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
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Some Current Deep Space Missions

- **Cassini**: Saturn
- **Dawn**: Asteroids
- **Hayabusa**: Asteroid
- **Kepler**: Extrasolar Planets
- **GRAIL**: Moon
- **Mars Odyssey**
- **Mars Express**
- **New Horizons**: Pluto
- **Rosetta**: Comet
- **Voyager**: Interstellar
- **SIRTF**: Astronomy
- **WMAP**: Astronomy
- **Mars Reconnaissance Orbiter**
- **MEOSSER**: Mercury
Deep Space Telemetry

Doubling ~1.2 years – much faster than Moore’s Law
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DSN Facilities

Goldstone, California

- DSS-14 70m
- DSS-15 34m HEF
- DSS-24 34m (BWG-1)
- DSS-25 34m (BWG-2)
- DSS-26 34m (BWG-3)
- DSS-27 34m (HSB)
- DSS-28 34m (HSB)
- DSS-29 34m (HEF)

Madrid, Spain

- DSS-34 34m (BWG-1)
- DSS-35 34m (in 2015)
- DSS-43 70m
- DSS-45 34m (HEF)

Canberra, Australia

- DSS-45 34m (HEF)
- DSS-35 34m (HEF)

JPL, Pasadena

- Network Operations Control Center (NOCC)

ITT, Monrovia

- Service Preparation, Logistics, Compatibility Testing, O&M Analysis

CTT-22 Compatibility Test Trailer

MIL-71 Launch Support Facility at KSC

JPL, Pasadena Network Operations Control Center (NOCC)
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
Deep Space Link Parameters

- Data Rate, \( r \)
- Power, \( P_T \)
- Wavelength, \( \lambda \)
- Antenna Efficiency, \( \mu_T \)
- Antenna Aperture, \( A_T \)
- Pointing Loss, \( L_T \)
- Space Loss, \( L_S \)
- Pointing Loss, \( L_{PR} \)
- Antenna Aperture, \( A_R \)
- Antenna Efficiency, \( \mu_R \)
- Receiver Noise

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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**

\[ T = T_{\text{cosmic background}} + T_{\text{hot bodies}} + T_{\text{RFI}} + T_{\text{atmosphere}} + T_{\text{receiver}} \]

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

\[ \frac{P_R}{N_0} = \frac{\text{constant}}{d^2} \]

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

<table>
<thead>
<tr>
<th>Place</th>
<th>Distance</th>
<th>Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo</td>
<td>4x10^4 km</td>
<td>Baseline</td>
</tr>
<tr>
<td>Moon</td>
<td>4x10^5 km</td>
<td>100</td>
</tr>
<tr>
<td>Mars</td>
<td>3x10^8 km</td>
<td>5.6x10^7</td>
</tr>
<tr>
<td>Jupiter</td>
<td>8x10^8 km</td>
<td>4.0x10^8</td>
</tr>
<tr>
<td>Pluto</td>
<td>5x10^9 km</td>
<td>1.6x10^10</td>
</tr>
</tbody>
</table>

Performance \sim \frac{1}{\text{distance}^2}
Big Antennas

\[ \frac{P_R}{N_0} = \text{constant} \times A_T \times A_R \]

- 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
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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
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

\[ \frac{P_R}{N_0} = \text{constant} \times \mu_T \times \mu_R \]

- Spacecraft and DSN antennas are at least 70% efficient.
- DSN maintains this efficiency even as the huge antennas are rotated and elevated, by:
  - Adjusting the subreflector
  - 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 a 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

### Relative Performance of Ka-Band to X-band (dB)

- Ideal
- Ideal with Gnd-Based Tracking
- With no SC Losses
- Realistic Advantage
- Current X-Band

<table>
<thead>
<tr>
<th></th>
<th>DSN Losses</th>
<th>Atmosphere</th>
<th>Spacecraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>Attenuation</td>
<td>Atmospheric Noise Temp</td>
<td>System Noise Temperature (Excluding Atmospherics)</td>
</tr>
<tr>
<td>Ideal with Gnd-Based Tracking</td>
<td>Ant. Efficiency</td>
<td>Ant. Pointing</td>
<td>Ant. Pointing</td>
</tr>
<tr>
<td>With no SC Losses</td>
<td>Ant. Pointing</td>
<td>Ant. Pointing</td>
<td>Amp. Efficiency</td>
</tr>
<tr>
<td>Realistic Advantage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current X-Band</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.
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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 an 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 even 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” 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
• 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 booked 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
Here is a summary of the various improvements and showing their contribution to the $10^{16}$ result.

<table>
<thead>
<tr>
<th>Area</th>
<th>Improvement to date (dB)</th>
<th>Improvement by 2025 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>35.8</td>
<td>44.3</td>
</tr>
<tr>
<td>Frequency</td>
<td>20.6</td>
<td>37.6</td>
</tr>
<tr>
<td>Power</td>
<td>38.4</td>
<td>38.4</td>
</tr>
<tr>
<td>Noise</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Modulation, Coding,</td>
<td>16.7</td>
<td>23.8</td>
</tr>
<tr>
<td>Compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>129.2</td>
<td>161.6</td>
</tr>
</tbody>
</table>
### Downlink Data Rate Possibilities

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

* 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 = 6.3x10\(^{-19}\) 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