Radio Frequency Optics Design of the 12-Meter Antenna for the Array-Based Deep Space Network

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Development of very large arrays of small antennas has been proposed as a way to increase the downlink capability of the NASA Deep Space Network (DSN) by two or three orders of magnitude, thereby enabling greatly increased science data from currently configured missions or enabling new mission concepts. The current concept is for an array of 400 × 12-meter antennas at each of three longitudes. The DSN array will utilize radio astronomy sources for phase calibration and will have wide bandwidth correlation processing for this purpose. JPL currently is building a 3-element interferometer composed of 6-meter antennas to prove the performance and cost of the DSN array. This article describes the radio frequency (RF) design of the 12-meter reflector that will use the same feed and electronics as the 6-meter antenna. The 6-meter antenna utilized Gregorian optics to enable tests with a low-frequency prime focus feed without removing the subreflector. However, for the 12-meter antenna, maximum gain divided by noise temperature (G/T) is the overriding requirement, and a trade-off study demonstrated that Cassegrain optics is far superior to Gregorian optics for maximum G/T. Hence, the 12-meter antenna utilizes Cassegrain optics.

I. Introduction

The 6-meter design is described in [1,2] and consisted of Gregorian optics modified from an original maximum gain design to a maximum gain divided by noise temperature (G/T) design. For maximum flexibility in the testing and evaluation phase of the project, Gregorian optics was selected to allow tests with prime focus feeds without removing the subreflector. However, for the antenna that will actually be used in the final array, G/T is the overriding requirement. The question then becomes, which design—Gregorian or Cassegrain—provides the maximum G/T? A trade-off study was performed, which concluded that, at least for the case of designs using very low noise amplifiers, Cassegrain optics is superior to Gregorian optics for a maximum G/T design. One additional constraint of the 12-meter design was that it was to use the same feed design [3] as the 6-meter antenna. The trade-off study and final selected design are described in the following sections.

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[1] Communications Ground Systems Section.

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II. Optimizing for Maximum *G/T*

In a dual-reflector-antenna 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 [4]. 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 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 Deep Space Network (DSN) typically has 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 selected radius and then taper the illumination to zero at the reflector edge, also reducing the rear spillover. The 70-meter antennas, the high-efficiency (HEF) antenna, the DSS-13 antenna, 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. This study will use method 1.

III. Cassegrainian or Gregorian

The study will be done in two parts. The first part will determine whether there is any G/T performance difference between the two types of designs, and, if so, the second part will refine the design of the selected choice to best match the mechanical design.

The coordinate system used for shaping is shown in Fig. 1. Parameters available for the design are the subreflector radius k, the main reflector radius x_m, the subreflector edge angle θ_m, the central hole diameter, the feed radiation pattern, and the location of the horn focus a. Since an existing feed is to be used, the feed radiation pattern is given and will be approximated by a $\cos(\theta)^{**}Q$ pattern with $Q = 4.96$. The choice of a can be determined by minimizing the difference between the resulting shape and a given focal-length-to-diameter ratio (F/D). Since it is known that the G/T performance is only minimally affected by the focal length, an $F/D = 0.375$ was selected to be similar to the breadboard antenna. For the initial study, a 10 percent subreflector diameter of 1.2 meters was selected, with a corresponding central hole diameter also of 1.2 meters. The two parameters to be optimized were then the diameter for uniform illumination and the subreflector edge angle. Tables 1 and 2 compare the performance of a Cassegrainian and Gregorian design. For the G/T computation, an amplifier noise temperature of 15 K was assumed, and the gain calculation did not include all the estimated losses that would be common to both designs. Since the spillover is greatest at the lowest frequency, the design was optimized at the lowest DSN X-band frequency of 8.4 GHz. Also, the antenna is assumed to be pointed upward (elevation = 90 degrees) so all the spillover hits the hot Earth.

As can be clearly seen from the two tables, there is a clear advantage for the Cassegrain design. The optimum G/T for the Gregorian design is 47.29 dB, while the optimum G/T for the Cassegrain design is 0.82 dB greater at 48.11 dB. Additional calculations were made for a larger subreflector (1.8 meters) and for different F/D ratios, but the substantial advantage of the Cassegrain design of about 0.7 to 0.8 dB remained. Method 2 (as described above) also was examined, but, as expected, the difference in performance between the two methods for optimum G/T design was less than 0.1 dB. Hence, a Cassegrain design was chosen for the 12-meter reflector.

It is interesting to note that the peak gain of both designs is virtually identical. To understand why the Cassegrain design has the better G/T performance, it is only necessary to look at the subreflector scatter patterns. Figure 2 shows the subreflector scatter patterns for the case of peak gain. Notice the substantial spillover for the Gregorian design. To reduce the spillover, it is necessary to illuminate

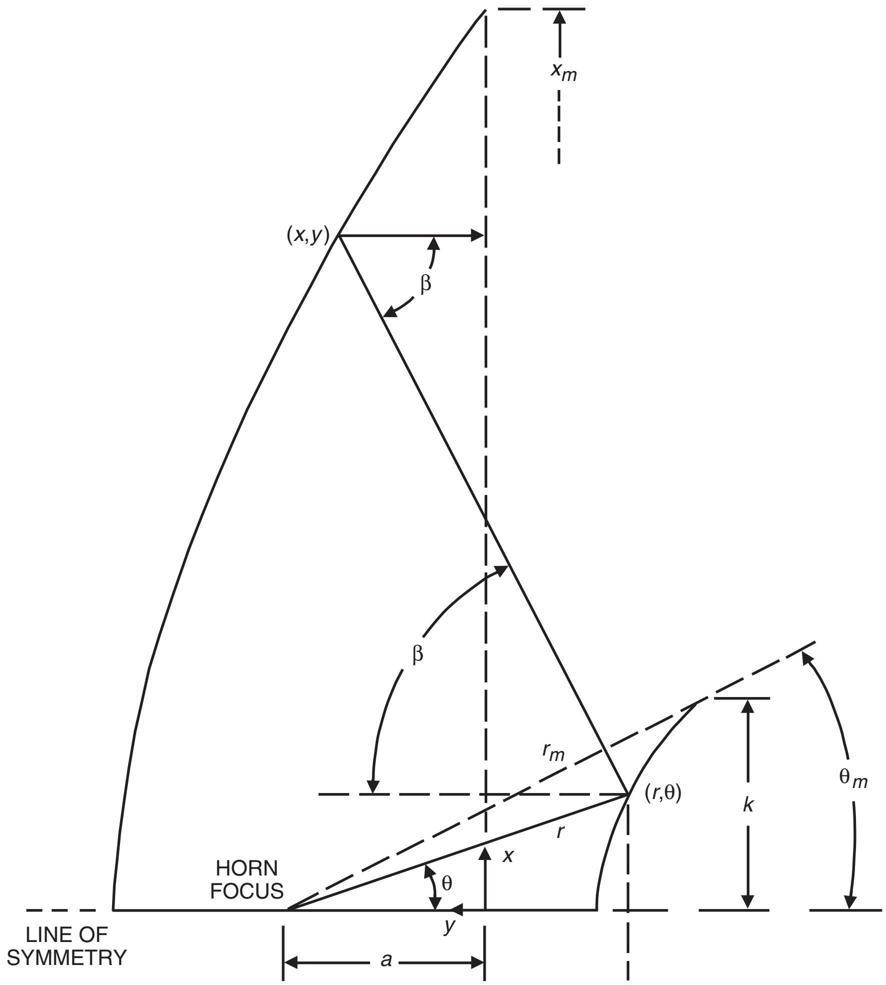

Fig. 1. Coordinate system for shaping.

less of the main reflector, thus using the outer edge of the reflector as a noise shield. Figure 3 compares the scatter patterns for the case of optimum G/T. Notice the lower peak illumination and wider skirts to the pattern for the Gregorian case. It's also to be noted that this difference in G/T would be substantially smaller for a high-noise amplifier.

IV. Cassegrainian Design

To select the specific design parameters, G/T calculations also were made at Ka-band (32 GHz), and the results are shown in Table 3.

In computing Table 3, the calculated feed patterns were used and an amplifier noise temperature of 15 K for X-band and 35 K for Ka-band was assumed. Either the 50-degree subreflector edge angle with a uniform illumination radius of 5.8 meters or the 55-degree subreflector edge angle with a uniform illumination radius of 5.8 meters appears to offer a good compromise between X-band and Ka-band performance. However, the smaller angle is preferred because the feed is further away from the subreflector, posing less of a feed blockage problem.

Table 1. Gregorian design.

Radius, m	Gain, dB	T_a, K	G/T
45-deg subreflector edge angle			
6.0	59.85	14.93	45.09
5.8	59.87	7.78	46.29
5.6	59.72	3.91	46.95
5.4	59.44	2.02	47.13
5.2	59.08	1.20	46.99
50-deg subreflector edge angle			
6.0	59.97	17.86	44.81
5.8	60.01	8.78	46.25
5.6	59.82	3.86	47.07
5.4	59.49	1.70	47.26
5.2	59.11	0.89	47.10
55-deg subreflector edge angle			
6.0	60.03	21.07	44.46
5.8	60.08	10.18	46.07
5.6	59.84	4.03	47.05
5.4	59.46	1.49	47.29
5.2	59.07	0.65	47.17
60-deg subreflector edge angle			
6.0	60.04	24.02	44.13
5.8	60.11	11.76	45.83
5.6	59.81	4.32	46.94
5.4	59.39	1.34	47.25
5.2	58.99	0.53	47.09

To examine the F/D dependence, calculations were made for $F/D = 0.35$, 0.375, and 0.4 and the results summarized in Table 4. As can be seen from the table, there is virtually no difference in the radio frequency (RF) performance of the shaped system for different F/D ratios. The F/D ratio then could be selected based upon mechanical considerations. For similarity with the 6-meter design, an $F/D = 0.375$ was chosen. The DSN Array Project is procuring a 12-meter research and development antenna. This vendor was given the opportunity to change the F/D, but declined.

When the geometry of the 50-degree subreflector edge angle and the 18.1-cm feed diameter are examined, it is seen [Fig. 4(a)] that the ray from the center of the subreflector to the main reflector is blocked by the feed. It is necessary to use a 15 percent (1.8-meter)-diameter subreflector to provide sufficient feed spacing from the subreflector to prevent the feed blockage [Fig. 4(b)]. The final design is then a sub-

Table 2. Cassegrain design.

Radius, m	Gain, dB	T_a, K	G/T
45-deg subreflector edge angle			
6.0	59.85	3.58	47.16
5.8	59.92	1.49	47.66
5.6	59.67	0.74	47.70
5.4	59.40	0.52	47.49
50-deg subreflector edge angle			
6.0	59.97	2.93	47.43
5.8	59.95	0.99	47.94
5.6	59.78	0.38	47.91
5.4	59.50	0.29	47.65
55-deg subreflector edge angle			
6.0	60.03	2.78	47.52
5.8	60.02	0.62	48.08
5.6	59.83	0.22	48.00
5.4	59.52	0.19	47.70
60-deg subreflector edge angle			
6.0	60.05	2.93	47.51
5.8	60.04	0.60	48.11
5.6	59.83	0.19	48.01
5.4	59.50	0.17	47.69

reflector edge angle of 50 degrees, a uniform illumination radius of 5.8 meters, and a 1.8-meter subreflector.[2] Interestingly enough, for this design, the G/T at X-band is 48.13 dB, which is 0.01 dB higher than the largest value in Table 2.

V. *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 system of 15-K at X-band and 35 K at Ka-band. The purpose of this section is to provide a more complete G/T performance estimate including the expected uncertainties. The performance estimates for the X- and Ka-band amplifiers can be found in [1]. They are the wideband monolithic microwave integrated circuit (MMIC) design. A typical estimate for the system noise temperature is given in Table 5, and a typical gain budget is given in Table 6. Estimated G/T is from 45.8 to 48.1 dB/K at X-band (8.4 GHz) and 53.4 to 55.3 dB/K at Ka-band (32 GHz).

[2] The geometry is documented in JPL Control Drawing #9623454 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 8, 2004.

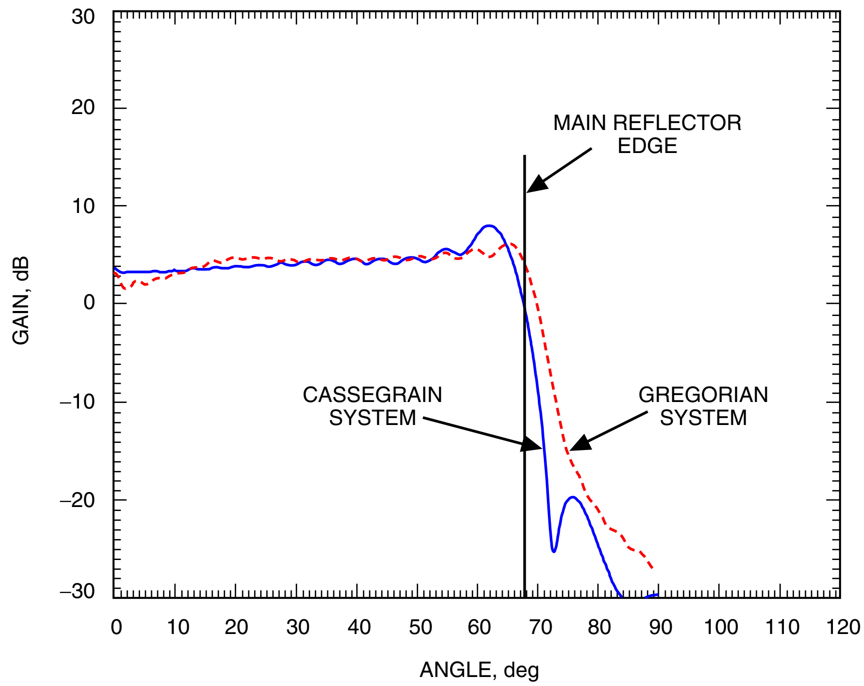

Fig. 2. Subreflector scatter patterns: the peak gain case.

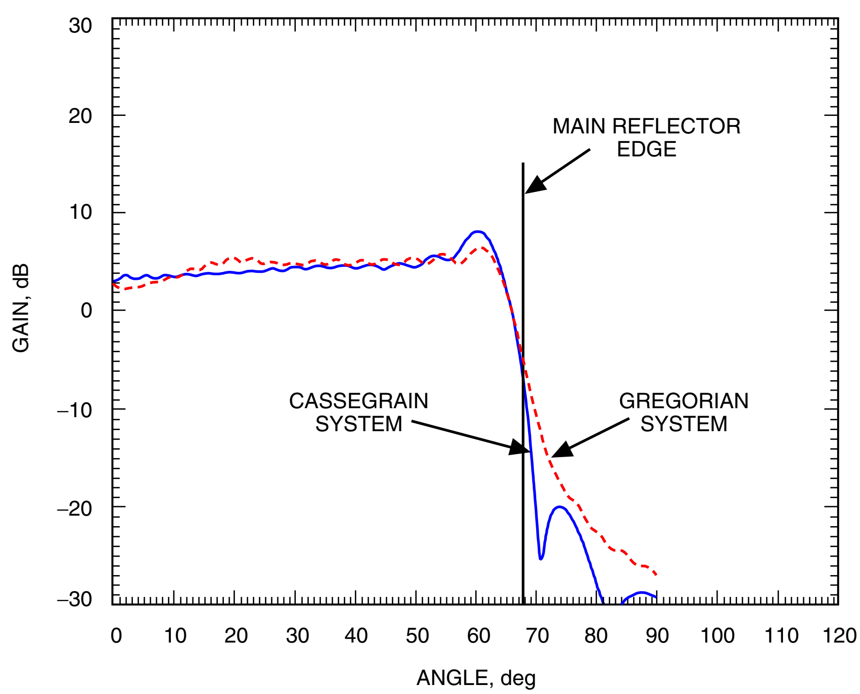

Fig. 3. Subreflector scatter patterns at peak *G*/*T*.

Table 3. *G/T* at X- and Ka-band for the Cassegrainian design.

Radius, m	X-band (8.4 GHz)			Ka-band (32 GHz)		
	Gain, dB	T_a, K	G/T	Gain, dB	T_a, K	G/T
45-deg subreflector angle						
5.9	59.86	2.28	47.48	71.62	0.65	56.10
5.8	59.82	1.49	47.66	71.52	0.24	56.05
5.7	59.76	1.00	47.72	71.38	0.00	55.94
50-deg subreflector angle						
5.9	59.98	1.63	47.77	71.70	0.09	56.24
5.8	59.95	0.99	47.94	71.57	0.00	56.14
5.7	59.88	0.55	47.97	71.43	0.00	55.99
55-deg subreflector edge angle						
5.9	60.04	1.37	47.90	71.73	0.19	56.27
5.8	60.02	0.62	48.08	71.59	0.00	56.15
5.7	59.94	0.31	48.09	71.44	0.00	56.00
60-deg subreflector edge angle						
5.9	60.07	1.37	47.93	71.74	0.05	56.29
5.8	60.04	0.60	48.11	71.58	0.21	56.11
5.7	59.96	0.29	48.12	71.44	0.17	55.97

Table 4. *F/D* dependence for a 5.8-meter radius, 10 percent subreflector diameter, and 50-deg angle.

F/D	Gain, dB	T_a, K	G/T
0.35	59.95	0.98	47.92
0.375	59.95	0.99	47.94
0.40	59.95	1.01	47.91

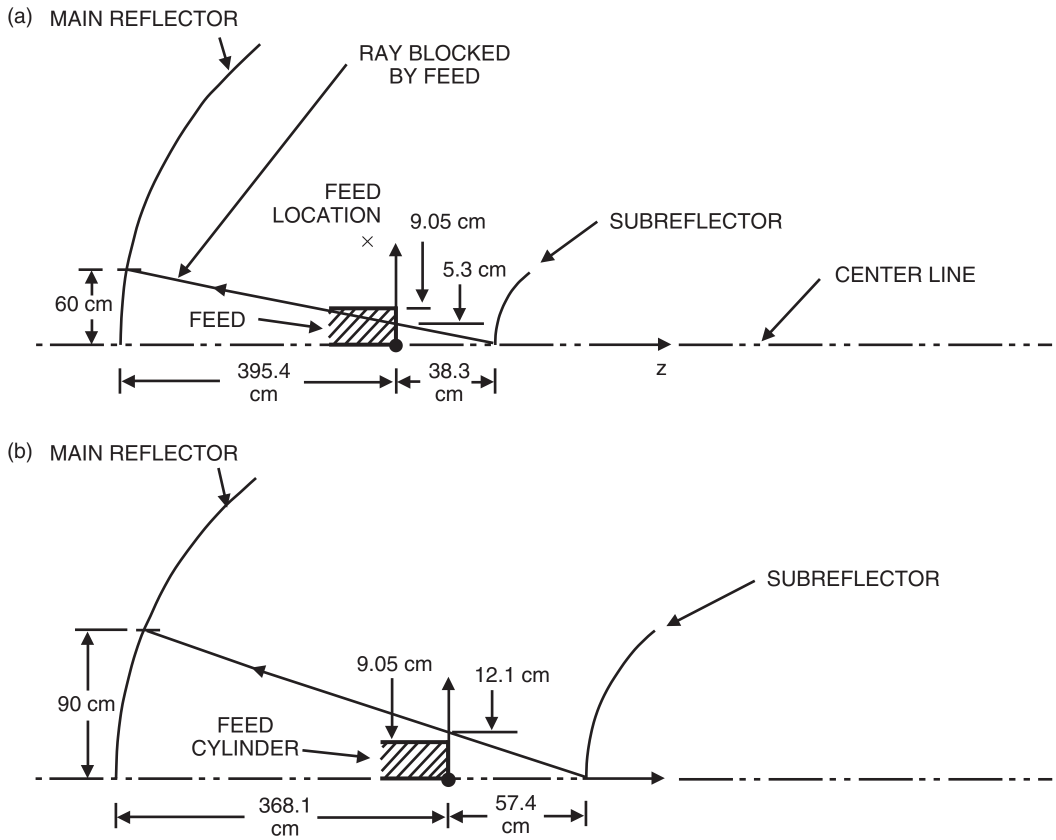

Fig. 4. Feed blockage: (a) 10 percent subreflector and (b) 15 percent subreflector.

References

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Table 5. 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 (average clear)
Forward spill	0.2	0.1	4% X-band, 1.5% Ka-band
Main reflector rear spill	0.3	1.0	—
Main reflector ohmic loss	0.1	0.2	Aluminum
Subreflector ohmic loss	0.1	0.2	Aluminum
Quadripod scatter	2/4	2/4	Estimated
Feed/amplifier	6.1/12.4	18.6/30.2	See [1]
Total noise, K	13.5/21.8	31.1/44.7	—

Table 6. Typical efficiency budget.

Element	Efficiency		Note
	X-band (8.4 GHz)	Ka-band (32 GHz)	
PO computed	0.891	0.865	100% = 60.48, X-band 100% = 72.09, 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	0.982	4 mils RMS
Feed support blockage	0.85/0.9	0.85/0.9	Estimated
Feed VSWR	0.999	0.999	—
Efficiency	0.745/0.789	0.609/0.645	—
Gain, dB	59.20/59.45	69.94/70.19	—