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DSN 70-Meter Antenna X- and S-Band Calibration Part II: System Noise Temperature Measurements and Telecommunications Link Evaluation

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The X- and S-band system operating noise temperatures of the DSN 70-m antennas are presented. Models of atmosphere and ground noise temperature contributions, as they affect the antenna calibrations, are given for future use in telecommunications link modeling. The measured 70-m antenna network G/T performance is presented. Compared with the earlier 64-m antenna network, G/T improvements of from 1.8 dB to 2.5 dB, depending on elevation angle, were achieved. G/T comparisons are made with the DSN/Flight Project Design Handbook and the Voyager telecommunications design control table. Actual Voyager telecommunications link performance is compared with predictions made by TPAP (the Voyager telecommunications prediction and analysis program) and with measured performance of the individual 70-m antennas. A modification in the use of antenna gain, system noise temperature, and atmospheric attenuation in existing telecommunications design control tables is suggested.

I. Introduction

This article is the second part of a two-part article covering the final calibration of the DSN 70-meter antennas in their upgrade from the original 64-meter configuration. This update occurred over a two-year period from fall 1986 through fall 1988 and was planned to enhance DSN performance at the time of the Voyager Neptune encounter (August 1989). Part I [1] contains material on the X-band (8420 MHz) and S-band (2295 MHz) gains of the antennas in addition to a rather comprehensive analysis of calibration radio source fluxes and size corrections for both the 64-meter and 70-meter antennas. Part II (this article) reports on the S- and X-band system noise temperatures and models for atmosphere and ground contributions to total system noise temperature. In addition, use of gain and noise temperature expressions in design control tables for telecommunications link analysis is also given. A comparison of measured 70-m antenna G/T (gain/system noise temperature) and the G/T model contained in the Voyager telecommunications prediction and analysis program (TPAP) is presented. Comparison of actual and TPAP-predicted Voyager telecommunications performance is presented as a test of the telecommunications link model used for that deep space mission.

The concept of "25-percent CD" weather is introduced here in order to clarify the description of weather-induced atmospheric attenuation and system noise temperature effects. "CD" means "cumulative distribution" and in this particular case, refers to that noise temperature or attenuation value which is not exceeded 25 percent of the time. "Twenty-five-percent weather" will now be used to describe an average clear-sky condition with no visible liquid water (clouds or rain). Previously, the term "clear-dry" has been used for this condition and it has been confused with a lowest-loss atmosphere containing no water vapor or liquid water, which will now be referred to as "0-percent CD" weather.

The efficiency and noise temperature calibrations of the DSN 64-meter network, carried out in 1986 and 1987, are presented in [2–4]. The present 70-meter antenna gain and noise temperature calibrations will be compared to the earlier values.

II. Measured X- and S-Band System Noise Temperatures

Figure 1 shows the X-band system operating noise temperatures (T_{op}, for selected sets of data) at all three stations during the calibration period. The upper set is the raw input data (off-source noise temperatures) taken during the efficiency scans. It should be noted that the DSS-14 noise temperature data shown are taken without the dichroic reflector in place. It has been estimated previously[1] that this results in a 1.2-K lower T_{op} than when the antenna is in its normal configuration. This difference is readily seen in Fig. 1 when the DSS-14 near-zenith noise temperatures are compared with the mean noise temperature (20.9 K) of the other two stations. The 1.4-K difference is the sum of the dichroic contribution (1.2 K) and the atmosphere difference (0.2 K) between DSS-14 and the other two stations, as estimated from surface meteorological parameters that existed at the time of the efficiency measurements.

A without-atmosphere T_{op} model can be created from the measured values by subtracting out, on a point-by-point basis, the atmospheric contributions which existed at the time of the calibration tests. Based on actual surface meteorological values, the approximate values for the X-band zenith atmospheric noise temperature and attenuation contributions were

DSS-14: 2.28 K/airmass (0.037 dB/airmass)

DSS-43: 2.52 K/airmass (0.041 dB/airmass)

DSS-63: 2.48 K/airmass (0.040 dB/airmass)

The resulting without-atmosphere noise temperature values are shown as the bottom three data sets in Fig. 1. It was decided to create a composite model of system noise temperature by averaging the DSS-43 and DSS-63 data. This decision is supported by the fact that the DSS-14 near-zenith data (adjusted upward by the 1.4-K difference from the other stations) lies very nearly between the other two curves. The final result is to have a zenith noise-temperature peak-to-peak spread of 0.5 K, which is 0.1 dB of the average value of 20.9 K. It is thus determined that the 70-m X-band antenna zenith T_{op} values with and without atmospheric contribution are

$$T_{op,zenith,x} = 20.9 \text{ K, with atmosphere}$$

$$T_{op,zenith,x} = 18.4 \text{ K, without atmosphere}$$

Similar data reduction techniques for a minimal amount of S-band calibration data yield

$$T_{op,zenith,s} = 18.3 \text{ K, with atmosphere}$$

$$T_{op,zenith,s} = 16.5 \text{ K, without atmosphere}$$

The S-band T_{op} model indicates an atmospheric noise temperature contribution of 1.80 K/airmass (0.029 dB/airmass) for the conditions which existed at the time of the calibration tests.

These zenith noise temperatures represent substantial improvements (lower noise temperature) over comparable values determined for the antennas in their 64-m configurations [2–4]. Typical without-atmosphere improvements were 1.5 K at S-band and 0.7 K at X-band. Complete descriptions of both 64-m and 70-m antenna design considerations are given in [5].

Figure 2 shows curves fitted to both X- and S-band values of T_{op}, with and without atmospheric contribution. The 1.2-K dichroic adjustment for DSS-14 is included in these curves.

At or above 10-deg elevation, the system noise temperature is given by

$$T_{op} = a_0 + a_1 \alpha + a_2 \alpha^2 + a_3 \alpha^3 \qquad (1)$$

where

$$\alpha = \frac{1}{\theta}$$

and

θ = elevation angle, deg

[1] D. A. Bathker, personal communication.

Below 10-deg elevation, T_{op} is given by:

$$T_{op} = b_0 + b_1 \theta + b_2 \theta^2 \tag{2}$$

where

θ = elevation angle, deg

The coefficients for these expressions are given in Table 1.

Strictly speaking, T_{op} is the *total* system operating noise temperature and includes the atmosphere; however, in this article it is used to indicate noise temperatures with and without atmospheric effects included. It should be noted that there are no experimental data below 10-deg elevation angle; therefore, the latter noise temperature expression (Eq. 2) is totally an extrapolation and may have large errors (several K). On the basis of curve-fitting alone above 10-deg elevation, the error for X-band (with atmosphere) is ±1.2 K ($3 - \sigma$); for S-band (with atmosphere) the error is ±0.4 K ($3 - \sigma$). The data do not appear able to support an attempt to distinguish among the antennas at the 0.1- to 0.2-K level (zenith, with atmosphere), which is what one would see due to altitude differences of the stations.

Receiver and square-law detector non-linearities, VSWR of the ambient load, temperature readout errors, and numerous other contributions all conspire to reduce the calibration accuracy of the radiometer noise diodes used during the antenna measurements. Thus, the knowledge of the absolute X- or S-band T_{op} for the 70-m antennas is estimated[2] to be no better than ±10 percent ($3 - \sigma$). This is a ±2-K error for a 20-K system.

III. Atmosphere and Ground Modeling for Telecommunications Link Analysis

It is seen in [1] that the X- and S-band antenna gain curves are presented without atmospheric effects included, i.e., as though the antenna existed in a vacuum. Indeed, gain and efficiency represent an inherent quality or condition of the antenna; outside influences should not be included in these characteristics. An antenna with poor efficiency may have large spillover and scattering noise temperature contributions, but for telecommunications link analysis the received signal power is only a function of antenna gain (without atmosphere) and atmospheric loss. Inherent in antenna gain are certain system losses such as those due to the waveguide and dichroic plate, but these are constant with time (unless the antenna is modified) and are not a function of elevation angle, as is the atmospheric loss.

[2] C. T. Stelzried, private communication.

The raw antenna noise temperature data are taken under a range of (usually) clear weather conditions. The data are corrected for the atmospheric conditions that existed at the time of the measurements, yielding a without-atmosphere determination of efficiency and gain. For telecommunications link analysis, a particular weather condition must be postulated. A description of X-band weather-related attenuation and noise temperature is given in the *DSN/Flight Project Interface Design Handbook*[3] (herein referred to as "810-5"). A new revision of this document is being developed which will include updated S- and X-band performance, and the addition of Ka-band (32 GHz) performance estimates for use in the DSN.

A nominal clear-sky weather condition is postulated as one in which there are no clouds in the sky and the relative humidity is neither low (clear dry) nor high (clear humid). Based on the rule-of-thumb that clouds are not present 50 percent of the time, the "average" clear weather condition is defined as "25-percent weather" as discussed earlier. For comparison with previous "clear sky" (but otherwise uncharacterized) measurements, the concept of 25-percent weather is introduced.

The presentation of predicted antenna gains in 810-5 includes a clear-sky (but undefined) atmospheric loss. "Without-atmosphere" gains would not include this loss, and lacking information regarding test conditions during the gain measurements, one must assume that a nominal 25-percent weather condition existed. For a standard atmosphere [6] with a surface water vapor density of 7.5 g/m^3 the surface parameters are:

Temperature = 15°C

Pressure = 1013 mb, at sea level

Relative Humidity = 58 percent

Using these surface values at the altitudes of the three DSN 70-m locations results in clear-sky, 25-percent weather zenith-effect models for the three locations as given in Table 2. Also shown for comparison is a DSS-14 condition with no water vapor (minimum-loss atmosphere, 0-percent weather) in acknowledgment of the fact that Goldstone may have a significantly lower average relative humidity than do the other two 70-m sites.

It is seen that the effects at the three sites are uniformly distributed with a mean close to the effects at DSS-63. (The mean height above sea level is 0.825 km.) The DSS-14 no-water-vapor case shows significantly lower atmospheric effects. Climatalogically, Goldstone (DSS-14) is quite different from

[3] *Deep Space Network/Flight Project Interface Design Handbook*, Rev. D, JPL 810-5 (internal document), July 1988.

the other two locations. As an example, the mean rainfall there is 3.5 in./year. At DSS-43 it is 23.0 in./year, and at DSS-63 it is 19.6 in./year. Thus, the overseas sites receive about six times as much rain as does Goldstone. It is assumed that cloud effects are also proportionately larger.

For clear-sky (25-percent weather) modeling, it may be of little consequence whether one uses either the nominal or dry zenith models for DSS-14. The error in calculating the X-band received power level will be less than 0.1 dB at a 6-deg elevation angle. The noise temperature error calculated at the same elevation angle may be as much as 6 K out of a total T_{op} of about 50 K, resulting in a calculated SNR (signal-to-noise-ratio) error of about 0.5 dB. As given in Table 1 (cf. also Fig. 2) the without-atmosphere values of T_{op} reflect the effect of a changing spillover and scatter contribution as a function of elevation angle. All other contributions to noise temperature are constant with elevation angle, except for a slightly changing cosmic background contribution. (This contribution varies less than 1 K for all elevation angles over a wide range of weather conditions; although, for the sake of completeness, this variation should be accounted for in design control tables.) An estimate of 70-m antenna zenith ground (rear spillover plus quadripod scatter) contribution is 3.0 ±0.5 K for X-band, and about 0.5 K more for S-band as a result of optimizing the X-band spillover design at the expense of S-band.[4]

The clear-sky (25-percent weather) total system noise temperatures at zenith are made up of the components shown in Table 3. Assuming nominal receiver values it can be seen from this table that the ground noise contribution may then be expressed as:

$$T_{ground,x}\ (\mathrm{K}) = T_{x,w/o\ atm} - 15.4 \tag{3}$$

$$T_{ground,s}\ (\mathrm{K}) = T_{s,w/o\ atm} - 13.0 \tag{4}$$

where $T_{w/o\ atm}$ is calculated from the values given in Table 1, and 15.4 K and 13.0 K are the receiver plus cosmic contributions to T_{op} at X- and S-bands, respectively.

Subtracting the 2.7-K cosmic background from the constants in the above two expressions, one then obtains the fixed receiver and waveguide contributions to system noise temperature, in this case 12.7 K (X-band) and 10.3 K (S-band). It should be noted that errors in the estimate of the "fixed" zenith ground contribution can be "traded-off" against noise temperature contributions from receiver and waveguide to give the total zenith T_{op} values shown in Fig. 2.

It is seen then that at 30-deg elevation the total ground contributions at X- and S-bands are 5.0 K and 4.5 K, respectively. The changes from the X- and S-band zenith values are 2.0 K and 1.0 K, respectively.

The 1.80-K S-band atmosphere described earlier is that which existed during antenna calibration tests and is thus shown in Fig. 2. This is 0.1 K lower than shown in Table 3, but is not inconsistent with the agreement between the X-band model and experiment, as the X- and S-band data sets were not taken at the same time. In other words, the atmospheric attenuation and noise temperature during the S-band calibrations were slightly less than nominal.

By separating out the atmosphere and ground noise temperature contributions separately, these effects are more easily handled in design control tables when the effect of a particular weather condition is studied, when changes are made in antenna configuration, or when particular antenna components are modified in any manner.

IV. G/T Improvement with the 70-m Antenna Network

The gain/noise temperature (G/T) ratio is generally regarded as the key figure-of-merit for a telecommunications antenna and receiver system. For the 70-m upgrade project, the maximization of this ratio at X-band was a key design parameter.

Substantial X-band gain improvements over those of the 64-m antennas were made. For an accurate gain comparison, the peak 64-m antenna gains as reported in [2–4] must be adjusted upward as a result of studies made during the analysis in [1]. A redetermination of radio source 3C274 flux contributes a +0.076-dB change. A recalculation of the 3C274 source-size correction for the 64-m antennas results in two corrections, one for DSS-14 and one for DSS-43 and DSS-63. As given in the DSN radio source catalog,[5] the source-size correction for 3C274 in use during the DSS-43 and DSS-63 calibrations was 1.085 (D-3801, rev. A). During the DSS-14 calibration the source-size correction was 1.089 (D-3801, rev. B). The latest calculated value [1] is 1.15, giving changes of +0.253 dB (DSS-43 and DSS-63) and +0.237 dB (DSS-14). Adding these to the 0.076-dB flux adjustment results in total gain changes of +0.313 dB (DSS-14) and +0.329 dB (DSS-43/63). Comparing the peak without-atmosphere gains of the

[4] D. A. Bathker, personal communication.

[5] *DSN Radio Source List for Antenna Calibration*, JPL D-3801, Rev. A and Rev. B, September 25, 1987, (internal document), hereafter referred to as D-3801.

64-m antennas (from [2–4], adjusted upward) and 70-m antennas [1], the gain improvements for each antenna are

DSS-14: +1.85 dB

DSS-43: +2.15 dB

DS-63: +2.37 dB

Of these totals, about 0.8 dB is due to area increase, and the remainder is due to efficiency improvement. The average X-band gain increase is about 2.1 dB, well above the project requirement of 1.9 dB. Repeating the results presented in [1], the final peak without-atmosphere gains and aperture efficiencies for the 70-m antennas are

DSS-14 (Goldstone): 74.172 dBi (68.50 percent)

DSS-43 (Canberra): 74.093 dBi (67.27 percent)

DSS-63 (Madrid): 74.287 dBi (70.34 percent)

The without-atmosphere noise temperature improvements (decreases) at zenith are discussed in Section II. The S-band improvement is about 0.4 dB, and the X-band improvement is about 0.2 dB.

Figure 3 shows the final 70-m X-band gain (as given in [1]) and system noise temperature performance compared with the model contained in the latest (1986 through 1988-era) 810-5 Design Handbook. This comparison is made to document the 1986 accuracy of predicting the G and T performance of the 1989 70-m antenna network. The initial predicted values were used in preliminary estimates of Voyager (and other) telecommunications link performances through the year 2000. The points plotted in the curves are measured values minus 810-5 modeled values (which include a clear-sky atmosphere). The measured 70-m gain values include a nominal 25-percent clear-sky weather attenuation (0.040 to 0.042 dB as given in Table 2) for comparison with the 810-5 values measured during what must now be assumed (years after the fact) to be also a 25-percent clear-sky condition. The zenith atmospheric attenuation value over the 0 to 50 percent CD (cumulative distribution) range is about 0.040 dB ±0.010 dB (cf. Table 2), which gives some idea of the maximum possible post facto error in the 25-percent CD assumption. The 70-m T_{op} values are those given in Table 1 and Fig. 2 (X-band with atmosphere).

It is seen that at low elevation angles, the measured (and extrapolated) T_{op} is much larger than the 810-5 model. This difference is 5.7 K at 5-deg elevation. Above 20-deg elevation, *the difference* is less than 1 K, with the measured values being larger than the 810-5 values. The measured 70-m antenna gain performance exceeded the model over most of the elevation angle range, with a maximum difference for DSS-63 of about 0.3 dB at 35–50-deg elevation. Below 10-deg elevation, only DSS-14 exceeds the model; the other antennas are as much as 0.35 to 0.5 dB below the model at 5-deg elevation. The ±0.3 dB (±7 percent) agreement range for all antennas extends from about 8-deg to 90-deg elevation.

The 810-5 modeled 70-m antenna performance was derived from a hybrid performance combination (increased by 1.9 dB) of the 64-m antennas as given in earlier versions of 810-5. The gain values used for DSS-14 and a combined DSS-43/63 differ uniformly by 0.12 dB and reflect the fact that the DSS-14 gain was somewhat higher than the gain of the overseas antennas. This difference underestimated the measured difference [2–4] of 0.40 dB, including adjustments. The shapes of the 810-5 gain curves reflect the flatter shapes of the DSS-14 and DSS-43 (64-m) curves, as compared to the DSS-63 (64-m) gain curve, which had a steep falloff at both low and high elevation angles [2–4]. This difference was due to a structural anomaly of the DSS-63 64-m antenna; the 70-m antennas are presently identical in construction. The 810-5 noise temperature values used were common to all antennas and give a zenith T_{op} value of 20.0 K. The tolerance of the 810-5 zenith noise temperature was ±3 K (σ not stated), which is comparable to the ±10-percent value given earlier in Section II.

Figure 4 shows the 810-5 G/T model and the measured G/T comparison for the 70-m antennas, in addition to a curve representing the 64-m network G/T performance. It is seen in the figure that the 810-5 models of 70-m performance (the pairs of data points, computed from G and T as described above) are quite accurate (±0.2 dB) over the 15- to 90-deg elevation angle range. Below 15-deg elevation, the greater measured T_{op} results in performance not agreeing with the model. Note that DSS-14 almost perfectly matches the 810-5 model of G/T from 10-deg elevation to zenith.

The 64-m G/T curve shown in Fig. 4 is a hybrid curve and represents the best possible performance that might have been achieved by the 64-m network. The curve combines the highest gain (DSS-14) and lowest noise temperature (DSS-43), both with atmosphere, as given in [3, 4]. The 64-m gain value has been adjusted upward by 0.313 dB, as discussed above. Measured individual 64-m antenna performances were somewhat lower than shown in this figure, due to either lower gain or increased T_{op}. This hybrid model is used to show the *minimum* G/T improvement of the 70-m network over the 64-m network. Comparing the DSS-14 G/T performance, the improvement ranges from a minimum of 1.8 dB at zenith to a maximum of almost 2.5 dB at 10-deg elevation. From 20-deg to 80-deg the DSS-14 improvement is about 2.0 dB (±0.2 dB).

It is seen that the 70-m antenna upgrade has resulted in a substantially more powerful DSN telecommunications operation than existed with the previous 64-m configuration.

V. Comparison of Measured DSN 70-m Antenna Performance, TPAP-Predicted Link Performance, and Actual Voyager Telecommunications Performance

An integral and absolutely vital part of the telecommunications link design control table (DCT) is an accurate description of the gain and system noise temperature characteristics of the antennas being used. Differences between measured performance and the DCT model (all other things being equal) will be reflected in either an excessive or inadequate link margin. The results, in short, will be unnecessary sacrifice of the quantity or the quality of pictures of Neptune (for example).

Clearly, two of the most important goals of the 70-m upgrade project were to obtain the maximum gain and the minimum noise temperature possible from the upgraded antennas. In telecommunications link operation, the maximum amount of data that can be received is directly proportional to the real G/T value of the receiving system at whatever elevation angle the spacecraft happens to be. It should be noted that in all discussions of G/T, one is talking about operational performance, and as such the effects of the atmosphere are included in both G *and* T. In order to maximize the data received, accurate predictions of link performance must be made in order to choose, among many other things, the transmitted data rate. Included in the link performance prediction are numerous other considerations among which are weather effects, spacecraft limit cycling (pointing), variations of transmitted power, and ground antenna pointing error (including conscan offset effect).

The Voyager design control table, TPAP (Telecommunications Prediction and Analysis Program), has within it models of antenna gain, system noise temperature, and certain adjustments for weather conditions more severe than the nominal 25-percent CD weather postulated for the 810-5 gain and noise temperature curves.

To verify the accuracy of TPAP, the following must be determined: (1) what antenna parameters are being used in the program, (2) whether they agree with an official project document or the 810-5 document, (3) whether they agree with the newly determined 70-m antenna performance characteristics [1], and (4) whether the Voyager telecommunications link actually operates as predicted.

It was found during the Voyager Uranus encounter (January 1986) using the DSN 64-m network, that there was an excess X-band link margin of approximately 1 to 2 dB, depending on the station, in benign weather conditions, as indicated by symbol signal-to-noise (SSNR) residuals.[6] (The Voyager Uranus encounter, of course, was eminently successful.) Subsequent to that encounter, elements of the 64-m TPAP program were changed to reflect updated 810-5 Design Handbook values. Included in these changes were a ground antenna gain increase of +0.3 dB, and a T_{op} decrease of 2.1 K (+0.4-dB improvement). The total adjustment was +1.0 dB. With the 70-m upgrade, the changes to the telecommunications database to be used for Neptune encounter totaled 3.3 dB, including the 1.0 dB described above.

Because of inconsistencies between the TPAP computational methods and the presentation of the 810-5 link parameters, attempts were made within TPAP to approximate the 810-5 values for gain and noise temperature. The resulting gain and T_{op} values do not agree exactly with the 810-5 values. The TPAP T_{op} values are all 0.5 K lower than the 810-5 values, e.g., with a zenith value of 19.5 K. This discrepancy is caused by the fact that the atmospheric noise increase with elevation angle is generated within TPAP from an atmosphere attenuation model; in 810-5 the noise temperature increase (ground and atmosphere) is given as a separate input. The single gain curve in TPAP is a hybrid 64-m curve raised 1.9 dB, with downward adjustments of -0.2 dB made for an asymmetric statistical gain distribution, and -0.1 dB made for conscan pointing offset. The elements of the gain curve, before the 0.3-dB adjustment, are given in *Voyager Telecommunications Design Control Document*.[7] Nevertheless, a single 70-m G/T curve can be generated from the TPAP parameters, and this can be compared with the three G/T curves shown for the 70-meter antennas (cf. Fig. 4).

Figure 5 shows the differences between the measured 70-m G/T and the model contained within TPAP. It is seen that the measured performance over the 20- to 90-deg elevation range tends to exceed the TPAP predictions for clear-sky conditions. A difference of as much as 0.3 dB exists (for DSS-14 at 20-deg elevation, and for DSS-63 at 35-deg elevation). At the lower elevation angles all antennas appear to drop off in performance compared to the TPAP model due to an incorrect 810-5/TPAP noise temperature model, and, in the cases of DSS-43 and DSS-63, there is a steep gain fall-off, more severe than in

[6] B. D. Madsen, personal communication.

[7] *Voyager Telecommunications Design Control Document*, JPL 618-257, rev. A (internal document), Jet Propulsion Laboratory, Pasadena, California, January 15, 1988.

the models. It should be noted that the excessive T_{op} values are compared with the TPAP model, not the slightly different 810-5 model. In actuality there was, in general, a decrease in real T_{op} contribution compared with the 64-meter network values. The present 810-5 and TPAP antenna performance models are somewhat unrealistic, but not so much as when they modeled the 64-m antenna performance.

Figure 6 shows the curves of Fig. 5 plotted with selected sets of Voyager symbol SNR (SSNR) residuals representing differences between actual Voyager telecommunications link performance and TPAP-predicted link performance. In the following discussion, "measured link" means measured 70-m antenna G/T, "modeled link" means the G/T model contained within the TPAP program, "actual performance" means actual Voyager SSNR, and "predicted performance" means TPAP-predicted Voyager SSNR. Comparisons among these four items require the use of the TPAP "transfer standards," in which accurate gain and noise temperature models (and numerous other factors) within TPAP imply an accurate prediction of received SSNR.

These data were recorded during the last quarter of 1988 and in early 1989. The straight line segments represent the Voyager 1 (Spacecraft 31) and Voyager 2 (Spacecraft 32) SSNR residuals during particular passes which appeared to represent the best actual performance of the link during the period mentioned (in other words, when everything was working well). These passes are annotated as STATION/SPACECRAFT/DOY. No appropriate data for DSS-43/Spacecraft-31 could be found. The data are restricted to the period after 1988 DOY 274, at which time there was a database change (an adjustment of system noise temperature) within TPAP. The comparison between measured link residuals (the curves) and actual performance residuals (the straight line segments) should be a valid test of the link model and telecommunications prediction methods used by the Voyager Project.

It is seen that for DSS-63 there is remarkable agreement between the actual Voyager excess performance (positive residuals) and the excess measured antenna G/T, compared with the TPAP models. Over the 20- to 50-deg elevation angle range, the agreement is within 0.1 dB, and shows as much as +0.3-dB link margin. For DSS-14 it appears that the Voyager link may be underperforming by as much as 0.2 dB over the elevation range 20- to 60-deg. The DSS-43 data appear to be 0.2 to 0.4 dB below what might be expected from the link. Again, these data were chosen from a very small number of passes, and given a larger database, higher performance may very well be seen. Long-term daily observations of the SSNR residuals by Voyager telecommunications analysts have not detected significantly inadequate performance of any station.[8] The uncertainty in both the G/T and SSNR residuals is about 0.2 dB (1-σ). No data were available at low elevation angles, thus it is not possible in this article to verify the large negative G/T residuals shown below 10-deg elevation.

VI. Use of Antenna Parameters in Telecommunications Design Control Tables

By the relationships given in [1] for S- and X-band antenna gain, and in this article for S- and X-band atmospheric contributions, ground noise temperatures, and microwave system constants, design control tables can be developed to predict G/T (gain/system noise temperature) for a given antenna, at a given elevation angle, for a given weather condition. The weather condition is referred to as "*x*-percent-weather," and is actually the cumulative distribution (CD) of the weather statistics at the point of interest. As an example, 90-percent weather (CD = 0.90) means that 90 percent of the time the weather effect (attenuation or noise temperature) is less than or equal to a particular value.

For example, consider the DSS-43 (Canberra) 70-m antenna, X-band, 90- through 10-deg elevation angle, 90-percent weather, worst month. Also included is a hot-body contribution at 0.5 K, as determined by methods presented in the 810-5 Design Handbook. Table 4 shows that portion of a design control table (DCT) concerned with antenna, atmosphere, and ground effects. The details of the calculation of each entry are given in the Appendix. It is seen in this example that in contrast to previous methods of calculating gain, attenuation, and noise temperature effects, atmospheric attenuation is not included in the antenna gain description, ground and atmosphere effects are separated, that there is not a single zenith T_{op} value which includes ground, atmosphere, receiver, waveguide, and cosmic contributions, and that the changes with elevation angle are simply calculated. The DCT portion presented here is formulated to lend itself to straightforward calculations by means of any spreadsheet program.

VII. Conclusion

The 70-meter antenna upgrade project has significantly improved the gain and noise temperature characteristics of the three large antennas in the NASA Deep Space Network.

[8] B. D. Madsen, personal communication.

Although the noise temperature improvements have been modest (0.2 to 0.4 dB at zenith), the peak gain increases have been substantial (1.85 to 2.37 dB over the comparable 64-m antennas). The combined effect of both contributions has been to increase the G/T (gain/noise temperature) performance of the DSN from a minimum of 1.8 dB to a maximum of 2.5 dB, compared to the best possible G/T of a 64-m antenna.

An analysis was made to determine the measured 70-m G/T performance compared with that presented in the 810-5 Design Handbook. It was found that compared to 810-5, the measured gains for all stations are within 0.3 dB from 8-deg elevation to zenith. The noise temperature agrees within 0.3 dB from 17-deg elevation to zenith. The G/T agreement is within 0.2 dB from 15-deg to zenith.

In anticipation of the Voyager Neptune encounter in August 1989, a comparison of measured 70-m antenna performance and actual Voyager telecommunications performance was made, both relative to the gain, noise temperature, and performance models contained within TPAP. Based on limited sets of link SSNR residuals for the period late-1988 through February 1989, it was found that the DSS-63 link at its best appears to perform in agreement with the measured 70-m antenna performance. In other words, they both appear to have the same amount of excess performance (up to 0.3 dB) compared to the models contained within TPAP. The DSS-14 link appears to be operating as much as 0.2 dB below its capability, although in agreement with the predictions of the TPAP model. The DSS-43 link appears to be operating as much as 0.3 to 0.4 dB below both its capability and its TPAP-predicted performance.

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The authors wish to thank all of the engineers and technicians of the DSN for their efforts in gathering the enormous amount of data necessary to characterize the performance of the 70-meter antenna network.

Table 1. Coefficients of polynomial expressions for 70-m system noise temperatures, T_{op}, K

Coefficient	X-band $T_{x,w/atm}$	X-band $T_{x,w/o\ atm}$	S-band $T_{s,w/atm}$	S-band $T_{s,w/o\ atm}$
a_0	17.31485	16.79863	16.03823	15.73028
a_1	260.33790	133.73960	170.74070	61.51348
a_2	−444.55570	−738.87820	−329.81790	−284.86760
a_3	−146.17770	1376.48100	−65.32625	461.33590
b_0	70.64852	28.57571	47.82000	22.47123
b_1	−4.58767	−0.53753	−2.52123	−0.41137
b_2	0.13988	0.00960	0.07142	0.01142

Note: High-elevation limits for T_{op} expressions (Eq. 1):

if $T_{x,w/atm} < 20.9$ then $T_{x,w/atm} = 20.9$

if $T_{x,w/o\ atm} < 18.4$ then $T_{x,w/o\ atm} = 18.4$

if $T_{s,w/atm} < 18.3$ then $T_{s,w/atm} = 18.3$

if $T_{s,w/o\ atm} < 16.5$ then $T_{s,w/o\ atm} = 16.5$

Table 2. Nominal clear-sky (25-percent weather) zenith atmospheric attenuation (*A*) and noise temperature (*T*) at DSN 70-m antenna locations

Station	X-band		S-band	
	A, dB	T, K	A, dB	T, K
DSS-14 0.993 km MSL	0.040	2.45	0.030	1.81
DSS-14 no water vapor (0-percent weather)	0.031	1.86	0.029	1.77
DSS-43 0.670 km MSL	0.042	2.60	0.032	1.93
DSS-63 0.812 km MSL	0.041	2.53	0.031	1.88

Table 3. Components of clear-sky (25-percent weather) total zenith system noise temperature, K

	Contribution to noise temperature, K	
	X-Band	S-Band
Receiver + waveguide	12.7 ±0.5	10.3 ±0.5
Atmosphere, nominal	2.5	1.9
Ground (spillover + scatter)	3.0 ±0.5	3.5 ±0.5
Cosmic background	2.7	2.7
Total	20.9	18.4

Table 4. Proposed Design Control Table (DCT); portion concerning antenna, atmosphere, and ground effects

1	Ground antenna diameter, m	Input	70.0000	70.0000	70.0000	70.0000	70.0000	70.0000
2	Frequency, GHz	Input	8.4200	8.4200	8.4200	8.4200	8.4200	8.4200
3	Wavelength, m		0.0356	0.0356	0.0356	0.0356	0.0356	0.0356
4	Elevation angle, deg	Input	90.0000	60.0000	45.0000	30.0000	20.0000	10.0000
5	Percent weather, CD	Input	0.9000	0.9000	0.9000	0.9000	0.9000	0.9000
6	Atmosphere attenuation total zenith, dB	Input	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700
7	Atmosphere attenuation total at elevation, dB		0.0700	0.0808	0.0990	0.1400	0.2047	0.4031
8	Atmosphere loss factor L at elevation		1.0162	1.0188	1.0231	1.0328	1.0483	1.0973
9	Ground antenna gain without atmosphere, 100 percent, dBi		75.8148	75.8148	75.8148	75.8148	75.8148	75.8148
10	Ground antenna gain without atmosphere at elevation, dBi		73.3753	74.0412	74.0900	73.9494	73.7505	73.4673
11	Receiver noise, K	Input	3.5000	3.5000	3.5000	3.5000	3.5000	3.5000
12	Waveguide noise, K	Input	9.2000	9.2000	9.2000	9.2000	9.2000	9.2000
13	Atmosphere physical temperature, K		278.5000	278.5000	278.5000	278.5000	278.5000	278.5000
14	Atmosphere noise, total, K		4.4529	5.1354	6.2764	8.8346	12.8202	24.6871
15	Ground noise, K	Input	3.0000	3.2580	3.8880	5.0230	6.4360	8.9570
16	Hot-body noise without atmosphere, K	Input	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
17	Hot-body noise, K		0.4920	0.4908	0.4887	0.4841	0.4770	0.4557
18	Cosmic noise temperature, K		2.6568	2.6502	2.6392	2.6144	2.5757	2.4607
19	Total system noise temperature, T_{op}, K		23.3017	24.2344	25.9923	29.6561	35.0089	49.2604
20	Gain/T_{op}, dB		59.6314	60.1160	59.8426	59.0883	58.1040	56.1392

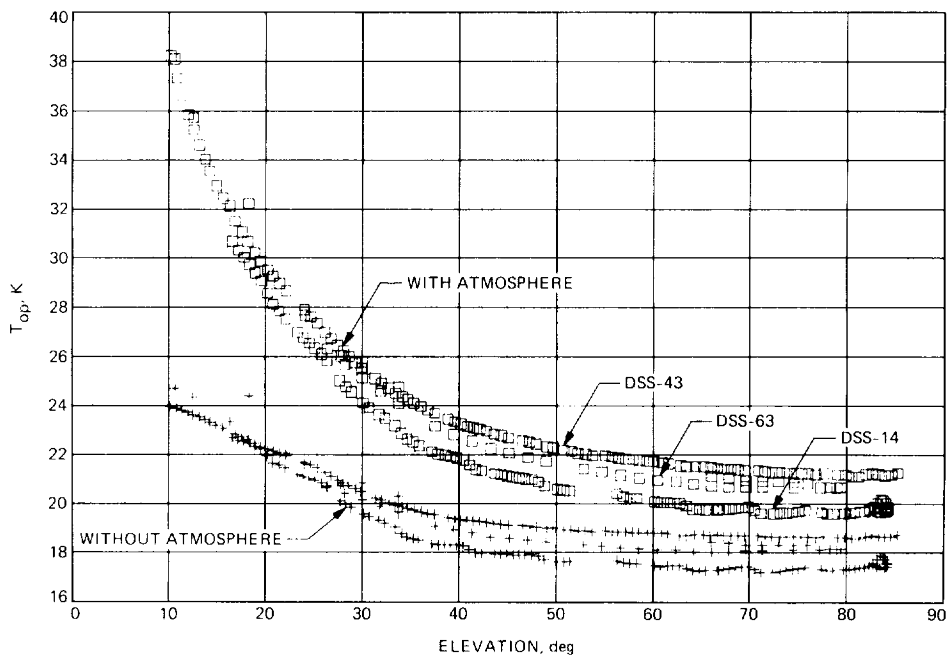

Fig. 1. The 70-m antenna X-band noise temperatures, with and without atmospheric contribution.

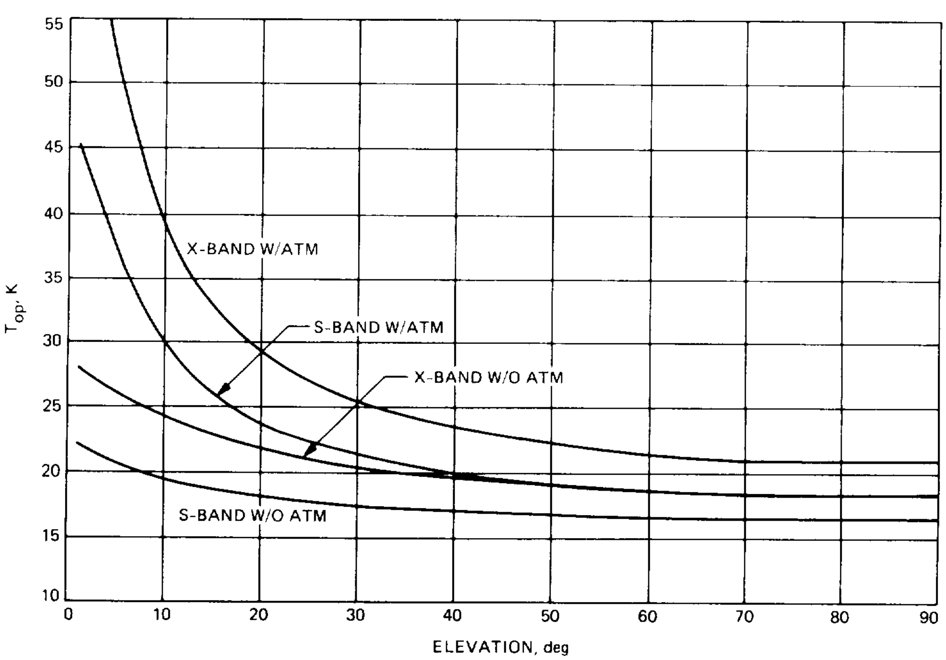

Fig. 2. S- and X-band noise temperature curve-fits, with and without atmospheric contribution.

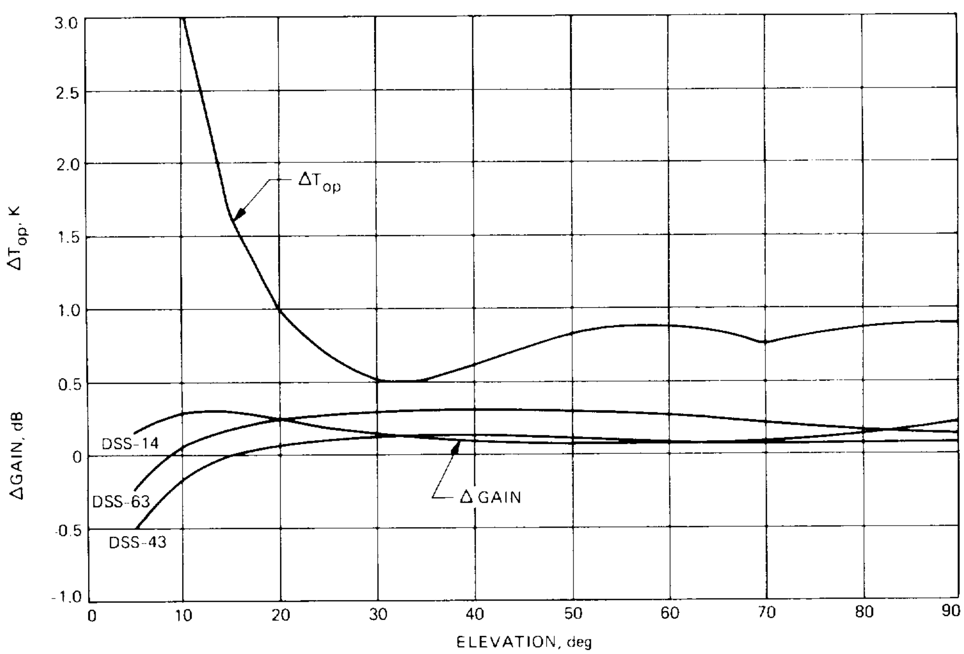

Fig. 3. The 70-m antenna measured minus 810-5 model of gain and system operating noise temperature.

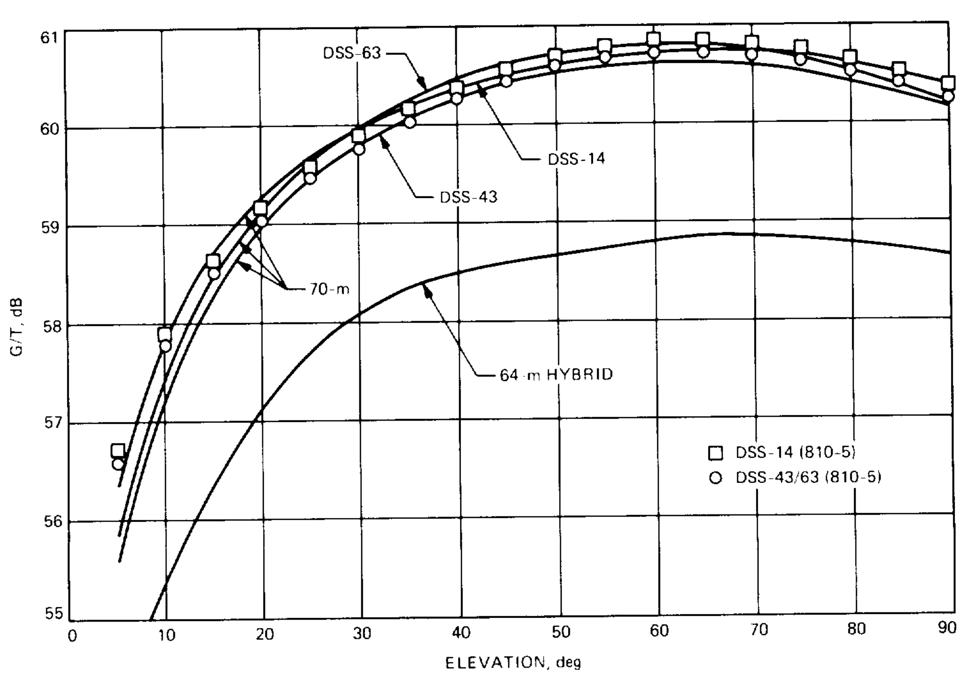

Fig. 4. Comparison of 70-m antenna measured and 810-5 G/T values, with best possible 64-m performance.

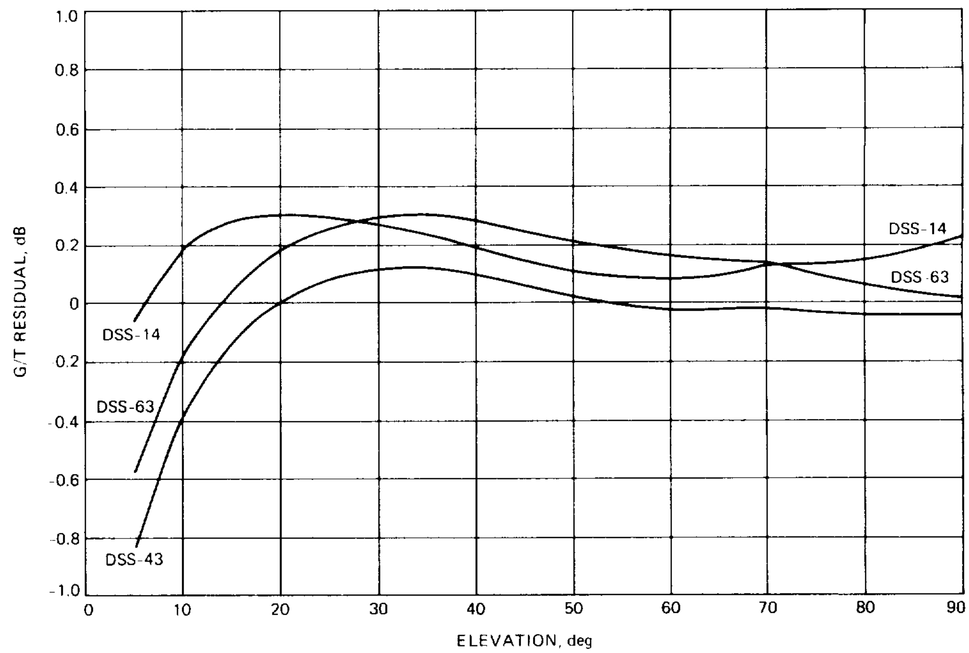

Fig. 5. The 70-m antenna measured G/T minus Voyager TPAP-predicted G/T.

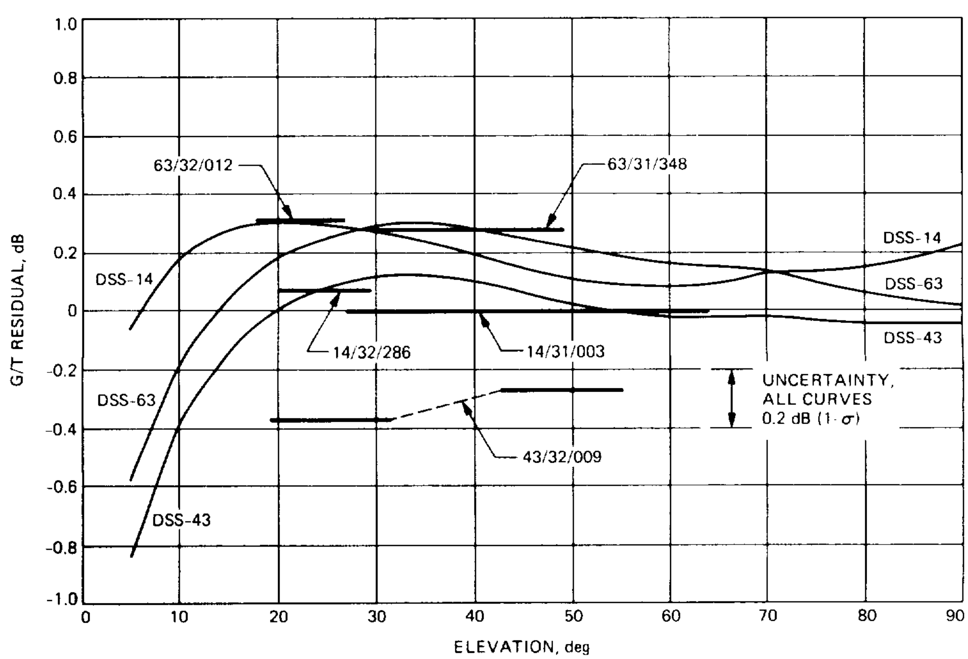

Fig. 6. The 70-m antenna measured G/T minus Voyager TPAP-predicted G/T, with Voyager SSNR residuals.

Appendix

Sample DCT for Antenna, Atmosphere, and Ground Effects

Following is a line-by-line listing of the entries in a design control table (cf. Table 4).

Line 1: INPUT ground antenna diameter, DIAM, meters.

Line 2: INPUT frequency, FREQ, GHz.

Line 3: The wavelength, meters, is calculated from

$$\text{WVLN} = 0.29979/\text{FREQ}$$

Line 4: INPUT elevation angle, ELEV, degrees.

Line 5: INPUT percent weather, cumulative distribution, CD, (0–1).

Line 6: INPUT total zenith atmospheric attenuation, AZEN, dB, for weather condition (CD) of interest. This will usually be found in an external source such as the 810-5 Design Handbook, or another source of measured or modeled weather effects. In the example presented here, the 0.070-dB value is calculated from values presented in the 810-5 Handbook, TCI-40: 0.033-dB baseline plus 0.037-dB increase.

Line 7: The total atmospheric loss, dB, at the elevation angle of interest is calculated from

$$\text{ADB} = \text{AZEN}/\sin(\text{ELEV})$$

This flat-earth model is accurate to within 4 percent down to an elevation angle of about 6 deg, in which case it overestimates the loss. The error at 12-deg elevation is an overestimate of about 1 percent.

Line 8: The atmospheric loss factor (dimensionless) is calculated from

$$\text{LATM} = 10^{\frac{\text{ADB}}{10}}$$

Line 9: The ground antenna gain, dBi, for 100-percent efficiency is calculated as a diagnostic only:

$$\text{G100} = 10 \log 10 \left(\frac{\text{PI} \cdot \text{DIAM}}{\text{WVLN}}\right)^2$$

where PI = 3.14159265.

Line 10: Ground antenna gain, dBi, without atmosphere as a function of elevation angle is calculated from

$$\text{GDB} = 73.10 + (4.09421\text{E}-02)\theta - (4.20925\text{E}-04)\theta^2$$

where

$$\theta = \text{elevation angle, deg}$$

This polynomial expression matches the DSS-43 without-atmosphere gain as presented in [1]. Expressions for gain will be found in the 810-5 design document, this article, or may be postulated for other frequencies. This calculated value should be compared with G100 for reasonableness.

Line 11: INPUT ground receiver noise temperature, TRCVR, K.

Line 12: INPUT ground antenna waveguide noise temperature, TWG, K.

Note: sum of lines 11 and 12 agrees with the value in Table 3.

Line 13: Atmosphere mean physical temperature, K, calculated as a function of cumulative distribution CD to reflect the fact that weather effects which dominate at the higher CDs generally occur closer to the ground and thus have a higher physical temperature.

$$\text{TPATM} = 265 + 15 \times \text{CD}$$

Line 14: Calculated atmospheric noise temperature, K:

$$\text{TATM} = \text{TPATM}\left(1 - \frac{1}{\text{LATM}}\right)$$

Line 15: INPUT ground noise temperature TGRND, K, calculated, (external to the spreadsheet) from:

$$\text{TGRND} = T_{w/o\ atm} - 15.4$$

This is Eq. (3), this article. Expressions for the $T_{w/o\ atm}$ contribution will be found in the 810-5 Design Handbook, this article, or may be postulated for other configurations. For use in spreadsheet calculations, the polynomial expressions given in Table 1 may be too complex, hence external calculations for given elevation angles may be required. Simplifications to the Table 1 expressions may be used in some applications, with some loss of accuracy.

Line 16: INPUT hot-body noise THOT, K, as given in 810-5, with the ground antenna pointing a fixed angular distance from the source. This may change during an encounter period.

Line 17: Hot-body noise, K, attenuated by the atmosphere is calculated from:

$$\text{THOTP} = \frac{\text{THOT}}{\text{LATM}}$$

Line 18: Cosmic noise temperature, K as attenuated by the atmosphere:

$$\text{TCOS} = \frac{2.7}{\text{LATM}}$$

Line 19: Total system noise temperature, T_{op}, K, as calculated from:

$$\begin{aligned}\text{TOP} &= \text{TRCVR} + \text{TWG} + \text{TATM} \\ &\quad + \text{TGRND} + \text{THOTP} + \text{TCOS}\end{aligned}$$

Line 20: G/T (gain/system noise temperature), dB, is calculated from:

$$\text{GT} = \text{GDB} - \text{ADB} - 10\log10(\text{TOP})$$

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[3] S. D. Slobin, "DSS-43 64-Meter S- and X-Band Efficiency and System Noise Temperature Calibrations, January 1987," *TDA Progress Report 42-90*, vol. April–June 1987, Jet Propulsion Laboratory, Pasadena, California, pp. 116–126, August 15, 1987.

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[5] D. A. Bathker and S. D. Slobin, "DSN 70-M Antenna Microwave Optics Design and Performance Improvements: Part I," *TDA Progress Report 42-97*, vol. January–March 1989, Jet Propulsion Laboratory, Pasadena, California, this issue.

[6] S. L. Valley, ed., *Handbook of Geophysics and Space Environments*, New York: McGraw-Hill, 1965.