DESIGNING GROUND ANTENNAS FOR MAXIMUM G/T: CASSEGRAIN OR GREGORIAN?

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ABSTRACT

For optimum performance, a ground antenna system must maximize the ratio of received signal to the receiving system noise power, defined as the ratio of antenna gain to system-noise temperature (G/T). The total system noise temperature is the linear combination of the receiver noise temperature (including the feed system losses) and the antenna noise contribution. Hence, for very low noise cryogenic receiver systems, antenna noise-temperature properties are very significant contributors to G/T.

It is well known that, for dual reflector systems designed for maximum gain, the gain performance of the antenna system is the same for both Cassegrain and Gregorian configurations. For a 12-meter antenna designed to be part of the large array based Deep Space Network, a Cassegrain configuration designed for maximum G/T at X-band was 0.7 dB higher than the equivalent Gregorian configuration. This study demonstrates that, for maximum G/T, the dual shaped Cassegrain design is always better than the Gregorian.

1. INTRODUCTION

To do its part effectively, the ground antenna system must maximize the ratio of received signal to the receiving system noise power, which is measured by an antenna figure of merit (FM), defined as the ratio of antenna gain to system-noise temperature (G/T). The total system noise temperature is the linear combination of the receiver noise temperature (including the feed system losses) and the antenna noise contribution. Hence, for very low noise cryogenic receiver systems, antenna noise-temperature properties are very significant contributors to the FM.

It is well known that, for dual reflector systems designed for maximum gain, the gain performance of the antenna system is the same for both Cassegrain and Gregorian configurations. There is some literature [1] that states, "The theory and experiment have shown that the pattern of the radiating system (subreflector + feed) of the Gregorian antenna has a higher radiation efficiency and abrupt field cut-off outside the optical edge, which reduces the antenna noise temperature". It thus came as quite a surprise that, for the 12-meter antenna designed to be part of the large array based Deep Space Network, a Cassegrain configuration designed for maximum G/T at X-band was 0.7 dB higher than the equivalent Gregorian configuration [2].

This then raised the question of which configuration, Cassegrain or Gregorian, is best for a ground antenna. To answer that question we will first review the design of the 12-meter antenna and then extend the study to larger range of feed designs and reflector sizes.

2. RF OPTICS DESIGN OF THE 12-METER ANTENNA

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 x 12-m 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 is currently building a 3-element interferometer composed of two 6-meter and one 12-meter antenna to prove the performance and cost of the DSN array.

The 6-meter design is described in [3,4] and consisted of Gregorian optics modified from an original maximum gain design to a maximum 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 tradeoff 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 [5] as the 6-meter antenna. The tradeoff study and final selected design is described in the following sections.

3. 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 [6]. 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 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 selected radius and then taper the illumination to zero at the reflector edge, also reducing the rear spillover. The 70-meter antennas, the HEF, DSS-13 and the ARST antennas used method 1) and the operational BWG antennas used method 2). Both methods yield virtually identical results for G/T. This study will use method 1.

4. CASSEGRAINIAN OR GREGORIAN?

The study will be done in two parts. 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(θ)**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 effected by the focal

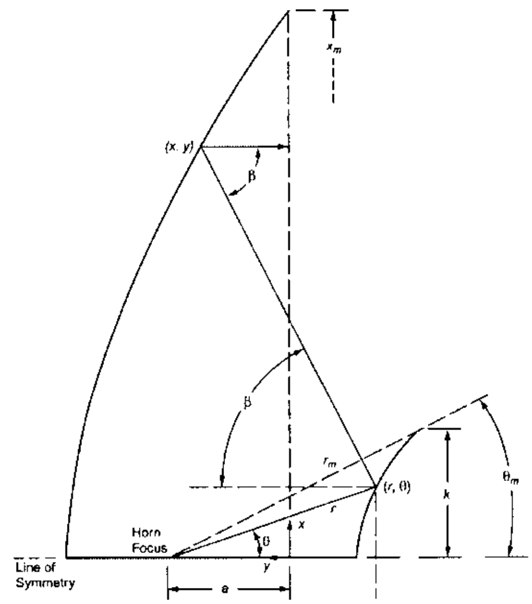

Fig. 1. Coordinate System for Shaping

length, a F/D = 0.375 was selected to be similar to the breadboard antenna. For the initial study, a 10% subreflector diameter of 1.2 meters was selected with a corresponding central hole diameter also 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 15K 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 presumed 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 0.7–0.8 dB remained. Method 2 (as described above) was also 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.

Table 1. Gregorian Design

Radius, m	Gain, dB	T_a, K	G/T
45 Degree 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 Degree 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 Degree 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 Degree 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

Table 2. Cassegrain Design

Radius, m	Gain, dB	T_a, K	G/T
45 Degree 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 Degree 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 Degree 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 Degree 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

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. Fig. 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 less of the main reflector, thus using the outer edge of the reflector as a noise shield. Fig. 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.

5. CASSEGRAINIAN DESIGN

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

In computing Table 3, the calculated feed patterns were used and an amplifier noise temperature of 15K for X-band and 35K 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

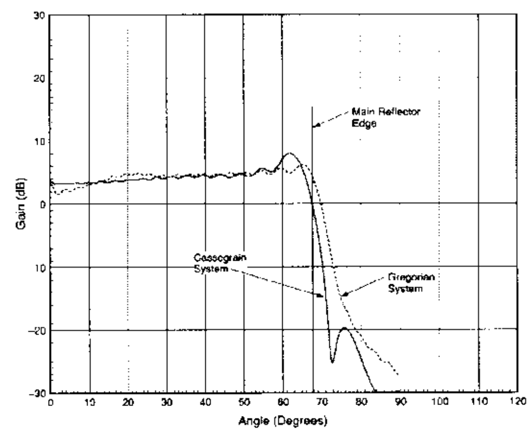

Fig. 2. Subreflector Scatter Patterns – Peak Gain Case

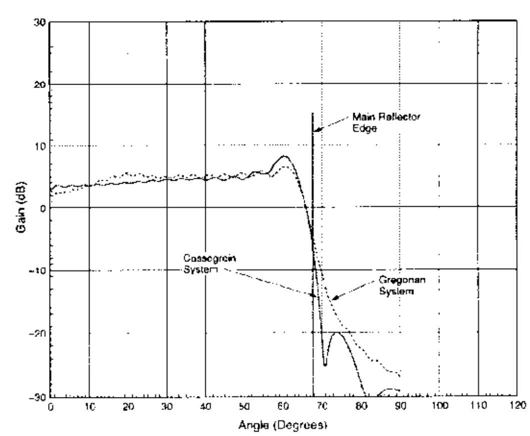

Fig. 3. Subreflector Scatter Patterns at Peak G/T

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

Radius, m	X-Band (8.4 GHz) Gain, dB	T_a, K	G/T	Ka-Band (32 GHz) Gain, dB	T_a, K	G/T
45 Degree 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 Degree 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 Degree 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 Degree 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

appears to offer a good comprise between X- 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.

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 RF performance of the shaped system for different F/D ratios. The F/D ratio could then be selected based upon mechanical considerations. For similarity with the 6-meter design, an F/D = 0.375 was chosen.

When the geometry of the 50-degree subreflector edge angle and the 18.1 cm feed diameter is examined, it is seen (Fig. 4a) 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% (1.8 m) diameter subreflector to provide sufficient feed spacing from the subreflector to prevent the feed blockage (Fig. 4b). The final design is then a subreflector edge angle of 50 degrees, a uniform illumination radius of 5.8 meters and a 1.8-meter subreflector. 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.

The above calculations were done primarily for tradeoff 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 PO programs and an estimated 15K noise temperature contribution from the low noise amplifier system at X-band and 35K at Ka-band. A

Table 4. F/D Dependence for 5.8m radius, 10% sub and 50 degree 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

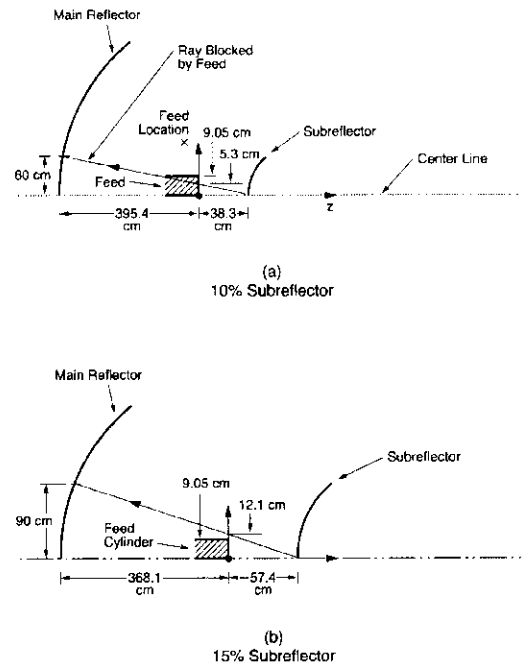

Fig. 4. Feed Blockage

more detailed performance estimate for the complete system can be found in [2].

6. OTHER CASES

The 12-meter dish at 8.4 GHz has a diameter of only 336 wavelengths and uses a relatively low gain feed. The question of whether or not the Cassegrain is advantage also holds for larger diameters or higher gain feeds was examined next.

6.1 Higher Gain Feed

The standard feed for DSN antennas is a 22.5 dB gain horn, a significantly higher gain than the 13.6 dB gain for the feed of [5]. Using the 22.5 dB gain feed, the same type of calculations was made for a 12-meter antenna at 8.4 GHz (336λ). Using the same 15K amplifier the results were as follows: For the Cassegrain design, the maximum G/T of 48.3 dB/K occurred with a 5.8 m optical edge radius and a 20 degree subreflector edge angle. For a Gregorian system the maximum G/T of 47.7 dB/K occurred with a 5.6 m optical edge radius and a 20-degree subreflector edge angle. Again, the

Cassegrain is better by 0.6 dB/K for the same reasons as the previous case.

Both designs were also optimized for a 100 wavelength reflector with the following results: For the Cassegrain design, the maximum G/T of 36.8 dB/K occurred with a 5.3 m optical edge radius and a 20 degree subreflector edge angle. For a Gregorian system the maximum G/T of 35.7 dB/K occurred with a 5.0 m optical edge radius and a 18-degree subreflector edge angle. The difference between the 2 designs is 1.1 dB/K. Observe that because of the larger diffraction effects (due to the smaller subreflector), the optical edge needed to be further inside the reflector to reduce the noise temperature contribution.

6.2 Larger Reflector

Using the higher gain feed of 22.5 dB, the designs were optimized for Ka-band on the 12-meter reflector, a diameter of 1281 wavelengths. Again, assuming a 15K amplifier the results were as follows: For the Cassegrain design, the maximum G/T of 60.2 dB/K occurred with a 6.0 m optical edge radius and a 20 degree subreflector edge angle. For a Gregorian system the maximum G/T of 59.8 dB/K occurred with a 5.7 m optical edge radius and a 19-degree subreflector edge angle. For this case the difference is only 0.4 dB/K since for the larger subreflector the skirts on the subreflector scatter pattern are steeper, giving lower overall noise temperature than for a smaller subreflector and allowing the a greater portion of the main reflector to be illuminated. Nonetheless, the Cassegrain continues to be better than the Gregorian.

7. CONCLUSIONS

Both for varying feed designs and a wide range of reflector sizes the Cassegrain system was shown to have a greater G/T than the Gregorian system. The reason can be clearly seen in Fig. 2, which shows the typical subreflector scatter patterns with the same optical edge. For all the cases considered, the Gregorian scatter pattern is outside the Cassegrain pattern. To reduce the noise contribution for the Gregorian, it is necessary to reduce the optical edge diameter, contributing to a lowering of the gain. Since the peak gain is the same for both systems it necessarily follows that the G/T for the Gregorian is lower. Of course, this advantage is reduced for either a larger reflector or a higher noise temperature receiver.

This result seems to contradict the statement of [1] quoted in the introduction.

8. ACKNOWLEDGMENT

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9. REFERENCES

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