Deep Space Communication and the Deep Space Network

Stephen A. Townes
Chief Technologist, Interplanetary Network Directorate
NASA/Jet Propulsion Laboratory
California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Agenda

- Introduction to Deep Space Communication
  - A little math
  - Brief look at the space side
- Deep Space Network
- Mars Relay Network
- Voyagers
- What’s Next? Optical Communication

Useful resources

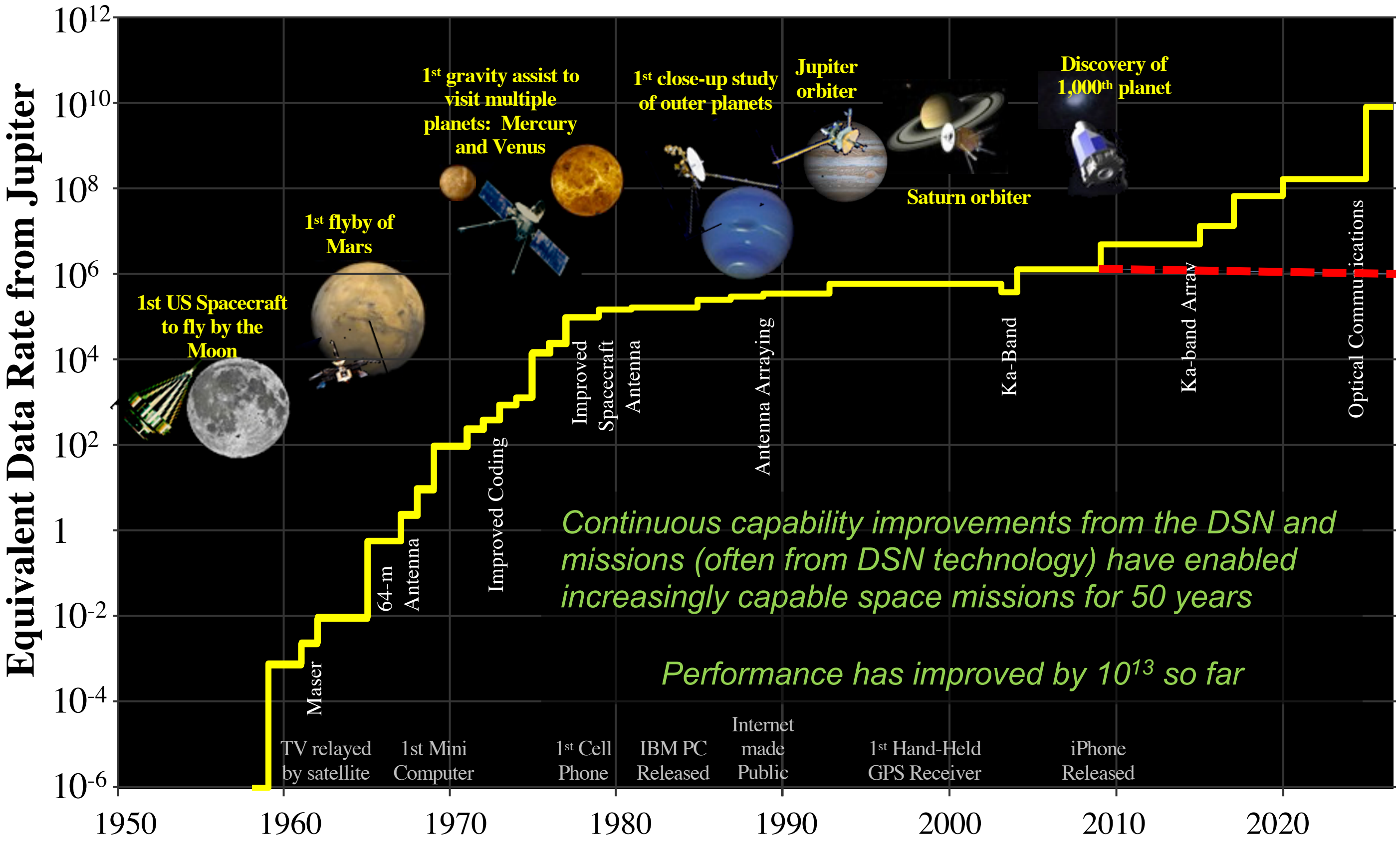
- https://eyes.nasa.gov/dsn/dsn.html
- https://deepspace.jpl.nasa.gov/
- https://deepspace.jpl.nasa.gov/dsndocs/810-005/
- https://descanso.jpl.nasa.gov/

Introduction

In the Interplanetary Network Directorate we like to say that one cannot do a deep space mission without us—no communication, no mission

Don’t leave Earth without us!

A History of Improving Deep Space Communications



Improvements follow technology trends

- Larger launch vehicles and spacecraft
- More spacecraft prime power
- Power amplifier output power and efficiency improvements
- Larger antennas—both flight and ground
- Moving up in frequency—optical is next

Plenty of room to continue to improve. We haven’t hit our “Moore’s Law” limit yet

The Link Equation—focus on the received downlink power

- The data rate supported by the link is a function of the received signal power, P_r

$$P_r = P_t G_t L_t L_{fs} G_r L_r$$

$$L_{fs} = \left(\frac{c}{4\pi d f}\right)^2,\ G_t = 4\pi A_t \left(\frac{f}{c}\right)^2,\ G_r = 4\pi A_r \left(\frac{f}{c}\right)^2$$

and with a little math-magic

$$\boldsymbol{P_r = P_t A_t L_t \left(\frac{f}{cd}\right)^2 A_r L_r}$$

  - Note that all things being equal, higher frequency is better! Everything else is fixed.

(it's never that easy)

- $L_{fs} = free\ space\ loss$
- $P_t = transmiter\ output\ power\ (W)$
- $G_t = transmit\ antenna\ gain$
- $L_t = transmit\ losses$
- $G_r = recieve\ antenna\ gain$
- $L_r = receive\ losses$
- $A_t = effective\ transmit\ antenna\ area\ (m^2)$
- $A_r = effective\ receive\ antenna\ area\ (m^2)$
- $c = speed\ of\ light\ (m/s)$
- $d = distance\ between\ transmitter\ and\ receiver\ (m)$
- $f = frequency\ (Hz)$

The Link Equation—focus on noise

- The downlink power has to “overcome” the noise at the receiver so we can extract the information
- Noise at the receiver can be caused by many factors
  - One is the inherent noise in the electronics
    - The electronics noise in bandwidth $B\ (Hz)$ is

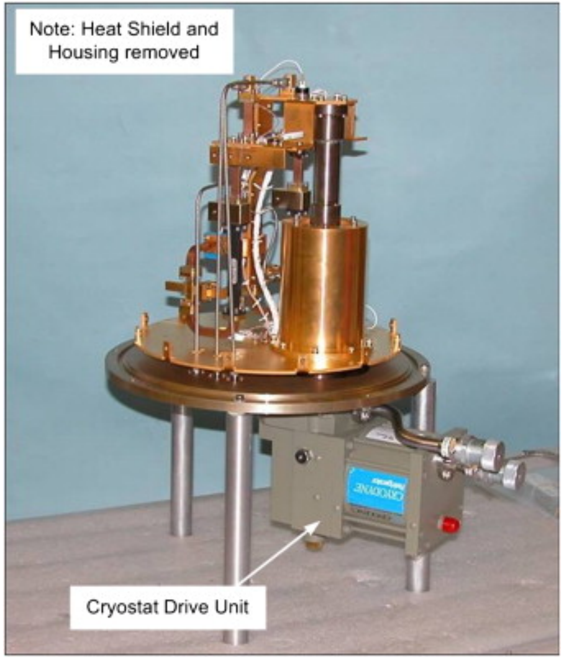
$$P_N = N_0 B = kTB$$

N_0 is the noise power spectral density (W/Hz)

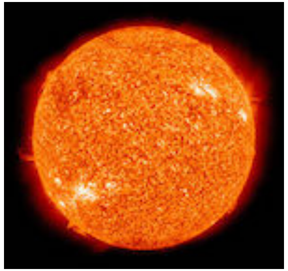
k is Boltzmann’s constant $1.38 \times 10^{-23}\ (W/K\ Hz)$

T is the system temperature (K)

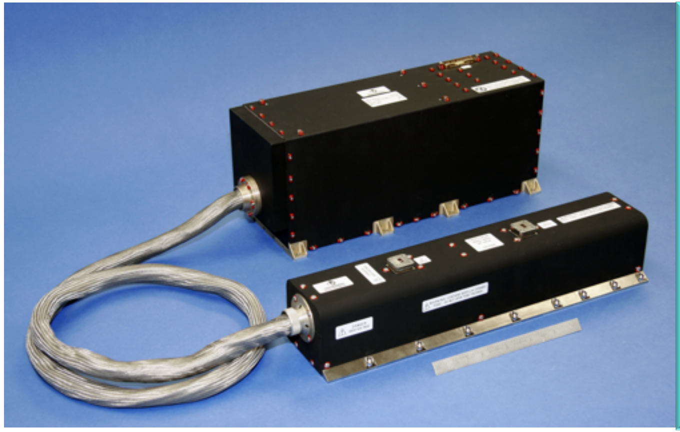
    - We use cryogenically cooled amplifiers to keep T down
- And there are other noise sources to take into account



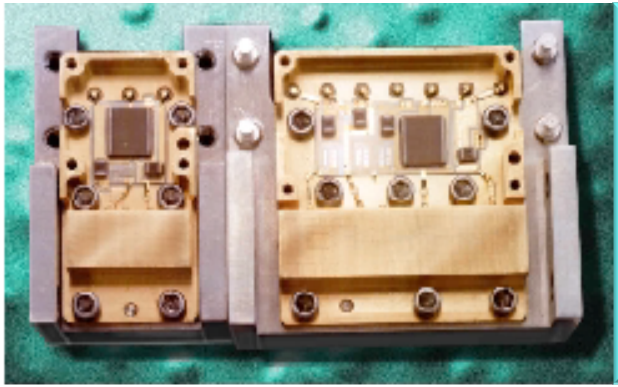
Ka-band (32 GHz) low noise amplifier



Power Amplifiers—Higher efficiency and Higher power



200 W Ka-band TWTA developed in mid 2000s but has yet to fly because no mission has, or has been willing to allocate, that sort of power to comm



2 W Lockheed Martin Ka-band SSPA developed for DS-1 late 1990s

Traveling Wave Tube Amplifiers (TWTA)

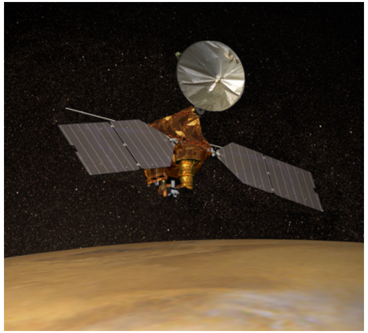
- Workhorse of deep space flight comm
- Vacuum system—somewhat of an art
- Power levels of 200 W and more at Ka-band
- Efficiency of 50%-60%--can get a bit higher
- High voltage power supplies, e.g., 350 V

Solid State Power Amplifiers (SSPA)

- Power levels of <10 W for Ka-band flight
- Efficiencies of 25% or less
- Goal of 10-50 W with 40%-50% efficiencies with GaN
- Expected to be smaller, lower mass, more rugged and easily manufacturable

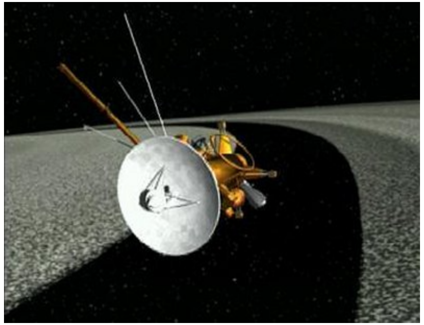
Ultimate limit is the spacecraft prime power

Antennas—Bigger is better

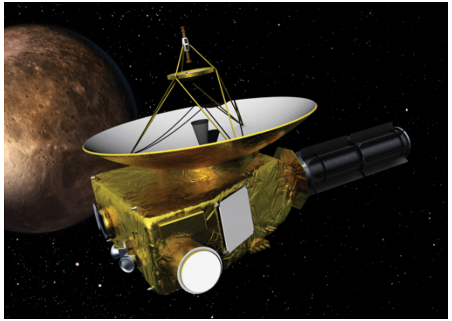


MRO X and Ka
3.0 m Solid
Mars

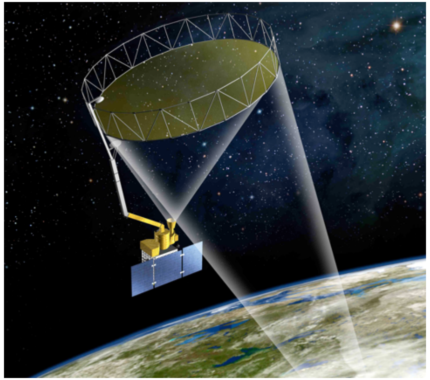
Galileo S & X-band
4.8 m Deployable (oops!)
Jupiter



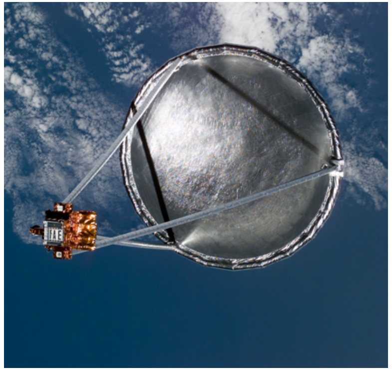
Cassini S, X and Ka-band
4.0 m Solid
Saturn



New Horizons X-band
2.1 m Solid
Pluto



SMAP L-Band
12.0 m Deployable



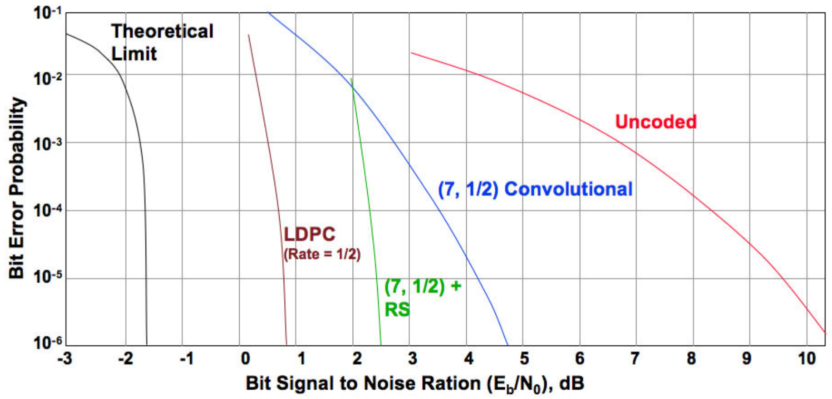
Inflatable Antenna Experiment
X-Band (?)
14.0 m Inflatable

What is wrong with this picture?

- Instrument data production rates continue to increase—no matter where in the Solar System
- As we go farther out we need larger antennas and/or more RF output power to return this data
- Large deployables—like those being used in GEO & LEO—will be needed
- Key is to keep mass low and aperture large

Limitation is getting the antenna mass out of the gravity well—big rocket!

Be as efficient as possible when sending data



Example of near-lossless compression performance on a calibrated MaRS hyperspectral image

	File Size	Bit Rate (bits/sample)	Compression
Original image file	385 MB	16	1×
Lossless compression, δ=0	135 MB	5.6	2.9×
Near-lossless, δ=1	96 MB	4.0	4×
Near-lossless, δ=4	67 MB	2.8	5.7×

δ = maximum error in reconstructing the corresponding sample in Data Number [6]

Error Correction Coding

- Adding "parity" bits to allow detection and correction of errors
- Reduces power required to send the "information bits"
- In deep space comm, usually implies larger RF bandwidth

Data Compression

- Don't send bits that don't need to be sent
- Examples:
  - Long runs of zeros can be represented by a single number--the number of zeros
  - Frequency bands with no content don't need to be sent
  - Bit patterns that occur more often can be encoded into shorter codewords—think Morse Code

NASA’s Deep Space Network (DSN)

Canberra Deep Space Communications Complex

COMPLEX SIZE: roughly 0.425 square kilometers

Goldstone Deep Space Communications Complex

COMPLEX SIZE: ~ 134 square kilometers

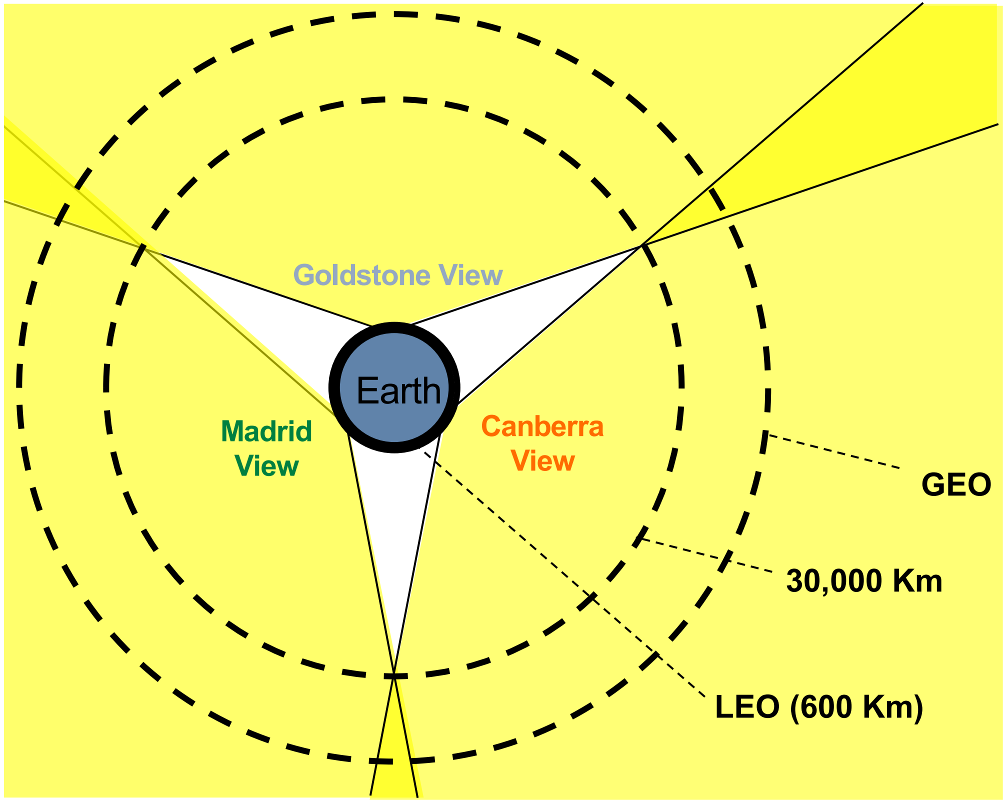
Madrid Deep Space Communications Complex

COMPLEX SIZE: roughly 0.490 square kilometers

- **NASA’s Deep Space Network (DSN) was established in December 1963 to provide a communications infrastructure for all of NASA’s robotic missions beyond Low Earth Orbit.**
- **DSN’s prime responsibility is telecommunications for NASA missions, but its also supports many international spacecraft as well as scientific investigations through radio astronomy, radio science, and radar activities.**
- **The DSN also supports many international agencies: the Japanese Space Agency (JAXA), the Indian Space Research Organization (ISRO), the European Space Agency (ESA), and the United Arab Emirates (UAE).**

DSN Geometry

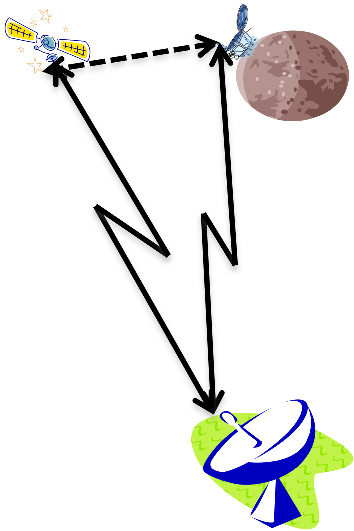
- Three "complexes", ~120^{o} around the Earth
- Can "see" spacecraft in deep space almost all the time
- Not great for low spacecraft – such as deep space mission *launches*!



View looking down on the Earth's North Pole

Functions of the DSN

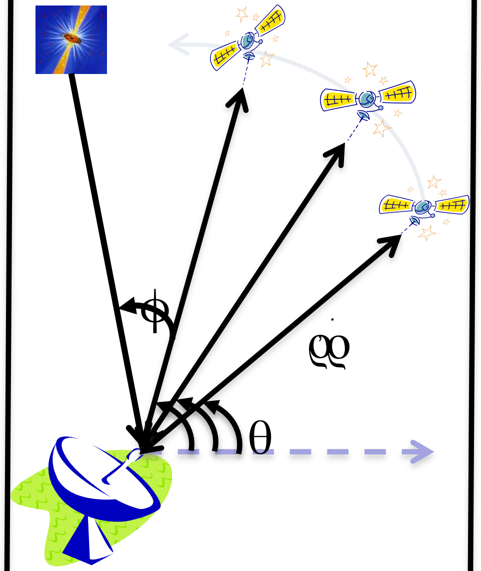
Telecommunication



Uplink (Command): 20KW Transmitters; S-band (2 GHz) and X-band (8 GHz); Data Rates from 10 bps to 10 Kbps

Downlink (Telemetry): S-band (2 GHz), X-band (8 GHz), Ka-band (26 or 32 GHz); Data Rates from 10 bps to 6.6 Mbps

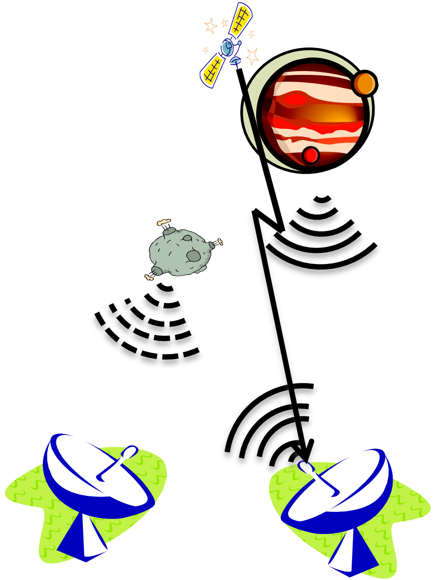
Tracking



Collect multiple data types used for orbit determination:

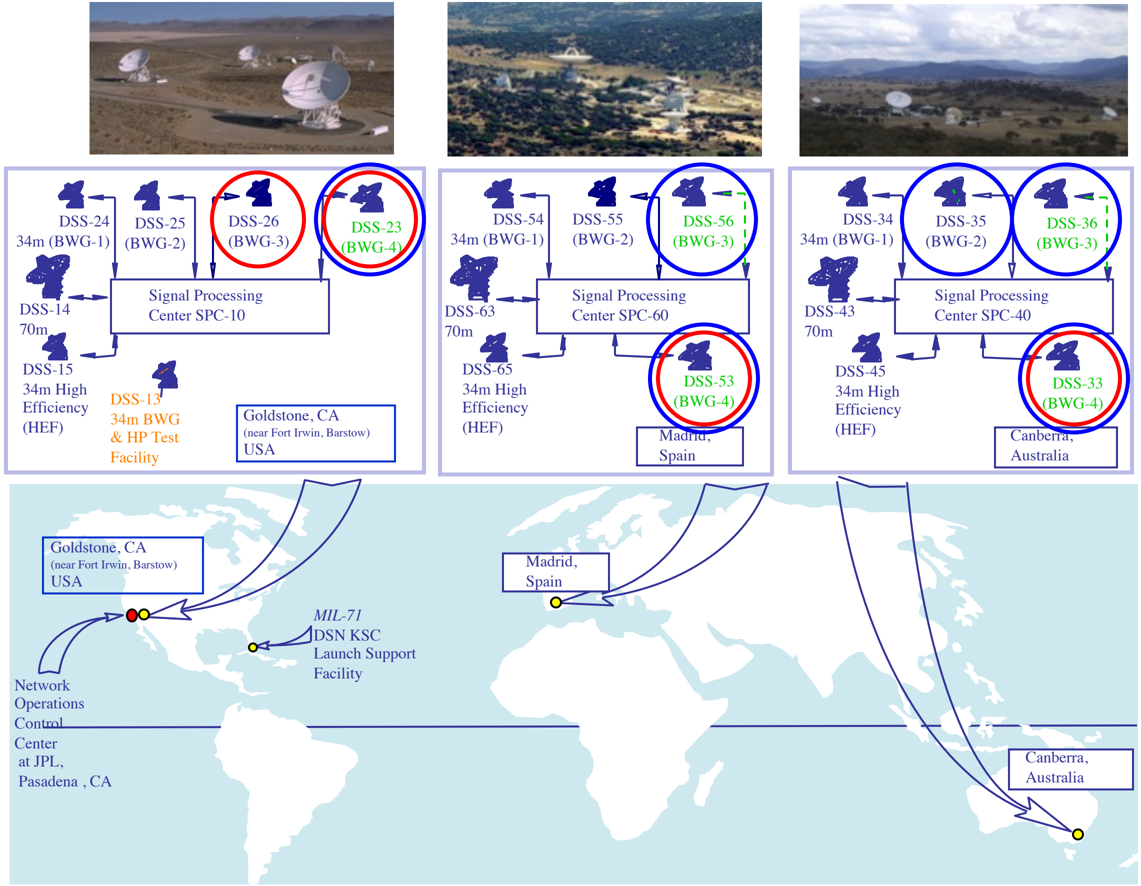
- Range
- Doppler
- Angles
- Delta-DOR
- Very Long Baseline Interferometry (VLBI)

Science



Radar: Bouncing a radio signal off a celestial body and processing the received reflected signal
Radio Science: Observations of changes in a spacecraft radio signal as it passes through a planetary atmosphere
Radio Astronomy: Observations of naturally occurring radio emissions

DSN Facilities by 2025



LEGEND

Antennas
Operational Dates

DSS-35	10/2014
DSS-36	10/2016
DSS-56	10/2019
DSS-53	10/2020
DSS-33	10/2022
DSS-23	10/2024

80 kW XTR
Operational Dates

DSS-26	9/2015
DSS-53	10/2020
DSS-33	10/2022
DSS-23	10/2024

Historically we have tried to reduce the burden on the deep space missions by building large antennas on Earth

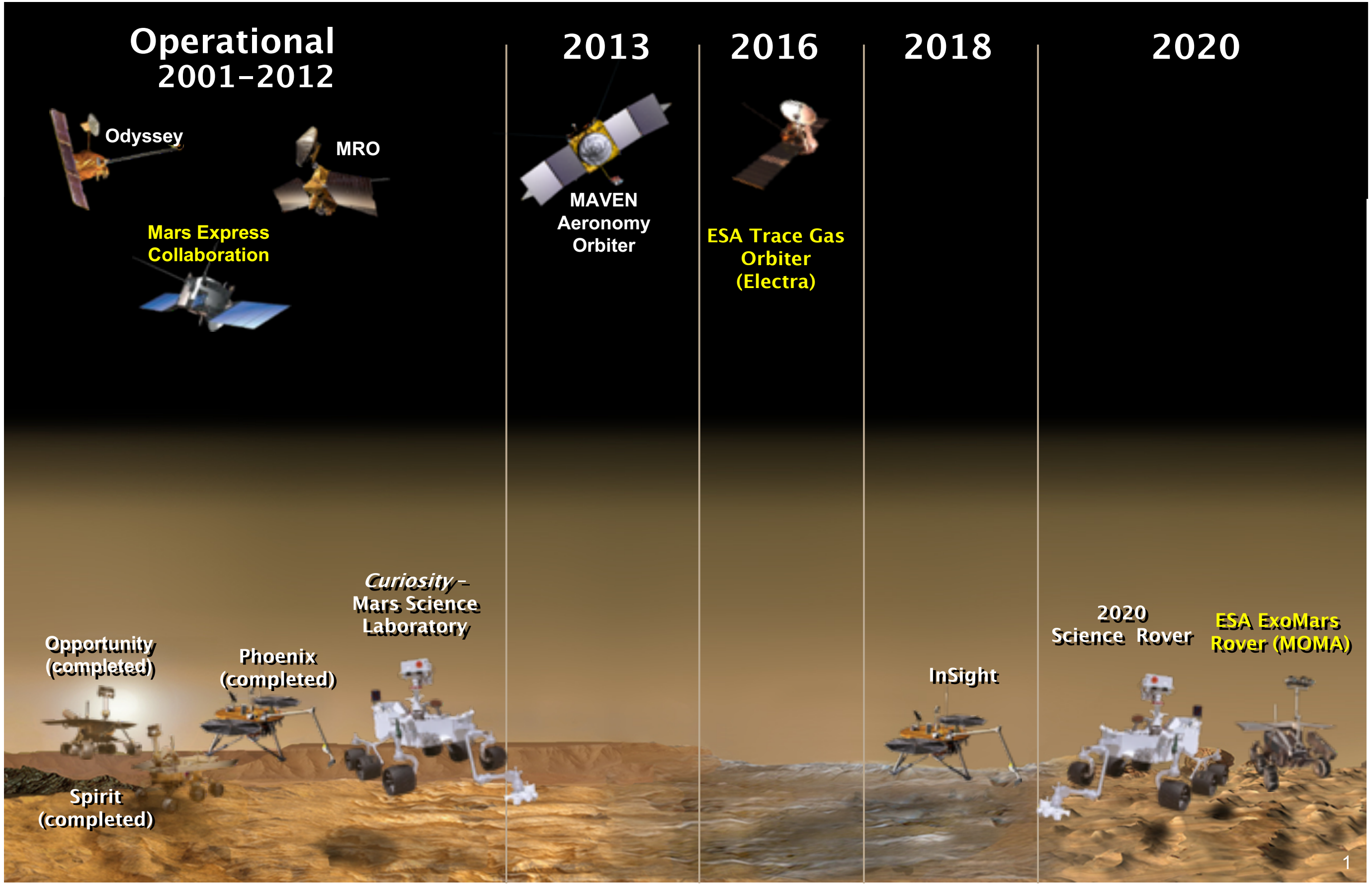
- *Receive*
  - *High gain*
  - *Low noise*
  - *Arraying*
- *Transmit*
  - *Higher output power*
  - *Arraying*
- *Support multiple missions simultaneously*

DSN Mission Set Example

Mars Relays—The Beginning of the Solar System Internet

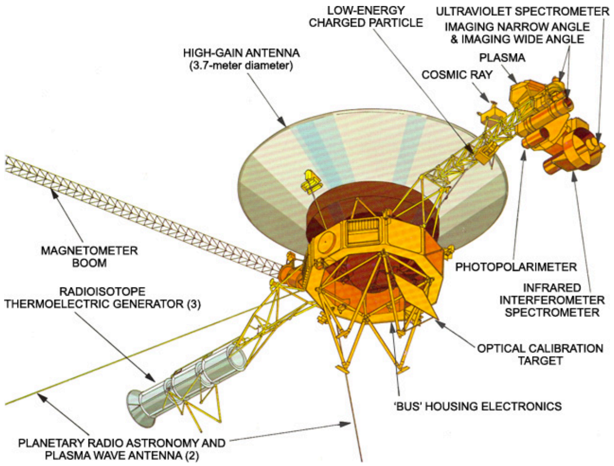
- Almost all data brought back from Mars these days comes to Earth via relays orbiting Mars

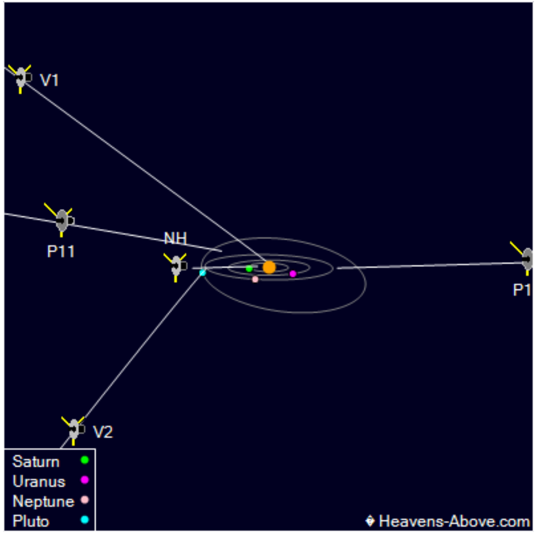
- Use of standards allows relays from multiple Agencies to communicate with rovers from multiple Agencies



Voyager 1 & Voyager 2

- Launched in 1977
- Both in interstellar space
  - VGR1: 14.1 billion miles from Earth (~148.6AU)
  - VGR2: 11.7 billion miles from Earth
- Powered by 3 radioisotope thermoelectric generators ~450W at launch
- Telecom
  - S-band up & down for TT&C—now only S-band up for commanding
  - X-band down for telemetry; 12/18 W TWTA
- Example: May 28, 2020 ~0430 UTC
  - tracking VGR1 with 70 m antenna in Goldstone at X-band
  - received signal was -155.61 dBm (0.00000000000000000028 Watts)
  - Data rate 159 b/s
  - RTLT 1.72 days
  - Range 22.22 Billion km





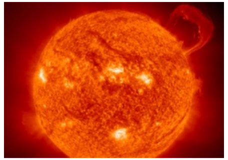
Why Optical Communication?

- Sponsor challenged us:

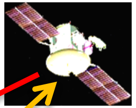
  "Increase data rate by factor of 10 relative to Mars Reconnaissance Orbiter Ka-band system (35W TWTA and 3m dish into a 34m antenna on the ground) with no increase in mass or power"

  ✓ *Increased data return for deep space science & exploration missions!*
- Optical could be more efficient because:
  - Higher frequency implies narrower beamwidth for given aperture size relative to Ka-band
  - Smaller component sizes—lots of commercial investment
  - Lots of bandwidth available—higher data rates—no spectrum regulation
- Challenges
  - Pointing, acquisition and tracking
  - Daytime as well as nighttime operation—particularly close to the Sun
  - No existing ground infrastructure—maybe some astronomical telescopes—baseline 12 m effective aperture
  - Lifetime & space qualification
  - New ops concept for handling weather

Deep Space Optical Communications



Sun
Can be in field of view
Primary source of optical noise



Deep Space
Large distance
Large $1/R^2$ range loss
Large 2R/c round-trip light time (RTLT)

Point-Ahead Angle

Downlink
- Stabilized by disturbance rejection system & uplink beacon tracking
- Gb/s return link data
- Ranging

Earth at T_1+RTLT

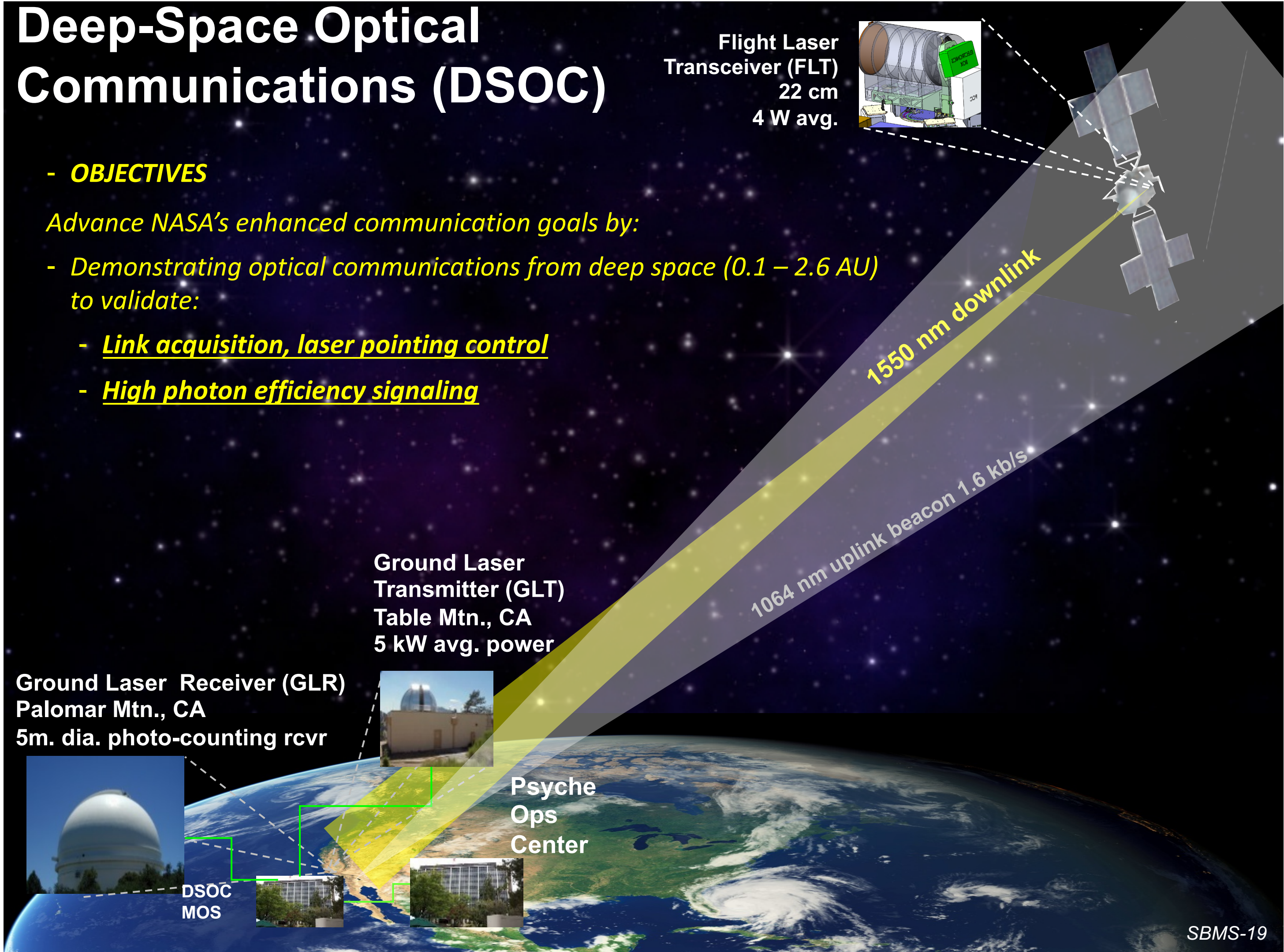
Earth at T_1

Uplink
- Blind points to spacecraft
- Aids downlink pointing
  - *Reference for removal of spacecraft jitter*
  - *Reference for point-ahead angle*
- Mb/s forward link data
- Ranging

Deep space optical communications improves over RF performance by:
- **Pointing:** Narrow beams from small transmit apertures deliver more power "on target"
  - *Requires pointing ~500 times more precise than Ka band RF*
- **Modulation:** Pulse Position Modulation (PPM) for more "bits-per-photon" than RF
  - *Requires high peak-to-average power lasers*
- **Detection:** Efficient and high rate photon counting both in space an on ground "makes every photon count"
  - *The optical channel is not thermal noise limited*

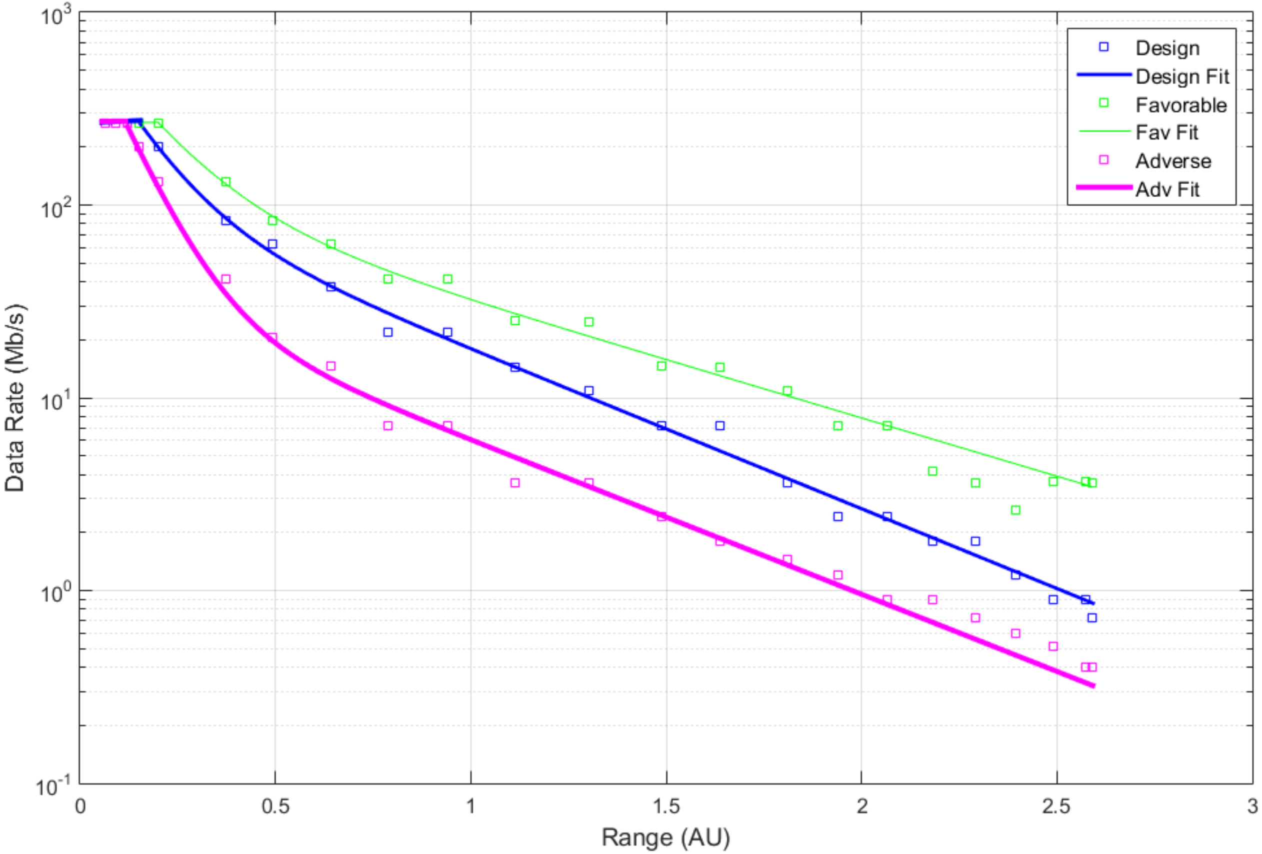
DSOC

- First demonstration of deep space optical comm beyond the Moon
- Technology Demonstration planned for the Psyche Mission—August 2022 launch
- Testing all aspects including the new Consultative Committee Space Data Systems (High Photon Efficiency) Optical Comm Standards
- Hopefully a chance to “interoperate” with other Space Agencies



Example DSOC Predicted Performance

- Highest data rates ever returned from these distances
  - MRO 6 Mb/s at Mars close range
- Allows testing of channel conditions and operations strategies
- Looking for other potential ground stations
- Need increase in data rate at Mars farthest range to support future Human Exploration
  - More flight aperture and power
  - Larger ground stations

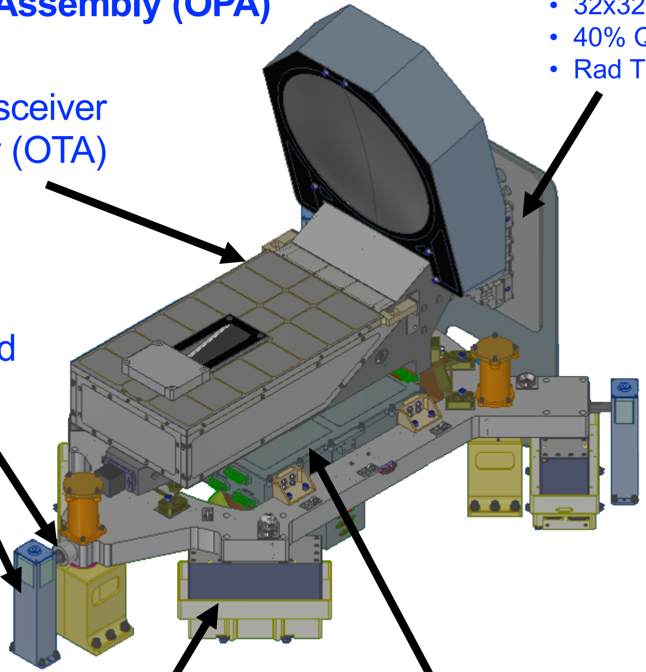


DSOC Flight Laser Transceiver

Optical Platform Assembly (OPA)

Optical Transceiver Assembly (OTA)

Launch locks and motion cages



Isolation Pointing Assembly Struts (IPA-S)

- 50 dB rejection

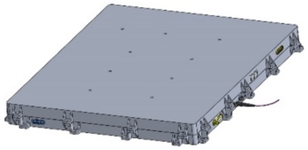
Floating Electronics Module (FEM)

Photon Counting Camera (PCC)

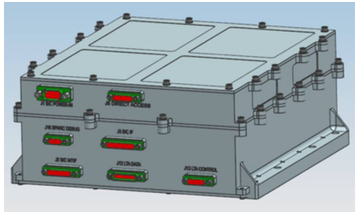
- 32x32 Array
- 40% Quantum Efficiency
- Rad Tolerant

Laser Transmitter Assembly (LTA)

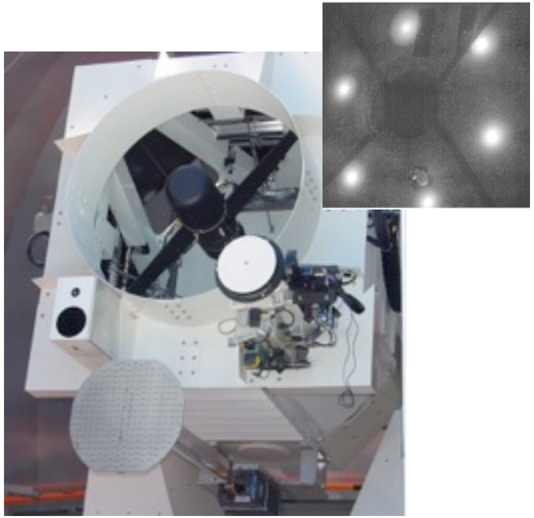
- 4 W average Output Power
- 160:1 Peak-to-Average
- 660 W Peak



Stationary electronics module (SEM)

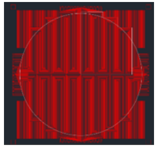


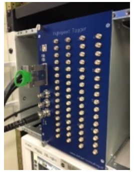
DSOC Ground System



Ground Laser Transmitter
Optical Communication Telescope Laboratory

- 1m aperture (multi-beaming sub aperture)
- 5 kW uplink lasers at 1064 nm

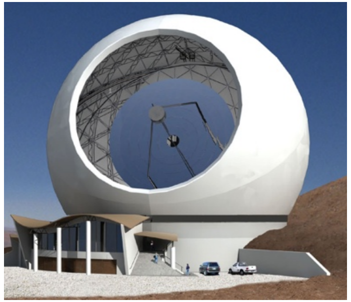




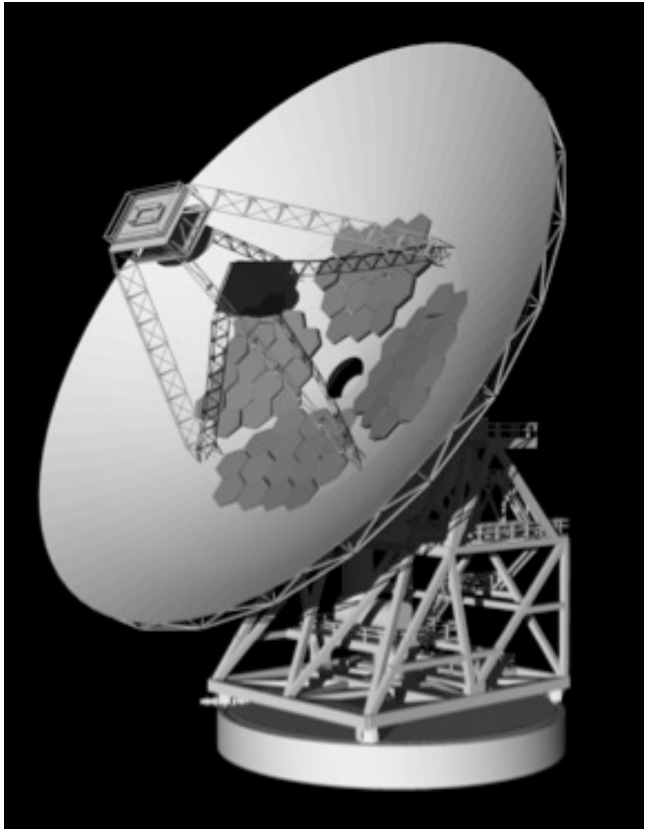
Ground Laser Receiver (GLR)

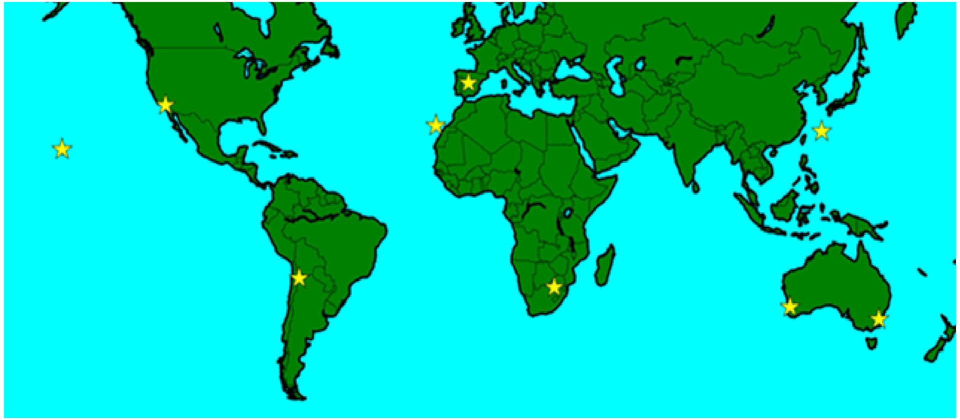
- Photon-counting ground detectors
- >50% Efficiency Tungsten Silicide (WSi) superconducting (<1 K) nanowire arrays
- Real time Time-to-Digital converter for PPM demodulation

Interoperable Optical Ground Stations—Still Needed


New Build—12 m


Joint-Use Astronomical Telescope


Hybrid RF-Optical 34 m Antenna (8m optical)


Example locations for deep space optical terminals

Still Work to Be Done

- Deep space optical comm hardware—flight and ground—still maturing
- DSOC is the first step for flight hardware
- Hybrid RF-Optical 34m antenna may be the first step for operational ground station
  - Note that arraying two 8m optical antennas closer to one 12m antenna
- We won’t get the 10X out of the first demo but we’re on the way!

Questions?

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov