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X-Band Noise Temperature Effects of Rain on DSN Antenna Feedhorns

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Simulated rain tests were carried out to determine the noise temperature contribution of liquid water adhering to the aperture cover material on both a standard DSN X-band feedhorn and on an S/X-band common aperture feedhorn. It was found that for the particular common aperture feedhorn tested, system noise temperature increases were much greater when the plastic horn cover material was old and weathered than when it was new. The age and condition of the aperture cover material is believed to be a major factor in the amount of degradation experienced by a telecommunications system during rain events.

I. Introduction

At microwave frequencies above about 5 GHz, rain is considered to be the major contributor to large signal-to-noise ratio (SNR) degradations in telecommunications systems. In most temperate locales, rain falls a total of about 5 to 7% of the time (as measured by minute-sized sample periods). This amounts to 400 to 600 hours per year (Ref. 1). For a location whose average total yearly rainfall is 500 mm (Pasadena, Calif.) this corresponds to a mean rain rate of about 1 mm/hr, or a very light rain. Link degradation comes from both spacecraft signal attenuation and increased system noise temperature due to emission from the liquid water particles themselves. As an example, at X-band, 30-deg elevation angle, a rain rate of 5 mm/hour (a moderate rain) will give an attenuation of 0.4 dB, a system noise temperature increase of 25 K, and a 3-dB SNR degradation for a 30 K baseline system noise temperature. The same rain at 32 GHz will give 9-dB attenuation, 220 K noise temperature increase, and an 18-dB SNR degradation. Fortunately, 5 mm/hour rain is exceeded only 0.2% of the year (18 hours) at Canberra, the rainiest of the DSN tracking antenna locations. Again, fortunately, using the Canberra example, fully half the total yearly rainfall (approximately 580 mm) is deposited at a rate less than about 3 mm/hour (a rate exceeded only 0.5% of the year, 45 hours). For X-band, the *atmospheric* effects of rain are expected to be small more than 99% of the time.

It has been found, however, during tracking of spacecraft that significant telecommunications link degradation occurs during periods of even light rain. This degradation can last as long as an entire pass (approximately eight hours) as has been observed during a Voyager 1 Jupiter near-encounter pass over DSS 43 (Canberra) in 1979. The rain rate during this pass was measured by an on-site rain gauge to be quite low (approximately 1 mm/hour) but continuous for the entire day. All antenna components were continually wet and this condition contributed to significant and continuous link degradation.

The antenna components which were wetted, in particular, were the plastic sheet covering the antenna feedhorn and the metallic surfaces of the antenna reflector system, the paraboloid, hyperboloid, and reflex feed elements. The "attachment" of rain to these various surfaces is of two types: "wetting" and "non-wetting." As a common example of a "wetted" surface, one may consider a common schoolroom blackboard that has been washed off in order to remove chalk dust. The surface character changes as the water fills the microscopic pores and scratches of the board. The board becomes covered with a thin sheet of liquid water. After a short while, the water evaporates, leaving a dry, non-shiny surface. A "non-wetted" surface is one such as a newly waxed automobile hood, which when rained upon becomes covered with beads or drops of water ranging in size from 1 mm diameter to as much as 25 mm diameter, approximately. It was found that the wetted surface causes larger noise temperature effects than does the non-wetted surface. This noise temperature increase can cause serious problems during low signal level tracking periods, for example, Voyager at Uranus and Neptune. It has thus become necessary to ascertain the effects of rain on antenna components and to propose methods of overcoming the resulting degradation.

A previous study at the DSN Madrid tracking station (Ref. 2) has shown a remarkable agreement between experimental and theoretical results of noise temperature measurements of sheets of water held in a container over the aperture of both S-band and X-band horns. Significant levels of noise temperature (100 K at X-band) and attenuation were measured for water layers as thin as 0.1 mm. Those tests did not involve wetting of the feedhorn cover; the results presented in this report are obtained from wetting of actual DSN antenna feedhorns.

II. Experiment Description

An experiment was devised to test the effects of simulated rain on the X-band feedhorns used on the DSN antennas. A standard X-band feedhorn, an S/X-band common aperture feedhorn, and an ambient load were connected to a maser as shown in Fig. 1. The system noise temperature (T_{op}) for each horn path was calculated by comparing the power level with that from the ambient load path. A Y-factor measurement technique is used in which

$$\begin{aligned} Y\,(\mathit{ratio}) &= \frac{\mathit{power\ from\ ambient\ load}}{\mathit{power\ from\ horn}} \\ &= \frac{T_{op,\ ambient\ load}}{T_{op,\ horn}} \\ &= \frac{T_{ambient} + T_{maser}}{T_{op,\ horn}} \end{aligned} \qquad (1)$$

where

T_{op} = system operating noise temperature, K

$T_{ambient}$ = ambient load physical temperature, K

T_{maser} = maser noise temperature, K

The maser noise temperature is assumed to be 5 K for the purposes of these calculations. The actual determination of T_{op} by Eq. (1) is insensitive to the value of T_{maser}. T_{op} includes the cosmic background noise temperature (2.7 K), the atmosphere (2.5 K, clear sky), horn and waveguide (approximately 11 K in this test), and maser (approximately 5 K). The maser noise temperature itself can be determined from a separate test in which a calibrated waveguide horn is attached directly to the maser. Power levels are recorded looking at both the clear sky and an aperture load. A Y-factor is determined:

$$\begin{aligned} Y &= \frac{\mathit{power\ level\ on\ aperture\ load}}{\mathit{power\ level\ on\ clear\ sky}} \\ &= \frac{T_{op,\ load}}{T_{op,\ clear\ sky}} \\ &= \frac{T_{maser} + T_p}{T_{maser} + T_{cosmic} + T_{atm} + T_{horn}} \end{aligned} \qquad (2)$$

where

T_{maser} = maser noise temperature to be determined

T_{cosmic} = cosmic background noise temperature (2.7 K)

T_p = physical temperature of aperture load and horn

T_{atm} = atmospheric noise temperature (2.5 K)

T_{horn} = noise temperature of calibrated horn (1.5 K)

The maser noise temperature is then found from

$$T_{maser} = \frac{T_p - Y(T_{cosmic} + T_{atm} + T_{horn})}{Y - 1} \qquad (3)$$

The system operating noise temperature (T_{op}) when looking at the large S/X horn is determined from Eq. (1) for a specific example using the following input values.

$$T_{ambient} = 290.2\text{ K} \ \ (17^\circ\text{C})$$

$$T_{maser} = 5.0\text{ K}$$

$$Y = 14.09 \ \ (11.49\text{ dB})$$

Then,

$$T_{op,\,S/X} = 20.95\text{ K}.$$

This value is typical of the clear sky noise temperature and includes approximately 9 K contributed by 127 cm of waveguide, orthomode transducer, waveguide bend, and curved waveguide switch port.

The method of carrying out the rain tests was to measure the degradation of each horn relative to the other horn, which then serves to eliminate the effect of small changes in the atmospheric noise temperature contribution.

A plastic spray bottle with a positive displacement (0.8 cm^3) pump was filled with distilled water and used to provide the "rain" for these tests. Both horns were pointed vertically (toward the zenith), which, however, is not a normal tracking position. This position allowed a maximum of water to remain on the horn, although there was no pooling of liquid in the center of the aperture cover, due to the domed shape caused by internal waveguide and horn pressurization. A normal average tracking elevation angle might be 45 deg, in which case some water is expected to run off the horn in worst-case conditions. The spray bottle delivered 0.8 cm^3 per spray, generally in a large number of very tiny drops. Upon striking a surface, many of these drops would coalesce to form 3-mm to 10-mm-size drops on the surface, depending on whether the surface was wetting or non-wetting.

The first test series was carried out on the large S/X feedhorn with weathered Kapton (manufactured by Du Pont) aperture cover material. This material was approximately four years old at the time of the tests and had been exposed every day to sunlight, rain, and blowing dust and sand (2 years at Goldstone and 2 years at JPL). Water was sprayed on the Kapton first on the center and then at increasing distances from the center to create as uniform a coverage as possible.

After a given number of sprays, the water droplets on the Kapton were smeared by hand. Then an additional 250 cm^3 (approximately) of water was poured all over the horn cover. This amount of water caused runoff and represented a maximum water retention case for vertical pointing. It is expected that more nominal pointing angles (45-deg elevation) would not retain as much water. Power levels were measured at all points in the experiment. These tests were repeated on new shiny Kapton material placed over and touching the old material. Clean, dry, new Kapton did not measurably increase the noise temperature of the system. Table 1 gives the results of these tests. It is seen that the weathered Kapton material exhibits much higher noise temperature effects than does the new material.

The film thickness of 100 sprays (80 cm^3) of water smeared evenly on an area 116.8 cm in diameter is 0.074 mm; 312 cm^3; of water make a film thickness of 0.29 mm. Smearing water on a shiny surface does not distribute it evenly but merely causes it to coalesce into larger drops or areas of water.

In addition to tests on the large S/X common aperture horn, the small (18.4-cm-diameter) standard DSN feedhorn was tested in a similar manner. The aperture material was Kapton, in shiny, good condition. Table 2 presents results of the small horn tests. Five sprays (4 cm^3) on the small horn deposited a substantial amount of water (the horn was very wet); the noise temperature increase when smeared was moderate (37 K). The ratio of horn areas is about 40 to 1; thus 4 cm^3 on the small horn is equivalent to about 160 cm^3 on the large horn. The effects of water on Teflon (Du Pont) material was measured on the small horn. A piece of Teflon sheet (0.13 mm thick, 30 × 70 cm) was placed over the horn. The clean dry Teflon did not measurably increase the noise temperature of the system. System performance is substantially improved by the use of Teflon as opposed to the new shiny Kapton material for small amounts of water that would be equivalent to conditions experienced during light rainfall.

Another test compared the large and small horns when equal water densities were applied to the aperture covers. The diameter of the large horn is 116.8 cm, and of the small horn is 18.4 cm. The area ratio is 40.3. Numerous single-spray measurements were made on the small horn. Each single-spray covered most of the aperture of the small horn with water drops. Forty-spray measurements were made on the large horn with both the weathered aperture material and the new Kapton material. Table 3 presents the results of these tests. These results are more or less consistent with the results shown in Table 1 for the large horn. The one-spray value in Table 2 for the small horn is about 70% higher than for this test. This may be due to a difference in water particle distribution in the two cases. The fact that the large horn/new Kapton increase of 3.74 K (Table 3) is double that of the small horn/new Kapton value (1.80 K), for the same water particle density, may be attributable to the fact that the phase center of the large horn is located 171.5 cm from the aperture, whereas the phase center of the small horn is only 3.6 cm from the aperture. Perhaps differences in aperture electric field strength create the measured difference.

III. Noise Temperature of S/X Common Aperture Feedhorn

The noise temperature contribution of the S/X common aperture feedhorn was determined by comparing the system noise temperature of this horn with that of a standard X-band *reference* horn (not the DSN X-band horn). This reference horn was carefully calibrated by the National Bureau of Standards and was found to contribute a noise temperature of 1.5 K. Using the DSN horn as a baseline, the S/X and reference horns were alternately connected to the same waveguide switch port and common waveguide run. The results indicate that the S/X common aperture horn (with 12.7-cm round aluminum waveguide/rotary joint, 10.2 cm quarter-wave polarizer, and 0.13-mm-thick Kapton) is 1.14 K hotter than the NBS reference horn with 0.025 mm Kapton.

IV. Conclusion

The series of tests described here indicates the seriousness of the noise temperature effects due to water on the aperture covers of DSN feedhorns. Noise temperature increases in excess of 30 K begin to degrade the telecommunications link; increases of 100 K or more generally result in loss of spacecraft signal.

It has been shown that weathered Kapton aperture cover material exhibits greater rain-induced degradation than does new, unweathered material. New Teflon exhibits less degradation than new Kapton for small amounts of water. The aging and weathering properties of Teflon are not presently known. A careful review of data taken during these preliminary tests shows that additional work is needed to determine methods of reducing the rain-induced degradation using passive means. These tests indicate that large improvements in spacecraft communications can be made in the DSN during periods of rain.

References

1. Potter, P. D., et al., "A Study of Weather-Dependent Data Links for Deep Space Applications," Technical Report 32-1392, Jet Propulsion Laboratory, Pasadena, Calif., Oct. 15, 1969.

2. Urech, J. M., "Preliminary Report on DSN System Performance Under Local Weather Effects," *DSN Progress Report 42-52*, Jet Propulsion Laboratory Pasadena, Calif., Aug. 15, 1979.

Table 1. Results of simulated rain tests on S/X common aperture feedhorn with old and new Kapton aperture cover material

Test		X-band noise temperature increase, K	
		Old Kapton	New Kapton
1.	Clean, dry	0.00	0.00
2.	One spray in center (0.8 cc)	1.31	0.33
3.	2 sprays total	2.07	0.75
4.	3 sprays total	3.55	0.89
5.	4 sprays total	5.00	1.10
6.	5 sprays total	6.98	1.52
7.	6 sprays total	7.67	1.81
8.	7 sprays total	8.76	1.95
9.	8 sprays total	9.68	2.17
10.	9 sprays total	10.20	2.75
11.	10 sprays total, 38 cm square	11.04	3.49
12.	Smeared by hand, 46 cm square	12.22	4.26
1.	Clean, dry	0.00	0.00
2.	30 sprays total (24 cm^3)	25.78	4.34
3.	30 sprays total smeared 90 cm diameter	28.16	4.96
1.	Clean, dry	0.00	0.00
2.	100 sprays total (80 cm^3)	54.20	–
3.	100 sprays total smeared	43.93 (0.074 mm thick)	9.59
4.	Water poured on	141.16 K (312 cm^3 total, 0.29 mm thick) 188.11 K (910 cm^3 total, 0.85 mm thick)	112.81 K (397 cm^3 total, 0.37 mm thick)

Table 2. Results of simulated rain tests on standard DSN feedhorn (18.4 cm diameter) with and without Teflon sheet on top of Kapton aperture material

Test		X-band noise temperature increase, K	
		Horn with Teflon	Horn without Teflon
1.	Clean, dry	0	0
2.	1 spray total (0.8 cm^3)	0.43	3.04
3.	2 sprays total	3.35	6.73
4.	3 sprays total	9.59	8.49
5.	4 sprays total	7.33	13.17
6.	5 sprays total	11.39	14.50
7.	5 sprays smeared	–	36.73

Table 3. Equal drop-density comparison of large and small feedhorn noise temperature increase

	X-band noise temperature increase, K
Small horn New shiny Kapton 1 spray average	1.80
Large horn Weathered Kapton aperture material 40 sprays	35.09
Large horn New shiny Kapton 40 sprays	3.74

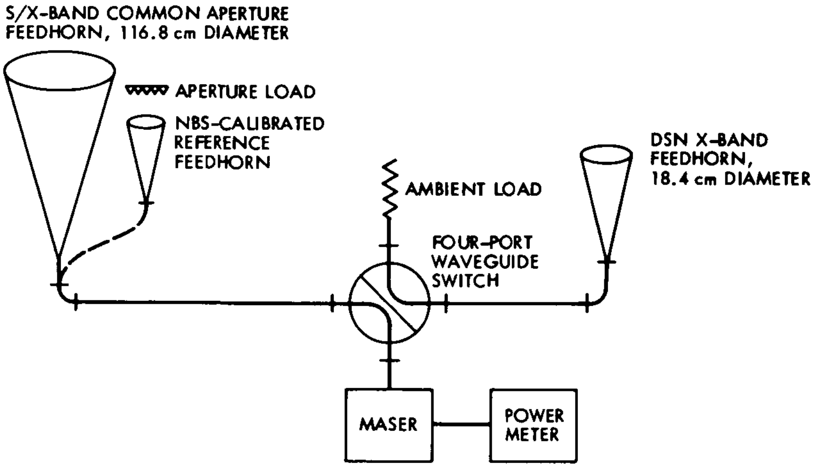

Fig. 1. Experimental setup for testing rain effects on X-band feedhorns