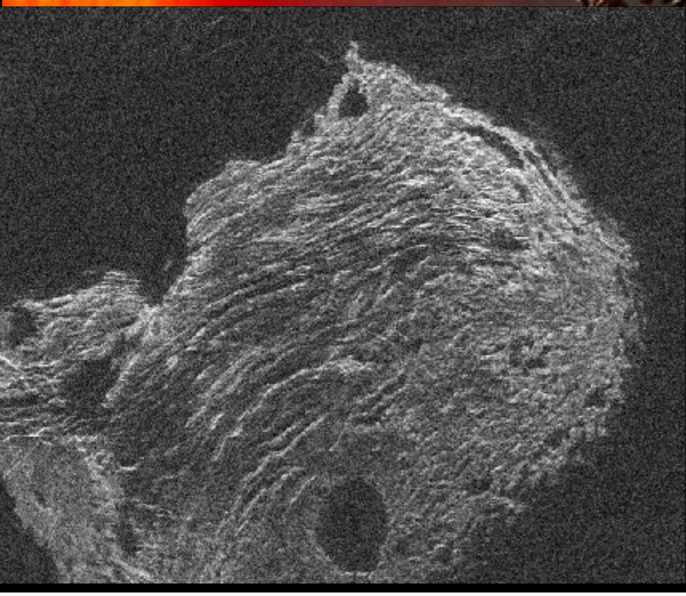
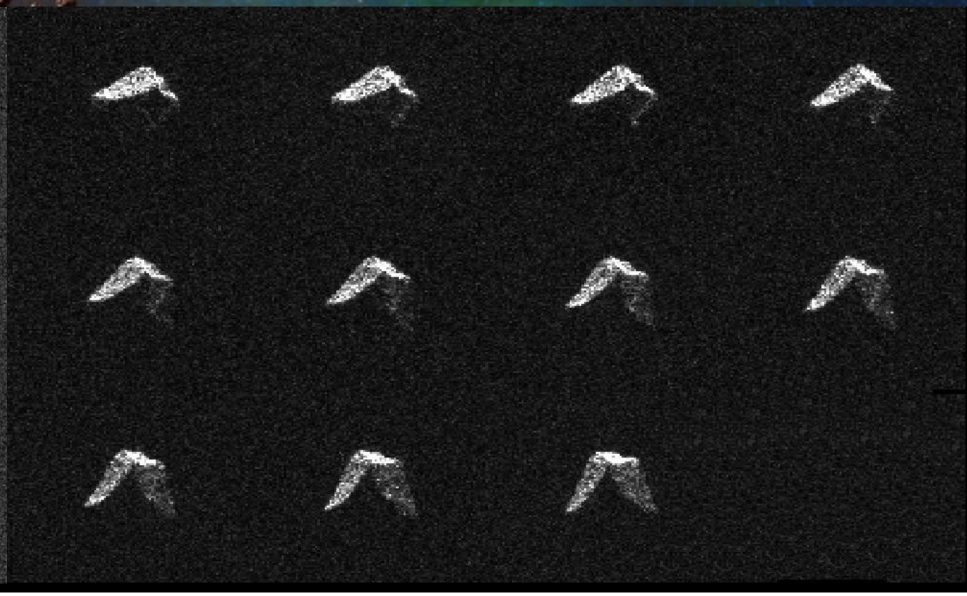
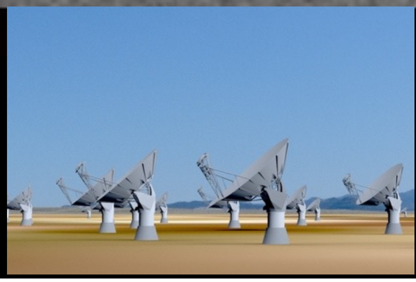




# Next-Generation Ground-Based Planetary Radar

**Arecibo Observatory Colloquium**

Jet Propulsion Laboratory
California Institute of Technology

**Joseph Lazio**

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

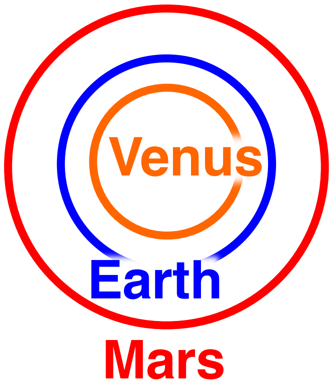
# Outline

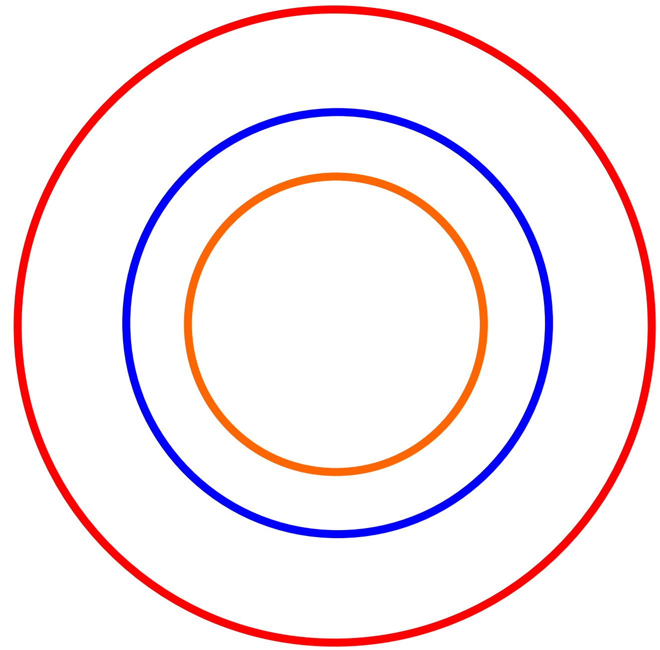
Me, as summer student, with Arecibo dish in the background!

- Scientific Motivation
- Radar Arrays
  - Technical Aside
  - Radio Astronomy Arrays
  - Radar Astronomy Arrays
  - Calibration of Radar Astronomy Arrays
- Looking toward the Future

# Scale of the Solar System

## Relative sizes of planetary orbits known for centuries



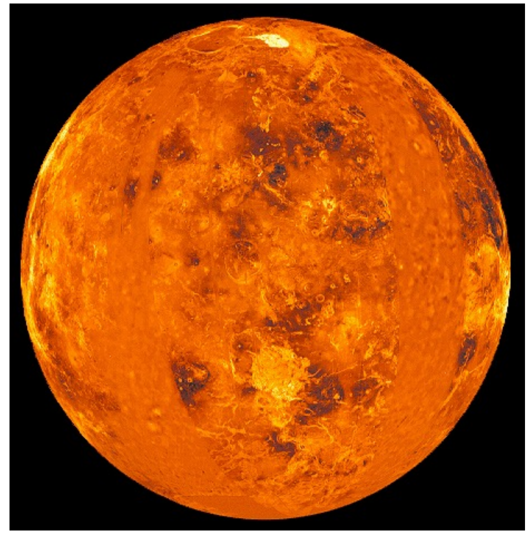



**Radar provided absolute sizes of planetary orbits at precision needed for interplanetary navigation**

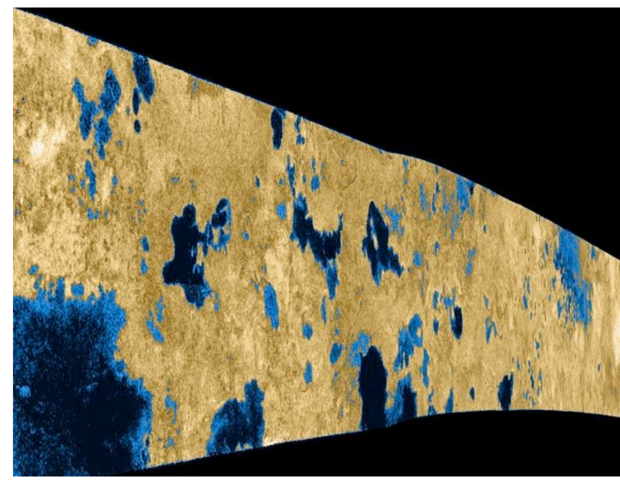
- **Precision measurements from DSIF [DSN] radar measurements**
- **Reduced uncertainty to about 400 km (~ 0.0003%)**

# Planetary Radar Accomplishments

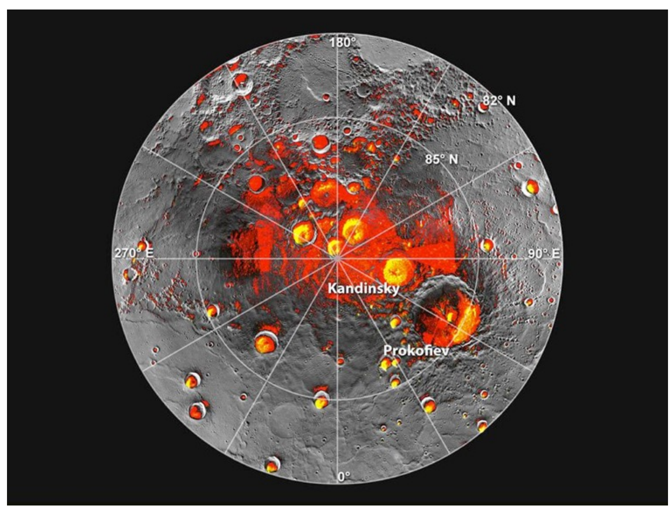
- **Discovered Venus retrograde rotation (1962)**
- **Probing the surfaces of asteroids (1976)**
- **First radar returns from Titan (1989-1993), suggestive of icy surface but with potential liquids**
- **Anomalous reflections from Mercury (1991), indicative of polar ice**



***Magellan*** **radar image of Venus (NASA/Caltech/JPL)**



***Cassini*** **radar image of Titan (NASA/JPL/USGS)**



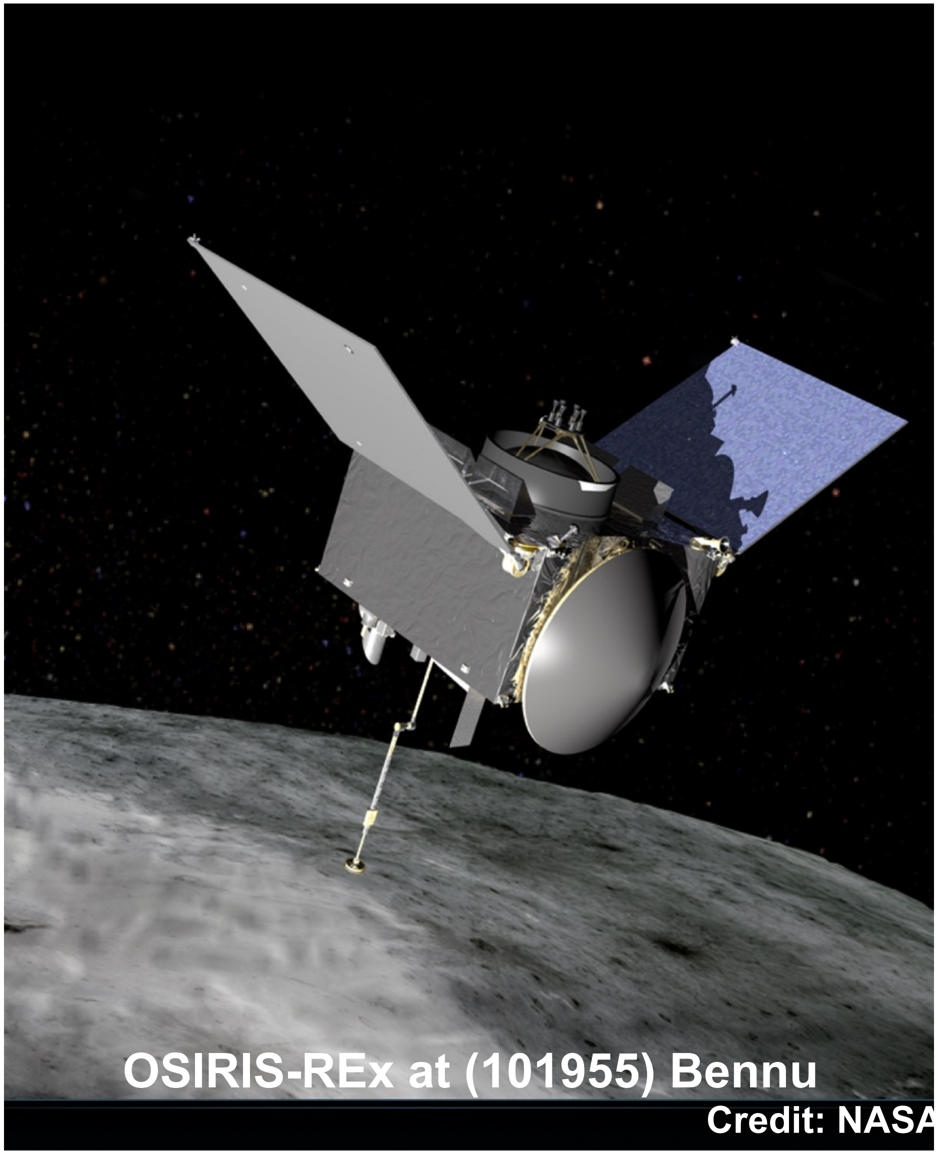

**MESSENGER+radar image of Mercury (NASA/HU APL/CIW/NAIC)**

# 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

# Radar Contributions to Space Missions



OSIRIS-REx at (101955) Bennu
Credit: NASA

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Shape model and surface properties of the OSIRIS-REx target Asteroid (101955) Bennu from radar and lightcurve observations

Michael C. Nolan [a,*], Christopher Magri [b], Ellen S. Howell [a], Lance A.M. Benner [c], Jon D. Giorgini [c], Carl W. Hergenrother [d], R. Scott Hudson [e], Dante S. Lauretta [d], Jean-Luc Margot [f], Steven J. Ostro [c,1], Daniel J. Scheeres [g]

[a] Arecibo Observatory, HC 3 Box 53995, Arecibo, PR 00612, USA
[b] University of Maine at Farmington, 173 High St, Preble Hall, Farmington, ME 04938, USA
[c] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[d] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[e] Washington State University, Tri-Cities, Richland, WA 99354, USA
[f] Department of Earth and Space Sciences, University of California, Los Angeles, CA 90295, USA
[g] University of Colorado at Boulder, 429 UCB, Boulder, CO 80309-0429, USA

# International Radar Assets

**Goldstone Solar System Radar (DSN)**
**70 m antenna, 450 kW transmitter, 4 cm wavelength (X band)**



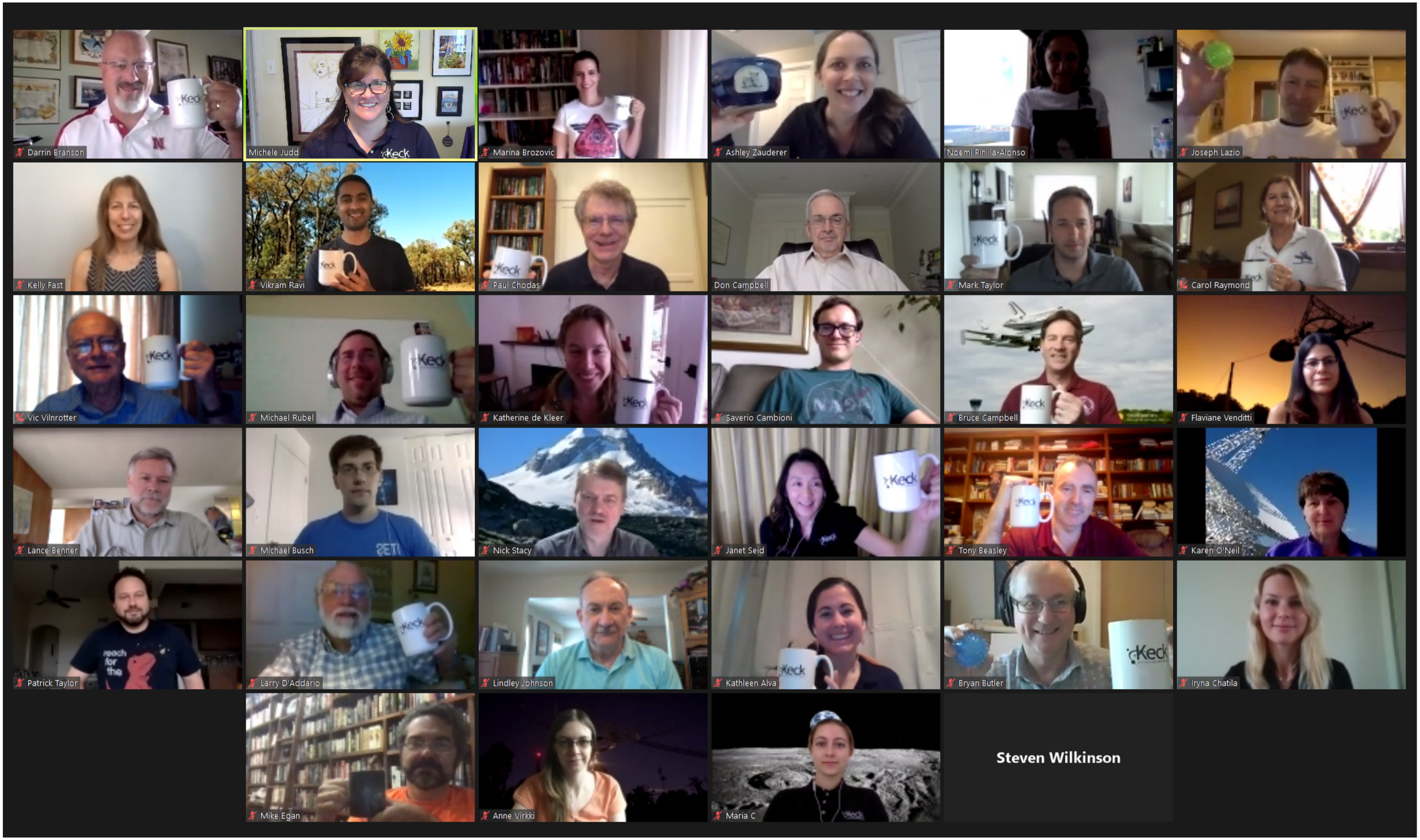
**Arecibo (NAIC)**


**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**

+

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




Arecibo Observatory

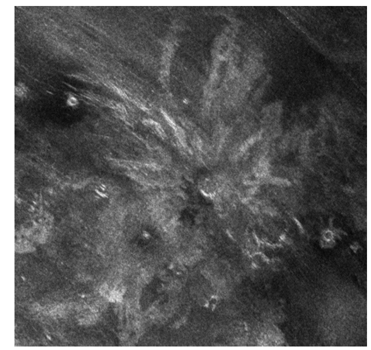
# Science Case – Next-Generation Planetary Radar

## Driving use cases identified at KISS Workshop

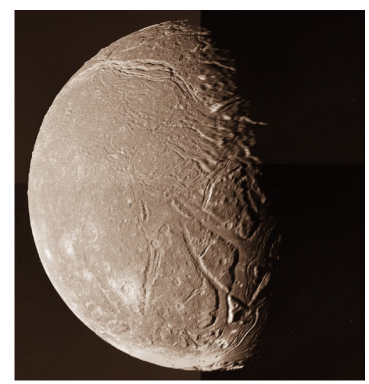
- Near-Earth Asteroids and Planetary Defense
- Venus
- Outer Solar System satellites

**Other potential targets**

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

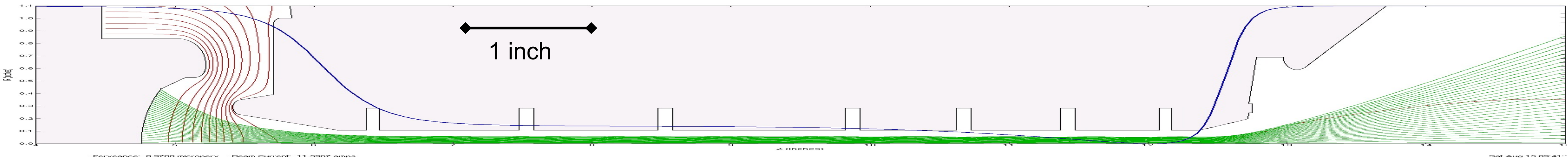


Venus / Sif Mons



Ariel

# Future Aside: Modular, Solid-State Amplifiers



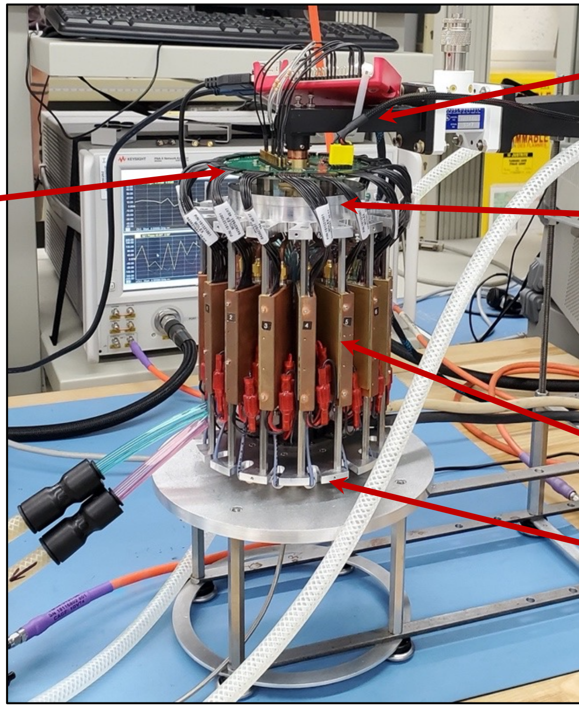

**State of the Art: high-power amplification via klystrons (vacuum tubes)**

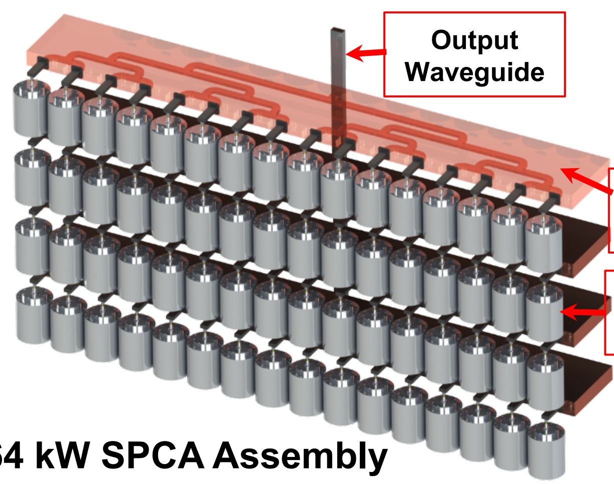
- **Planetary radar klystrons have challenging power densities and manufacturing tolerances (~ 1 MW/mm$^2$)**
  - **Only 50% efficient**
  - **Even small beam deviations lead to potentially damaging heat dissipation**

Arecibo Observatory

# Future Aside: Modular, Solid-State Amplifiers

**1 kW Spatial Power Combining Amplifier (SPCA)**

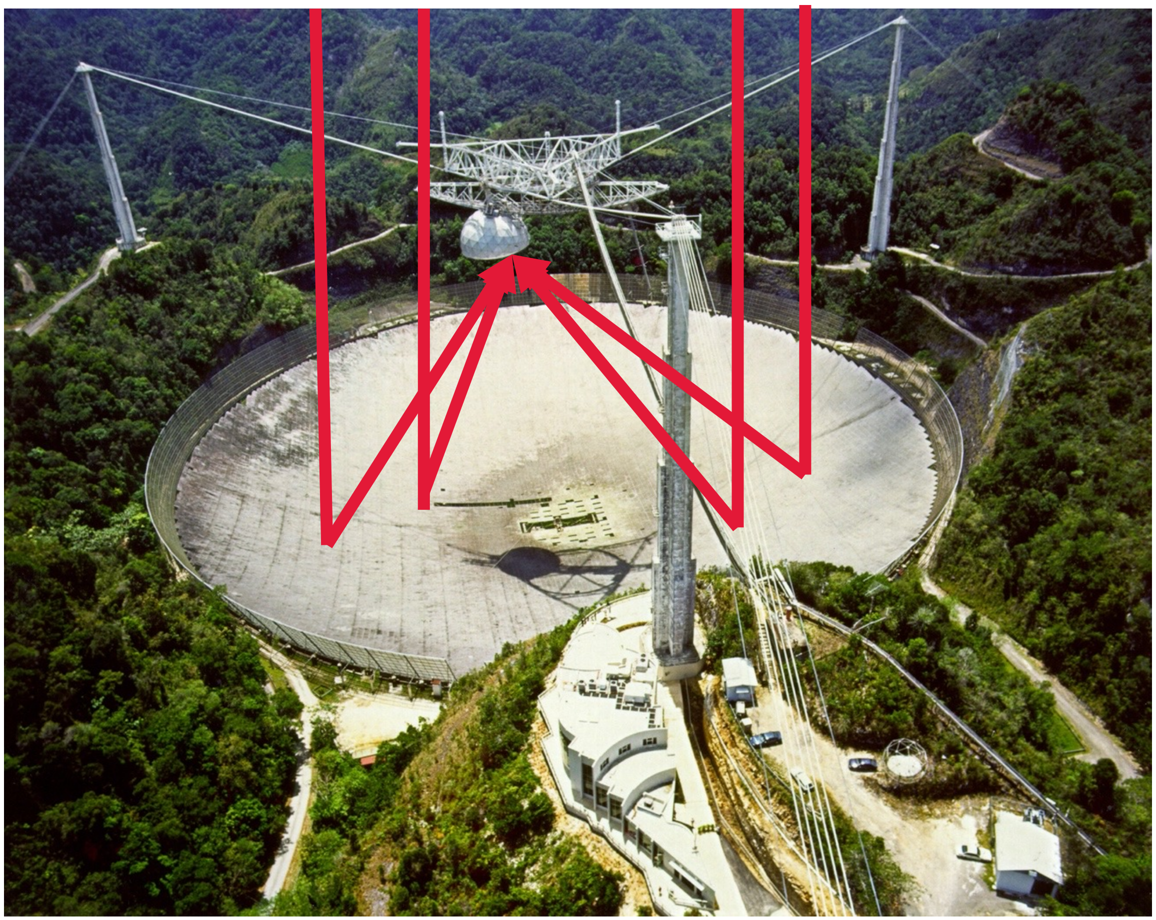



**64 kW SPCA Assembly**

- Klystrons have challenging power densities and manufacturing tolerances (~ 1 MW/mm$^2$)
- **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

# How Do Telescopes Work?



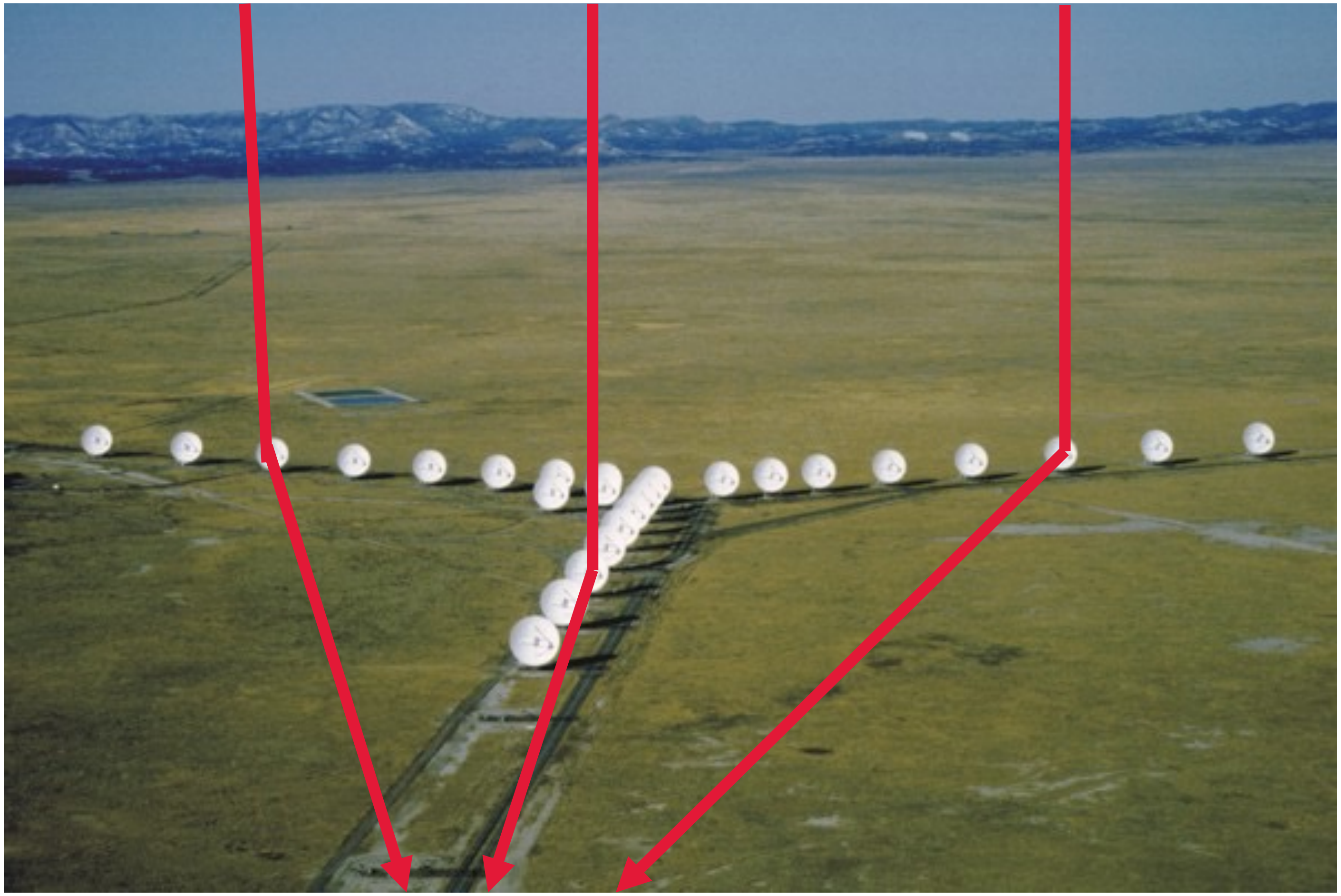
**Exercise for the reader:**

**Consider a parabolic surface.**

**Show that initially parallel light rays, all traveling at the speed of light *c*, reach a common point, *the focus*, at the same time no matter where they reflect from the surface of the reflector.**

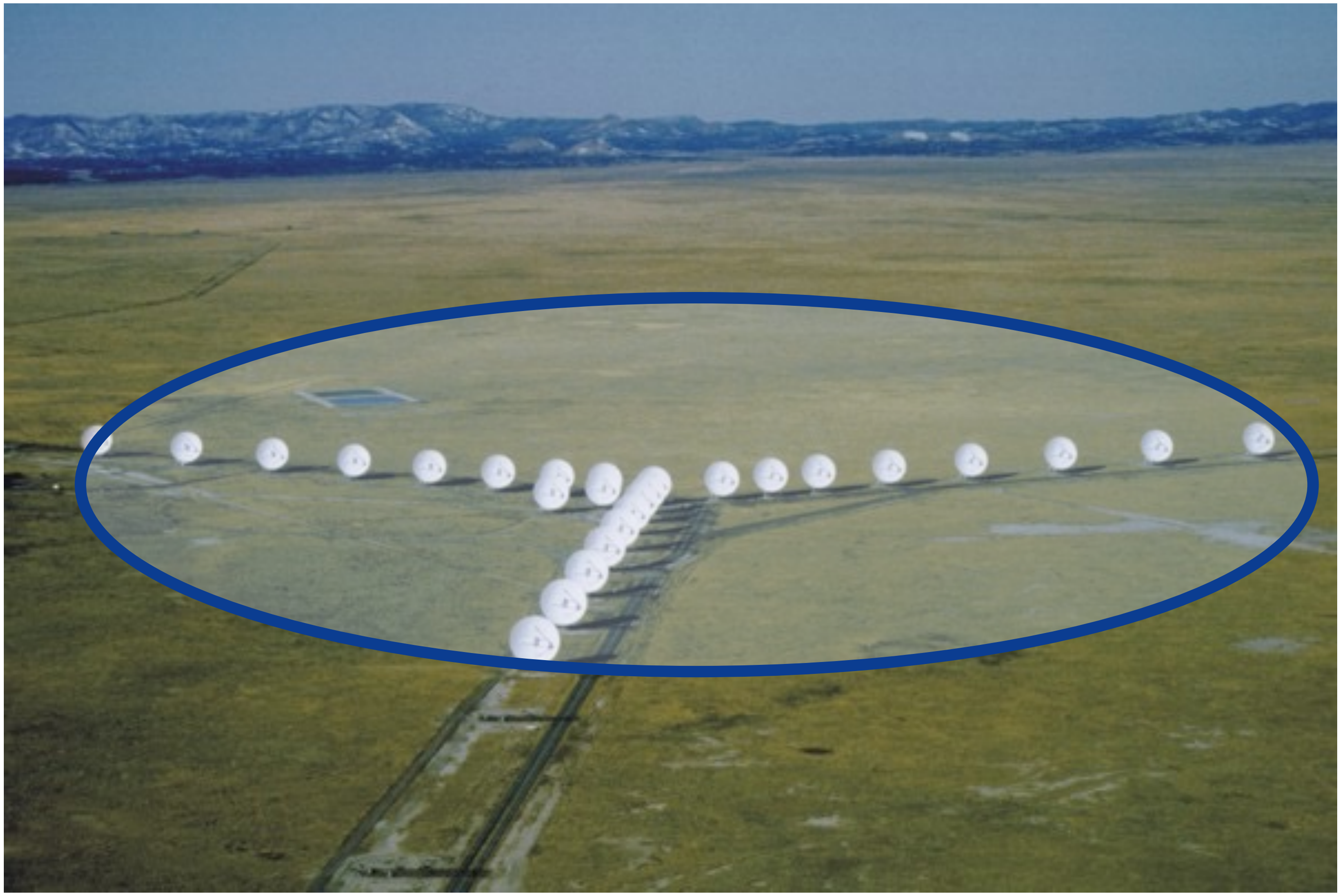
**Extra credit: Repeat for a spherical reflector such as Arecibo and show that the focus is a line.**

# Aperture Synthesis



1. Record signals at individual antennas
2. Bring them together “at the same time” (coherently)
3. Then …

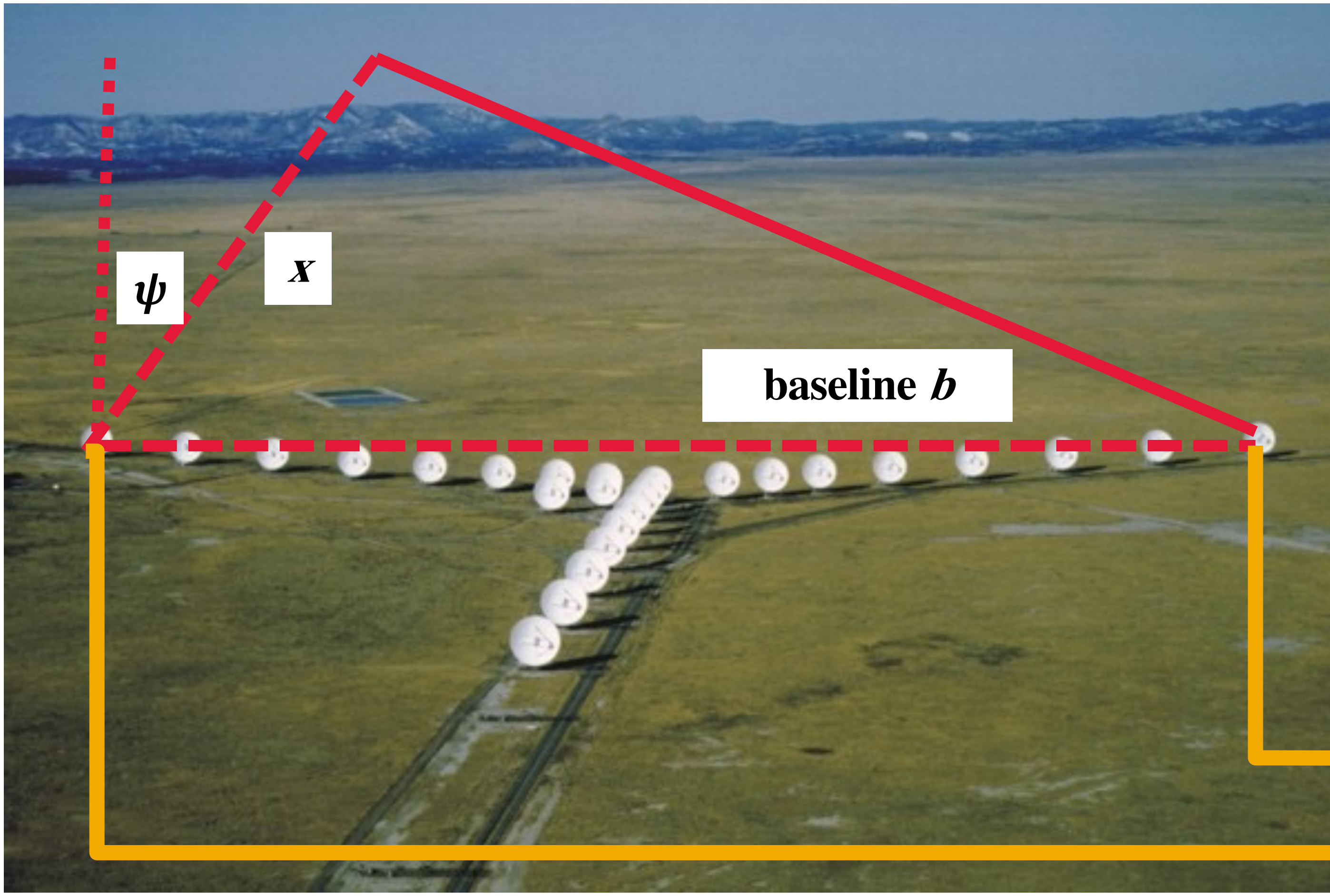
# Interferometry or Aperture Synthesis



1. **Record signals at individual antennas**
2. **Bring them together "at the same time" (coherently)**
3. **Then synthesize aperture!**

**a.k.a. build a telescope that's mostly holes!**

# Aperture Synthesis




**Extra path length:**

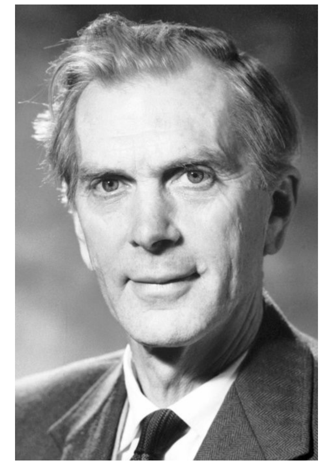
$$x = b \sin \psi$$

**Geometric delay:**

$$\tau_g = x/c = (b/c) \sin \psi$$

# Interferometry or Aperture Synthesis

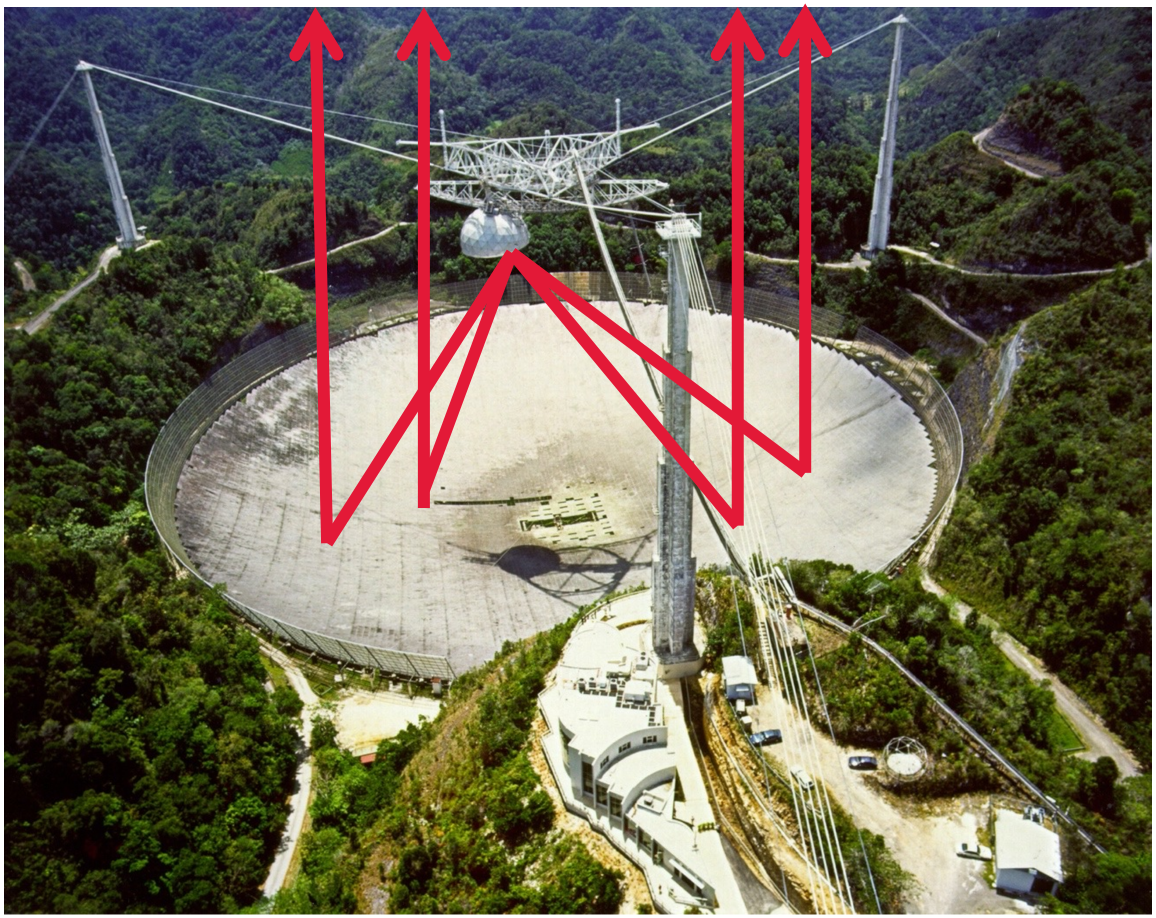
**The 1974 Nobel Prize in Physics was awarded jointly to Sir Martin Ryle and Antony Hewish "for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars."**




**Arrays are generally approach being adopted for current and future radio telescopes**

- LOFAR
- MWA
- HERA
- MeerKAT
- ASKAP
- SKA1-Mid and SKA1-Low
- ngVLA

# How Do Telescopes Work?



**Reciprocity**

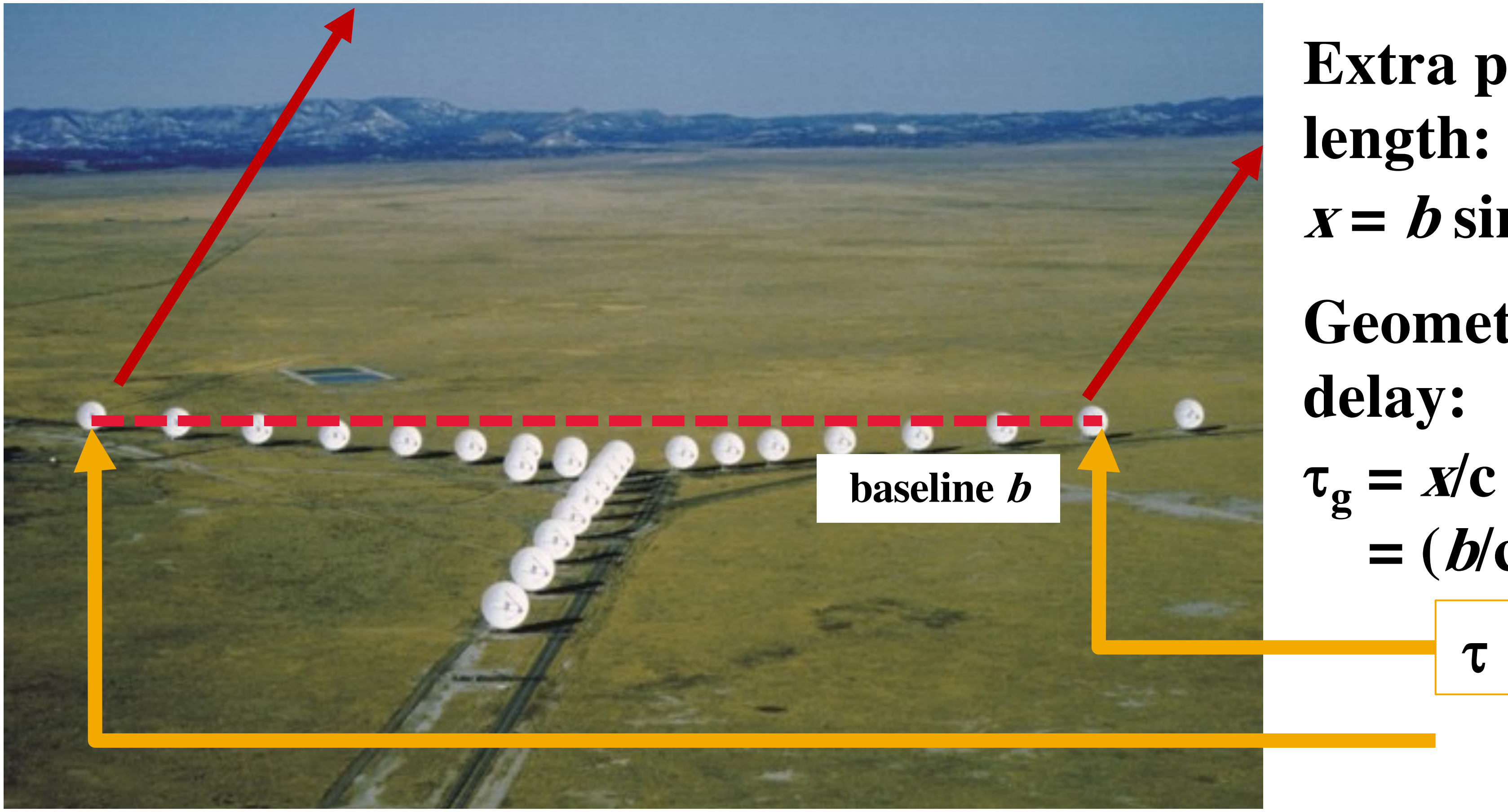
**Antennas work equally well as transmitters or receivers**

- **e.g., “feed illuminates subreflector” for radio telescope for which no transmitter exists**

**Radar!**

Arecibo Observatory

# Radar Array




**Extra path length:**

$x = b \sin \psi$

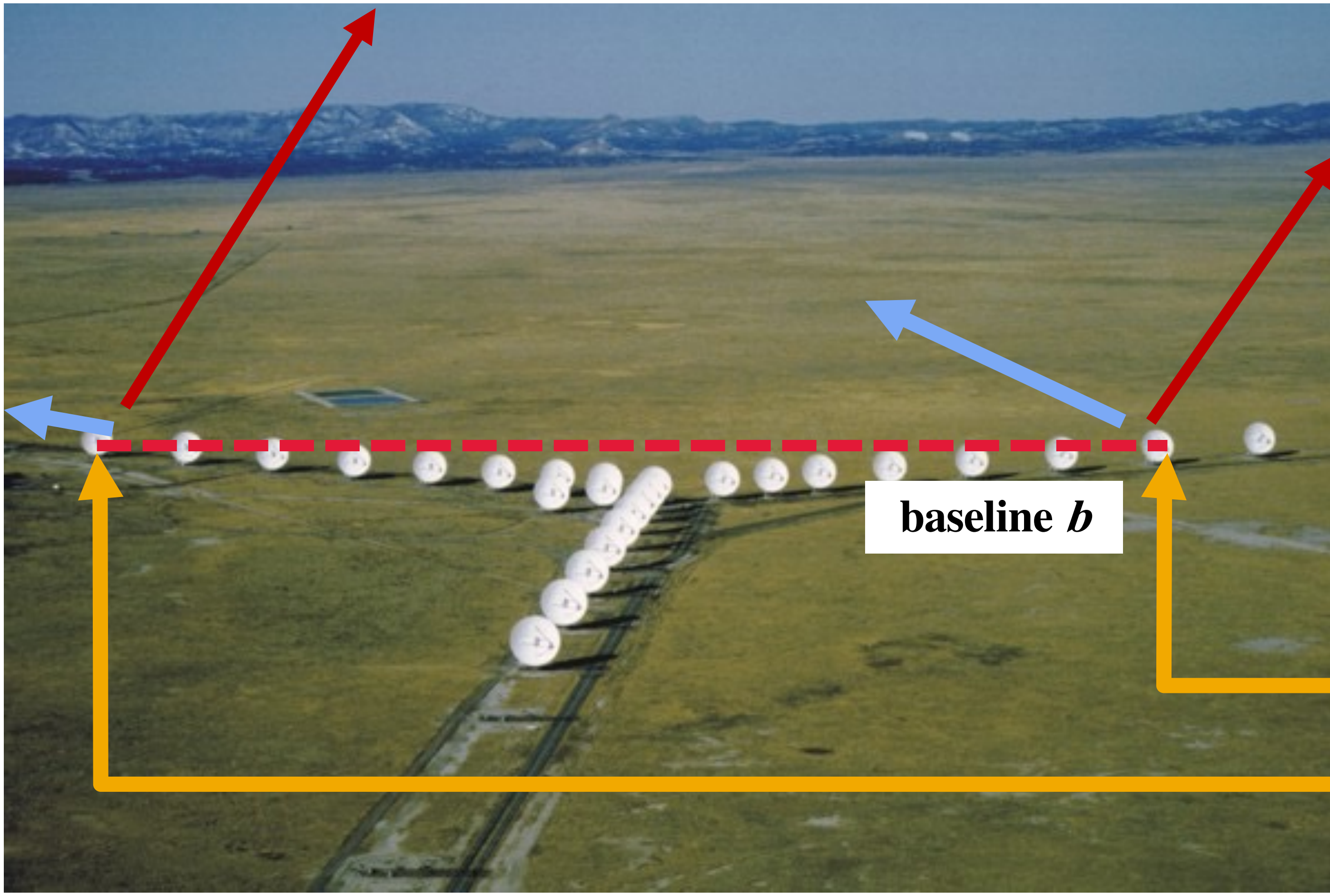
**Geometric delay:**

$\tau_g = x/c$

$= (b/c) \sin \psi$

**By reciprocity, in principle, adding transmitters and injecting appropriate delays can enable phased transmissions**

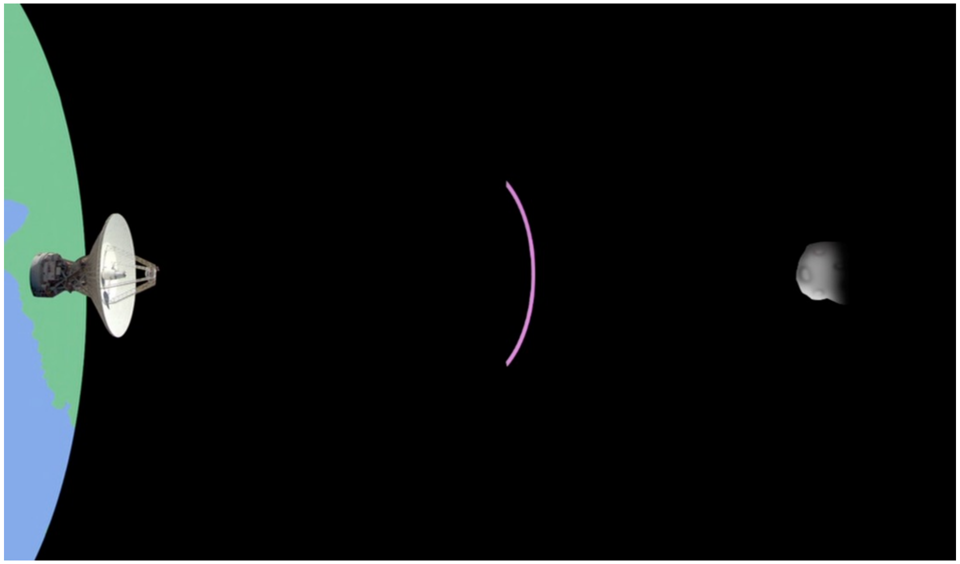
# Radar Array



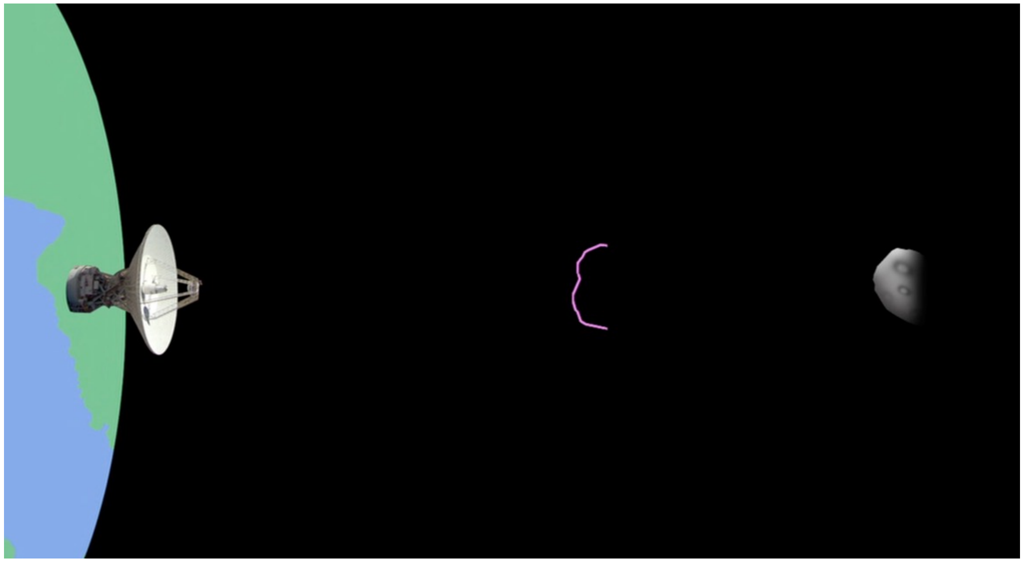

**Need ephemeris to compensate for relative velocities of antennas**

# Planetary Radar

## Huygens–Fresnel principle



**Radar transmitter transmits toward target …**



**Target reflects, a.k.a. re-transmits, radar signal.**

# Planetary Radar Trade Space

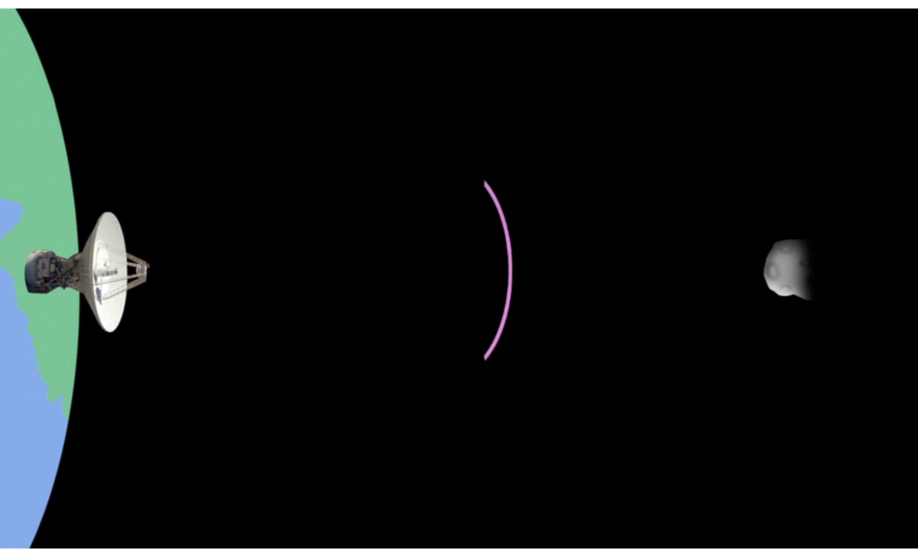
Received Power (a.k.a. Radar Equation, and Tyranny of)

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

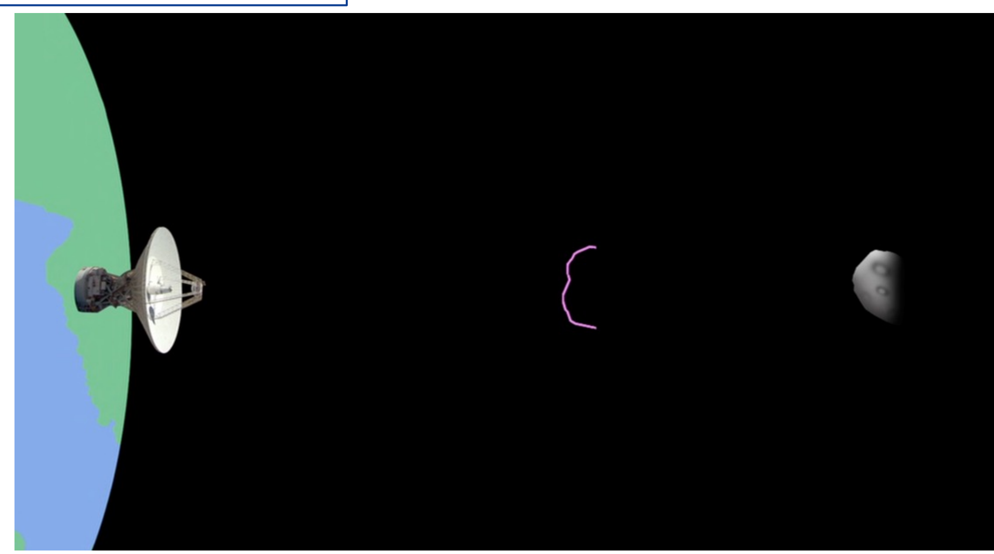
**Receiver Gain**

**Effective Isotropic Radiated Power**

***Target Characteristics***



**Radar transmitter transmits toward target …**



**Target reflects, a.k.a. re-transmits, radar signal.**

# Planetary Radar Trade Space

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

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

Receiver Gain

Effective Isotropic Radiated Power

$$G = 4\pi \frac{A_{\mathrm{eff}}}{\lambda^2}$$

## Monolithic single dish

- $P_{TX}$ limited by high-power transmitter and amplifier engineering
- $G_{TX}$ limited by size of antenna
- Many single point failures

* $G = 1$ (= 0 dBi) for isotropic radiator
$G > 10^7$ (70 dBi) for Goldstone, Arecibo

# Planetary Radar Trade Space

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

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

Receiver Gain

Effective Isotropic Radiated Power

$$G = 4\pi \frac{A_{\text{eff}}}{\lambda^2}$$

## Monolithic single dish

- $P_{TX}$ limited by high-power transmitter and amplifier engineering
- $G_{TX}$ limited by size of antenna
- Many single point failures

## Array of N antennas

- $P_{TX} = N\, p_{TX}$, with $p_{TX}$ smaller and much more feasible
- $G_{TX} = N\, g_{TX} \propto N a_{\text{eff}} \propto N d^2$, more feasible to manufacture
- More graceful degradation
- Is same array used to transmit and receive? $G_{TX} = G_{RX}$

# Arrays of Transmitting Antennas

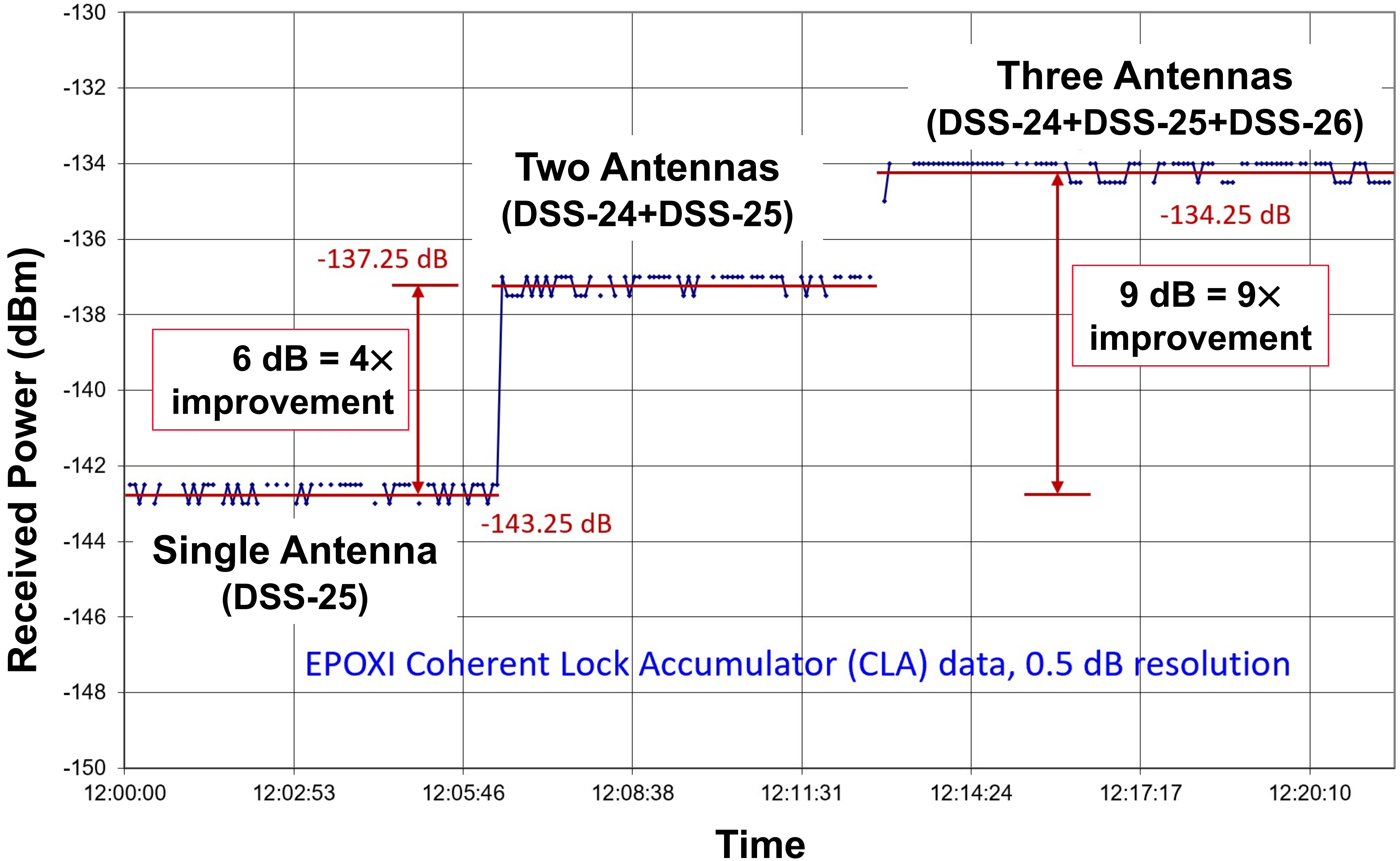
DSN antennas @ Goldstone


Loop Canyon test site

Vilnrotter et al.;
D'Addario et al.

# Three-Antenna Uplink Array Demonstration

## EPOXI Spacecraft

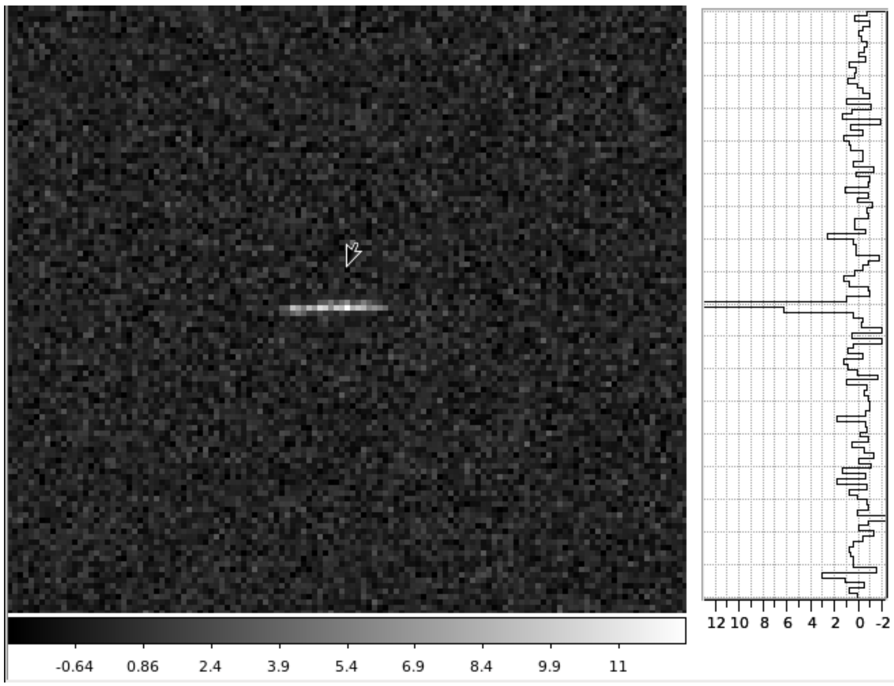



Vilnrotter et al.

# Uplink Array Demonstration: 3 antennas vs. 1 antenna

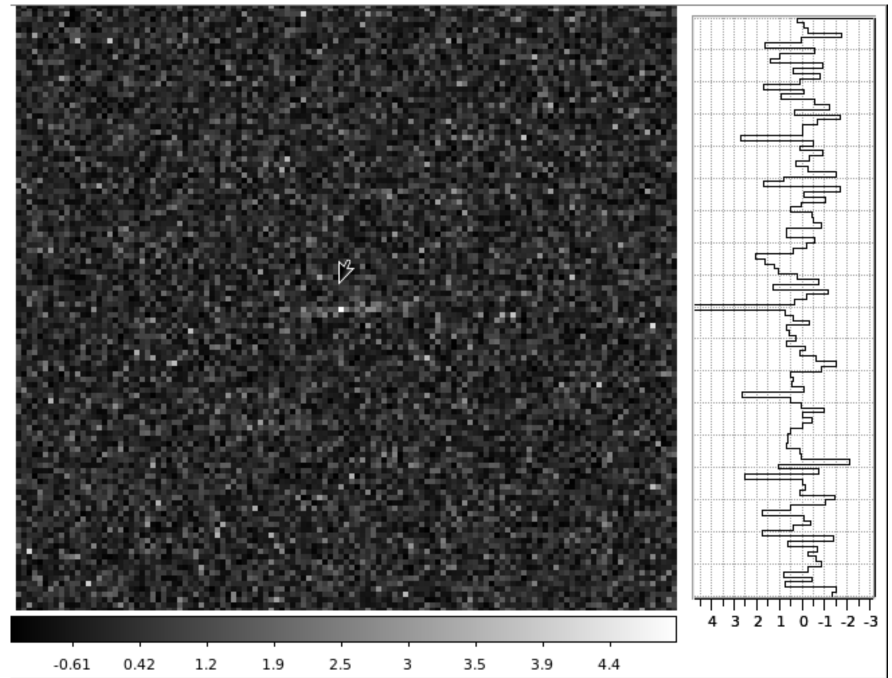
## Delay-Doppler Improvement

**2007 WV4 Image using 3-antenna Uplink Array**




**DSS24 + DSS-25 + DSS-26**
**(20 kW) (20 kW) (80 kW)**

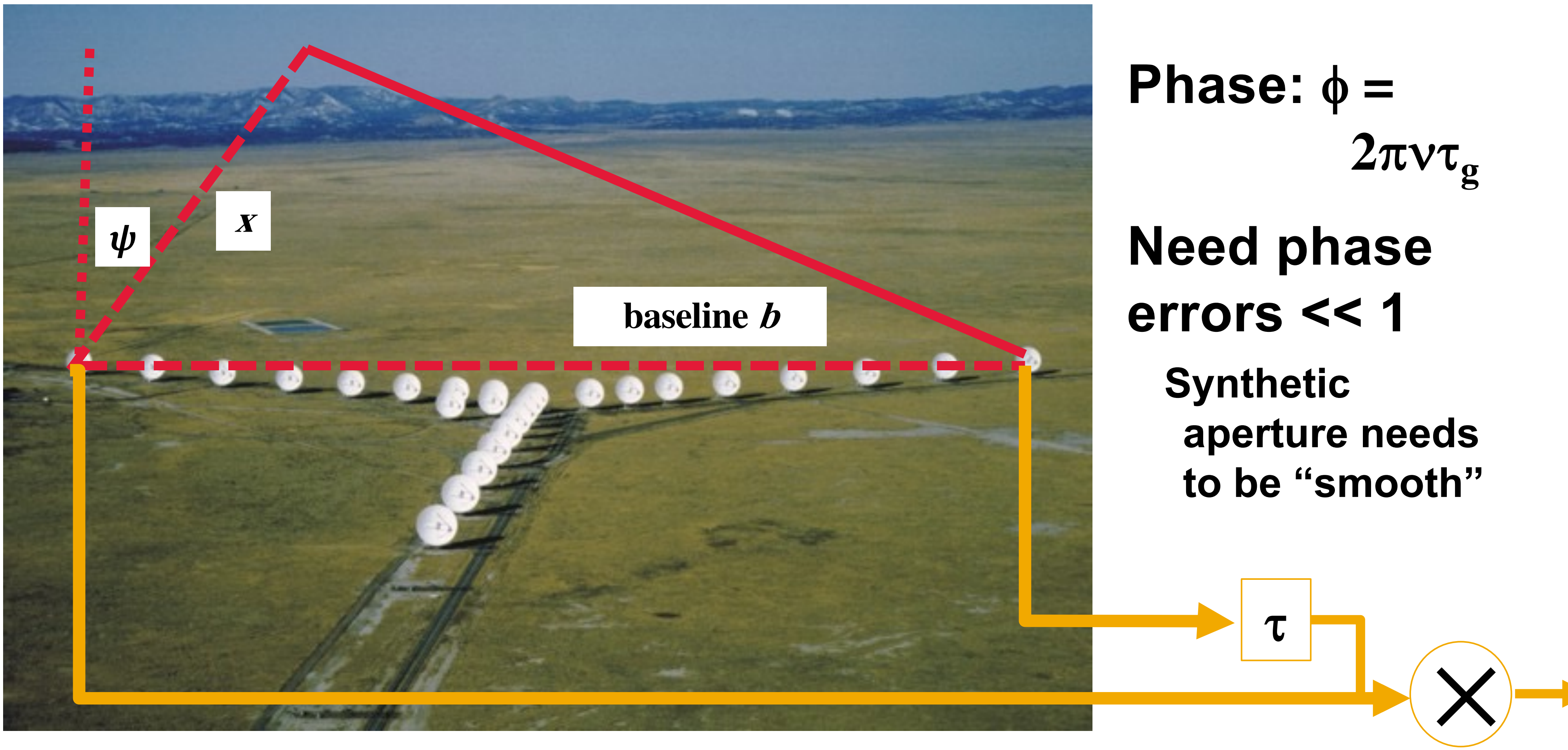
**2007 WV4 Image using Single Antenna (DSS-26)**




**DSS-26**
**(80 kW)**

**… but only 750 m resolution**

# Radio Astronomy Array Calibration

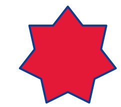


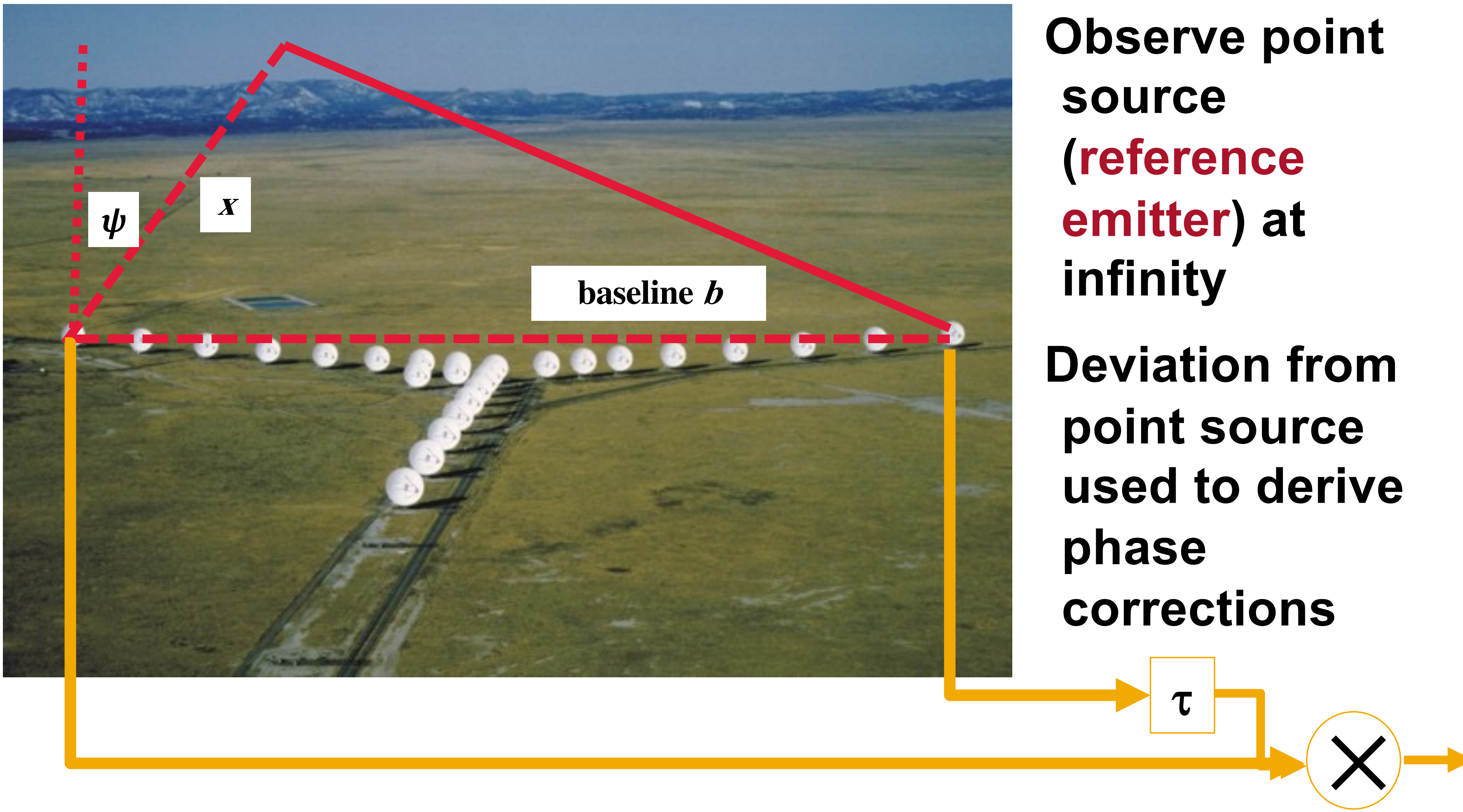

**Phase: $\phi = 2\pi\nu\tau_g$**

**Need phase errors << 1**

- **Synthetic aperture needs to be "smooth"**

# Radio Astronomy Array Calibration

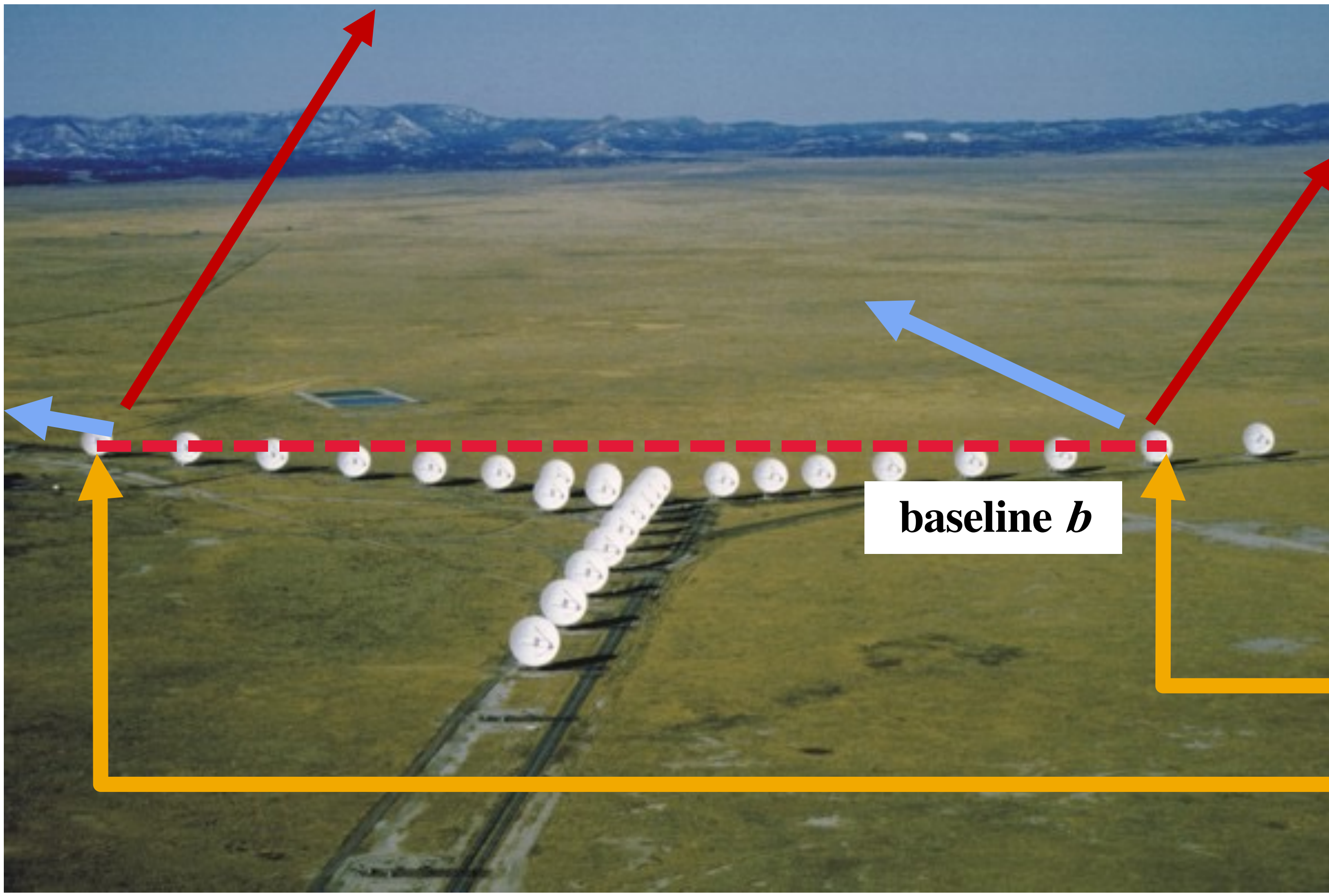



**Observe point source (reference emitter) at infinity**

**Deviation from point source used to derive phase corrections**

# Radar Array Calibration




**Need electric fields in phase at infinity**

**Need reference receiver**

# Arrays of Transmitting Antennas

Calibration, calibration, calibration

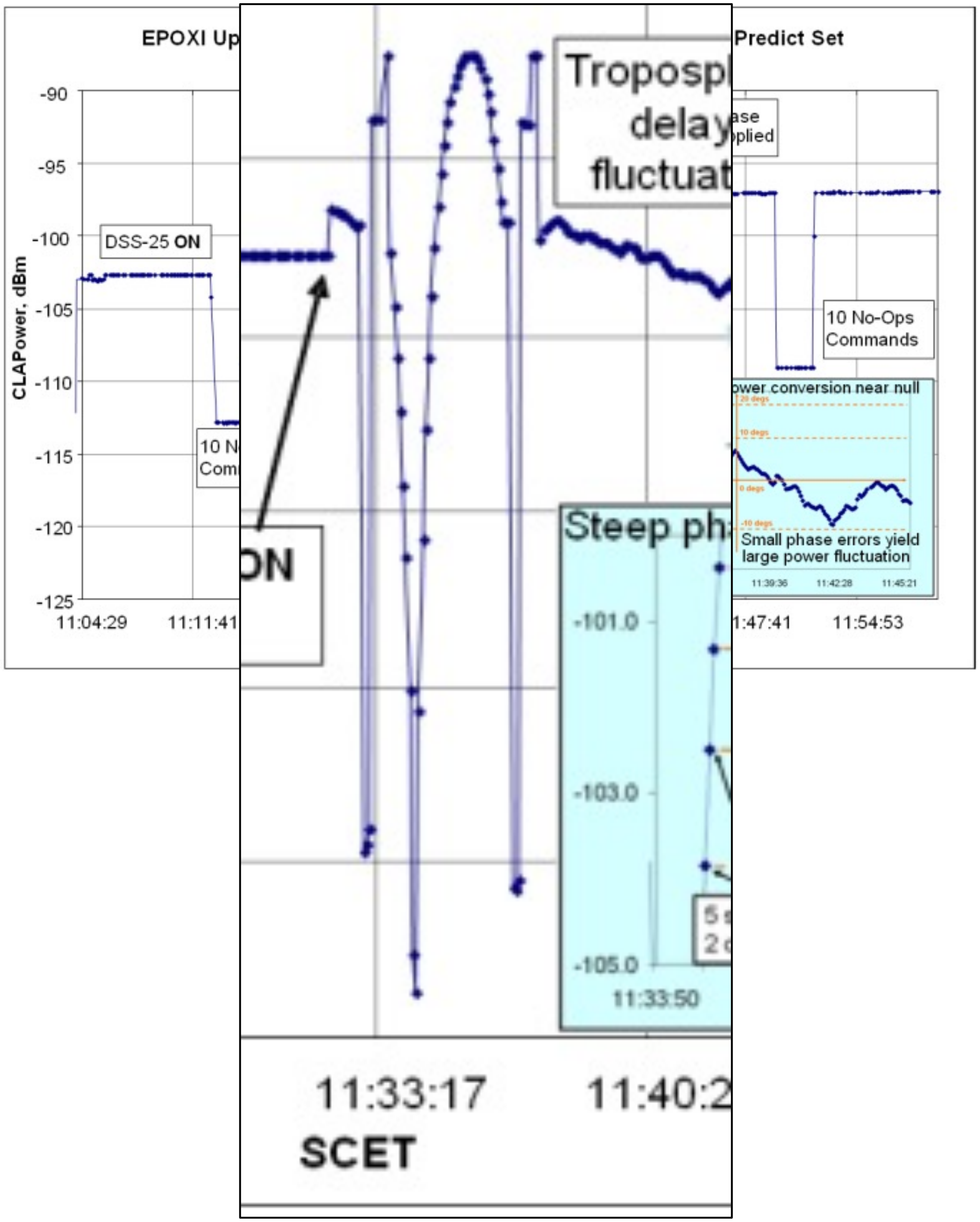
- **Use Moon as reflector**
- **Use receiver on spacecraft**
- **Use terrestrial receiver**

**DSN antennas @ Goldstone**


**Loop Canyon test site**

Vilnrotter et al.; D'Addario et al.

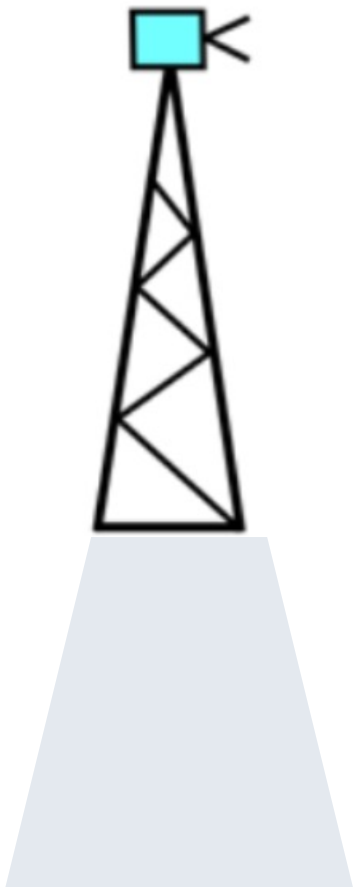
# Radar Array Calibration




- Use Moon as reflector
- **Use receiver on spacecraft**

DSN antennas @ Goldstone

# Arrays of Transmitting Antennas

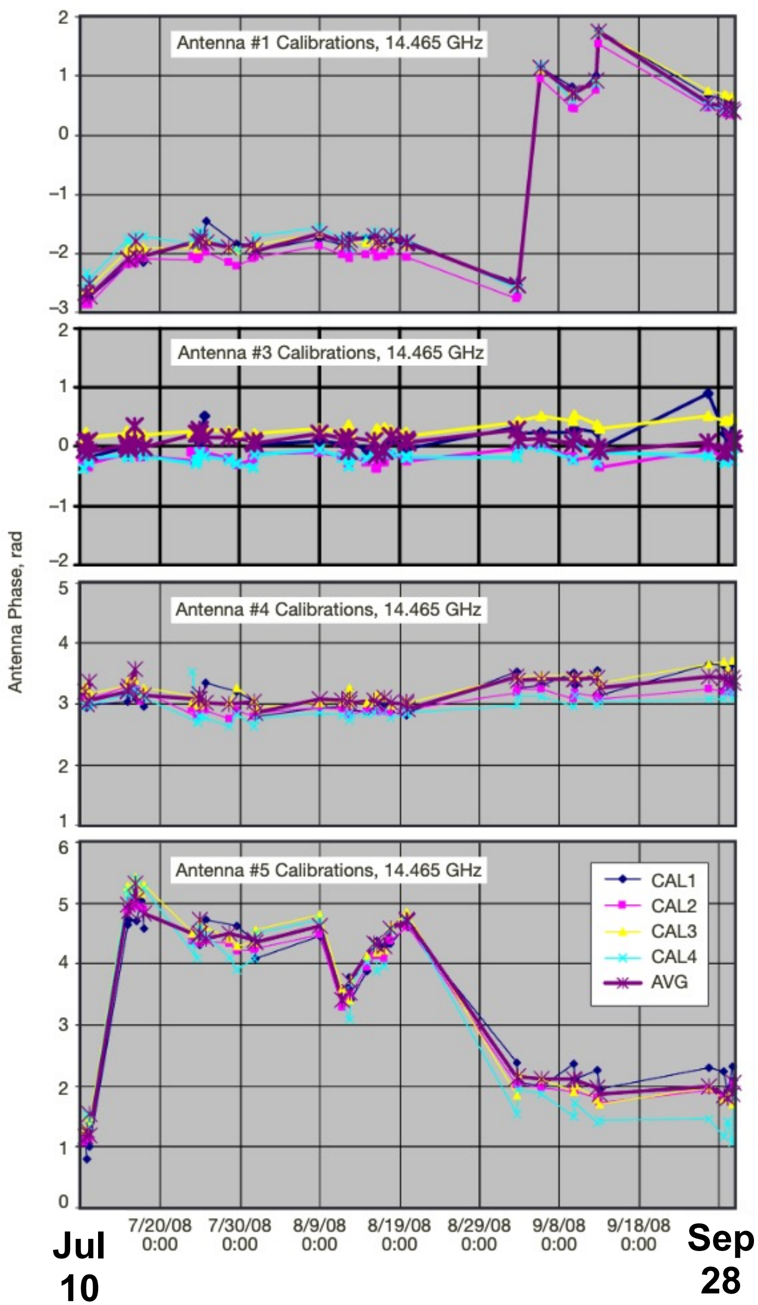


**Place reference receiver on tower**


**Loop Canyon test site**

D'Addario et al.

# Arrays of Transmitting Antennas




## Place reference receiver on tower


**Loop Canyon test site**

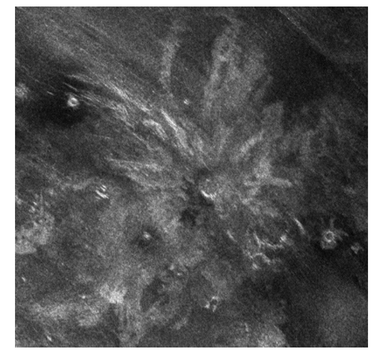
# Science Case – Next-Generation Planetary Radar

## Driving use cases identified at KISS Workshop

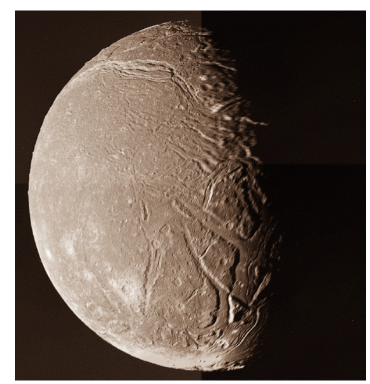
- **Near-Earth Asteroids and Planetary Defense**
- **Venus**
- **Outer Solar System satellites**

**Other potential targets**

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

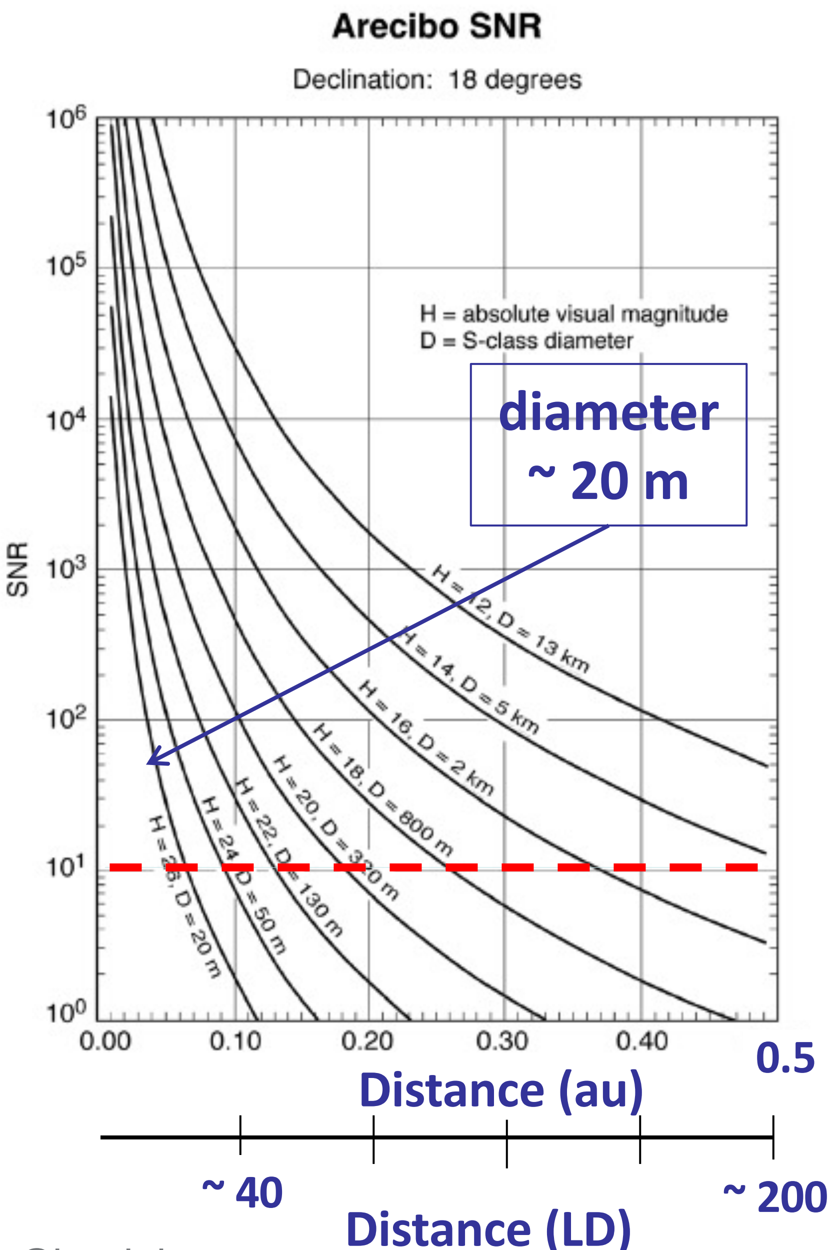


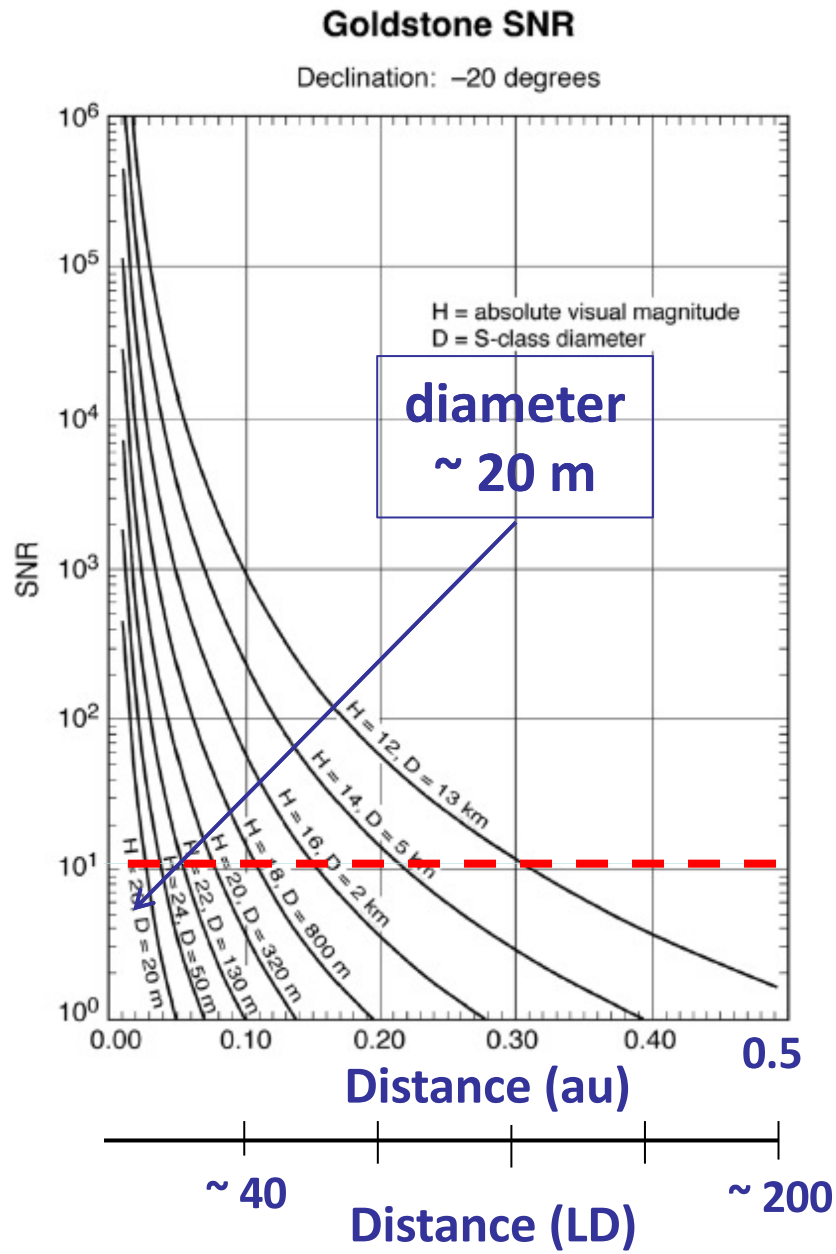
Venus / Sif Mons



Ariel

# Radar and NEA Detectability



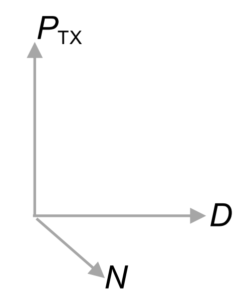



# Planetary Radar Trade Space

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

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

$$\text{EIRP} \propto \underbrace{N^2}_{\text{Number of Antennas}} \underbrace{D^2}_{\text{Antenna Diameter}} \underbrace{P_{TX}}_{\text{Transmitter Power per Antenna}}$$

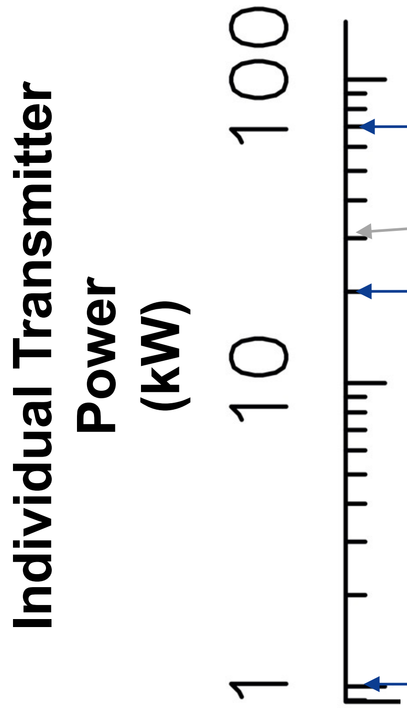



- **Maximize $P_{RX}$ subject to cost cap, including operations!**
  - **Operations $\propto N$**
  - **Using array for both transmit and receive changes result**

# Planetary Radar Trade Space

## Transmitter Power $P_{TX}$

**Focus on ”lower power,” more reliable systems**

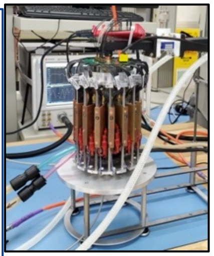



**DSN 80 kW klystron**

**JAXA 30 kW solid state**

**DSN 20 kW klystron**

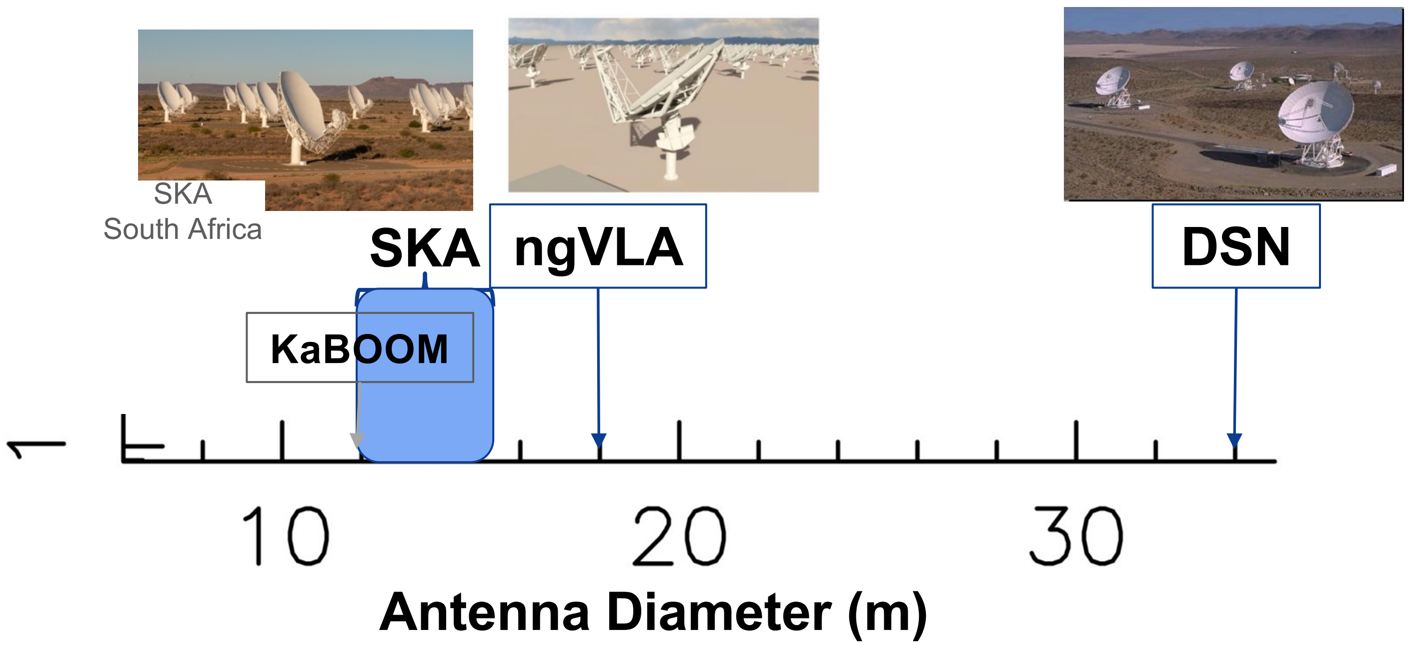
**JPL 1 kW solid state prototype**



# Planetary Radar Trade Space

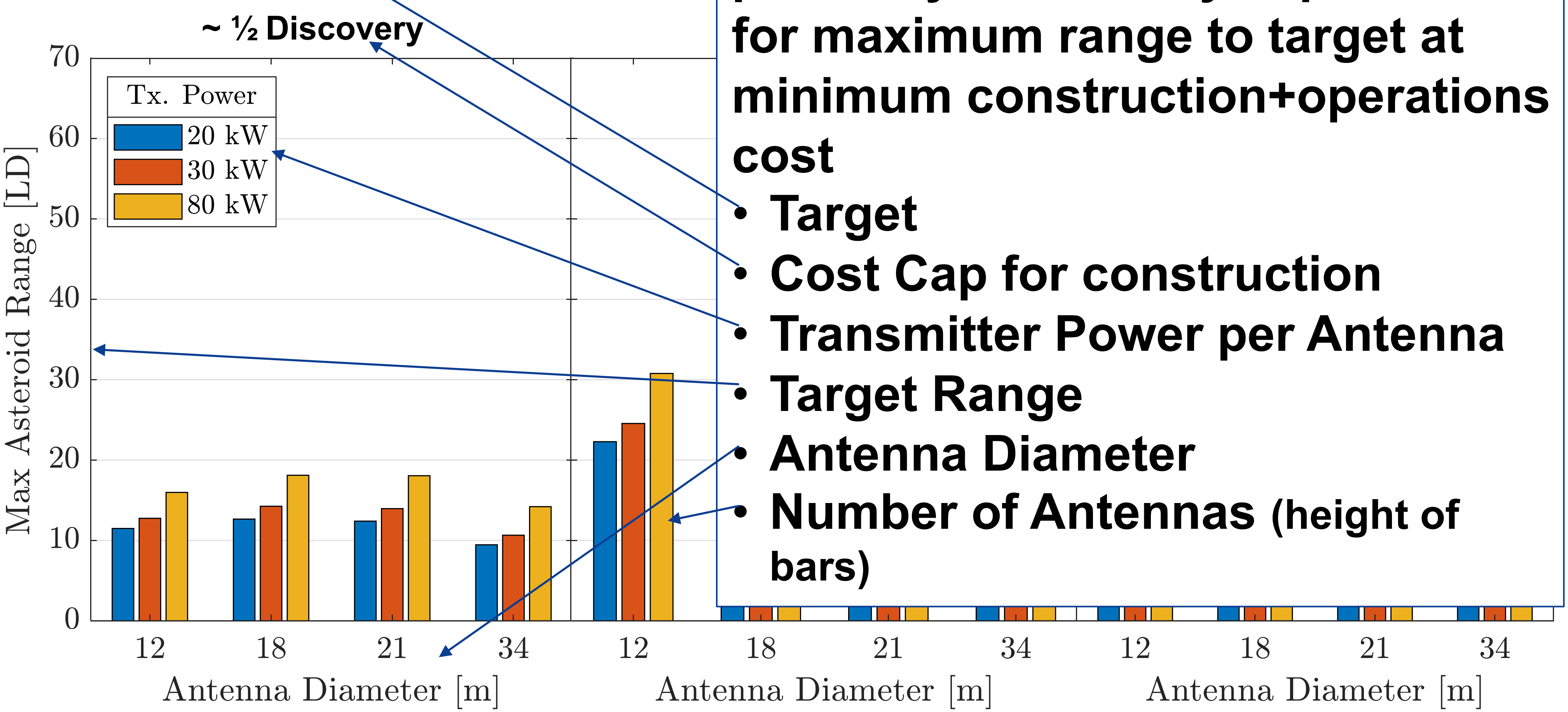
## Antenna Diameter *D*

**Focus on smaller, deployed or to be deployed, antennas**



# Radar Array Performance and Optimization

Target

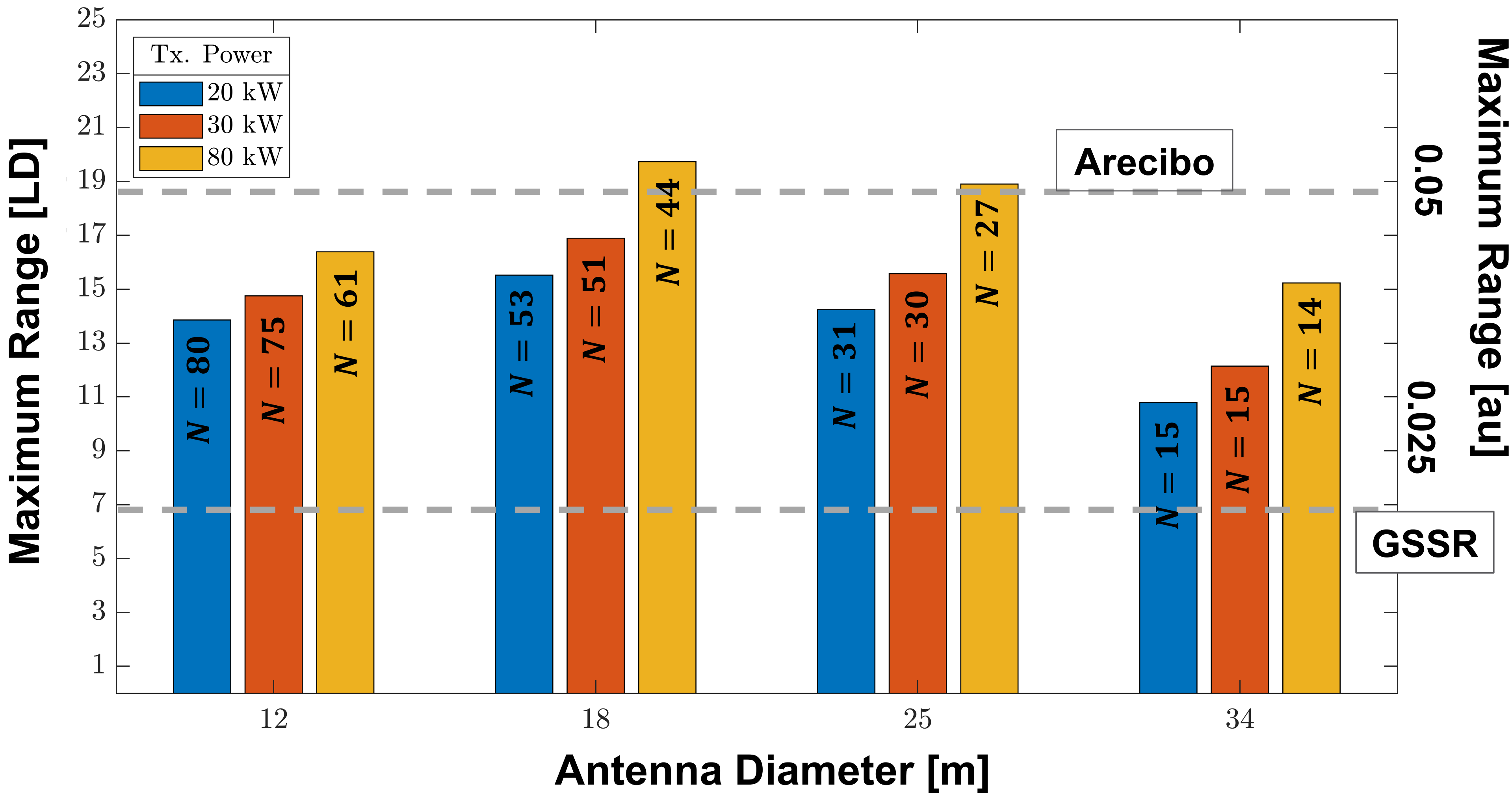



**Following slide describes planetary radar arrays optimized for maximum range to target at minimum construction+operations cost**

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

# Planetary Radar Array Performance: 20 m asteroid

## Cost Cap ~ Discovery-class mission




1 lunar distance (LD) = 380,000 km

# Summary

## Multi-antenna array transmit-receive system feasible

- 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