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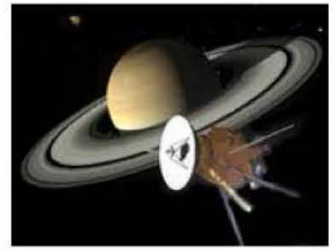
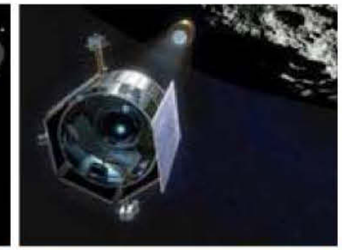


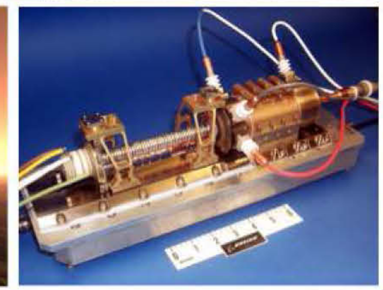


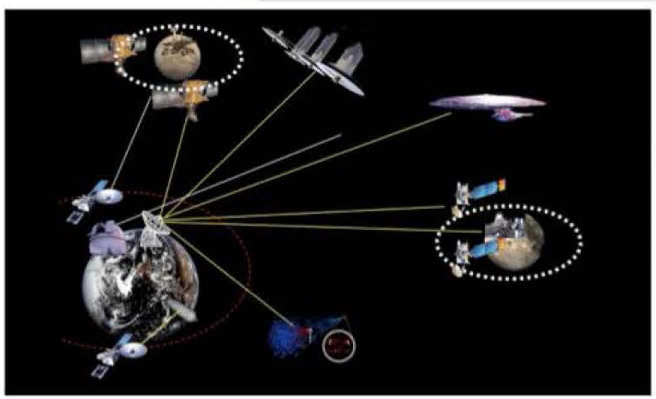
Improving by a Factor of 10^{16}

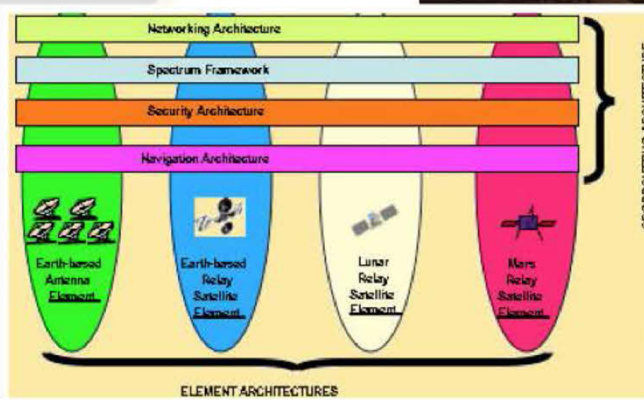
A History of Pushing All the Boundaries in Deep Space Communications

Dr. Les Deutsch
Interplanetary Network Chief Technologist
Jet Propulsion Laboratory
California Institute of Technology

June 28, 2012







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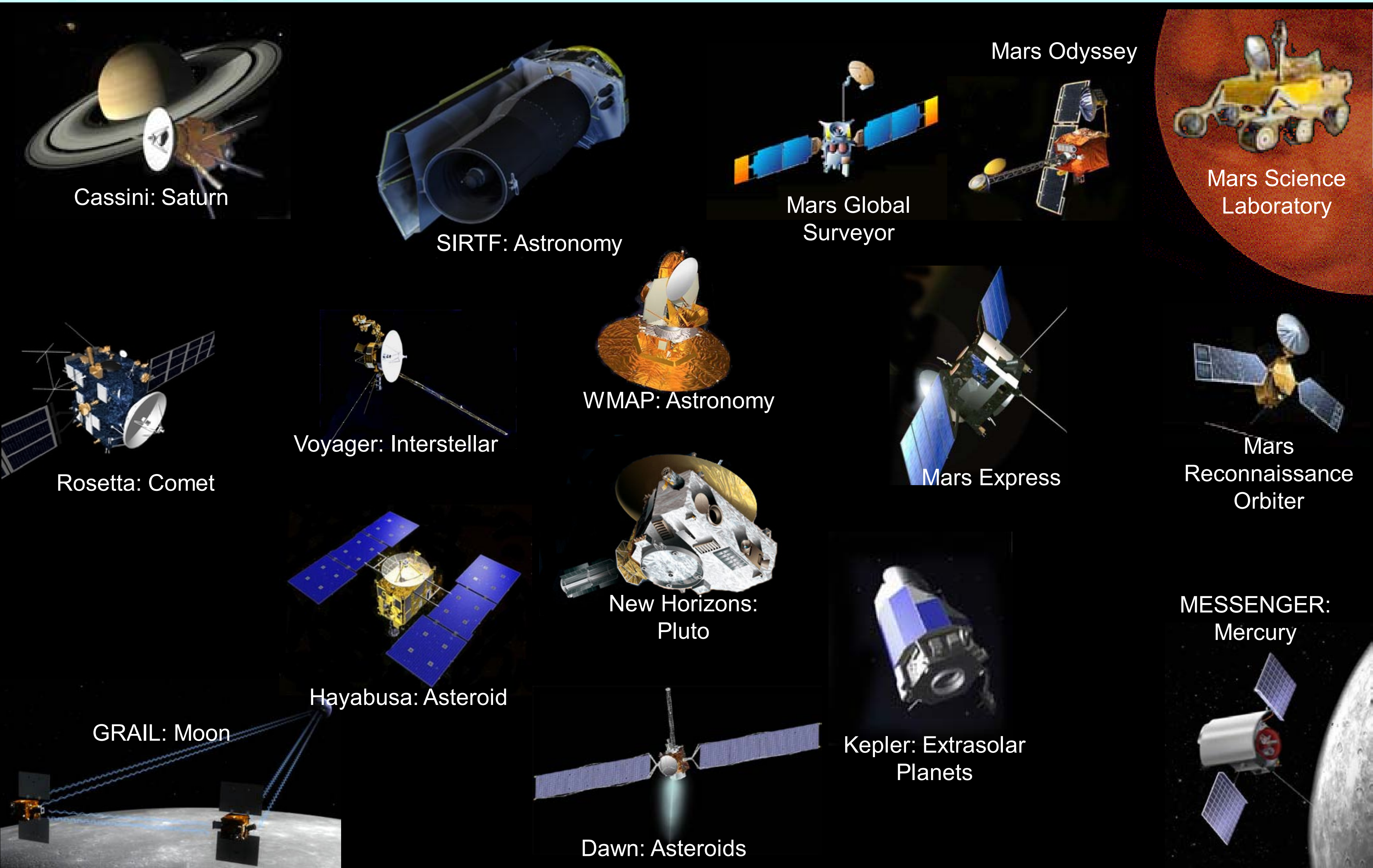
Some Current Deep Space Missions



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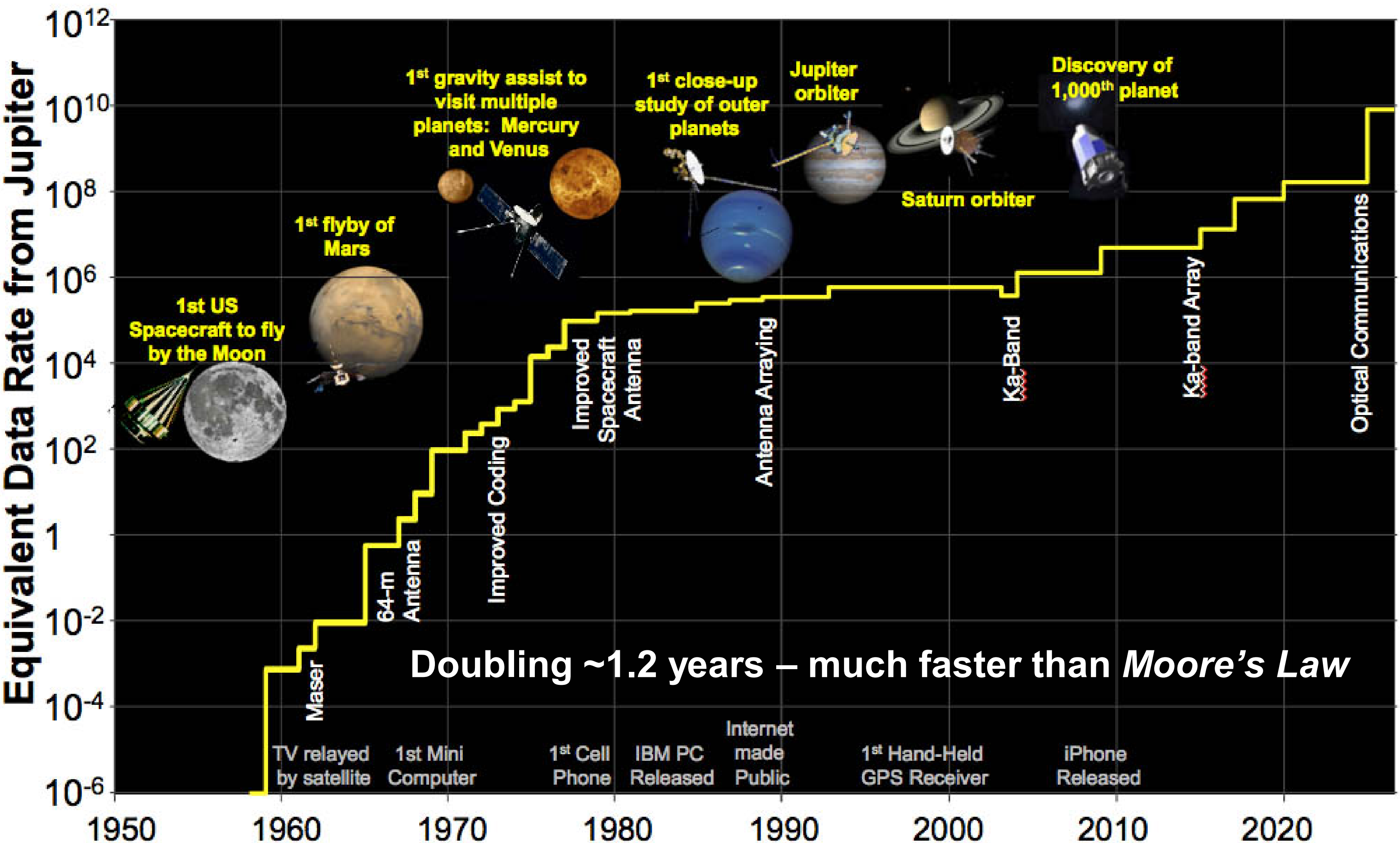
Deep Space Telemetry



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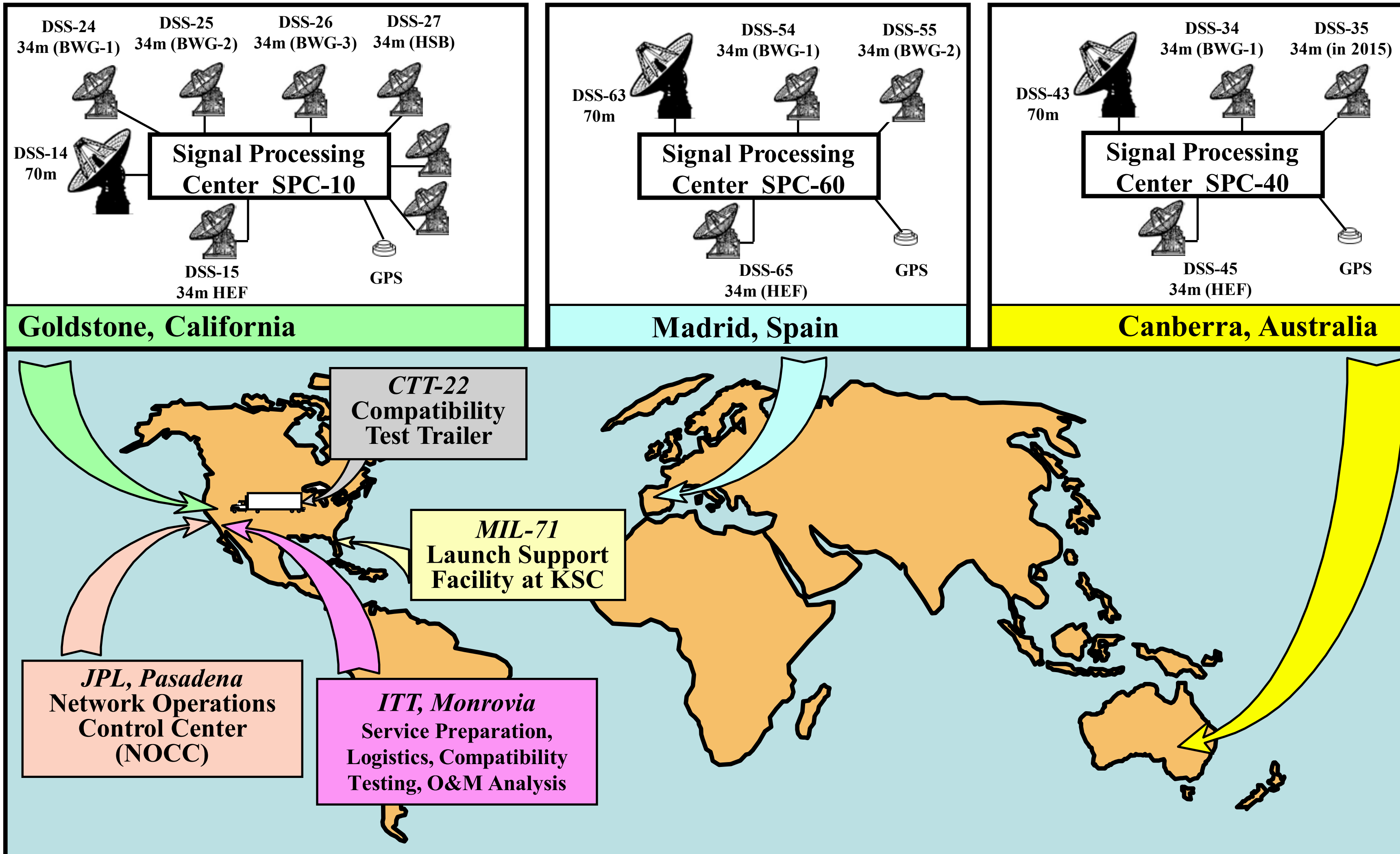
DSN Facilities



DSN Antennas in Madrid, Spain

This is a Small Part of a Big Story

- The history of communications with deep space is full of interesting problems that have been solved
- This talk concentrates on only one of these: receiving digital information from spacecraft far from Earth
- Other interesting subjects include
  - Getting information from Earth to deep space
  - Navigating spacecraft across the solar system using radio and/or optical signals
  - Using the communications link as a science instrument to probe planets, moons, small bodies, and the bounds of theoretical physics

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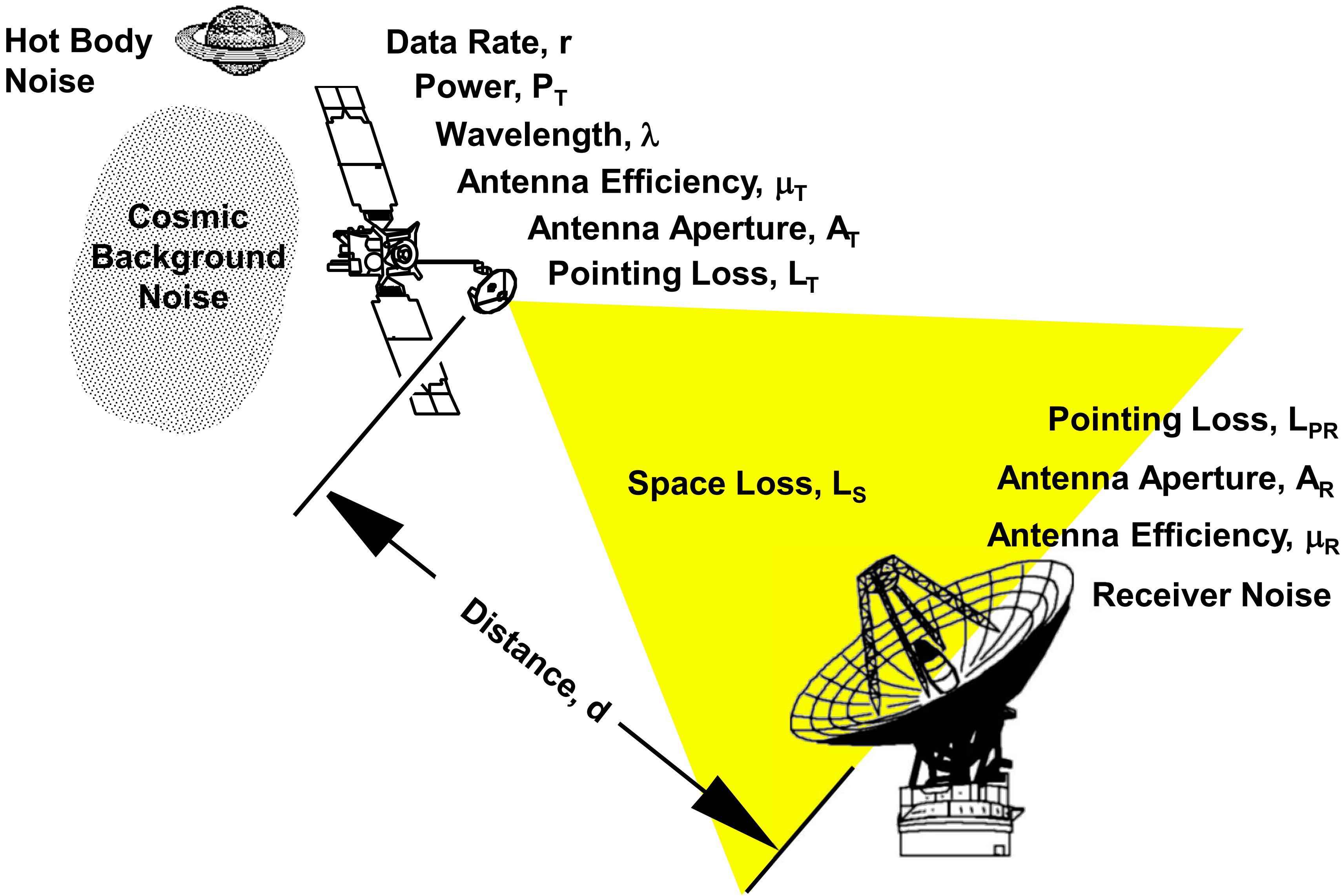
Deep Space Link Parameters



Deep Space Link Equations

Space Loss

$$L_S = \left(\frac{\lambda}{4\pi d}\right)^2$$

Antenna Gain

$$G_i = \frac{4\pi\mu_i A_i}{\lambda^2}$$

Received Power Per Bit

$$P_R = P_T G_T L_{PT} L_S L_{PR} G_R / r$$

Noise Spectral Density

$$N_0 = kT$$

Noise Sources

$$T = T_{cosmic\ background} + T_{hot\ bodies} + T_{RFI} + T_{atmosphere} + T_{receiver}$$

Overall performance is a function of Signal-to-Noise ratio

$$\frac{P_R}{N^0} = \frac{P_T G_T L_{PT} L_S L_{PR} G_R / r}{kT}$$

The goal is to maximize data rate (r), while maintaining reasonable (affordable) values of all the other parameters!

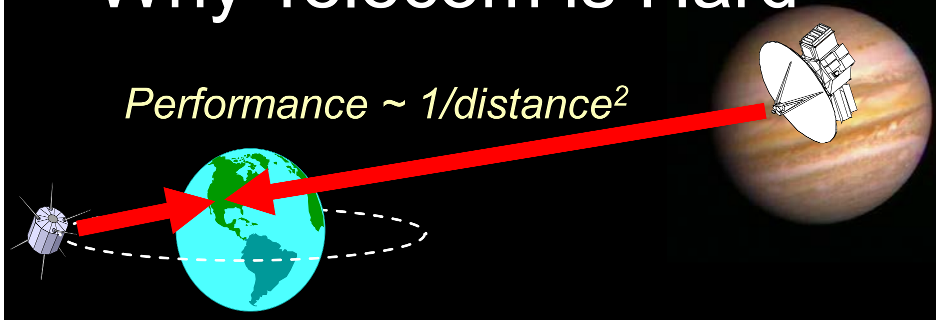
Space Loss

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

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

- **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	$1.6x10^{10}$

Big Antennas

$$P_R/N_0 = \text{constant} * A_T * A_R$$

- Big antennas are good for deep space
- Spacecraft antennas have grown as the size of spacecraft fairings have grown
- The big payoff is in ground antennas
  - A single large investment serves all space missions
- This is why the DSN has the largest steerable communications antennas in the world

History of DSN Antennas

1958, 26m Station

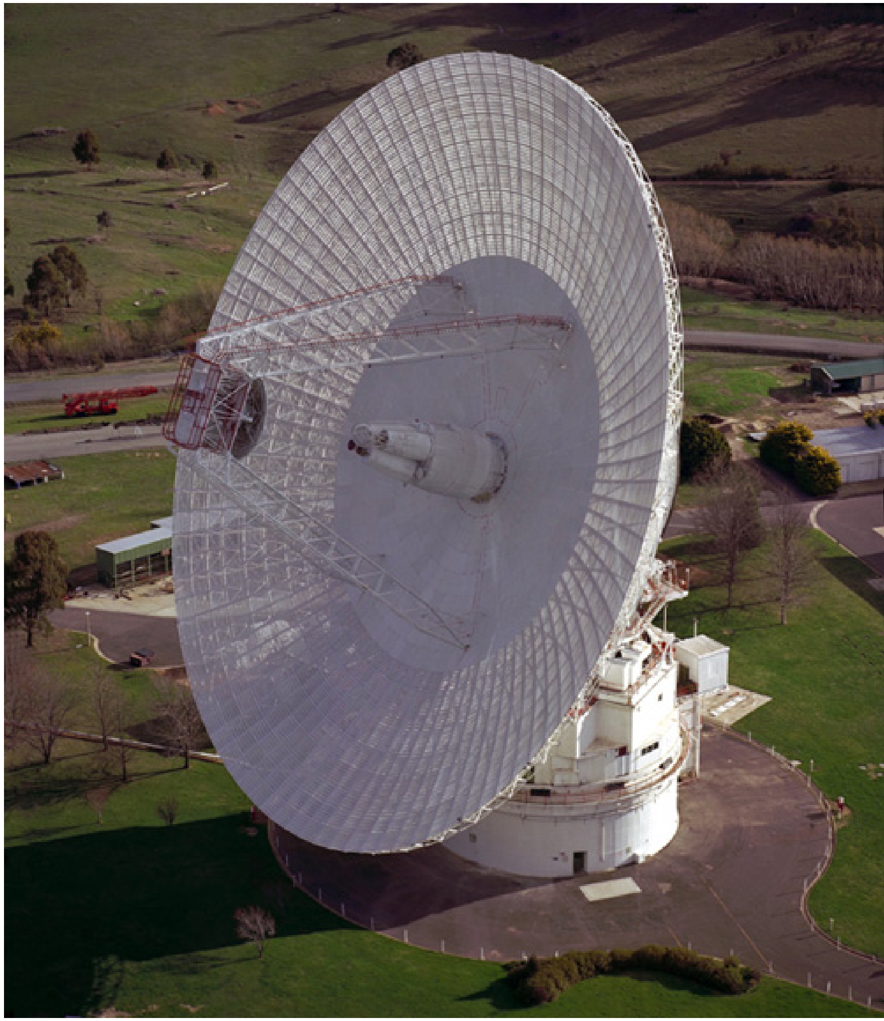
1966, 64m Station

1979, 34m Station

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

The DSN's Huge Antennas

- **This is what people recognize most about the DSN**
- **DSN's 70m antennas are the largest steerable communication antennas in the world**
- **Each also has a 20 KW transmitter**



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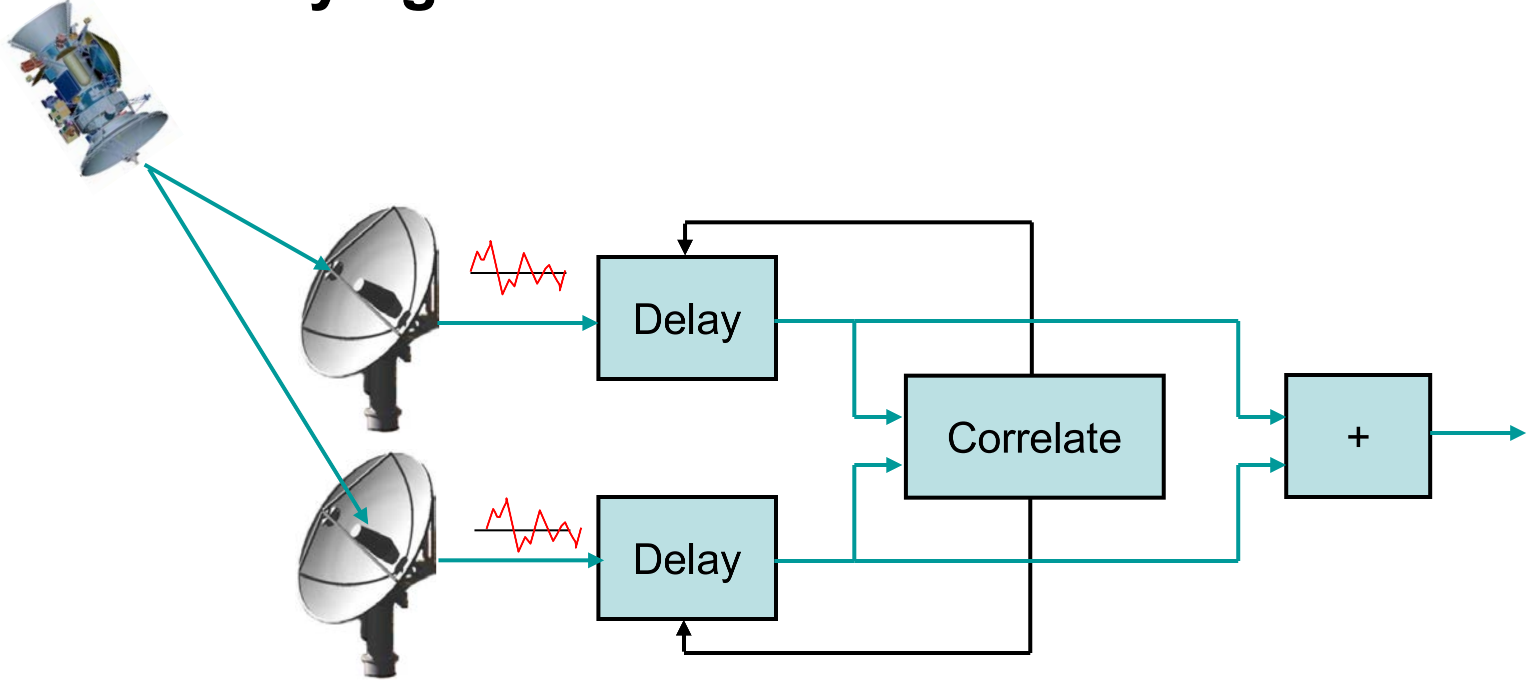
Even More: Antenna Arraying

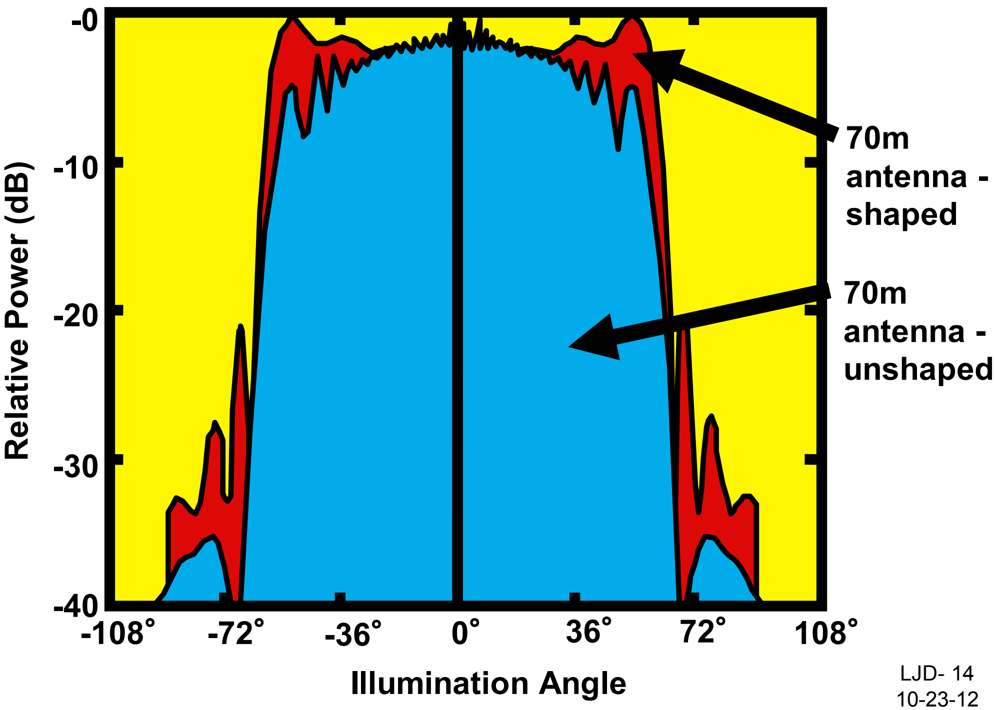
- By carefully aligning and adding the signals from multiple antennas, a performance approaching that of the sum of the apertures is achieved
- Used to help “save” the Galileo mission to Jupiter when its deployable antenna failed to open
- Receive arraying is a standard service in the DSN today



Antenna Efficiency

$$P_R/N_0 = \text{constant} * \mu_T * \mu_R$$

- Spacecraft and DSN antennas are at least 70%
- DSN maintains this efficiency even as the huge antennas are rotated and elevated, by:
  - Adjusting the subrefelector
  - Using master equatorials
  - Using the received signal to adjust pointing
- DSN antennas have "shaped reflectors"



Aperture: So Far

- **Increases in spacecraft and ground apertures, improvements in antenna efficiency, and the use of arraying have so far led to an total improvement of**

44.3 dB

or

a factor of more than 27,000

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

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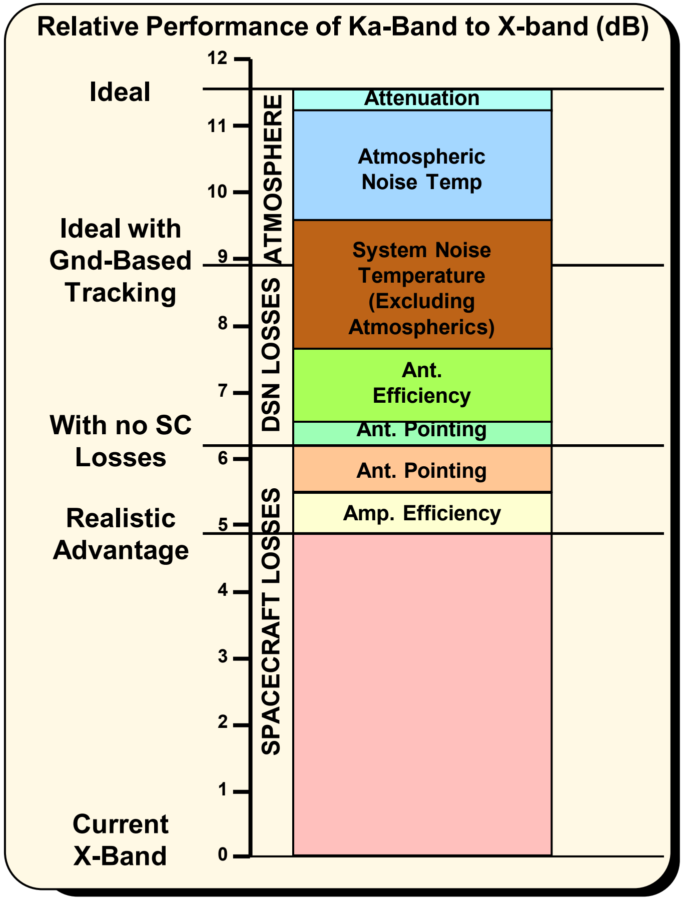
Higher frequencies = some losses!

- The higher the frequency
  - the better you have to point the antennas
  - the more loss there will be in Earth's atmosphere
  - the less efficient the electronics on the spacecraft
- This focuses technology development



Higher Frequencies: So Far

- As of today, the improvements to the system from using higher frequencies have amounted to

20.6 dB, a factor of ~115

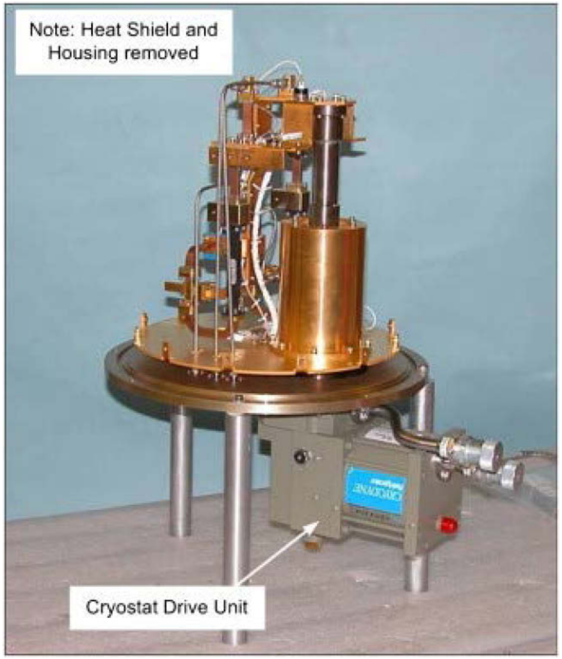
- When we add optical communications, the total will increase to

37.6 dB, a factor of ~5,800

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

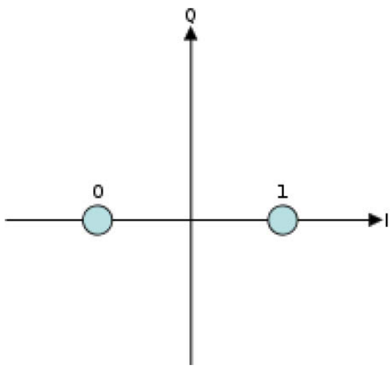
System Noise: So Far

- This one is harder to track
- Many other major system improvements have come with some associated lowering of T
  - e.g. larger antennas mean narrower beams, so less background noise enters the system
- As far as improvements that were directed specifically at T, so far we have had am improvement of

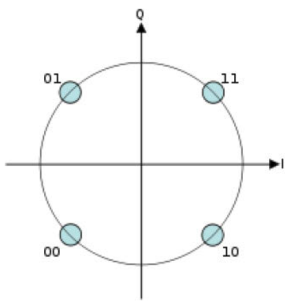
17.5 dB, or a factor of ~57

Modulation – Optimizing P

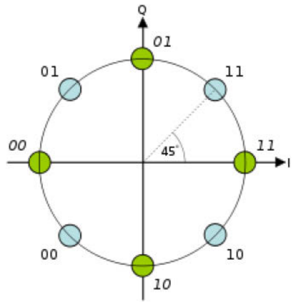
- The way in which data is modulated onto a carrier plays a big part in communications performance
- Consider these standard signaling sets



Binary Phase Shift Keying (BPSK)



Quadrature Phase Shift Keying (QPSK)



Eight Phase Shift Keying (8PSK)

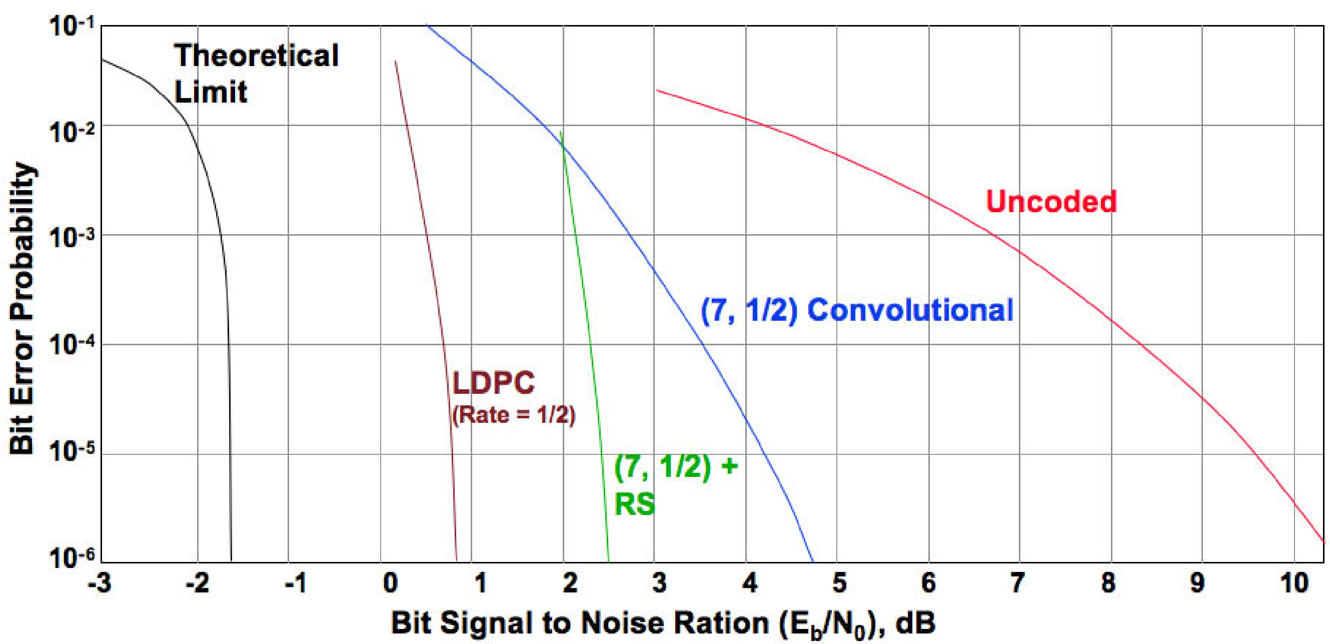
- BPSK has the best performance because the distance between adjacent signals is greatest for the same power

Deep Space vs. Earth Orbiters

- **Because power is at such a premium for deep space missions, BPSK is typically the preferred modulation scheme**
- **For spacecraft closer to home – Earth orbiters – the situation is different**
  - **They have "power to burn" because they are so close to home**
  - **Because of this, they can fly massive, data-hungry instruments requiring Gbps of return link**
  - **This leads to their use of higher-order modulation types like QPSK and 8PSK – or event higher in some cases!**

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" top 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

Modulation, Coding, Compression… so far

- These improvements typically are inexpensive and quick – my favorite kind!
- I cannot even monitor all of them – since improvements in onboard processing and autonomy are bookkept within each flight project and not even considered part of the communications system
- So far, improvements in this area – in modulation and coding alone – have amounted to a total of

23.8dB or a factor of ~240

A Rack-Up

- **Here is a summary of the various improvements and showing their contribution to the 10^{16} result.**

Area	Improvement to date (dB)	Improvement by 2025 (dB)
Aperture	35.8	44.3
Frequency	20.6	37.6
Power	38.4	38.4
Noise	17.5	17.5
Modulation, Coding, Compression	16.7	23.8
Total	129.2	161.6

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Downlink Data Rate Possibilities

	Data Rate Today		Data Rate ~2020		Data Rate ~2030	
Spacecraft Capabilities	3m Antenna X-Band 100 W Xmitter		3m Antenna Ka-Band 180 W Xmitter		5m Antenna Ka-band 200 W Xmitter	
DSN Antennas	1 x 34m	3 x 34m	1 x 34m	Equiv to 3 x 34m	1 x 34m	Equiv to 7 x 34m
Mars (0.6 AU)	20 Mbps	60 Mbps	400 Mbps	*1.2 Gbps	*1.3 Gbps	*9.3 Gbps
Mars (2.6 AU)	1 Mbps	3 Mbps	21 Mbps	64 Mbps	71 Mbps	*500 Mbps
Jupiter	250 Kbps	750 Kbps	5 Mbps	15 Mbps	16 Mbps	115 Mbps
Saturn	71 Kbps	213 Kbps	1.4 Mbps	4 Mbps	4.7 Mbps	33 Mbps
Neptune	8 Kbps	24 Kbps	160 Kbps	470 Kbps	520 Kbps	3.7 Mbps

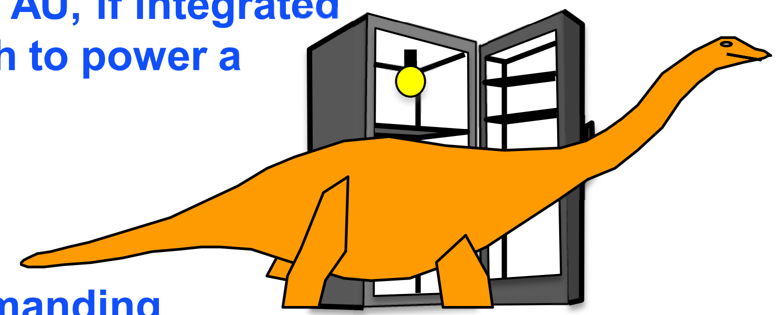
* Reference spacecraft is MRO-class (power and antenna), Rate 1/6 Turbo Coding, 3 dB margin, 90% weather, and 20° DSN antenna elevation

** Performance will likely be 2 to three times lower due to need for bandwidth-efficient modulation to remain in allocated spectrum

Some Amazing DSN Facts

Received Signal Sensitivity:

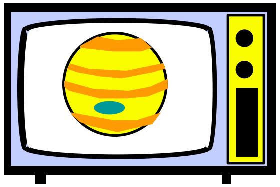
The received energy from Voyager at 100 AU, if integrated for 10 trillion years, would be just enough to power a refrigerator light bulb for one second!



Received power = 6.3×10^{-19} W

Command Power:

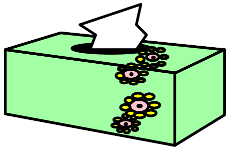
The DSN puts out enough power in commanding Voyager that it could easily provide high quality commercial TV at Jupiter!



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}

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