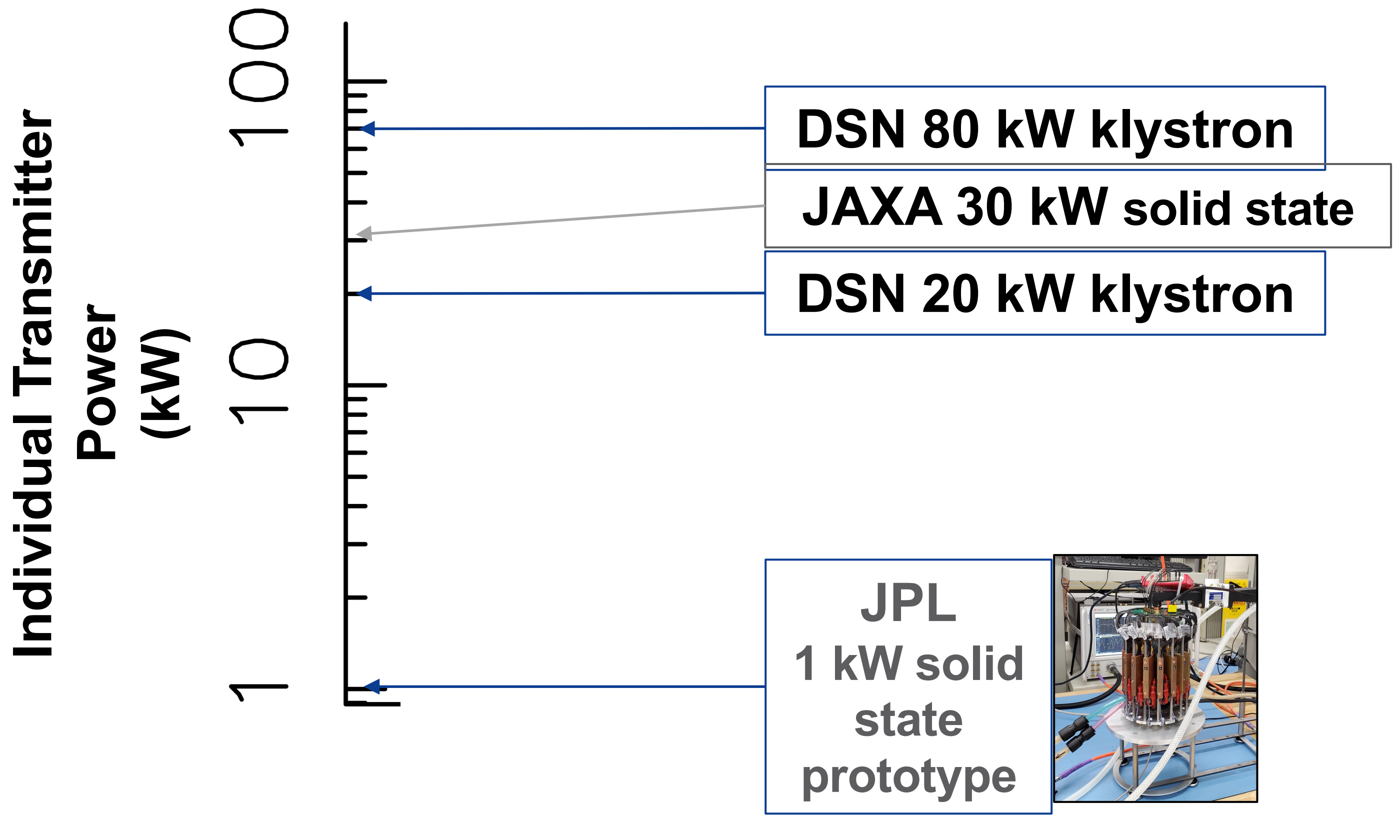


- ➢ **Maximize P_{RX} subject to cost cap including operations!**

Planetary Radar Trade Space

Transmitter Power P_{TX}

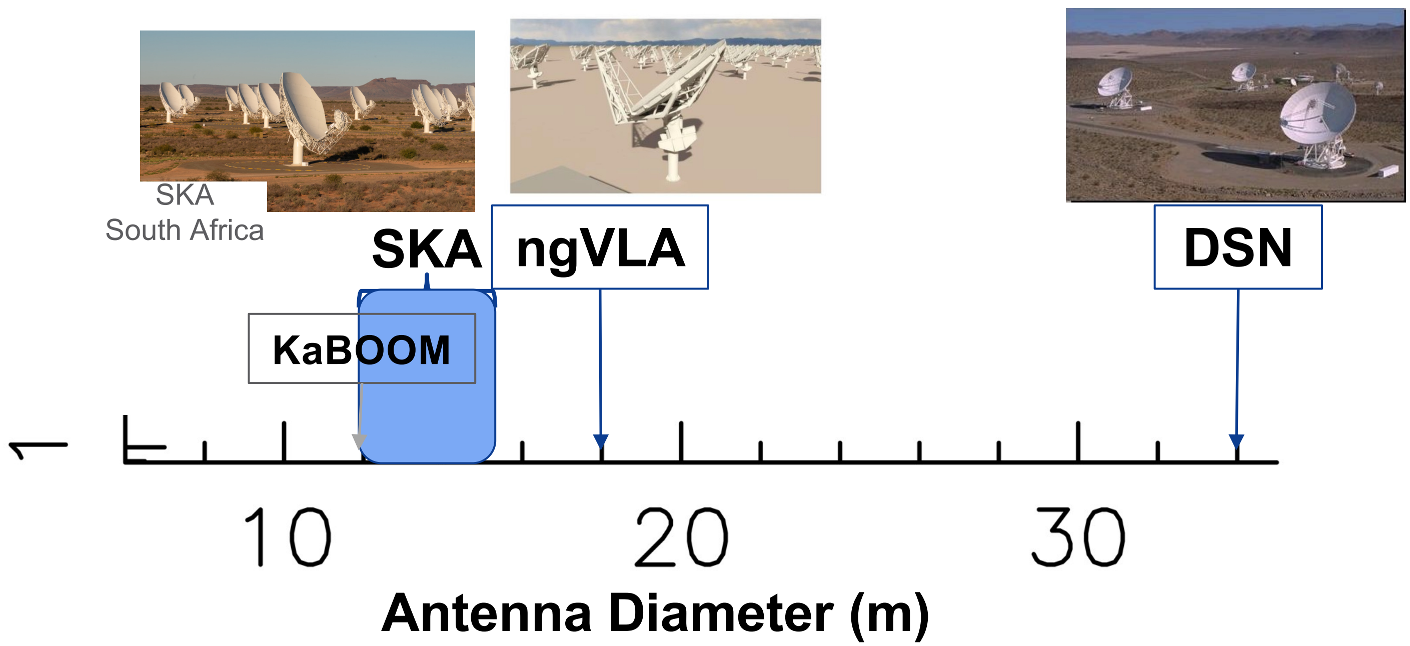
Focus on ”lower power,” more reliable systems



Planetary Radar Trade Space

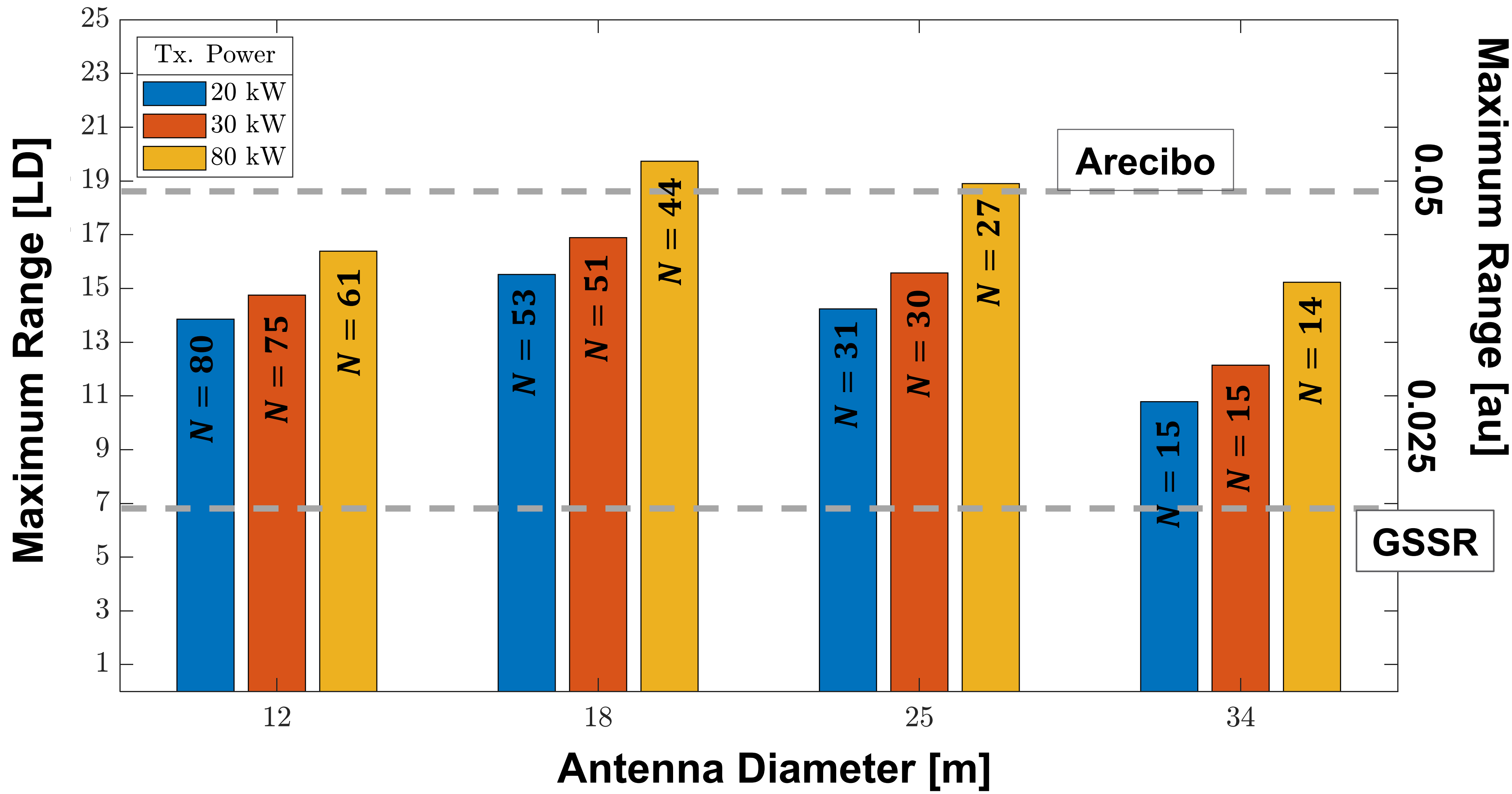
Antenna Diameter *D*

Focus on smaller, deployed or to be deployed, antennas



Planetary Radar Array Performance: 20 m asteroid

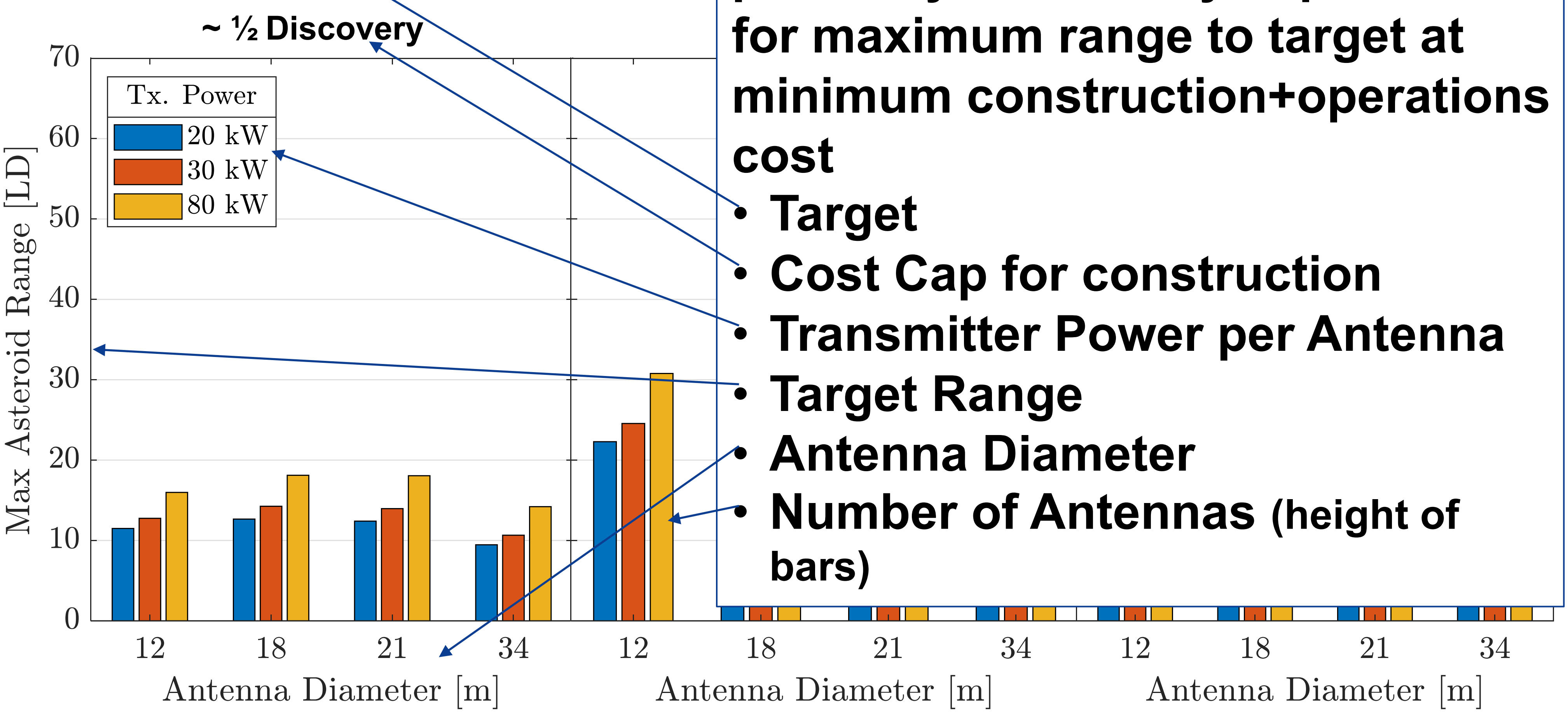
Cost Cap ~ Discovery-class mission



1 lunar distance (LD) = 380,000 km

Radar Array Performance and Optimization

Target

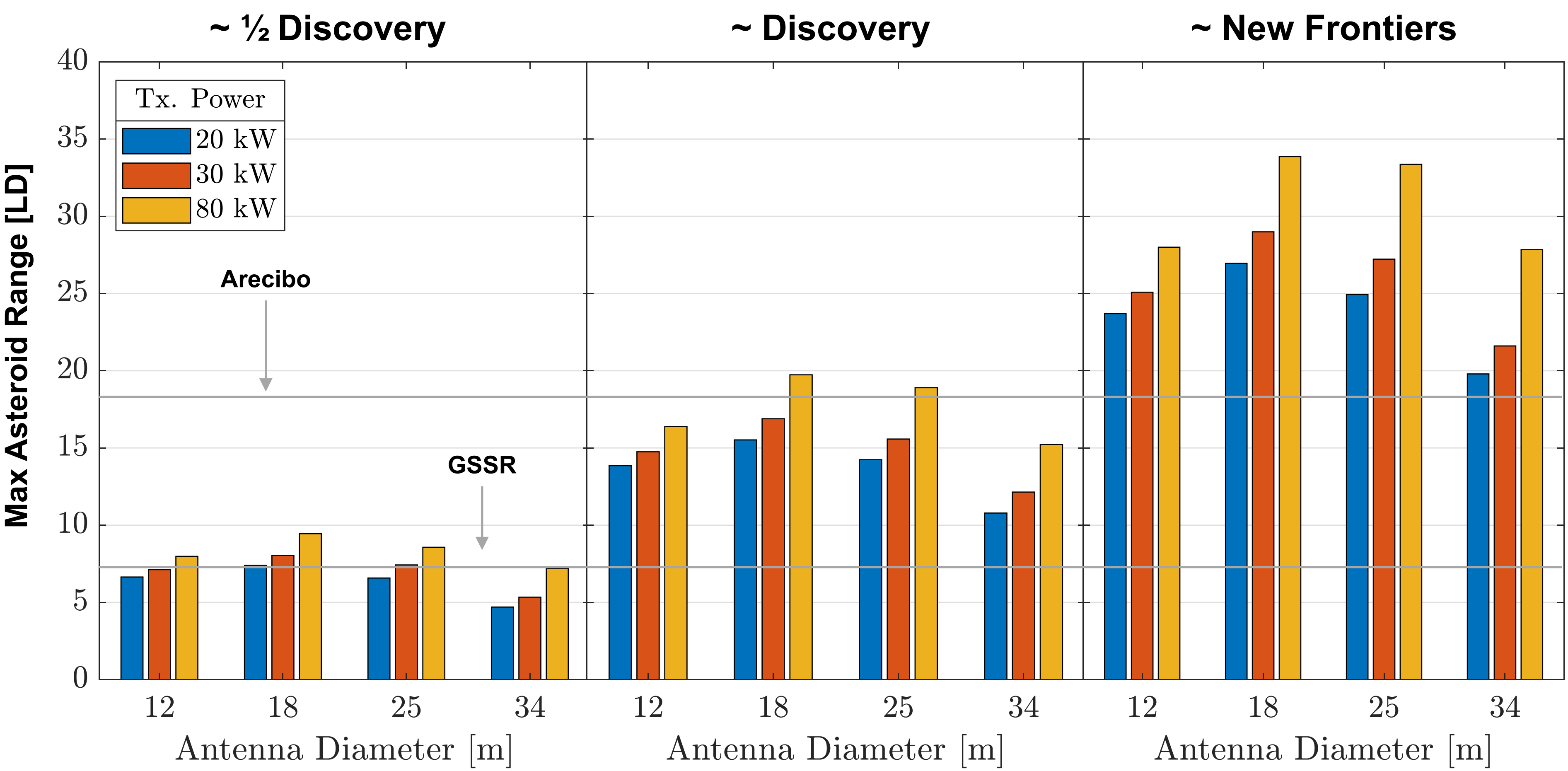


Following three slides describe planetary radar arrays optimized for maximum range to target at minimum construction+operations cost

- **Target**
- **Cost Cap for construction**
- **Transmitter Power per Antenna**
- **Target Range**
- **Antenna Diameter**
- **Number of Antennas (height of bars)**

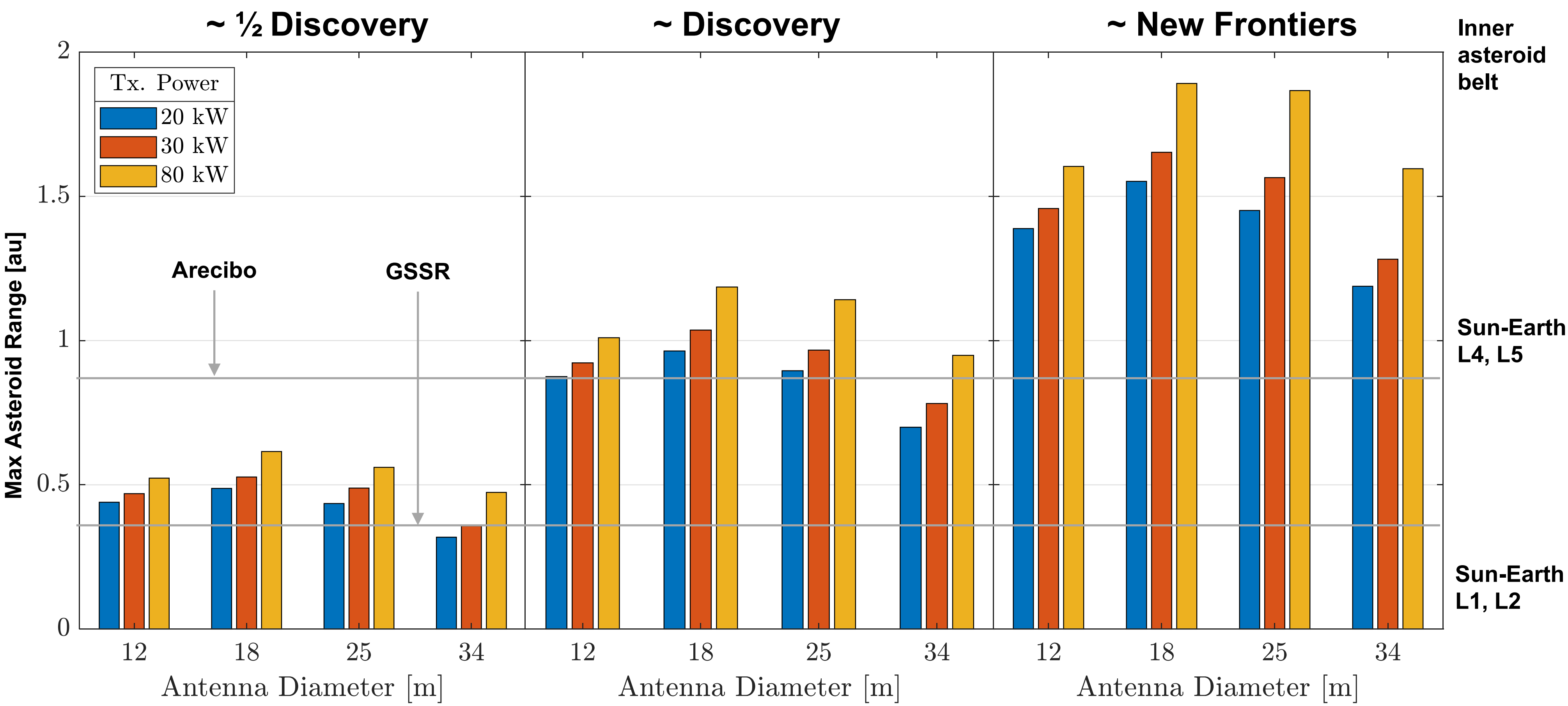
Planetary Radar Array Performance

Target: 20 m S-class Asteroid



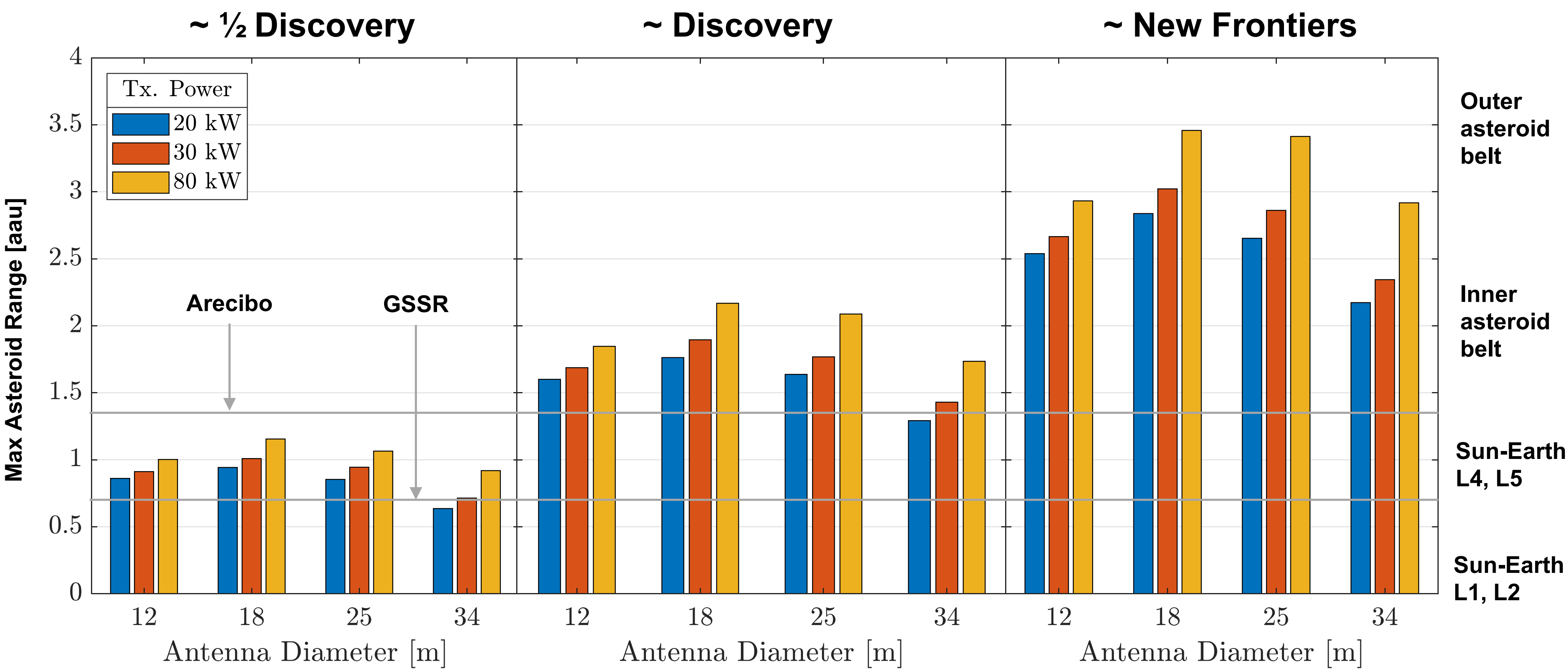
Planetary Radar Array Performance

Target: 20 km S-class Asteroid

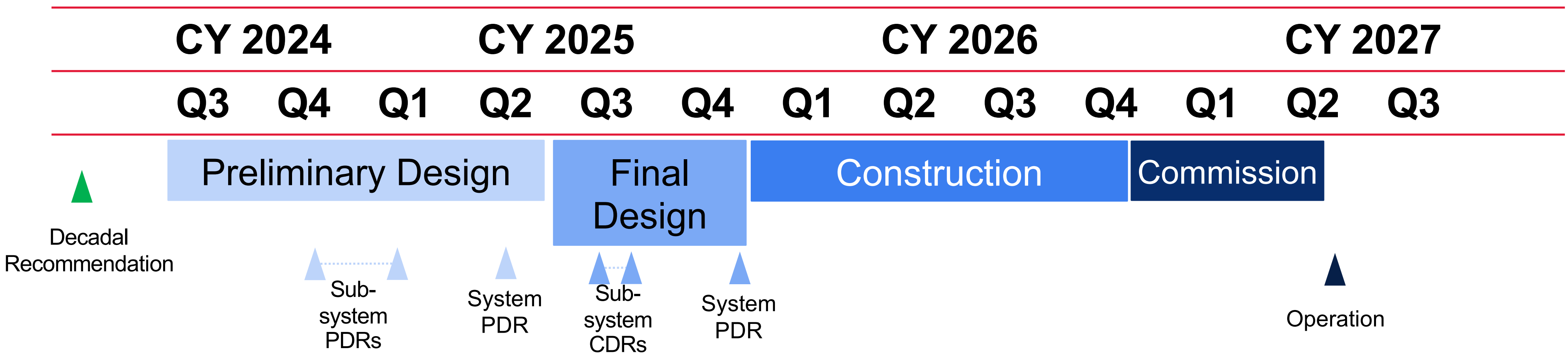


Planetary Radar Array Performance

Target: 100 km S-class Asteroid



Schedule



Elements of preliminary design include

- **Antenna optics**
- **Transmitter and power supply (klystron or solid state)**
- **Site infrastructure**

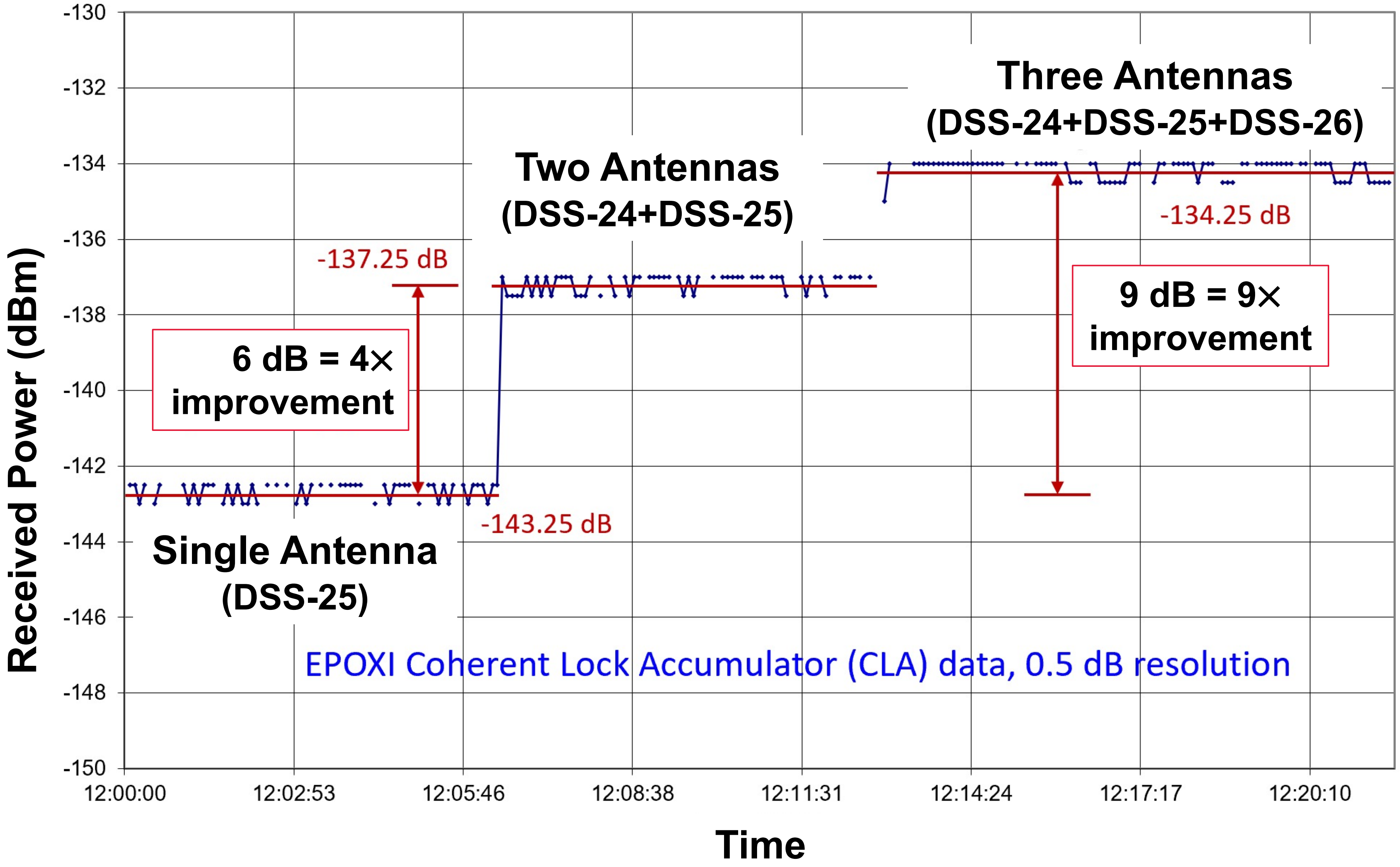
Summary

Multi-antenna array transmit-receive system feasible ~ 2026

- **Benefits**
  - **Enable diverse science portfolio**
  - **Individual transmitters would be lower power, (much) higher reliability projected**
  - **Graceful degradation**
    - **Today: loss of one klystron = 50% decrease**
    - **Array: Loss of one antenna/transmitter decreases EIRP by ~ (1−1/N)**
  - **Potential synergies with radio astronomy array projects requiring new antennas**

Three-Antenna Uplink Array Demonstration

EPOXI Spacecraft



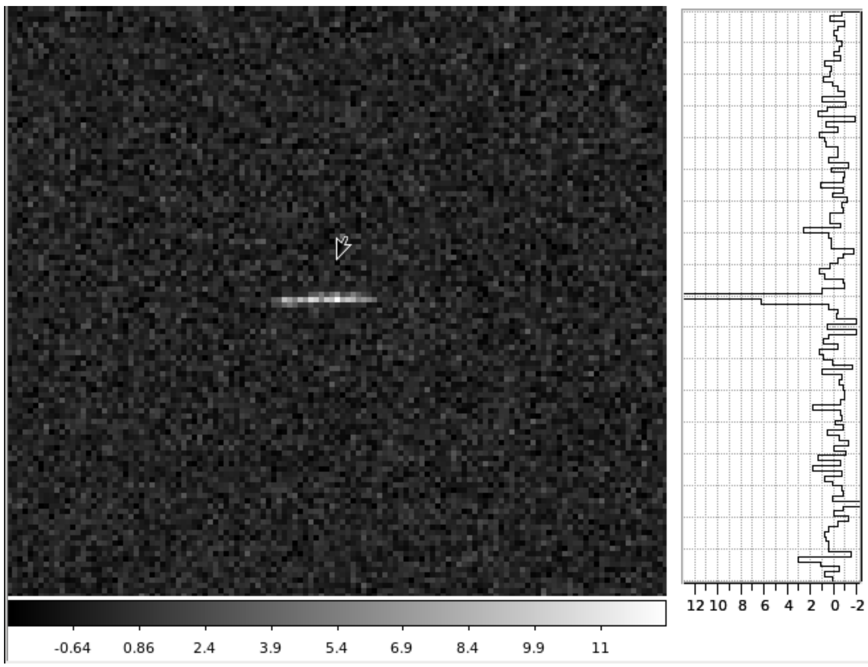
Uplink Array Demonstration

Delay-Doppler Improvement

3-antenna Uplink Array vs. Single Antenna Comparison

- Comparison of DSS24/25/26 (20kW/20kW/80kW) 3-antenna uplink array image vs. DSS26 (80kW) single antenna image
- Both images are with 5-μs chips (750-m resolution) and 300-sec integration

2007 WV4 Image using 3-antenna Uplink Array



2007 WV4 Image using Single Antenna (DSS-26)