Relative Performance of 8.5-GHz and 32-GHz Telemetry Links on the Basis of Total Data Return per Pass

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The performance of X-band (8.5-GHz) and 32-GHz telemetry links is compared on the basis of the total data return per DSN station pass. Differences in spacecraft transmitter efficiency, transmit circuit loss, and transmitting antenna area efficiency and pointing loss are not considered in these calculations. Thus, the performance differentials calculated in this memo are those produced by a DSN 70-m station antenna gain and clear weather receiving system noise temperature and by weather.

These calculations show that, assuming mechanical compensation of the DSN 70-m antenna for 32-GHz operation, a performance advantage for 32 GHz over X-band of 8.2 dB can be achieved for at least one DSN station location. Even if only Canberra and Madrid are used, a performance advantage of 7.7 dB can be obtained for at least one DSN station location. A system using a multiple beam feed (electronic compensation) should achieve similar results.

I. Introduction

The various contributions, positive and negative, to the performance differential between X-band and 32-GHz telemetry links for interplanetary missions can be divided into spacecraft-related contributions and DSN-related contributions. The spacecraft-related contributions are the differences in transmitter efficiency, transmitting circuit loss, and the transmitting antenna area efficiency and pointing loss. These differences are very dependent on the spacecraft mission and the hardware to be employed. For example, the difference between X-band and 32-GHz TWTA efficiency may be significantly less than the difference between X-band and 32-GHz solid-state power amplifier efficiency, and the differential in spacecraft antenna pointing loss may be a strong function of the antenna diameter. These differences also may decrease significantly as technology improves. The DSN-related contributions are those arising from the difference in DSN station antenna gain and clear-weather system noise temperature, weather effects, and DSN antenna pointing loss. These differences are mission independent and should change less as improved technology becomes available than the spacecraft-related contributions.

The objective of the calculations in this report is to establish the net DSN-related contributions to the performance differential between X-band and 32-GHz telemetry links. As a further simplification, the differential in DSN antenna pointing loss used in all these calculations assumes the X-band and 32-GHz DSN 70-m station antenna pointing errors are 0.003°

and 0.001°, producing X-band and 32-GHz DSN antenna pointing losses of -0.1 dB and -0.17 dB, respectively. Thus the difference between 32-GHz and X-band DSN 70-m station antenna pointing loss is only -0.07 dB for all of the results shown in this report. Thus, these calculations provide a baseline to which the spacecraft-related performance differentials for transmitter efficiency, transmitting system circuit loss, and transmitting antenna area efficiency and pointing loss, as well as the difference in DSN 70-m station antenna pointing loss, must be added.

A major choice to be made in calculating the DSN-related contributions to the 32-GHz to X-band performance differential is that of the parameter used to measure link performance. Typically, achievable data rate has been used. However, as the DSN 70-m station antenna gain and clear-weather system noise temperature and the weather effects all depend on the DSN station elevation angle, the achievable data rate for both X-band and 32-GHz links will be a function of elevation angle. The ratio of 32-GHz to X-band achievable data rate could be computed as a function of elevation angle, but one is left with a somewhat arbitrary choice of elevation angle. Typically, a 30° elevation angle has been used.

In this report the number of bits returned (total data return) per DSN station pass is used as the measure of link performance. Thus, the ratio of 32 GHz to X-band link performance is the ratio of the corresponding total data returns per DSN station pass. This ratio is computed for the total data returns obtained using (1) the best fixed data rate, (2) the best two data rates, and (3) a continuously variable data rate. The best fixed data rate is the single data rate which yields the greatest total data return per pass. The total data return for the best two rates is the result of a similar calculation, when two data rates, with one increase and one decrease in data rate per pass, can be used. The continuously variable data rate provides an upper bound in performance. This system continuously uses the maximum rate allowed by the instantaneous performance.

The calculation of the 32-GHz to X-band performance advantage for these three different levels of operational complexity gives some insight into the effect of data rate strategy on the ratio of 32-GHz to X-band link performance. As we shall see, because of the greater sensitivity of 32-GHz links to elevation angle, the 32-GHz to X-band performance advantage increases with the number of data rates one can employ during a DSN station pass.

As the spacecraft declination (with respect to Earth) and the DSN station location determine the elevation angle profiles (elevation angle versus time) for the station and 32-GHz links are affected more by elevation angle than X-band links, the ratios of 32-GHz to X-band performance calculated in this article vary with declination and DSN station location. As we shall see, the ratio of 32-GHz to X-band link performance increases with increasing declination for Goldstone and Madrid, the northern hemisphere stations, and decreases with increasing declination for Canberra, the southern hemisphere station.

II. DSN Antenna Gain Models

The five DSN 70-m station antenna gain versus elevation angle models used in these calculations are shown in Fig. 1. There is one X-band model and four 32-GHz models. The DSN 70-m station antenna gains shown in Fig. 1 include the clear-weather atmospheric attenuation.

A. X-Band Model

The X-band DSN 70-m station antenna gain versus elevation angle model shown in Fig. 1 is that specified by the DSN for use by the VRM project, less 0.1 dB to allow for diplexing loss. This model is also being used for the MM II/CRAF link performance calculations.

B. 32-GHz/Baseline Model

This 32-GHz antenna gain model is an estimate of the 32-GHz performance of a DSN 70-m station with no improvements for 32 GHz. This model was obtained by a somewhat different process than the X-band model discussed above and may represent a somewhat more optimistic view of the unimproved DSN 70-m station performance.

For the 32-GHz/Baseline antenna gain model, the net antenna gain will be

$$G_R = G_{RB} + L_{FX} + L_{GV} + L_{TU} + L_{ATM} \tag{1}$$

where G_{RB} is 87.412 dB, the gain at 32 GHz of a 70-m parabolic antenna with 100% area efficiency, L_{FX} is the sum of the fixed losses, those that do not vary with elevation angle, L_{GV} is the loss due to gravitational deformations, L_{TU} is the loss due to atmospheric turbulance, and L_{ATM} is the clear-weather atmospheric attenuation. For the 32-GHz/Baseline antenna gain model, L_{FX} is -3.841 dB. The factors contributing to this fixed loss are listed in Table 1.

The loss L_{GV} at 32 GHz from gravitational deformation of the DSN 70-m antenna surface is extrapolated from estimates for X-band. The assumption is that

$$L_{GV} = 10 \log_{10} [\exp(-(4\pi\sigma_{GV}/\lambda)^2)] \tag{2}$$

where σ_{GV} is the standard deviation of the surface deformations caused by gravity and λ is the RF wavelength. Given this assumption,

$$(L_{GV})\ 32\ \text{GHz} = 14.4608\ (L_{GV})\ \text{X-band} \tag{3}$$

where 14.4608 is the square of the ratio of 32 GHz to the X-band RF frequency (8.415 GHz). Using this approach, one obtains the data in Table 2. Values of L_{GV} for values of elevation angle between those given in Table 2 are computed using second-order (quadratic) interpolation. The resulting values of L_{GV} are plotted as a function of elevation angle in Fig. 2.

In these calculations, the DSN 70-m antenna gain reduction from atmospheric turbulance L_{TU} is calculated following the approach used in Ref. 1. Sufficient data is given in Ref. 1 for this loss to be computed at 10°, 30°, and 90° elevation angles. At 10° elevation angle, L_{TU} is -0.878 dB. At 30° elevation angle, L_{TU} is -0.524 dB. At 90° elevation angle, L_{TU} is is -0.142 dB. Second-order (quadratic) interpolation is used to compute L_{TU} for values of elevation angle other than 10°, 30°, and 90°. The resulting values of L_{TU} are plotted as a function of elevation angle in Fig. 2.

As noted above, the DSN 70-m antenna gains shown in Fig. 1 include the loss L_{ATM} from the clear-weather atmospheric attenuation. For all four 32-GHz models,

$$L_{ATM} = -0.081/\sin(\text{ELE})\ \text{dB} \tag{4}$$

where -0.081 dB is the average of the clear-weather atmospheric attenuations for Goldstone (-0.079 dB) and the overseas stations (-0.083 dB) obtained from the S. Slobin 32-GHz weather model (see Subsection 4). The resulting values of L_{ATM} are plotted as a function of elevation angle in Fig. 2.

C. 32-GHz/Passive Improvements Model

The DSN 70-m station 32-GHz/Passive Improvements antenna gain model differs from the DSN 70-m station 32-GHz/Baseline antenna gain model only in the reduction of L_{FX}, the sum of those losses that do not vary with elevation angle, by 1.43 dB from -3.841 dB to -2.411 dB.

This 1.43-dB improvement is comprised of a 0.1-dB reduction in quadrapod blockage, 0.2 dB from stiffening of the antenna structure to resist deflections caused by wind, 0.81 dB from more accurate setting (0.203 mm (0.008 in.) rms) of the panels which make up the main reflector surface, and 0.32 dB from the use of a new, more accurate (0.152 mm (0.006 in.) rms) subreflector.

D. 32-GHz/Mechanical Compensation Model

With active mechanical compensation for deflections of the DSN 70-m antenna surface, the loss due to gravitational deflections of the antenna surface can be reduced to -0.126 dB, independent of elevation angle, and the losses from wind and thermal distortions can be reduced by 0.5 dB and 0.4 dB, respectively. These improvements together with the 0.1-dB reduction in quadrapod blockage, 0.81 dB from more accurate setting of the main reflector panels, and 0.32 dB from a more accurate subreflector, yield an antenna gain of

$$G_R = G_{RB} + L_{FX} + L_{TU} + L_{ATM} \tag{5}$$

where in this case L_{FX} is -1.837 dB and G_{RB}, L_{TU}, and L_{ATM} are the same as for the DSN 70-m station 32-GHz/Baseline antenna gain model discussed above.

E. 32-GHz/Electronic Compensation Model

With the use of a multiple-beam, cryogenically-cooled feed, the potential exists for reduction of the losses from atmospheric turbulence as well as those from gravitational, wind, and thermal distortion of the main reflector surface. The calculations presented in this report assume that, temporarily neglecting atmospheric attenuation, the antenna area efficiency L_{EC} is -2.22 dB (60%) at a 45° elevation angle and -3.01 dB (50%) at elevation angles of 10° and 90°. Second-order (quadradic) interpolation is used to obtain L_{EC} at elevation angles other than 10°, 45°, and 90°. Having calculated L_{EC}, the net DSN 70-m station antenna gain for the 32-GHz/Electronic Compensation Model is

$$G_R = G_{RB} + L_{EC} + L_{ATM} \tag{6}$$

where G_{RB} and L_{ATM} are as discussed above for the DSN 70-m station 32-GHz/Baseline antenna gain model.

III. Clear-Weather System Noise Temperature Models

The DSN 70-m station X-band and 32-GHz clear-weather receiving system noise temperature models used in these calculations are based on the DSN 64-m station X-band clear-weather receiving system noise temperature model.[1] This reference specifies that the noise temperature for a non-diplexed (listen-only) system is 20 K at zenith (90° elevation angle) and the increase above the zenith noise temperature, for

[1] *Deep Space Network/Flight Project Interface Design Handbook*, JPL Document 810-5: Vol. II, Module TCI-10, Sept. 1, 1981, Jet Propulsion Laboratory, Pasadena, Calif. (JPL internal document).

elevation angles other than 90°, is that given by the "X-band" curve in Fig. 3.

A. X-Band

The DSN 70-m station X-band clear-weather receiving system noise temperature model used in these calculations is for diplexed operation. The diplexer is expected to increase the noise temperature about 5 K. Thus, these calculations assume that the DSN 70-m station X-band clear-weather receiving system noise temperature at zenith is 25 K and that the noise temperature increase above the zenith noise temperature, for elevation angles other than 90°, is the same as that for the DSN 64-m nondiplexed station, shown as the curve labeled "X-band" in Fig. 3.

B. 32 GHz

With the exception of the atmospheric contribution, these calculations assume the DSN 70-m station 32-GHz clear-weather receiving system noise temperature is the same as the DSN 64-m station clear-weather receiving system noise temperature. After correction for the difference in the X-band and 32-GHz atmospheric contributions, the DSN 70-m station 32-GHz clear-weather receiving system noise temperature at zenith is 23.15 K, and the increase above the zenith noise temperature, for elevation angles other than 90°, is given by the curve labeled 32 GHz in Fig. 3.

IV. Weather Degradation Model

A weather model provides a means of calculating the cumulative probability distribution of the weather degradation for different DSN station locations and elevation angles. The weather degradation in decibels is the sum of the incremental atmospheric attenuation in decibels, above that for clear weather, and the ratio in decibels of the system noise temperature with weather of a given cumulative probability to the clear-weather system noise temperature. Results are presented in this article for four different weather models. All of the models were created by S. D. Slobin of JPL's Radio Frequency and Microwave Subsystems Section. One of the weather models, hereafter referred to as the Slobin/810-5 weather model,[2] was developed as a X-band weather model and is currently being used for the MM II/CRAF X-band link performance calculations.

The other three models, hereafter designated the Slobin/Best, Slobin/Average, and Slobin/Worst weather models, are based on a combination of K-band radiometer measurements at Goldstone at 30° elevation angle and cloud-cover and rainfall statistics for sites similar to the DSN station locations. The Slobin/Average weather model is used to calculate most of the results presented in this article. For these three models, the Canberra and Madrid weather statistics are the same. Table 3 tabulates the 32-GHz noise temperature increase at 30° elevation angle as a function of cumulative probability for the Slobin/Best, Slobin/Average, and Slobin/Worst weather models for both Goldstone and the two overseas sites. Using the data in Table 3 for the selected model as a starting point, the Slobin/810-5 weather model methodology[2] can be employed to calculate the weather degradation as a function of cumulative probability for any desired elevation angle and DSN station location.

As the objective of this article is to compare X-band and 32-GHz link performance, it is desirable to use the same weather model for both the X-band and 32-GHz link calculations. If one assumes, as this article does, that the weather effects are entirely caused by water droplets in clouds and by rain, the 32-GHz atmospheric attenuation due to weather will be 14.4608 times the X-band atmospheric attenuation. The factor 14.4608 is the square of the ratio of the 32-GHz and X-band (8.415-GHz) RF frequencies. Using this relationship between the X-band and 32-GHz atmospheric attenuations caused by weather, one can easily compute the 32-GHz weather degradation from the X-band weather degradation or vice versa. However, because of the large multiplication factor, a small error in a X-band weather degradation can create a very large error in the 32-GHz weather degradation. Coupled with the very qualitative observation that the X-band Slobin/810-5 model appears slightly conservative, this suggests that one – Slobin/Best, Slobin/Average, or Slobin Worst – of the weather models based partly on 32-GHz radiometer measurements at Goldstone is a more appropriate weather model for the comparisons of X-band and 32-GHz link performance than the Slobin/810-5 weather model. As noted previously, the Slobin/Average weather model is used for the bulk of the calculations presented in this report.

V. Calculation of Achievable Data Rate

Having defined the models to be used for the DSN 70-m station X-band and 32-GHz antenna gain and clear-weather receiving system noise temperature and models to be used to calculate the weather degradation, the next step is to use these models to calculate achievable data rate. Sample calculations of achievable data rate for X-band and 32-GHz links and the Canberra DSN 70-m station are shown in Tables 4 and 5. These sample calculations are for a 30° elevation angle (listed under item 10 in each table). The achievable data rate is listed under item 13 in each table.

[2] *Deep Space Network/Flight Project Interface Design Handbook*, JPL Document 810-5: Vol. I, Module TCI-40, Rev. B, Dec. 1, 1983, Jet Propulsion Laboratory, Pasadena, Calif. (JPL internal document).

Items 1 through 9 of each table list the RF link parameter values used in this calculation and item 10 shows the available ratio of total received power to receiving system noise spectral density (P_T/N_O) for clear weather. Note that, as discussed in the introduction, the transmitting system RF power output, circuit losses, and antenna pointing losses in Tables 4 and 5 are the same. The transmitting antenna gains in Tables 4 and 5 differ only by the square of the ratio of 32-GHz to the X-band link RF frequency (8.415 GHz). Thus, the transmitting antenna area efficiencies are the same. Furthermore, as discussed in the introduction, the DSN antenna pointing loss in the X-band link performance estimate in Table 4 is -0.10 dB (for 0.003-degree pointing error) and that for the 32-GHz link performance estimate in Table 5 is -0.17 dB (for 0.001-degree pointing error). Thus, the ratio of 32-GHz to X-band DSN antenna pointing loss in Tables 4 and 5 and in all the other numerical results shown in this article is -0.07 dB.

In the link performance calculations shown in Tables 4 and 5, the mean of the performance margin (item 14 in Tables 4 and 5) has been adjusted to make the resulting link reliability (item 15 in Tables 4 and 5) equal to 0.95. The link reliability is the probability that the mean, clear-weather performance margin is greater than the deviation from mean, clear-weather link performance due to both weather and link parameter variations. Then, as there is no ranging suppression, the mean required P_T/N_O (item 13 in Tables 4 and 5) can be, at most, the difference between the mean available P_T/N_O (item 10) and the mean, clear-weather performance margin (item 14). Given the RF receiver threshold noise bandwidth shown near the top of Tables 4 and 5 and the required carrier margin and E_B/N_O, listed under item 13 in Tables 4 and 5, the achievable data rate is determined.

The computation of the link reliability is a matter of finding that value of the cumulative probability distribution of the sum of the degradation from weather and link parameter variations that corresponds to a degradation equal to the mean clear-weather performance margin. In this case the inverse calculation is needed. One starts with the required link reliability, and needs to calculate the sum of the potential link degradations from weather and link parameter variations that has that cumulative probability.

A piecewise linear approximation is used for the cumulative probability distribution of the weather degradation, with the break-points calculated using the selected weather model. For the Slobin/810-5 weather model, the cumulative probabilities at which the break-points (discontinuities in slope) occur are those given in Table 1 of footnote 2. For the Slobin/Best, Slobin/Average, and Slobin/Worst weather models, the cumulative probabilities at which the breakpoints occur are those in Table 3 of this article (11 breakpoints, not including zero probability). The variance of a parameter's variation is computed for each of the link parameters, assuming the parameter either has a uniform distribution or a triangular distribution between the limits defined by the positive and negative tolerances shown in Tables 4 and 5. For the triangular distribution, the peak of the triangle is at the parameter design value. The distribution used is designated by a "U" (uniform) or "T" (triangular) in the "DIST" column of Tables 4 and 5. The resulting variances, shown under the "variance" column in Tables 4 and 5, are added to yield the variance for the clear-weather performance margin.

The corresponding standard deviation "SIGMA" is listed under the link reliability (Item 15) in the "mean" column. Note that the "SIGMA" in Table 5 is the same as that in Table 4. The 32-GHz link tolerances in Table 5 are typical of those used at the time of a project start and do not reflect current uncertainties. Using the assumption that the sum of the parameter variations is Gaussian (central limit theorem) and the piecewise approximation for the cumulative probability distribution of the weather degradation, an expression has been derived for the desired cumulative probability distribution. The resulting expression is a summation which requires the evaluation of one exponential function and one error function per breakpoint in the piecewise linear approximation.

By repeating the calculation shown in Tables 4 and 5 for different elevation angles and calculating the ratio of 32-GHz to X-band achievable data rate, one can produce curves such as those shown in Fig. 4. In Fig. 4, the ratio of 32-GHz to X-band achievable data rate is plotted as a function of elevation angle for Goldstone, Canberra, and Madrid for link reliabilities of 0.90 and 0.95. The results shown in Fig. 4 are for the DSN 70-m station 32-GHz/Mechanical Compensation antenna gain model, diplexed X-band, and Slobin/Average weather. With such a comparison, however, the problem remains as to which elevation angle is "significant," since during a DSN station pass the elevation angle may vary over nearly the full range shown in Fig. 4.

VI. Calculation of Total Data Return Per Pass

The first step in calculating total data return per pass is to calculate achievable data rate as a function of time during the pass. For a given declination, the DSN station elevation angle can be computed as a function of time for the three DSN station locations. Combining such a calculation with a calculation of achievable data rate, similar to those shown in Tables 4 and 5, yields achievable data rate as a function of time during a one-day period for the three DSN station locations. The result of a sample calculation for 0° declination is shown in Fig. 5. These curves were computed using 51 points, evenly spaced in time, starting with the time of minimum elevation angle, which is 10°, and ending with the time of peak elevation angle. The curve for a DSN station location is symmetric about the time of peak elevation angle.

Results are shown in Fig. 5 for X-band and 32-GHz links, 0.90 and 0.95 link reliability, and the three DSN station locations. With the exception of those link parameters dependent on elevation angle and/or link reliability, the link parameter values for the X-band results in Fig. 5 are those shown in Table 4 and the link parameter values for the 32-GHz results in Fig. 5 are those shown in Table 5. The 32-GHz/Mechanical Compensation DSN 70-m station antenna gain model and the Slobin/Average weather model were used. The range for the performance estimates in both Tables 4 and 5 and Fig. 5 was 10 AU.

Obtaining the total data return from achievable data-rate profiles for a one-day period requires the selection of a data-rate strategy. The selection of the data-rate strategy depends on the amount of operational complexity permitted. In this article, 32-GHz and X-band performance will be compared for three different data-rate strategies.

The fixed-rate strategy allows one to use any data rate during a DSN station pass, but the rate must remain fixed during the pass. For the fixed-rate strategy, the total data return is the product of the selected data rate and the time per pass this data rate can be supported with the required link reliability. The results shown in this article assume that the best fixed rate is selected. Thus, the comparisons of X-band and 32-GHz total data return for the fixed-rate strategy are made using the best fixed-rate total data returns per pass.

The two-rate strategy allows the use of two data rates per pass, with one increase and one decrease in data rate per pass. As in the fixed-rate strategy, these calculations assume that the best two rates would be used. Thus, the comparisons of 32-GHz and X-band total data return for the two-rate strategy are made on the basis of the best two-rate total data returns per pass.

The variable-rate strategy allows a continuously variable data rate during a DSN station pass. For this strategy, the total data return per pass is simply the integral of the achievable data rate versus time. The integral is calculated using a trapezoidal approximation with 101 points per pass. While this strategy would never be used with the current DSN telemetry hardware, comparisons of X-band and 32-GHz total data return per pass for a variable data-rate strategy do provide an upper bound on the increase in the 32-GHz to X-band performance advantage to be achieved by using more than two data rates per DSN station pass.

VII. Numerical Results

With the exception of those parameters dependent on elevation angle and/or link reliability, the X-band and 32-GHz link parameter values used to calculate the results shown in this section are the same as those shown in Tables 4 and 5. However, since the ratio of 32-GHz to X-band total data return is being computed, the absolute values of the X-band and 32-GHz spacecraft-related link parameters used for these calculations are not important, as long as their relative values remain the same.

To simplify figure labeling, R1, R2, and RV will be used for the ratio of the 32-GHz to X-band total data return per pass using the best fixed (one) data rate, the best two data rates, or a variable data rate during a DSN station pass. Note that all values of R1, R2, and RV shown in this article are expressed in decibels.

A. Comparison of R1, R2, and RV

Figure 6 shows curves of R1, R2, and RV as a function of spacecraft declination for the three DSN station locations. These results assume a mechanically compensated DSN 70-m antenna for 32 GHz, the DSN 70-m antenna is diplexed at X-band, the Slobin/Average weather model, and a 0.95 required link reliability. The primary purpose of this figure is to show, at least for a mechanically compensated DSN 70-m antenna at 32 GHz, that the difference between the performance advantages of 32 GHz over X-band for the fixed-rate and variable-rate strategies is almost independent of both declination and DSN station location and is approximately 1 dB. The difference between the performance advantages of 32 GHz over X-band for the fixed-rate and two-rate strategies is also almost independent of both declination and DSN station location and appears to be about 0.2 dB. The rest of the results shown in this report consider only R1, the 32-GHz over X-band performance advantage for a fixed- (one) rate data-rate strategy. However, it is important to remember, in examining subsequent figures, that a more complex data-rate strategy could improve the performance advantage of 32 GHz over X-band from 0.2 dB to 1.0 dB.

B. Effect of Link Reliability

Figure 7 shows curves of R1 as a function of declination for the three DSN station locations and link reliabilities of 0.90 and 0.95. These results assume a mechanically compensated DSN 70-m antenna for 32 GHz, diplexed operation at X-band, and the Slobin/Average weather model. Clearly, decreasing the required link reliability increases the performance advantage of 32 GHz over X-band. The difference between the performance advantage of 32 GHz over X-band for 0.90 link reliability and that for 0.95 link reliability varies somewhat with declination. For Goldstone the difference is 0.39 dB at -25° declination and 0.14 dB at +25° declination. For Canberra the difference is 0.26 dB at -25° declination and 0.61 dB at +25° declination. For Madrid the difference is 0.73 dB for -25° declination and 0.26 dB at +25° declination. Note that the difference for Goldstone is significantly less than that for Canberra and Madrid, and that, for all three DSN station locations, the largest of these differences occurs for the least favorable declination (-25° declination for Goldstone and Madrid, which are northern hemisphere stations, and +25° for Canberra, which is a southern hemisphere station).

The reason for these differences is that the allowance that must be made for weather and link parameter variations is much greater for 32-GHz links than for X-band links. Examining item 14 in Tables 4 and 5, the sample X-band and 32-GHz link performance estimates, this allowance is 1.38 dB for the X-band link performance estimate in Table 4 and 4.27 dB for the 32-GHz link performance estimate in Table 5. As the allocation for weather and link parameter variations will be much greater at 32 GHz than at X-band for any required link reliability, one would logically expect that the difference between the allocations for two different link reliability levels will be much greater at 32 GHz than at X-band. The difference, for 0.90 and 0.95 link reliability, between the 32-GHz difference in allocation and the X-band difference in allocation is the separation of the curves in Fig. 7. The reason the separation between curves in Fig. 7 (for a given station location) is greatest at the most unfavorable declination is that: (1) the difference is created by weather effects, (2) the weather effects are greatest at low elevation angles, and (3) the unfavorable declination is where the peak elevation angle for a DSN station pass is least.

C. Effect of Declination

Examination of the data in Figs. 6 and 7 shows the performance advantage of 32 GHz over X-band is a strong function of declination. For 0.95 link reliability, the variation in R1 shown in Fig. 7 is 2.03 dB for Goldstone, 2.53 dB for Canberra, and 3.25 dB for Madrid. These differences illustrate the importance of being able to use the most favorable DSN station location for a given declination. The advantage of being able to use the most favorable DSN station location for each declination is not unique to 32 GHz. During the MM II/CASSINI (1993 launch) encounter (the orbital phase of the mission), which lasts for nearly four years, the spacecraft declination varies between 19° and 22°. At the first Titan encounter after SOI (Saturn orbital insertion), the declination is 21° and the total data return with an X-band link using the Goldstone DSN 70-m station is 2.7 times that which can be obtained using the Canberra DSN 70-m station.

D. Effect of DSN 70-m Station Improvements for 32 GHz

Figure 8 shows curves of R1 as a function of declination for the three DSN station locations and the "Baseline," "Passive Improvements," and "Mechanical Compensation" DSN 70-m station 32-GHz antenna gain models. Results for the "Electronic Compensation" DSN 70-m station antenna gain model were omitted because its performance, as shown in Fig. 1, is very nearly the same as that of the "Mechanical Compensation" DSN 70-m station 32-GHz antenna gain model. The results in Fig. 8 are for a 0.95 link reliability and the Slobin/Average weather model. For 0° declination, the separation of the "Baseline" and "Passive Improvement" curves in Fig. 8 is 1.43 dB, independent of DSN station location. For 0° declination, the differences between the "Mechanical Compensation" and "Passive Improvement" curves are 0.76 dB for Goldstone, 0.81 dB for Canberra, and 0.75 dB for Madrid. Remember that this difference includes only a -0.07 dB pointing error differential, which is based on 0.001° 32 GHz and 0.003° X-band DSN 70-m station antenna pointing errors. Achieving a 0.001° DSN antenna pointing error is probably not feasible with the "Baseline" antenna. With the current accuracy of about 0.005°, the DSN 70-m station antenna pointing loss at 32 GHz would be about 4.5 dB. At 0.005° pointing error, the DSN 70-m station antenna pointing loss at X-band would be about 0.3 dB.

E. Effect of Weather Model

Figure 9 differs from the preceding figures in that it is not a comparison of 32-GHz link total data return with X-band link total data return, but a comparison of 32-GHz total data returns for different weather models. There are three sets of curves in Fig. 9 with three curves, for the three DSN station locations, in each set. The sets compare 32-GHz link performance using the Slobin/Best, Slobin/Worst, and Slobin/810-5 weather models with that achieved using the Slobin/Average weather model. Performance with the Slobin/Best weather model is no more than about 1 dB better than performance with the Slobin/Average weather model. Performance with the Slobin/Worst weather model is no more than about 1.2 dB worse than performance with the Slobin/Average weather model. However, performance with the Slobin/810-5 weather model (year average weather) can be as much as 6.5 dB worse than performance with the Slobin/Average weather model. As noted previously, qualitative observations indicate the Slobin/810-5 model appears slightly conservative for X-band links, and extrapolation to 32 GHz would greatly magnify such errors.

VIII. Conclusions

This report compares X-band 8.5-GHz and 32-GHz link performance on the basis of the number of bits returned during a DSN station pass using a fixed- (one) rate, two-rate, or variable-rate data-rate strategy. For the fixed- or two-rate strategy, use of the best rate or rates is assumed. For each DSN station location, the 32-GHz performance advantage over X-band is plotted as a function of declination. The advantage of this approach is that declination changes slowly with time during a mission. During the four-year MM II/SOTP (1993 launch) encounter period, the declination remains within the 19° to 23° range. Previously, the ratio of achievable data rate was used to measure the performance advantage of 32 GHz over X-band. This ratio is a function of DSN station elevation angle, which varies over a major part of its possible range during a single DSN station pass.

Figures 6 through 8 show that the performance advantage of 32 GHz over X-band is very dependent on declination and DSN station location. However, examining Fig. 7 one finds that a 8.2-dB advantage can always be obtained for at least one DSN station. Even if Goldstone is not used, a 7.7-dB advantage can be obtained for at least one DSN station. These improvements assume the use of a fixed (one) data rate for each DSN station pass. If multiple rates can be used during each DSN station pass, increasing the complexity of mission operations, Fig. 6 shows that the performance advantage of 32 GHz over X-band can be increased further by 0.2 to 1.0 dB. Figures 6 and 7 assume the use of a mechanically compensated DSN 70-m antenna for 32 GHz and the Slobin/Average weather model. Comparison of the DSN 70-m station "mechanically compensated" and "electronically compensated" 32-GHz antenna gain models shown in Fig. 1 suggests that the performance advantage of 32 GHz over X-band for the electronically compensated DSN 70-m antenna would be similar to the results discussed above for the mechanically compensated DSN 70-m antenna.

The comparison of the 32-GHz link performance using the Slobin/Best, Slobin/Worst, and Slobin/810-5 weather models with 32-GHz link performance using the Slobin/Average weather model in Fig. 9 shows that the selection of the weather model has a very significant impact on 32-GHz link performance. The Slobin/Average weather model was used for the results shown in Figs. 4 through 8. The Slobin/Best, Slobin/Average, and Slobin/Worst weather models are all based on Goldstone K-band radiometer noise temperature measurements at 30° elevation angle with extrapolation to the overseas stations and other elevation angles using weather statistics for comparable sites. The Slobin/810-5 weather model is based on models for X-band attenuation from water vapor, clouds, and rain for sites similar to the DSN station locations. The curves in Fig. 9 show that the Slobin/Best and Slobin/Worst weather model cause 32-GHz link performance to vary at most +1.0, -1.2 dB from that for the Slobin/Average weather model. However, with the Slobin/810-5 weather model, the 32-GHz link performance is as much as 6.5 dB worse than that with the Slobin/Average weather model. The conclusion is that either the Slobin/810-5 weather model at 32 GHz is unduly conservative or the Slobin/Best, Slobin/Average, and Slobin/Worst weather models are very optimistic. Qualitative experience suggests the Slobin/810-5 X-band model is slightly conservative, and the method of extrapolating weather effects from X-band to 32 GHz would tend to greatly magnify any error. Finally, it should be noted that the DSN 70-m station 32-GHz antenna gain models and the 32-GHz weather models used in these calculations are very preliminary engineering estimates. The DSN 70-m station clear-weather noise temperature model at both X-band and 32 GHz should be reviewed to reflect improvements expected to be incorporated by the mid-1990s. Because the effect of weather on receiving system noise temperature is much greater for 32 GHz than X-band, an equal decrease in 32 GHz and X-band clear-weather receiving system noise temperature would reduce the performance advantage of 32 GHz over X-band. Most of all, considerable additional attention should be placed on the construction of better 32-GHz weather models than those used in this report.

Reference

1. Potter, P. D., "64-Meter Antenna Operation at K_a-Band," *JPL TDA Progress Report 42-57*, March and April 1980, pp. 65-70.

Table 1. 32-GHz/Baseline antenna gain versus elevation angle model fixed losses

RF losses	Loss, dB
Waveguide loss	-0.088
Forward spillover	-0.132
Rear spillover	-0.013
Illumination	-0.088
Phase	-0.087
Central blockage	-0.044
M No. 1 modes	-0.096
VSWR	-0.044
Mesh loss	-0.009
RF loss Subtotal	-0.601
Mechanical and other losses	
Quadrapod blockage	-0.364
Reflector panels (0.127 mm (0.005 in.))	-0.126
Panel setting (0.381 mm (0.015 in.))	-1.133
Subreflector (0.254 mm (0.010 in.)	-0.504
Thermal (0.254 mm (0.010 in.)	-0.504
Wind (32.2 km/h (20 mph), 0.279 mm (0.011 in.))	-0.609
Mechanical and other loss subtotal	-3.240
Total fixed loss	-3.841

Table 2. DSN 70-m 32-GHz/Baseline antenna gain reduction from gravity-induced surface distortions

Elevation angle, deg	L_{GV}, dB
6.	-2.495
10.	-1.907
20.	-0.889
30.	-0.316
40.	-0.086
50.	-0.215
60.	-0.514
70.	-1.219
80.	-1.979
90.	-2.940

Table 3. DSN 70-m station 32-GHz system temperature increase from weather at 30° elevation angle

Cumulative probability	Noise temperature increase, K					
	Goldstone			Canberra and Madrid		
	Best	Average	Worst	Best	Average	Worst
0.0	10.0	10.0	10.0	10.5	10.5	10.5
0.2	13.5	14.0	14.5	16.5	17.5	18.5
0.5	17.0	18.0	19.0	23.0	25.0	27.0
0.7	19.0	20.5	22.0	26.0	28.5	32.0
0.8	21.0	23.0	25.0	29.0	32.0	37.0
0.9	24.0	26.0	30.0	33.0	38.0	45.0
0.95	27.0	31.0	35.0	37.0	46.0	55.0
0.98	32.0	37.0	43.0	46.0	62.0	120.0
0.99	36.0	44.0	53.0	57.0	120.0	180.0
0.995	41.0	53.0	69.0	75.0	150.0	220.0
0.998	51.0	80.0	175.0	180.0	215.0	260.0
0.999	65.0	120.0	240.0	260.0	270.0	279.0

Table 4. Sample X-band link performance estimate

COMPUTER PROGRAM NO. 530-P 09-26-86

TELECOMMUNICATION SYSTEM DOWNLINK PERFORMANCE ESTIMATE

TEST CASE FOR K-BAND/X-BAND COMPARISON (1-9-86)

X-BAND/10.7 W XSSPA
X-BAND/3.67 M BODY-FIXED HGA, 0.18 DEG. POINTING ERROR
DSN 70 M STATION/X-BAND/DIPLEXED/PE = 0.003 DEG.
CANBERRA/EXTRAPOLATION FROM K-BAND NOISE TEMPERATURE MEASUREMENTS/AVERAGE
DSN BLOCK III RECEIVER/10.8 HZ BANDWIDTH MODE
REED-SOLOMON/VITERBI CHANNEL, PB = 1.E-6

ACHIEVABLE DATA RATE AT 10 AU

	DESIGN VALUE	TOLERANCE		DIST	MEAN	VARIANCE
TRANSMITTING SYSTEM PARAMETERS						
1. RF POWER OUTPUT	40.29 DBM	1.00 DB	-1.00 DB	T	40.29 DBM	.1667 DB**2
2. TRANSMITTER CIRCUT LOSS	-.45 DB	.20 DB	-.20 DB	U	-.45 DB	.0133 DB**2
3. ANTENNA CIRCUT LOSS	-.30 DB	.10 DB	-.10 DB	U	-.30 DB	.0033 DB**2
4. ANTENNA GAIN	48.80 DB	.50 DB	-.50 DB	T	48.80 DB	.0417 DB**2
(REFERENCED TO CP)						
ANTENNA ELLIPTICITY	1.70 DB	.00 DB	.00 DB			
5. ANTENNA POINTING LOSS	-1.00 DB	.00 DB	.00 DB	T	-1.00 DB	.0000 DB**2
PATH PARAMETERS						
6. SPACE LOSS	-294.44 DB				-294.44 DB	
RANGE = 10.0000 AU						
FREQUENCY = 8.4150 GHZ						
RECEIVING SYSTEM PARAMETERS						
7. POLARIZATION LOSS	-.01 DB	.05 DB	-.07 DB	U	-.02 DB	.0011 DB**2
8. ANTENNA GAIN	73.76 DB	.60 DB	-.60 DB	U	73.76 DB	.1200 DB**2
(FOR MATCHED POLARIZATION)						
ANTENNA ELLIPTICITY	1.00 DB	.20 DB	-.50 DB			
9. ANTENNA POINTING LOSS	-.10 DB	.00 DB	.00 DB	U	-.10 DB	.0000 DB**2
10. NOISE SPECTRAL DENSITY	-183.83 DBM/HZ	.41 DB	-.46 DB	T	-183.85 DBM/HZ	.0317 DB**2
SYSTEM NOISE TEMPERATURE	29.98 K	3.00 K	-3.00 K			
ZENITH NOISE TEMPERATURE	25.00 K	3.00 K	-3.00 K			
ADD. FOR ELEVATION ANGLE	4.98 K	.00 K	.00 K			
ELEVATION ANGLE	30.0000 DEG					
11. AVAILABLE PT/NO					50.38 DB.HZ	.3778 DB**2
TELEMETRY PERFORMANCE ESTIMATE						
12. RANGING CARRIER SUPPRESSION	.00 DB	.00 DB	.00 DB	T	.00 DB	.0000 DB**2
13. REQUIRED PT/NO	49.00 DB.HZ	.50 DB	-.50 DB	U	49.00 DB.HZ	.0833 DB**2
(RANGING OFF)						
DATA RATE	30699.3542 BPS					
REQUIRED EB/NO	4.0000 DB					
REQUIRED CARRIER MARGIN	18.3500 DB					
MODULATION LEVEL (RMS)	60.0000 DEG	.50 DB	-.50 DB			
14. PERFORMANCE MARGIN					1.38 DB	.4612 DB**2
15. LINK RELIABILITY					.9500	
SIGMA					.68 DB	

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Table 5. Sample K-band link performance estimate

COMPUTER PROGRAM NO. 530-P 09-26-86

TELECOMMUNICATION SYSTEM DOWNLINK PERFORMANCE ESTIMATE

TEST CASE FOR K-BAND/X-BAND COMPARISON (1-9-86)

K-BAND/10.7 W KSSPA
K-BAND/3.67 M BODY-FIXED HGA, 0.047 DEG. POINTING ERROR
DSN 70 M STATION/K-BAND/MECHANICAL COMPENSATION/PE = 0.001 DEG.
CANBERRA/EXTRAPOLATION FROM K-BAND NOISE TEMPERATURE MEASUREMENTS/AVERAGE
DSN BLOCK III RECEIVER/10.8 HZ BANDWIDTH MODE
REED-SOLOMON/VITERBI CHANNEL, PB = 1.E-6

ACHIEVABLE DATA RATE AT 10 AU

	DESIGN VALUE	TOLERANCE		DIST	MEAN	VARIANCE
TRANSMITTING SYSTEM PARAMETERS						
1. RF POWER OUTPUT	40.29 DBM	1.00 DB	-1.00 DB	T	40.29 DBM	.1667 DB**2
2. TRANSMITTER CIRCUT LOSS	-.45 DB	.20 DB	-.20 DB	U	-.45 DB	.0133 DB**2
3. ANTENNA CIRCUT LOSS	-.30 DB	.10 DB	-.10 DB	U	-.30 DB	.0033 DB**2
4. ANTENNA GAIN	60.40 DB	.50 DB	-.50 DB	T	60.40 DB	.0417 DB**2
(REFERENCED TO CP)						
ANTENNA ELLIPTICITY	1.70 DB	.00 DB	.00 DB			
5. ANTENNA POINTING LOSS	-1.00 DB	.00 DB	.00 DB	T	-1.00 DB	.0000 DB**2
PATH PARAMETERS						
6. SPACE LOSS	-306.04 DB		•		-306.04 DB	
RANGE = 10.0000 AU						
FREQUENCY = 32.0000 GHZ						
RECEIVING SYSTEM PARAMETERS						
7. POLARIZATION LOSS	-.01 DB	.05 DB	-.07 DB	U	-.02 DB	.0011 DB**2
8. ANTENNA GAIN	84.89 DB	.60 DB	-.60 DB	U	84.89 DB	.1200 DB**2
(FOR MATCHED POLARIZATION)						
ANTENNA ELLIPTICITY	1.00 DB	.20 DB	-.50 DB			
9. ANTENNA POINTING LOSS	-.17 DB	.00 DB	.00 DB	U	-.17 DB	.0000 DB**2
10. NOISE SPECTRAL DENSITY	-183.66 DBM/HZ	.40 DB	-.44 DB	T	-183.67 DBM/HZ	.0293 DB**2
SYSTEM NOISE TEMPERATURE	31.20 K	3.00 K	-3.00 K			
ZENITH NOISE TEMPERATURE	23.15 K	3.00 K	-3.00 K			
ADD. FOR ELEVATION ANGLE	8.05 K	.00 K	.00 K			
ELEVATION ANGLE	30.0000 DEG					
11. AVAILABLE PT/NO					61.27 DB.HZ	.3754 DB**2
TELEMETRY PERFORMANCE ESTIMATE						
12. RANGING CARRIER SUPPRESSION	.00 DB	.00 DB	.00 DB	T	.00 DB	.0000 DB**2
13. REQUIRED PT/NO	56.99 DB.HZ	.50 DB	-.50 DB	U	56.99 DB.HZ	.0833 DB**2
(RANGING OFF)						
DATA RATE	193253.2285 BPS					
REQUIRED EB/NO	4.0000 DB					
REQUIRED CARRIER MARGIN	18.3500 DB					
MODULATION LEVEL (RMS)	80.0000 DEG	.50 DB	-.50 DB			
14. PERFORMANCE MARGIN					4.27 DB	.4587 DB**2
15. LINK RELIABILITY					.9500	
SIGMA					.68 DB	

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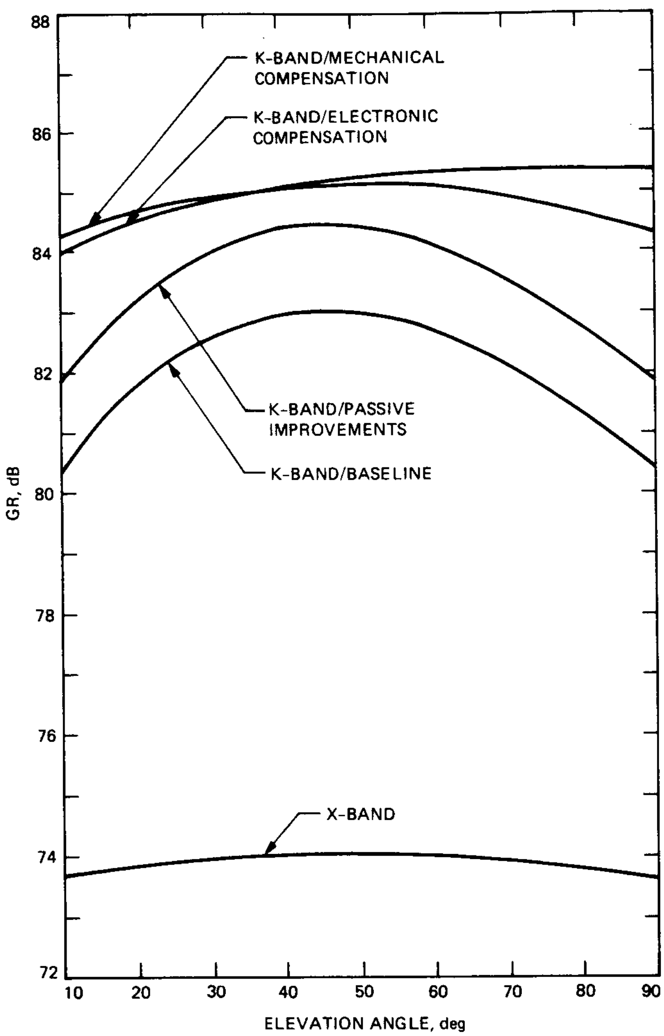

Fig. 1. DSN 70-m station X-band and K-band antenna gain models

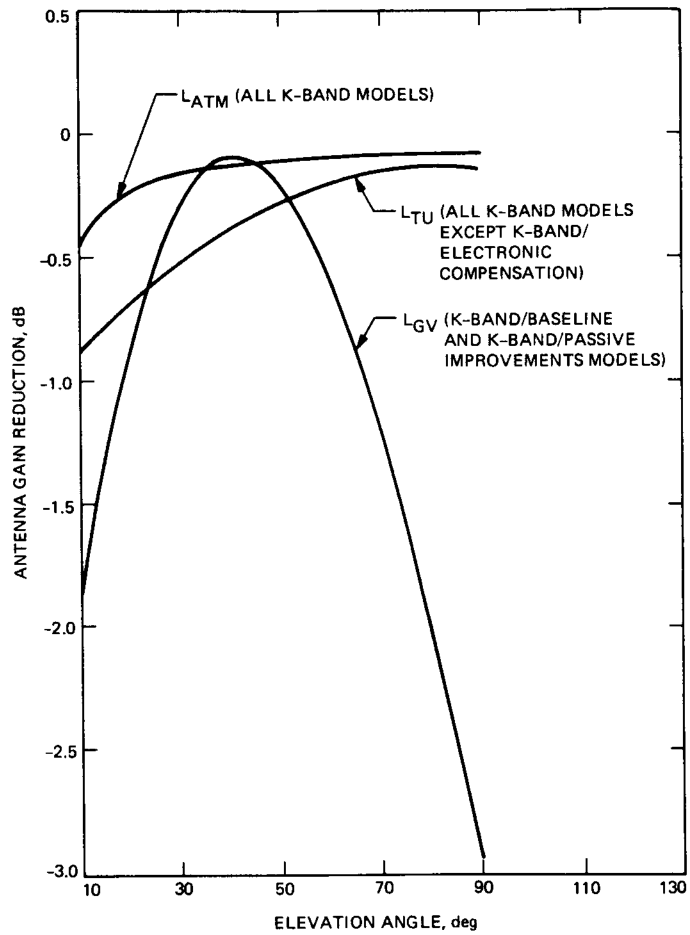

Fig. 2. DSN 70-m station K-band antenna gain reduction from gravity-induced surface distortions, atmospheric turbulance, and atmospheric attenuation

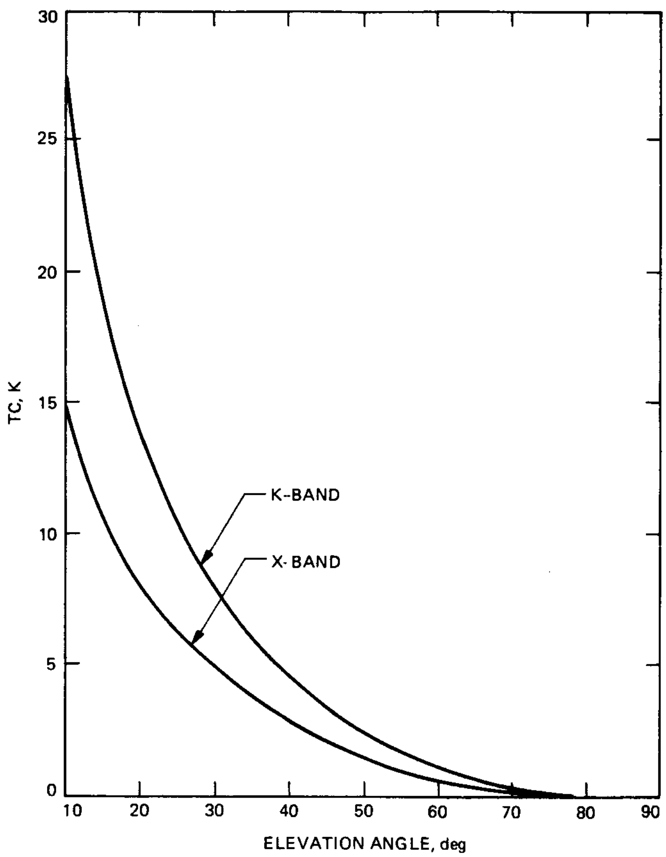

Fig. 3. DSN 70-m station clear-weather receiving system noise temperature increase for nonzenith elevation angles

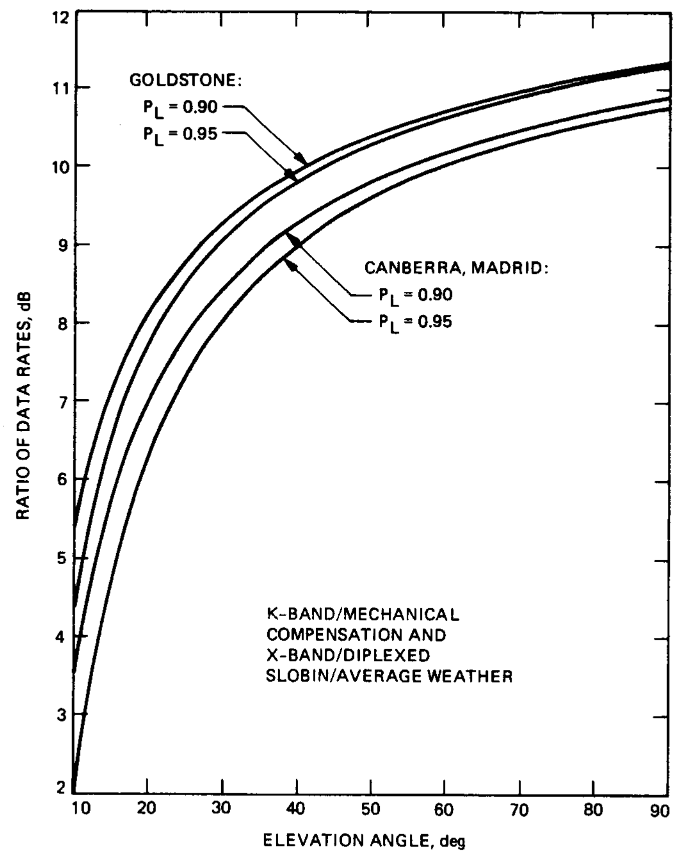

Fig. 4. Ratio of K-band to X-band achievable data rate as a function of elevation angle with DSN station location and link reliability as the curve parameters

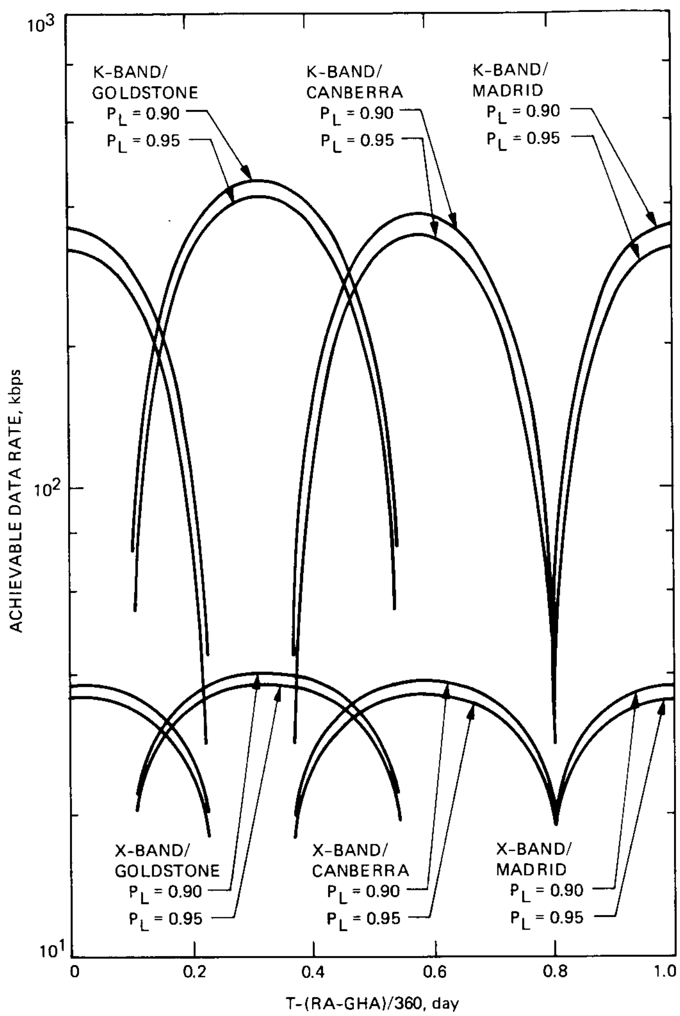

Fig. 5. Comparison of X-band and K-band achievable data rate as a function of time for a one-day period at 0° declination for a DSN 70-m station K-band antenna with mechanical compensation and Slobin/Average weather

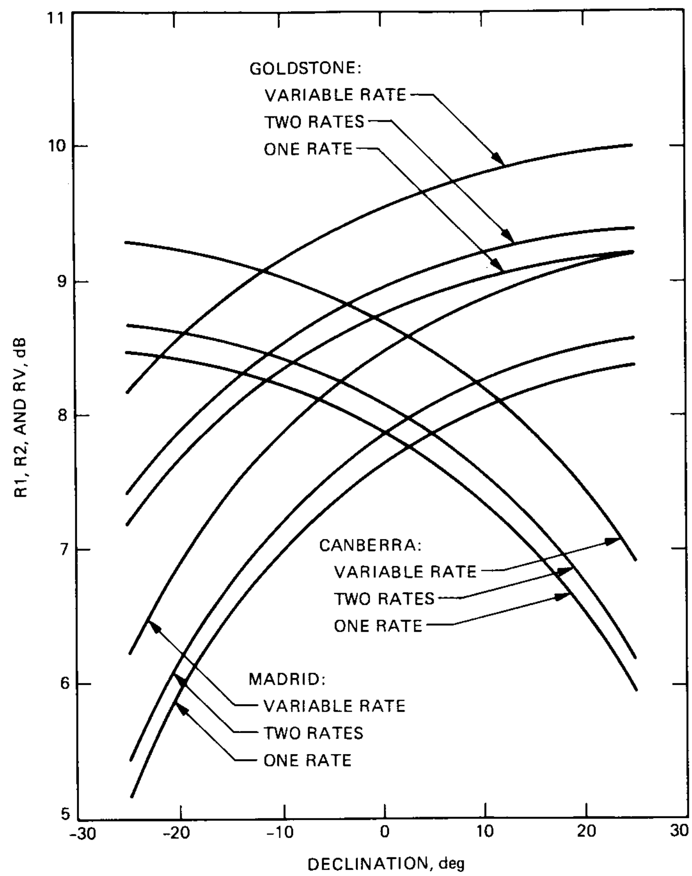

Fig. 6. Ratio of K-band to X-band total data return per pass as a function of declination for a fixed-rate, two-rate, and variable-rate data-rate strategy and for a DSN 70-m station K-band antenna with mechanical compensation, Slobin/Average weather, and 0.95 link reliability

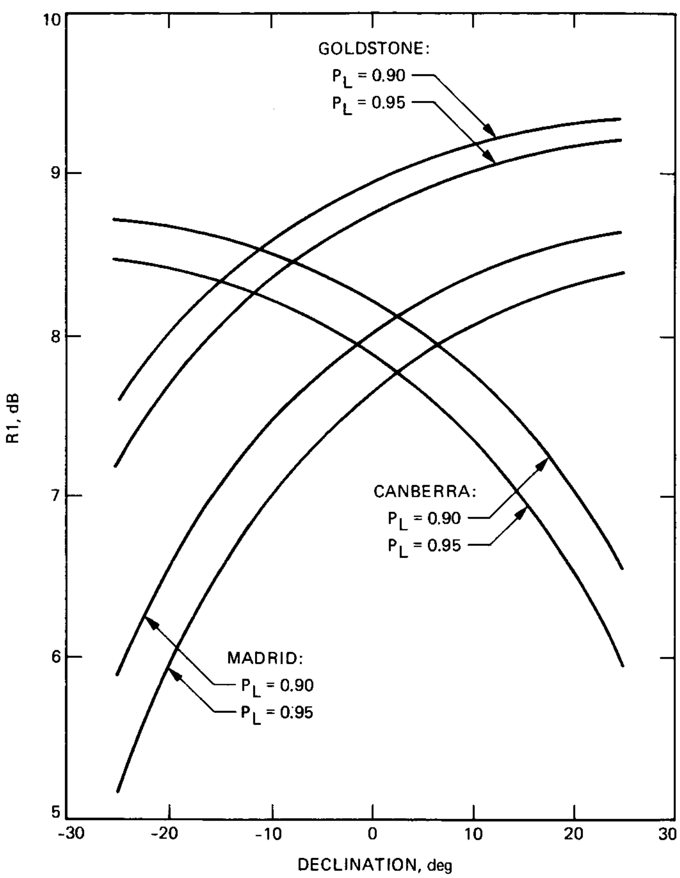

Fig. 7. Ratio of K-band to X-band total data return per pass as a function of declination for a fixed data-rate strategy and for a DSN 70-m station K-band antenna with mechanical compensation and Slobin/Average weather

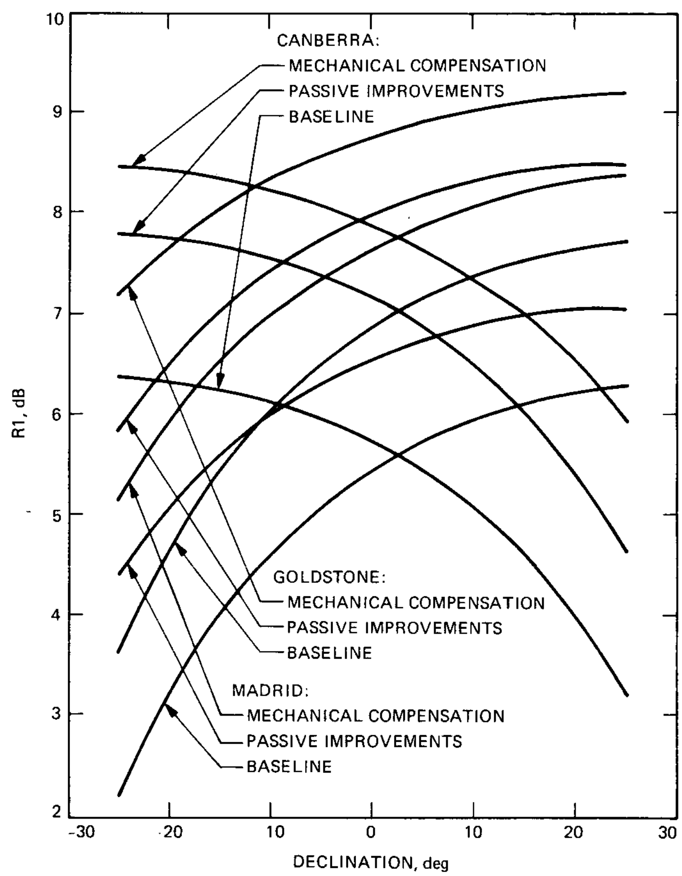

Fig. 8. Ratio of K-band to X-band total data return per pass as a function of declination for a fixed data-rate strategy, Slobin/Average weather, and 0.95 link reliability with DSN station location and the DSN 70-m station K-band antenna gain model as the curve parameters

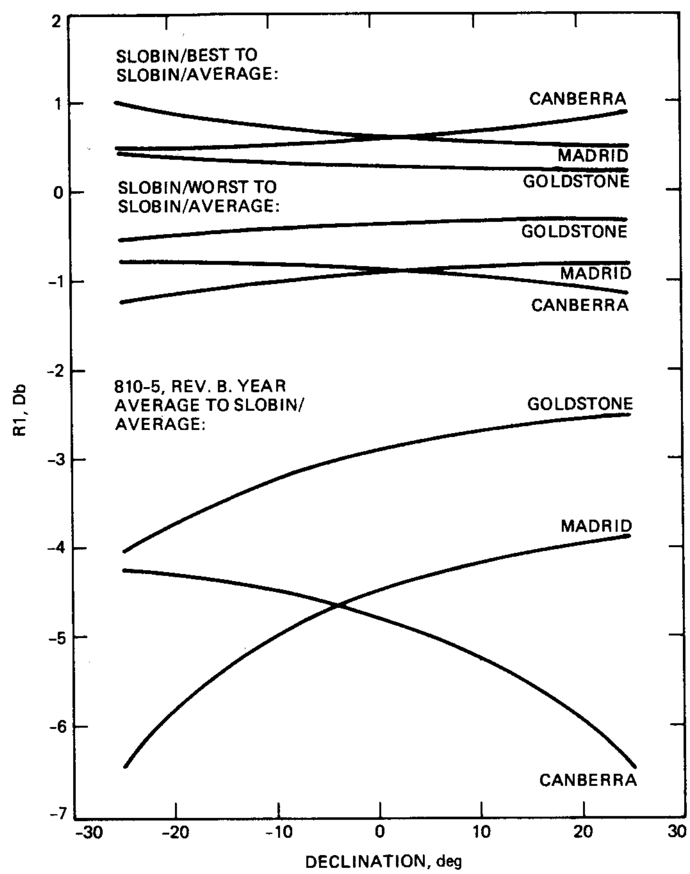

Fig. 9. Comparison of K-band total data return per pass using the Slobin/Best, Slobin/Worst, and Slobin/810-5 weather models with that using the Slobin/Average weather model for a DSN 70-m station K-band antenna with mechanical compensation and 0.95 link reliabiity