Deep Space Communications

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Jet Propulsion Laboratory
California Institute of Technology

What is NASA?

National **A**eronautics and **S**pace **A**dministration

What is JPL?

Jet **P**ropulsion **L**aboratory

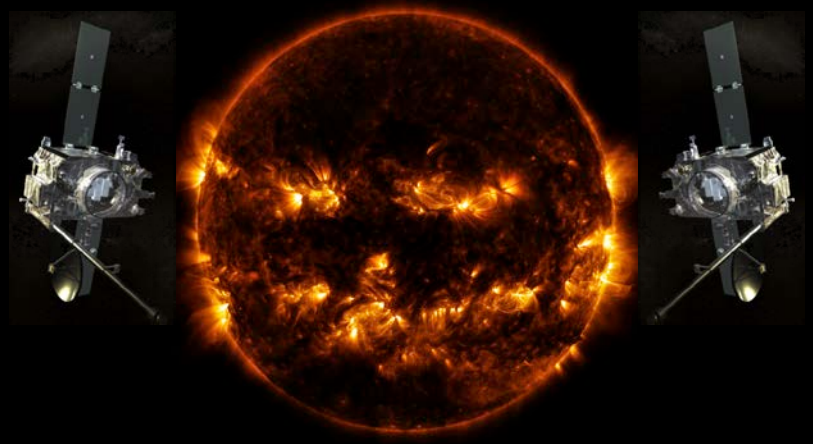
One of 10 NASA centers – Robotic exploration of the Universe

I am Les Deutsch

- Education
  - BS Mathematics, Caltech 1976
  - MS Mathematics, Caltech 1977
  - PhD Mathematics, Caltech 1980
- Career
  - Inventor, Deutsch Research Laboratories
  - Researcher, JPL, NASA
  - Technology Manager, JPL, NASA
- Currently
  - Leads communications and navigation for NASA's deep space missions
  - Steering committee, Keck Institute for Space Science
  - Caltech organist

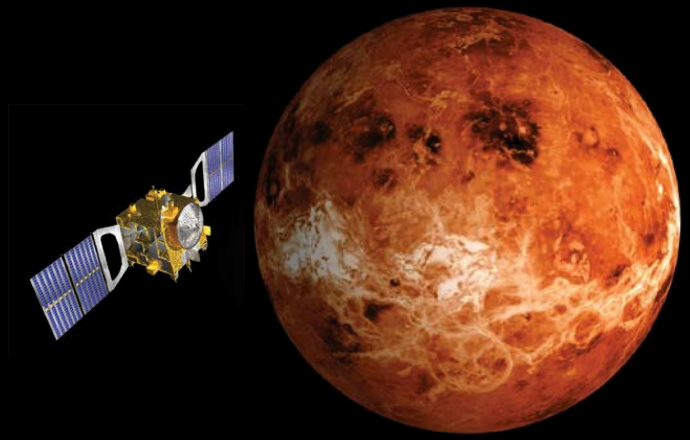
- Message: School is important – especially math!

Sun
STEREO

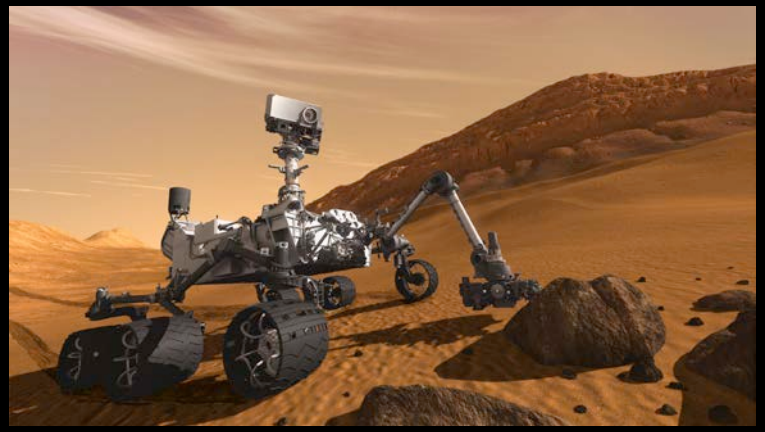


Mercury
MESSENGER 2011 to 2015

Venus
ESA's Venus Express spacecraft



Mars
Orbiters, landers, and rovers

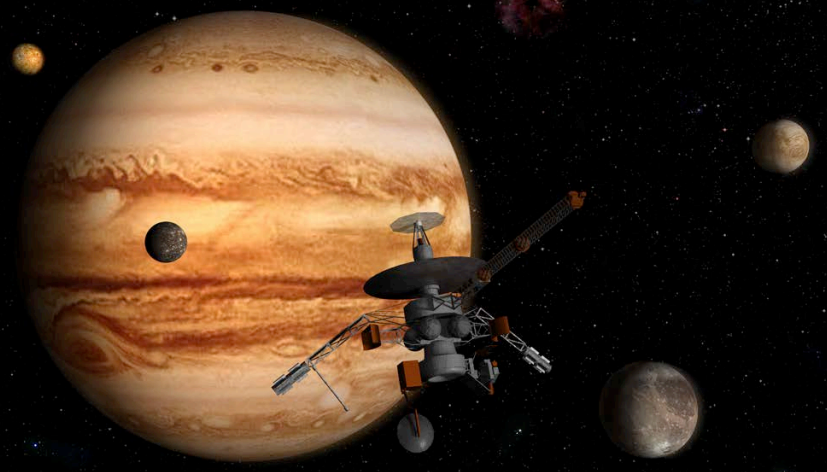


Asteroids

Dawn spacecraft, Solar System Radar

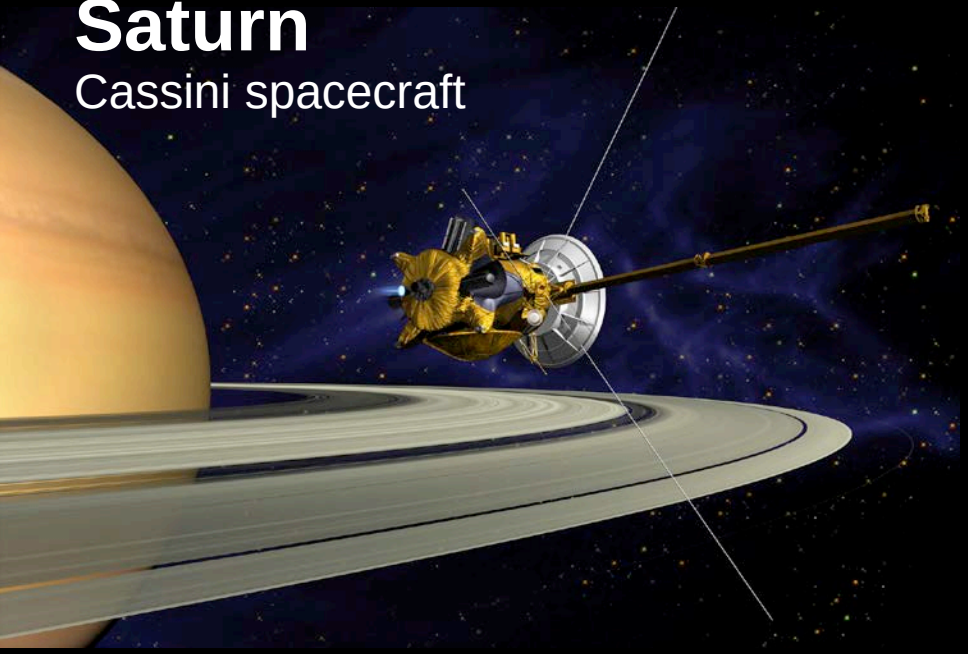
Jupiter

Galileo spacecraft – Juno on the way



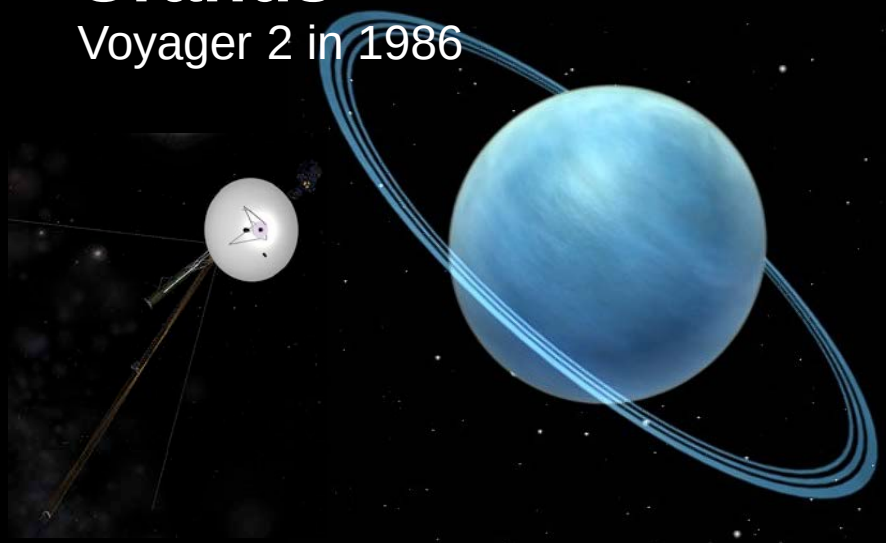
Saturn

Cassini spacecraft



Uranus

Voyager 2 in 1986



Neptune

Voyager 2 – in 1989

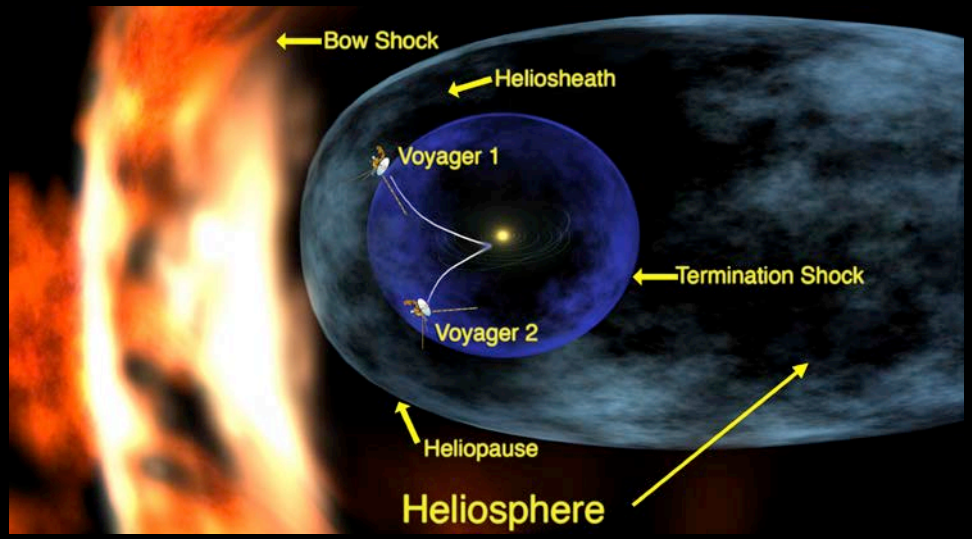
Pluto

New Horizons spacecraft

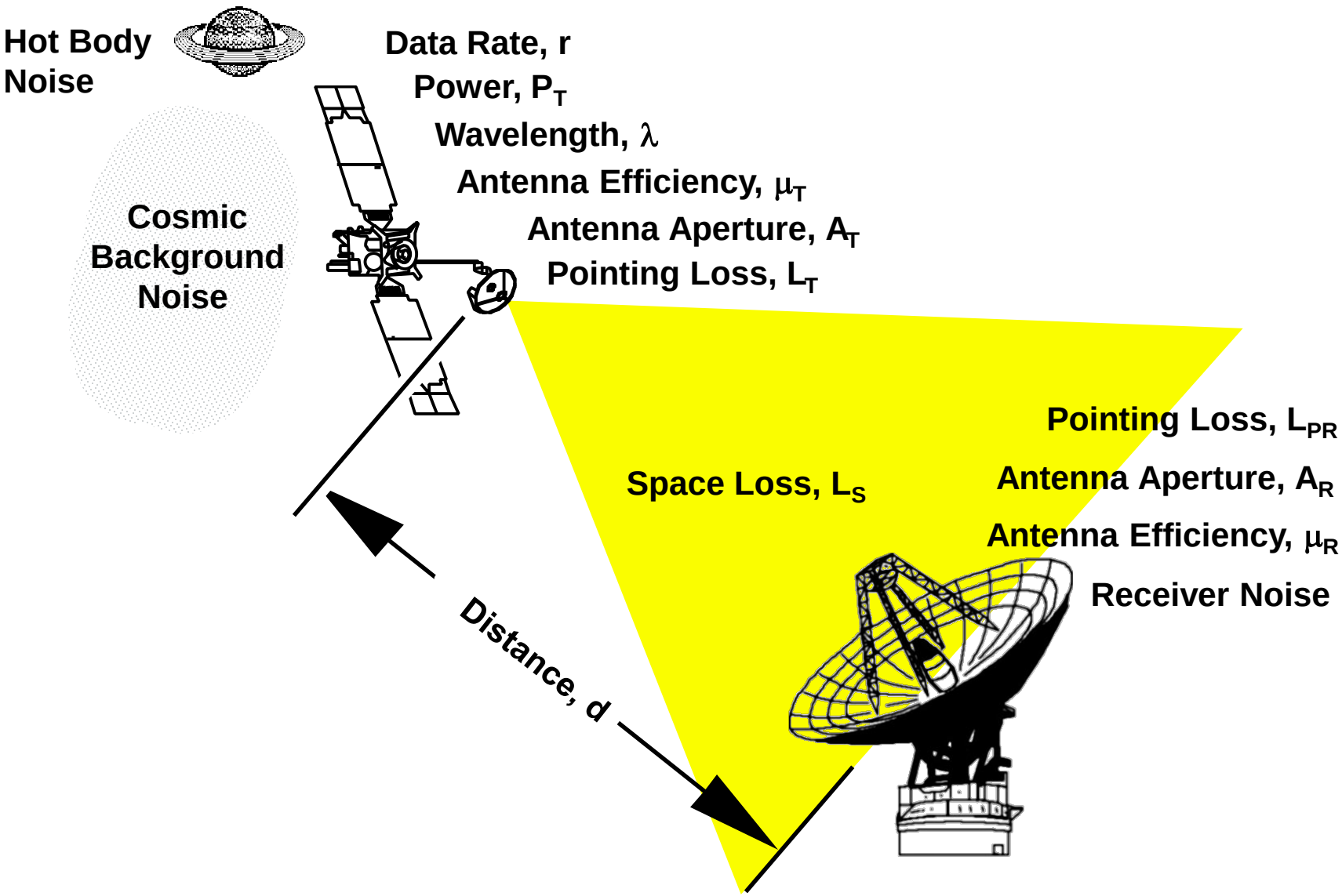
Comets

ESA's Rosetta spacecraft

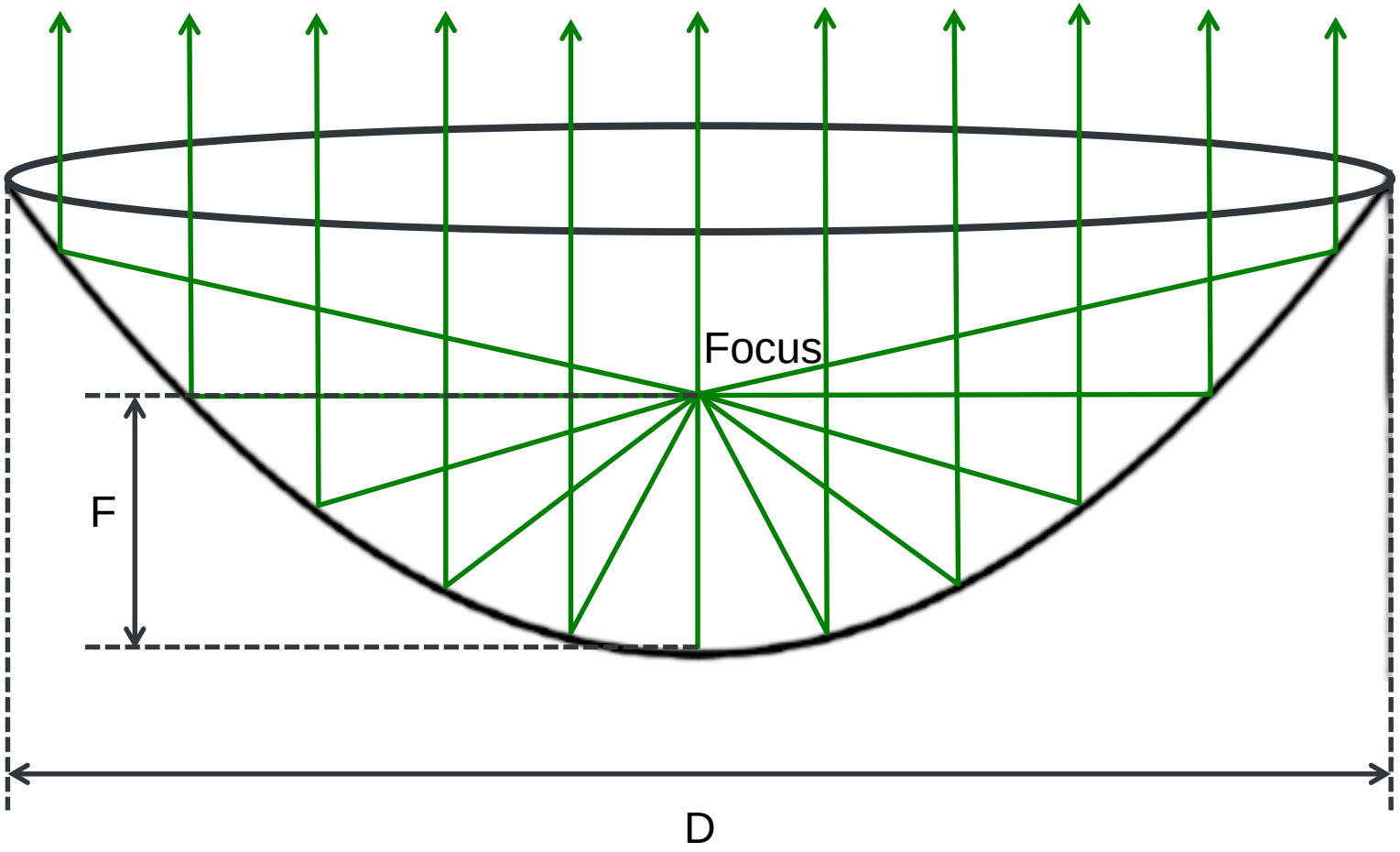
Interstellar Space



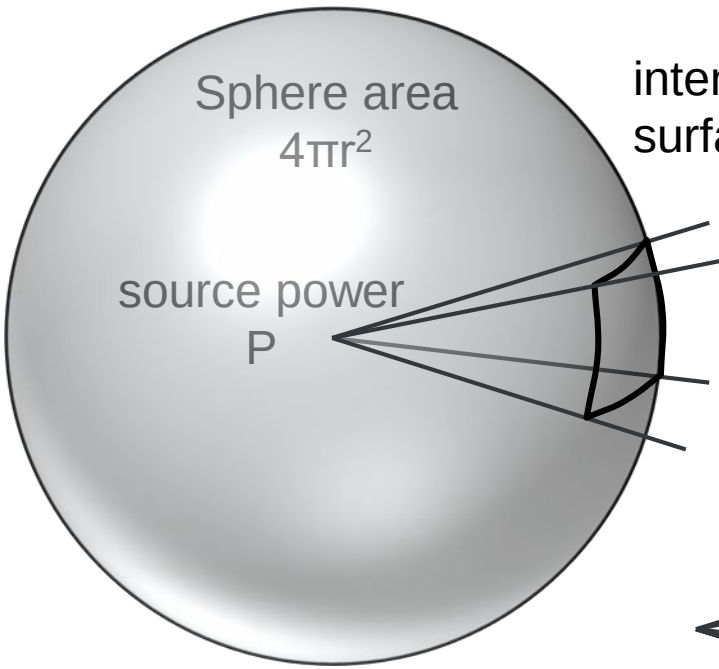
Deep Space Link Parameters



Parabolic Antennas

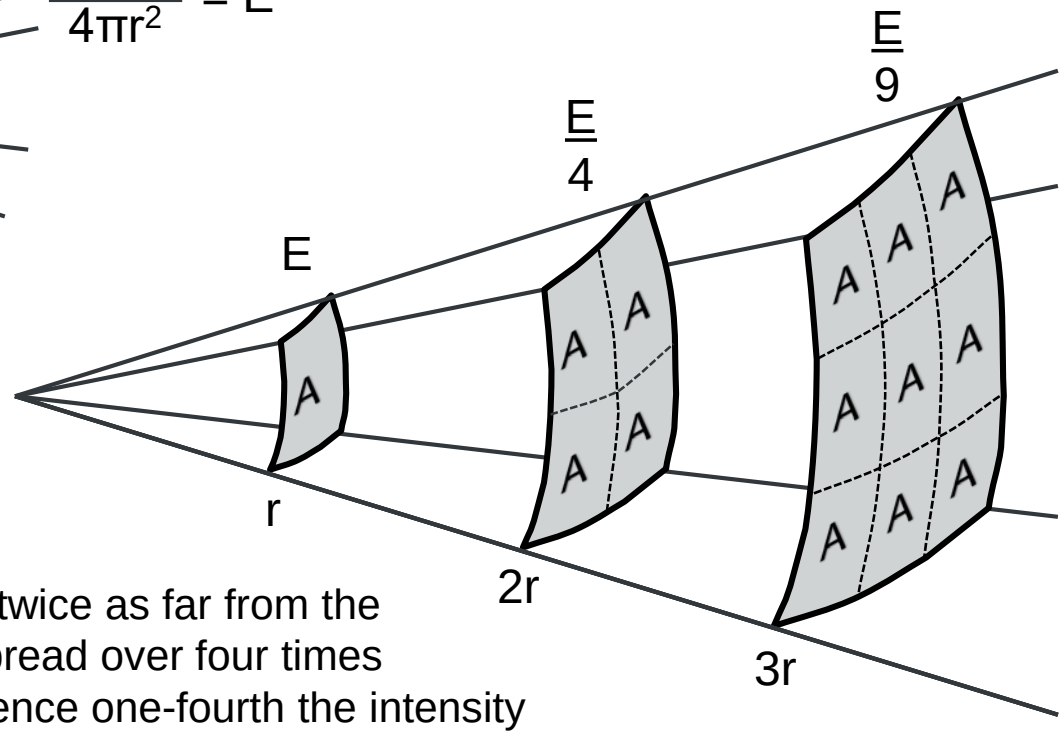


Inverse Square Loss



intensity at
surface of sphere

$$\frac{P}{4\pi r^2} = E$$



The energy twice as far from the
Source is spread over four times
The area, hence one-fourth the intensity

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

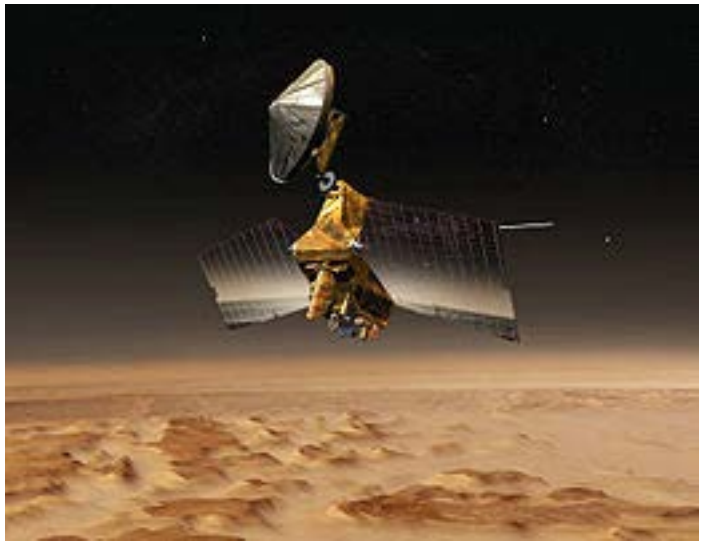
Relative Difficulty

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*	*$1.6x10^{10}$*

History of Spacecraft Transmitter Power

1964, 10W Mariner 4

1980, 20W Viking



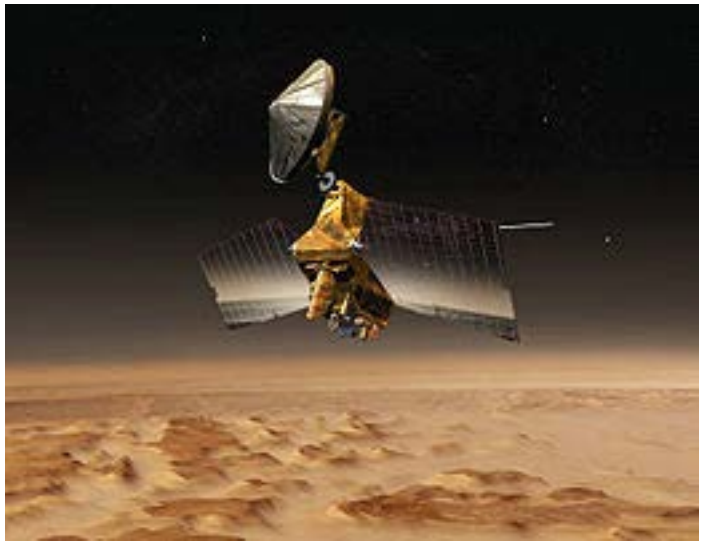
2005, 100W Mars Reconnaissance Orbiter

History of Spacecraft Antennas

1964, 0.12m Mariner 4

1966, 1m Mariner 6

1980, 1.5m Viking



2005, 3m Mars Reconnaissance Orbiter

History of Ground Antennas

1958, 26m Station

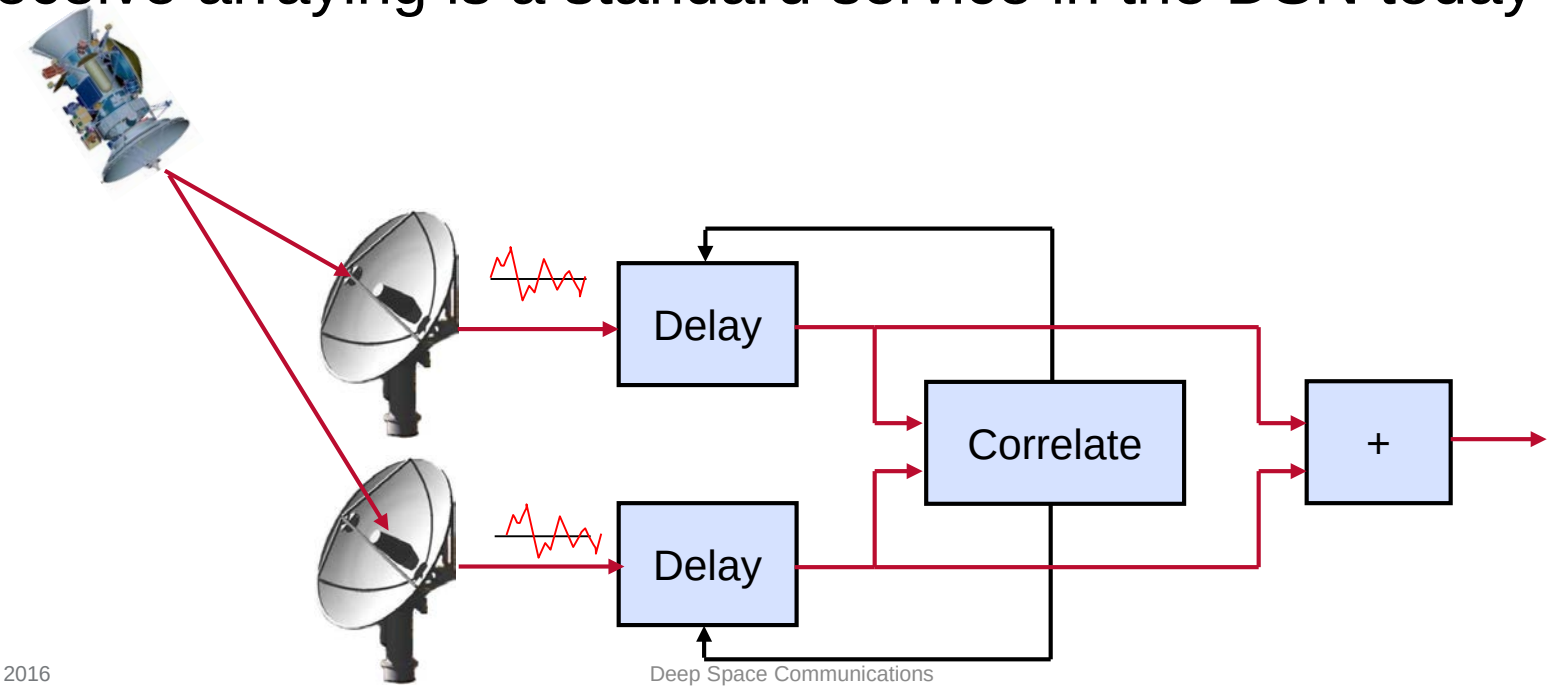
1966, 64m Station

1979, 34m Station

1988, 70m Station
(converted from prior 64 antennas)

Antenna Arraying

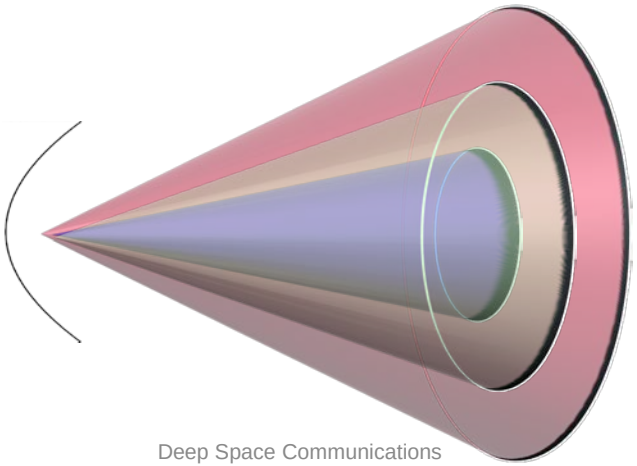
- By carefully aligning and adding the signals from multiple antennas, a performance approaching that of the sum of the apertures is achieved
- Used to help “save” the Galileo mission to Jupiter when its deployable antenna failed to open
- Receive arraying is a standard service in the DSN today



Higher Frequency is Good

$$P_R/N_0 = \text{constant}/\lambda^2$$

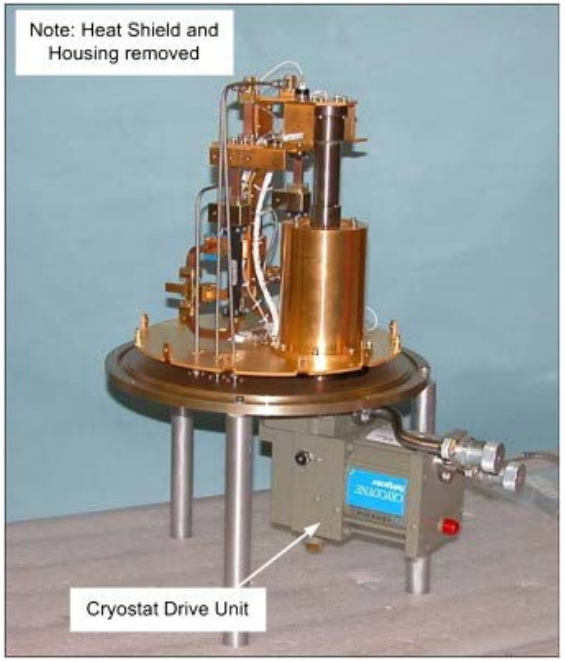
- The first deep space missions transmitted at 960 MHz
- 2.2 GHz (S-band) became standard in 1969
- 8.4 GHz (X-band) became prevalent in the early 1970s
- 32 GHz (Ka-band) is now becoming the standard
- Optical communications is currently in demonstration phase and will become operational in the next decade



Lowering the System Noise

$$P_R/N_0 = \text{constant}/T$$

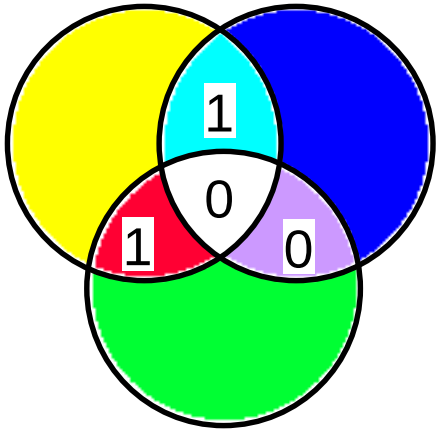
- Some elements to T cannot be controlled
- We concentrate on the contributions of spacecraft and DSN electronics to T
- We carefully avoid RFI
  - Deep space research has its own spectrum assignments from the ITU
- DSN detectors use the best low noise amplifiers we can build or buy
  - Hydrogen masers or HEMTs
  - Physical temperature is ~12 K



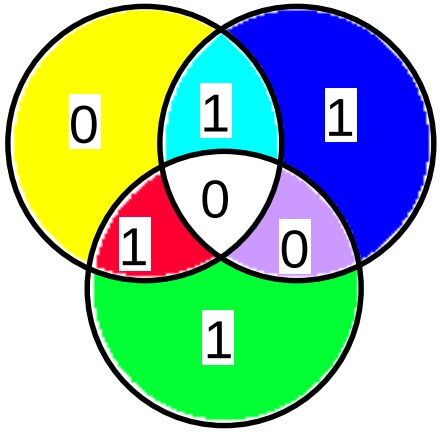
Ka-band (32 GHz) low noise amplifier

Using Codes to Improve Performance

An example of coding: the (7, 4) Hamming code

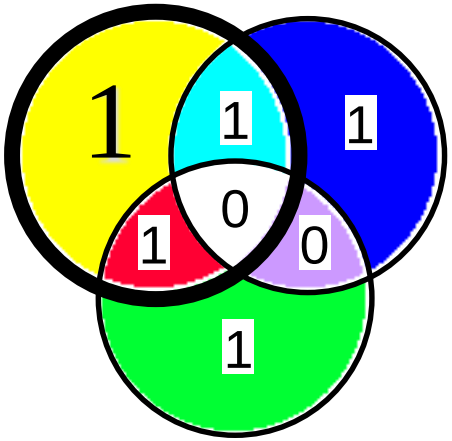


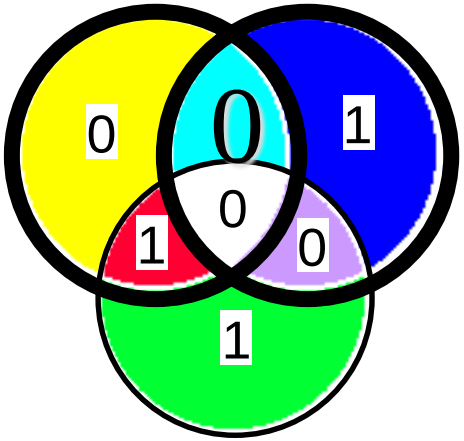
Place 4 information bits in the intersections of the Venn diagram



Fill in the diagram so that the circles have an even number of 1's

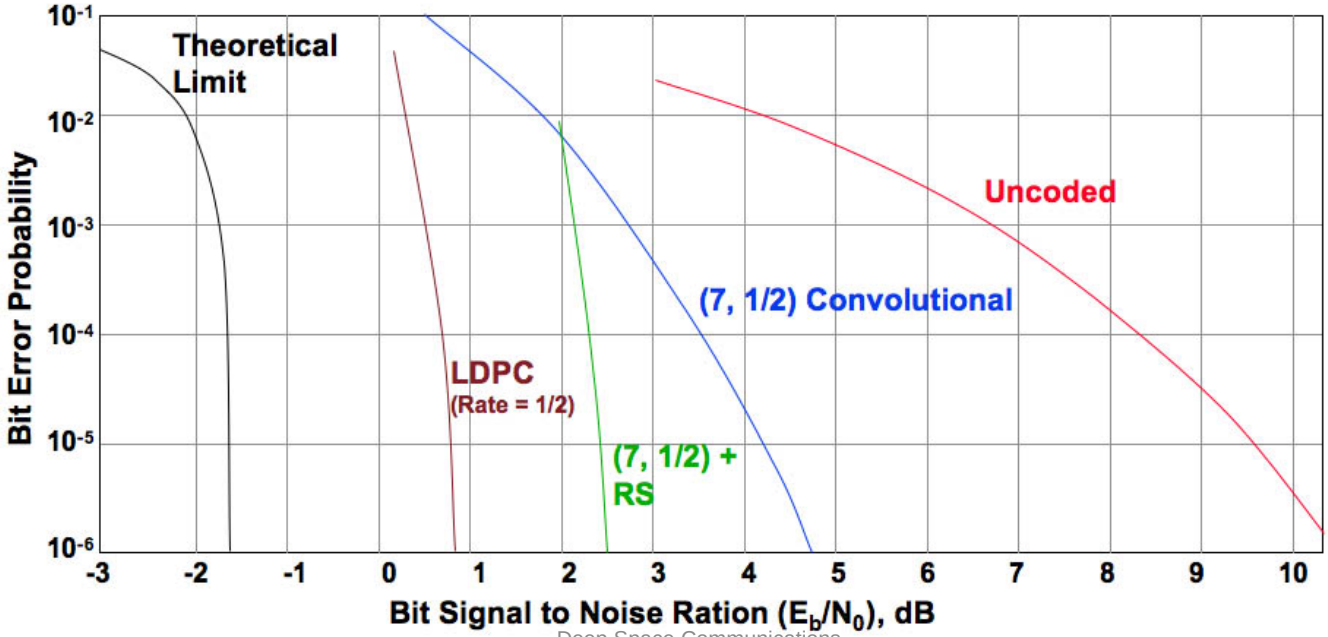
If a single error occurs, it can be corrected by locating the circles with an odd number of 1's and changing the bit in their intersection





Error-Correcting Codes

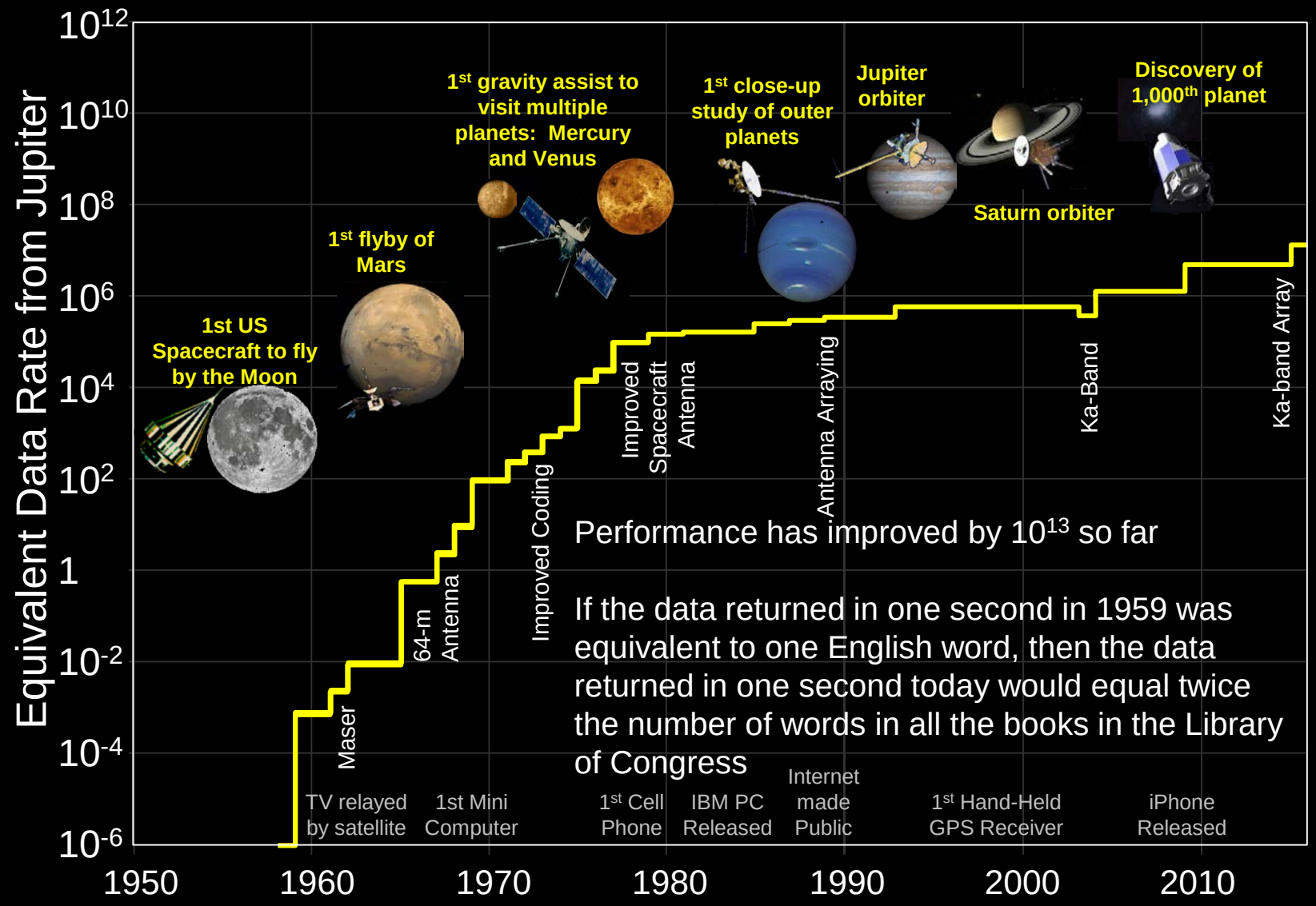
- Controlling redundancy in the data stream can result in the ability to correct errors in reception
- Shannon theory showed that it is “easy” to come out ahead – which is a very non-intuitive result: it is better, and even easy, in most cases to add bits to the data stream without adding information!



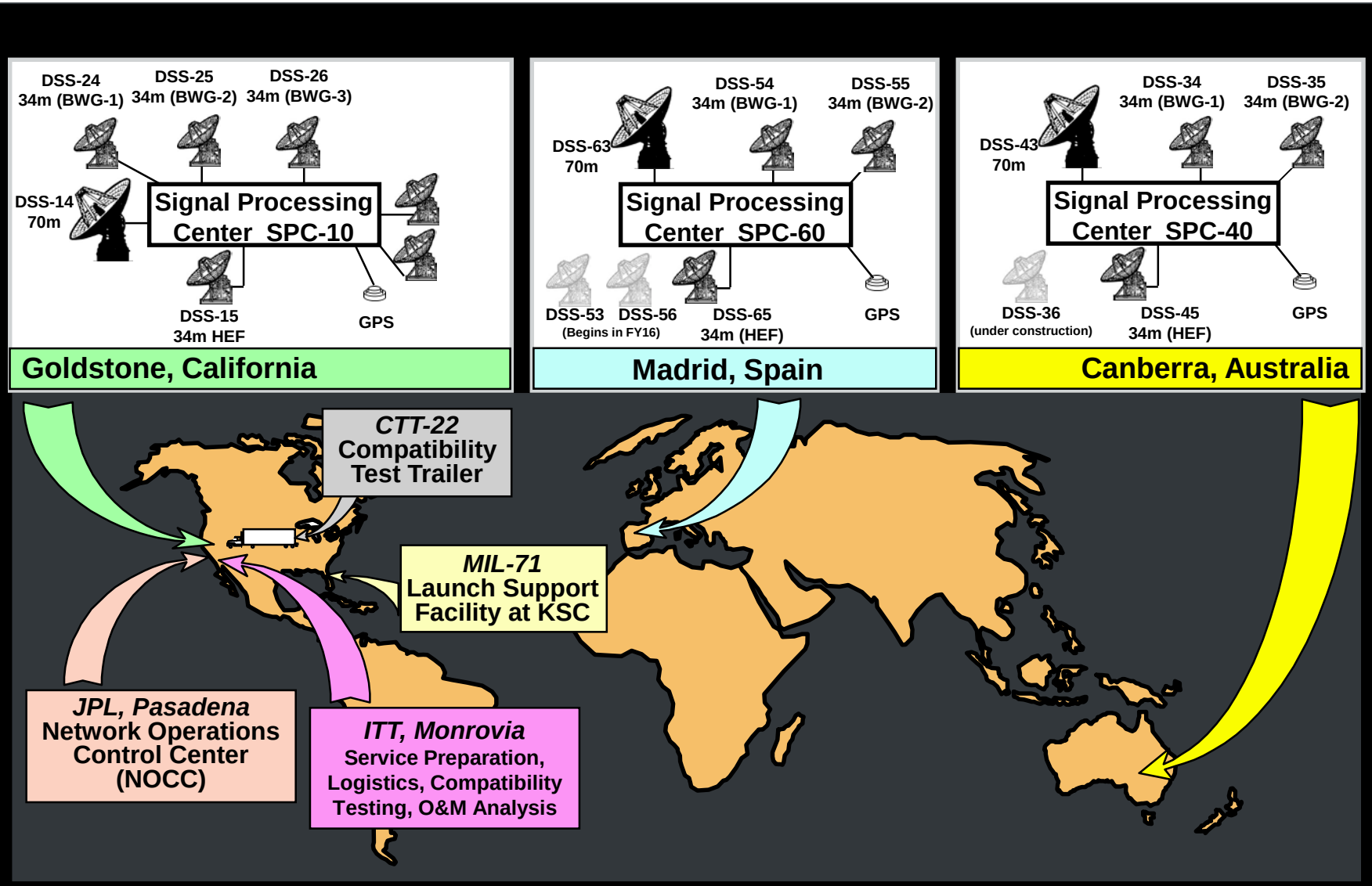
Being stingy with Spacecraft bits

- Data compression
  - “Lossless” image compression has been used since Voyager
  - Today, more advanced algorithms can reduce transmitted data by more than a factor of 10 without detectable losses in fidelity
  - Larger compression ratios are used for less sensitive data
- Onboard processing
  - Advances in spacecraft computers have allowed preprocessing of science data onboard, resulting in fewer bits transmitted to Earth
- Autonomous operations
  - If Earth-based teams can be removed from decision loops, the associated data need not be moved to the Earth at all
  - Some of or modern spacecraft make major decisions autonomously: navigation, mobility, targeted science observations

Continually Enabling Missions

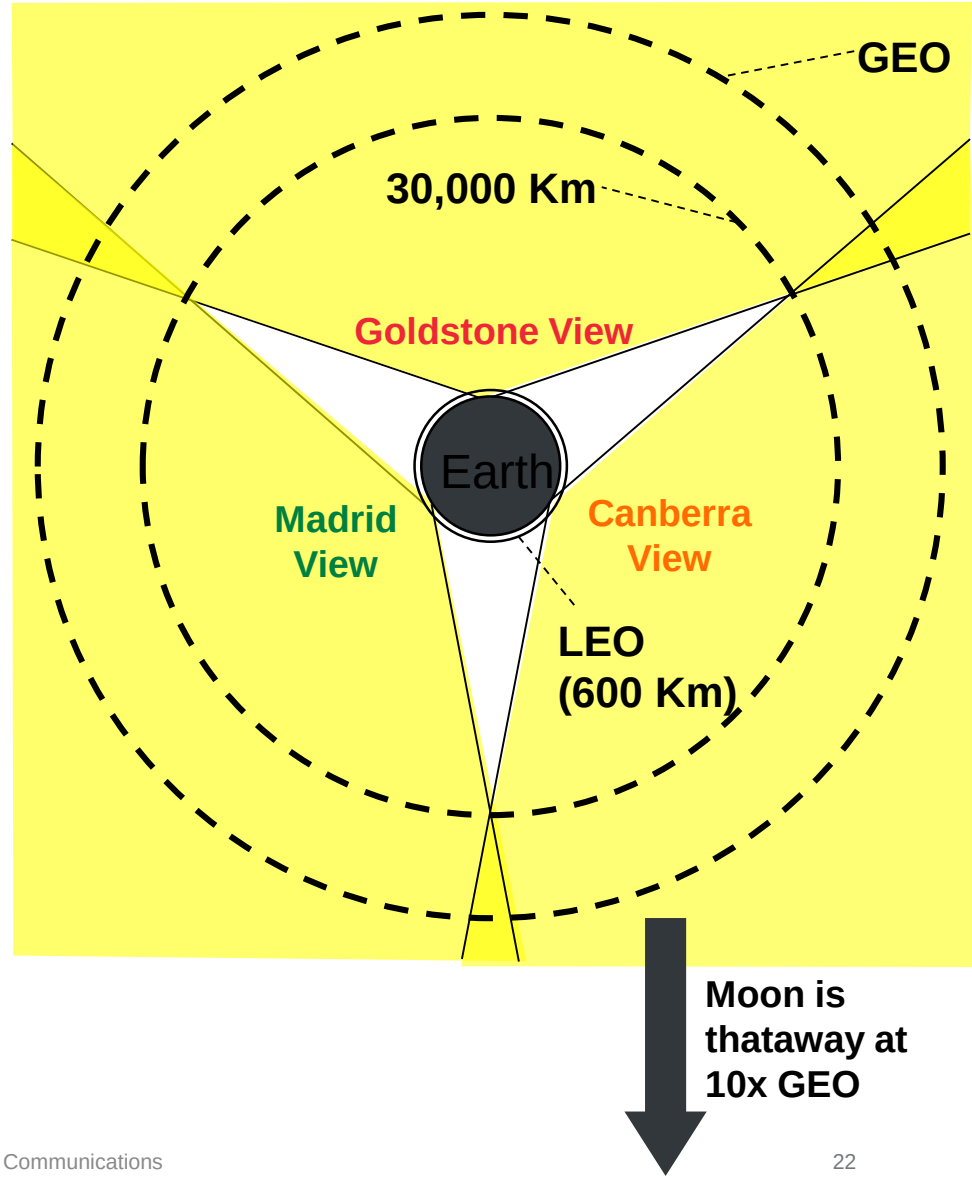


DSN Facilities



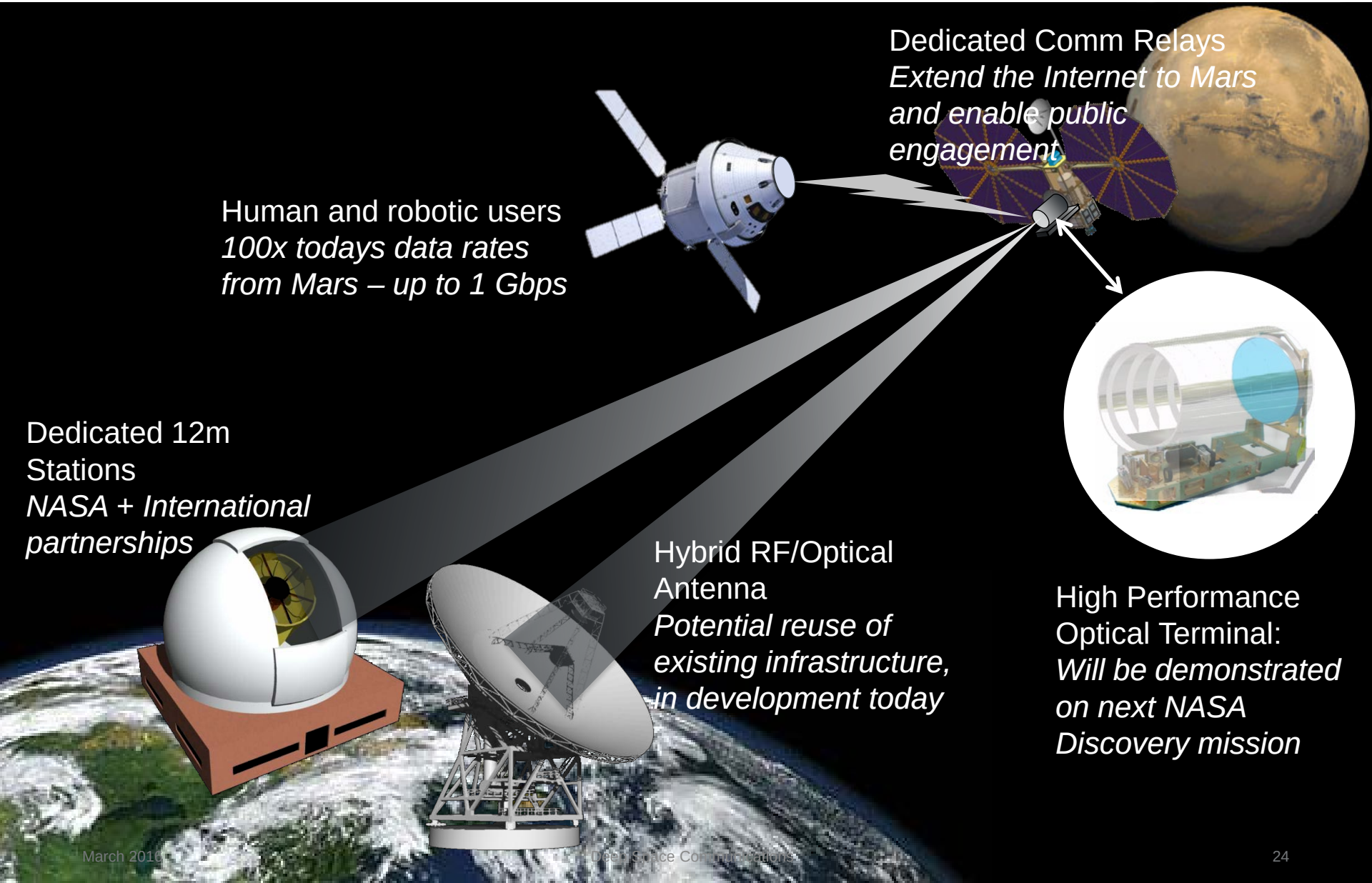
DSN Sites

- 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

Deep Space Optical Comm (DSOC) Terminal



Future Challenges for the DSN

- Space mission communication needs follow a “Moore’s Law” requiring ~factor of 10 improvement per decade
- Human spaceflight will venture beyond low Earth orbit into deep space
  - Data rates will have to be much larger to support both the needs of the astronauts and the desires of the public
- Deep space optical communication will come into its own in the next couple of decades
- The DSN will evolve to meet these challenges and continue to enable space missions for at least the next 50 years

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

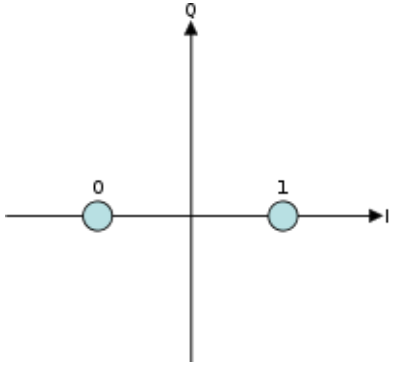
DARE MIGHTY THINGS

Far better it is to dare mighty things, to win glorious triumphs even though checkered by failure, than to rank with those timid spirits who neither enjoy nor suffer much because they live in the gray twilight that knows neither victory nor defeat.

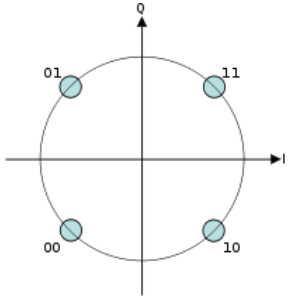
Backup

Modulation – Optimizing P

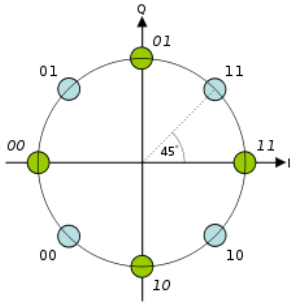
- The way in which data is modulated onto a carrier plays a big part in communications performance
- Consider these standard signaling sets



Binary Phase Shift Keying (BPSK)



Quadrature Phase Shift Keying (QPSK)



Eight Phase Shift Keying (8PSK)

- BPSK has the best performance because the distance between adjacent signals is greatest for the same power

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

CT scans

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

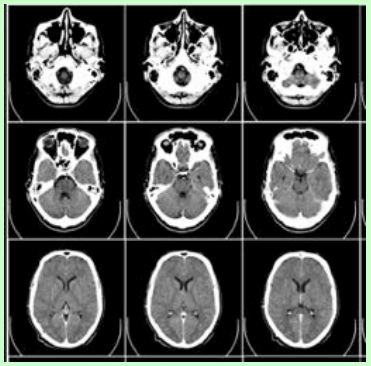


Plate Tectonics

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

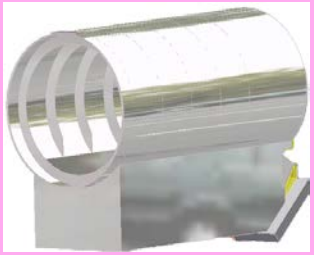
Fiber-Optic Frequency Distribution

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

Phase-coherent Doppler

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

Future: Optical Comm



The systems being developed by the DSN today will help fuel a $B industry in the US

Radio Science

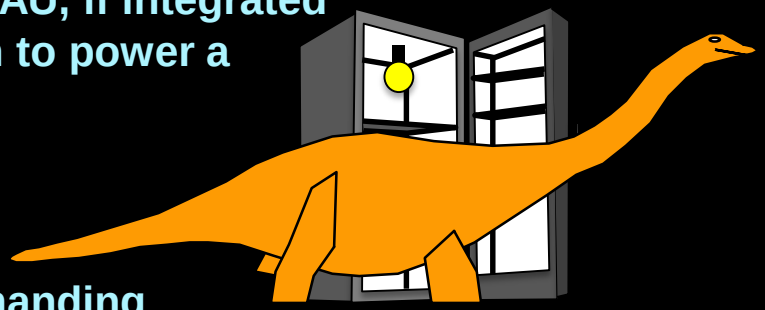
- Tracking spacecraft near or behind targets yields important science
- Atmospheric dynamics
  - Circulation
  - Vertical structure
  - Turbulence
- Atmospheric density
- Gravity field mapping
- Special high dynamics receivers are used for this in the DSN

Some Amazing DSN Facts

Received Signal Sensitivity:

The received energy from Voyager at 100 AU, if integrated for 10 trillion years, would be just enough to power a refrigerator light bulb for one second!

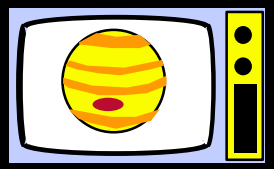
Received power = 6.3×10^{-19} W



Command Power:

The DSN puts out enough power in commanding Voyager that it could easily provide high quality commercial TV at Jupiter!

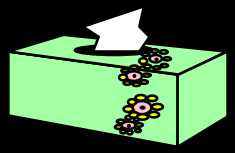
Transmitted power = 400 kW



Dynamic Range of the DSN:

The ratio of the received signal power to the DSN transmitting power is like comparing the thickness of a sheet of tissue paper to the entire Earth!

Ratio = 10^{27}



Reference Clock Stabilities:

The clocks used in the DSN are so stable that they would drift only about 5 minutes if operated over the age of the universe!

1 part in 10^{15}