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

Timothy Pham

Jet Propulsion Laboratory

California Institute of Technology

Jet Propulsion Laboratory
California Institute of Technology

Outline

1. Deep space communications systems
2. Performance analysis processing
3. Expectations vs. lessons learned

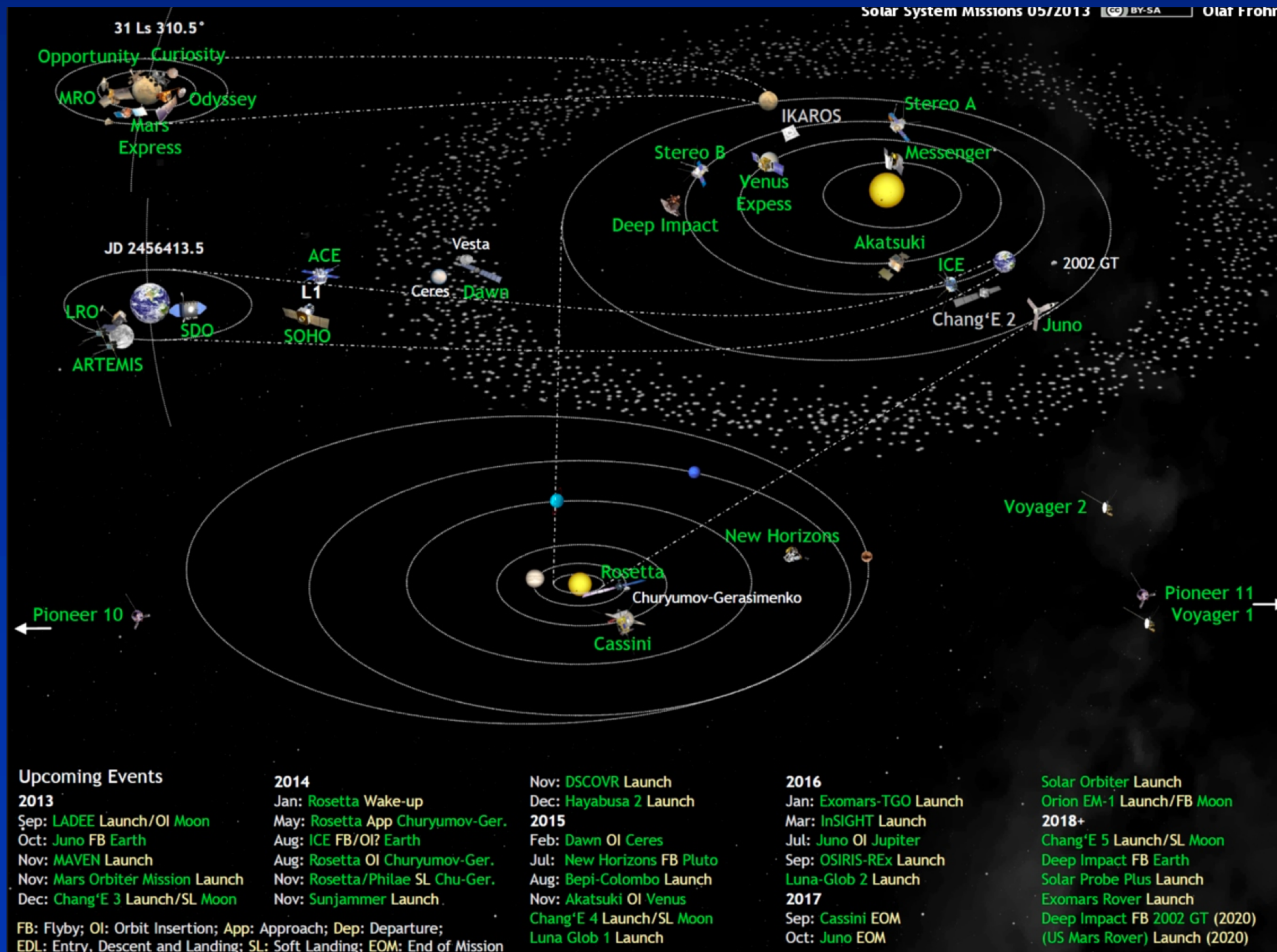
1. Deep Space Communications System

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

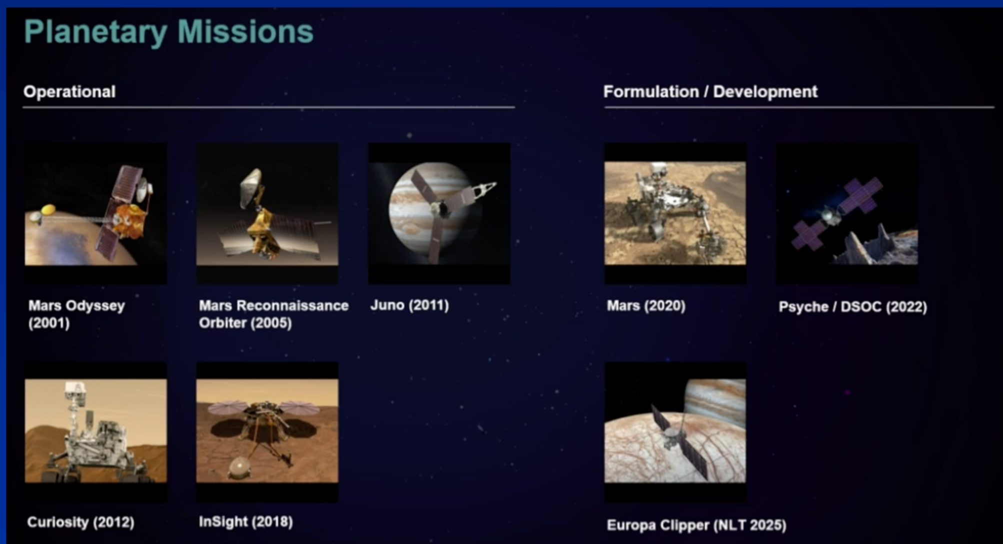
Jet Propulsion Laboratory
California Institute of Technology

Science Missions Exploration



Jet Propulsion Laboratory
California Institute of Technology

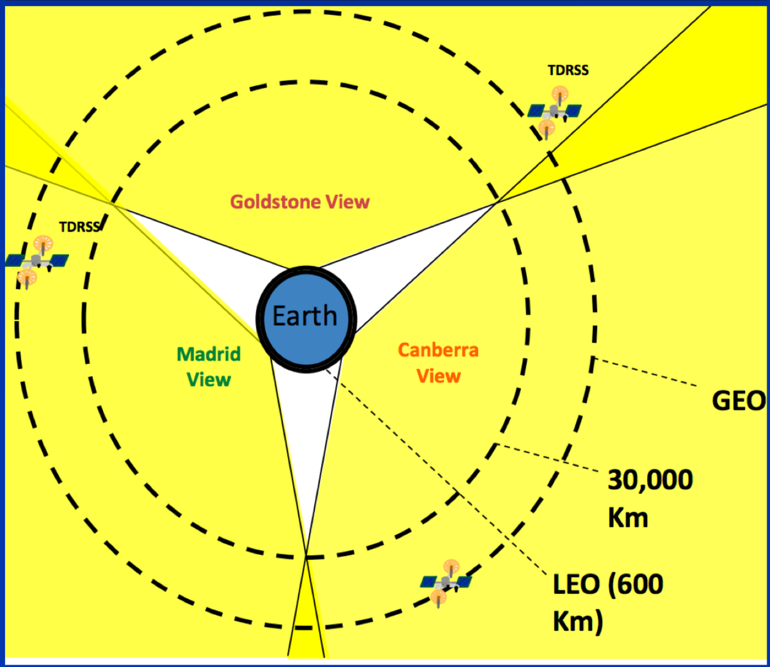
Current & Future JPL Missions Development



Jet Propulsion Laboratory
California Institute of Technology

Deep Space Communications Networks

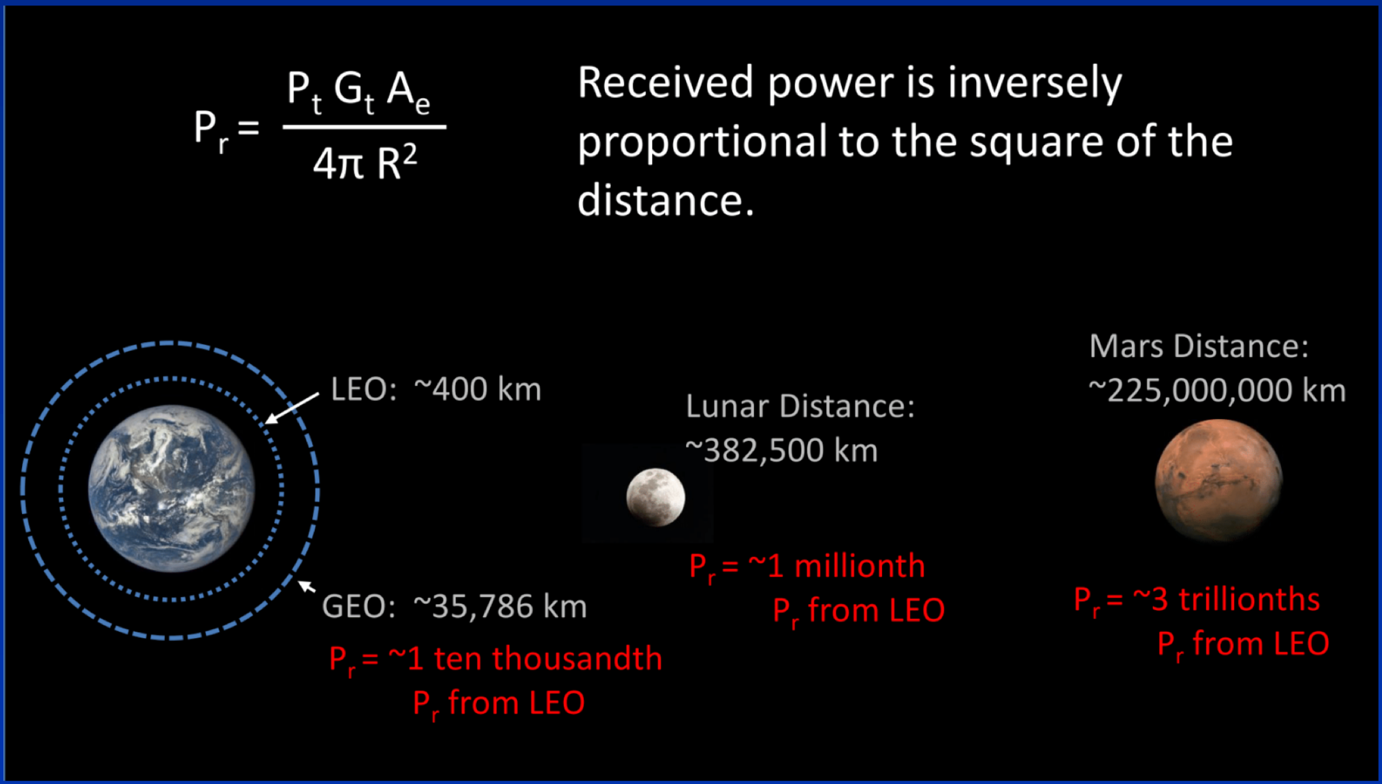
- International space agencies
  - NASA, ESA, JAXA, etc.
    - Large aperture antennas (30-70 m)
  - Mission support
    - Mostly network centric
    - With some cross support
- Interplanetary spacecraft communications
  - Telemetry, Tracking and Command (TTC)
  - Science (Radio Science, Radar, Very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



Jet Propulsion Laboratory
California Institute of Technology

Challenge - Long Distance, Extreme Low Power

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



D. Abraham, Working Toward More Affordable Deep Space Cubesat Communications: MSPA and OMSPA, *https://www.dropbox.com/sh/fx8auva239g0wx9/AADMzWa7wgXpl0KmmoFk2rgaa/D2-Abraham?dl=0&preview=ISSC2016_WorkingTowardAffordableCommunications_URS257550.pptx#*

Jet Propulsion Laboratory
California Institute of Technology

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

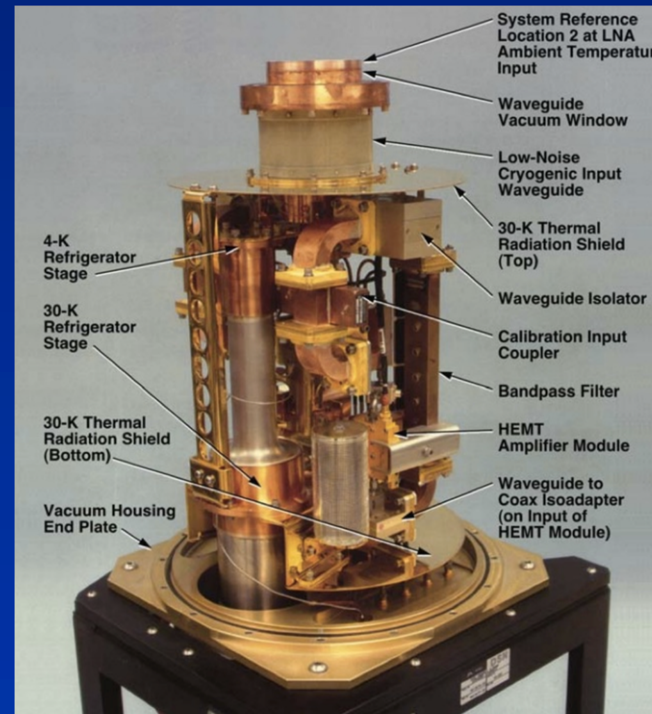
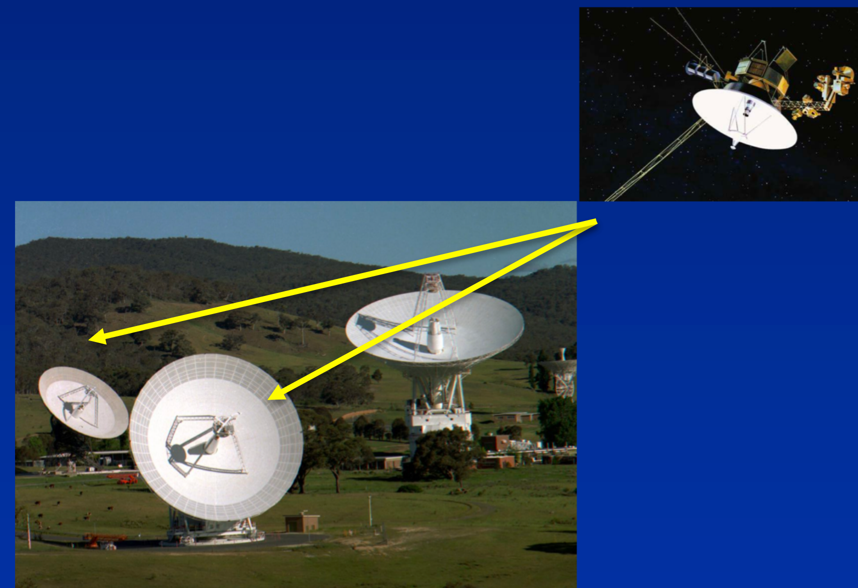
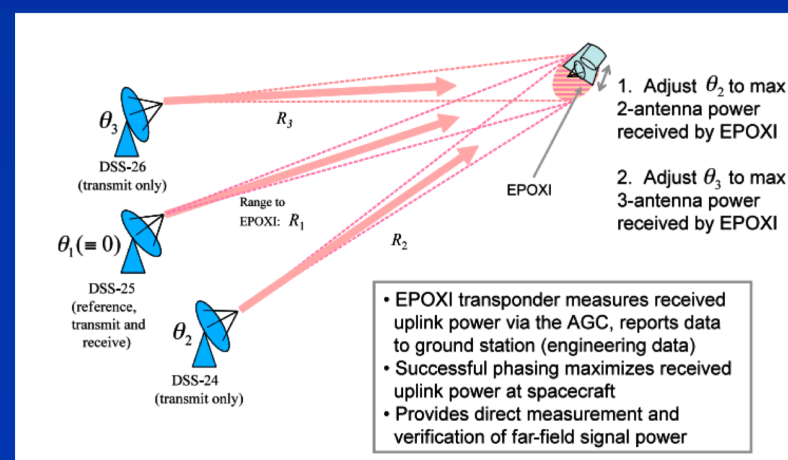


Fig. 2-12. Goldstone 70-m antenna XTR cone X-band HEMT amplifier.

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)



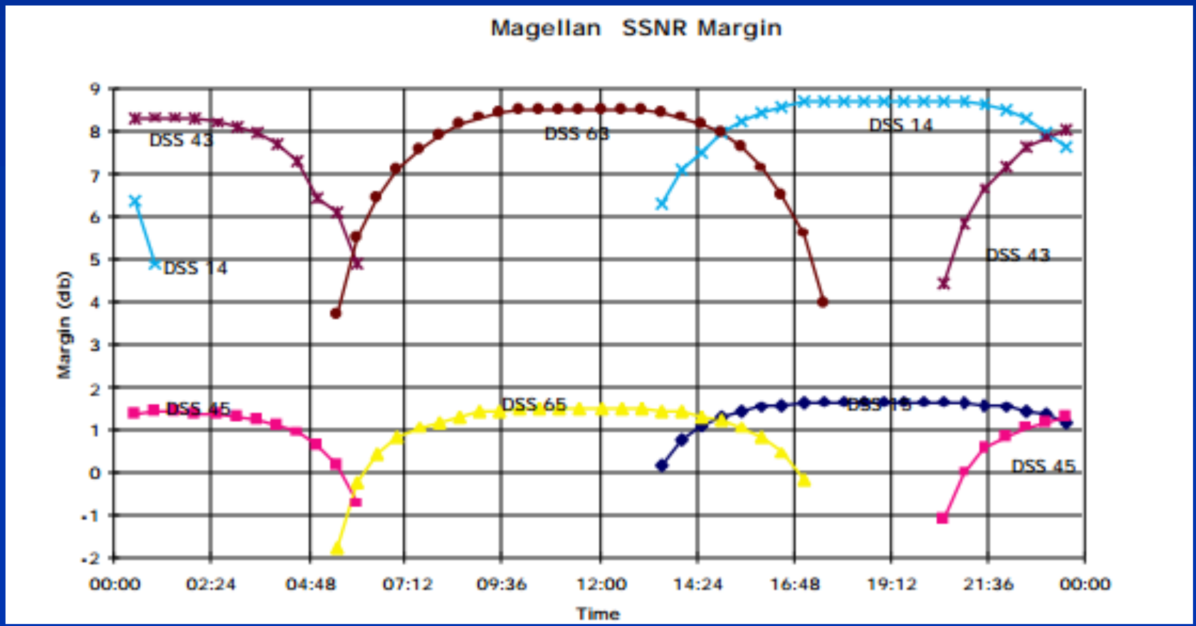


Jet Propulsion Laboratory
California Institute of Technology

Ref.: Vilnrotter, Uplink Array Concept Demonstration with the EPOXI Spacecraft, IEEE Aerospace, 2009

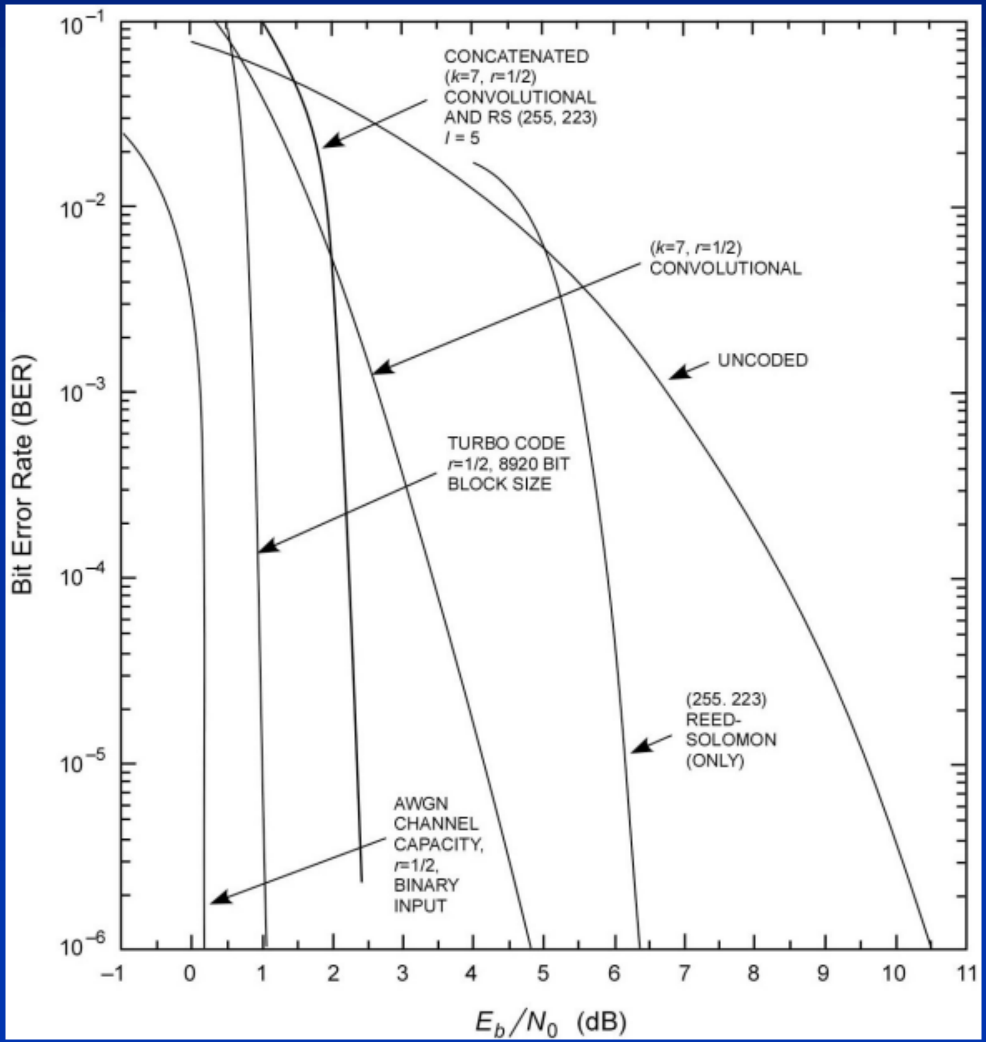
Maximizing Data Return via Adaptive Data Rate

- 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

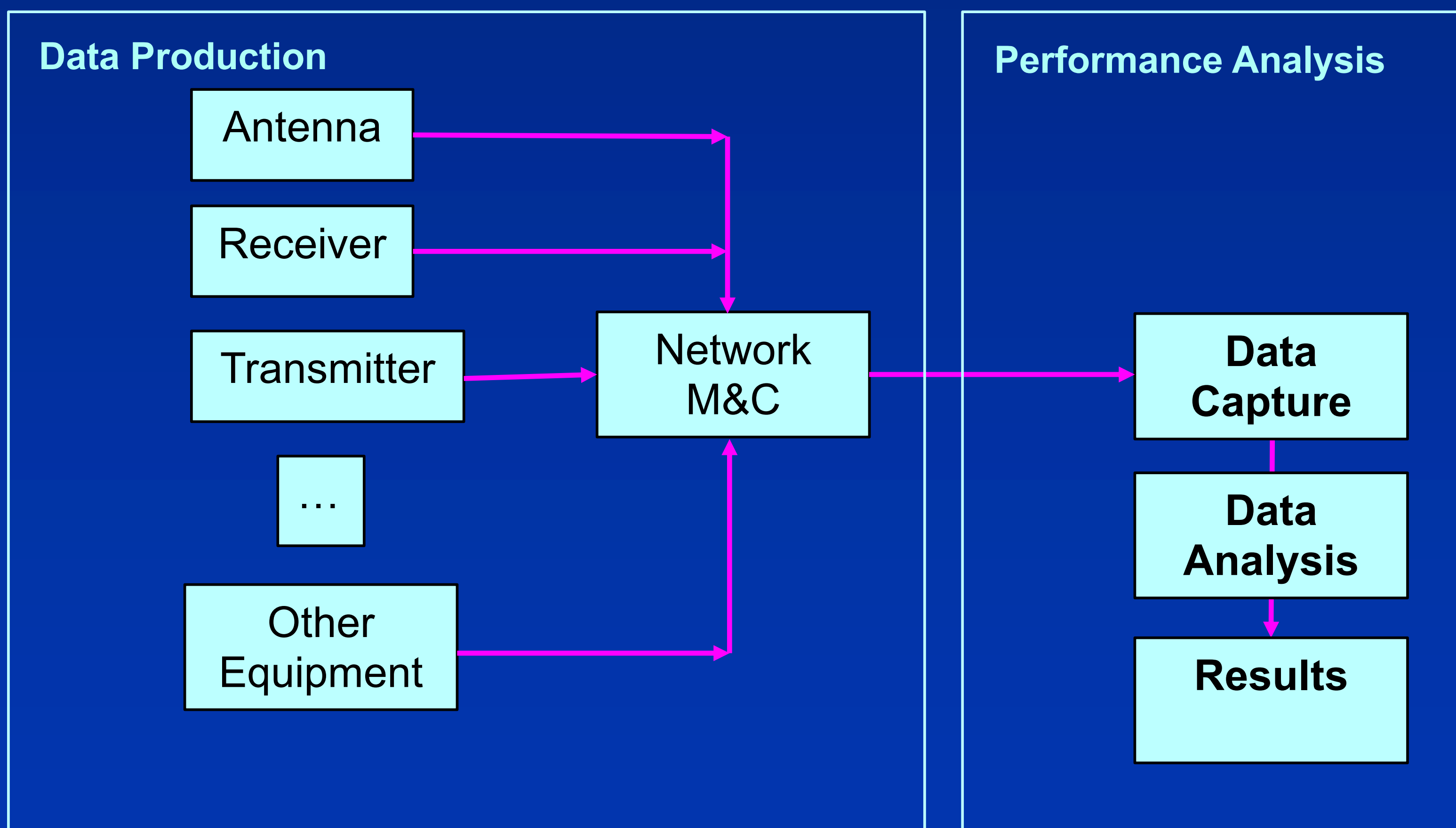
- Trading complexity (with lower processing rate) to gain better Eb/No performance
  - Within 1 dB of AWGN channel capacity
  - Convolutional, Reed Solomon, Concatenated, Turbo, and Low-Density Parity Check codes



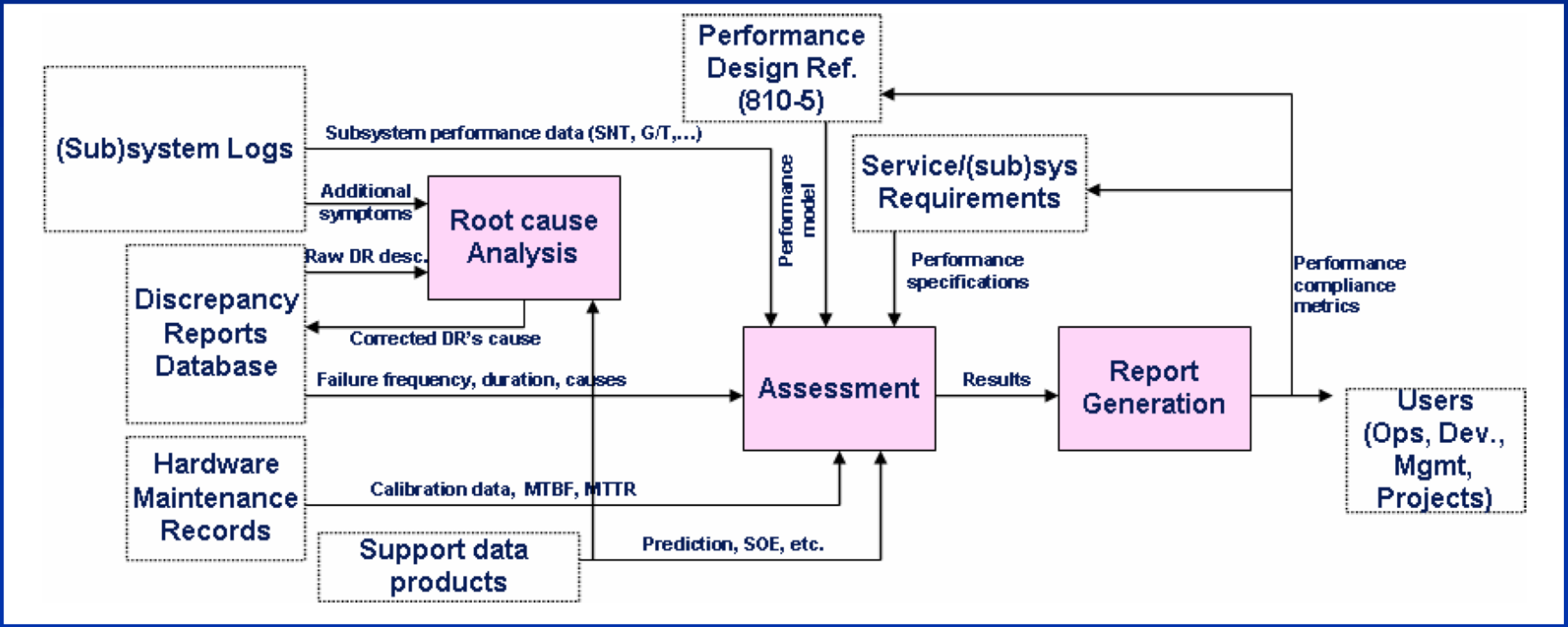
http://deepspace.jpl.nasa.gov/dsndocs/810-005/208/208A.pdf

2. Performance Analysis Processing

Monitor Data Capture



Key Processing Functions



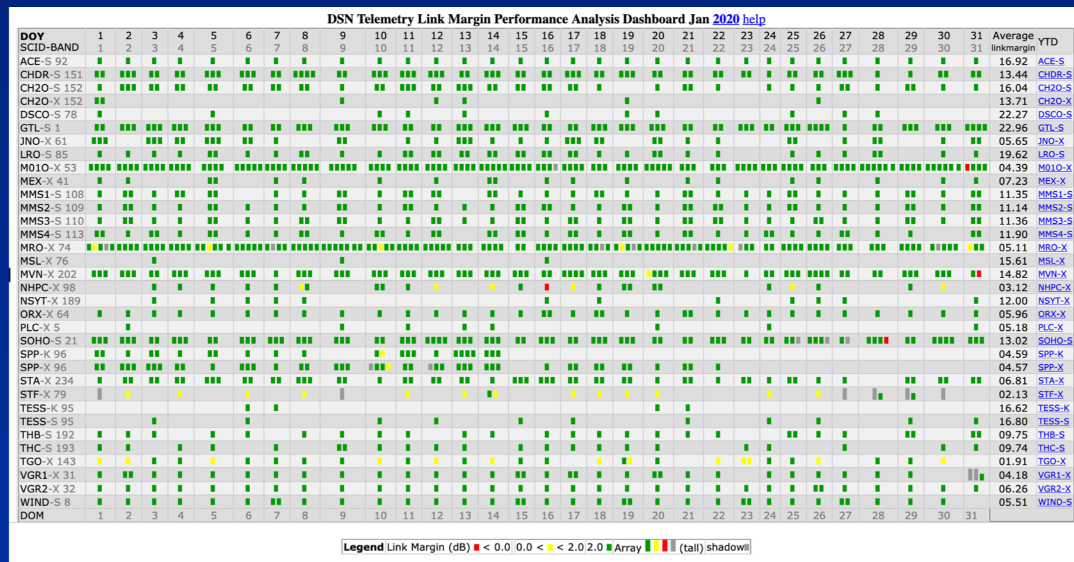
Key Metrics of Interest

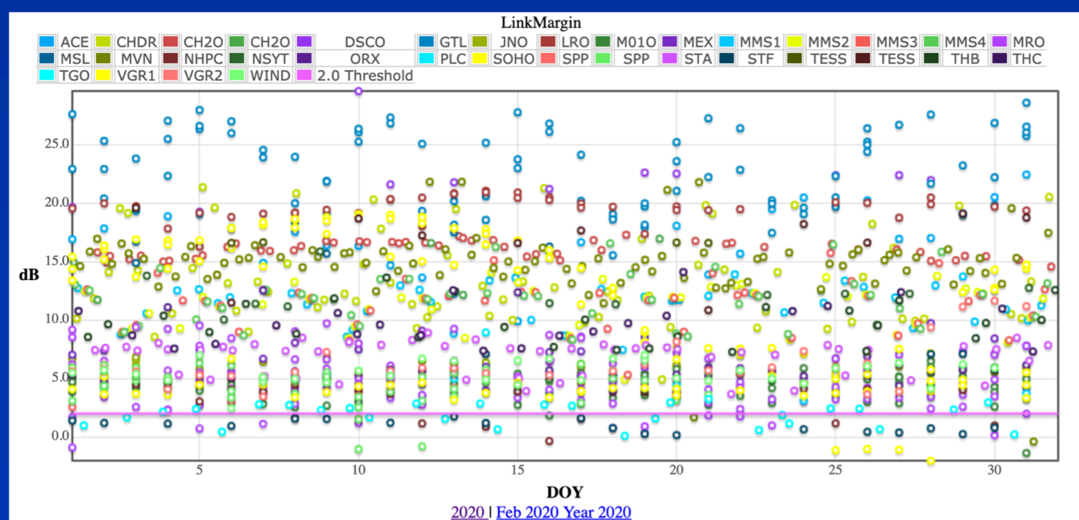
- G/T (Gain/System Noise Temperature)
- Operating link margin
- Data accountability
- Frequency stability
- Link setup time
- Resource utilization, e.g., WAN bandwidth
- Etc.

Performance Dashboard

Dashboards	years	year 2019	year 2020	
Data				
Linkmargin				
Linkmargin	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
70m	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Command Margin	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Accountability				
Doppler Accountability	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Ranging Accountability	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Delta-DOR Accountability	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Telemetry Accountability	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Command Accountability	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Utilization				
Ranging Utilization	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Command Utilization	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Antenna Pointing				
Conscan	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw query
Monopulse	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw query
QQCL				
Frame Quantity Accountability	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Frame Quality Accountability	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Telemetry Latency (Timely)	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Telemetry Latency (Complete)	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
Frame Gap (Continuity)	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	
System Noise Temperature				
SNT	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw query
SNT New Threshold	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	810-5
Radiometric				
Doppler Noise	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Ranging Noise	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Ranging Precal	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Radio Science				
Amplitude Stability	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Allan Deviation	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw summary
Precal Time				
Precal Time	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Signal Acqusition Time				
Signal Acqusition(nmclog)	2014 2015 2016 2017 2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	raw
Signal Acqusition (MIA)	2018	2019 1 2 3 4 5 6 7 8 9 10 11 12	2020 1 2 3 4 5 6 7 8 9 10 11 12	

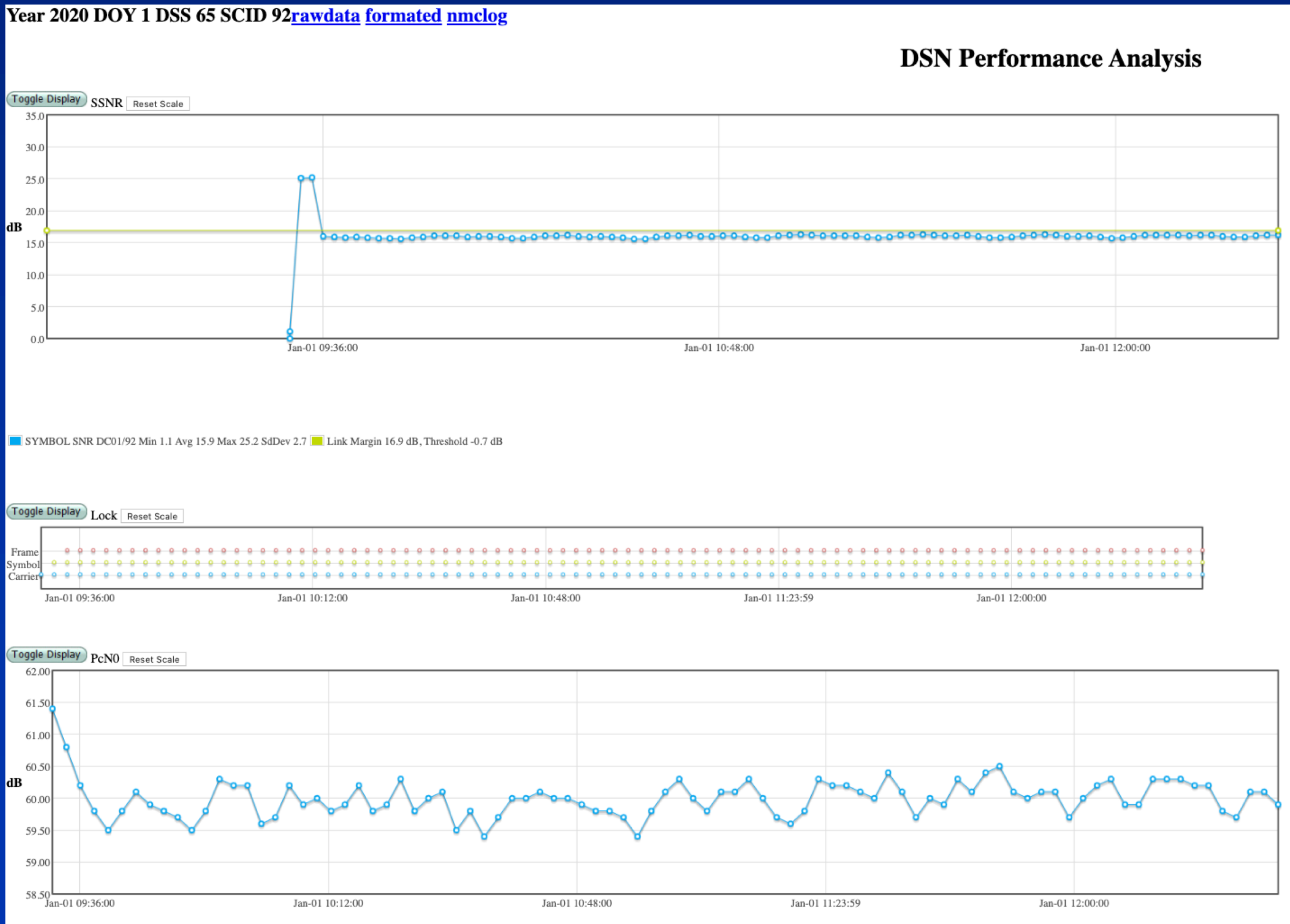
Sample Dashboard – Telemetry Link Margin





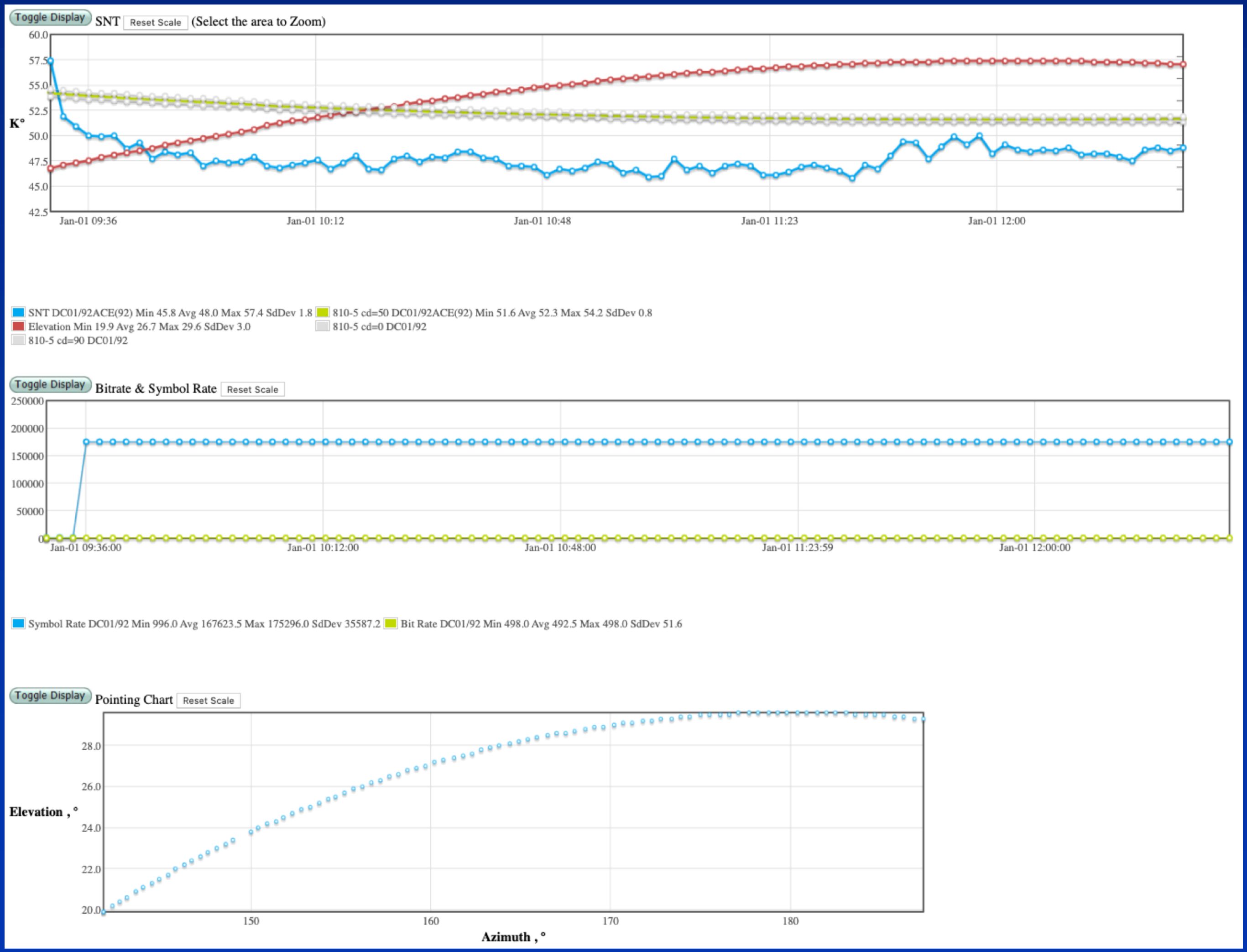
Jet Propulsion Laboratory
California Institute of Technology

Sample - Key Metrics Within a Pass



Jet Propulsion Laboratory
California Institute of Technology

Sample – Key Metric Within a Pass



Jet Propulsion Laboratory
California Institute of Technology

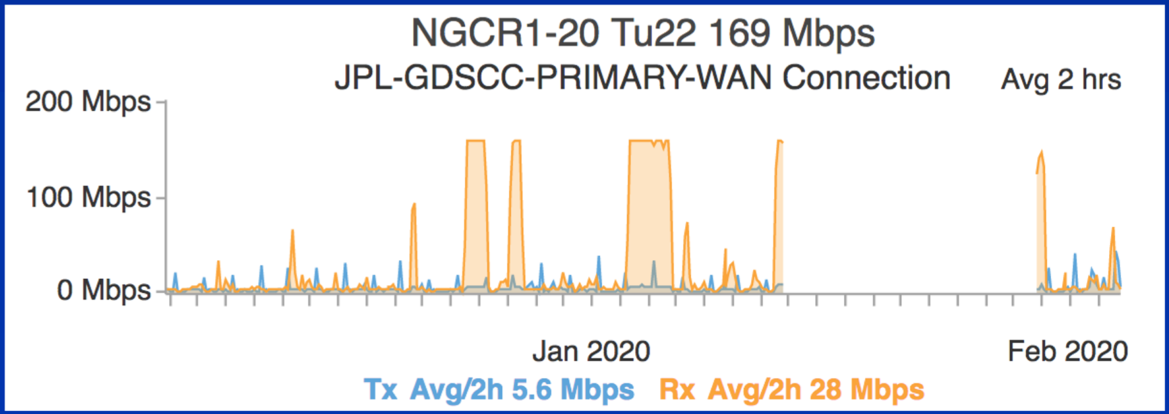
3. Expectation vs. Lessons Learned

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

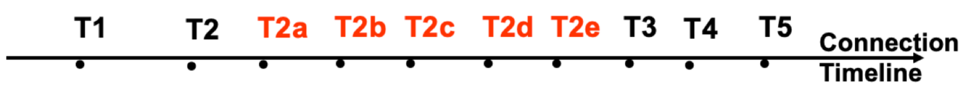
- Data Accounting
  - # of telemetry frames successfully decoded/ # of expected frames downlink by spacecraft
- WAN bandwidth usage
  - Aggregated data flow / Line capacity



Jet Propulsion Laboratory
California Institute of Technology

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



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

Jet Propulsion Laboratory
California Institute of Technology

Metrics Require Extensive Accounting

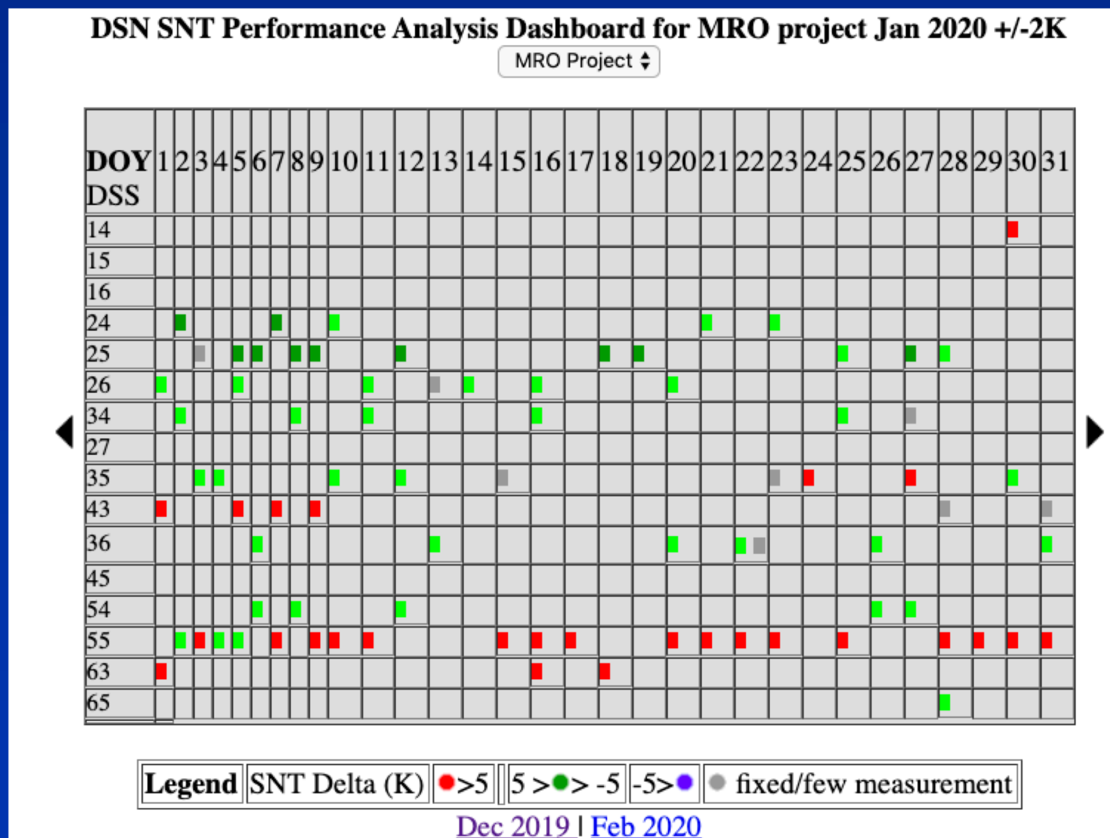
- G/T - Key parameter to monitor in comm system
  - Especially in deep space communications
- Gain (G) not measurable in typical spacecraft tracking pass
  - Leaving SNT (T) as monitored parameter available

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

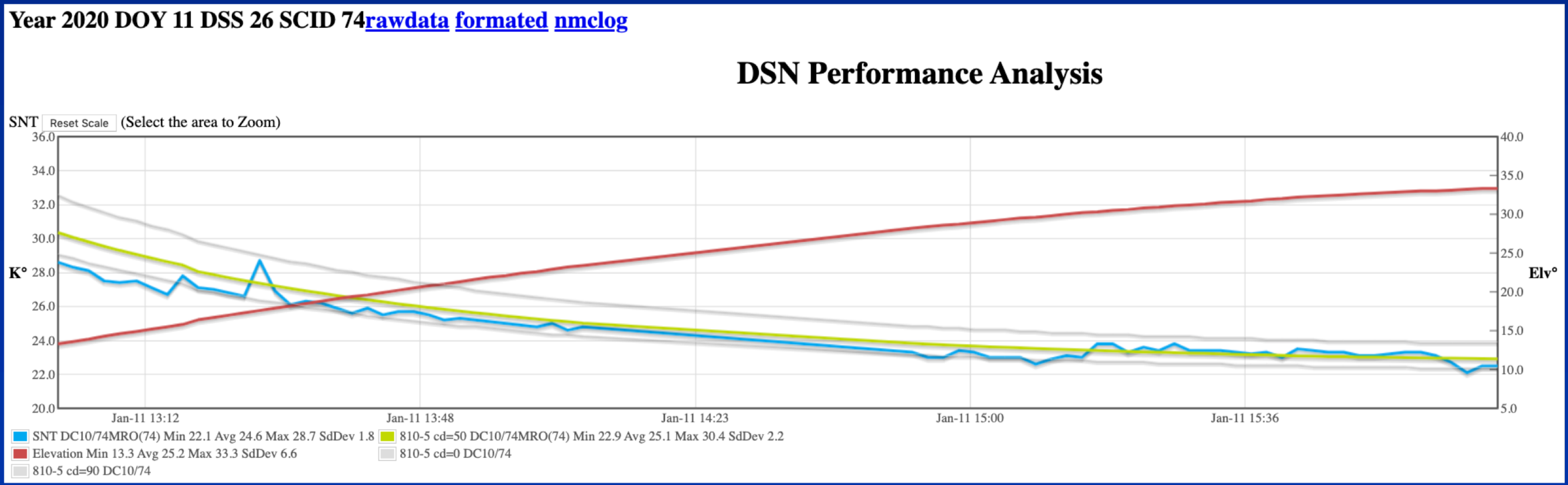
Relative SNT Monitoring

- Identify anomalous trend on one antenna vs. the rest



Expectations

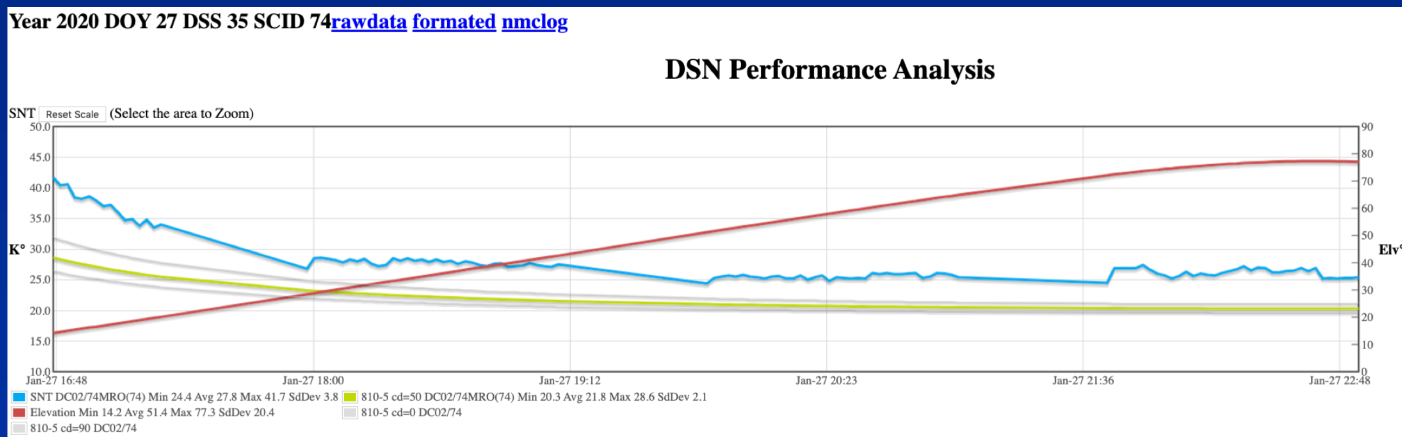
- Nominal behavior



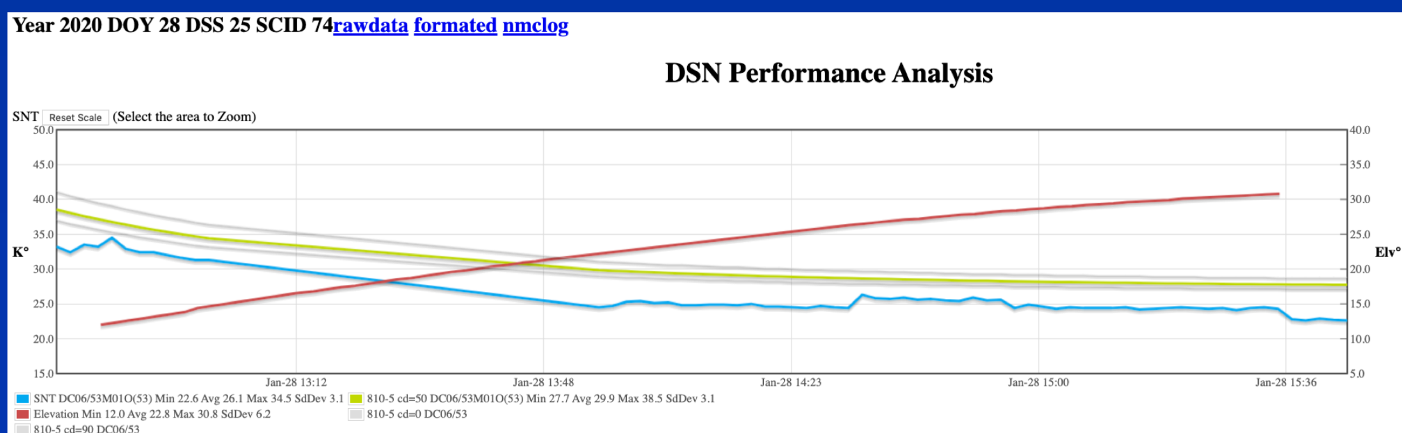
Jet Propulsion Laboratory
California Institute of Technology

Unexpected Observations

- Higher than expected



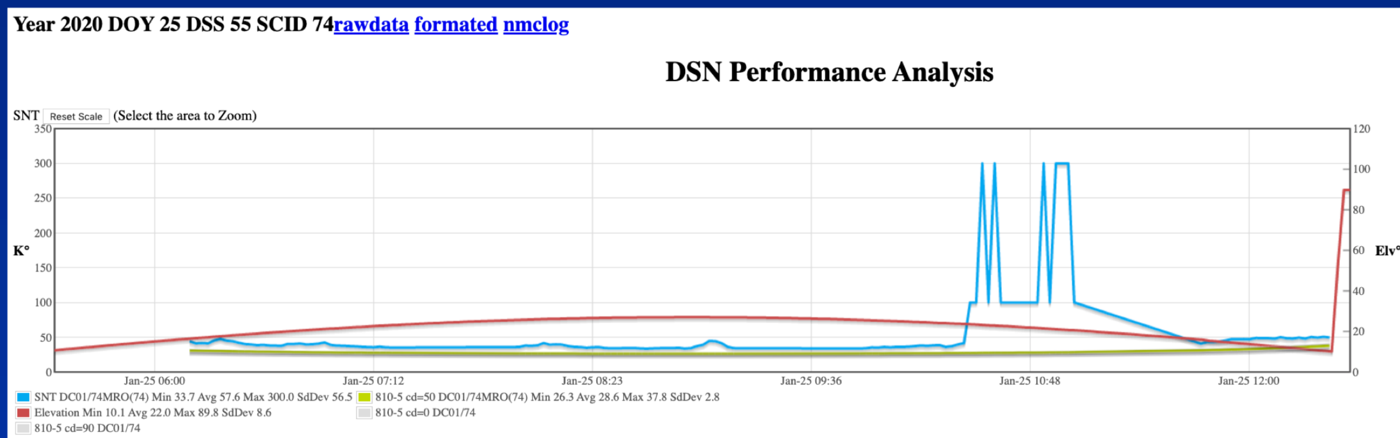
- Lower than expected



Jet Propulsion Laboratory
California Institute of Technology

Unexpected Observations

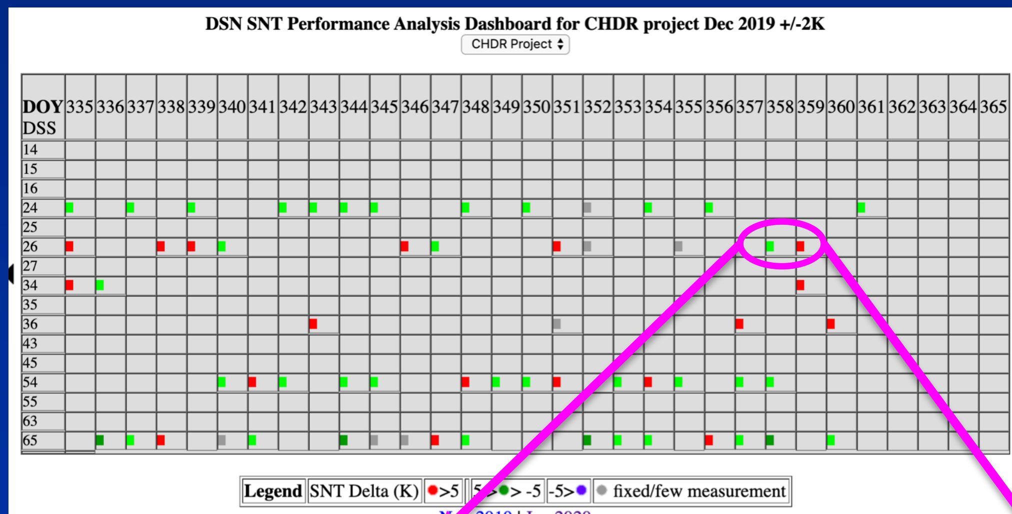
- Sudden jump in mid pass

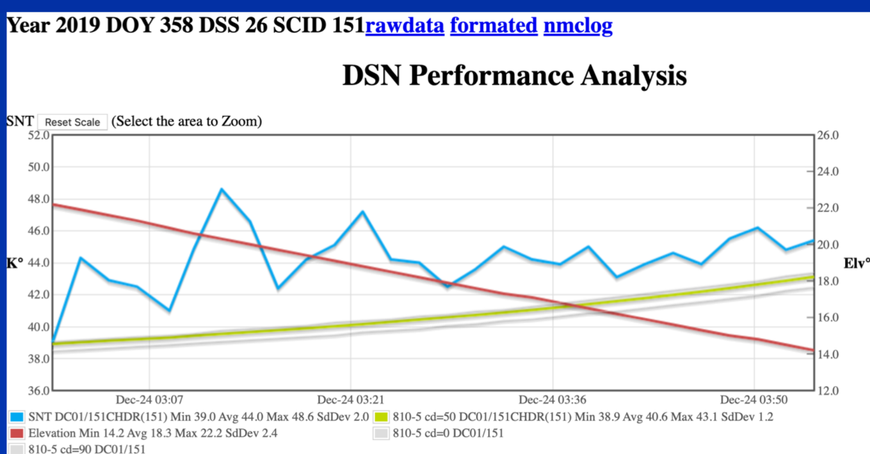


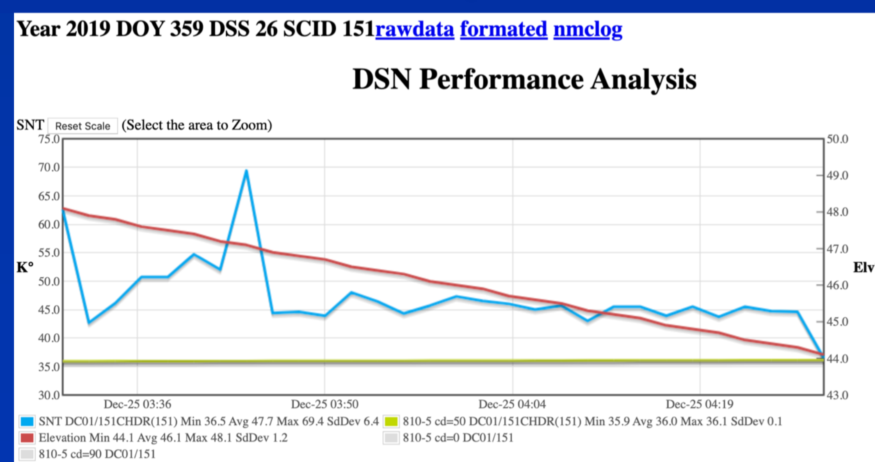
Jet Propulsion Laboratory
California Institute of Technology

Unexpected Observations

- Inconsistent data from same spacecraft and same antenna







Delta=3.4 K

Delta=11.7 K

Jet Propulsion Laboratory
California Institute of Technology

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

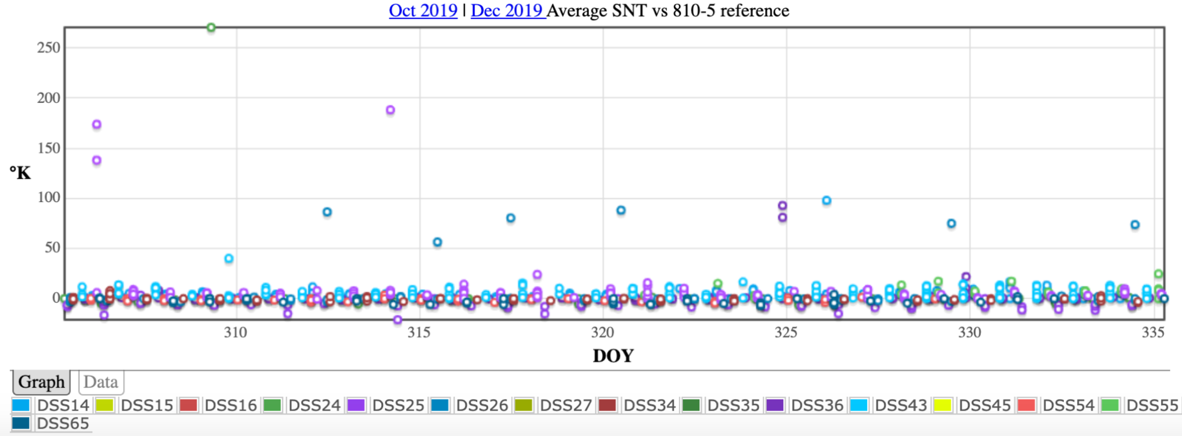
DSN SNT Performance Analysis Dashboard for X Band Nov 2019 Threshold SNT cd=90 +/- 2 K

X Band

DOY DSS	305 1	306 2	307 3	308 4	309 5	310 6	311 7	312 8	313 9	314 10	315 11	316 12	317 13	318 14	319 15	320 16	321 17	322 18	323 19	324 20	325 21	326 22	327 23	328 24	329 25	330 26	331 27	332 28	333 29	334 30	% red	% purple	total pass	DSS	SNT diff
14																															69% (61)	0%(0)	88	14	5.5
15																															0%(0)	0%(0)	0	15	
16																															0%(0)	0%(0)	0	16	
24																															0%(0)	61% (19)	31	24	3.4
25																															0%(0)	100% (62)	62	25	-6.9
26																															11%(5)	9%(4)	44	26	7.6
27																															0%(0)	0%(0)	0	27	
34																															5%(3)	8%(5)	63	34	-0.5
35																															0%(0)	0%(0)	0	35	
36																															11%(8)	0%(0)	74	36	3.1
43																															79% (107)	0%(0)	135	43	6.5
45																															0%(0)	0%(0)	0	45	
54																															0%(0)	16%(5)	32	54	-1.2
55																															93% (27)	0%(0)	29	55	7.8
63																															62% (75)	0%(0)	121	63	8.7
65																															3%(1)	61% (20)	33	65	-2.6

Legend SNT Delta (K) >SNT cd=90 +2 | < SNT cd=0 -2 SNT cd=90> | >SNT cd=0 | Fix Value/bad SNT

Oct 2019 | Dec 2019 Average SNT vs 810-5 reference



Jet Propulsion Laboratory
California Institute of Technology

Results Before and After Exclusions

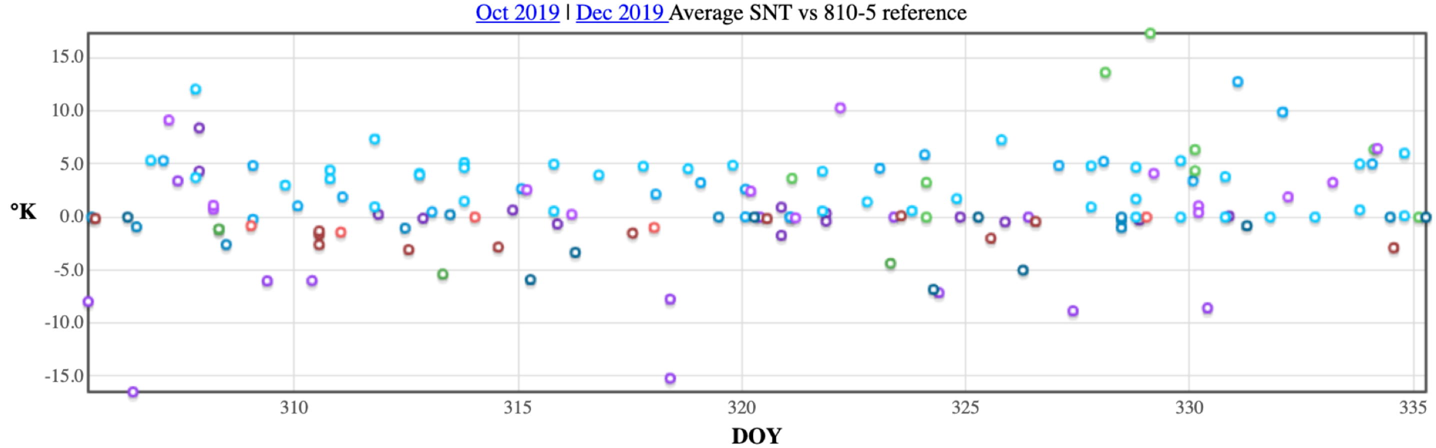
DSN SNT Performance Analysis Dashboard for X Band Nov 2019 +/- 2 K

X Band

DOY / DSS	305 / 1	306 / 2	307 / 3	308 / 4	309 / 5	310 / 6	311 / 7	312 / 8	313 / 9	314 / 10	315 / 11	316 / 12	317 / 13	318 / 14	319 / 15	320 / 16	321 / 17	322 / 18	323 / 19	324 / 20	325 / 21	326 / 22	327 / 23	328 / 24	329 / 25	330 / 26	331 / 27	332 / 28	333 / 29	334 / 30	% red	% purple	total pass	DSS	SNT diff
14																															**50%**(9)	0%(0)	18	**14**	3.6
15																															0%(0)	0%(0)	0	**15**	
16																															0%(0)	0%(0)	0	**16**	
24																															0%(0)	**50%**(2)	4	**24**	-3.0
25																															0%(0)	**100%**(10)	10	**25**	-6.2
26																															0%(0)	0%(0)	6	**26**	-0.6
27																															0%(0)	0%(0)	0	**27**	
34																															0%(0)	33%(4)	12	**34**	-1.5
35																															0%(0)	0%(0)	0	**35**	
36																															15%(2)	0%(0)	13	**36**	0.8
43																															**60%**(21)	0%(0)	35	**43**	3.3
45																															0%(0)	0%(0)	0	**45**	
54																															0%(0)	0%(0)	3	**54**	-0.6
55																															**67%**(4)	0%(0)	6	**55**	6.1
63																															21%(3)	0%(0)	14	**63**	3.1
65																															0%(0)	**60%**(3)	5	**65**	-2.4

Legend SNT Delta (K) >SNT cd=90 +2 | < SNT cd=0 -2 | SNT cd=90> | >SNT cd=0 | Fix Value/bad SNT

Oct 2019 | Dec 2019 Average SNT vs 810-5 reference



Graph | Data

DSS14 DSS15 DSS16 DSS24 DSS25 DSS26 DSS27 DSS34 DSS35 DSS36 DSS43 DSS45 DSS54 DSS55 DSS63 DSS65

Jet Propulsion Laboratory
California Institute of Technology

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

Jet Propulsion Laboratory
California Institute of Technology