Noise Temperature and Gain Loss due to Paints and Primers on DSN Antenna Reflector Surfaces

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The last of a series of three articles on the subject, this final paint study article presents excess noise temperatures and added-gain losses at 32 GHz for various combinations of paints and primers currently being studied for use on DSN antenna reflector surfaces. It is shown that 500FHR6 acrylic urethane-based paint has the lowest excess noise-temperature contribution and should be used for all new DSN beam-waveguide antennas being constructed and for all those 34-m and 70-m antennas whose reflector surfaces need repainting.

I. Introduction

A paint study was initiated to determine how much degradation of antenna noise temperature and gain occur as functions of paint thickness on antenna reflector surfaces. The first and second paint study articles [1,2] presented measured complex dielectric constant data for paints and primers currently being used on DSN antennas as well as data on paints and primers that are candidate replacements. In this third and final article of the paint study, noise temperatures and gain losses at 32 GHz will be presented for various combinations of paints and primers as functions of paint thickness, incidence angle, and polarization.

Section II of this article will discuss theoretical methods that were investigated for determining complex dielectric constants of paints. Section III presents the equations for calculating excess noise temperatures and added-gain loss due to paint and primer layers on a reflector surface, and Section IV presents the desired antenna performance degradation data in graphic and tabular form.

II. Theoretical Studies

In conjunction with the use of experimental methods for determining the complex dielectric constant of paints, theoretical methods were also investigated. For completeness of reporting on this paint study, the results of these theoretical studies are presented in the following.

It is commonly thought that if the complex dielectric constants of the individual paint ingredients and their volumetric ratios are known, then it should be possible to derive theoretical formulas for calculating the overall complex dielectric constant of the paint mixture. The term "volumetric ratio" is defined here as the ratio of the volume of a particular ingredient to the sum of the volumes of all the ingredients.

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A. Two-Mix Ingredient Model

One of the methods investigated was the two-mix formula method [3,4]. This formula has been used successfully in the past to compute complex dielectric constants of a mixture of salt in distilled water, microballoon inclusions in polymer epoxy resin [4], and artificial dielectrics.

In order to use this two-mix-ingredient formula for Triangle no. 6 paint (a patented paint), which has three main ingredients, it was necessary to use the formula two ingredients at a time. For the first step, the complex relative dielectric constants and volumetric ratios of two of the ingredients with smaller volumetric ratios were input into the quadratic equation given in [3]. The solved equation resulted in a complex relative dielectric constant of $(4.87 - j0.085)$ for the mix. The second step was to take this new equivalent single ingredient and mix it with the main ingredient, titanium dioxide (TiO_2), whose volumetric ratio was known and was assumed to have a complex relative dielectric constant value of approximately $(80 - j0.020)$ at 32 GHz [5,6]. The overall complex relative dielectric constant of the three main ingredients of Triangle no. 6 paint was calculated to be $(15.2 - j0.07)$. Other small volumes of solvents used in Triangle no. 6 paint were ignored because all solvents eventually evaporate. Since the actual volumetric ratios and names of some of the other ingredients used in Triangle no. 6 paint may be a trade secret, this information will not be revealed in this article. However, this information is not necessary for this article, since it is intended that only the theoretical procedure and results be presented.

This theoretically calculated complex relative dielectric constant of $(15.2 - j0.07)$ for Triangle no. 6 paint is significantly different from the measured value of $(5.9 - j0.18)$ at 32 GHz [1]. It is concluded that the theoretical two-mix-ingredient formula, valid for dry ingredient mixtures, cannot be used to accurately calculate the complex dielectric constant of paints because solvents used in the mix cause chemical changes of the combined ingredients.

B. Equivalent Circuit Model

Another theoretical technique that was investigated was suggested by R. Clauss of JPL. This approach is to represent individual paint ingredients as slabs of equal length and width but of different heights inside a parallel plate waveguide. Then, for each individual slab, formulas for an equivalent capacitance and resistance were derived. It was assumed that the capacitance and resistance value for each slab could be expressed in terms of its complex relative dielectric constant and slab height [7], where the height is proportional to the paint ingredient's volumetric ratio. Then the individual capacitors and resistors were put in series. The final steps were to calculate the overall equivalent capacitance and equivalent resistance and convert them back to an overall complex relative dielectric constant. This technique gave a complex relative dielectric constant value of $(7.02 - j0.01)$ as compared with a measured value of $(5.9 - j0.18)$. Although this method gave a value reasonably close to the measured value for the real part of the complex relative dielectric constant, it is not known if the assumptions used in this equivalent circuit-modeling method are valid.

At this time, it appears that the only accurate way to determine both the real and imaginary parts of the complex relative dielectric constants of paints is through measurement methods such as the one described in the two previous articles on this paint study [1,2].

III. Excess Noise Temperature and Added-Gain Loss

A computer program for calculating reflection and transmission coefficients of a multilayer dielectric stack [8] was provided by the University of California, Los Angeles (UCLA) Electrical Engineering Department. The inputs to the UCLA computer program are perpendicular or parallel polarization, frequency, incidence angle, and the complex relative dielectric constant and thickness for each layer in the multilayer stack. For the results at 32 GHz in this article, the complex relative dielectric constant values shown in Table 1 were used.

Table 1. Average measured paint/primer complex relative dielectric constant values in the 32-GHz frequency region.[a]

Paint or primer	Frequency, GHz	ε_r'	ε_r''	Loss tangent	Electrical conductivity, mhos/m
Triangle no. 6 paint	31–33	5.908 0.019 SD	0.148 0.014 SD	0.025 0.002 SD	0.2631
Zinc chromate primer	32–34	4.361 0.001 SD	0.0949 0.0001 SD	0.0218 0.00003 SD	0.1687
18FHR6 paint	31–33	5.275 0.012 SD	0.153 0.008 SD	0.0291 0.0014 SD	0.2720
283 primer	31–33	3.300 0.001 SD	0.121 0.001 SD	0.0367 0.0003 SD	0.2151
500FHR6 paint	31–33	4.691 0.001 SD	0.111 0.001 SD	0.0236 0.0002 SD	0.1973

[a] SD = the standard deviation of the average based on the number of frequency points.

Complex relative dielectric constant = $(\varepsilon_r' - j\,\varepsilon_r'')$.

Loss tangent = $\varepsilon_r''/\varepsilon_r'$.

Electrical conductivity = $\varepsilon_r'' \times \text{Frequency(GHz)}/18$. For this table, Frequency(GHz) = 32.0 was used.

To employ the UCLA program for the painted reflector case, the final dielectric layer of the stack was chosen to be a thick 6061-T6 aluminum sheet, which is the material used for the reflector surfaces of DSN antennas. When a thick metallic plate is used as the last layer, the useful outputs of the UCLA program are the overall multilayer input voltage reflection coefficient (magnitude and phase) and return loss in dB. A second program was written to input the reflection coefficient values and compute noise temperatures and gain losses for perpendicular and parallel polarizations from the equations that will be given in the following.

In practice, what is measured is the total noise temperature of a reflector surface coated with paint and primer layers. Often the changes of noise temperature due to these paint and primer layers are so small that it is difficult to show these changes on a total noise-temperature plot. Therefore, in this article, the contributions of paint and primer only will be shown. This contribution is defined as excess noise temperature, whose equation will be derived and shown below.

Once the input reflection coefficient is known for a particular paint/primer thickness, incidence angle, and polarization, the overall noise temperature of a painted reflector can be calculated from

$$T_n = \left(1 - |\Gamma_{in}|^{2N}\right) T_p \tag{1}$$

where

$\Gamma_{in} = $ the input voltage reflection coefficient as seen looking at the painted reflector. It applies to a particular polarization and incidence angle.

$N = $ the number of times that the incident wave reflects off identical reflectors in cascade before arriving at cold sky.

$T_p = $ the physical temperature of the reflector surface, K.

If one is interested in the excess noise-temperature (ENT) contribution due to paint or primer or both, the following equation applies for the N number of reflectors case:

$$\Delta T_n = T_{n2} - T_{n1}$$

$$= \left(1 - |\Gamma_2|^{2N}\right) T_p - \left(1 - |\Gamma_1|^{2N}\right) T_p \tag{2}$$

where Γ_1 and Γ_2 are the input voltage reflection coefficients as seen looking at the unpainted (bare metal) and painted reflector surfaces, respectively. There are no restrictions in Eq. (2) regarding the value of N. It is required only that the values of $|\Gamma_1|$ and $|\Gamma_2|$ be less than or equal to unity and greater than or equal to zero. It also is required that $|\Gamma_1| \geq |\Gamma_2|$. Note that if N becomes very large, $|\Gamma_{in}|^{2N}$ in Eq. (1) will go towards zero and T_n approaches being equal to T_p, as it should. In addition, when N becomes large, the excess noise temperature given by Eq. (2) will go towards zero.

For low-loss cases and $N \leq 10$ cases, an approximate expression for ENT can be derived as follows. Let

$$|\Gamma_1|^2 = (1 - x_1) \tag{3}$$

$$|\Gamma_2|^2 = (1 - x_2) \tag{4}$$

Then using a series expansion and dropping off higher-order terms,

$$|\Gamma_1|^{2N} = (1 - x_1)^N \sim 1 - N x_1 \quad \text{for } \begin{cases} x_1 \leq 0.01 \\ N \leq 10 \end{cases} \tag{5}$$

$$|\Gamma_2|^{2N} = (1 - x_2)^N \sim 1 - N x_2 \quad \text{for } \begin{cases} x_2 \leq 0.01 \\ N \leq 10 \end{cases} \tag{6}$$

Substitution of Eqs. (5) and (6) into Eq. (2) gives an approximate equation for ENT of

$$\Delta T_n \sim N \left(x_2 - x_1\right) T_p \tag{7}$$

The purpose of deriving this approximate expression is to show that for low loss or the $x_1, x_2 \ll 1$ and $N \leq 10$ cases, the ENT for the N mirror case is approximately equal to N times the ENT for the $N = 1$ mirror case.

Also of interest is the added-gain loss due to the paint and primer on a reflector surface. Added-gain loss is defined as the total gain loss of the lossy reflector with the paint and primer layers minus the gain loss of the reflector only. For the N number of similarly painted mirror case, the added-gain loss expressed in positive dB is

$$\Delta G_{\mathrm{dB}} = 10 \log_{10} |\Gamma_1|^{2N} - 10 \log_{10} |\Gamma_2|^{2N}$$

$$= N \left(10 \log_{10} |\Gamma_1|^2 - 10 \log_{10} |\Gamma_2|^2\right) \tag{8}$$

Note that the added-gain loss for the N mirror case is exactly equal to N times the added-gain loss for the single $N = 1$ mirror case. This equation can be used for any value of N, but it is required that the values of $|\Gamma_1|$ and $|\Gamma_2|$ be less than or equal to unity and greater than zero, and it is required that $|\Gamma_1| \geq |\Gamma_2|$.

The appropriate reflection coefficient for perpendicular or parallel polarization is used in the above equations to obtain excess noise temperatures for perpendicular and parallel polarizations. The excess noise temperature for circular polarization is obtained by taking the average of the excess noise temperatures of perpendicular and parallel polarizations [9].

IV. Results

A. General Comments

The plots for this section of the article will be shown for incidence angles from 0 to 60 deg. The 60-deg limit was chosen for the following reason: Although the maximum incidence angle is about 30 deg for the main-reflector and is less for subreflector surfaces, some of the reflectors in a beam-waveguide (BWG) antenna system have incidence angles of 45 deg. One of the BWG mirrors has an incidence angle of about 60 deg near its edges. Stray signal reflections off the BWG shroud walls can have incidence angles of 60 deg or greater, and these plots can be useful for BWG shroud noise-temperature contribution analyses.

Even though the results presented in this article apply to the plane-wave case, plane-wave solutions can be applied to small localized areas of curved mirrors. It was shown in [8] that, when localized individual plane wave contributions were added up, good results for the entire curved surface antenna were obtained.

For all noise temperatures and excess noise temperatures presented in this article, the operating frequency is 32 GHz, and paints, primers, and reflectors are at a physical temperature of 293.2 K (20 deg C).

B. Plots as Functions of Incidence Angles

Figures 1 and 2 show the noise temperature and gain loss, respectively, of a 6061-T6 flat mirror for perpendicular and parallel polarizations. The noise-temperature and gain-loss values for 6061-T6 aluminum are based on an electrical conductivity of 2.3×10^7 mhos/m [10]. From Fig. 1, it can be seen
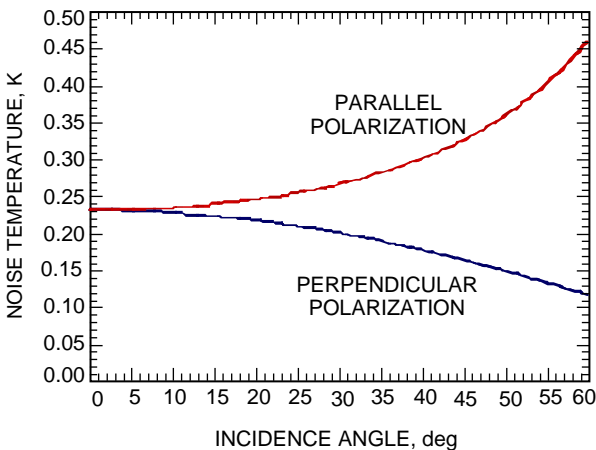

Fig. 1. The noise temperature of a flat 6061-T6 aluminum mirror at 32 GHz and 293.2 K (20 deg C) physical temperature.
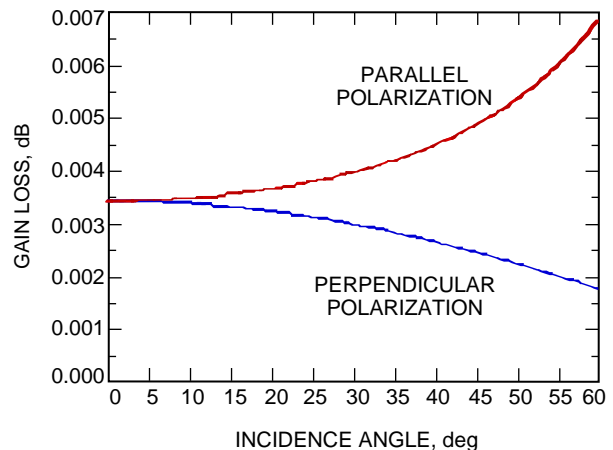
Fig. 2. The gain loss due to conductivity loss of a flat 6061-T6 aluminum mirror at 32 GHz.

that, at 0-deg incidence angle, the noise temperature of 6061-T6 aluminum is 0.23 K, and the gain loss is 0.0034 dB. At 60-deg incidence angle, the noise temperature for parallel polarization increases rapidly and is nearly 0.5 K, and added-gain loss is close to 0.007 dB. The noise temperatures of the 6061-T6 aluminum mirror at 32 GHz seem high, but the same high value at 0-deg incidence angle was obtained through the use of approximate formulas given in [10]. As may be seen from Eq. (7), if six mirrors are involved, these noise temperatures for bare-metal mirrors alone are increased by about a factor of six, which is surprisingly high.

Excess noise temperatures and added-gain losses as functions of incidence angles at 32 GHz are shown in the Figs. 3 through 10 for four specific thickness layers of paints and primers, as follows:

(1) Figures 3 and 4 apply to the configuration of 0.127-mm (5-mil)-thick Triangle no. 6 paint and 0.0152-mm (0.6-mil)-thick zinc chromate primer on a 6061-T6 aluminum flat mirror.

(2) Figures 5 and 6 apply to the configuration of 0.0508-mm (2-mil)-thick 500FHR6 acrylic urethane-based paint with no primer on a flat 6061-T6 aluminum mirror.

(3) Figures 7 and 8 apply to the configuration of 0.127-mm (5-mil)-thick 18FHR6 paint and 0.0152-mm (0.6-mil)-thick 283 water-based primer on a flat 6061-T6 aluminum mirror.

(4) Figures 9 and 10 apply to the configuration of 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.

Note that in Figs. 3 through 10 for parallel polarization, excess noise temperatures and added-gain losses increase rapidly with increasing incidence angles after 30 deg, while, for perpendicular polarization, the values decrease with increasing incidence angles.

Triangle no. 6 paint, 500FHR6 paint, 18FHR6 paint, and 283 primer are manufactured by Triangle Coatings, Inc., located in San Leandro, California. All of these named paints are thermal-diffusive white paints specially invented for the purpose of diffusing the heat generated when sunlight radiates on the metallic reflector surfaces. It is known that Triangle no. 6 paint's main ingredient is titanium dioxide, but the main ingredients of the other paints and primers manufactured by Triangle Coatings are not known to the authors. It is only known that 500FHR6 paint has an acrylic urethane base, while the 18FHR6 paint and 283 primer are water based.
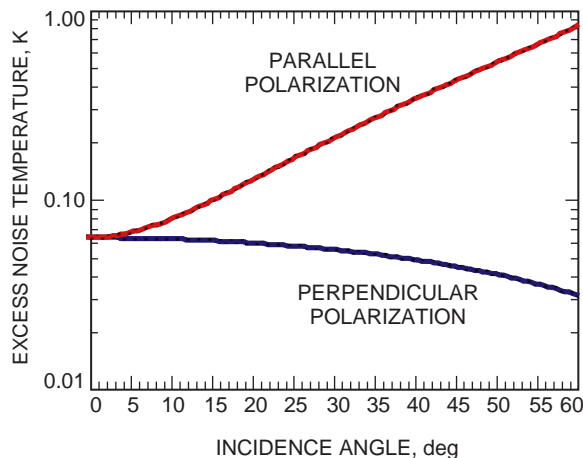

Fig. 3. The excess noise-temperature contribution at 32 GHz due to 0.127-mm (5-mil)-thick Triangle no. 6 paint and 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.
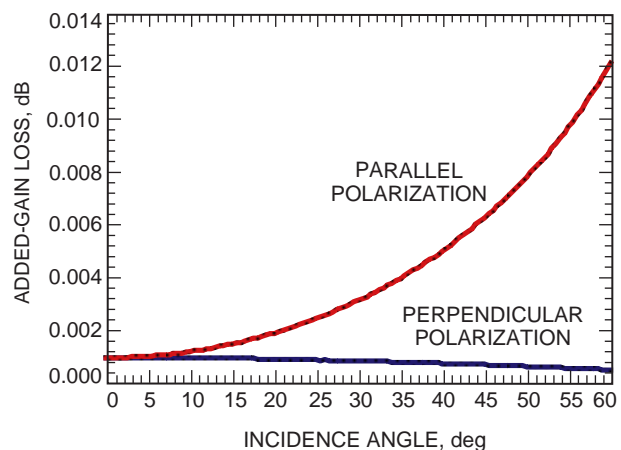
Fig. 4. The added-gain loss at 32 GHz due to 0.127-mm (5-mil)-thick Triangle no. 6 paint and 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.
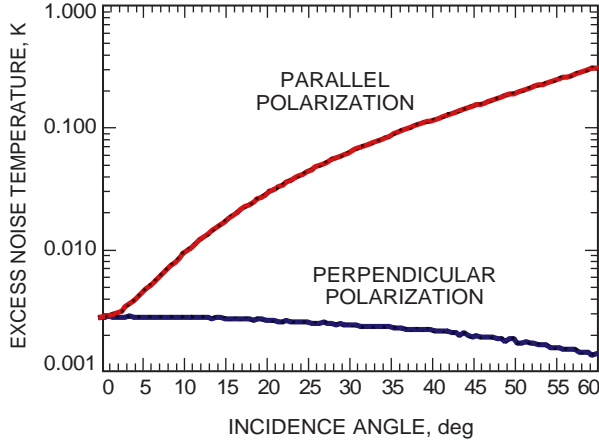
Fig. 5. The excess noise temperature at 32 GHz due to 0.0508-mm (2-mil)-thick 500FHR6 paint and no primer on a flat 6061-T6 aluminum mirror.
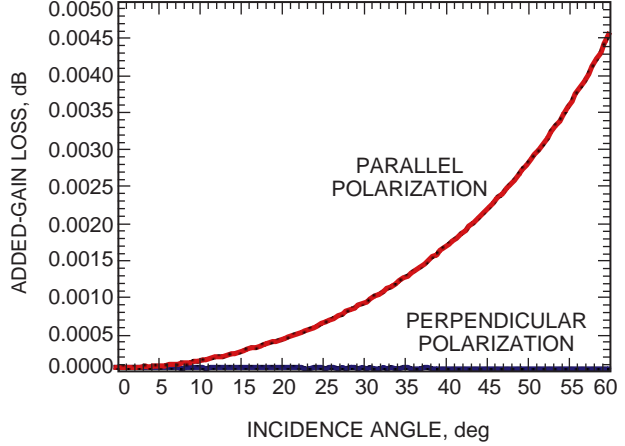

Fig. 6. The added-gain loss at 32 GHz due to 0.0508-mm (2.0-mil)-thick 500FHR6 paint and no primer on a flat 6061-T6 aluminum mirror.
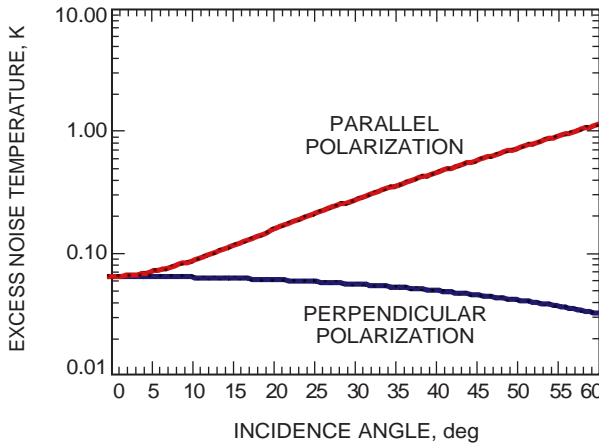

Fig. 7. The excess noise-temperature contribution at 32 GHz due to 0.127-mm (5-mil)-thick 18FHR6 paint and 0.0152-mm (0.6-mil)-thick 238 primer on a flat 6061-T6 aluminum mirror.
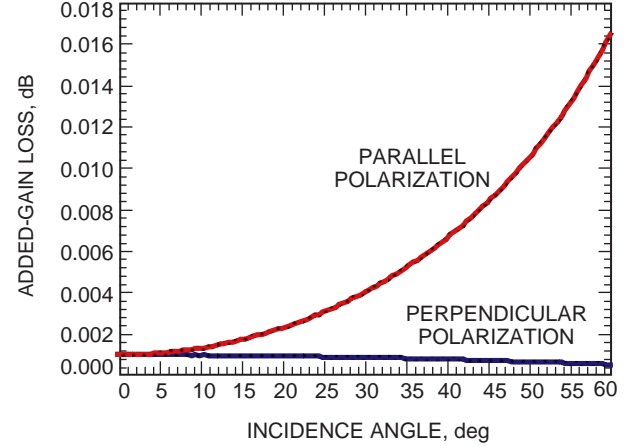
Fig. 8. The added-gain loss at 32 GHz due to 0.127-mm (5.0-mil)-thick 18FHR6 paint and 0.0152-mm (0.6-mil)-thick 283 primer on a flat 6061-T6 aluminum mirror.

The paint and primer thicknesses given above are based on thickness values in units of mils in the DSN paint specifications document.[3,4] It is easy to confuse metric units of mm (0.001 m) for English units of mils (0.001 inch). The formula for conversion from thickness t in mils to thickness t in mm is

$$t_{\mathrm{mm}} = 0.0254 \times t_{\mathrm{mil}}$$

In order to avoid confusion, the plots and tables will show both metric and English units for paint-layer thicknesses.

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[3] T. C. Sink, *Painting or Thermal-Coating DSN Antenna and Structures Standard Procedure*, DSN-STD-1006, Rev. G (internal document), Jet Propulsion Laboratory, Pasadena, California, February 15, 1996. Appendix C specifies zinc chromate primer and Triangle no. 6 paint thicknesses and procedures for thermal coating aluminum for RF reflective surfaces.

[4] T. C. Sink, *Painting or Thermal-Coating DSN Antenna and Structures Standard Procedure*, DSN-STD-1006, Rev. H (internal document), Jet Propulsion Laboratory, Pasadena, California, September 17, 1999. Appendix C specifies 500FHR6 and no primer for thermal coating of aluminum RF reflective surfaces. Although a thickness of 0.0305 mm (1.2 mils) was specified, it was requested by Cognizant Engineer T. Sink that a thickness of 0.0508 mm (2 mils) be investigated instead.
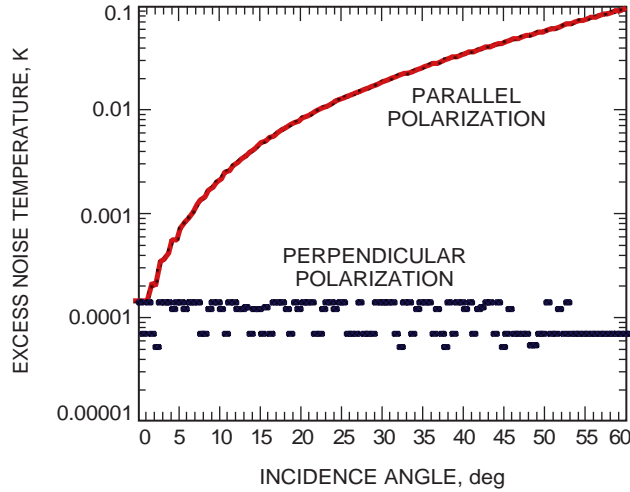
Fig. 9. The excess noise-temperature contribution at 32 GHz due to 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.
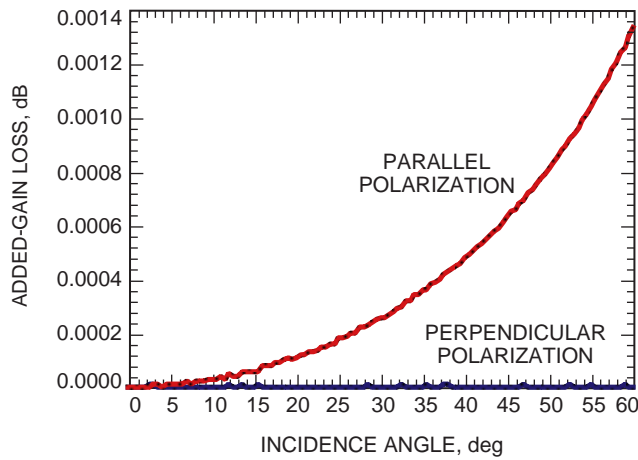

Fig. 10. The added-gain loss at 32 GHz due to 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.

C. Plots as Functions of Paint and Primer Thickness

An alternate and perhaps better way of showing excess noise temperatures is to show excess noise temperatures as functions of paint- and primer-layer thicknesses at selected incidence angles. The selected incidence angles for this article are 0, 15, 30, 45, and 60 deg. For these plots, the excess noise temperatures will be shown for perpendicular, circular, and parallel polarizations.

Figures 11 through 15 are excess noise temperature plots presented as functions of thickness t at these incidence angles for Triangle no. 6 with a fixed zinc chromate primer-layer thickness of 0.0152 mm (0.6 mil). Note that when thickness t goes to zero, the noise temperature does not go to zero. The reason is that the residual noise temperature is due to the primer layer, which is not a function of thickness t.
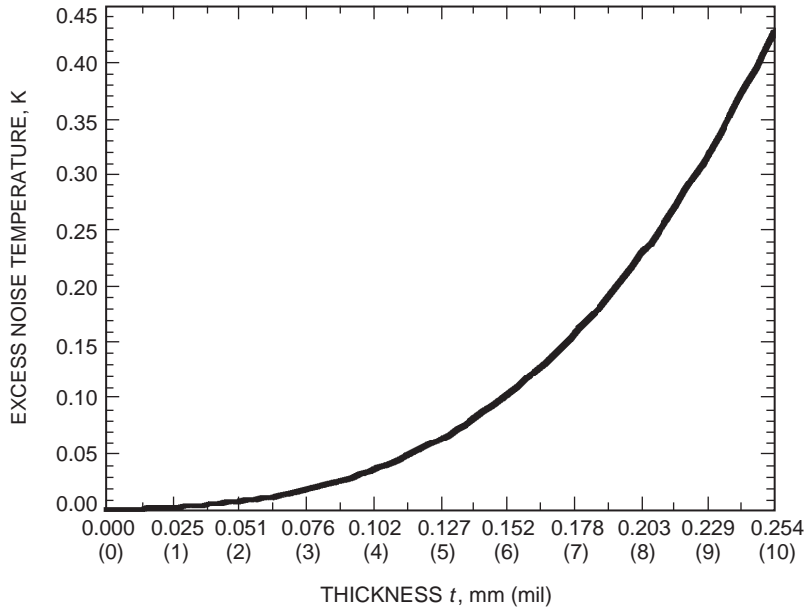
Fig. 11. The total excess noise temperature due to a Triangle no. 6 paint layer of thickness *t* and a fixed zinc chromate primer-layer thickness of 0.0152 mm (0.6 mil) at 0-deg incidence angle and 32 GHz. The single curve applies to parallel, circular, and perpendicular polarizations.
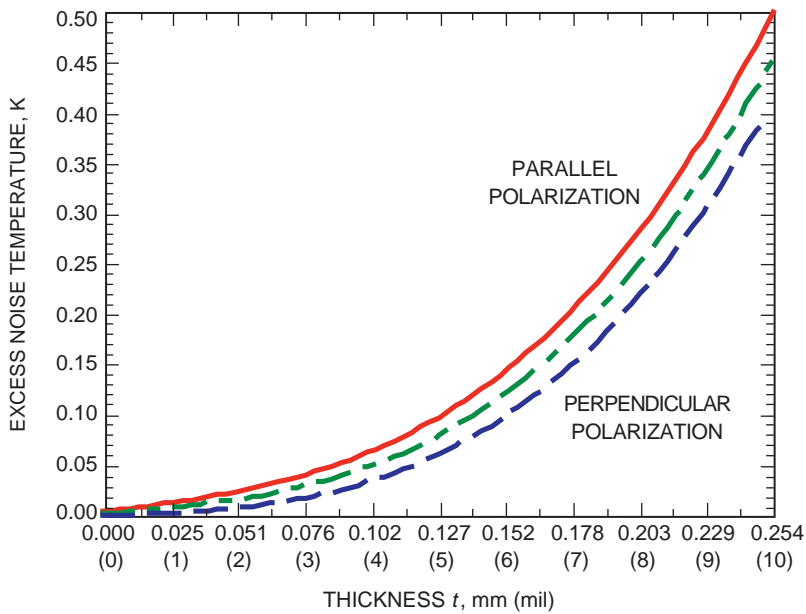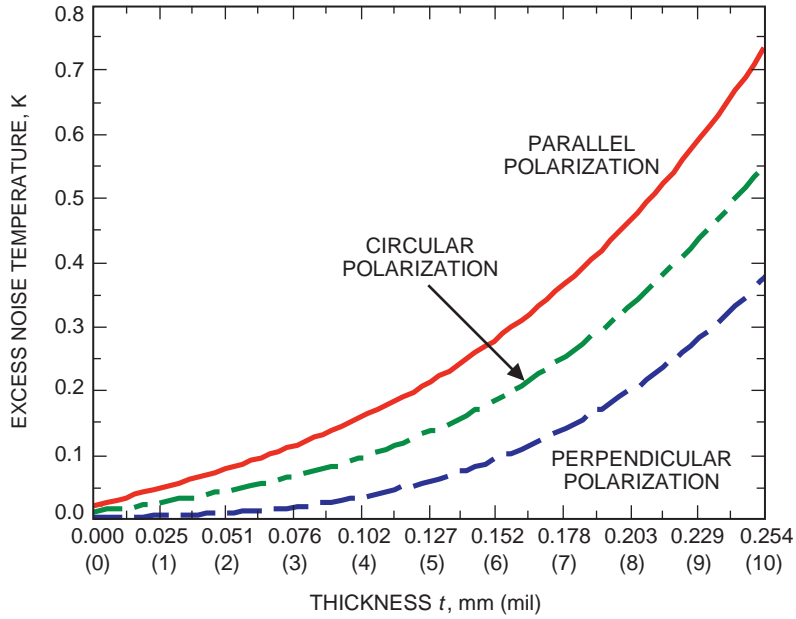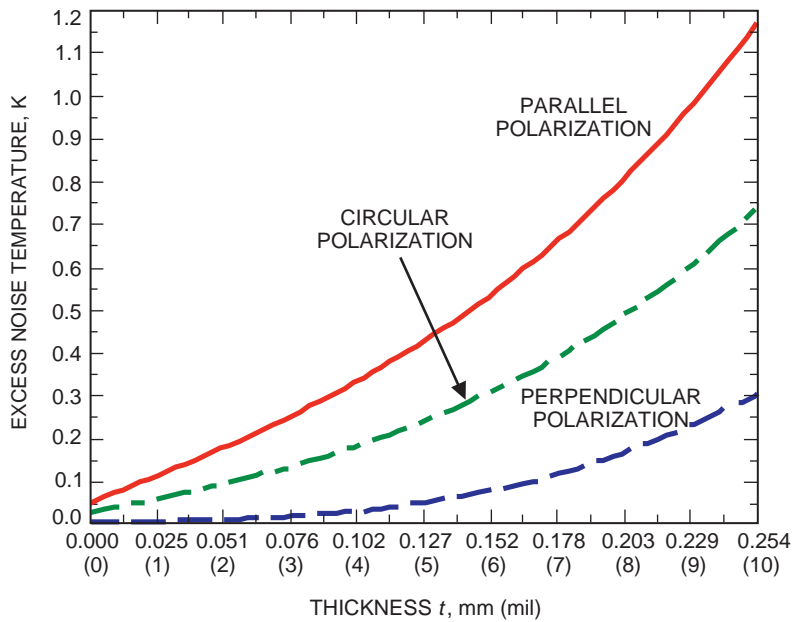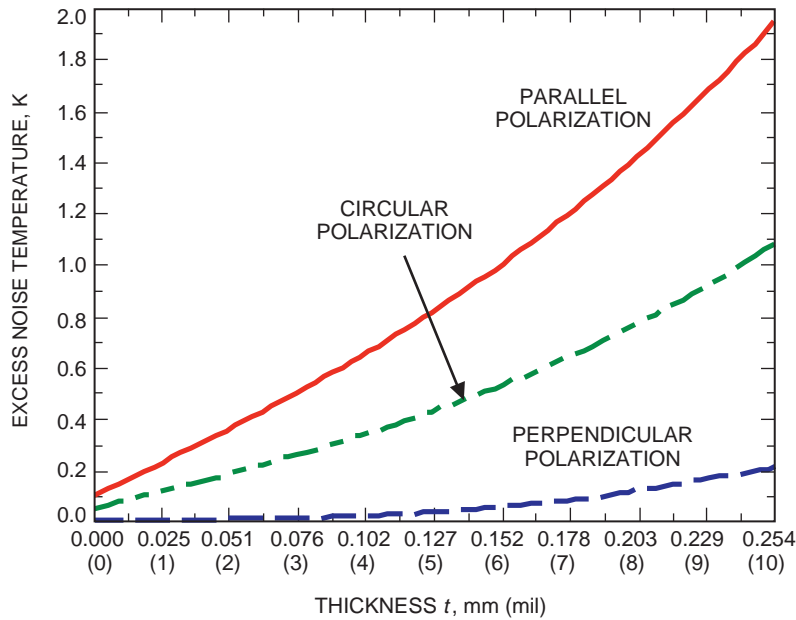

Fig. 12. The total excess noise temperature due to a Triangle no. 6 paint layer of thickness *t* and a fixed zinc chromate primer-layer thickness of 0.0152 mm (0.6 mil) at 15-deg incidence angle and 32 GHz. The middle curve is the average of parallel and per-pendicular polarization excess noise temperatures and applies to circular polarization.

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Fig. 13.   The total excess noise temperature due to a Triangle no. 6 paint layer of thickness *t* and a fixed zinc chromate primer-layer thickness of 0.0152 mm (0.6 mil) at 30-deg incidence angle and 32 GHz.

Fig. 14.   The total excess noise temperature due to a Triangle no. 6 paint layer of thickness *t* and a fixed zinc chromate primer-layer thickness of 0.0152 mm (0.6 mil) at 45-deg incidence angle and 32 GHz.

Fig. 15. The total excess noise temperature due to a Triangle no. 6 paint layer of thickness *t* and a fixed zinc chromate primer-layer thickness of 0.0152 mm (0.6 mil) at 60-deg incidence angle and 32 GHz.

Figures 16 through 20 are plots for 500FHR6 paint with no primer; Figs. 21 through 25 are plots for a 18FHR6 paint layer and a fixed 283 primer-layer thickness of 0.0152 mm (0.6 mil); and Figs. 26 through 30 are plots for zinc chromate primer only. Note the steep rise of the parallel polarization curve and high noise temperatures (about 2 K) for all cases of 0.254-mm (10-mil) thickness at 60-deg incidence angle.

For quick comparison purposes, the excess noise temperatures are given in Table 2 for these paints (with fixed primer layers) for selected thicknesses of 0.0508 mm (2 mil), 0.127 mm (5 mil), 0.1778 mm (7 mil), and 0.254 mm (10 mil). Although not shown in the plots, Table 2 also gives the results for a very thick 0.381-mm (15-mil) layer for all paints and zinc chromate primer. Note that at this 0.381-mm thickness the excess noise temperatures for Triangle no. 6 paint cases are 1.5 K or greater at all incidence angles. This is important to show because, on some of the 70-m antenna reflector surfaces, repainting several times over 35 years may have built up paint layers to be much thicker than the DSN paint-thickness specifications without knowledge of the detrimental effects that excessive paint thickness have on noise temperature.

In Table 2, it can be seen that the 0.127-mm (5-mil) thickness for Triangle no. 6 paint and its primer layer thickness produce an excess noise temperature of 0.13 K at 30-deg incidence angle as compared with 0.03 K for 0.0508-mm (2-mil) 500FHR6 paint. These are of interest because they are the paint and primer thicknesses specified in the DSN paint specification documents.[5,6] Most of the higher noise temperature for the Triangle no. 6 paint configuration is due to the difference of a larger paint thickness and the existence of a primer layer. Note that the 18FHR6-paint with 283-primer-layer results are very similar to those for Triangle no. 6 paint with a zinc chromate primer layer. The excess noise temperatures of 500FHR6 paint with no primer are similar to the results produced by zinc chromate primer alone.

[5] T. C. Sink, Rev. G, op. cit.

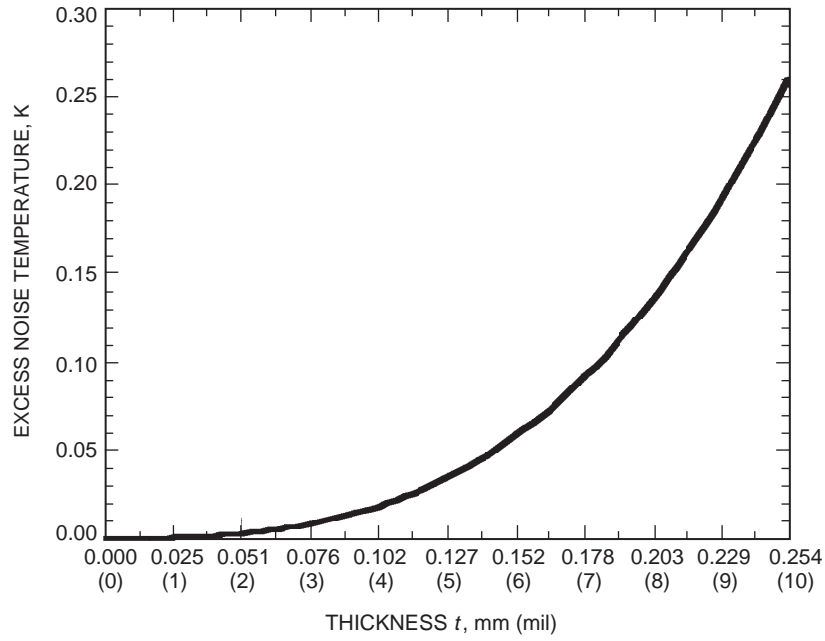[6] T. C. Sink, Rev. H, op. cit.

Fig. 16. The total excess noise temperature due to a 500FHR6 paint layer of thickness t and no primer layer at 0-deg incidence angle and 32 GHz. The single curve applies to parallel, circular, and perpendicular polarizations.
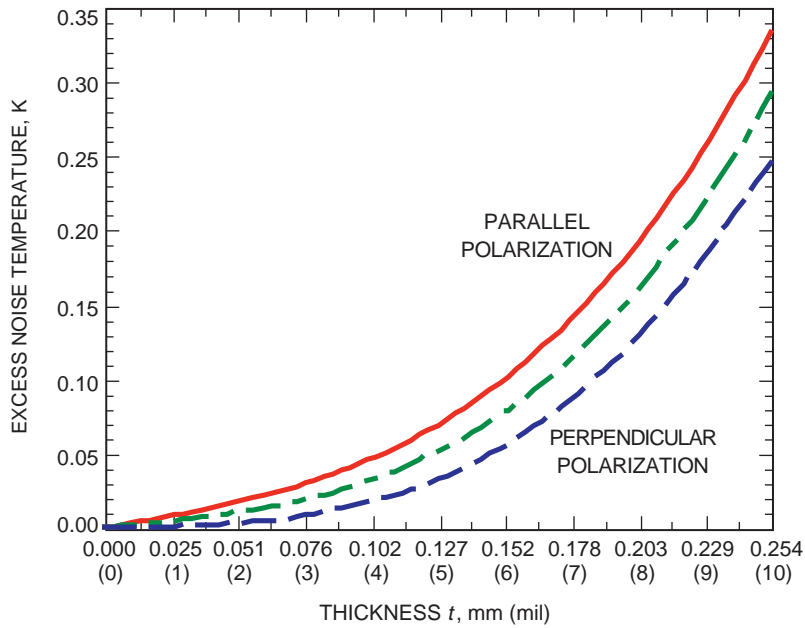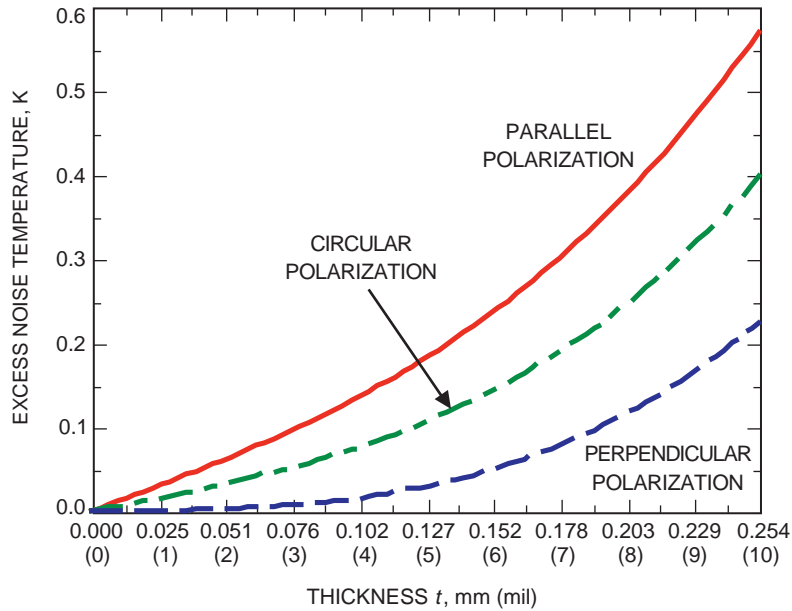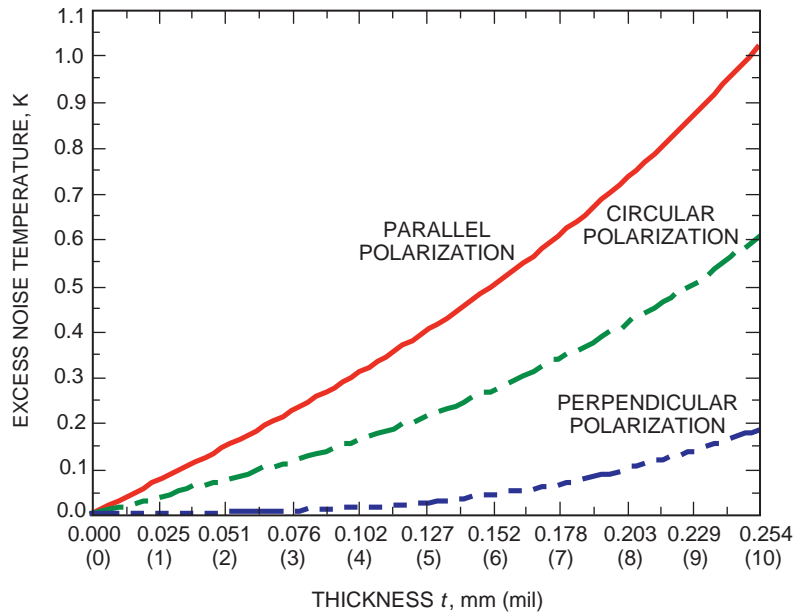

Fig. 17. The total excess noise temperature due to a 500FHR6 paint layer of thickness t and no primer layer at 15-deg incidence angle and 32 GHz. The middle curve is the average of parallel and perpendicular polarization excess noise temperatures and applies to circular polarization.

Fig. 18. The total excess noise temperature due to a 500FHR6 paint layer of thickness *t* and no primer layer at 30-deg incidence angle and 32 GHz.

Fig. 19. The total excess noise temperature due to a 500FHR6 paint layer of thickness *t* and no primer layer at 45-deg incidence angle and 32 GHz.

It was shown in Eq. (7) that excess noise temperature is additive for low-loss reflectors. Therefore, if there are six reflectors involved, such as the six BWG mirrors at DSS 13, each with only a zinc chromate primer layer, the total excess noise temperature will be about six times higher than the value for the single zinc chromate primer-painted mirror shown in Table 2. This kind of result was not known prior to this paint study.
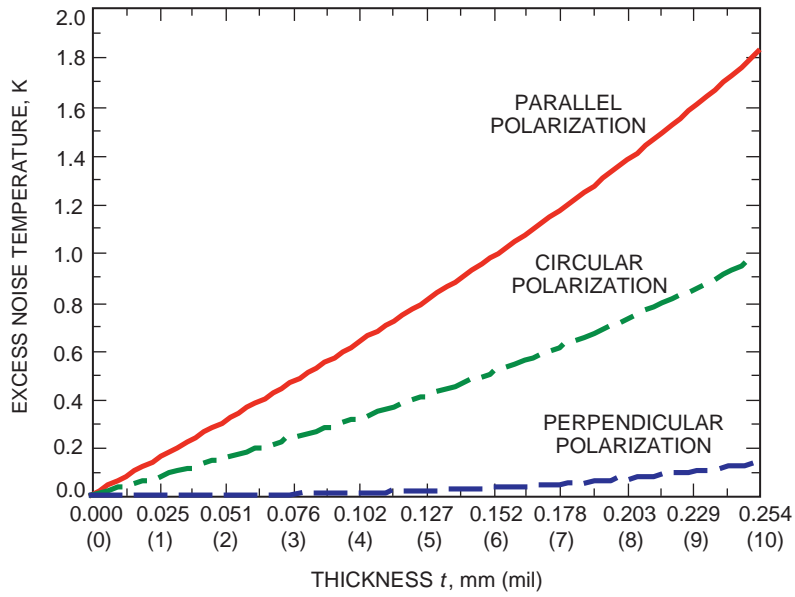
Fig. 20. The total excess noise temperature due to a 500FHR6 paint layer of thickness *t* and no primer layer at 60-deg incidence angle and 32 GHz.
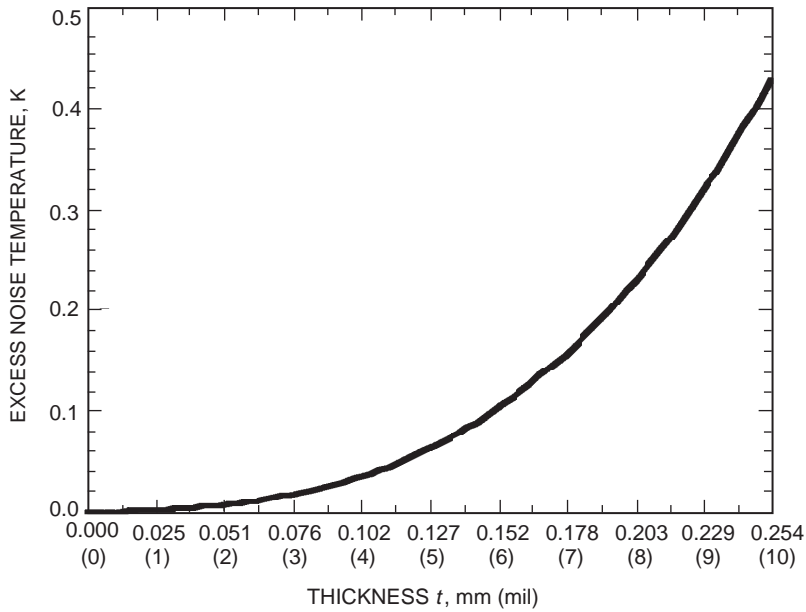

Fig. 21. The total excess noise temperature due to a 18FHR6 paint layer of thickness *t* and a fixed 283 primer-layer thickness of 0.0152 mm (0.6 mil) at 0-deg incidence angle and 32 GHz. The single curve applies to parallel, circular, and perpendicular polarizations.
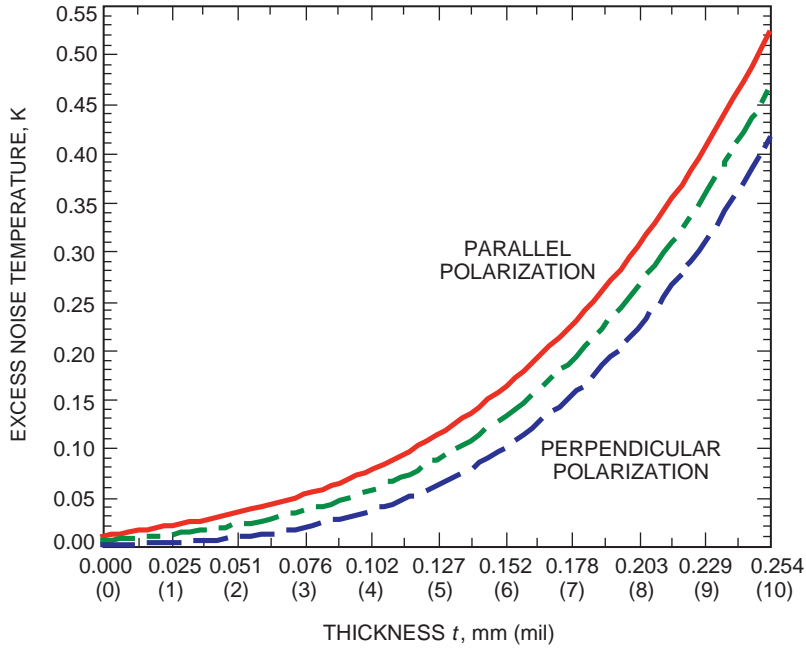
Fig. 22. The total excess noise temperature due to a 18FHR6 paint layer of thickness *t* and a fixed 283 primer-layer thickness of 0.0152 mm (0.6 mil) at 15-deg incidence angle and 32 GHz. The middle curve is the average of parallel and perpendicular polarization excess noise temperatures and applies to circular polarization.
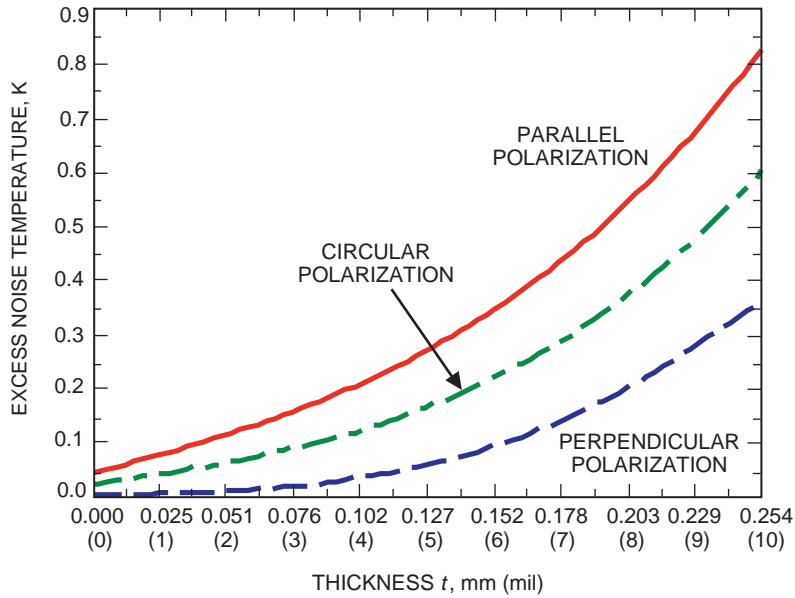

Fig. 23. The total excess noise temperature due to a 18FHR6 paint layer of thickness *t* and a fixed 283 primer-layer thickness of 0.0152 (0.6 mil) at 30-deg incidence angle and 32 GHz.
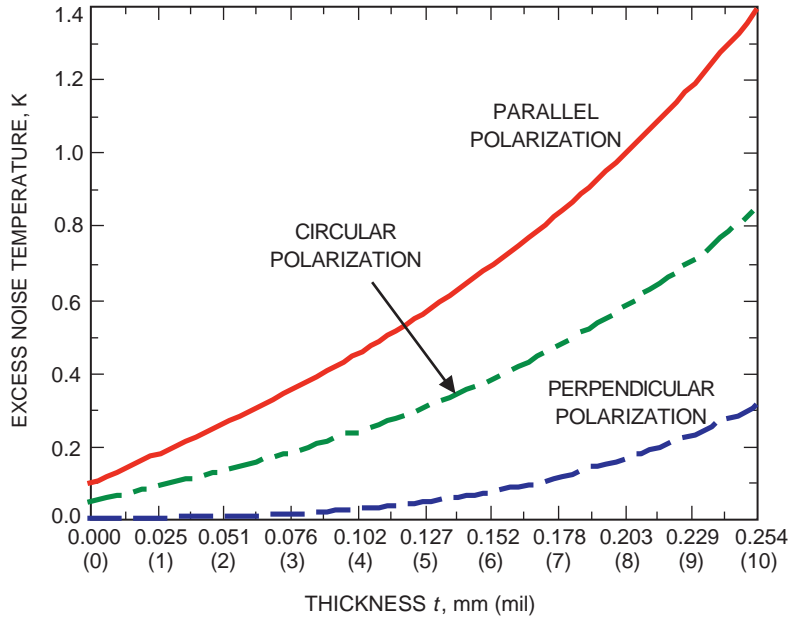
Fig. 24.   The total excess noise temperature due to a 18FHR6 paint layer of thickness *t* and a fixed 283 primer-layer thickness of 0.0152 mm (0.6 mil) at 45-deg incidence angle and 32 GHz.
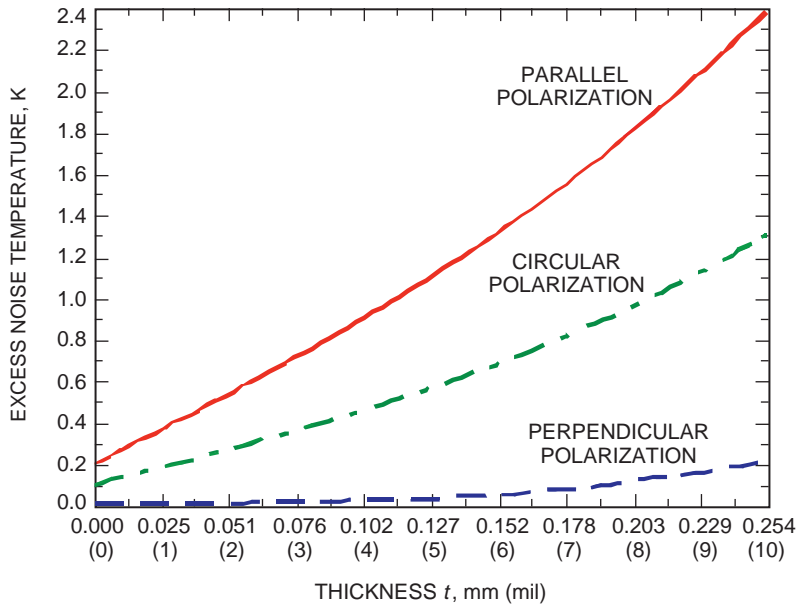

Fig. 25.   The total excess noise temperature due to a 18FHR6 paint layer of thickness *t* and a fixed 283 primer-layer thickness of 0.0152 mm (0.6 mil) at 60-deg incidence angle and 32 GHz.
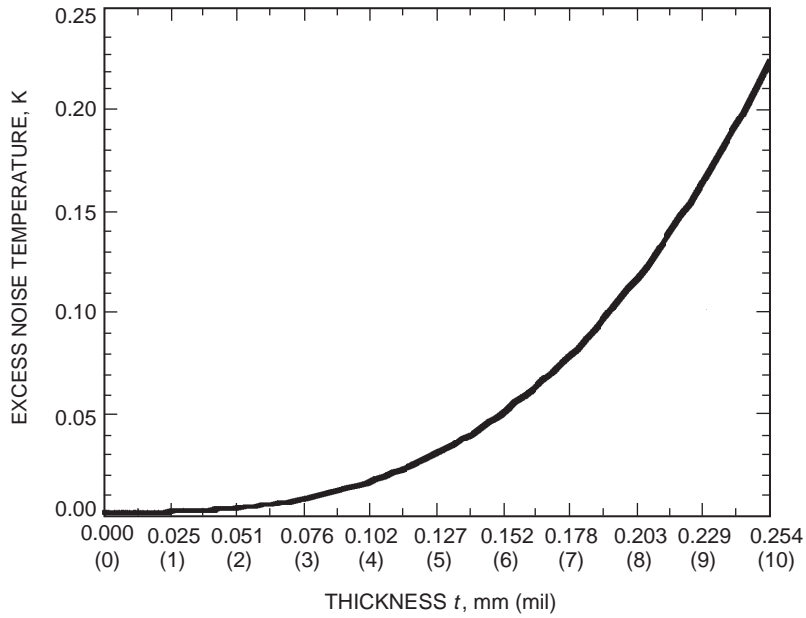
Fig. 26. The excess noise temperature due to a zinc chromate primer layer of thickness _t_ at 0-deg incidence angle and 32 GHz. The single curve applies to parallel, circular, and perpendicular polarizations.
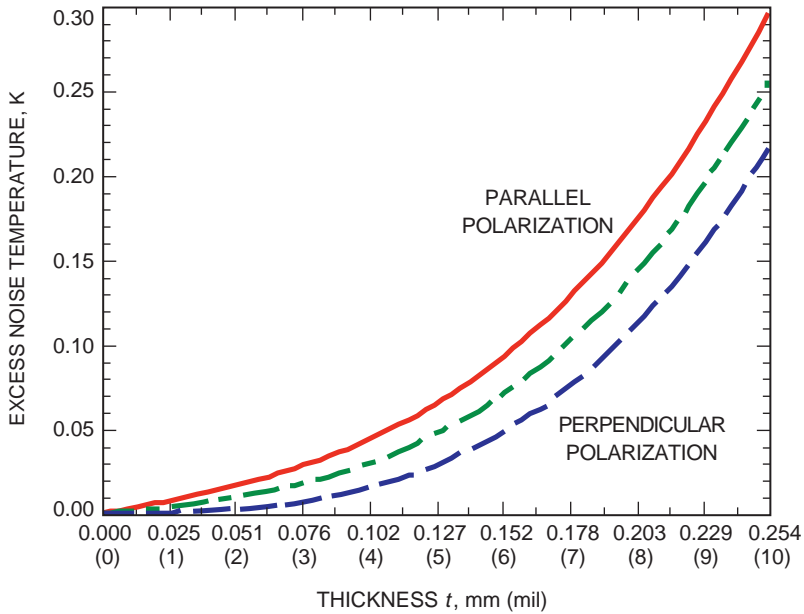

Fig. 27. The excess noise temperature due to a zinc chromate primer layer of thickness _t_ at 15-deg incidence angle and 32 GHz. The middle curve is the average of parallel and perpendicular polarization excess noise temperatures and applies to circular polarization.
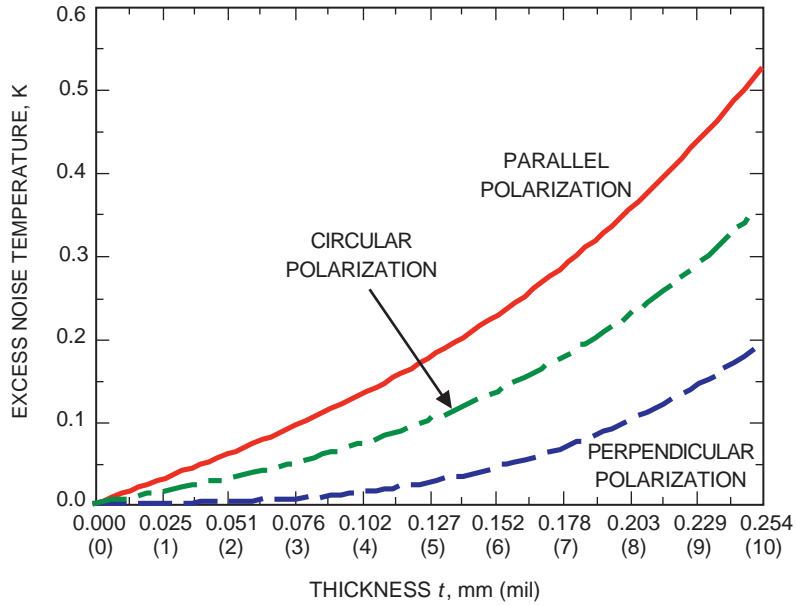
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Fig. 28. The excess noise temperature due to a zinc chromate primer layer of thickness *t* at 30-deg incidence angle and 32 GHz.
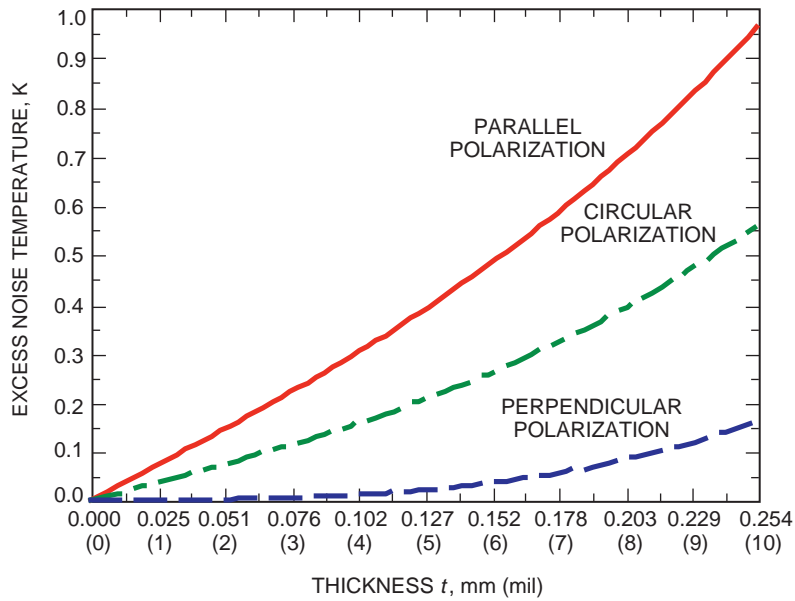

Fig. 29. The excess noise temperature due to a zinc chromate paint layer of thickness *t* at 45-deg incidence angle and 32 GHz.
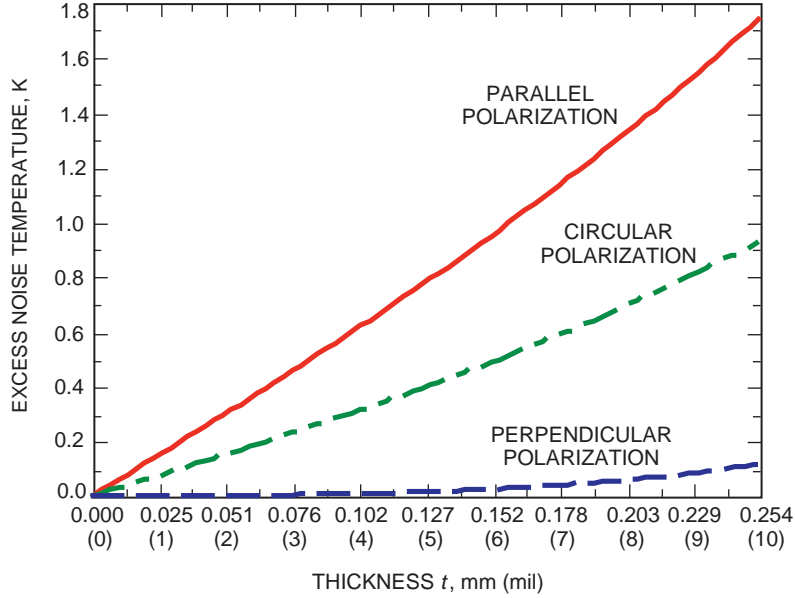
Fig. 30. The excess noise temperature due to a zinc chromate primer layer of thickness *t* at 60-deg incidence angle and 32 GHz.

D. Phase Plots

Depolarization due to paint on a reflector is a topic that often has been overlooked. A literature search revealed two articles [11,12] that discuss this topic. A complete study of depolarization is beyond the scope of this paint study, but some plots will be included in this article to show that future studies of depolarization effects need to be done.

For each set of curves in the following figures, the solid curves going upward from the 0-deg incidence-angle values are for parallel polarization, and the dashed curves going downward are for perpendicular polarization. Delta phase is equal to 180 deg minus the reflection coefficient phase. A flat reflector surface having no dissipative losses will have a delta phase value equal to zero. Comparisons of delta phase with and without paint and/or primer are given in these figures for nominal and worst-case paint- and primer-layer thicknesses on a flat 6061-T6 aluminum mirror. Only the values for perpendicular and parallel polarizations are shown. The results are grouped in four main paint–primer configurations as follows:

(1) Figures 31 and 32 are delta phase plots for 0.127-mm (5-mil)- and 0.254-mm (10-mil)-thick Triangle no. 6 paint, respectively, on a 0.0152-mm (0.6-mil) layer of zinc chromate primer.

(2) Figures 33 and 34 are delta phase plots for 0.0508-mm (2-mil)- and 0.254-mm (10-mil)-thick 500FHR6 acrylic urethane-based paint, respectively, with no primer.

(3) Figures 35 and 36 are delta phase plots for a 0.127-mm (5-mil)- and 0.254-mm (10-mil)-thick 18FHR6 paint layer, respectively, on a 0.0152-mm (0.6-mil) layer of 283 water-based primer.

(4) Figures 37 and 38 are delta phase plots for 0.0152-mm (0.6-mil)- and 0.254-mm (10-mil)-thick zinc chromate primer, respectively.

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Table 2. Comparison of excess ENTs for circular polarization at 32 GHz for four different configurations of paint and primer layers at selected thicknesses and incidence angles.

Thickness t, mm	Thickness t, mil	Triangle no. 6 configuration[a] ENT, K	500FHR6 configuration[b] ENT, K	18FHR6 configuration[c] ENT, K	Zinc chromate configuration[d] ENT, K
		0-deg incidence angle			
0.0508	2	0.008	0.003	0.007	0.002
0.1270	5	0.063	0.034	0.063	0.029
0.1778	7	0.154	0.089	0.154	0.077
0.2540	10	0.426	0.259	0.426	0.221
0.3810	15	1.523	0.932	1.498	0.786
		15-deg incidence angle			
0.0508	2	0.015	0.010	0.019	0.009
0.1270	5	0.079	0.051	0.086	0.046
0.1778	7	0.176	0.113	0.185	0.100
0.2540	10	0.455	0.292	0.466	0.254
0.3810	15	1.557	0.976	1.548	0.830
		30-deg incidence angle			
0.0508	2	0.040	0.032	0.058	0.031
0.1270	5	0.131	0.105	0.160	0.100
0.1778	7	0.245	0.188	0.281	0.175
0.2540	10	0.548	0.397	0.594	0.358
0.3810	15	1.670	1.118	1.708	0.972
		45-deg incidence angle			
0.0508	2	0.088	0.074	0.131	0.073
0.1270	5	0.231	0.210	0.301	0.203
0.1778	7	0.380	0.333	0.467	0.318
0.2540	10	0.731	0.599	0.842	0.557
0.3810	15	1.899	1.392	2.023	1.244
		60-deg incidence angle			
0.0508	2	0.178	0.153	0.270	0.151
0.1270	5	0.420	0.405	0.566	0.396
0.1778	7	0.633	0.603	0.814	0.584
0.2540	10	1.072	0.971	1.299	0.923
0.3810	15	2.308	1.876	2.579	1.723

[a] Triangle no. 6 paint and a 0.0152-mm (0.6-mil)-thick layer of zinc chromate primer.

[b] 500FHR6 paint only.

[c] 18FHR6 paint and a 0.0152-mm (0.6-mil)-thick layer of 283 primer.
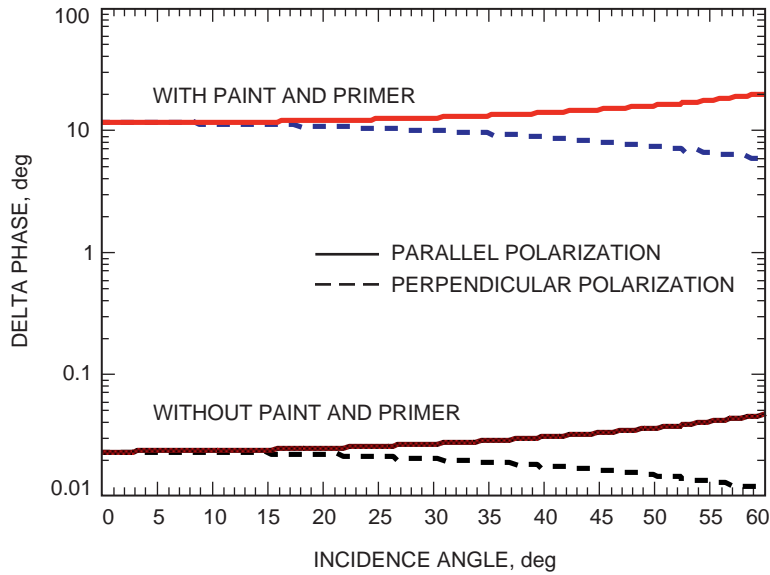
[d] Zinc chromate primer only.

Fig. 31. A comparison of delta phase with and without 0.127-mm (5-mil)-thick Triangle no. 6 paint and 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.
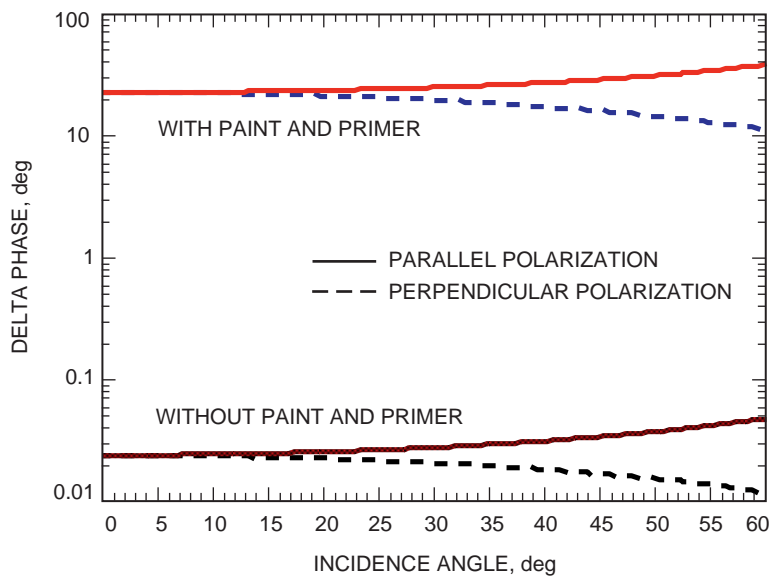

Fig. 32. A comparison of delta phase with and without 0.254-mm (10-mil)-thick Triangle no. 6 paint and 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.

For all cases, the delta phase increases with increasing incidence angle for parallel polarization and decreases with increasing incidence angles for perpendicular polarization. Figure 31 shows that, for the 0.127-mm (5-mil)-thick Triangle no. 6 paint configuration of (1) above, the delta phase at 0-deg incidence angle is about 10 deg. Figure 33 shows that, for the 0.0508-mm (2-mil) 500FHR6 paint-thickness configuration, the delta phase at 0-deg incidence angle is about 4 deg. Similar observations and comparisons can be made for the 18FHR6 paint configuration of (3) above. For the thin zinc chromate primer layer of 0.0152-mm (0.6-mil) thickness, the delta phase at 0-deg incidence angle is only about 1 deg. When any of the paint and primer has a thickness of 0.254 mm (10 mil), the delta phase is about 20 deg.

It is not clear whether delta phase values of 4 to 10 deg or even 20 deg are detrimental to antenna performance, but these delta phase values might be equivalent to phase errors on main reflector or subreflector patterns. This is a subject area that needs to be investigated in future paint studies.
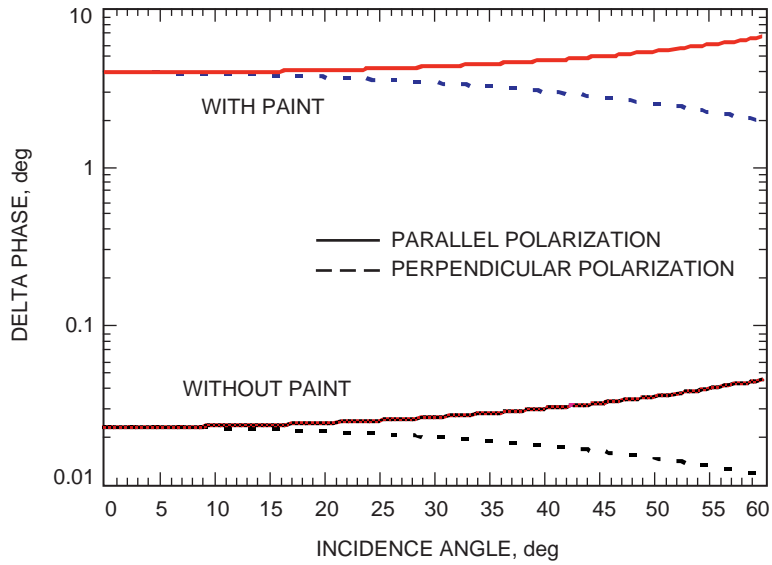

Fig. 33. A comparison of delta phase with and without 0.0508-mm (2-mil)-thick 500FHR6 acrylic urethane-based paint on a flat 6061-T6 aluminum mirror.
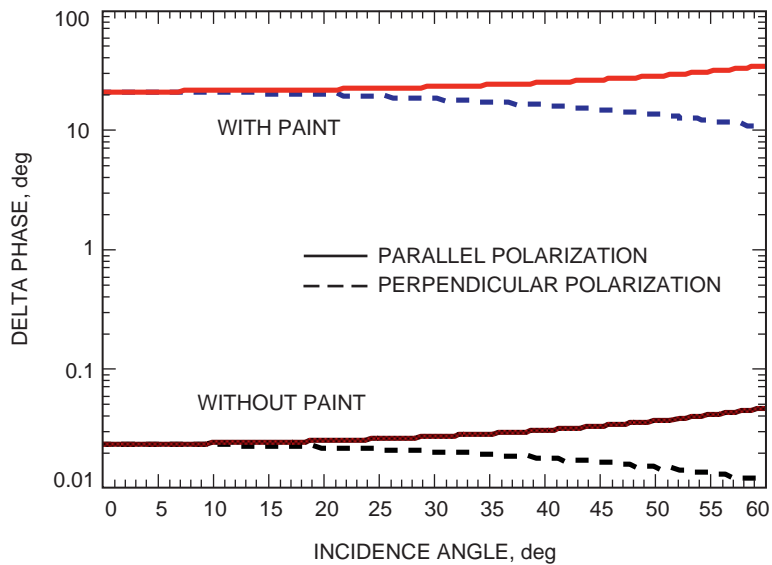

Fig. 34. A comparison of delta phase with and without 0.254-mm (10-mil)-thick 500FHR6 paint with no primer on a flat 6061-T6 aluminum mirror.
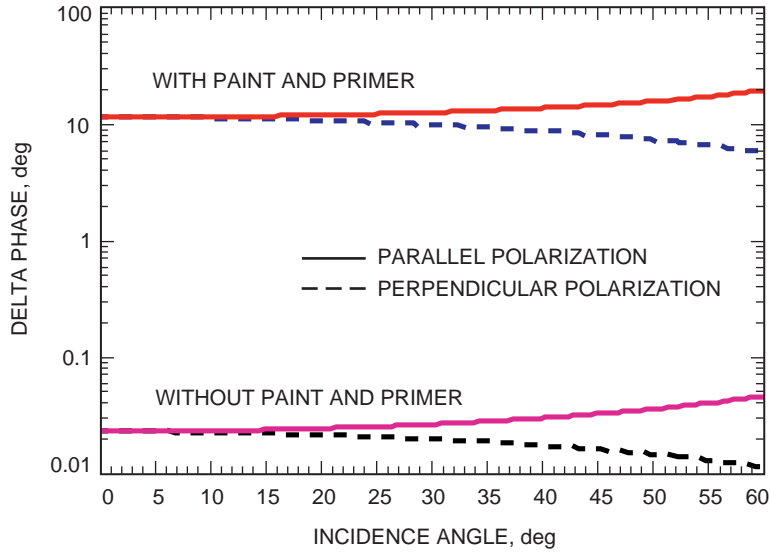
Fig. 35. A comparison of delta phase with and without 0.127-mm (5-mil)-thick 18FHR6 water-based paint and 0.0152-mm (0.6-mil)-thick 283 water-based primer on a flat 6061-T6 aluminum mirror.
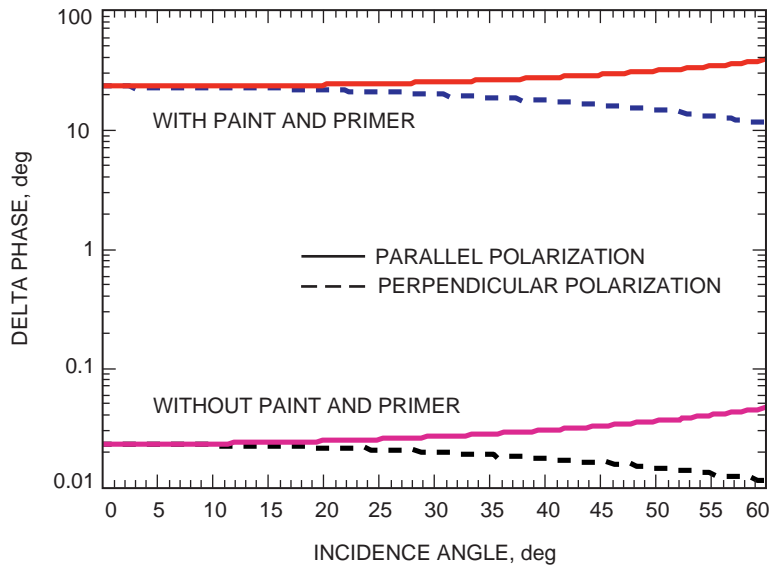

Fig. 36. A comparison of delta phase with and without 0.254-mm (10-mil)-thick 18FHR6 water-based paint and 0.0152-mm (0.6-mil)-thick 283 water-based primer on a flat 6061-T6 aluminum mirror.

V. Recommendations and Conclusion

A suggested criterion for maximum allowable excess noise temperature due to paint and primer is 0.2 K at 32 GHz and 30-deg incidence angle for circular polarization. This criterion is selected on the basis that this excess noise temperature is a practical achievable value that does not cause significant degradation of antenna performance at 32 GHz.
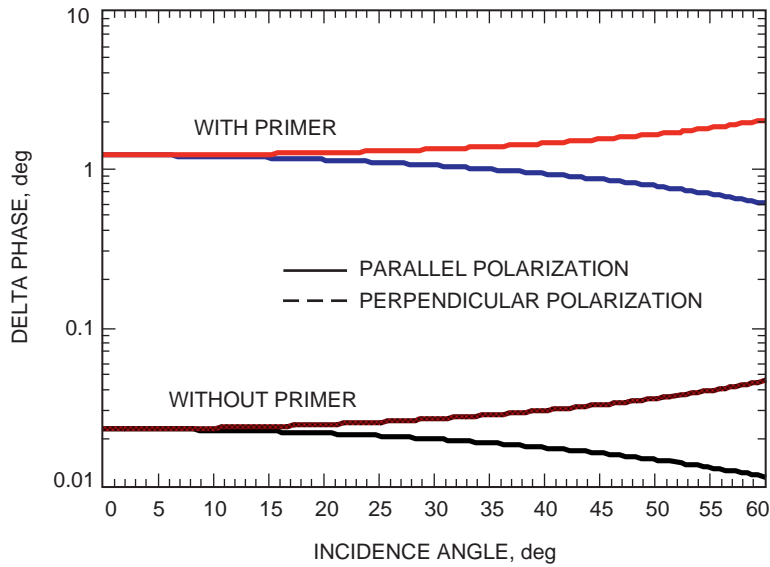
Fig. 37. A comparison of delta phase with and without 0.0152-mm (0.6-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.
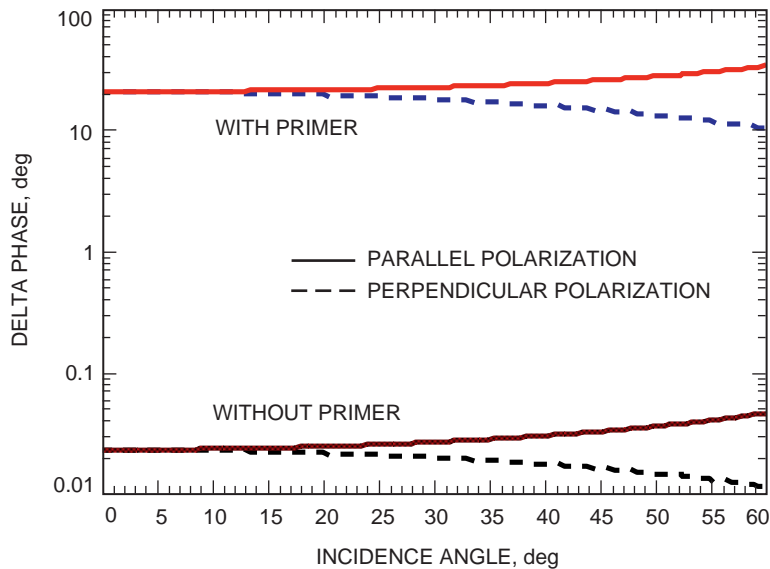

Fig. 38. A comparison of delta phase with and without 0.254-mm (10-mil)-thick zinc chromate primer on a flat 6061-T6 aluminum mirror.

The value of DSN antennas is represented by their figures of merit [13], which are equal to G/T, where G is the receive system antenna gain and T is the receive system noise temperature. With these expensive DSN antenna systems operating at their current low system noise temperatures, the penalty is severe for any unnecessary increase of system noise temperature. DSN antennas operating at Goldstone at Ka-band (32 GHz) are expected in the future to have noise-temperature performances of about 50 K at 30-deg elevation angle (accounting for the effect of the atmosphere).[7] Therefore, if system noise temperature

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[7] C. T. Stelzried, personal communication, Jet Propulsion Laboratory, Pasadena, California, December 29, 1999.

is increased 1 K, the penalty to the DSN is to reduce the DSN antenna value by 2 percent per kelvin. Then, for the above suggested criterion, if paint and primer cause the system noise temperature to be increased a maximum of 0.2 K at 30-deg elevation angle, the penalty will be 0.4 percent. It should be pointed out that the actual total penalty will be slightly larger because, as was shown in this article, small but non-negligible losses due to paint and primer also cause a decrease of antenna gain. Therefore, every effort should be made to minimize paint and primer noise temperature and gain-loss contributions.

Based on the results presented in this article, a recommendation was made to use a 0.0509-mm (2-mil) or thinner layer of 500FHR6 paint with no primer on reflector surfaces for all new 34-m BWG antennas being built and for all existing 34-m and 70-m DSN antenna reflector surfaces that need repainting. This recommendation was incorporated into the updated DSN paint document.[8]

Paint on reflector surfaces can cause depolarization and associated degradations of antenna performance. Depolarization due to paint was not studied in this current study, but is an effect that should be investigated in the future.

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