Deep Space Communication*

Farzin Manshadi
JPL Spectrum Manager
September 20-21, 2012

* Based on Material provided by Dr. Les Deutsch
Deep Space Communication

Introduction

• ITU defines deep space as the volume of Space at distances from the Earth equal to, or greater than, $2 \times 10^6$ km

• Deep Space Spacecraft have to travel tens of millions of km from Earth to reach the nearest object in deep space

• Spacecraft mass and power are precious

• Large ground-based antennas and very high power transmitters are needed to overcome large space loss and spacecraft’s small antennas and low power transmitters

• Navigation is complex and highly dependent on measurements from the Earth

• Every deep space mission is unique and therefore very costly to develop
Deep Space Communication

Spacecraft Mass and Power are Precious

- Deep space missions must leave Earth’s gravity – very difficult
  - An Atlas V 551 can lift about 19,000 kg to low Earth orbit but only ~500 kg to deep space
- Power generation is very difficult for a spacecraft far from the sun
  - Solar flux goes down by a factor of four each time the distance from the Sun doubles, so a solar panel at Jupiter can only generate a billion\textsuperscript{th} the power as at Earth
  - Nuclear-based generators are both expensive and politically sensitive
Deep Space Communication

Spacecraft Mass and Power are Precious-Consequence

• Deep space spacecraft look like giant antennas with Instruments attached
  ▪ Cannot afford high power
  ▪ Transmitters typically tens of Watts

• Trajectories are optimized for lowest propellant consumption
  ▪ Demands on navigation are extreme
  ▪ Lots of critical events
  ▪ Very minor mistakes can lead to mission failure
Deep Space Communication

Spacecraft Mass and Power are Precious—Example Cassini

Cassini “cruise” trajectory:
- Multiple “swing-bys” generated “gravity assists” to save propellant
Deep Space Communication

Spacecraft Travel Very Long Distances from Earth

- Communications performance is inversely proportional to distance squared
- Deep space ground antennas are very large
- System cannot waste any dBs!
- Spacecraft must be autonomous

Why Telecom is Hard

Performance $\sim 1/\text{distance}^2$

Relative Difficulty

<table>
<thead>
<tr>
<th>Place</th>
<th>Distance</th>
<th>Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo</td>
<td>$4 \times 10^4$ km</td>
<td>Baseline</td>
</tr>
<tr>
<td>Moon</td>
<td>$4 \times 10^5$ km</td>
<td>100</td>
</tr>
<tr>
<td>Mars</td>
<td>$3 \times 10^8$ km</td>
<td>$5.6 \times 10^7$</td>
</tr>
<tr>
<td>Jupiter</td>
<td>$8 \times 10^8$ km</td>
<td>$4.0 \times 10^8$</td>
</tr>
<tr>
<td>Pluto</td>
<td>$5 \times 10^9$ km</td>
<td>$1.6 \times 10^{10}$</td>
</tr>
</tbody>
</table>
Spacecraft Travel Very Long Distances from Earth-Consequence

- Very large ground antennas are needed to compensate for the space loss
- Example: NASA’s Deep Space Network 70m antennas
  - largest steerable communication antennas in the world
  - Each has a 20 KW transmitter for communication with deep space spacecraft
Deep Space Communication

Other Antenna Designs for Deep Space Communications

- 34m class Beam Waveguide Antenna is today’s standard for deep space communication
  - Electronics in basement lab environment
    - Signal is transmitted or received through a system of mirrors
  - Easy to update
  - Easy to service
  - Safer to operate
Deep Space Communication

Deep Space Communication Must be Very Efficient

• Cannot waste a fraction of dB of performance
• Deep space missions operate close to theoretical communications efficiency limit (within 1 dB, typically)
• Example: If a spacecraft designed to work with a 70-m antenna lost a dB of performance it would take an additional 32-m antenna to make up the difference!
  ▪ Cost for three 32m antennas = ~$100M!
Deep Space Spacecraft Must be Autonomous

- It can take minutes to many hours for signals to travel between a deep space spacecraft and Earth
- Decisions must often be made faster than this – requiring spacecraft autonomy
- Spacecraft are usually “sequenced”, meaning they are programmed to operate for long periods without commands from Earth
- Spacecraft manage the data they acquire, storing it until it can be sent back to Earth
- Emergencies require special “safing” algorithms
Deep Space Communication

Navigation Is Complex and Highly Dependent on Earth

- Precise measurements of the radio signals used to help navigate spacecraft
  - Ranging: measurement of the distance to the spacecraft
  - Doppler: measurement of the relative spacecraft motion
  - Interferometric techniques: using multiple ground antennas to measure precise spacecraft angle on the sky
- Beyond GPS orbit, these are the best source of navigation data
- Usually augmented by on-board spacecraft sensors
  - Gyroscopes
  - Star and sun sensors
  - Spacecraft photos of targets against stellar background

An interferometric technique, ΔDOR: delta differenced one-way ranging
Every Deep Space Mission is Unique

- There are a myriad of deep space targets: planets, moons, asteroids, comets, and parking spaces for astronomical observatories - each with their own
  - Set of scientific questions
  - Unique trajectory challenges
  - Unique spacecraft bus, instruments, and propulsion
- Even popular targets (e.g. Mars) are visited only every few years, with differing spacecraft
- Communications and navigation can be different for each mission
  - Often requires special studies to optimize performance and maximize success
- New technology is often infused in both the spacecraft and the ground network – creating something new for every mission
Deep Space Communication

Radio Science

• Tracking spacecraft near or behind targets yields important science

• Atmospheric dynamics
  ▪ Circulation
  ▪ Vertical structure
  ▪ Turbulence

• Atmospheric density

• Gravity field mapping
Deep Space Communication

Trends in Deep Space Communications and Navigation (Angular Tracking)

- Mariner 2 - Venus
- Mariner 4 - Mars
- Mariner 9 - Mars
- Mariners 6, 7 - Mars
- Voyager - Uranus
- Voyager - Saturn
- Galileo - Jupiter
- Odyssey - Mars
- MRO - Mars

ΔVLBI: Delta Very Long Baseline Interferometry
FSR: Full Spectrum Recorder

Geocentric Angular Accuracy (nrad)

10^6 10^5 10^4 10^3 10^2 10^1 10^0


F. Manshadi - 15
9/20/2012
Deep Space Communication

The Impact of Deep Space Science
Deep Space science has provided a continuing torrent of forefront discoveries – many high impact papers and mission investigators.
Deep Space Communication

DSN Antennas in Madrid, Spain
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 = \(6.3 \times 10^{-19} \text{W}\)

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 \(10^{15}\)