NASA's Deep Space Network

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Deep Space exploration is Unique

- Spacecraft mass and power are precious
- Spacecraft go huge distances from Earth
- Navigation is highly dependent on Earth
- Comm system is also a science instrument
- Every mission is unique

The Deep Space Network
NASA's Connection to the Moon, Planets, & Beyond

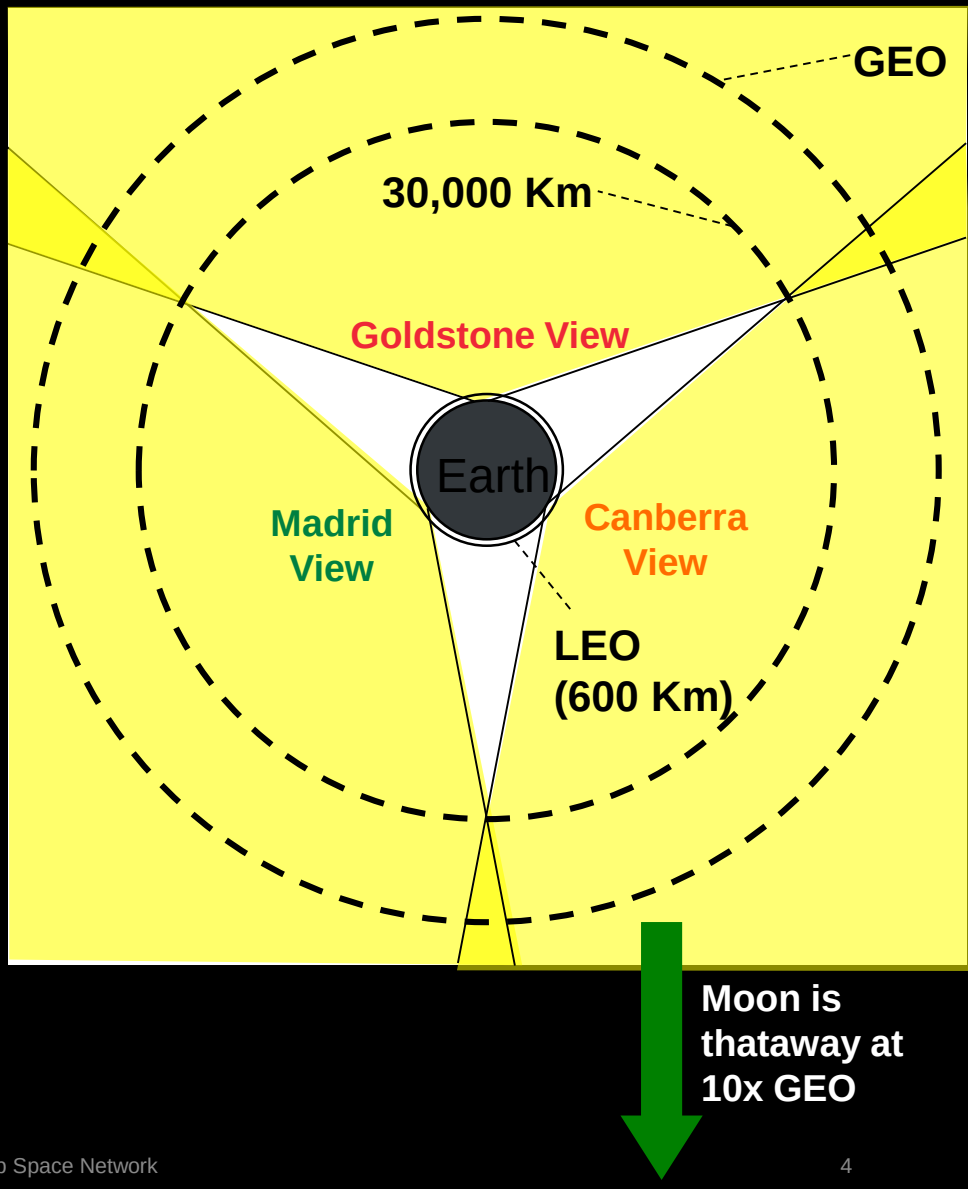
- Three global locations
  - California, Spain, Australia
- Captures all information from our spacecraft
  - Most sensitive receivers
- Sends all instructions to them
  - Most powerful transmitters
- Provides most of the navigation
  - Most stable clocks and best algorithms

Enabling more than 30 spacecraft in flight today

DSN 70m Antenna at Goldstone, California

DSN Sites

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



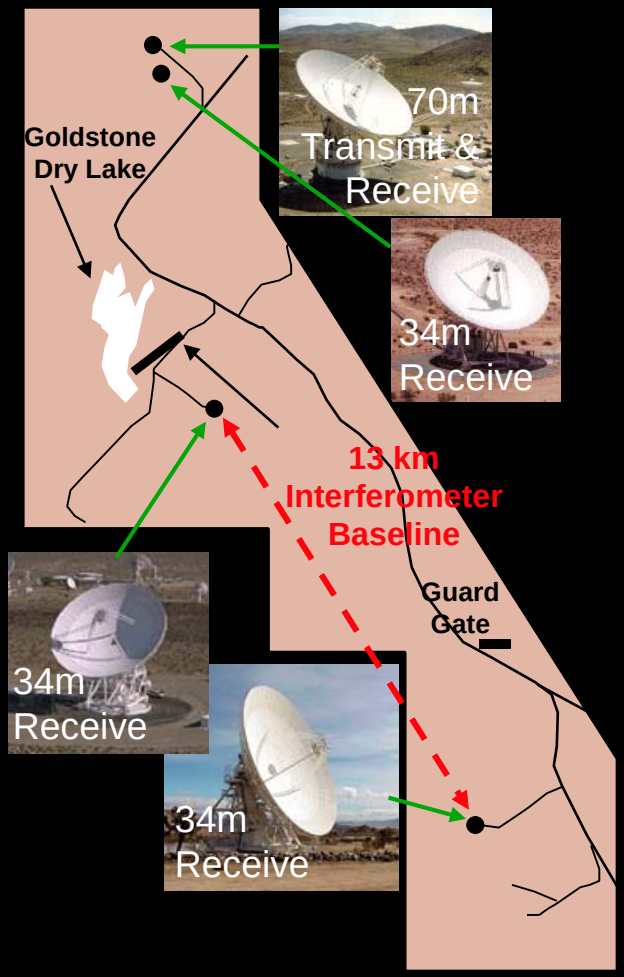
DSN Antennas in Madrid, Spain

Radio Science

- Tracking spacecraft near or behind targets yields important science
- Atmospheric dynamics
  - Circulation
  - Vertical structure
  - Turbulence
- Atmospheric density
- Gravity field mapping
- Special high dynamics receivers are used for this in the DSN

The Goldstone Radar

- Unique for high-res ranging and imaging of planets, small-bodies
  - 500 kW X-band transmitter
  - Can be used with Arecibo and Greenbank
- Wide variety of science
  - Surfaces: images, topography, ice, physical characteristics, chemical composition
  - Dynamics: Orbits, rotations, spin axes
- Mission use
  - Landing site evaluation, emergency support, …
  - Mission science support
- NASA approved science investigators



50 Years of DSN and Science

On December 24, 1963 William Pickering established the Deep Space Network

The *Council for the Advancement of Science Writing* published a “top 50 science results list” – starting in 1957. The Deep Space Network was intimately involved with 22!

1. Satellites (1957)
5. Plate tectonics (1961)
6. The environmental movement (1962)
7. Quasars (1962)
9. Big Bang's afterglow (1964)
11. Moon landing (1969)
12. Internet (1969)
14. Medical scanners (1972)
18. Pictures from other planets (1976)
20. Farthest frontier (1977)
24. Killer asteroid (1980)
25. Cosmic inflation (1980)
31. Catching up with comets (1986)
33. Witnessing a cosmic crash (1994)
36. Alien planets (1995)
38. Big bounce on Mars (1997)
39. Dark energy (1998)
43. Age of the universe (2001)
45. Titan revealed: (2005)
46. Planets realigned (2005)
49. Tasting Martian water (2008)
50. Water on the moon (2009)

Space Loss

All else being equal, communications performance is inversely proportional to distance squared

P_R/N_0 = constant / d^2

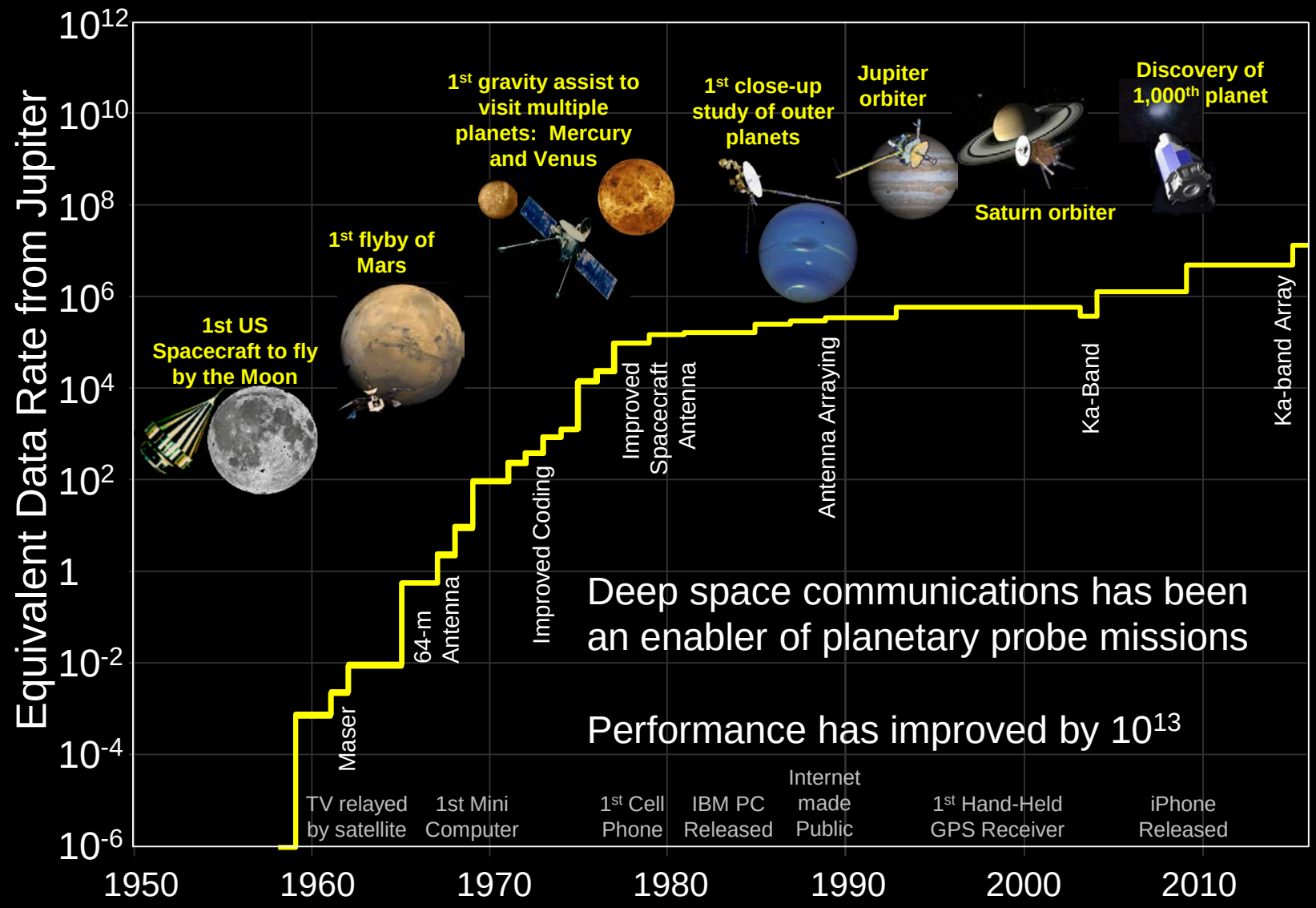
Need to overcome this problem of physics to be successful in deep space

Why Telecom is Hard

Relative Difficulty

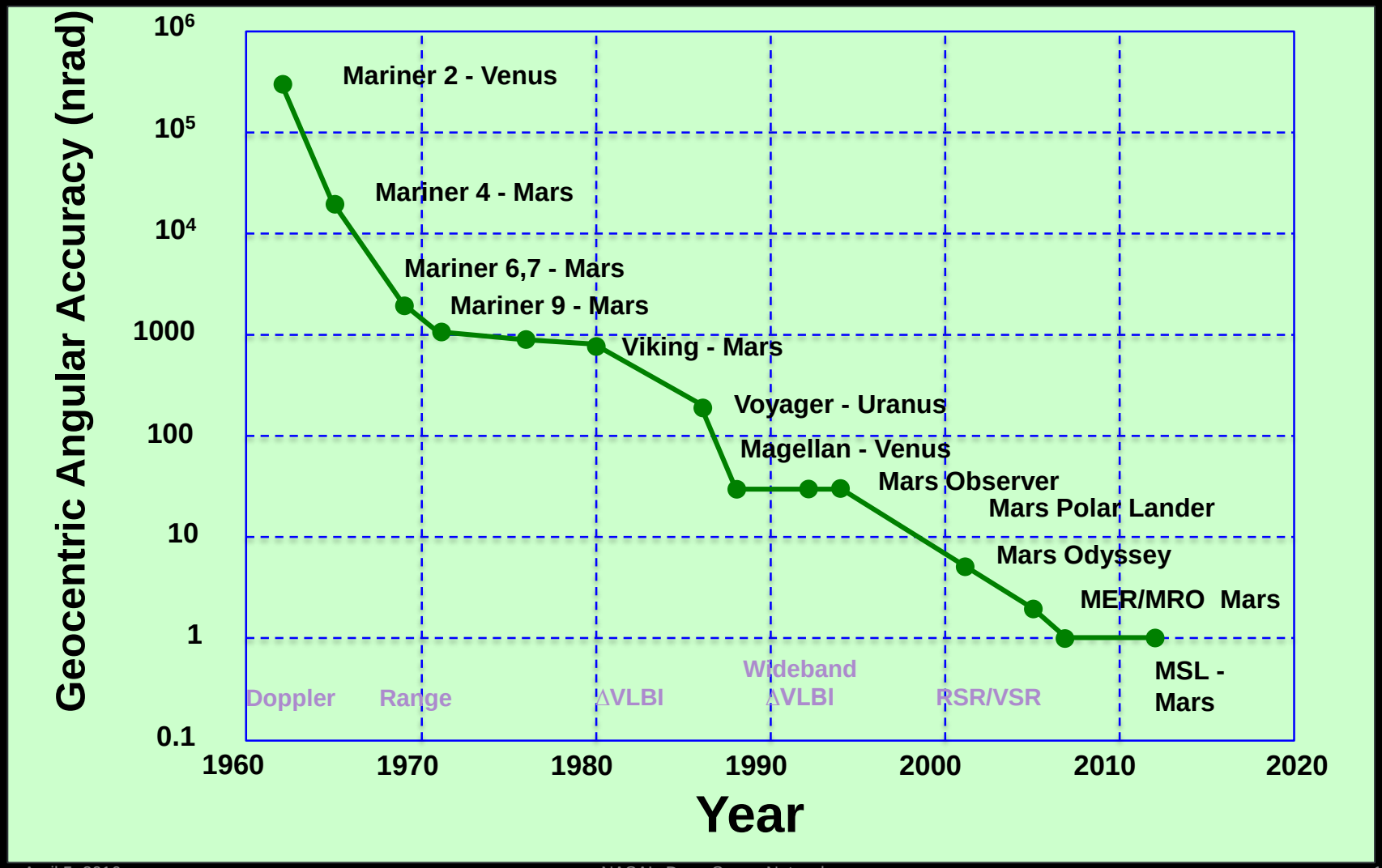
Place	*Distance*	*Difficulty*
Geo	*$4x10^4$ km*	*Baseline*
Moon	*$4x10^5$ km*	*100*
Mars	*$3x10^8$ km*	*$5.6x10^7$*
Jupiter	*$8x10^8$ km*	*$4.0x10^8$*
Pluto	*$5x10^9$ km*	*$1.6x10^{10}$*

Deep Space Communication: Trunk lines



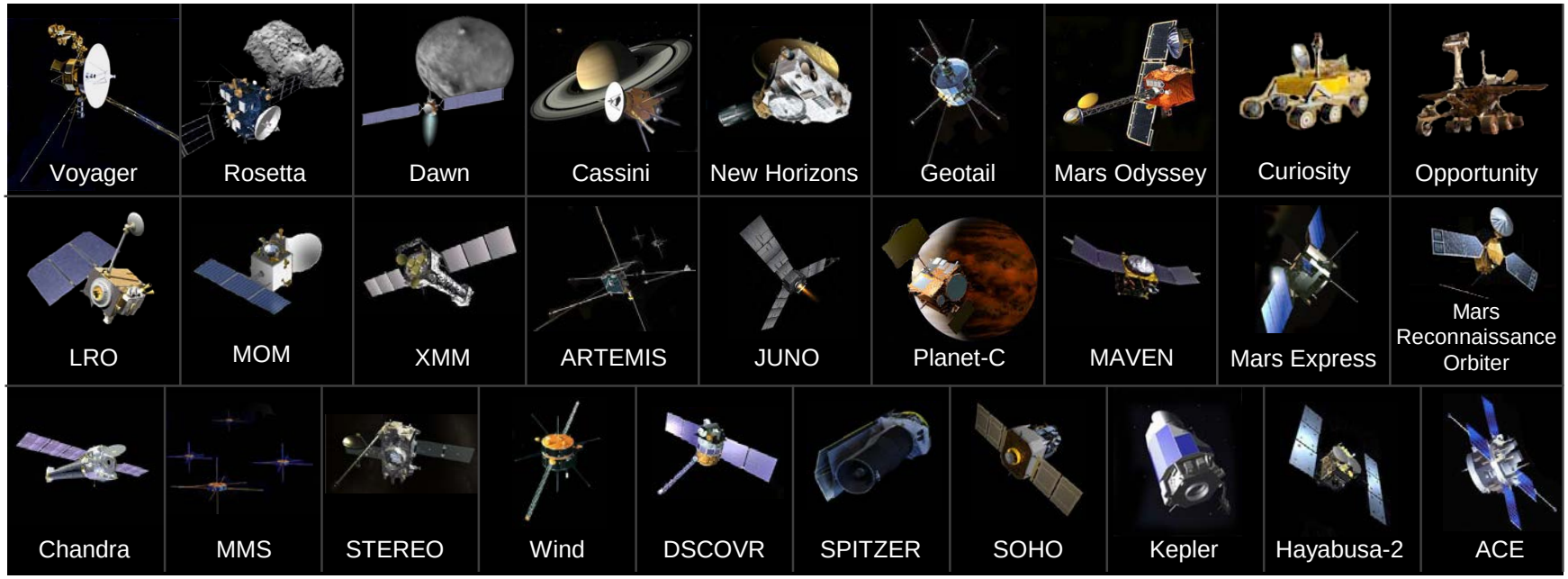
Deep Space Navigation

- Steering a probe to its destination is often a critical problem
- Measurements of the communication links provide much of the data



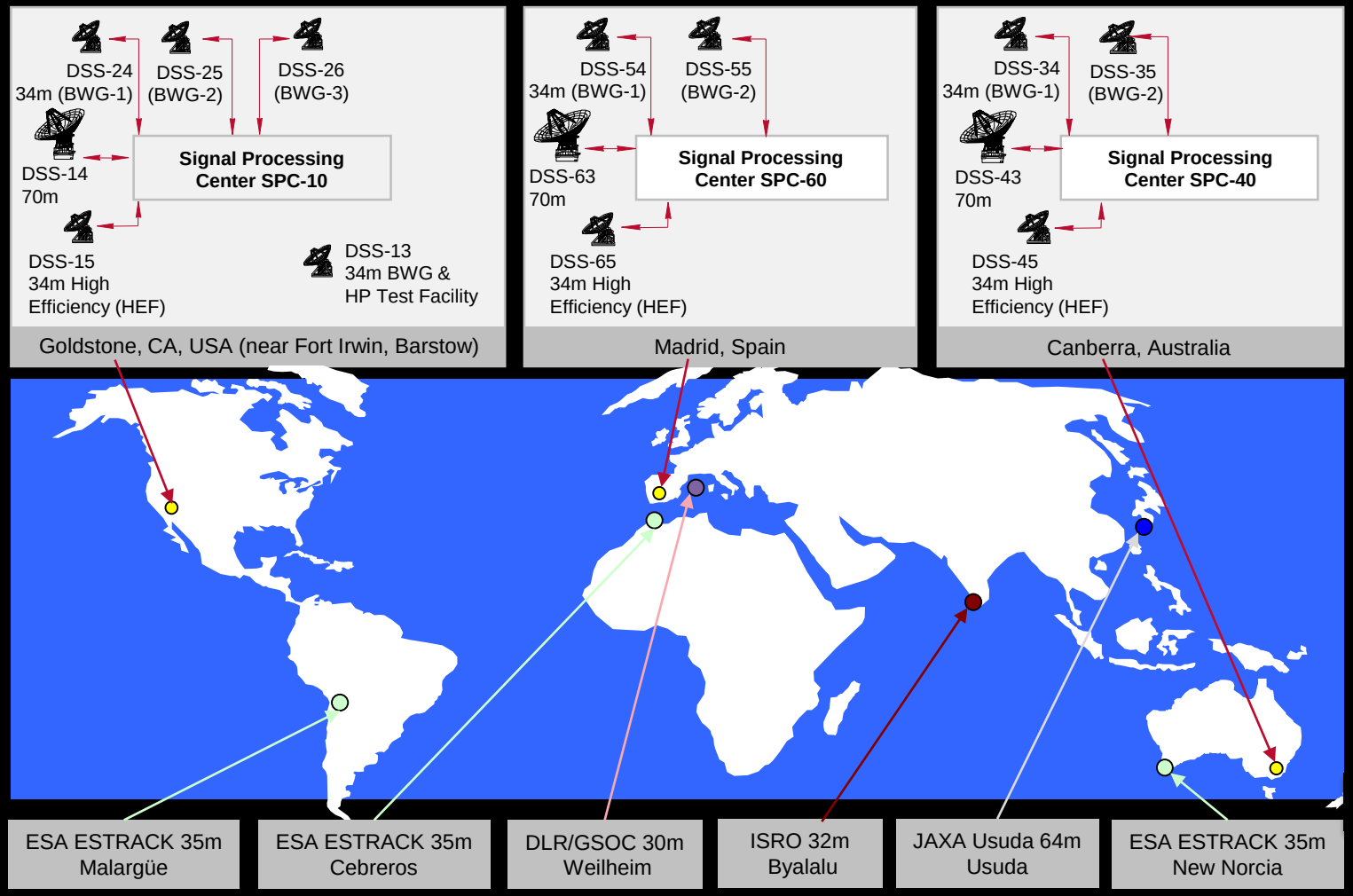
The sky is crowded

- We enable dozens of operating missions



You're not going anywhere very far away without us!

Today's Earth Stations



Plans for the DSN: Antennas

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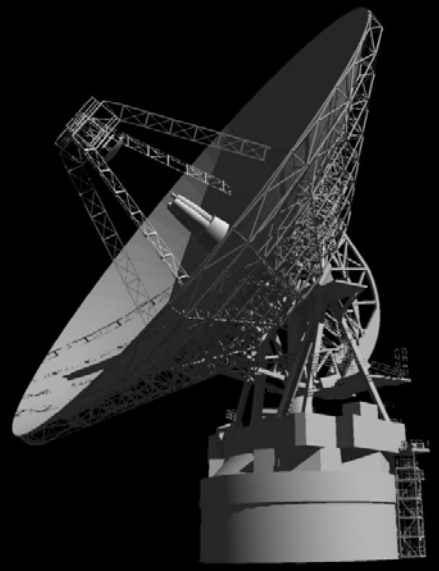


More DSN capability

More southern hemisphere coverage

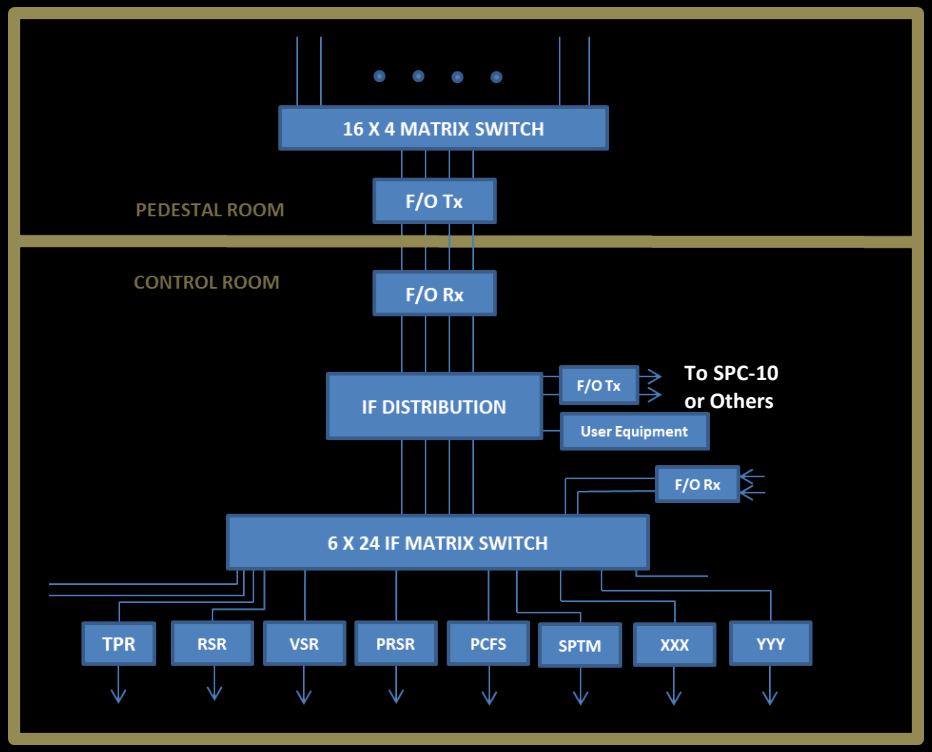
More Ka-band

No more 70m single points of failure

At all DSN locations

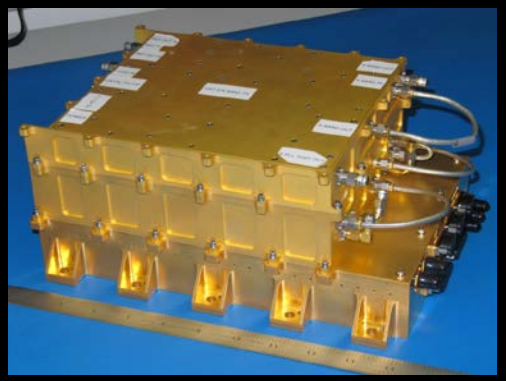
More DSN Plans

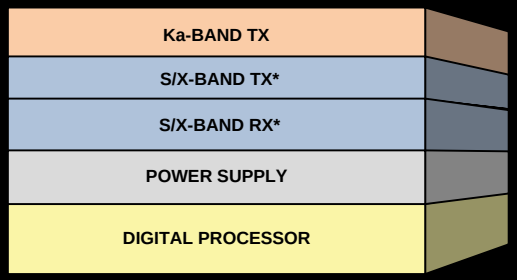
- "Common Platform" receiver
  - Software defined radio
  - Deep space and near-Earth telemetry, radio science, radar …
- Additional coding and modulation
  - LPDC coding suite
- Higher data rates
  - Data rates greater than 200 Mbps
- More frequent antenna arraying
- More tracking of multiple spacecraft in a single beam
  - Increase from today's two to four and maybe more

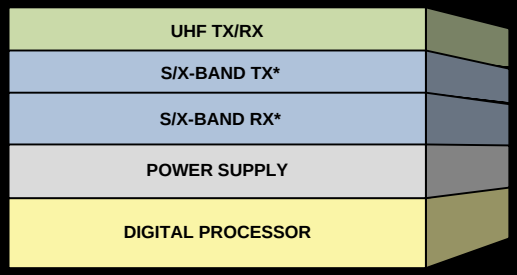


Universal Space Transponder

- Powerful, reprogrammable Software Defined Radio (SDR)
  - Enables post-launch infusion of new capabilities, upgrades & fixes
  - NASA Space Telecommunications Radio System (STRS) Standard
  - Advanced communications protocols (e.g., Prox. 1, DTN)
  - Can perform functions normally handled by spacecraft computer
- Can be multi-band (e.g., UHF/X-band & X/Ka-band)
  - Simultaneous Direct-to-Earth and Relay
- Higher bi-directional data rates
  - 7.8 bps – 20 Mbps on forward link
  - 10 bps – 300 Mbps on return link
- Frequency agility to tune to any channel in a given band
- Arbitrary modulations and pulse shaping
- Advanced radiometrics
  - Pseudo Noise ranging
  - Wider separation ranging tones improve double nav accuracy
  - Open loop recording

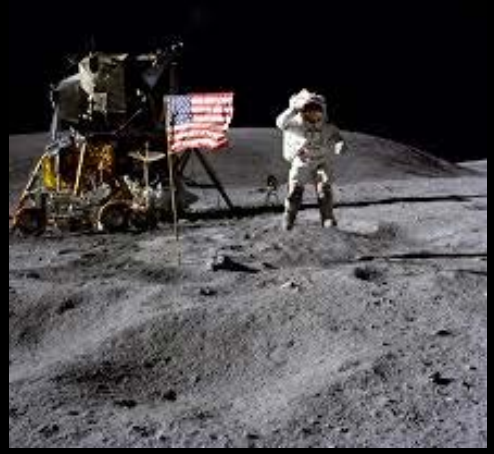






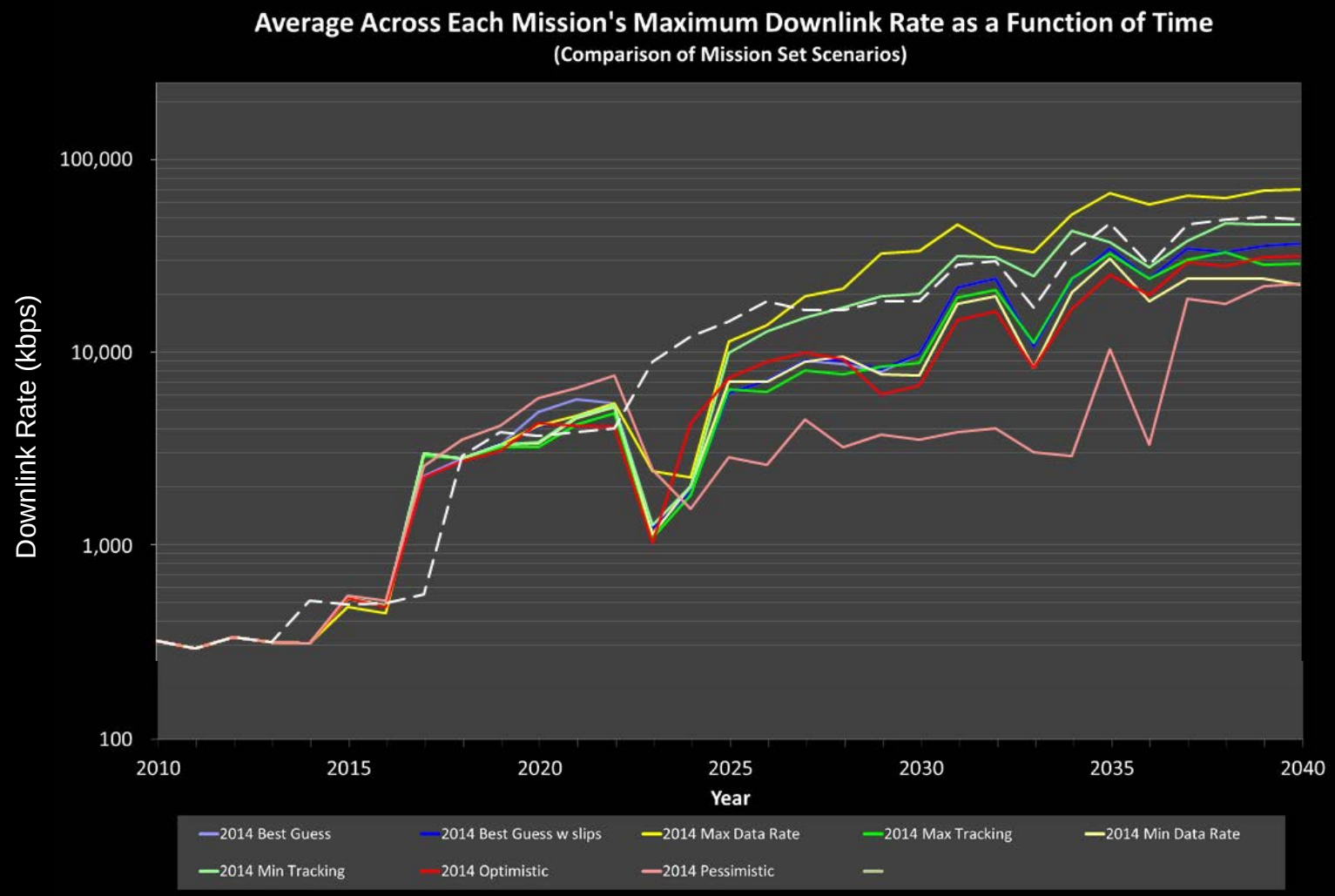
Enabling Human Spaceflight Once Again

- The DSN enabled the Apollo lunar missions in the 1960s
- Today, we are working to enable humankind's return to deep space:
  - Lunar missions
  - Asteroid missions
  - Mars missions
- Beginning with communications and navigation support to NASA's EM-1 and EM-2 Orion flights



What Will We Need for the Future?

- Analysis of likely future missions to be tracked by the DSN indicates a need for 10x improvement in data rate per decade



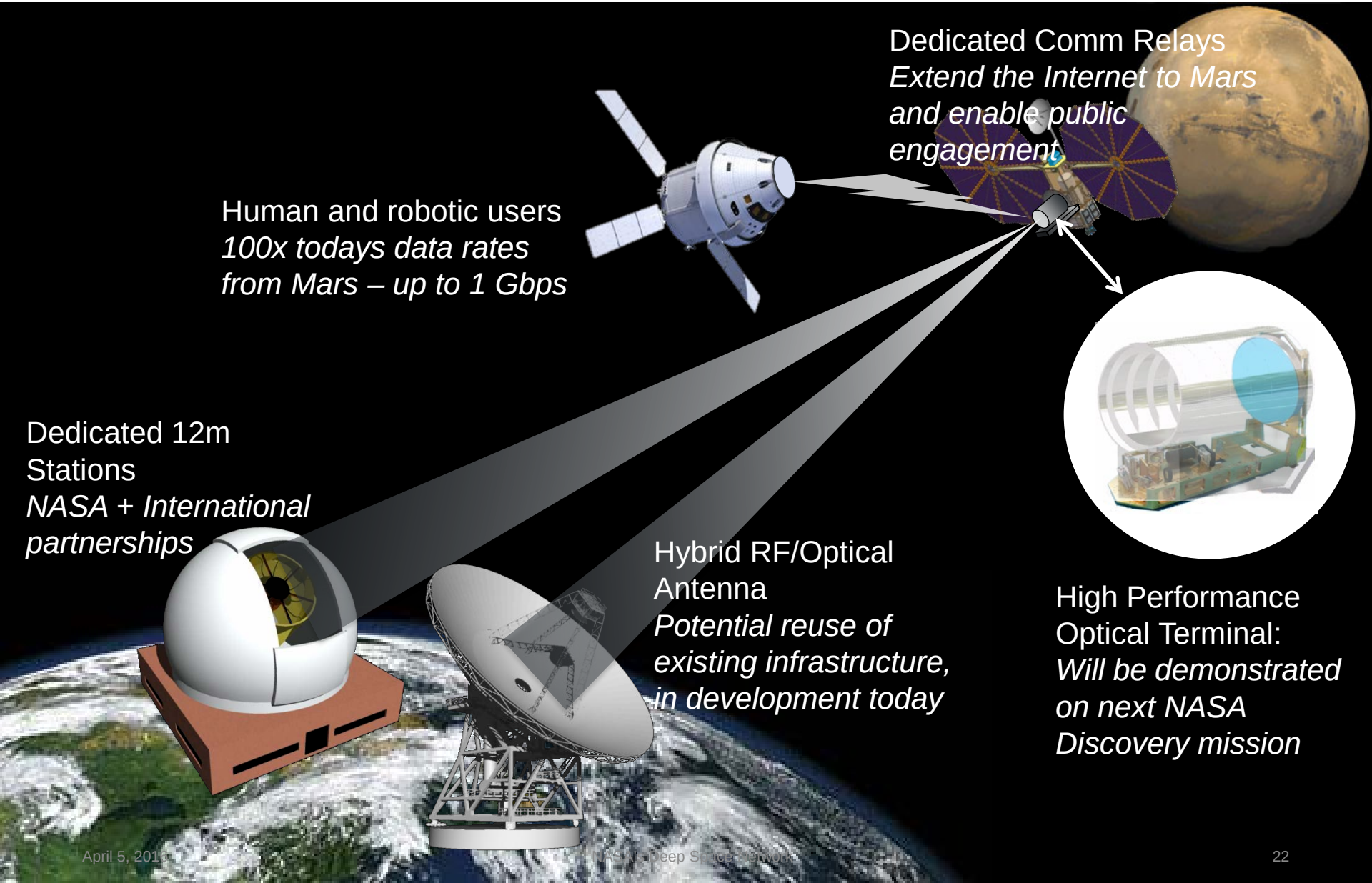
Optical Communications

- All else being equal, communication performance increases like the square of the carrier frequency
  - Due to the beam width of a signal from a fixed aperture
- We predict performance 10x Ka-band in the near term and 100x within another decade
  - For the same aperture mass, and power in space and a 12m Earth receive aperture
- There is a LOT of interest in optical communications worldwide – mostly for near-Earth applications where the big payoff is more bandwidth and less international restrictions
  - Radio spectrum is big business and very expensive to obtain
- In deep space, we will use the 10-100x advantage in various ways
  - More returned bits, smaller spacecraft, more accurate “light science” …

Deep Space Optical Communications

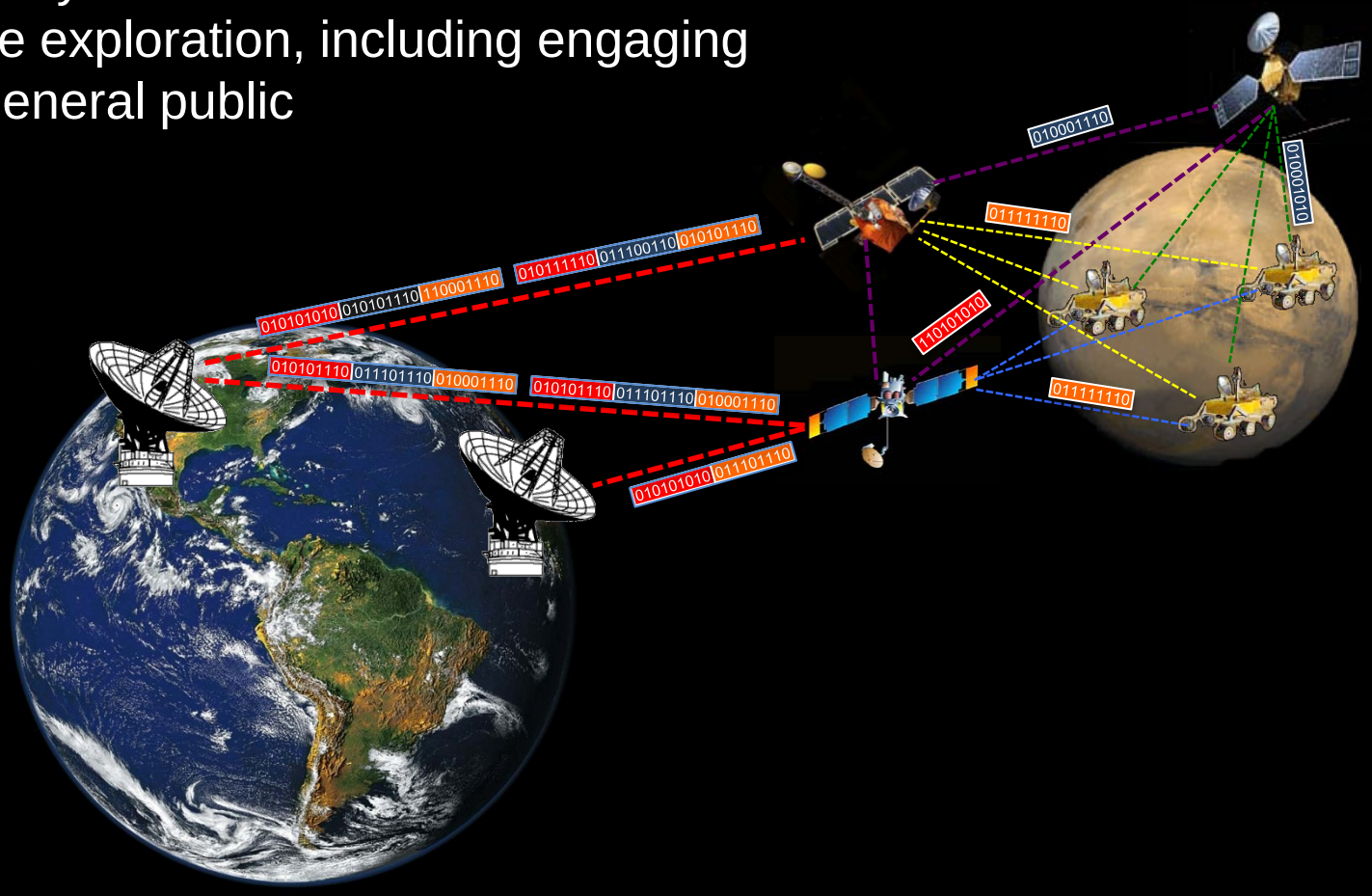
- Different from near-Earth systems
  - Individual photons matter
  - Pointing is difficult – including “point ahead”
- NASA flew the LL-built Lunar Laser Comm Demonstration (LLCD) on the Lunar Atmosphere and Dust Environment Explorer spacecraft
- Demonstrated optical communications from the Moon to Earth at rates up to 622 Mbps into a 40 cm ground receiver
  - Equivalent to ~11.5 kbps at Mars
  - …or 10.3 Mbps if we had a 12m ground station
- Also demonstrated operational diversity to mitigate weather effects, using three ground terminals

Deep Space Optical Comm (DSOC) Terminal



The DSN enables the Interplanetary Internet

Extends today's Internet across the Solar System to enable a new era in space exploration, including engaging the general public



Possible Future Performance

- With the planned capabilities discussed today, we can expect this for trunk lines:

	Distance (AU)	Today (Mbps)			2025 (Mbps)			2035 (Mbps)
DSN Configuration		34m X-band	3 x 34m X-band	34m Ka-band	4 x 34m Ka-band	4 x 34m Ka-band	Optical	Optical
Spacecraft Configuration		3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/2 LDPC code	3m antenna 180 W transmitter 1/2 LDPC code	0.3m optics 10 W transmitter PPM modulation	0.5m optics 50 W transmitter PPM modulation
Venus (Closest)	0.3	80.0	240	320	1,280	2,304	2,800	29,461
Venus (Farthest)	2.4	1.3	3.8	5	20	36	44	460
Mars (Closest)	0.6	20	60	80	320	576	700	7,365
Mars (Farthest)	2.6	1.1	3.2	4.26	17	31	37	392
Jupiter	5.4	0.247	0.741	0.99	3.95	7.11	8.6	91
Saturn	10.1	0.071	0.212	0.28	1.13	2.03	2.5	26
Uranus	19	0.020	0.060	0.08	0.32	0.57	0.70	7.3
Neptune	30.3	0.008	0.024	0.03	0.13	0.23	0.27	2.9

Note: these rates are indicated by physics and may be lessened due to systems limitations

- With planned in-situ links, there should be no problem achieving this performance all the way from the probe to Earth

Spinoffs & Benefits to Society

Audio CDs, GPS & Cell Phones

Pseudo-noise & Error-Correcting codes had first practical use in the DSN. They are fundamental enabli technology for these consumer devices

Plate Tectonics

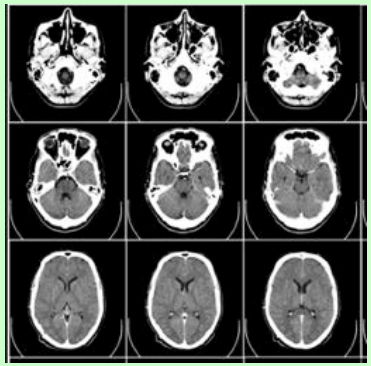
Before GPS, Simultaneous observations of radio sources from DSN antennas on different continents provided the best evidence for plate movement

Fiber-Optic Frequency Distribution

Developed by the DSN to synchronize antennas, this forms the basis for many of today's TV systems

CT scans

The mathematics for navigation using multiple DSN antennas led to medical scanners, revolutionizing the medical industry



Phase-coherent Doppler

DSN navigation and radar techniques contributed to development of additional sensor systems

Summary

- The DSN has served us well for more than 50 years
  - Enabled much of Earth's exploration of the solar system and beyond
  - Provided revolutionary technology for the general public
- The DSN is alive and well today, continuing its mission
  - Enables ~35 space missions in any given month
  - Now serves as a member of global community of deep space providers including NASA, ESA, JAXA, … and growing
- The future looks very bright for deep space communications and navigation
  - The DSN will enable the return of astronauts beyond GEO – and then on to the other planets