Analyzing Deep Space Network System Performance and Lessons Learned

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Information about Speaker

- Current responsibility
  - Chief System Engineer of the NASA Deep Space Network (DSN) at Jet Propulsion Laboratory, Pasadena, California
- Area of interests
  - System engineering
    - DSN systems for spacecraft communications and science observations
  - System development
    - Galileo telemetry, antenna arraying, Entry Descent Landing signal detection for Mars Rovers Spirit & Opportunity, Voyager 2 heliopause data return using CSIRO Parkes antenna, Morehead State University's 21-m antenna upgrade
  - Consultative Committee for Space Data Systems (CCSDS)
    - Cross Support Transfer Services Area, CCSDS Engineering Steering Group
- Professional recognitions
  - NASA Exceptional Service Medal, NASA Exceptional Achievement Medal, and several NASA New Technology and Space Act Awards
  - IARIA Fellow

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Analyzing Deep Space Network System Performance and Lessons Learned

- Nature of deep space communications & navigation
- Key performance metrics to be monitored
- Challenges observed
- Lessons learned

1. Deep Space Communications & Navigation

Deep Space Communications Environment

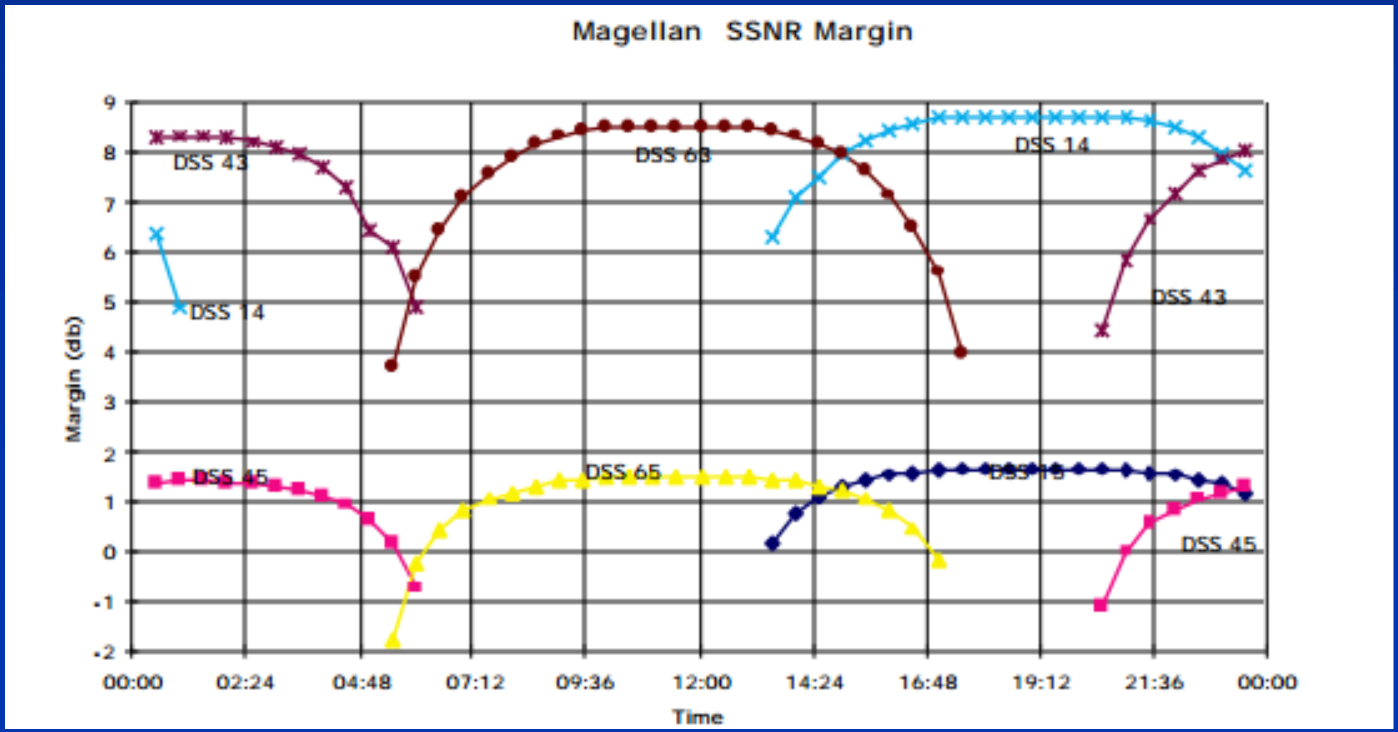
- Long distance communications
  - Lunar missions (0.002 AU) to Voyager at 100 AU

	Distance Scale	Power scale
LEO	1	1.0E+00
Moon (e.g., LRO; Human Exploration)	800	6.4E+05
Mars (e.g., Perserverance rover, MRO)	300,000	9.0E+10
Jupiter (e.g. Juno, Europa)	1,560,000	2.4E+12
Saturn (e.g. Cassini)	2,850,000	8.1E+12
Neptune (e.g., Voyager)	8,800,000	7.7E+13
Pluto (e.g., New Horizons)	10,100,000	1.0E+14
Edge of solar system (e.g., Voyager)	30,000,000	9.0E+14

- Low power reception, high power transmission
  - Require large antenna with high G/T and high EIRP
  - Optimal modulation & forward error correction codes
    - Special modes
      - MFSK for Entry Decent Landing when signal is extremely weak
      - Beacon tones for long duration flight to minimize track time and cost
  - Antenna arraying with multiple aperture to increase SNR

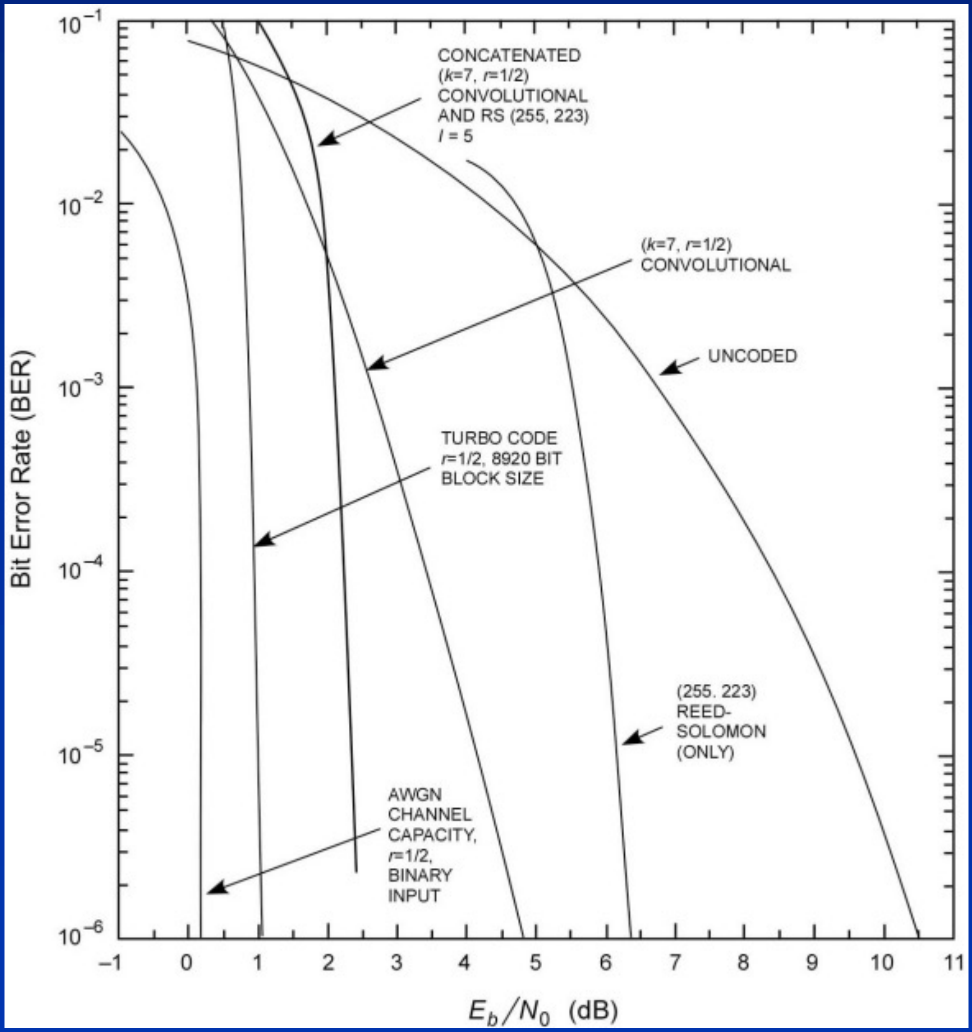
Optimized Performance with Variable Data Rate

- Link margin changed by varying elevation during the pass
  - More important at higher operating frequency
  - Adjusting rate per available link margin to maximize data return



Optimized Performance with Error Correction Codes

- Employed special forward error correction codes (e.g., concatenated convolutional/Reed Solomon, Turbo, LDPC) to gain better performance
  - Within 1 dB of AWGN channel capacity
- Minimized system loss in system design
  - Typically less than 1 dB



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

Doppler & Ranging Data for Navigation

- Precise measurement of Doppler and Ranging
  - 50 microHz/s Doppler, 1-m ranging
    - 10^$^{-14}$ of 2-30 GHz carrier frequency

- Calibration data needed to minimize systematic errors
  - Earth orientation parameters
  - Media delay in Earth troposphere and ionosphere

2. Key Performance Metrics

Key Performance Metrics

- Some key metrics
  - Signal reception – G/T
  - Signal transmission – EIRP
  - System SNR loss from antenna to telemetry decoder
- Data collected from operational setting with spacecraft tracking
  - Reflect true operational performance relevant to missions
  - Leverage on abundance of operational data

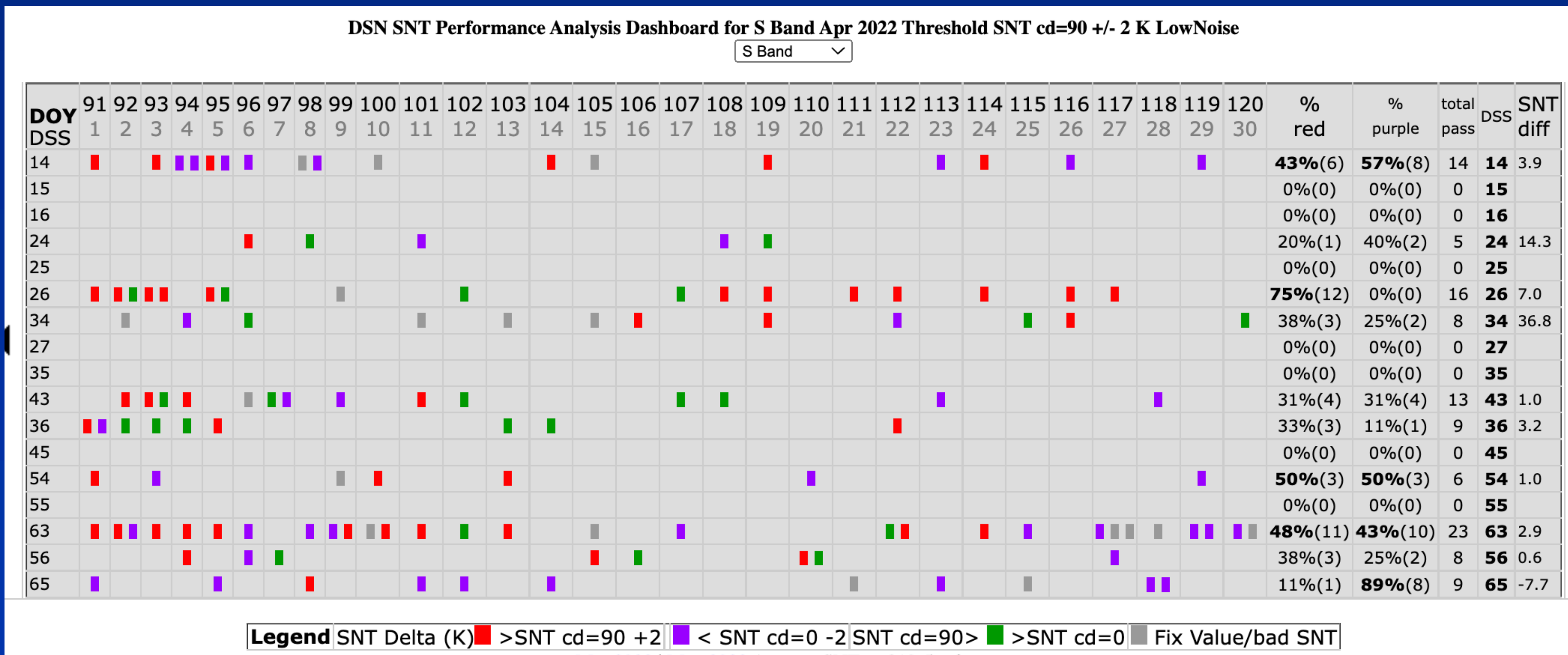
Sample Display - Categories

DSN Performance Analysis

Internal PAR Dash Boards

Dashboards	years	year 2021	year 2022	
Linkmargin				
Linkmargin	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
70m	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Command Margin	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Accountability				
Doppler Accountability	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Ranging Accountability	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Delta-DOR Accountability	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Telemetry Accountability	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Command Accountability	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Utilization				
Ranging Utilization	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Command Utilization	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Antenna Pointing				
Conscan	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw query
Monopulse	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw query
QQCL				
Frame Quantity Accountability	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Frame Quality Accountability	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Telemetry Latency (Timely)	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Telemetry Latency (Complete)	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
Frame Gap (Continuity)	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	
System Noise Temperature				
SNT	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw query
SNT New Threshold	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| 810-5
Radiometric				
Doppler Noise	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Ranging Noise	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Ranging Precal	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Radio Science				
Amplitude Stability	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Allan Deviation	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw summary
Precal Time				
Precal Time	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Signal Acqusition Time				
Signal Acqusition(nmclog)	2016 2017 2018 2019 2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	| raw
Signal Acqusition (MIA)	2020	2021 1 2 3 4 5 6 7 8 9 10 11 12	2022 1 2 3 4 5 6 7 8 9 10 11 12	

Sample Display – System Noise Temperature



DSN SNT Performance Analysis Dashboard for S Band Apr 2022 Threshold SNT cd=90 +/- 2 K LowNoise

S Band

DOY DSS	91 1	92 2	93 3	94 4	95 5	96 6	97 7	98 8	99 9	100 10	101 11	102 12	103 13	104 14	105 15	106 16	107 17	108 18	109 19	110 20	111 21	112 22	113 23	114 24	115 25	116 26	117 27	118 28	119 29	120 30	% red	% purple	total pass	DSS	SNT diff
14																															**43%**(6)	**57%**(8)	14	**14**	3.9
15																															0%(0)	0%(0)	0	**15**	
16																															0%(0)	0%(0)	0	**16**	
24																															20%(1)	40%(2)	5	**24**	14.3
25																															0%(0)	0%(0)	0	**25**	
26																															**75%**(12)	0%(0)	16	**26**	7.0
34																															38%(3)	25%(2)	8	**34**	36.8
27																															0%(0)	0%(0)	0	**27**	
35																															0%(0)	0%(0)	0	**35**	
43																															31%(4)	31%(4)	13	**43**	1.0
36																															33%(3)	11%(1)	9	**36**	3.2
45																															0%(0)	0%(0)	0	**45**	
54																															**50%**(3)	**50%**(3)	6	**54**	1.0
55																															0%(0)	0%(0)	0	**55**	
63																															**48%**(11)	**43%**(10)	23	**63**	2.9
56																															38%(3)	25%(2)	8	**56**	0.6
65																															11%(1)	**89%**(8)	9	**65**	-7.7

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

Sample Display – Link Margin

DSN Telemetry Link Margin Performance Analysis Dashboard Apr 2022 help

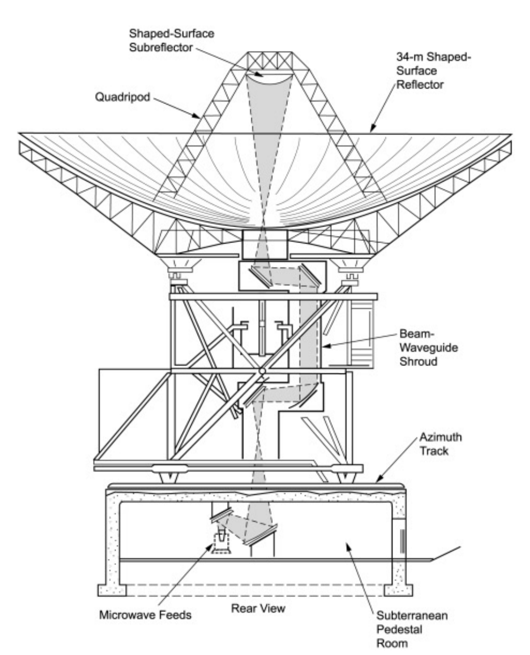
DOY SCID-BAND	91 1	92 2	93 3	94 4	95 5	96 6	97 7	98 8	99 9	100 10	101 11	102 12	103 13	104 14	105 15	106 16	107 17	108 18	109 19	110 20	111 21	112 22	113 23	114 24	115 25	116 26	117 27	118 28	119 29	120 30	Average linkmargin	YTD
ACE-S 92																															19.52	ACE-S
CHDR-S 151																															13.03	CHDR-S
DART-X 135																															12.69	DART-X
DSCO-S 78																															19.24	DSCO-S
EMM-X 62																															10.77	EMM-X
GTL-S 1																															20.57	GTL-S
JNO-X 61																															05.12	JNO-X
JWST-K 170																															12.62	JWST-K
JWST-S 170																															13.81	JWST-S
LRO-S 85																															19.00	LRO-S
LUCY-X 49																															05.29	LUCY-X
M01O-X 53																															02.54	M01O-X
MEX-X 41																															08.12	MEX-X
M20-X 168																															15.22	M20-X
MMS1-S 108																															11.30	MMS1-S
MMS2-S 109																															11.08	MMS2-S
MMS3-S 110																															10.83	MMS3-S
MMS4-S 113																															10.89	MMS4-S
MRO-X 74																															05.26	MRO-X
MSL-X 76																															13.72	MSL-X
MVN-X 202																															11.34	MVN-X
NHPC-X 98																															04.58	NHPC-X
NSYT-X 189																															07.84	NSYT-X
ORX-X 64																															10.15	ORX-X
PLC-X 5																															04.03	PLC-X
SOHO-S 21																															11.09	SOHO-S
SPP-K 96																															03.57	SPP-K
STEREOA-X 234																															12.71	STEREOA-X
TESS-K 95																															-5.06	TESS-K
TESS-S 95																															11.52	TESS-S
THB-S 192																															09.79	THB-S
THC-S 193																															09.94	THC-S
TRACE-X 143																															05.72	TRACE-X
VGR1-X 31																															04.34	VGR1-X
VGR2-X 32																															04.86	VGR2-X
WIND-S 8																															07.21	WIND-S
XMM-S 60																															09.32	XMM-S
DOM	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		

Legend	Link Margin (dB) < 0.0	0.0 < < 2.0	2.0	Array (tall)	shadow

3. Challenges Observed

Challenges with Antenna Gain Measurements

- Antenna Gain (G) is a key parameter of system G/T
  - Affected by
    - antenna beam illumination in its optical path
    - antenna main reflector surface accuracy
    - antenna surface deformation during the track, especially at low elevations
  - Determinable only with special calibration with known radio source
    - At the time of antenna commissioning or special need for calibration
  - For spacecraft tracking, assume antenna performed at level determined by calibration



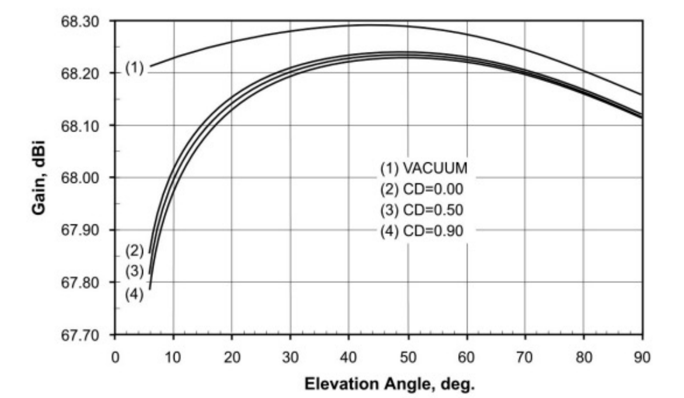


Figure 15. DSS-26 (Goldstone) X-Band Receive Gain versus Elevation Angle, X/Ka-Mode, 8420 MHz

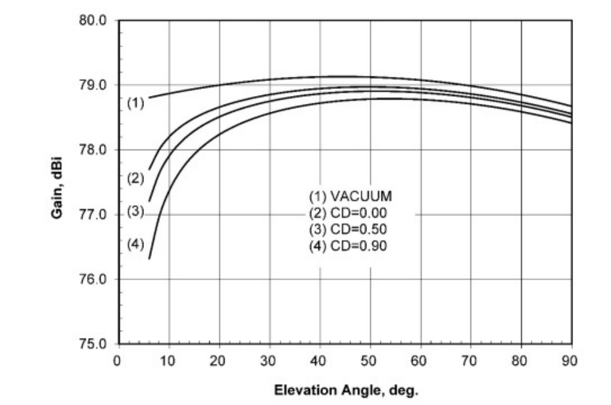


Figure 25. DSS-26 (Goldstone) Ka-Band Receive Gain versus Elevation Angle, X/Ka-Mode, 32000 MHz

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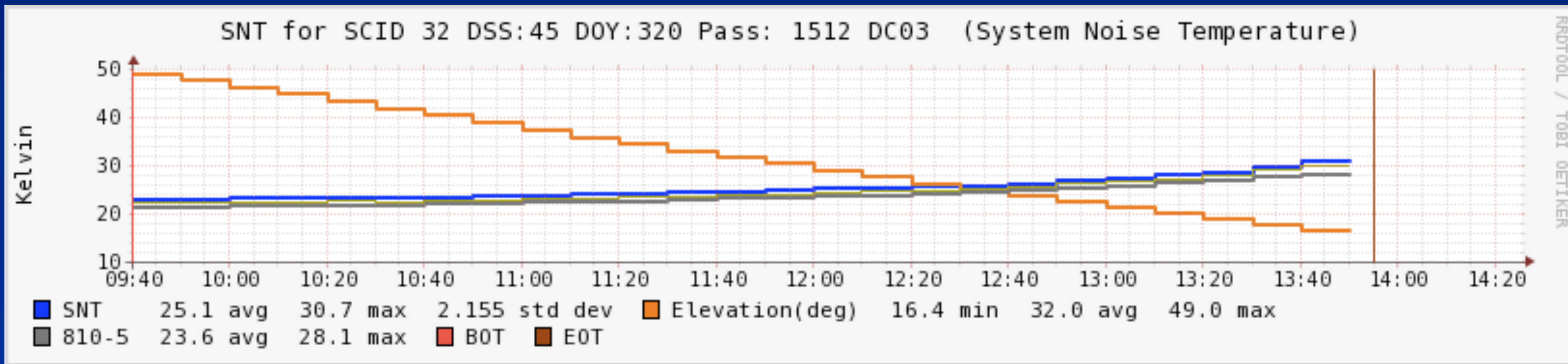
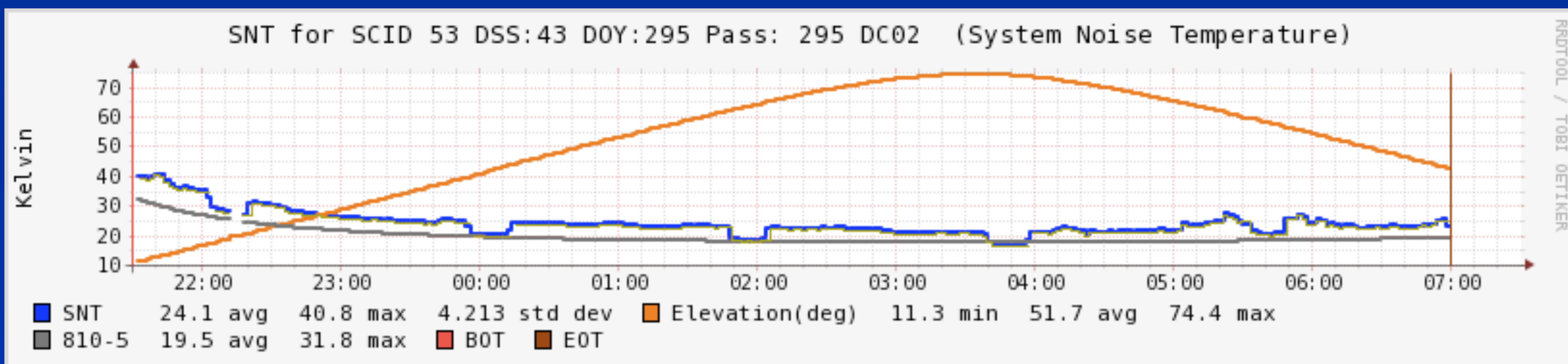
Challenges with System Noise Temperature Measurements

- System noise temperature (SNT) is part of the G/T
  - Measurements done with and without added calibrated noise enables determination of system noise temperature (Y-factor method)
  - Typically measured during the spacecraft tracking passes
    - Varied by elevations
    - Affected by weather
  - Measurements have many exceptions that need to be accounted for in the processing algorithm
    - Frequency and LNA device/path dependent
    - Algorithm tailored to low SNR, not accurate for very strong signal
    - Noise contribution from planetary bodies within the antenna beam, e.g., Moon
    - Operator override, e.g., disabling of SNT measurements
    - Uncalibrated noise diode, e.g., overdue calibration
    - Other anomalous behaviors (shown in next chart)

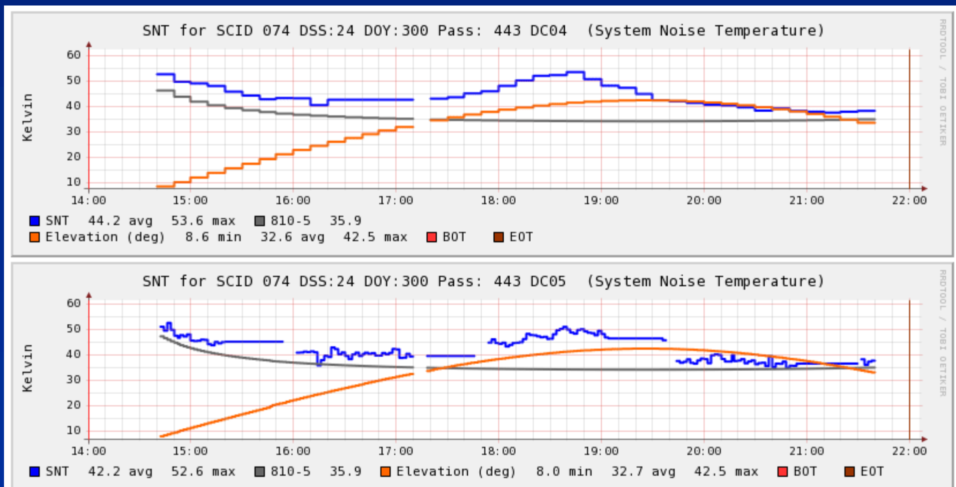
Sample of Nominal SNT



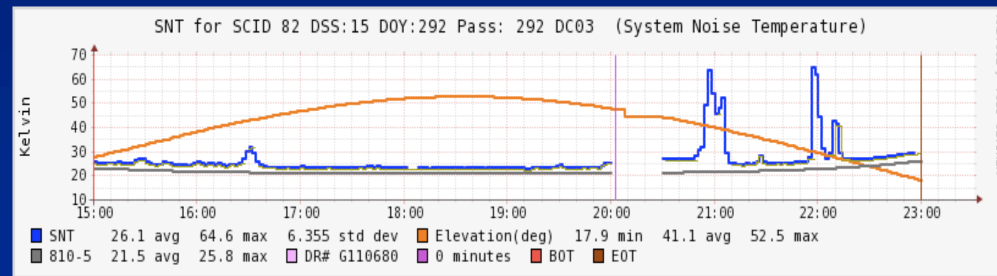


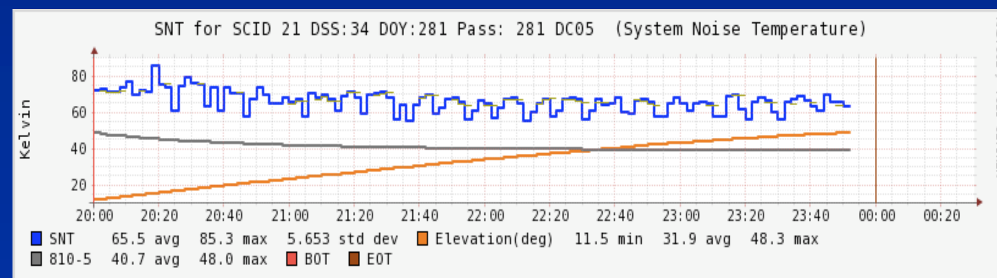
- Similar profile between actual and predicted SNT
- Averaged Delta SNT between actual and predicted < 5 K
- Smooth curve. No spike or large offset

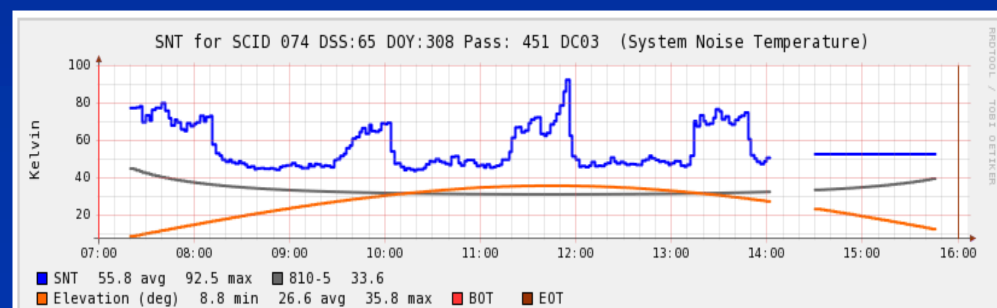
Sample of Anomalous SNT



- Large variations in mid track







- Significant delta SNT
- Oscillating profile, presence of large spikes

- A simple threshold method would not sufficiently characterize the SNT measurements

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Challenges with EIRP Measurements

- Signal transmission EIRP is partly inferred
  - EIRP = Transmitting Power * Antenna Gain
  - Antenna gain assumed, not measurable
  - Transmitting power is monitored
    - But measurement point is before the radiation end point of the ground antenna

Challenges with Link Margin Characterization

- Link Margin = Operating SNR – Decoder threshold
  - Objective: assess robustness of the link on data transmission/reception
  - Affected by:
    - antenna pointing
    - accuracy of modelled EIRP & G/T parameters, for both flight and ground equipment
    - decoder threshold offered by type of error correcting codes and code rate
    - system loss contribution from analog-to-digital converter, filters, cabling, etc.
    - weather conditions
- Operating SNR
  - SNR estimate is noisy, within few tenths of dB
- Decoder threshold
  - Code information data not as reliably accurate
- Observation – Spacecraft with dual frequencies operates with different margin for each frequency link

4. Lessons Learned

Lessons Learned

- Imperfect characterization of system performance
  - Measurements could be closed to truth, but require some extrapolation/assumptions, such as assumed antenna gain
- Operations data from spacecraft tracking vs. specific test data at commission
  - Operations data tend to be different from calibration measurements that are done by experts at time of system commission
  - With much larger variation and not necessarily conform with nominal behaviors
  - Useful for relative performance comparison between antennas
    - Harder to validate against the design specifications
- Data visualization
  - Need to account for configuration variations
    - Subgroup data in common configuration for correct interpretation, e.g.
      - SNT – received only, transmitted & received, frequency-specific, high vs. low SNR, exclusion of planetary background cases
      - Link Margin – frequency specific, antenna size

Lessons Learned

- Algorithm adaptive
  - Need to adapt to the fact that the system under measured changes over time
  - Need to adapt to changes in input data as the system under measured evolves over time
    - e.g., specific events in monitor & control log, changes in performance model
  - Need to check on additional data that affect validity of measurements
    - e.g., validity of noise diode calibration
- Subject matter expertise and neural net algorithm
  - Subject matter expertise required for proper accounting of system behaviors
  - Neural net algorithm could be helpful, e.g., data classification of SNT behaviors between nominal and anomalous categories

Acronyms

- AU – Astronomical unit (150,000, 000 km)
- AWGN – Additive White Gaussian Noise
- dB – decibel
- DSN – (NASA) Deep Space Network
- EIRP - Equivalent Isotropic Radiating Power
- G/T – Gain/Temperature
- K – Kelvins degree
- LDPC – Low Density Parity Check
- MFSK – Multiple Frequency Shift Key
- RF – Radio Frequency
- SNR – Signal to Noise Ratio
- SNT – System Noise Temperature