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Models of Weather Effects on Noise Temperature and Attenuation for Ka- and X-Band Telemetry Performance Analysis

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Models that show the effects of weather on noise temperature and attenuation of deep space telemetry signals received by the Deep Space Network (DSN) at Ka- and X-band (32 GHz and 8.5 GHz) are developed. These models have been used to compare the performance of telemetry links at these two frequencies. The models build on an earlier 1982 model that used three months of water vapor radiometer measurements (31.4 GHz) at Goldstone, augmented with one year of radiosonde measurements made at Edwards Air Force Base. This 1986 model accounts for annual variations of rainfall and extends to a model for Canberra, Australia, and Madrid, Spain. The results show, for example, that at Ka-band, 30-degree elevation angle, Goldstone weather adds less than 23 ± 2 K to the system temperature 80% of the time, while Canberra or Madrid weather adds less than 32 ± 5 K 80% of the time. At X-band, the comparable numbers are 5.1 ± 0.2 K and 5.7 ± 0.4 K. A simple analysis shows a substantial telemetry system signal-to-noise ratio advantage when operating at Ka-band compared to X-band.

I. Introduction

X- and Ka-band (8.5 GHz and 32 GHz) weather-effects models are developed for use in a comparison of DSN telemetry link performance at these two frequencies (Ref. 1). A large number of independent weather models and statistical studies exist at various frequencies, but they are unrelated, of different data types, and the data are taken under varying and different experimental conditions. A direct comparison of any two such models would not allow satisfactory comparison of link performances at the two frequencies of interest. Therefore, new models have been created.

A Ka-band noise temperature and attenuation model developed at JPL was used as a starting point (Ref. 2). This model is based on 31.4-GHz water vapor radiometer measurements carried out at Goldstone, augmented by one year's radiosonde measurements made at Edwards Air Force Base. That Ka-band model for Goldstone was developed in such a way as to ensure a worst-case analysis, i.e., the model may be considered as typical of a "worst-year." If this is considered to be a 2-sigma case, then only one year in fifty would have more water vapor, clouds, and rain, and thus more atmospheric attenuation and higher noise temperatures.

With this limited model (the radiometer measurements were only made during a three-month period, the winter), the problem then existed as to how to model average and best years at Goldstone, and then how to model the overseas DSN stations at Madrid and Canberra.

II. Methodology of Weather Modeling

The derivative models (from Goldstone, worst-year) were developed on the basis that when one year has less total rain than another, it is because it rains fewer total minutes rather than the same number of minutes at a lower rate. It is recognized that the actual situation is a combination of these two conditions. Thus, in modeling for average and best cases, using the worst-case as a starting point, adjustments were made to the cumulative distribution (CD) value for a given value of noise temperature. For example, if an average year had half the rain of a worst-case year, then the noise temperature value at the 98% CD value (for worst-case) was used for the noise temperature value at CD = 99%. Or, in other words, a noise temperature value (corresponding to a particular rain rate) which is exceeded 2% of the time in a worst-case year is exceeded only 1% of the time in an average year.

Table 1 shows the reported Goldstone Ka-band, worst-month weather effects model as presented in Ref. 2. This table may be interpreted to read, for example: "95% of the time the total Ka-band atmospheric noise temperature is 35 kelvins or less," subject to the conditions stated in the table description. Figure 1 shows the graphical display of the cumulative distribution. As the distribution of values above 99% is important to illustrate the occurrence of rare events, "probability paper" is used in these presentations.

The first step in modeling the Goldstone average and best cases was to determine the relationship among the worst, average, and best years on the basis of some measure or factor. A study of Los Angeles rainfall records for the 106-year period 1877–1983 showed that compared to an average year, the rainiest years had about twice the average rainfall, and the driest years had about one-third the average rainfall. For Los Angeles, the three rainfall values are, approximately, 5, 15, and 30 inches (12.7, 38.1, and 76.2 cm) per year. The distribution is not Gaussian. Forty-four years had above-average rainfall, and sixty-two years had below average. The lowest rainfall year had 4.85 inches (12.32 cm), the average had 15.11 inches (38.38 cm), and the highest had 38.18 inches (96.98 cm). Values greater than +/– "two-sigma" were discarded in this qualitative analysis.

Two other qualitative arguments were brought to bear in this model development. First, that on a worldwide average, there is 50% cloud cover (by area or time); and, secondly, that during the 4400 non-cloudy, non-rainy hours of the year, the clear-sky attenuation and noise temperatures have the same distribution, independent of wet or dry years. The latter argument results in an *a priori* decision that the cumulative distributions would be identical up to the 50% level, and that only above that level would they diverge into best, average, and worst cases.

The arguments used to develop best and average cases (for Goldstone) from the worst-case model can best be described as heuristic. To link the rainfall factors (1/2 and 1/6 compared to maximum) with the requirement at 50% CD, a sliding scale (based on CD) was developed which was applied to the cumulative distribution value for the particular noise temperature value given in Table 1. Thus, for example, to derive a CD value for average-year at Goldstone for 69 kelvins, the CD value of 99.5% is changed to 99.75%. That is, in a worst-year where the noise temperature value of 69 kelvins is exceeded 0.5% of the time, in an average-year it is exceeded only 0.25% of the time. Similarly, in a best-year, it is exceeded only 0.083% of the time (1/6 of 0.5%) and the CD becomes 99.917% at 69 kelvins. Note that the ratios of the exceedance percentages are the same as the rainfall ratios discussed earlier. The effect of the changing exceedance values is to move the cumulative distribution curves "up" toward 100% when moving from worst to best cases. The sliding CD scale is used to move noise temperature points half-way or 5/6 way (for average and best, respectively) at CD's near 100% (the CD region in which rain is an important contributor). Points with lower CD values are moved less (in the cloud region) until at 50% CD, the worst, average, and best curves intersect. Below 50% only one CD curve exists, the one shown in Fig. 1.

Now that the three distribution curves for Goldstone can be generated, the question remains as to the modeling of Canberra and Madrid Ka-band statistics. Again, rainfall is used as the factor by which one site or condition may be compared to another. The Goldstone yearly rainfall average is 3.5 inches (8.9 cm). Canberra and Madrid average 23.0 and 19.6 inches (58.4 and 49.8 cm), respectively. For the purposes of this report, it was decided to treat Canberra and Madrid as similar in terms of weather. Year-to-year variations in rainfall at either station are certainly greater than the difference between the stations, and they are certainly more like each other in vegetation and appearance than when compared to Goldstone (3.5 inches or 8.9 cm) or New York (40 inches or 102 cm). The average rain for the two overseas sites is then 21.3 inches (54.1 cm), a factor of 6.08 higher than the Goldstone rain total.

To generate the Ka-band average-year curve for Canberra/Madrid, the exceedance percentages for the Goldstone curve (1%, 5%, etc.) are simply multiplied by a factor of 6 to reflect the rainfall ratio. In this method, it is also assumed that the cloudiness factor (the product thickness and occurrence) is greater by the same factor. There is no sliding CD scale as in the calculation of cases at a particular location. As an example, a 98% CD for Goldstone becomes 88% for Canberra/Madrid, 95% becomes 70%, and so forth. Clearly this cannot go on for all values (83% does not go to 0%). It is known that the theoretical clear-dry, oxygen-only 0% CD value of noise temperature for Canberra/Madrid (average altitude = 0.730 km MSL) at 30-degree elevaton angle is 10.5 kelvins. Thus the average noise temperature curve must pass through this point at 0% CD. Judicious choice of plotting techniques (which invoked a natural requirement that the CD curves be smooth, orderly, and separated) resulted in a set of 6 curves for Goldstone and Canberra/Madrid which give the range of total atmospheric noise temperature at all DSN sites over what is believed to be an approximately 2-sigma range of yearly-average weather conditions. The curves thus generated are shown in Fig. 2, for a 30-degree elevation angle. It should be noted that the curves deviate slightly from the requirement of equality below 50% CD.

III. Models for Attenuation and Elevation Angle Effects

In order to generate noise temperatures for a range of elevation angles, it is first necessary to create an attenuation model. This attenuation model (at 30-degree elevation) can be moved by 1/sin (elevation) to yield attenuation models at other elevation angles. The noise temperatures themselves cannot be so modeled.

First, for 30-degree elevation, an attenuation model for CD's on the six noise temperature curves is generated from

$$ATTN30 = 10 * LOG((TP/(TP-T30))$$

where

TP = physical temperature of the atmosphere, typically 280 kelvins

T30 = noise temperature values at 30-degree elevation for each CD

Table 2 gives the 30-degree elevation values for noise temperature and attenuation models at Goldstone and Canberra/Madrid. The attenuation values can be modeled by 1/sin(elev) to create attenuation values at other elevation angles. New noise temperature values can then be created from these attenuation values by

$$TEMP = TP * (1-1/L)$$

where

TP = 280 K

L = 10 ** (ATTN/10)

ATTN = attenuation value in dB at another elevation angle, modeled as described above

In this way complete noise temperature and attenuation values for all locations, conditions, elevation angles, and CDs can be created from the initial six Ka-band noise temperature curves at a 30-degree elevation angle as described above. The multitude of numbers presented in the Ka-band study are not presented here.

IV. Modeling Noise Temperature and Attenuation Values at X-Band

In order to make the comparison of telecommunication performance at X- and Ka-bands, another complete set of noise temperature and attenuation values must be created for X-band. It is acknowledged that the effects of water vapor, clouds, and rain for the two frequencies 8.5 and 32 GHz hold an approximately frequency-squared relationship with one another. This ratio is 14.2. Clearly, if extrapolation by frequency is to be done, it is much better to go down in frequency than up. This is because errors in the higher frequency model are reduced by a factor of 14 when creating a model at the lower frequency. In the other direction, small errors at the lower frequency are greatly magnified when moving up in frequency.

As only the "wet" components (water vapor, clouds, rain) have a frequency-squared relationship between X- and Ka-bands, the "constant" oxygen value at Ka-band must be removed first. The modeling will be first done with the attenuation values, so, for example, the 0% CD values (oxygen only) of 0.158 and 0.166 dB at 30-degree elevation are subtracted from all attenuation values (c.f. Table 2). Other clear-air oxygen-only values will apply at other elevation angles. The remaining wet-component attenuation values are divided by 14.2 to create the X-band wet-component attenuation values. The X-band clear-air oxygen-only values are then added back in to create the total X-band attenuation values. For the example presented, at 30-degree elevation, these clear-air values are 0.064 dB, approximately, for all three stations. Then, in a process as described above, X-band noise temperature values can be calculated from the attenuations to create a complete X-band noise temperature and attenuation model for all stations, conditions, and elevation angles. The 30 degree elevation results are given in Table 3.

V. Integration of the Atmospheric Effects Model With the Telecommunications Performance Analysis Model

As developed a number of years ago, DSN telecommunications performance analysis programs contain a couple of awkward but correct steps in the calculation of antenna gain and system noise temperature at X-band. Curves of X-band antenna gain and efficiency created by observation of known radio sources contain within them the elevation angle effects of clear-sky atmospheric attenuation. Presumably, at the time of measurement, it was not possible to account for the atmospheric effects and they were retained in "antenna gain." It is incorrect and misleading (especially at higher frequencies) not to account separately for the atmospheric effects and just lump them in with antenna gain. If this is done, without adequate monitoring of temperature, pressure, and relative humidity during clear-sky conditions, it will not be possible to adequately calibrate antenna performance. Day-to-day atmospheric variation will mask any subtle changes in antenna performance obtained by panel adjustment, pointing improvement, subreflector positioning, etc. The ground noise contribution from quadripod scatter and rear spillover with decreasing elevation angle are included in a baseline curve of "clear weather receiving system noise temperature increase for nonzenith elevation angles.[1]" For X-band, the actual variable clear-sky noise temperature differences from those included in the gain and efficiency curves are probably not enough to create large errors in a model of total system noise temperature. If these curves were used at Ka-band, large noise temperature errors would probably result. Atmospheric effects, antenna gain, and ground noise contribution must be determined separately from one another; and during any antenna calibrations at frequencies higher than X-band, an adequate monitor of atmospheric parameters must be maintained at all times.

[1]"DSN Telecommunications Interfaces, Atmospheric and Environmental Effects," TCI-40, Dec. 1, 1983, in *Deep Space Network/Flight Project Interface Design Handbook, Volume I: Existing DSN Capabilities*, Revision D, JPL Internal Document 810-5, Jet Propulsion Laboratory, Pasadena, California.

Because of the awkward construction of the telecommunications analysis programs, the 0% CD values presented here in all models must be subtracted from all noise temperature and attenuation models so that the remaining atmospheric model is relative to the clear-sky baseline at the elevation angle of interest. The actual clear-sky values of attenuation and noise temperature are included in elevation angle curves of antenna gain and system noise temperature, respectively.

VI. Conclusions

The X- and Ka-band noise temperature models developed here allow a direct comparison of telemetry system performance at the two frequencies. All other things being equal (e.g., spacecraft transmitter power, antenna efficiency, antenna pointing), the gain advantage obtained by operating an antenna at Ka-band rather than X-band (proportional to frequency-squared, 11.5 dB) more than outweighs the additional atmospheric attenuation and noise temperature increase at the higher frequency. As an example, using the atmospheric models developed here and following the argument presented in Ref. 2, it can be shown that for Canberra/Madrid, 30-degree elevation angle, 80% of the time the signal-to-noise ratio (SNR) advantage of Ka-band over X-band will be 8 dB or more. This represents a substantial improvement in DSN telemetry system performance and warrants further detailed measurements and analyses of Ka-band atmospheric effects. Scattered, short-term measurements by JPL at Ka-band tend to support the models presented here; however, greater confidence in these models (or development of updated ones) will depend on long-term measurements (typically five to ten years) at all DSN antenna locations.

References

1. Koerner, M. A., "Relative Performance of 8.5-GHz and 32-GHz Telemetry Links on the Basis of Total Data Return per Pass," *TDA Progress Report 42-87*, pp. 65-80, Jet Propulsion Laboratory, Pasadena, California, November 15, 1986.

2. Clauss, R. C., Franco, M. M., and Slobin, S. D., "K_A-Band Weather-Dependent System Performance Estimates for Goldstone," *TDA Progress Report 42-71*, pp. 60-65, Jet Propulsion Laboratory, Pasadena, California, November 15, 1982.

Table 1. Ka-band noise temperature and attenuation model for Goldstone, worst-month, 30-degree elevation angle (Ref. 2)

Cumulative Distribution, %	Total Atmosphere Noise Temperature, K	Total Atmosphere Attenuation,[a] dB
99.5	69	1.07
99	53	0.82
98	43	0.67
95	35	0.54
90	29	0.45
80	25	0.39
50	19	0.29
0[b]	9.84[c]	0.15

[a]Derived from noise temperature by 0.1 dB = 6.45 K.
[b]Clear-dry, typical of a very cold winter night.
[c]Theoretical oxygen-only.

Table 2. Ka-band noise temperature and attenuation models for Goldstone and Canberra/Madrid for 30-degree elevation angle

	Goldstone			Canberra/Madrid		
CD, %	Best	Avg	Worst	Best	Avg	Worst
Noise Temperature, K						
99.9	65.	120.	240.	260.	270.	279.
99.8	51.	80.	175.	180.	215.	260.
99.5	41.	53.	69.	75.	150.	220.
99.	36.	44.	53.	57.	120.	180.
98.	32.	37.	43.	46.	62.	120.
95.	27.	31.	35.	37.	46.	55.
90.	24.	26.	30.	33.	38.	45.
80.	21.	23.	25.	29.	32.	37.
70.	19.	20.5	22.	26.	28.5	32.
50.	17.	18.	19.	23.	25.	27.
20.	13.5	14.	14.5	16.5	17.5	18.5
0.	10.	10.	10.	10.5	10.5	10.5
Attenuation, dB						
99.9	1.147	2.430	9.451	11.461	14.472	24.472
99.8	0.873	1.461	4.260	4.472	6.342	11.461
99.5	0.688	0.911	1.229	1.354	3.332	6.690
99.	0.598	0.742	0.911	0.989	2.430	4.472
98.	0.527	0.616	0.724	0.779	1.087	2.430
95.	0.440	0.510	0.580	0.616	0.779	0.950
90.	0.389	0.423	0.492	0.545	0.633	0.761
80.	0.339	0.372	0.406	0.475	0.527	0.616
70.	0.305	0.330	0.355	0.423	0.466	0.527
50.	0.272	0.289	0.305	0.372	0.406	0.440
20.	0.215	0.223	0.231	0.264	0.280	0.297
0.	0.158	0.158	0.158	0.166	0.166	0.166

Table 3. X-band noise temperature and attenuation models for Goldstone and Canberra/Madrid for 30-degree elevation angle

	Goldstone			Canberra/Madrid		
CD, %	Best	Avg	Worst	Best	Avg	Worst
Noise Temperature, K						
99.9	8.5	14.1	38.9	50.4	61.3	94.1
99.8	7.3	9.9	21.9	22.7	30.4	50.4
99.5	6.5	7.5	8.9	9.4	17.9	31.8
99.	6.1	6.7	7.5	7.8	14.1	22.7
98.	5.7	6.1	6.6	6.8	8.2	14.1
95.	5.4	5.7	6.0	6.1	6.8	7.6
90.	5.1	5.3	5.6	5.8	6.2	6.8
80.	4.9	5.1	5.2	5.5	5.7	6.1
70.	4.8	4.9	5.0	5.2	5.4	5.7
50.	4.6	4.7	4.8	5.0	5.2	5.3
20.	4.4	4.4	4.4	4.5	4.6	4.7
0.	4.1	4.1	4.1	4.1	4.1	4.1
Attenuation, dB						
99.9	0.134	0.224	0.649	0.861	1.073	1.779
99.8	0.114	0.156	0.353	0.368	0.500	0.861
99.5	0.101	0.117	0.140	0.148	0.287	0.524
99.	0.095	0.105	0.117	0.122	0.224	0.368
98.	0.090	0.096	0.104	0.107	0.129	0.224
95.	0.084	0.089	0.094	0.096	0.107	0.119
90.	0.080	0.083	0.088	0.091	0.097	0.106
80.	0.077	0.079	0.082	0.086	0.089	0.096
70.	0.074	0.076	0.078	0.082	0.085	0.089
50.	0.072	0.073	0.074	0.079	0.081	0.083
20.	0.068	0.069	0.069	0.071	0.072	0.073
0.	0.064	0.064	0.064	0.064	0.064	0.064

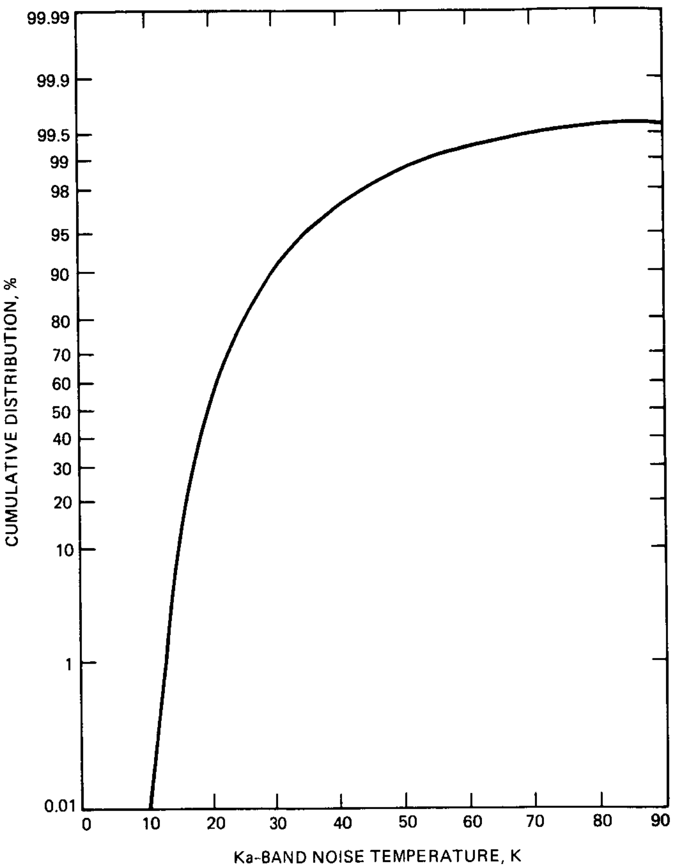

Fig. 1. Ka-band atmospheric noise temperature statistics: worst case, Goldstone, 30-deg elevation angle (Ref. 2)

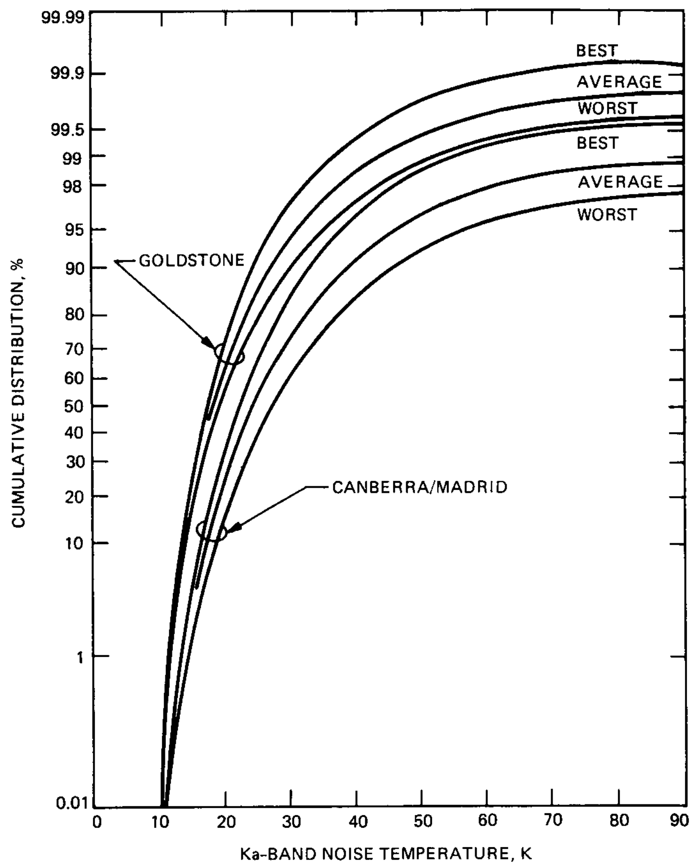

Fig. 2. Ka-band atmospheric noise temperature statistics: all sites, 30-deg elevation angle