

DSN 70-Meter Antenna Microwave Optics Design and Performance Improvements Part II: Comparison With Measurements

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This article compares the measured DSN 70-meter antenna performance at S- and X-bands with the design expectations presented in Part I of this report. A discussion of natural radio-source calibration standards is given. New estimates of DSN 64-meter antenna performance are given, based on improved values of calibration source flux and size correction. A comparison of the 64- and 70-meter performances shows that average S-band peak gain improvement is 1.94 dB, compared with a design expectation of 1.77 dB. At X-band, the average peak gain improvement is 2.12 dB, compared with the (coincidentally similar) design expectation of 1.77 dB. The average measured 70-meter S-band peak gain exceeds the nominal design-expected gain by 0.02 dB; the average measured 70-meter X-band peak gain is 0.14 dB below the nominal design-expected gain.

I. Introduction

This article is the second part of a two-part report [1] detailing the design performance expectations and comparison with actual performance of the DSN 70-meter antennas in their upgrade from the original 64-meter configuration. The actual 70-meter antenna gain and noise temperature performance is documented in [2, 3].

Two of the important elements of the 64-70 meter antenna performance upgrade project were (1) to determine

if the project specifications were met and (2) to quantify, with an estimated absolute accuracy, the actual efficiency/gain levels achieved. The project specifications of 1.9-dB X-band and 1.4-dB S-band gain increases are "improvement" specifications and do not effectively quantify absolute performance levels; there remains the issue of quantitatively defining the baseline performance level of the 64-m antennas. In this situation, the DSN had three differently performing 64-m antennas [4-6]. For example, it was clear (but not specifically measured) that the Goldstone 64-m antenna had reflecting panels which

were manufactured and/or adjusted better than those on the Madrid and Canberra 64-m antennas. Also, the Goldstone and Canberra 64-m antennas had been previously upgraded with a gravity-distortion-reducing major structural brace system which generally performed successfully, but was not accompanied with the exact required subreflector active focus command programs. The Madrid 64-m antenna was further unique in that the structural brace upgrade was installed but certain superfluous older bracing was intentionally not removed due to time constraints. This combination was known to be counter-productive. Because of noncritical tracking requirements, this was an acceptable configuration for a short interim period prior to planned 70-m upgrade but, in fact, it produced an antenna system with degraded shape and nonoptimum subreflector focus performance. In short, the 64-70 meter upgrade project began with three quite differently performing "baseline" 64-m antennas, and these needed to be carefully calibrated to assist settling project baseline definition questions.

II. Natural Radio Source Calibration Standards

DSN antenna calibrations are wholly dependent upon viewing natural radio noise sources (radio galaxies, quasars) with estimated microwave flux densities. Obtaining such calibrations by the alternative of overall deep space telecommunication link performance has proven a more difficult matter because of the great number of variables involved. The absolute accuracy of natural radio-source flux densities has been estimated to be 0.50 dB, (3σ) at X-band [4]. It was believed even with the difficult absolute accuracy issue at the half-dB level, at least very accurate comparison measurements would ensue, and the 70-m calibrations would be no worse on an absolute basis than the 64-m calibrations.

The 70-m antennas provided more detailed radio-source observation by virtue of much narrower antenna X-band beamwidth (0.0305 deg versus 0.036 deg). Narrower beamwidth results from both larger diameter and substantially higher area efficiency. Various sources which formerly appeared consistent in strength on the 64-m and smaller DSN antennas immediately appeared with inconsistent apparent strengths on the new 70-m antennas—an indication of source size/beam width (source resolution)

increase. Although never an issue at S-band, the DSN radio source list "standards" document¹ in fact was shown inadequate at X-band for the very narrowbeam 70-m. The approximately 15-percent narrower X-band 70-m beamwidth is about 0.0305 deg or 1.83 arcmin. This proved to better resolve the primary calibrator 3C274 and reveal the previous inaccuracies, especially in the source size/beamwidth correction factor, but to a lesser degree in the absolute flux scale as well.

Table 1 provides a summary of data corrections needed when using natural radio sources with these extremely large, high-efficiency X-band antennas. The resolution provided by significantly sharper (high-efficiency) 70-m beamwidth, together with careful analytical work at JPL (M. Klein and P. Richter, private communication), revises the primary and secondary DSN calibrator sources, as detailed in Table 1. The effects on gain are shown in parentheses.

Updated Table 1 values, and others, will be published in the Revision C version of JPL Document D-3801. Accordingly, within this article, previously published [4-6] 64-m X-band results are rescaled according to Table 1 values. The 70-m X-band results herein are also based on Table 1. At S-band, due to wider beamwidth, no noticeable source size/beamwidth or flux effects were expected or determined. At S-band, previous DSN calibrations with National Bureau of Standards (now NIST) certified standards have proven that natural radio-source S-band flux values are known to 0.22 dB, 3σ [7].

A rigorous analysis of absolute accuracy presently attained in DSN antenna gain measurements using natural sources is not available. The three dominant error contributors are natural source flux, instrumentation accuracy, and data repeatability. Tests for and corrections of these errors are applied in data reduction for pointing errors as needed and receiver linearity. It is believed the S-band flux accuracy is 0.22 dB and that the X-band accuracy is improved, due to the 70-m narrowbeam experience, to not worse than 0.40 dB, both numbers quoted at high (3σ) confidence. It is believed that the instrumentation accuracy is 0.15 dB, and that data repeatability is generally 0.09 dB, both 3σ . Taking these dominant error sources

¹ *DSN Radio Source List for Antenna Calibration*, JPL D-3801, Rev. B (internal document), Jet Propulsion Laboratory, Pasadena, California, September 25, 1987.

as independent, it is reasonable to accept overall absolute accuracies of 0.28 dB (S-band) and 0.44 dB (X-band), $3\text{-}\sigma$, for normally appearing data sets. At both frequency bands, it is significant that the natural-source flux uncertainty is the dominant component of the total measurement uncertainty.

III. Adjustment of 64-m Antenna Calibrations

All three 64-m antennas were calibrated at S- and X-bands within a month or two prior to removal from service for 70-m conversion. DSS-63 was calibrated in July 1986; DSS-43 in January 1987; and DSS-14 in September 1987. The JPL DSN radio-source flux standard D-3801, Rev. A, was in effect throughout the DSS-43/63 period, and Rev. B during the DSS-14 period. Consistency in the use of equipment, technique, and standards was sought and is believed to have been achieved. The results are initially reported in [4-6].

In view of the natural radio source size and flux corrections, the 64-m calibrations are now adjusted in order to allow accurate comparison with the 70-m results. DSS-14 64-m X-band results are increased +0.313 dB, changing the X-band peak efficiency and gain values in [6] from 0.498 (+72.01 dBi) to 0.535 (+72.33 dBi). DSS-43 is adjusted +0.329 dB, changing the X-band peak efficiency and gain values in [5] from 0.454 (+71.61 dBi) to 0.490 (+71.94 dBi). DSS-63 is also adjusted +0.329 dB, changing the X-band peak values in [4] from 0.451 (+71.58 dBi) to 0.487 (+71.91 dBi). All X-band results apply at a frequency of 8420 MHz, and the peak-to-peak spread, 0.42 dB, was rather large.

At S-band, the 64-m antennas yielded an average of 58.2 (+1.2/ - 0.8)-percent area efficiencies (61.36 dBi at the test frequency of 2285 MHz, or 61.40 dBi adjusted to 2295 MHz for comparison with 70-m results). DSS-14 peaked at 59.4 percent, DSS-43 at 57.7 percent, and DSS-63 at 57.4 percent, a peak-to-peak spread of 0.15 dB.

IV. 64-m Calibrations Compared With Design Expectations

Figure 1 shows the 64-m antenna X-band gain with elevation angle response, adjusted as described above. Both

DSS-14 and DSS-43 exhibited generally flat response, not unlike the design-expected shape, albeit everywhere below the expectation. DSS-63 clearly exhibited the interim dual-brace arrangement, known to degrade antenna gain response away from the setting angle. The reader is reminded that the 64-m design-expected peak value is based on 1.14-mm rms (normal) small-scale surface roughness. This was the original design value and was likely never achieved. Limited holographic imaging on the DSS-63 64-m antenna indicates the small-scale effective roughness was near 1.7-mm rms, consistent with the actual performance described in [4], although the DSS-14 64-m antenna was clearly better, perhaps 1.35-mm normal rms.

Two X-band design expectations were discussed in Part I [1] of this article. The first is considered a "nominal" expectation, in terms of likelihood, and the second is considered an "estimated minimum-likely" value. Both are highly dependent on the small-scale roughness term, which was poorly known for the 64-m antennas. The procedure adopted to form the estimated minimum-likely value, as discussed, takes one-third of the estimated peak limits. This is equivalent to the nominal estimate, minus approximately $1\text{-}\sigma$. In the 64-m case, this is believed to lead to overestimating the real performance to be expected. If high-resolution holographic imaging of all 64-m antennas was available, the estimates could be improved; however, such imaging is not available on all those antennas. Accordingly, in the absence of further quantitative information, the original design rms, the nominal design-expected, and the estimated minimum-likely 64-m efficiency values must be accepted. Comparisons with measurements are shown in Table 2.

The S-band average measured difference from estimated minimum-likely is 0.07 dB. The X-band difference is 0.05 dB at DSS-14 and about 0.38 dB at DSS-43 and DSS-63. Clearly, DSS-43 and DSS-63 had surfaces whose roughness was larger than both the original specification and the one-third peak value adopted in the minimum-likely estimating procedure. It requires 1.24 dB of small-scale roughness loss to reconcile DSS-43/63 X-band 64-m actual performance with expectations. This indicates an effective normal surface roughness of 1.6 mm (0.063 inch), not an unreasonable value. At S-band, it should be noted that the DSS-14 64-m antenna in particular met and appeared to slightly exceed the estimated minimum-likely efficiency (0.594 versus 0.591).

V. 70-m Antenna Calibrations

Immediately upon conclusion of final upgrade structural work, the 70-m antenna calibrations commenced. Inclement weather at DSS-63, the interim fiberglass subreflector at DSS-43, and other factors delayed completion until August 1988. Early informal performance reports, especially for X-band, were gauged against the then-existing D-3801, Rev. B flux standard document, even though the very narrowbeam 70-m antennas immediately revealed inconsistencies among the X-band calibration sources. In the following discussion, the revised flux and source size/beamwidth corrections discussed earlier are properly used. The 70-m X-band peak efficiencies and gains as reported in [2] are: DSS-14, 68.4 percent (74.17 dBi); DSS-43, 67.3 percent (74.10 dBi); and DSS-63, 70.1 percent (74.28 dBi). These values are more closely grouped than the three 64-m antenna X-band performances were. The DSS-14 peak occurs at 46-deg elevation, DSS-43 at 46-deg elevation, and DSS-63 at 47-deg elevation.² The standard deviation of DSS-14 efficiency data (318 points) is 0.7 percent, or 0.04 dB. The DSS-43 data standard deviation (540 points) is likewise 0.7 percent. The DSS-63 standard deviation (176 points) is 1.0 percent, or 0.06 dB.

The 70-m X-band gains as functions of elevation angle are shown in Fig. 2. The design-expectation curve has a peak value as determined in Table 4 of [1] and a shape determined from GTD calculations, which consider main reflector structural deformation due to gravity loading. The DSS-14 elevation function is seen to follow the design-expected elevation function, albeit 0.15 dB low at the adjustment angle and less than 0.2 dB low from 0 to 80-deg elevation. Both DSS-43 and DSS-63 exhibit elevation functions which are considerably steeper than design expectations.

In view of the very small standard deviations in the measured data, the measured X-band elevation functions are judged statistically significant and indicate a real difference in structural or focus performance among the 70-m antennas. It should be noted in Fig. 2 that small atmospheric loss terms have been removed from the observed data, according to on-site meteorological measurements taken during the tests. In short, the data in Fig. 2 are

² The main reflector surfaces were adjusted based on holographic imaging as follows: DSS-14 at 47.0 deg, April 1988; DSS-43 at 47.3 deg, June 1988; and DSS-63 at 41.8 deg, July 1987.

as self-consistent as can be expected, and the DSS-43 and DSS-63 antennas indeed behave alike and somewhat differently with elevation angle than does the DSS-14 antenna.

At S-band, limited 70-m data were collected, in favor of the more revealing X-band data. At S-band, the peak efficiency is 0.761 (+63.34 dBi at 2295 MHz), and the elevation response is essentially flat, as expected. Figure 3 shows the average result from two antennas, DSS-14 and DSS-43. The DSS-63 S-band 70-m data were self-inconsistent for reasons not understood, therefore judged invalid. Operationally, it is not expected that DSS-63 will perform differently from the other stations at S-band, and indeed no significant difference has been observed.

VI. 70-m Calibrations Compared With Design Expectations

Table 3 summarizes the nominal design-expected and estimated minimum-likely 70-m efficiency values and measurements. The "best" X-band antenna, DSS-63 with 0.701 efficiency, is 0.09 dB above the measurement average while the "worst" antenna at 0.673 efficiency is 0.08 dB below the measurement average. In reality, these are exceedingly small differences, and the qualitative descriptions above should not be interpreted too literally. At X-band, all antennas are below the nominal design expectation by an average of 0.14 dB. The S-band average is 0.02 dB above the nominal design expectation.

The improved agreement in 70-m actual performance against design expectations is directly traceable to improved knowledge gained through use of high-lateral-resolution microwave holographic imaging. The holography illumination amplitude image gives a clear view of quadripod shadowing while the phase image gives an excellent estimate of small-scale surface roughness. All 70-m antennas yielded high-quality holographic data and the nearly 1,300 individual reflector panels on each antenna were adjusted according to those data.

In actuality, all 70-m antenna surface (and focus) adjustments were seriously time-compromised. The high-resolution holographic data type inherently provides panel-setting data based on individual-panel 3-degree-of-freedom best fits, within a global best-fit reference system. Rather precise information (approximately 50 microns or

0.002-inch repeatability) for each panel corner is provided. In the time-constrained 70-m project a compromise was necessary. At each intersection of four panel corners, the necessary individual settings, which are in general different, were simply averaged. Thus, all panels are, in general, misset and in fact very slightly twisted. Further, panel corners in *average* error by 0.015 inch (0.37 mm) or less were not adjusted at all. This is clear from the resultant 0.7-mm rms small-scale roughness achieved compared with the initial Project goal of 0.5-mm rms, and further compared to the holography-determined theoretical minimum (given perfect adherence to setting directions) of 0.3-mm rms. An rms of 0.3 mm is effectively the manufacturing precision of the panels and subreflector, as independently determined during manufacture, plus a small incoherent holography data-system noise component. If time had permitted refinement of the 0.7-mm quick setting to a practical 0.4 mm, the X-band gain would increase 0.13 dB, changing the average measured 68.6 percent efficiency to 70.7 percent. At a higher frequency such as 32 GHz, the gain difference developed by improving a 0.7-mm surface to 0.4 mm is nearly 1.9 dB.

VII. Gain Performance Increases

A. S-Band

Tables 1 and 2 of [1] give the design-expected S-band gain increase (70-m over 64-m) as +1.77 dB. From measurements, the efficiencies determined are 0.582 (+61.40 dBi at 2295 MHz) for the 64-m antennas and 0.761 (+63.34 dBi) for the 70-m antennas. The measured increase is thus +1.94 dB. Both 70-m measurement sets show very small differences between the antennas. The Project specification (+1.4 dB) was, of course, based on predesign estimates. Detailed design extracted 0.5 dB more gain than initial estimates for the 70-m antennas.

B. X-Band

Tables 3 and 4 of [1] give the design-expected X-band gain increase (70-m over 64-m) as +1.77 dB. However, this is based on the originally specified 64-m surface tolerance of 1.14 mm which is unrealistically low, as discussed before. Likewise, the estimated minimum-likely efficiencies in Table 6 of [1] for 64-m X-band (0.533 for DSS-43/63 and 0.541

for DSS-14) are considered too high, due to the adopted one-third peak estimating method used. The measurements (simply averaged) show +74.18 dBi for 70-m and +72.06 dBi for 64-m antennas. On this simple averaged basis, the 70-m upgrade project provided +2.12 dB X-band gain improvement at or near the adjustment (peak gain) elevation angle. The best 64-m antenna, DSS-14, provided +72.33 dBi. After upgrade to 70-m, DSS-14 now provides +74.17 dBi. On this single antenna basis, the 70-m upgrade project provided +1.84 dB at DSS-14, the minimum improvement realized at X-band. For DSS-43 and DSS-63, the average X-band gain increase provided by the 70-m project is +2.27 dB. These improvements clearly exceed expectations simply because the 64-m surface tolerance was somewhat worse than our limited previous knowledge and estimates.

Table 4 presents a summary of the S- and X-band 64- and 70-meter antenna gains and efficiencies, plus the increases gained by the upgrade activities. Each reader can (and perhaps will) select his or her baseline of choice in this matter of three quite differently performing 64-m X-band antennas at the start of the project, and three very slightly differently performing 70-m X-band antennas at project conclusion. Nevertheless, perhaps the best value to use is the simple average of the before-to-after measures, that is, +2.1 dB at X-band. The specification (+1.9 dB) was, of course, based on predesign estimates. Detailed design extracted a bit less than the predesign X-band estimate from DSS-14. The necessary stovepipe feed and surface setting compromises, both of which are recoverable, would boost DSS-14 improvement from +1.84 to +2.08 dB with, of course, similar increases to the other 70-m antennas.

Figure 4 presents 64-m and 70-m measured X-band data for comparison. Included in Fig. 4 are the 64-m and 70-m design expectations (nominal, not estimated minimum-likely values). The peak design expectations are obtained directly from Tables 3 and 4 of [1]. The design-expected elevation functions are obtained from finite-element structural gravity distortion data, analytically smoothed for input to the GTD scattering program [8–10]. After smoothed GTD scattering a small-scale (nominally random) roughness term is added for the overall design estimate. Thus the large lateral-scale distortions are handled by direct integration, while the small-scale distortion is handled on the familiar statistical basis, according to the commonly used Ruze formulation [11]. This is the best technique known and possible at this time. Apply-

ing the simplified statistical method of Ruze is considered quite proper in this instance of 1,300 individual reflecting panels per 70-m antenna.

In Fig. 4 it is clear that the 64-m and 70-m design expectations compared with DSS-14 data are in general agreement. The DSS-63 64-m antenna was not expected to follow the design elevation function due to the temporary dual structural bracing configuration as discussed.

Both DSS-43 and DSS-63 70-m antennas do not presently follow the design-expected elevation function. Whether this is due to a real structural deficiency, a subreflector focus control deficiency, poor pointing during data collection, or other reasons is not known. The indications are that pointing was acceptable. Additional work is necessary to understand the DSS-43/63 elevation functions, and focus tests at high and low elevation angles are the likely priority. Separately, some very valuable holography data was obtained at low elevation angles at DSS-14 and to a lesser extent at DSS-63. These data, with a lateral resolution comparable with structural rib and hoop dimensions, may assist in detailed understanding of the gravity behavior of the DSN 70-m antenna structures.

VIII. System Noise Temperatures

No formal predictions of 64- to 70-m antenna upgrade noise improvement (or degradation) were made. The rear spillover noise, a component of the total, was expected to increase roughly 1 K at S-band, a consequence of the X-band optimum design (the former 64-m systems were S-band optimized). At X-band, the rear spillover was expected to decrease roughly 0.5 K. The deeper main reflector resulting from 64- to 70-m diameter increase, with approximately the same effective focal length, could be expected to slightly reduce noise with the 70-m antenna pointing below about 30-deg elevation and at zenith. The reduced quadripod shadowing might provide slightly reduced noise at all elevation angles. An upper bound on this might be 1 K.³

³ The 64-m systems utilized a special beamshaping flange around the periphery of the hyperboloidal portion of the subreflector, which was optimized for S-band. In any event, such appendages tend to be narrowband on a scale of an octave, thus of limited utility for wideband antennas.

Despite the above 70-m design tendencies, the JPL Technical Division and Project position was that the system noise temperature change, if any, was too close to quantify without significant additional work. This section will therefore briefly record measured noise results. The results presented here are slight modifications of the initial results presented in [3]. During the period of mechanical upgrade, some of the maser preamplifiers were serviced, and in some cases, outright exchanges were made. With at least twelve masers disposed among three stations, such servicings and exchanges require subcalibrations and become a difficult measurement, bookkeeping, and reporting task. Also during the period of mechanical upgrade, the X/S-band dichroic plates were serviced and upgraded. The paint in some cases appeared seriously checked and badly flaking from over 10 years exposure to weather. All three dichroic plates were stripped of paint and the aluminum alloy base metal was irridited. The irridite process is a thin film and considered sufficient weather protection for several years. It is unknown how much steady-state (dry) noise degradation was being experienced with the paint seriously flaking. The expectation is that at least following rain, the recovery time to normal system noise temperature will be considerably improved due to more rapid drying of the irridited noncapillary surfaces.

In summary, one might expect the S-band zenith noise to remain roughly the same and expect a small X-band noise zenith decrease. X-band noise recovery following rainy conditions should improve. Table 5 summarizes available measured zenith noise temperatures for 64- and 70-m antennas at S- and X-bands. From the measured values, composite S- and X-band noise temperature models were created, as described in [3]. The table is divided into two parts: measured totals (including atmosphere) and those values inferred for no atmosphere. The no-atmosphere data is based on local meteorological conditions existing at the time of the measurements and should be the more reliable (weather-independent) data for comparison purposes.

From Table 5, the DSS 63/64-m S-band noise appears abnormally high, and remains so after 70-m conversion. The 20.7 ± 0.6 -K DSS-14/43 S-band 64-m average (with atmosphere) is reasonable. After 70-m conversion, the DSS-14/43 average (with atmosphere) is again reasonable, at 18.9 ± 0.6 K. The average improvement of 1.8 K is a distinct S-band performance benefit. However, the atmosphere-free data is the more reliable. Here, the av-

erage difference is 1.5 K, still indicating a distinct S-band 70-m performance benefit.

At X-band, the DSS-14/64-m noise was abnormally high. However, after 70-m conversion all three antennas provided quite similar zenith noise performance of 20.9 ± 0.3 K. Ignoring the abnormal DSS-14 64- to 70-m difference, contaminated by the high 64-m data, and taking the atmosphere-free data as the more reliable, the average difference of 0.7 K (70-m improvement) again provides another distinct 70-m performance benefit.

It is noted that the DSS-43 70-m antenna has the best S-band zenith noise performance, at 18.3 K, while the others are considerably higher. In decibels, DSS-14 is 0.2 dB worse, while DSS-63 is fully 1 dB worse at S-band, clearly a candidate for maintenance attention to either operational or calibration equipment.

It is emphasized that considerable noise data are required for a fully reliable performance description. Selected 70-m data are presented here. Figure 5 shows 70-m S-band total system noise temperatures (including atmosphere) taken during the calibration measurements at three different stations. The DSS-63 operational or instrumentation anomaly is clear, and these data are ignored for system noise temperature modeling. The DSS-43 18.3-K zenith temperature and the elevation dependence should be achievable in principle, and probably in practice as well, by all stations.

Figure 6 shows three selected 70-m X-band total system noise temperature data sets, again including atmosphere. At the time the DSS-14 data were obtained, the dichroic plate had not yet been reinstalled. Thus the 19.7-K measured total DSS-14 zenith noise shown in Fig. 6 projects to 20.9 K in the normal operating configuration with the dichroic plate installed. Remarkably, the three very low noise antennas perform quite uniformly with a zenith noise temperature of 20.9 ± 0.3 K at X-band. Special efforts should be made to maintain this highly desirable and valuable performance condition.

From the limited data in Figs. 5 and 6, and the total system temperatures at zenith discussed above, the best present estimates of the DSN 70-m S- and X-band system noise temperatures are plotted in Fig. 7. The upper pair of plots are total system temperatures (with atmosphere) as functions of elevation angle. These are the operational noise temperatures (with slight adjustments) experienced in the nominal clear weather which existed at

the time of the calibration measurements. In the same figure, the lower pair of plots represents antenna performance alone, in what may be referred to as the "vacuum" condition, that is, with the nominal clear atmosphere removed. From atmosphere-removed plots, factors such as spillover and quadripod or other scatter may be estimated for detailed design evaluation purposes. For example, at 30-deg elevation, the atmosphere-removed 17.5-K (S-band) measurement is only 0.9 K above the the zenith (vacuum) of 16.6 K. Similarly, again at 30-deg elevation, the atmosphere-removed 20.6-K measurement (X-band) is only 2.2 K above the zenith (vacuum) of 18.4 K. These small noise terms are indeed difficult to know with great confidence, especially with limited data, but appear remarkably small and indicate the 70-m design has provided excellent low noise antennas.

In any careful future measurements and comparisons of antenna noise performance, it is recommended the feed-cone hoist cables and heavy large lifting sheaves and hooks be removed from the topmost two quadripod legs. These operationally needless (service) tools can only serve to degrade antenna noise performance, due to an unknown amount of ground noise pickup from additional scattering.

It can be concluded that the reduced cross-section 70-m quadripod, in the slightly deeper main reflector environment, is the key agent leading to 70-m system noise improvements. At zenith, 1.5-K S-band improvement and 0.7-K X-band improvement is observed. Observing noise as a function of elevation angle, one sees very small spillover and scatter components. It is quite clear, based on gain and noise temperature measurements, that the efforts expended to improve the 70-m quadripod structural design have yielded multiple benefits to microwave performance, at both frequency bands, to the three major antenna systems.

IX. Conclusion

The detailed design-expected area efficiencies for the high-efficiency (dual-shaped reflector) DSN 70-m antennas range from 74.9 to about 75.8 percent at S-band, and from 68.8 to about 70.8 percent at X-band, based on the best estimating practices available. Measurements carried out during 1988 show 76.1 percent has been achieved at S-band, and an average of 68.6 percent achieved at X-band. The highest measured peak efficiency (DSS-63) is 70.1 percent, while the lowest measured efficiency is 67.3 percent

(at the X-band) where small-scale surface roughness effects are dominant.

The 70-m upgrade project achieved all objectives and more. The noise performance of all three antennas was improved, and it is clear from the limited gain and noise temperature measurements that the reduced cross-section quadripod contributed significantly to the overall performance improvement.

Additional X-band microwave performance is easily obtainable: the feedhorn design can be improved by 0.1 dB; and main reflector panels can be reset to obtain an additional 0.1 dB. Both the feedhorn and surface adjustment compromises were based on time and financial resource limitations. Nevertheless, those remain important, but recoverable, performance compromises.

One question remains unanswered. The structural/gravity (or focus) performance with elevation angle change is not as good as expected for two of the antennas (DSS-43 and DSS-63). Further work in this area will be accomplished in a post-project phase, beginning with focus tests at high and low elevation angles, and the study of valuable low-elevation holography images. These are expected to reveal actual structural gravity behavior for comparison with theoretical models.

The DSN 70-m project was a significant undertaking, and by any reasonable standard, was severely time constrained to fit between the Voyager Uranus (1986) and Neptune (1989) planetary encounters. Good design, management, contracting, scheduling, fieldwork, and technology formed a powerful combination. The use of microwave holography proved to be vital to the Project success.

Acknowledgments

It would be impossible to individually acknowledge all of the people on three continents who contributed to the success of the DSN 70-m antenna upgrade project. Each of those many individuals can be assured that his or her efforts have contributed to greatly improved performance of the NASA/JPL Deep Space Network.

References

- [1] D. A. Bathker and S. D. Slobin, "DSN 70-Meter Antenna Microwave Optics Design and Performance Improvements Part I: Design Optimization," *TDA Progress Report 42-97*, Jet Propulsion Laboratory, Pasadena, California, pp. 306-313, May 15, 1989.
- [2] P. H. Richter and S. D. Slobin, "DSN 70-Meter Antenna X- and S-Band Calibration Part I: Gain Measurements," *TDA Progress Report 42-97*, Jet Propulsion Laboratory, Pasadena, California, pp. 314-351, May 15, 1989.
- [3] S. D. Slobin and P. H. Richter, "DSN 70-Meter Antenna X- and S-Band Calibration Part II: System Noise Temperature and Telecommunications Link Evaluation," *TDA Progress Report 42-97*, Jet Propulsion Laboratory, Pasadena, California, pp. 352-366, May 15, 1989.
- [4] S. D. Slobin, "DSS 63 64-m Antenna S- and X-band Efficiency and System Noise Temperature Calibration, July 1986," *TDA Progress Report 42-90*, Jet Propulsion Laboratory, Pasadena, California, pp. 103-115, August 15, 1987.

- [5] S. D. Slobin, "DSS 43 64-Meter Antenna S- and X-Band Efficiency and System Noise Temperature Calibrations, January 1987," *TDA Progress Report 42-90*, Jet Propulsion Laboratory, Pasadena, California, pp. 116–126, August 15, 1987.
- [6] S. D. Slobin, "DSS 14 64-Meter Antenna S- and X-Band Efficiency and System Noise Temperature Calibrations, September 1987," *TDA Progress Report 42-92*, pp. 138–146, February 15, 1988.
- [7] P. D. Batelaan, A. J. Freiley, and D. A. Bathker, "Absolute Flux Density Calibrations of Radio Sources: 2.3 GHz," *JPL Technical Memorandum 33-806*, Jet Propulsion Laboratory, Pasadena, California, 1977.
- [8] J. M. Schredder, "Seventy-Meter Antenna Performance Predictions: GTD Analysis Compared With Traditional Ray-Tracing Method," *TDA Progress Report 42-92*, Jet Propulsion Laboratory, Pasadena, California, pp. 166–174, February 15, 1988.
- [9] S. D. Slobin and W. A. Imbriale, "DSS 43 Antenna Gain Analysis for Voyager Uranus Encounter: 8.45-GHz Radio Science Data Correction," *TDA Progress Report 42-90*, Jet Propulsion Laboratory, Pasadena, California, pp. 127–135, August 15, 1987.
- [10] S. D. Slobin and D. A. Bathker, "DSN 70-Meter Antenna X-Band Gain, Phase, and Pointing Performance, With Particular Application for Voyager 2 Neptune Encounter," *TDA Progress Report 42-95*, Jet Propulsion Laboratory, Pasadena, California, pp. 237–245, November 15, 1988.
- [11] J. Ruze, "Antenna Tolerance Theory—A Review," *Proceedings of the IEEE*, vol. 54, no. 4, pp. 633–640, April 1966.

Table 1. 8420-MHz sources for DSN antenna calibrations

Source	Flux, Jy	Source Size/Beamwidth Correction, C(R)	
		64-m	70-m
3C274	Old: 46.00	Old: 1.085 ^a 1.089 ^b	Old: 1.106
	New: 45.20	New: 1.15	New: 1.18
	(+0.076 dB)	(+0.253 dB) ^a (+0.237 dB) ^b	(+0.281dB)
Others	(+0.076 dB)	Varies according to source size	

Notes:

Jy = Jansky = 10^{-26} W/m²/Hz

^aJPL Document D-3801, Rev. A (DSS-43/63, 64-m calibration)

^bJPL Document D-3801, Rev. B (DSS-14, 64-m, and initial 70-m calibrations)

Table 2. Summary of design expected and average measured efficiencies, 64-m antennas

64-m Antenna/Band	Design-expected nominal efficiency	Estimated minimum-likely efficiency	Average measured efficiency
All/S-Band	0.603	0.591	0.582
DSS-14/X-Band	0.565	0.541	0.535
DSS-43/X-Band	0.565	0.533	0.490
DSS-63/X-Band	0.565	0.533	0.487

Table 3. Summary of design-expected and average measured efficiencies, 70-m antennas

70-m Antenna/Band	Design-expected nominal efficiency	Estimated minimum-likely efficiency	Average measured efficiency
All/S-band	0.758	0.749	0.761
All/X-band	0.708	0.686	0.686

Table 4. Summary of measured S- and X-band gain and efficiency results

	DSS-14 X-Band	DSS-43 X-Band	DSS-63 X-Band	All Stations S-Band
64-m				
Gain, dBi	72.33	71.94	71.91	61.40
Efficiency	0.535	0.490	0.487	0.582
70-m				
Gain, dbi	74.17	74.10	74.28	63.34
Efficiency	0.684	0.673	0.701	0.761
64-70-m				
Gain improvement, dB	+1.84	+2.16	+2.37	+1.94

Table 5. Summary of zenith system noise temperatures for 64/70-m antennas

Antenna/System	S-Band Zenith noise, K	X-Band Zenith noise, K
With Atmosphere		
DSS-14/64-m	21.2	25.2*
DSS-14/70-m	19.5 (-1.7)	20.9 (-4.3)*
DSS-43/64-m	20.1	21.8
DSS-43/70-m	18.3 (-1.8)	21.2 (-0.6)
DSS-63/64-m	27.7*	22.0
DSS-63/70-m	23.0 (-4.7)*	20.6 (-1.4)
Without Atmosphere		
DSS-14/64-m	19.1	23.2*
DSS-14/70-m	17.7 (-1.4)	18.7 (-4.5)*
DSS-43/64-m	18.2	19.2
DSS-43/70-m	16.5 (-1.7)	18.7 (-0.5)
DSS-63/64-m	25.6*	19.0
DSS-63/70-m	21.2 (-4.4)*	18.1 (-0.9)

* Considered abnormal, and change not representative of design improvement.

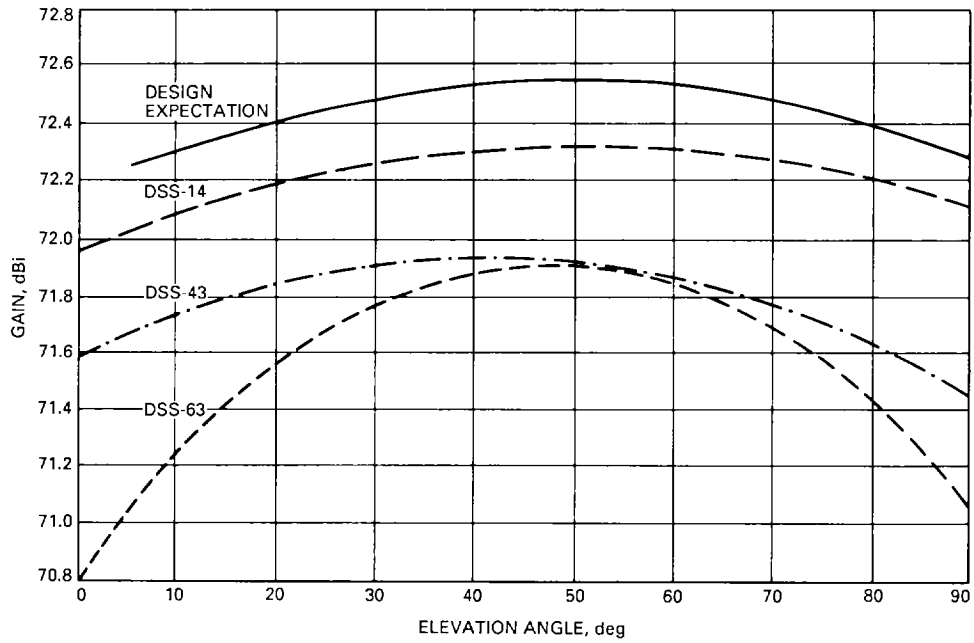


Fig. 1. DSN 64-m antenna X-band gain performance (without atmosphere), plus design expectation.

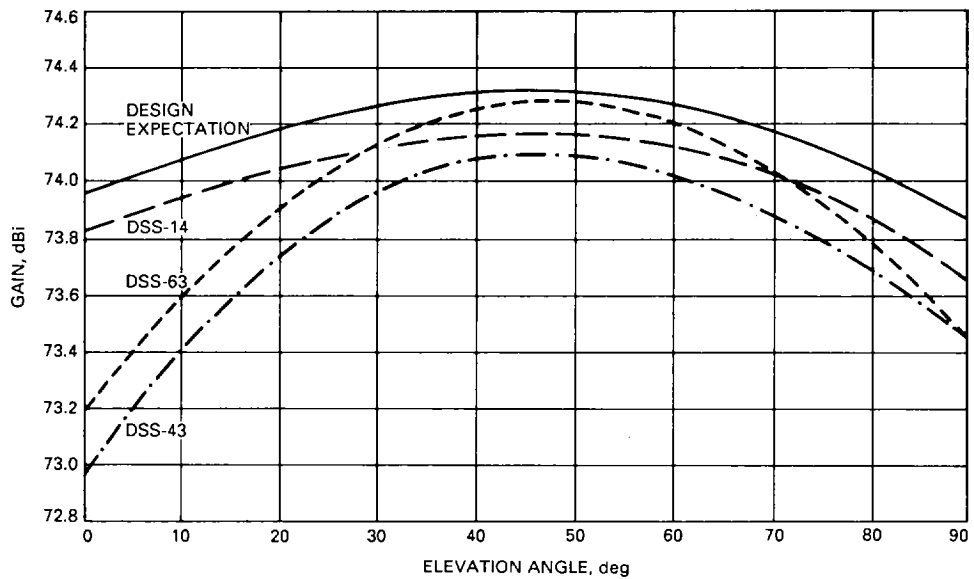


Fig. 2. DSN 70-m antenna X-band gain performance (without atmosphere), plus design expectation.

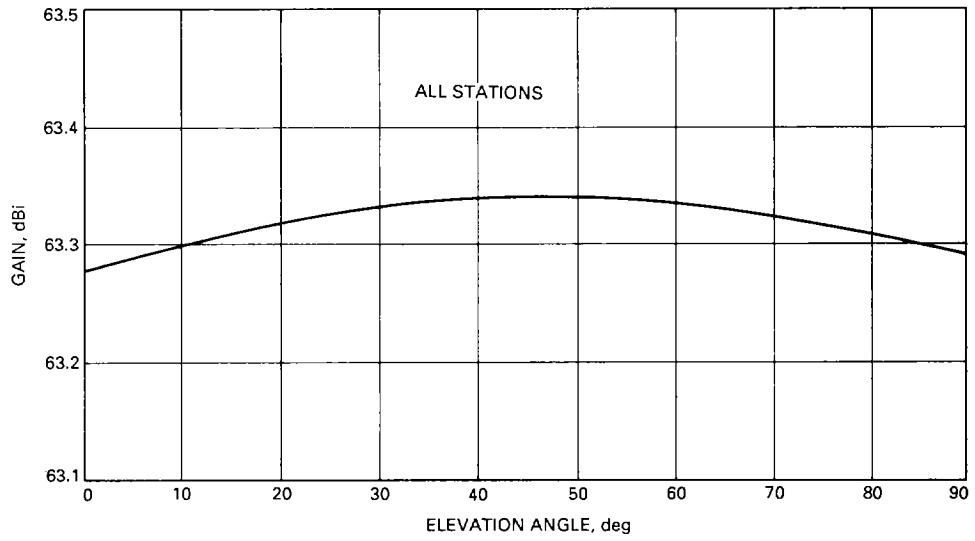


Fig. 3. DSN 70-m antenna S-band gain performance (without atmosphere).

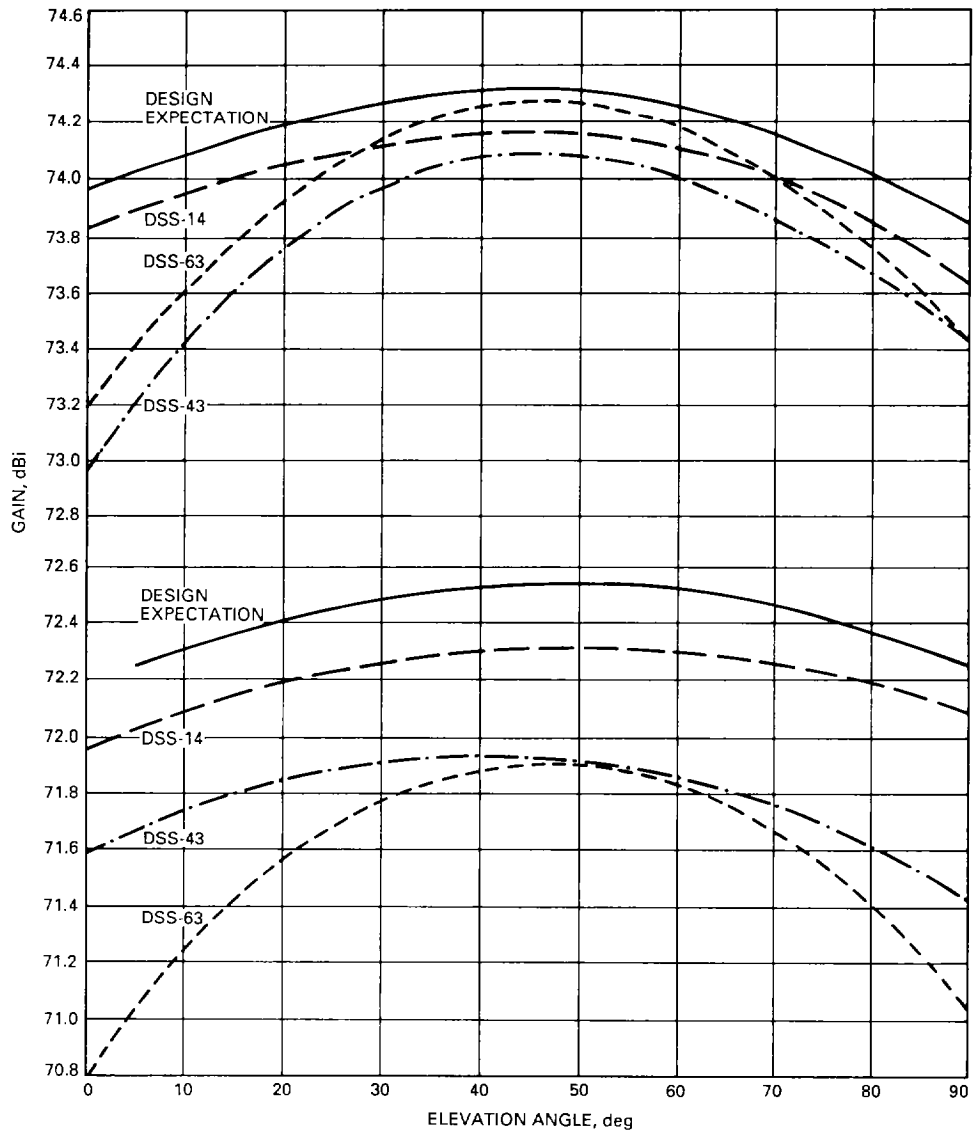


Fig. 4. DSN 64/70-m antenna X-band gain comparison (without atmosphere), plus design expectation.

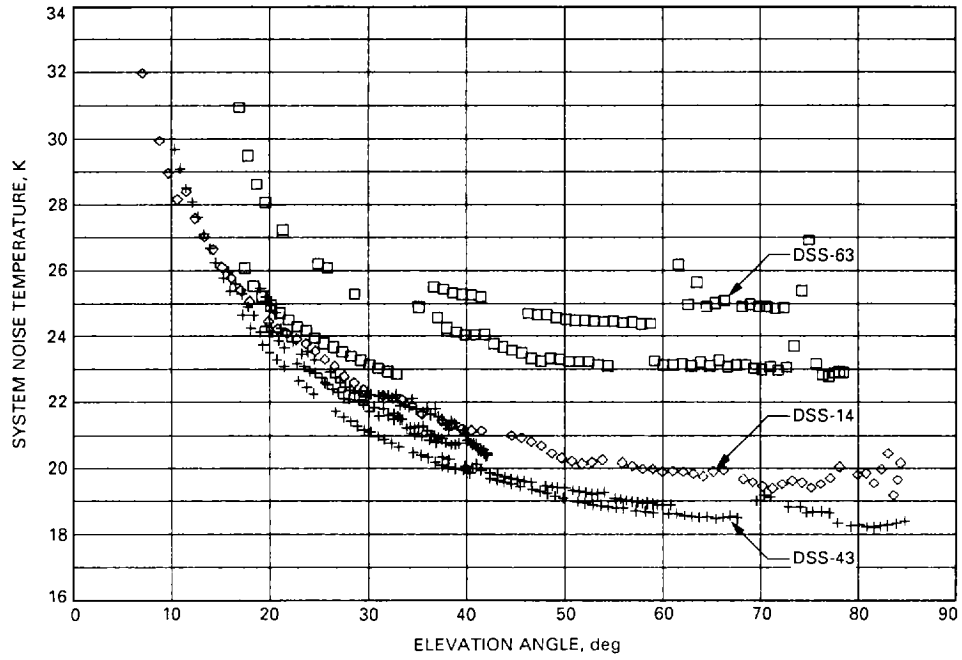


Fig. 5. DSN 70-m antenna S-band system noise temperature (raw data, with atmosphere).

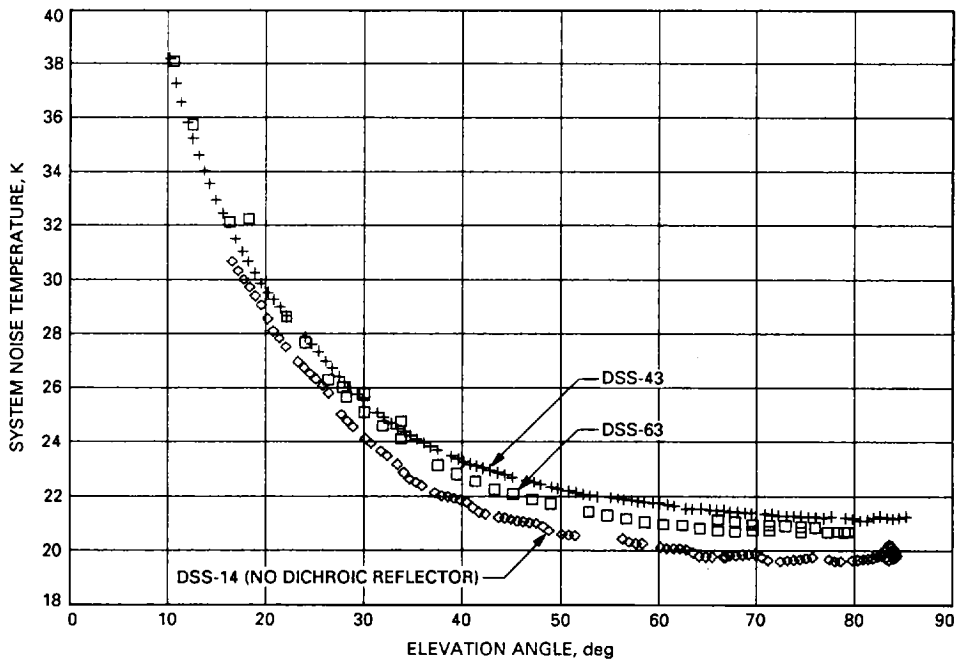


Fig. 6. DSN 70-m antenna X-band system noise temperatures (raw data, with atmosphere) (DSS-14: no dichroic reflector).

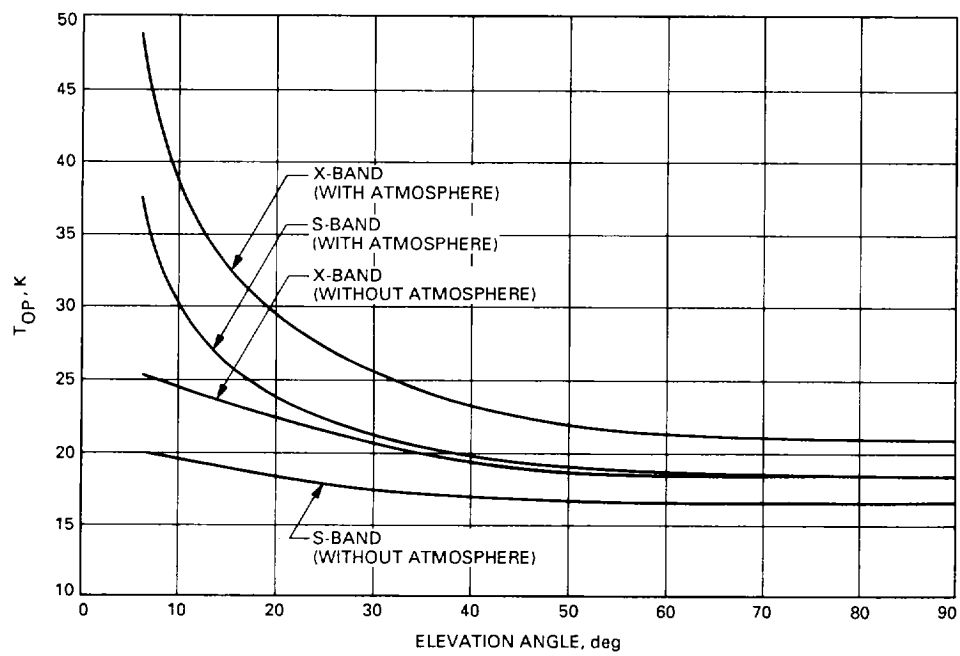


Fig. 7. DSN 70-m S- and X-band system noise temperatures (with nominal clear atmosphere, and in "vacuum" condition).