Performance Analysis of NASA Deep Space Communications Systems – Expectations and Lessons Learned

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Outline

1. Deep space communications systems
2. Performance analysis processing
3. Expectations vs. lessons learned
1. Deep Space Communications System
An Instrument of Space Science Research

• Answer key scientific questions such as
  – Are we alone in the universe?
  – How did the universe start?

• Support robotic missions
  – Explorations of the Moon, Solar system bodies and their moons
    • e.g., LRO, STEREO, Magellan, Mars rovers, Juno, Cassini, New Horizons, Voyager
  – Astrophysics studies of exoplanets, cosmic evolution
    • e.g., Kepler, TESS, SIRTF, JWST

• Support emerging human exploration
Science Missions Exploration

Upcoming Events

2013
- Sep: LADDEE Launch/OI Moon
- Oct: Juno FB Earth
- Nov: MRO Launch
- Dec: MAVEN Launch

2014
- Jan: Rosetta Wake-up
- Feb: Dawn Ceres
- Mar: New Horizons/Pluto
- Apr: Rosetta/Philae SL Chu-Ger.
- May: Rosetta/Philae SL Chu-Ger.
- Jun: Rosetta/Philae SL Chu-Ger.
- Jul: Rosetta/Philae SL Chu-Ger.
- Aug: Rosetta/Philae SL Chu-Ger.
- Sep: Juno
debut
- Oct: New Horizons
- Nov: Deep Impact
- Dec: Hayabusa 2 Launch

2015
- Jan: Exomars-TGO Launch
- Feb: Exomars TGO
- Mar: InSight Launch
- Apr: Juno
- May: New Horizons
- Jun: New Horizons
- Jul: New Horizons
- Aug: New Horizons
- Sep: New Horizons
- Oct: New Horizons
- Nov: New Horizons
- Dec: New Horizons

2016
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- Aug: New Horizons
- Sep: New Horizons
- Oct: New Horizons
- Nov: New Horizons
- Dec: New Horizons

2018
- Jan: Exomars TGO
- Feb: Exomars TGO
- Mar: InSight
- Apr: Juno
- May: New Horizons
- Jun: New Horizons
- Jul: New Horizons
- Aug: New Horizons
- Sep: New Horizons
- Oct: New Horizons
- Nov: New Horizons
- Dec: New Horizons

2020
- Jan: Exomars Rover
- Feb: Exomars Rover
- Mar: Exomars Rover
- Apr: Exomars Rover
- May: Exomars Rover
- Jun: Exomars Rover
- Jul: Exomars Rover
- Aug: Exomars Rover
- Sep: Exomars Rover
- Oct: Exomars Rover
- Nov: Exomars Rover
- Dec: Exomars Rover
Current & Future JPL Missions Development

### Planetary Missions

**Operational**
- Mars Odyssey (2001)
- Mars Reconnaissance Orbiter (2006)
- Juno (2011)
- Curiosity (2012)
- InSight (2018)

**Formulation / Development**
- Mars (2020)
- Psyche / DSO (2022)
- Europa Clipper (NLT 2025)

### Astrophysics Missions

**Operational**
- Two Voyagers (1977)
- WISE 2009 (Restarted for NEOWISE 2013)
- NuSTAR (2012)
- HAWC+ on SOFIA (2016)
- Cold Atom Laboratory (2018)

**Formulation / Development**
- SPHEREX (2023)
- NEOSM (2025)
- WFIRST Coronagraph (2025)
- CASE (2028)
- ASTHROS (2023)
Deep Space Communications Networks

- International space agencies
  - NASA, ESA, JAXA, etc.
    - Large aperture antennas (30-70 m)
  - Mission support
    - Mostly network centric
    - With some cross support
- Interplanetary spacecraft communications
  - Telemetry, Tracking and Command (TTC)
  - Science (Radio Science, Radar, Very Long Baseline Interferometry)
Challenge - Long Distance, Extreme Low Power

- Long distance communications
  - Lunar missions (0.002 AU) to Voyager at 140 AU

Received power is inversely proportional to the square of the distance.

\[ P_r = \frac{P_t G_t A_e}{4\pi R^2} \]

- LEO: ~400 km
- GEO: ~35,786 km
- Lunar Distance: ~382,500 km
- Mars Distance: ~225,000,000 km

\[ P_r = \sim1 \text{ millionth} \]
\[ P_r \text{ from LEO} \]
\[ P_r = \sim1 \text{ ten thousandth} \]
\[ P_r \text{ from LEO} \]

\[ P_r = \sim3 \text{ trillionths} \]
\[ P_r \text{ from LEO} \]

D. Abraham, Working Toward More Affordable Deep Space Cubesat Communications: MSPA and OMSPA, https://www.dropbox.com/sh/fx8auva239g0wx9/AADMzWa7wgXpi0KmnoFk2rgaa/D2-Abraham?dl=0&preview=ISSC2016_WorkingTowardAffordableCommunications_URS257550.pptx#
Technical Focus in Deep Space Communications

• Low-power communications require:
  – Large antenna with maximum G/T
    • Cryo-cooled LNA
    • Listen only vs. diplexed
  – Modulation & coding optimized for low power regime
    • Modulation: BPSK, QPSK
    • Coding: Convolutional, Reed Solomon, Concatenated, Turbo, Low-density parity check
  • Special operation:
    – MFSK for EDL
    – Beacon for long duration flight
  – Maximum EIRP for spacecraft emergency mode
Antenna Arraying to Aid Really Low Signal

- A way to enhance antenna aperture
  - Routinely used by Voyager, Spitzer, New Horizons
- Downlink array
  - 34-m/70-m arraying
  - Polarization combining
- Uplink array (R/D capability)
  - Gain proportional to N^2 instead of N (as with downlink)

Ref.: Vilnrotter, Uplink Array Concept Demonstration with the EPOXI Spacecraft, IEEE Aerospace, 2009
Maximizing Data Return via Adaptive Data Rate

- Adjusting data rate per available link margin during the pass
  - More important at higher operating frequency
    - Steeper curves
  - Higher performance with continual adjustment of data rate
    - Requiring more capable flight system
High Performance Coding

- Trading complexity (with lower processing rate) to gain better Eb/No performance
  - Within 1 dB of AWGN channel capacity
  - Convolutional, Reed Solomon, Concatenated, Turbo, and Low-Density Parity Check codes

2. Performance Analysis Processing
Monitor Data Capture

Data Production

Antenna
Receiver
Transmitter
...
Other Equipment

Network M&C

Performance Analysis

Data Capture
Data Analysis
Results
Key Processing Functions
Key Metrics of Interest

- G/T (Gain/System Noise Temperature)
- Operating link margin
- Data accountability
- Frequency stability
- Link setup time
- Resource utilization, e.g., WAN bandwidth
- Etc.
### Performance Dashboard

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<th>year 2020</th>
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</table>
Sample Dashboard – Telemetry Link Margin

### Telemetry Link Margin Performance Analysis Dashboard Jan 2020

| TVA | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | Average | TVD |
|-----|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| SP2-40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SP2-79 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TESS-455 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TESS-695 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TESS-1052 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| THC-219 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| THC-545 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GSR-337 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GSR-323 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DOY | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | Average | TVD |

**Legend**
- **Link Margin (dB)**:
  - < 0.0
  - 0.0 - 0.5
  - 0.5 - 2.0
  - 2.0 - 4.0
  - 4.0 - 6.0
  - > 6.0

**DOY**
- 2020 Jan
- 2020 Feb
- 2020 Year
- 2020

**Source**
- NASA Jet Propulsion Laboratory
- California Institute of Technology
Sample - Key Metrics Within a Pass

DSN Performance Analysis

Year 2020 DOY 1 DSS 65 SCID 92 rawdata formatted nmclg

Symbol SNR: DCU/92 Min 1.1 Avg 15.9 Max 25.2 Sdev 2.7 Link Margin 16.9 dB Threshold -0.7 dB

Lock: Reset Scale

P/N: Reset Scale

NASA Jet Propulsion Laboratory
California Institute of Technology
Sample – Key Metric Within a Pass

- **SNT** - Reset Scale. (Select the area to zoom)
- **Bitrate & Symbol Rate** - Reset Scale
- **Pointing Chart** - Reset Scale

![Graphs and charts depicting various data metrics, including SNT, bitrate, symbol rate, and pointing charts.](image)
3. Expectation vs. Lessons Learned
Observations

• Some metrics monitoring are easy to process
  – Data accounting, WAN bandwidth usage
• Some metrics require moderate accounting logics
  – Service pre-cal time
• Some metrics require lots of logics
  – System noise temperature
Easy-to-Process Metrics

- **Data Accounting**
  - # of telemetry frames successfully decoded/ # of expected frames downlink by spacecraft
- **WAN bandwidth usage**
  - Aggregated data flow / Line capacity
Metrics with Moderated Accounting

- Pre-track setup time
  - Account for possible idle time in sequence of
    - Putting equipment into a link
    - Calibrating equipment, e.g. transmitter
    - Safety paging prior to moving antenna
    - Moving antenna to on-point

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
<th>T2a</th>
<th>T2b</th>
<th>T2c</th>
<th>T2d</th>
<th>T2e</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
</tbody>
</table>

| T1 | Time connection log opened |
| T2 | Time pre-cal TDN started  |
| T2a| Time of 'The start block is now running' message. |
| T2b| Time of 'Block "Cal Transmitter" is waiting for input' safety page message |
| T2c| Time 'Block "Cal Transmitter" received input' message |
| T2d| Time of 'Block "CNF Antenna" is waiting for input' safety page message |
| T2e| Time of 'Block "CNF Antenna" received input' message |
| T3 | Time of "Move Antenna to Point' block is now running' message |
| T4 | Time of antenna ‘COMPLETED. RESM TRK’ message |
| T5 | Time antenna ‘On-Point’ message |

If (T2 – T1) ≤ 10 minutes, connection Pre-Cal time = (T5 – T1) – (T4 – T3)
If (T2 – T1) > 10 Minutes, connection Pre-Cal time = (T5 – T2 + 5 minutes) – (T4 – T3)

If (T2a – T2) > 10 minutes, subtract (T2a – T2 – 5 minutes) from the above
If (T2c – T2b) > 1 minute, subtract (T2c – T2b – 1 minute) from above
If (T2e – T2d) > 1 minute, subtract (T2e – T2d – 1 minute) from above
Metrics Require Extensive Accounting

- G/T - Key parameter to monitor in comm system
  - Especially in deep space communications
- Gain (G) not measurable in typical spacecraft tracking pass
  - Leaving SNT (T) as monitored parameter available
Example - SNT Characterization

- SNT – dependent on many factors
  - Antenna pointing elevation
  - Listen-only vs. listen & transmit (diplexed)
  - Signal SNR
  - Not too weak, not too strong
  - Contribution from planetary body
  - Distinction of lunar orbiters
  - Weather effect, e.g., rain, heavy cloud
  - Erroneous reported measurements
  - Set to predicted or fixed value
  - Outdated noise diode calibration
Relative SNT Monitoring

- Identify anomalous trend on one antenna vs. the rest
Expectations

- Nominal behavior
Unexpected Observations

- Higher than expected

- Lower than expected

[Graphs showing DSN Performance Analysis with data points for SNT and K^* for different dates.]
Unexpected Observations

- Sudden jump in mid pass
Unexpected Observations

- Inconsistent data from same spacecraft and same antenna

Delta=3.4 K

Delta=11.7 K
Approach Taken for SNT Analysis

- Exclude missions with high SNR
- Exclude lunar orbiters
- Exclude data with fixed SNT
- Group data in the same configuration (listen-only vs. diplexed)
- Exclude data with fast changing, high variation
### Results Before Exclusions

**DSN SNT Performance Analysis Dashboard for X Band Nov 2019 Threshold SNT cd=90 +/- 2 K**

<table>
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<th>DOY</th>
<th>DSS</th>
<th>% red</th>
<th>% purple</th>
<th>total pass</th>
<th>SNT diff</th>
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**Legend:**
- SNT cd=90 -2: >SNT cd=90 - 2
- SNT cd=0 -2 SNT cd=90+2: >SNT cd=0 - 2
- SNT cd=0: >SNT cd=0
- Fix Value/bad SNT

**Graph:**
- Oct 2019 vs Dec 2019: Average SNT vs 810.5 reference
Results Before and After Exclusions

The image shows a comparison of data before and after exclusions in the context of DSN SNT Performance Analysis Dashboard for X Band Nov 2019 +/- 2 K. The table and graph indicate changes in performance metrics such as red, purple, pass, and SNT diff. The legend explains the symbols used in the graph, which tracks temperature (°K) against DOY (Days of Year). The data is indicated by various markers such as DSS14, DSS15, and DSS63, among others.
Lessons Learned

• Monitor data from operational systems has large variation compared to a well-calibrated data set
• Data cultivation, with subject expertise, is essential in system performance analysis
• Data visualization is important for observations of large data sets