Radio Frequency Performance of DSS 14 64-Meter Antenna at X-Band Using an Improved Subreflector

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In February and March 1980, the DSS 14 64-meter antenna X-band gain was determined using the R&D XKR feedcone. Tests prior to, and following the installation of an improved subreflector, proved the new unit largely (if not totally) restored initial performance levels at that station. The X-band peak gain with the new subreflector is +71.8 dBi (area efficiency of 47.3 percent); an increase of +0.47 dB due to the new unit installation. The tests further showed a significant shift in the axial focus required (function of elevation angle) which, if not implemented operationally, will cause a serious degradation.

An historical summary of all documented X-band gain measurements at DSS 14, covering the period 1968 to 1980, is included and reviewed. This summary traces the initial performance through various major configuration changes such as the installation of the X-band dual hybrid mode horn within the operational XRO feedcone. Finally, based on the summary and recent data, a peak X-band antenna gain of +72.1 dBi (area efficiency of 50.8 percent) is projected for the operational feedcone. Recommendations for further work are given.

I. Introduction

The X-band radio frequency performance of the NASA/JPL Deep Space Network 64-meter antenna at DSS 14 was measured in February and March 1980 at 8420 MHz (3.56-cm wavelength) to evaluate the expected improved antenna gain performance due to the installation of a new subreflector with improved surface tolerance. The replacement of the subreflector was part of total Voyager Enhancement Task to realize 2 dB of vital X-band gain and noise temperature improvements in the ground station performance for the Voyager Saturn encounter, and beyond.

To more fully appreciate the results presented here, an historical summary of DSS 14 64-meter antenna X-band gain measurements spanning the years 1968 to 1980 is presented with emphasis on the measurements of February and March 1973. In February and March 1973, DSS 14 was fitted with (1) a major structural brace to improve the gravity-induced, large-scale structural deviations of the main reflecting surface (dependent on elevation angle), and (2) a modified subreflector with welded seams to improve noise burst problems associated with diplexed high-power microwave transmission. The distorted subreflector and reset main reflector (necessitated by the structural brace installation) unexpectedly resulted in a 0.46-dB loss of peak X-band gain, however, the incremental gain loss with elevation angle due to the gravity-induced surface tolerance deviation was improved. That is, the structural brace appeared successful in "flattening" the gain function with elevation angle, compared with the initial performance. The detailed results are reported in Ref. 1.

The February and March 1980 X-band antenna performance was measured by observing selected radio sources (3C274 and DR21) before and after the installation of the new subreflector. These radio source calibrators are generally well suited for the calibration of large ground-based reflector antennas and were selected to maintain consistency with previous measurements. The gain-stabilized noise-adding radiometer (NAR) was employed to measure the system noise temperature (Ref. 2), and to a large degree is responsible for the precision of the measurements reported here. The problematic absolute accuracy of this work is most likely ±0.5 to 0.6 dB (3σ) primarily due to radio source flux uncertainty, but the gain differences reported herein are considered highly accurate (±0.04 dB, 3σ) as well as exhibiting high precision in the order of hundredths of a decibel.

II. Microwave Receiving System

The receiving system used to perform the measurements reported herein incorporated the X- and K-Band Radar (XKR) feedcone followed by an R&D receiver. The microwave feed features a single hybrid mode corrugated conical feed horn with 22 dB of gain, selectable right and left circular polarization (RCP/LCP), and a low-noise traveling wave maser (TWM). The functional block diagram of the receiving system is given in Fig. 1. The receiving bandwidth was limited to ±5 MHz by the IF filter just preceding the broadband square law detector (Ref. 3). This system offered a total system operating noise temperature at zenith of 20 kelvins. Of this 20 kelvins, the TWM contributed 8 kelvins and the R&D receiver follow-up contributed 0.2 to 0.4 kelvin.

III. Antenna Modification

As part of the Voyager Enhancement Task, two major activities were scheduled during March 1980 that required evaluation. The first was to replace the original welded subreflector with an improved surface tolerance model. The root-mean-square (rms) surface tolerance of the new hyperboloid was reported to be 0.25 mm (0.010 inch); similar to the original tricone subreflector (1970) at 0.30 mm (0.012 inch) rms (Ref. 4). The second activity was to optically measure and reset the surface of the main reflector. RF gain measurements were to be performed before and after each activity to document the improvement of each step. If the improved subreflector realized an increase in antenna gain of 0.25 dB or better, the reset of the main reflector surface would then be deemed too risky in terms of possible mishap, and the loss of Voyager operational antenna tracking time would be deferred.

IV. Technique

The radiometric techniques used to evaluate the improvement in antenna gain were the same as was described in Ref. 5 with the addition of a system linearity test. The boresight optimization was achieved by using the conical scan technique. The antenna focal length changes were measured using the technique of stepping the subreflector in the axial or Z direction while measuring the loss in antenna gain at each step to determine the optimum setting. The actual gain or efficiency measurements employed the on-off sequence of system temperature measurements that yields the increase in system noise contributed by the radio source calibrator as measured with the NAR. The calibration of the NAR used the ambient calibration load as a temperature reference.

To achieve the accuracies and precisions necessary to determine the small changes in overall antenna performance, the Receiving System must have the linearity to accommodate all expected noise levels. The linearity of the receiver is a vital part of that capability. As part of a precal of each observing session, a system linearity test measured the input-output noise characteristics of the Receiving System. Excess noise was injected at the TWM input and measured as an increase in normal operating system temperature. By examining the increase at each of two noise levels produced by the normal zenith looking system and the calibration ambient load, a measure of the system linearity is achieved. The results of this test are discussed in Section VI.

V. Radio Source Calibrators

The standard radio sources, 3C274 and DR21, were selected as prime calibrators for this series of observations. The source availability during the allotted scheduled time for the measurements and maintenance of consistent calibrations (both before and after the antenna modification as well as antenna calibration measurements previously reported) were considered in source selection (Refs. 1 and 5).

The assumed flux density and other source parameters are given in Table 1. The assumed flux density S, is the result of radio source ratio measurements reported in Ref. 6. The source temperature, T_s, is the standard value on which the system efficiency is based and is determined from the flux density at the frequency of interest for a 100-percent efficient antenna by the relationship.

$$T_s = \frac{S A_p}{2k}$$

where A_p is the physical area of the antenna and k is Boltzmann's constant (1.380622×10^{-23} W/H_z - K). The typical corrected peak antenna temperatures, ΔT_a are also listed for reference in any future work. The source resolution correction, C_r, was applied to the measured antenna temperature, ΔT_a, to correct for the systematic error resulting from partial resolution of the radio source by the antenna beam. These sources are considered to exhibit strong, time-stable flux levels, and are well suited for use as gain standards for large ground-based antennas.

VI. Radiometric Observation

Observing sessions were conducted during February and March 1980 to determine the X-band performance of the 64-meter antenna. Special considerations were given to the areas of antenna pointing, optimum focus with elevation angle, receiver linearity, system temperature, as well as the overall antenna gain. The gain improvement realized from the new subreflector was sufficient to defer the measurement and reset of the main reflector surface. Therefore, only two extensive observing sessions, one prior to (February 1980) and one following (March 1980) the subreflector installation, were all that was allotted to achieve the performance verification.

A. Antenna Pointing

The antenna pointing system performed well during the observing sessions: no difficulties were encountered. A comparison of offsets prior to and following the subreflector replacement indicated no notable change as measured by the conical scan boresight technique. The scan radius used to boresight the antenna ranged from 0.015 to 0.020 degrees with a scan period of about 60 seconds. The beamwidth of the antenna at X-band was 0.038 degrees (137 arc seconds) and no change attributed to the subreflector replacement was measured.

B. Axial Focus

The subreflector axial focus positions as a function of elevation angle were measured to determine any shift in the optimum focus curve. The standard technique as described in Ref. 5 was used for this measurement. The measurements of the optimum axial focus position as a function of elevation angle are presented in Fig. 2 and show a significant shift between the before and after measurements. The optimum axial focus curve indicates a nominal 1.3-centimeter (0.5-inch) shift. At the high elevations, the difference is in the order of 1.0 centimeter (0.4 inch), and at the low elevation it is in the order of 1.5 centimeters (0.6 inch). Comparison of the axial focus for the before case and for the previous measurements reported in Ref. 5 show good agreement given the limited amount of data and the time between measurements. This minor difference is considered to be of little significance. However, the 1.3-centimeter (0.5-inch) shift detected by this series of measurements suggest a significant change that could and would affect the optimum antenna gain performance as a function of elevation angle. If ignored, this important offset could cause as much as 0.45-dB reduction in peak antenna gain. Apparently, the "match" between the main reflector (paraboloid) focal point and the subreflector (hyperboloid) focal point has been dramatically affected. It is not known if this might be a "best RF fit" (in a rms sense) due to a previously distorted subreflector, or merely an offset bias, due perhaps to different backup attachment details on the subreflector.

C. System Temperature

The total operating system noise temperature is a cornerstone of the large antenna gain measurements, and its accuracy and stability is of major importance. The operational XRO feedcone was to be the prime system used for this series of antenna measurements. During the February to March 1980 period, this system experienced gain stability problems of a few tenths of a dB (in the radiometric precision sense). In all cases, however, the XRO system was within specification for spacecraft tracking wherein slight gain instabilities are unimportant. Subsequent improvements in cabling details improved the XRO system, but not within the time frame for the antenna measurements. Therefore, the more stable XKR feed system was employed with its R&D receiver. The zenith operating system noise temperature was 20 kelvins including the TWM contribution of 8 kelvins and the R&D receiver follow-up contribution of 0.2 to 0.4 kelvin.

D. System Linearity

To measure Receive System linearity performance, the manual Y-factor instrumentation was used. The noise power contributed to the system from the noise diode can be measured at two points on the characteristic noise power input-output curve. The system is switched first to the ambient calibration load at about 300 kelvins, then the noise power from noise diode is injected and the amplitude of the noise power is measured. Then the system is switched to the feedhorn with the noise diode off. The noise power level falls to about 20 kelvins. Again, the noise power contributed by noise diode is injected into the system and its amplitude is again determined. The discrepancy between the two indicated noise diode temperatures is a measure of the system ability to linearly handle system noise temperatures in the range of 300 to 400 kelvins. For this XKR receiving system, the noise diode contributed 101 kelvins to the normal operating temperature. (i.e., 400-kelvin maximum levels must be transferred through all receiver stages, without clipping or saturating.)

This requires the system to have a linear response over a 13-dB range from 20 to 400 kelvins (zenith T_{op} = 20 kelvins: calibration load plus noise diode T_{op} = 400 kelvins). For typical DSN Receiving Systems with TWM gain set at 45 dB and the Block IV DSN receiver, the measurement of noise diode temperature at the high power levels is typically 10 to 20 percent lower than the same measurement at the zenith operating temperature. This demonstrates system saturation or clipping at the higher levels. To insure quality measurements with such a system, the gain of the TWM is reduced 3 to 6 dB to achieve linear operation. The R&D receiver used for 1980 measurements required no more than a 3-dB reduction in maser gain to achieve a linear receiver characteristic. However, this 3-dB gain reduction does cause the receiver follow-up temperature to double, but offered no difficulty in accomplishing the needed measurements.

E. System Gain

The intent of replacing the subreflector was to restore the previous (January 1973) performance as reported by the measurements reported in Ref. 1. In those measurements the system efficiency decrease was reported to be from 51.3 to 46.1 percent, based on an accepted flux density for 3C123 of 9.4 Jansky. Since the first JPL X-band measurements in 1968 (Ref. 7), 9.4 Jansky was the best available estimate of flux density. Later measurements and open literature reports of 3C123 flux density proved the 9.4 Jansky to be in error, and established the level at 10.05 Jansky (Ref. 6). Applying the revised flux density for the January and May 1973 measurements, performance levels were in actuality 48.0 and 43.1 percent, respectively. This translates to a gain loss of 0.46 dB due to the subreflector and concurrent main reflector work.

The recent measurements in February to March 1980 are presented in Fig. 3. The system efficiency shown as a function of elevation angle includes the atmospheric loss nominally incurred. Prior to the subreflector replacement, the peak system efficiency was 42.5 percent at 42.7-degrees elevation. Following the change, the peak system efficiency was 47.3 percent at 43.9-degrees elevation. The gain improvement attributed to the improved subreflector was 4.8 percent increase in system efficiency which corresponds to 0.47-dB increase in the overall antenna gain. This reliable result was quite sufficient to defer the planned main reflector surface reset since it is clear the welded subreflector was primarily responsible for the gain degradation in 1973. The gain deficiency of the DSS 14 64-meter antenna has been largely (perhaps totally) corrected and the gain performance has been reestablished at the 71.8-dBi level for XKR R&D feedsystem.

Comparison of the 1980 and 1973 results shows remarkable repeatability and similarity. The high-level performance measurements prior to the 1973 modifications and after the 1980 subreflector installation agree to within 0.7 percent and the lower level performance of the intervening years agree to within 0.6 percent. The elevation angle at which the peak performance occurs agrees to within 2 degrees in all cases. The agreement of these measurements taken 7 years apart indicate the antenna system has experienced very little or no "aging" or loss of performance with time during that period and is in contrast to the conclusions reached in Ref. 5.

A complete summary of DSS 14 64-meter antenna X-band performance measurements is given in Table 2. The measurements are classified by date and the feedcone system used for the measurements. The entries for March 1980 using the XRO dual hybrid mode horn feedcone are not measured values but have been predicted based on the November 1979 measurements and February to March 1980 measured performance increase. The significant figures of the values presented here do not necessarily denote the absolute accuracy of the measurement but are presented to provide resolution into the order and repeatability of the measurements.

VII. Conclusions

The performance of the DSS 14 64-meter antenna at X-band was measured using the XKR feedcone. The performance level anticipated with the 1973 antenna upgrade has finally been achieved. The antenna efficiency as measured with the XKR feed has increased from 42.5 to 47.3 percent, which nets an increase of 0.47 dB. With this increase, the overall gain of the 64-meter antenna with the XKR feed is 71.8 dBi. The gain of the antenna using the operational XRO feed with the recently installed dual hybrid mode feed will also exhibit a similar gain change of 0.47 dB above that reported in Ref. 5. This performance should be 50.8 percent efficient, which corresponds to a peak antenna gain at 72.1 dBi. A natural follow-on activity should pursue the measurements of antenna gain using the XRO with the new feed, confirm that performance level, and check the critical Z-axis focus characteristics.

Comparison of the measurements of antenna efficiency reported here and that of Ref. 1 (both using the XKR feed) shows good agreement both in peak performance and in the pointing angles at which that performance occurs. However, the measurement using the XRO feed shows distinct differences in the shape of the efficiency curve with elevation

(Ref. 5). The peak performance occurred at about the 52-degree elevation and was consistent prior to and following the installation of the new feed. This compares to the 42-degree elevation angle peak of this current set of measurements, which agrees more closely with the mechanical analysis of the 64-meter antenna (Ref. 8) and the 1973 measurements. Resolution of this discrepancy would improve the communication link predictions and analysis for spacecraft tracking, and would enable improved confidence in engineering predictions for possible future performance enhancement of the 64-meter antenna system, as well as other important DSN antenna projects.

The optimum axial focus has changed significantly with the installation of the improved subreflector. The optimum focus curve has shifted axially approximately −1.3 centimeters (−0.5 inch); physically the optimum subreflector focus is now closer to the feed. In anticipation of the requirement for automatic subreflector focusing for spacecraft tracking, a complete measurement of optimum axial focus for the XRO feed should be undertaken and analyzed. Also, periodic optical alignment of the main reflector panels of all 64-meter antennas is recommended to maintain the network performance at or above this high level.

To enhance the accuracy of antenna gain measurements, improvements in the following areas are needed and recommended: (1) the noise instrumentation, both Y factor and NAR, should be upgraded; (2) the system linearity, mainly within the receivers (especially the DSN Block IV Receivers) needs improvement. The DSN Block IV Receiver typically exhibits 10 to 20 percent nonlinearity at a 300 to 400 kelvin noise level into the maser input. The linearity problems outlined are present with the standard 40-MHz bandwidth TWM. With the new Block IIA 100-MHz bandwidth units, the linearity problems will become more acute. Last, but by no means least, the absolute flux density of the X-band radio source calibrators should be established to a level comparable to the S-band calibrators reported in Ref. 9.

Finally, the influence of the structural brace on the vital X-band efficiency with its elevation angle dependency is emphasized. The other 64-meter stations (DSSs 43 and 63), although fitted with dual hybrid mode feeds, good subreflectors, and other common features, do not have the structural brace installed as yet. This feature should be finally implemented at those stations to realize the full potential of the 64-meter network.

References

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Table 1. Radio source calibrations for 64-meter antenna

Source	Flux density[a] 8420 MHz S, Jansky	Source temperature (100% efficient antenna) T_S, kelvin	Typical measured antenna temperature ΔT_a, kelvin	Source resolution correction C_r	Source position (1950.0)	
					Right ascension, hr-min-s	Declination, deg-min-s
3C274	46.0	53.6	25.4	1.085	12 28 17.3	12 39 48
DR21	21.4	25.0	11.8	1.030	20 37 14.2	42 09 07

[a]Flux density values from Ref. 6.

Table 2. Historical summary of X-band performance measurements of DSS 14 64-meter antenna

Measurement date	Feedcone designation	Peak antenna efficiency η, %	Elevation angle, deg	Antenna gain G, dBi	Gain increase ΔG, dB
Feb. 1968[a,b]	XCE	48.6	≈47	71.91	–
Jan. 1973[b,c]	XKR	48.0	≈42	71.85	Ref.
May 1973[b,c]	XKR	43.1	≈42	71.38	−0.46
July 1979[d]	XRO	42.0	52	71.27	Ref.
Nov. 1979[d]	XRO	45.6	52	71.63	+0.36
Feb. 1980	XKR	42.5	43	71.32	Ref.
Mar. 1980	XKR	47.3	44	71.78	+0.47
Mar. 1980[e]	XRO	50.8	≈52	72.10	–

[a]Ref. 7, single feedcone configuration; all others are tricone configuration.

[b]1968 and 1973 measurements have been corrected by the ratio of the original assumed source flux density to the improved value.

[c]Ref. 1.

[d]Ref. 5.

[e]Predicted XRO performance based on the November 1979 measured performance and the February to March, 1980 measured performance increase.

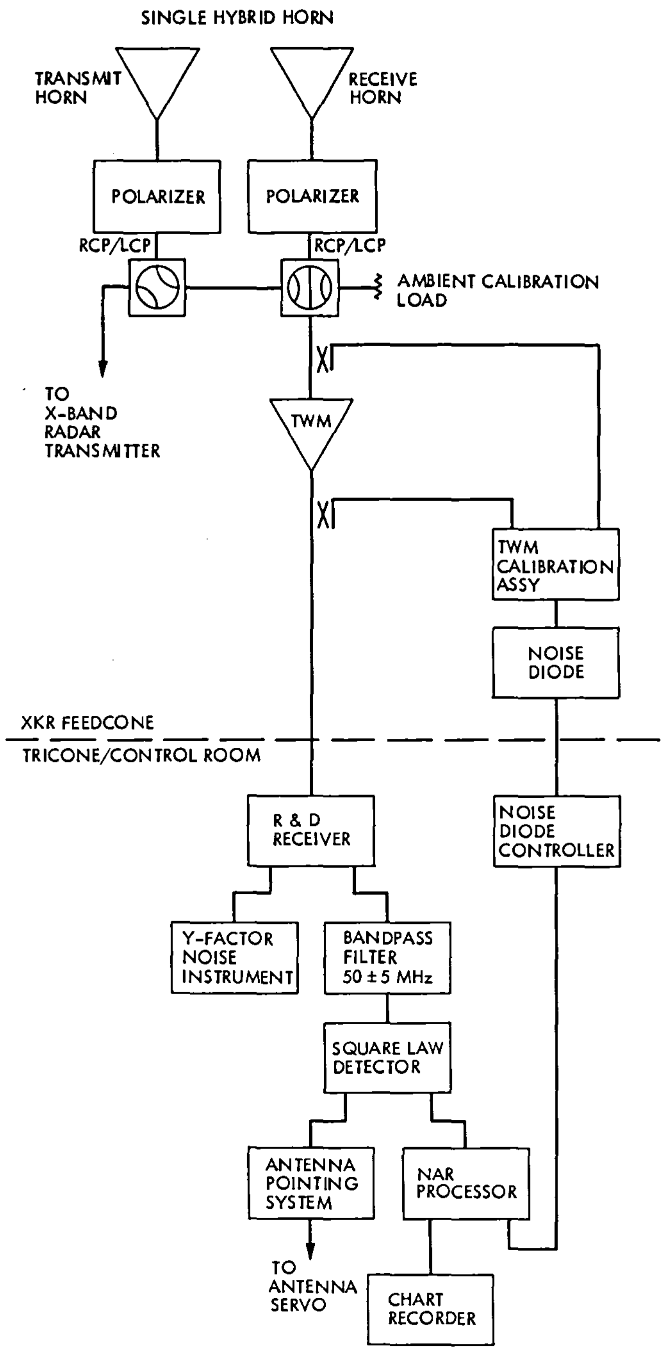

Fig. 1. The XKR X-band receiving system functional block diagram

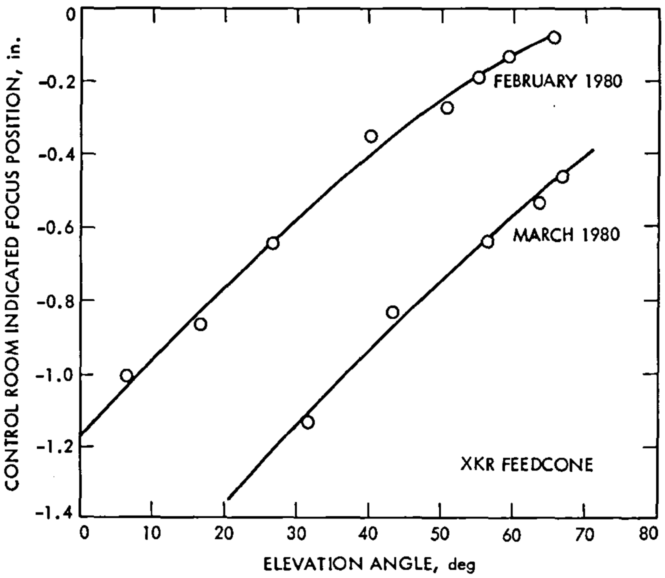

Fig. 2. DSS 14 64-meter antenna X-band optimum axial focus position as a function of elevation angle

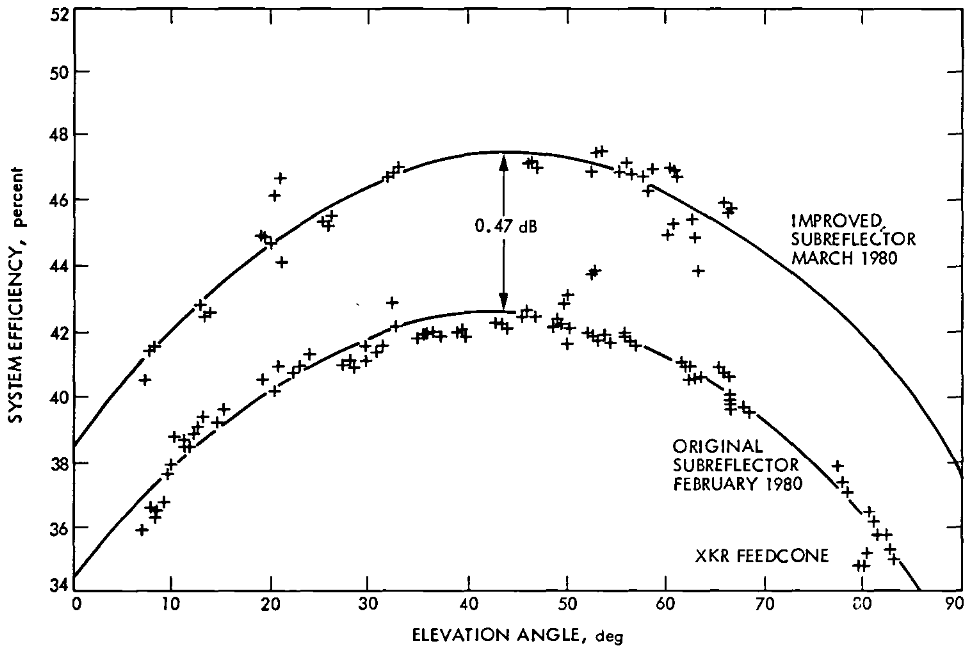

Fig. 3. DSS 14 overall antenna system efficiency at X band (8.42 GHz) with an improved subreflector