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GBT Paint Thickness

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Introduction

The paint on the panels for the GBT is an electrostatically applied powder paint that has not been used on a high frequency reflective surface previously — at least to our knowledge. The paint traditionally used on our telescopes is a paint manufactured by the Triangle Paint Company and was selected for its infrared emitting properties to minimize panel heating with solar radiation. This paint uses titanium dioxide as a prime ingredient and the dielectric constant has been measured several times and is in the range 4–5.

The National Physical Laboratory in London measured the reflective properties of the new powder paint (1) and these measurements were followed by a set of measurements by James Lamb at 90 GHz (2). The measurements indicated that the reflectivity of the painted surface would be more than adequate for use up to 100 GHz. The specifications concerning both the thickness and the evenness of the paint layer at that time were such that, even with a high dielectric constant, phase shifts through the paint layer would have negligible effect. Now it appears that these specifications will be hard to meet and this note examines the effect of a thicker, more uneven layer of paint.

Reflection off a Painted Surface

When a radio wave is incident on a painted surface, a fraction of the wave is reflected directly off the front paint surface. For this fraction of the signal, the important surface accuracy is that of the paint, not that of the precisely formed surface panel beneath. In addition, the phase of the radiation that passes through the paint and is reflected by the metal panel will be changed according to the thickness of the paint and its dielectric constant. Again, a fraction of this wave will emerge from the surface of the paint, and so on.

A useful concept is the "apparent surface" — that is the surface (behind the metallic surface) from which the wave appears to be reflected. This was developed by James Lamb (3) and is also described by Battilana (4). Lamb and Battilana develop quite different equations for the apparent surface displacement, but Shillue has shown them to give identical results.

A key result here is that the sensitivity of the apparent surface displacement to surface irregularities is strongly dependent on paint thickness. Ideally, the paint layer should be thin and even. The repainting of antenna surfaces should be done with caution.

The variation in apparent surface displacement with paint thickness for different dielectric constants is shown in Figure 1. For convenience, the axes are specified in wavelengths. From this Figure, it is obvious that for paint layers of any dielectric constant (up to 10) that are thinner than 0.05 wavelengths, the effect of the paint is negligible.

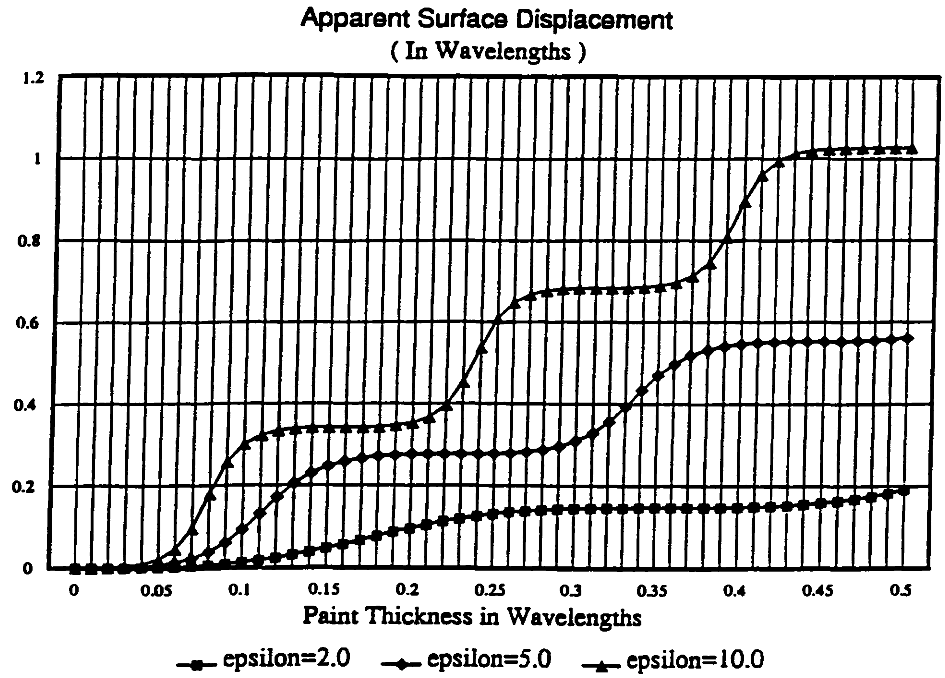

Figure 1.

Figure 2 is an expansion of Figure 1 for the thinner paint layers. If we assume the highest dielectric constant likely for the paint (10), we can make some statements about the desirable paint thickness and variation of thickness on the GBT—considering the performance at 100 GHz.

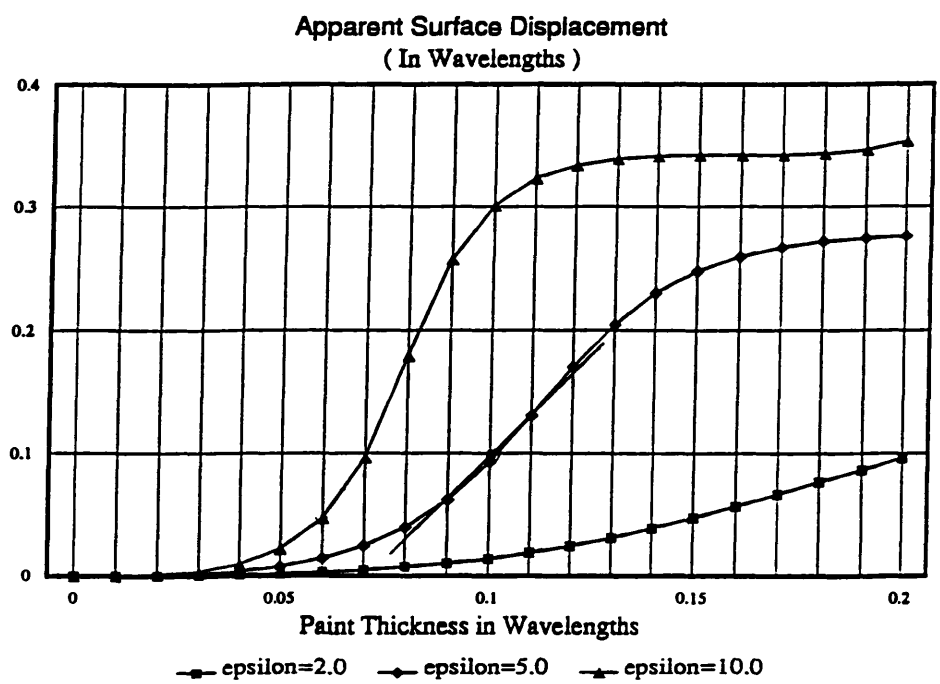

Figure 2.

The quoted RMS surface accuracy for the unpainted panels for the GBT is 75–88 microns. If we set the goal of requiring the application of the paint to limit the degradation of the equivalent panel accuracy at the highest frequency of operation to around 110 microns, we can arrive at some paint specifications. Conversations with Lee King suggest that a suitable mean paint thickness is 0.005", both from a durability standpoint and also ease of application. If we assume the highest reasonable dielectric constant of 10 (it would be prudent to confirm this), then we may use the curves in Figure 2 to arrive at the maximum permissible variation in thickness. Given the permitted degradation to 110 microns, we may assume a quadratic summation of the panel and paint errors. Assuming a ratio between peak to peak and RMS of 4, we use the curve for $\epsilon = 10$ in Figure 2 to arrive at the maximum paint thickness variation. A degradation to 110 microns from 80 microns gives a maximum paint contribution of 75 microns RMS, at $\lambda = 3$ mm a peak to peak variation of $\lambda/10$. From Figure 2, a paint thickness of 0.005" = 0.042 λ and a paint variation of +0.03λ and -0.04 λ (to bare metal) is permissible. We probably need a minimum of 0.003" for surface protection, so a reasonable specification would be:

Dielectric Constant = 10

Paint Thickness = 0.005", +0.0035", -0.002"

If a literature search (at present being conducted) or tests yield a lower dielectric constant, the paint specifications may be relaxed. For a dielectric constant of 5, for example, the value for the triangle paint, the following would be reasonable:

Dielectric Constant = 5

Paint Thickness = 0.005", +0.010", -0.002"

There has been a problem in the initial powder paint process of an excess build-up of paint at the panel edges. This should be kept to a minimum; in the case of $\epsilon = 10$, a maximum thickness of 0.01" in the outer 3 inches of the panel would be acceptable; for $\epsilon = 5$, a similar build-up of 0.015" would not present a problem. Of course, such regularly spaced "stripes" will contribute to sidelobes, but this effect will be masked by the panel gaps.

Acknowledgments

Discussions with James Lamb and Darrel Emerson were most helpful.

References

1. GBT Memo #74
2. GBT Memo #74
3. Memo to L. King, March 25, 1988
4. Battilana, Tony, "Ensure uniformity when specifying paint for reflectors," *Microwaves and RF*, March 1988

GBT Surface Coating Specification: Supplementary Information

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NRAO, Charlottesville, VA
March 29, 1996

Appendix A: Effect of Dielectric Layer Thickness

In the limit the conductor and dielectric losses are small, the apparent reflector surface position in wavelengths is given by [2, 3],

$$S/\lambda_o = \frac{1}{2\pi} \tan^{-1}\left(\frac{\tan\phi_{\epsilon r}}{\sqrt{\epsilon_r}}\right), \tag{1}$$

where $\phi_{\epsilon r}/2\pi = t\sqrt{\epsilon_r}/\lambda_o$ is the paint's electrical thickness in wavelengths (t is the paint's physical thickness, ϵ_r is the dielectric constant of the layer, and λ_o is the free-space wavelength). Taking the derivative with respect to the paint thickness, we find the sensitivity of the surface rms to variations in the dielectric thickness. The relative variance can be expressed as,

$$\sigma_S^2/\sigma_t^2 = \frac{1}{\left(\cos^2\phi_{\epsilon r} + \frac{1}{\epsilon_r}\sin^2\phi_{\epsilon r}\right)^2}, \tag{2}$$

where σ_S^2 is the variance in the apparent surface and σ_t^2 is the variance in the physical thickness (see Figure 1).

In order to limit these effects over a broad frequency range, we need the electrical thickness of the paint to be less than an eight wavelength in the material (*i.e.*, $\phi_{\epsilon r} < \pi/4$). Employing this criteria, we find the physical thickness of the paint should be chosen such that,

$$t < \lambda_o^{\min}/8\sqrt{\epsilon_r}, \tag{3}$$

where $\lambda_o^{\min}$ is the shortest observing wavelength. For the GBT reflector: $\epsilon_r \simeq 5$ and $\lambda_o^{\min} = 3000\,\mu$m (90 GHz). We find the paint's maximum thickness should be less than $200\,\mu$m (0.008 in). A minimum thickness of $80\,\mu$m (0.003 in) is desired for surface protection. We note in considering the paint's contribution ($\sigma_S \sim 1.5\sigma_{\epsilon r}$) to the GBT's total surface tolerance ("unpainted" $\sim 80\,\mu$m (0.003") rms) that this constraint can be slightly relaxed without adversely affecting the performance for reasonable values of σ_t.

In the above discussion, it has been implicitly assumed that the rays incident upon the paint are normal to the surface. The GBT reflector surface is curved and offset (the angle of incidence is in the range $3.8° < \theta_i < 76°$). Thus, the signal will also be depolarized by differences in the surface's perpendicular and parallel complex reflectivities. To minimize these effects, the paint thickness should be held to the *thinest* layer practical.

Appendix B: Characterization of the Dielectric Constant

The dielectric constant of samples of powder paint (Corvel 31-1004 TGIC Polyester, Color "Ultimate Antenna White") and Triangle No. 6 paint (Alkyd Enamel Color White, No. 27875) were measured. The samples consisted of $\sim 100\,\mu$m (0.004") of paint on an aluminum sheet with a zinc-chromate primer. The static dielectric constant was measured with a Hewlett Packard 4332A LCR meter by forming a capacitor from the material and taking the ratio of measured capacitance to a theoretical air-filled parallel plate structure with the same dimensions. Samples $\sim 2\,\mathrm{cm}^2$ were prepared as follows: the aluminum sheet was employed as one electrode of a capacitor and the other contact was formed with silver epoxy (EPO TEK-H20E, Epoxy Technology, Inc., Billerica, MA) for one set of trials and by burnishing an indium sheet to the surface for the second set of trials.

The dielectric constant at 24–41 GHz was obtained by the following method: A sample was cut to fit along the broadwall of a WR28 cavity 5.1 cm long. Next, the aluminum sheet was dissolved in HCl (5–10% solution) and the paint sample was cleaned and dried. By measuring the shift in the cavity's resonant frequencies as a function of sample volume, the dielectric constant was inferred at each resonance in the test band. Similarly, from the Q at each cavity resonance, the sample loss was investigated. (See, *e.g.*, Altman [1]. The data was taken with the HP8510C Network Analyzer. A magic-tee which was used to compare the signal from the cavity's coupling aperture to a sliding short. The resulting reflectometer offset was ~ 0.1 dB over the test band.) The measurement results are summarized in Table 1.

During the measurements, the following observations were made: 1) The powder paint displayed a loss tangent ~ 0.5 the magnitude of Triangle #6 and consistently resulted in a lower cavity loading for the same sample volume. When combined with the static dielectric constant measurements, this indicates that the powder paint is a superior electrical material for this application (*i.e.*, lower dielectric constant and lower loss). 2) The powder paint is very mechanically robust: the Triangle #6 is prone to cracking and chipping (the sample used also displayed poor adhesion). 3) Once removed from the aluminum substrate, the Triangle #6 paint tended to curl when exposed to humidity. Under the same environmental conditions, the powder paint did not appear to change. 4) For applications where a low out-gassing rate is desired, the composition of the powder paint tested is non-ideal.

Acknowledgments:

Discussions with D. Boyd, N. Horner, W. Lakatosh, and V. Summers regarding sample preparation and measurement were very beneficial. Conversations with L. King and J. Payne were also greatly appreciated.

TABLE 1

SUMMARY OF PAINT DIELECTRIC CONSTANT MEASUREMENTS:

ϵ_r(Powder Paint)	ϵ_r(Triangle #6)	Notes:
5.1 ± 0.2	5.3 ± 0.2	Static, Epoxy Contact, Sample (1A)
5.4 ± 0.2	6.7 ± 0.2	Static, Epoxy Contact, Sample (1A)
5.0 ± 0.2	5.8 ± 0.2	Static, Epoxy Contact, Sample (2A)
5.0 ± 0.2	5.2 ± 0.2	Static, Epoxy Contact, Sample (2B)
5.3 ± 0.2	7.3 ± 0.2	Static, Indium Contact, Sample (1)
4.1 ± 1	6.5 ± 1	WR28 cavity (extrapolate to zero cavity coupling)
4.4 ± 2	–	WR28 cavity (extrapolate to zero sample volume)
4 ± 2	5 ± 2	WR28 cavity (fit to resonance data)
$\sim 5 \pm 1$	$\sim 6 \pm 1$	Best Estimate, ϵ_r ($\tan\delta \sim 0.001$)

For the static measurements, the uncertainty in the thickness determination dominates the error budget. A higher variance than expected from this source was observed during the determination of the static dielectric constant of the Triangle #6 paint samples. The source of this systematic error was not readily evident; however, the evidence at hand indicates that the geometry was slightly compromised in attaching the second electrode to the sample. To reduce this sensitivity, a thicker/larger paint sample should be obtained and other methods of test investigated. [a]

[a]Fourier Transform Interferometer (FTS) measurements made at the British National Physical Laboratory provide some additional information concerning the dielectric constant of these materials. From J. Lamb's measurements of powder paint [6], we note that the dielectric constant is greater than $\epsilon_r > (\lambda_o^{\rm min}/4\,t_{\rm max})^2 = ([830\,\mu{\rm m}]/4[100\,\mu{\rm m}])^2 \sim 4.3$ and $\tan\delta < 0.002$ at millimeter wavelengths. The reflectivity of Triangle #6 is discussed by W. Horne [5]. From the positions of the nulls and maximum in the FTS data, the estimated dielectric constant is $\epsilon_r \simeq ([860\,\mu{\rm m}]/4[100\,\mu{\rm m}])^2 \sim 5$. (Note this should be considered a rough estimate—the sample thicknesses were specified as "light," "medium," and "heavy." The corresponding dimensions are not reported in this memo. From context, we assume the "standard" sample thickness was $\sim 100\,\mu$m.) Evaluation of Triangle #6 at the Jet Propulsion Laboratory (Pasadena, CA) indicates a degradation of the effective surface emissivity of 6061-T6 aluminum by a factor of $\alpha \sim 0.9$ due to the presence of a 15μm (0.0006") zinc-chromate primer and a 25μm (0.001") paint layer at 8.4 GHz [7]. (Note: roughly half of the observed loss increase was due to the dielectric, the remainder is due to the primer). Using the aluminum substrate's nominal skin depth at the measurement frequency, $\delta_\mu \simeq 1.14\mu$m, and equating the dielectric emission with the observed increase in emissivity; we find, $\tan\delta \simeq (1-\alpha')\delta_\mu/t\sqrt{\epsilon_r} \simeq (0.05)[1\,\mu{\rm m}]/[25\,\mu{\rm m}]\sqrt{5} \sim 0.001$. We note in passing that the total emission from the GBT surface, ~ 1 K, will be a perturbation on the system temperature contributions from atmospheric emission, panel gap leakage, ground spill, diffuse scattering. *etc.*, at $\lambda_o^{\rm min}$.

References:

[1] Altman, J. L., *Microwave Circuits,* 1964, D. Van Nostrand Co., New York. pp. 409–416.

[2] Battilana, T., "Ensure Uniformity When Specifying Paint for Reflectors," *Microwaves and RF,* vol. 27, no. 3, March 1988, pp. 113–122.

[3] Born, M. and Wolf, E., *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light, Sixth (Corrected) Ed.,* 1989, Pergamon Press, New York, pp. 632–633. (Equations to investigate depolarization properties of surface in the geometric limit.)

[4] Harvey, A. F., *Microwave Engineering,* 1963, Academic Press, New York. (Control of surface reflection, pp. 598–605; properties of layered dielectric materials, pp. 670–672.)

[5] Horne, W., "Reflective Surface Painting of the 25 Meter Antenna," 25 Meter Millimeter-Wave Telescope Memo #137, Feb. 10, 1980 (Cross-reference: Hogg, D., "Painting the Surface of the Green Bank Telescope," GBT Memo No. 46, March 22, 1990).

[6] Lamb, J., "Paint Performance at Millimeter Wavelengths." GBT Memo #74, Feb. 28, 1992.

[7] Otoshi, T. Y., and Franco, M. M., "The Electrical Conductivities of Steel and Other Candidate Materials for Shrouds in a Beam-Waveguide Antenna System," IEEE Trans. on Instrum. and Measurement, vol. 45, no. 1, Feb. 1996, pp. 77–83.

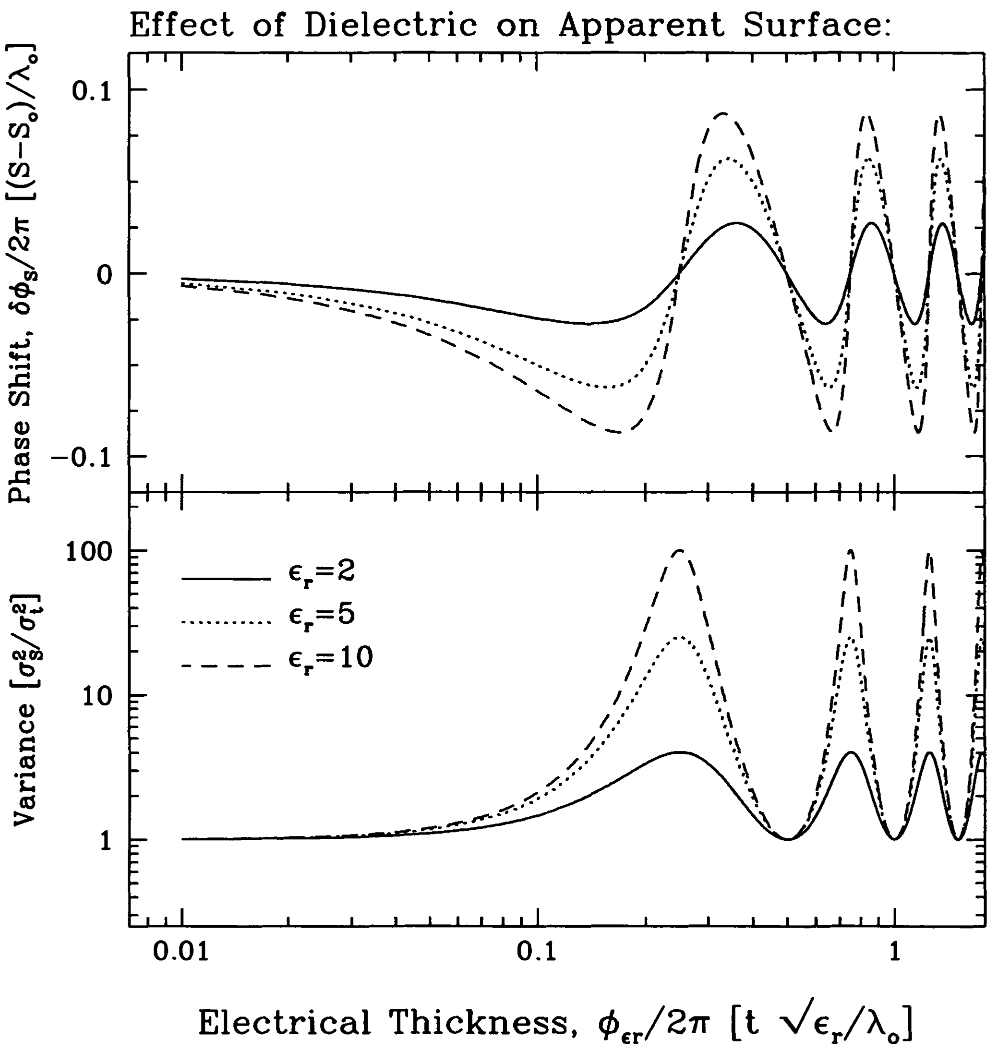

Figure 1. In the top panel the shift in the apparent reflector surface position is plotted as a function of the paint electrical thickness. A dielectric layer of the same thickness and $\epsilon_r = 1$ is used as the reference plane. The bottom panel is the relative variance of the apparent reflector position (*i.e.*, the sensitivity of the reflector surface rms to variations in paint thickness). In the calculation, it is assumed that the incident rays are normal to the surface, the paint's dielectric constant is uniform, and the ohmic losses are negligible.