Radio Frequency Optics Design of the Deep Space Network Large Array 6-Meter Breadboard Antenna

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This article describes the radio frequency (RF) design of the 6-meter breadboard antenna planned as part of the Deep Space Network (DSN) Large Array three-element interferometer. The design process, the expected RF performance using both the calculated and measured feed patterns, and the degradation due to mechanical displacements are shown. Using an estimated noise temperature for the low-noise amplifier (LNA), the maximum and minimum G/T performance is computed.

I. Introduction

An early version of the Deep Space Network (DSN) Large Array 6-meter breadboard antenna[2] was designed for maximum gain. This design had a gain of 52.82 dB and a gain-to-noise temperature ratio (G/T) of 38.49 dB/K (assuming a 240-K ambient temperature and an amplifier noise temperature of 15 K). It was calculated that an antenna designed for optimal G/T would yield a G/T of 40.9 dB/K. However, the main reflector profile of the early design had already been given to a vendor for fabrication. Therefore, to provide the maximum G/T attainable, the antenna was redesigned by reshaping the subreflector and moving the feed location, while retaining the main reflector design.

This article will describe the new design and the process by which it was attained, the expected radio frequency (RF) performance using the calculated and measured feed patterns, and the performance degradation due to mechanical displacements.

II. Optimizing for Maximum *G/T*

In a dual-reflector antenna that is geometrical optics shaped for maximum gain, the main reflector is illuminated by the subreflector in such a way as to produce a uniform aperture distribution [1]. This utilizes a subreflector pattern that has a high edge taper that is truncated to zero at the edge of the main reflector. Unfortunately, due to diffraction effects, a real subreflector pattern does not go to zero at the

[1] Communications Ground Systems Section.

[2] V. Jamnejad, "Shaping of 6-m Reflector," *Monthly Reports* (internal document), DSN Array Task, Jet Propulsion Laboratory, Pasadena, California, January 2003.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

main reflector edge, and there is substantial spillover in the rear direction. This spillover sees the hot Earth and consequently increases the noise temperature of the antenna system. The DSN has typically dealt with this problem in two ways: (1) select the uniform illumination function of the main reflector to be less than the physical aperture, thus using the remainder of the aperture as a noise shield and reducing the spillover energy that falls on the hot Earth, or (2) select the illumination function to be uniform to a given radius and then taper it to zero at the reflector edge, also reducing the rear spillover. The 70-meter antennas, the high-efficiency (HEF) antenna, DSS 13, and the Antenna Research System Task (ARST) antennas used method 1, and the operational beam-waveguide (BWG) antennas used method 2. Both methods yield virtually identical results for G/T.

To provide a measure of success for a new design optimized for G/T, it is necessary to know what could have been done with the existing design constraints if the main reflector was allowed to change. Using method 1 above and given the same feed and focal length, the two parameters to be optimized are the angle to the edge of the subreflector and the radius of the uniform illumination function. Table 1 summarizes the results and demonstrates that a G/T of 40.9 dB/T is achievable. It assumes that the spillover energy sees an ambient temperature of 240 K and that the amplifier noise temperature is 15 K. Interestingly enough, it also demonstrates that a gain of 54.11 dB is possible using a uniform illumination function with a radius less than the full aperture.

Since the problem with the maximum gain design is the rear spillover, it is possible to reduce the rear spillover by truncating the subreflector and letting the power spill in the forward direction, which only sees the cold sky. Figure 1 gives the G/T as a function of subreflector size. However, the reduction in subreflector size that is necessary to significantly reduce the real spillover loses a significant fraction of the gain to forward spillover. Observe that the maximum G/T obtainable using this method is about 1 dB below the optimum G/T.

Another method to reduce the forward spillover is to move the feed forward of the design position and then reshape the subreflector for perfect phase in the aperture. Selecting the amount of the main reflector illuminated by the subreflector controls the rear spillover. The position of the feed and the amount of the main reflector illuminated are the two parameters to be optimized. For each feed location and illumination radius, the subreflector was reshaped for uniform phase in the aperture. Figure 2 summarizes the results of the simulations.

Not included in the analysis was the feed blockage from the subreflector-scattered field. In order to ensure against undesired blockage from the horn with too extreme of a displacement, a 0.2-m maximum displacement was chosen. The corresponding main-reflector uniform illumination that yielded the greatest G/T, a 2.9-m illumination radius, was then chosen. This design demonstrates a gain of 53.56 dB and a G/T of 40.77 dB/K at 8.4 GHz, a 2.28-db/K G/T increase from the original design.

The above calculations were based upon a feed phase center selected for maximum gain. Optimizing the feed phase center location for maximum G/T then further increased this performance. After performing analysis to determine the optimal feed position for the antenna, we determined that a 0.00508-m offset yielded optimal performance over the bandwidth. This further increased the G/T to 40.82 dB/K, with an associated gain of 53.50 dB. This final design yields a 2.33-dB/K increase of G/T from the original design.

Figure 3 demonstrates the performance of the final antenna with a 0.2-m feed displacement from the original design, a 2.9-m uniform illumination radius, and a 0.00508-m feed phase center offset. The figure includes the data using the calculated radiation patterns of the feed as well as some measured feed patterns in the 8- to 9-GHz and 30- to 40-GHz bandwidths.

Table 1. Optimum *G/T* design trade-off.

Subreflector edge angle							
Radius, m	Gain, dB	T_a, K	G/T	Radius, m	Gain, dB	T_a, K	G/T
40 degrees				45 degrees			
3.048	53.589	16.032	38.671	3.048	53.818	19.128	38.487[a]
2.975	53.606	11.544	39.366	3.0	53.852	15.192	39.053
2.9	53.568	8.088	39.934	2.9	53.817	9.0	40.015
2.8	53.419	5.016	40.405	2.8	53.646	5.16	40.601
2.7	53.176	3.168	40.583	2.7	53.365	2.976	40.818
2.6	52.851	2.112	40.518	2.6	52.998	1.776	40.751
				2.5	52.583	1.176	40.494
50 degrees				55 degrees			
3.048	53.94	22.896	38.154	3.048	53.994	26.712	37.791
2.975	54.002	15.816	39.114	2.975	54.079	18.6	38.816
2.9	53.963	10.248	39.941	2.9	54.031	11.88	39.737
2.8	53.755	5.448	40.648	2.8	53.772	5.88	40.575
2.7	53.419	2.808	40.913[b]	2.7	53.382	2.736	40.893
2.6	53.025	1.512	40.847	2.6	52.96	1.272	40.846
60 degrees							
3.048	54.01	29.88	37.489				
2.975	54.111	21.336	38.508				
2.9	54.045	13.704	39.466				
2.8	53.722	6.504	40.397				
2.7	53.28	2.712	40.797				
2.6	52.852	1.128	40.776				

[a] Design from V. Jamnejad, op cit.

[b] Optimum G/T.

III. *G/T* Estimates

The above calculations were done primarily for trade-off comparisons and did not include all the estimated losses that would be common to all designs. The above results included the calculated losses from the physical optics (PO) programs and an estimated noise temperature contribution from the low-noise amplifier (LNA) system of 15 K at 8.4 GHz (X-band) and 40 K at 32.0 GHz (Ka-band). The purpose of this section is to provide a more complete G/T performance estimate including the expected uncertainties.

Tables 2 and 3 give the performance estimates for the X-band and Ka-band low-noise amplifiers. These are for the wideband monolithic microwave integrated circuit (MMIC) design. A typical estimate

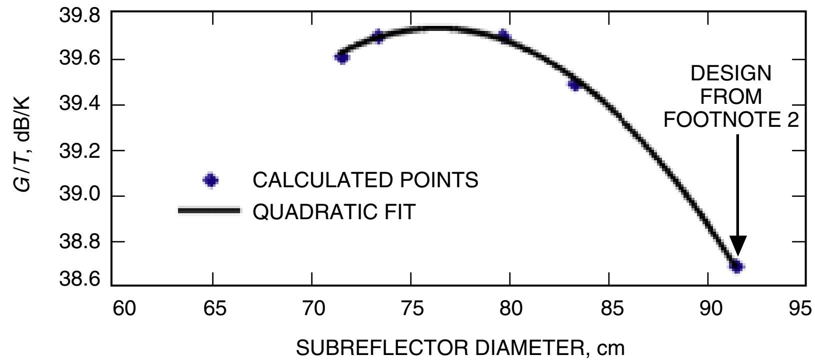

Fig. 1. *G/T* as a function of subreflector diameter.

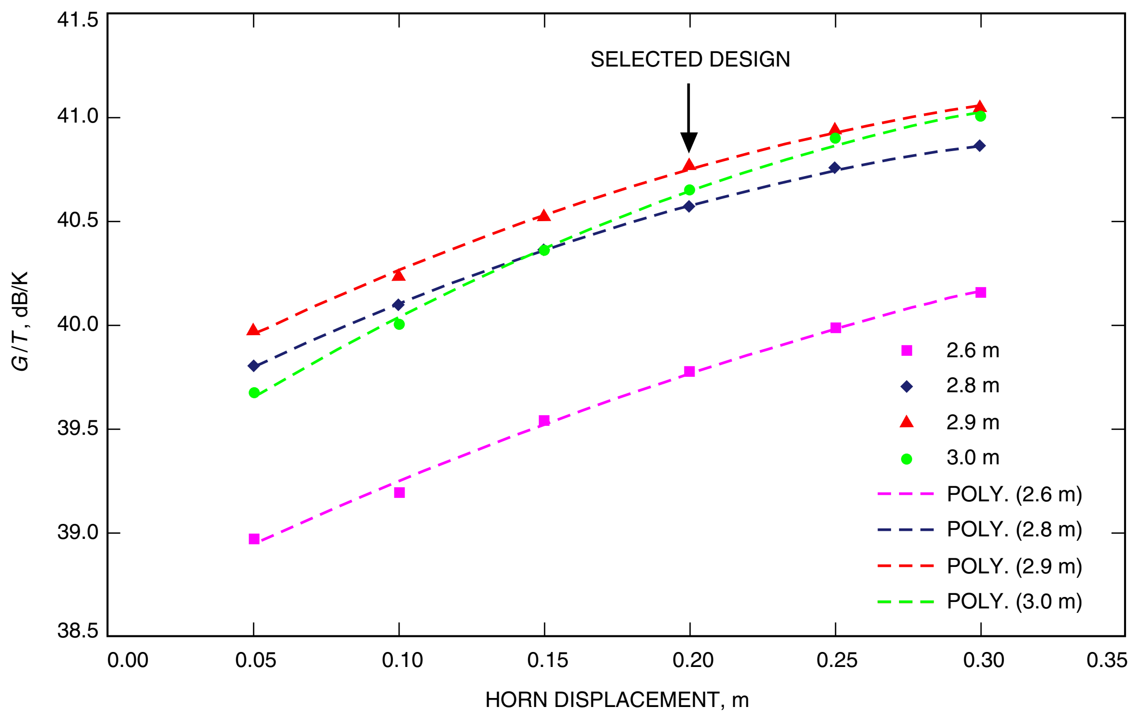

Fig. 2. *G/T* versus horn displacement for various illumination radii.

for the system noise temperature is given in Table 4, and a typical gain budget is provided in Table 5. Utilizing the data from these tables, along with the PO-calculated gain as a function of frequency using the theoretical feed patterns, the maximum and minimum estimated G/T's are shown in Fig. 4.

IV. Sensitivity to Mechanical Displacements

Finally, the tolerance of the antenna to variances in the mechanical structure was determined. Table 6 summarizes the results with offsets of the feed and subreflector positions that yield a 0.1-dB/K G/T loss.

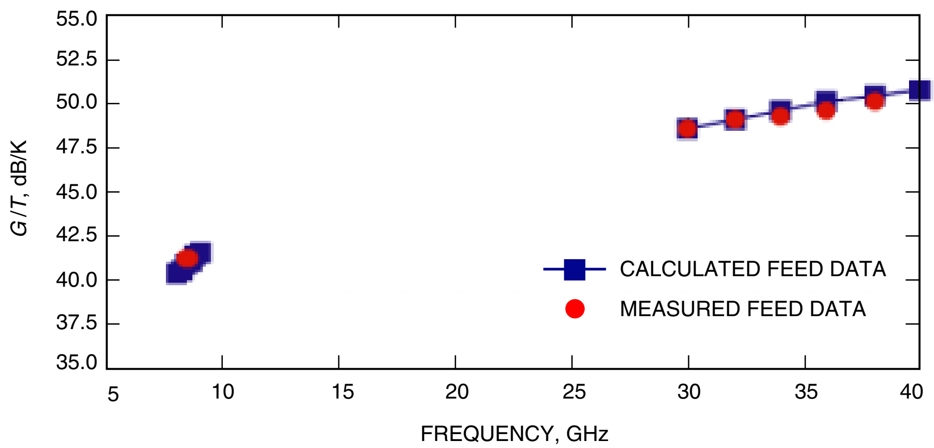

Fig. 3. *G/T* performance across bandwidth.

Table 2. X-band noise budget (S. Petty/M. Britcliffe).

Item	Loss L (dB)		Phy Temp T, K		Gain G, dB		Tin, K		Noise, K	
	Goal	Max	Goal	Max	Goal	Max	Goal	Max	Goal	Max
Mismatch loss, vacuum window (included in vacuum window resistive loss term below)									0.00	0.00
X-band combiners isolation noise term. Isolation = 26 dB goal, 23 dB max									0.03	0.06
X-band polarizer isolation noise term. Isolation = 23 dB goal, 20 dB max									0.06	0.12
Vacuum window	0.004	0.015	293	293					0.29	1.00
Goal: 11 mil Teflon, 3 mil Kapton, 1" Propozote Max: 11 mil Teflon, 0.25" Rexolite, 1" Propozote										
Feedhorn	0.008	0.014	50	60					0.10	0.19
Teflon torpedo/foam support	0.015	0.020	20	30					0.07	0.14
Waveguide Cu 1.5 inches	0.002	0.003	15.0	16.0					0.08	0.19
Slot combiner	0.025	0.050	13.0	15.0					0.08	0.18
WR112 7.5 inches straight, 2 miter bends	0.027	0.050	13.0	15.0					0.08	0.18
Slot combiner	0.025	0.050	13.0	15.0					0.08	0.18
Hybrid polarizer	0.030	0.050	13.0	15.0					0.09	0.18
WR bend	0.006	0.008	13.0	14.0					0.02	0.03
WR cal coupler (loss)	0.025	0.035	13.0	14.0					0.08	0.12
WR cal coupler (ind noise)	30.0	29.0	293	293					0.30	0.39
Goal: Coupler integrated in MMIC module Max: Coupler separate (same performance)										
WR/SMA male adapter	0.090	0.120	13.0	6.9					0.28	0.21
MMIC HEMT module					35.0	31.0	4.0	7.00	4.24	7.70
0.141 output coax, 12–70K	0.56	0.67	50	50					0.00	0.01
0.141 output coax, 70–293K	0.56	0.67	210	210					0.01	0.04
Loss between vacuum feed through, receiver assembly	0.40	0.50	293	293					0.01	0.04
Receiver assembly							150	250	0.15	0.90
Input Noise Temp Te(K)									6.14	12.35

Table 3. Ka-band noise budget (S. Petty/M. Britcliffe).

Item	Loss L (dB)		Phy Temp T, K		Gain G, dB		Tin, K		Noise, K	
	Goal	Max	Goal	Max	Goal	Max	Goal	Max	Goal	Max
Mismatch loss, vacuum window (included in vacuum window resistive loss term below)									0.00	0.00
Ka-band polarizer isolation noise term. Isolation = 20 dB goal, 17 dB max									0.25	0.35
Vacuum window	0.015	0.038	293	293					1.01	2.57
Goal: 11 mil Teflon, 3 mil Kapton, 1" Propozote Max: 11 mil Teflon, 0.25" Rexolite, 1" Propozote										
Feedhorn	0.020	0.032	50	60					0.23	0.45
Teflon torpedo/foam support	0.045	0.060	20	30					0.21	0.42
Round WG Cu 4.0 inches	0.004	0.006	15.0	18.0					0.01	0.03
Hybrid polarizer	0.050	0.075	13.0	15.0					0.15	0.27
WR28 waveguide bend	0.005	0.005	13.0	15.0					0.02	0.02
WR28 30 dB cal coupler (loss)	0.060	0.060	13.0	15.0					0.19	0.22
WR28 30 dB cal coupler (inj noise)	30.0	29.0	293	293					0.31	0.39
Goal: Coupler integrated in MMIC module Max: Coupler separate										
MMIC HEMT module					40.0	38.0	15	22	15.70	23.44
Output coax, 12–70K, 8 in. long	2.00	2.50	50	50					0.00	0.01
Output coax, 70–293K, 8 in. long	2.00	2.50	210	210					0.02	0.05
Loss between vacuum feed through, receiver assembly	1.00	1.40	293	293					0.02	0.06
receiver assembly							600	800	0.42	1.59
					Input Noise Temp Te(K)				18.6	30.2

Table 4. Typical noise temperature budget.

Element	Noise, K		Note
	X-band (8.4 GHz)	Ka-band (32 GHz)	
Cosmic background	2.5	2.0	Effective blackbody
Atmosphere	2.2	7.0	Goldstone (ave clear)
Forward spill	0.3	0	6% at X-band
Main reflector rear spill	3.6	1.0	—
Main reflector I^2R	0.1	0.2	Aluminum
Subreflector I^2R	0.1	0.2	Aluminum
Quadripod scatter	2/4	2/4	Estimated
Feed/amplifier cont	6.1/12.4	18.6/30.2	Tables 1 and 2
Total noise, K	16.9/25.2	31.0/44.6	

V. Summary

This article describes the RF design and performance of the 6-meter antenna intended for use in the three-element breadboard array. The main reflector, subreflector, and feeds have been fabricated and currently are being assembled into a complete antenna.

Reference

[1] W. A. Imbriale, *Large Antennas of the Deep Space Network*, Hoboken, New Jersey: John Wiley and Sons, Inc., pp. 20–23, 2003.

Table 5. Typical efficiency budget.

Element	Efficiency		Note
	X-band (8.4 GHz)	Ka-band (32 GHz)	
P.O. computed	0.777	0.780	100% = 54.59 X-band 100% = 66.21 Ka-band
Main reflector			
I^2R	0.999	0.999	—
RMS	0.988	0.846	12 mils RMS
Subreflector			
I^2R	0.999	0.999	—
RMS	0.999	0.8982	4 mils RMS
Feed support blockage	0.85/0.9	0.85/0.9	Estimated
Feed VSWR	0.999	0.999	—
Efficiency	0.650/0.688	0.549/0.581	
Gain, dB	52.72/52.97	63.61/63.85	

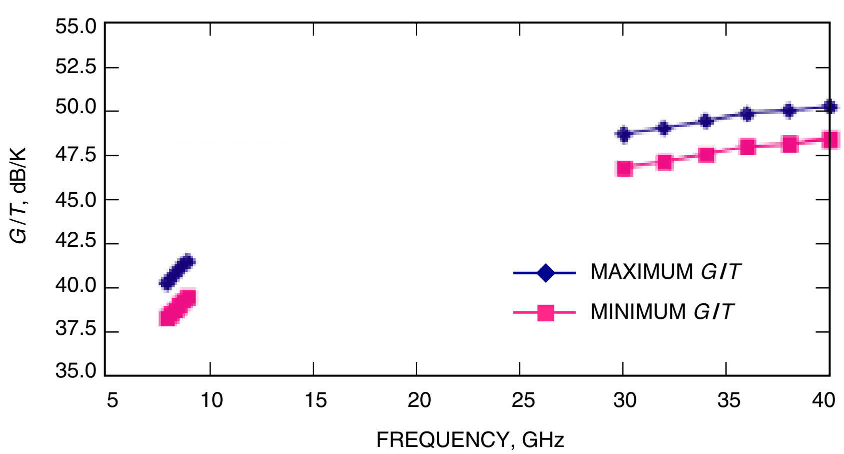

Fig. 4. Maximum and minimum *G/T*.

Table 6. Mechanical displacements that give a 0.1-dB *G/T* loss, assuming no repointing of the antenna

Element	8.4 GHz, mm	30 GHz, mm
Subreflector axial	$+5.33/-2.54$	$+1.91/-0.51$
Subreflector radial	± 3.0	± 0.90
Feed axial	$+13.21/-8.13$	$+1.78/-5.96$
Feed radial	± 3.0	± 0.85