Signal TransmissionThrough the LP Feed Glass Dewar

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I. Abstract

We study the effect of the glass dewar on the transmission of signals to the feed. The tip of the dewar is a hemisphere and the extension to the low frequency part of the feed is approximately a cone. Because the feed pattern is largely confined to a cone toward the tip end, we can estimate the transmission using a complete sphere as a model. For this structure an exact EM calculation can be made, including a spherical layer of Teflon adjusted to minimize the reflection of the glass structure. For the conical part of the feed we use an approximate model which is a plane layer of glass with a parallel plane layer of Teflon. The EM solution in this case is formally the same as that for the spherical region, and we can use the sphere results for the cone. Reflection for two thicknesses of glass plus Teflon are examined in detail. For one the glass thickness for the spherical region is .020" corresponding to typical light bulb thickness, and for the other the glass thickness is .040". With the proper choice of the Teflon layer, reflections can be kept to less than a few percent over the band $1 < f < 15$ GHz in both cases.

II. Introduction

One next version of the cm wave Log Periodic Feed will be encased in a glass vacuum dewar so that both the feed and the attachments between the LNA and the feed terminals can be cooled to about 65K. Extrapolations from the operation of the present feed and LNA suggest that this cooling will result in overall system temperatures of about 30K in the frequency range 1-15 GHz. This development raises issues about both the cooling of the feed in the presence of the ~300K thermal infrared background and the signal transmission through the glass. The thermal problems were discussed in memo # 14, where it was concluded that the feed could be cooled by a refrigerator connected to the large end of the feed with no more than about a 10K temperature rise along the feed. In this memo we discuss the transmission through the glass dewar and the use of a Teflon anti-reflection layer surrounding the glass dewar to lower the reflection from the glass.

Reflection from the Glass

Figure 1 shows the planned log periodic feed with the glass dewar surrounding it. The feed directivity is in the direction toward which the pyramidal feed points, and the active receiving part of the feed at any particular wavelength is at a distance from the feed vanishing point which is about 1.5 wavelengths. Thus the shortwave sensitivity is close to the tip, and the longer wave sensitivity is at the larger end of the feed. For any particular glass thickness the shorter wavelength transmission is more of a problem near the tip. The diagram of Figure 2 shows the detailed shape and the plan for a thin hemispherical section around the tip connecting to a conical section which expands in thickness toward the back part of the feed. The hemispherical region can be quite thin, e.g. ~.020", which is typical of an ordinary light bulb, and be structurally strong. The glass thickness is planned to be greater toward the large end of the feed for overall strength. Since the longer wavelengths are received at the larger end, it can be thicker there without producing a significant reflection. We can study the reflection problem from the sphere for the shorter wavelengths by calculating the reflection of a spherical wave originating at the center of the glass sphere.

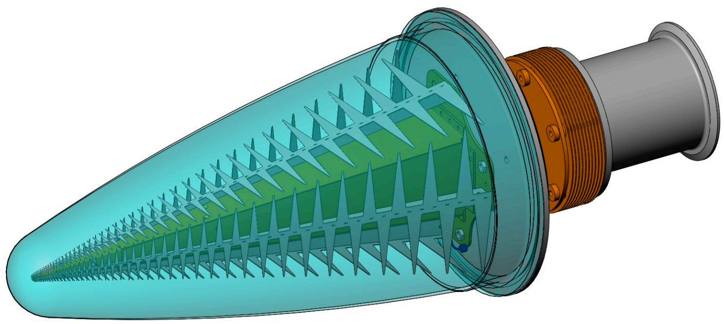

Figure 1. The feed inside the glass dewar

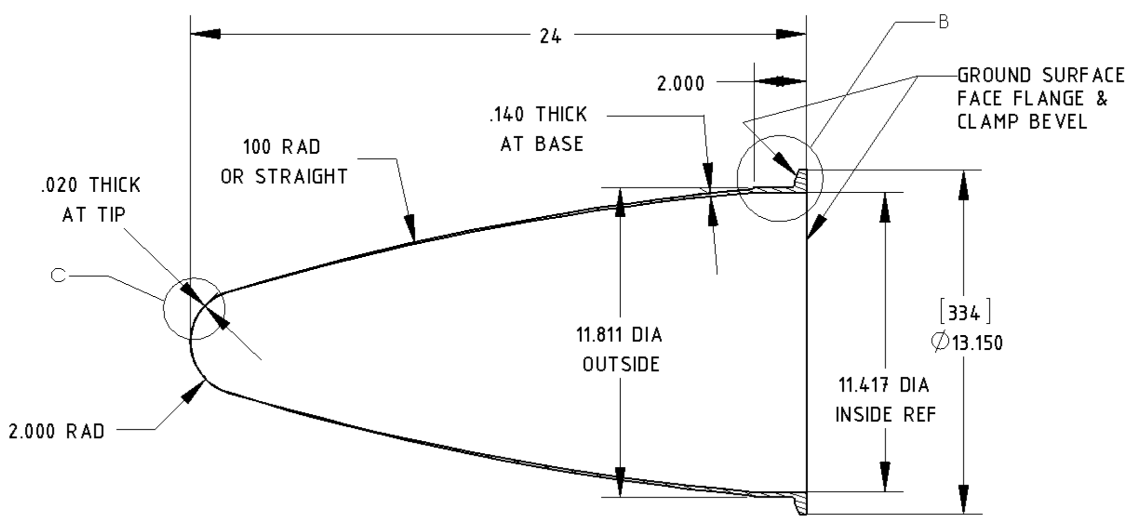

Figure 2. Section view of the glass dome.

III. Transmission Through the Spherical Tip of the Glass Dome

Here is the basic plan. We first find the field radiated from an elementary dipole current source at the center of the glass sphere, obtaining, in particular, the transmission through the sphere as a function of wavelength. We then make the plausible assumption that if the source were moved a small distance from the center of the sphere the transmission would not change significantly. Then we note that the actual feed current distribution could be synthesized as a distribution of the elementary currents over a short section of the feed at any particular wavelength. That is, the elementary solution is Green's function for the antenna problem, and we could use it to synthesize the pattern. With these assumptions, it is sufficient to study just the reflection for the elementary source to estimate the reflection of the antenna signal if it were transmitting. Because the final pattern is directed toward the tip, the complete sphere is a sufficient model for the hemisphere. Because of reciprocity, this calculation also gives the inward transmission from a distant source.

The elementary current distribution is a small source, and we put it at the center of the spherical coordinate system with its polarization oriented along a local z coordinate normal to the feed axis. For the log-periodic feed element two such sources on the two sides of the pyramid corresponding to the two arms will eventually be needed along with a distribution of sources distributed along a short length of the feed for a particular frequency and linear polarization. Again, it should be sufficient to study just the elementary source and field. The time dependence is $e^{i\omega t}$ so that the spatial part of an outgoing wave is $(1/r)e^{-ikr}$.

The Elementary Source and Its Field.

The vector current source is $\hat{a}_z\ I_o\,\Delta z$, and the field components for this source are well known (e.g., Stratton, 1941, p436).

$$E_\theta = I_o\,\Delta z\, e^{-ikr}\, \{i\omega\mu/4\pi r + \eta/4\pi r^2 + i\omega\varepsilon/4\pi r^3\}\, \sin\theta$$

$$E_r = I_o\,\Delta z\, e^{-ikr}\, \{2\eta/ 4\pi r^2 + 2/i\omega\varepsilon 4\pi r^3\}\, \cos\theta \qquad (1)$$

$$H_\varphi = I_o\,\Delta z\, e^{-ikr}\, \{ik/4\pi r + 1/4\pi r^2\}\, \sin\theta,$$

where ε is the permittivity, μ is the permeability, $\eta = \sqrt{(\mu/\varepsilon)}$, and $k=2\pi/\lambda$. The radius of the sphere is ~5 cm, and the leading terms in E_θ and H_φ dominate the field at the spherical surface for wavelengths shorter than ~5 cm. So we ignore the other terms in the matching of the boundary conditions at the spherical surface.

The Boundary Conditions

In addition to the glass layer extending from $r = r_1$ to $r = r_2$, we include a layer of Teflon above it which extends from $r = r_3$ to r_4, as shown in Figure 3. The thickness and radius of the Teflon will be adjusted so that the overall transmission will be maximized over the operating band 1 to 15 GHz. The form for the fields in the spaces between the bounding surfaces correspond to spherical TEM waves like the leading terms of the elementary source in equations (1). Both outgoing and incoming waves are included in every region except the outer most region where there must be only an outgoing wave. The tangential electric and magnetic fields, E_θ and H_φ, must be matched at each surface of discontinuity. These field terms are exact solutions to Maxwell's Equations for the simple spherical structure of the model. The diagram of Figure 3 outlines the five regions.

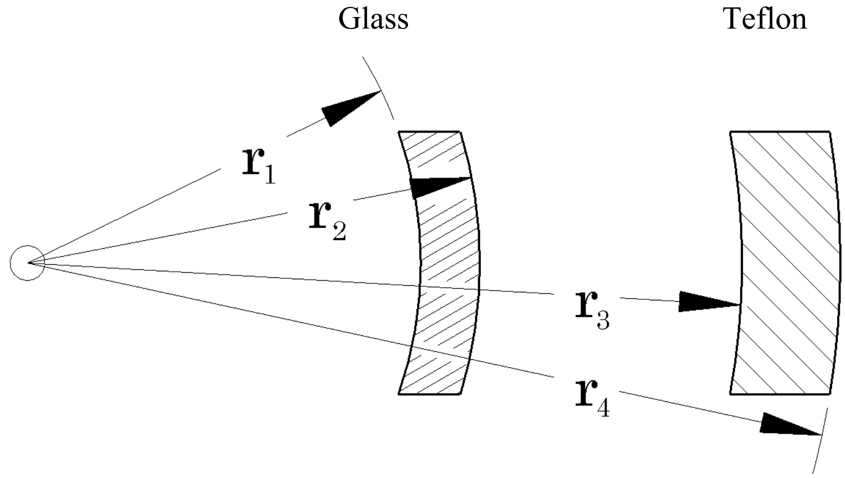

Figure 3: The spherical glass and Teflon layers

The field components of region 1, $r < r_1$, appear below with coefficients to be determined by the boundary conditions. The strength of the elementary outgoing field is normalized to unity for the electric field in this region.

$E_\theta = (\mathrm{Sin}\Theta/r)\mathrm{Exp}(-i\gamma_o r) + (B\mathrm{Sin}\Theta/r)\mathrm{Exp}(i\gamma_o r);$

$H_\varphi = (\mathrm{Sin}\Theta/\eta_o r)\mathrm{Exp}(-i\gamma_o r) - (B\mathrm{Sin}\Theta/\eta_o r)\mathrm{Exp}(i\gamma_o r)$ (2)

The subscripts on the wave numbers, γ_i, and characteristic impedances, η_i, correspond to the characteristics of the three regions: free space, glass, and Teflon. The characteristic impedances are defined above. The wave numbers defined in terms of the free space value k are given by $\gamma = k\sqrt{(k_e)}$, where k_e is the relative dielectric constant of the medium. Similar field components for the other regions are defined with initially undetermined coefficients: (C,D) for the outgoing and incoming components in region 2, $r_1 < r < r_2$, (E,F) for region 3, $r_2 < r < r_3$, (G,H) for region 4, $r_3 < r < r_4$ and I for the outgoing wave in region 5, $r > r_4$.

The boundary conditions, continuity of tangential electric field, E_θ, and tangential magnetic field, H_φ, must be satisfied at each boundary. This gives a pair of equations at each boundary. For example, at the boundary $r = r_3$: $E_{\theta 3} = E_{\theta 4}$ and $H_{\varphi 3} = H_{\varphi 4}$, require:

$E\ \mathrm{Exp}(-i\gamma_o r_3) + F\ \mathrm{Exp}(i\gamma_o r_3) = G\ \mathrm{Exp}(-i\gamma_t r_3) + H\ \mathrm{Exp}(i\gamma_t r_3)$;

$(E/\eta_o)\mathrm{Exp}(-i\gamma_o r_3) - (F/\eta_o)\mathrm{Exp}(i\gamma_o r_3) = (G/\eta_t)\mathrm{Exp}(-i\gamma_t r3) - (H/\eta_t)\mathrm{Exp}(i\gamma_t r_3)$ (3)

In addition to these, there are similar equation pairs for the other boundaries: r_1, r_2, and r_4. The common (1/r) factors as well as the sinΘ factors in each of these equations cancel out in the equations which determine the coefficients B,C,D,E,F,G,H, and I. To find the transmission from the central source through the glass and Teflon requires solving for the coefficient I for the amplitude of the outgoing wave. Since the amplitude of the outgoing electric field in region 1 is taken to be 1, I would be equal to 1 if the transmission through the glass and Teflon layers were perfect .The calculation is straight forward algebra, combining the equations in pairs to successively eliminate all the coefficients except I.

Here is the equation for I:

$$
\begin{aligned}
16/I = {} & Q_A (1 + \eta_g/\eta_o)(1 + \eta_o/\eta_g)\mathrm{Exp}\{i[\gamma_o(r_1 - r_2) + \gamma_g(r_2 - r_1)]\} \\
& + Q_B (1 - \eta_g/\eta_o)(1 + \eta_o/\eta_g)\mathrm{Exp}\{i[\gamma_g(r_2 - r_1) + \gamma_o(r_2 + r_1)]\} \\
& + Q_A (1 - \eta_g/\eta_o)(1 - \eta_o/\eta_g)\mathrm{Exp}\{i[\gamma_o(r_1 - r_2) + \gamma_g (r_1 - r_2)]\} \\
& + Q_B (1 + \eta_g/\eta_o)(1 - \eta_o/\eta_g)\mathrm{Exp}\{i[\gamma_o(r_1 + r_2) + \gamma_g (r_1 - r_2)]\}, \text{ where}
\end{aligned}
$$

$$
\begin{aligned}
Q_A = {} & \{(1 + \eta_t/\eta_o)(1 + \eta_o/\eta_t)\mathrm{Exp}\{i[(\gamma_t - \gamma_o)(r_4 - r_3)]\} \\
& + (1 - \eta_t/\eta_o)(1 - \eta_o/\eta_t)\mathrm{Exp}\{-i[(\gamma_o + \gamma_t)(r_4 - r_3)]\}\}, \text{ and}
\end{aligned}
$$

$$
\begin{aligned}
Q_B = {} & \{(1 + \eta_t/\eta_o)(1 - \eta_o/\eta_t)\mathrm{Exp}\{i[(\gamma_t - \gamma_o)(r_4 - r_3) - 2\gamma_o r_3]\} \\
& + (1 - \eta_t/\eta_o)(1 + \eta_o/\eta_t)\mathrm{Exp}\{-i[(\gamma_t - \gamma_o)(r_4 - r_3) + 2\gamma_o r_4]\}\}. \qquad (4)
\end{aligned}
$$

A First Example: The glass thickness of a typical incandesant light bulb is about .020". We take this case for our glass sphere and work out its transmission properties as a function of frequency for $1 < f < 15$ GHz. Then we add the layer of Teflon and vary its thickness and radial distance to maximize the transmission. Since all of the γ_i factors have the frequency as a factor, the plotting vs frequency is straight forward. We take the relative permitivity of the glass to be 4 and that of Teflon to be 2. Fused quartz, probably the best choice for the glass, actually has a permitivity of 3.8, but 4 is close enough for the example.

Figure 4 shows several transmission curves. The one for glass only shows power transmission, $|I|^2 > .99$ up to about 7 GHz but dropping to .955 by 15 GHz. If the feed structure is at a physical temperature of ~70K, the 1 percent implied reflection at 7GHz would add ~0.7K to the feed system temperature, and the 4.5 percent at 15 GHz would add about 3K to the system temperature apart from the small radiated and reflected noise contribution from the LNA. These numbers would be about four times higher if the feed were not physically cooled to 70K. The other curves show the effect of a .35mm layer of Teflon at various heights above the glass layer. The 5mm separation appears to give about the best overall improvement, with the transmission at 15 GHz raised to .97 and generally better results at the lower frequencies. In Figure 5 we show transmission curves keeping the 5mm separation and varying the Teflon layer thickness to get the best transmission. The .8mm thickness appears to be about the best. The scale of Figure 5 is finer than that of Figure 4, and the transmission is .99 or better for much of the range. Further optimization will probably not make significantly further improvement.

It is important to keep in mind that the other effect of any transmission loss is the loss in antenna gain. Keeping that loss to a few percent or less from the transmission through the dewar is almost as important as lowering the system temperature.

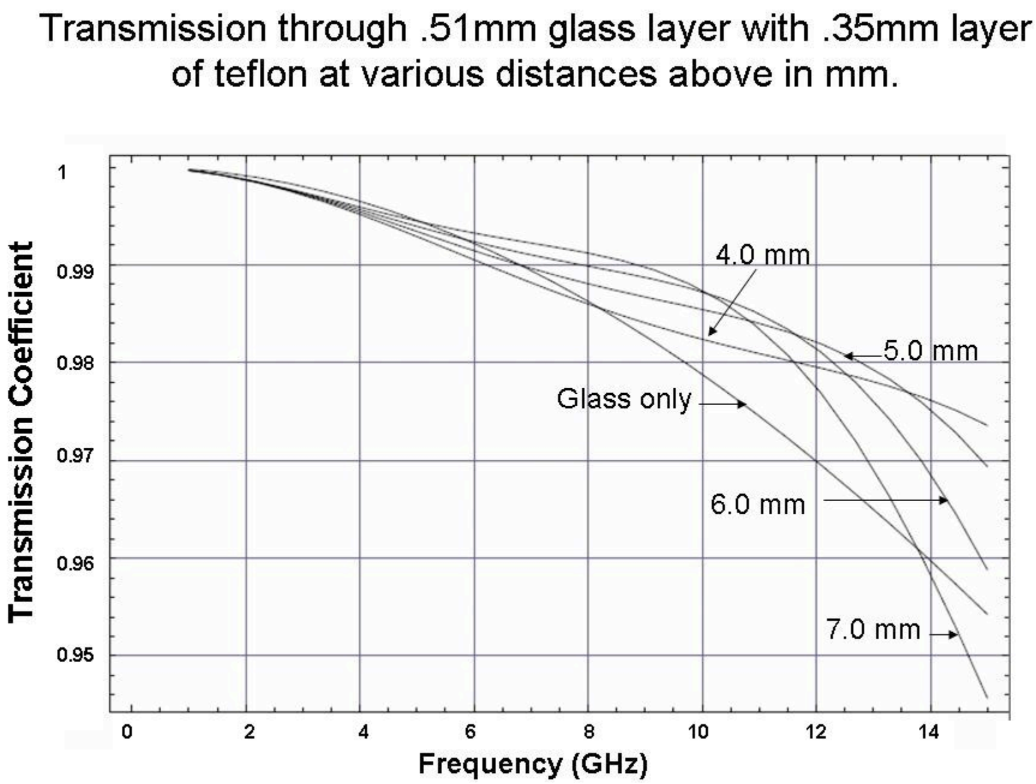

Figure 4. Transmission through the .51 mm glass and Teflon

A Second Example for the Sphere: For the second case, we take the thickness of the glass sphere to be 1mm, about double that of the first case, and discuss only a limited optimization. For this case we use the relative permittivity of 4.8 for the glass, which is appropriate for fused quartz. The results are shown in Figure 6. With just the glass, the transmission drops to 0.95 at 8 GHz and is .86 at 15 GHz. Based on the results of the first example, we put in a double thickness Teflon layer, 1.6mm, at the same 5.0 mm spacing that was used in Figure 5 with the 0.51mm thick glass. This makes a substantial improvement, raising the transmission to .97 or better out to about 11.5 GHz. Changing the Teflon layer thickness to 1.8 mm raises the transmission a little higher near 10 GHz and degrades it a little at the higher frequencies. Decreasing the Teflon layer spacing to 4.0 mm for the 1.6 mm thick layer provides a transmission of .95 or better out to 14 GHz with a minimum of .96 at 7 GHz. These are all interesting possibilities, and a detailed optimization can be developed for the finally chosen thickness of the glass.

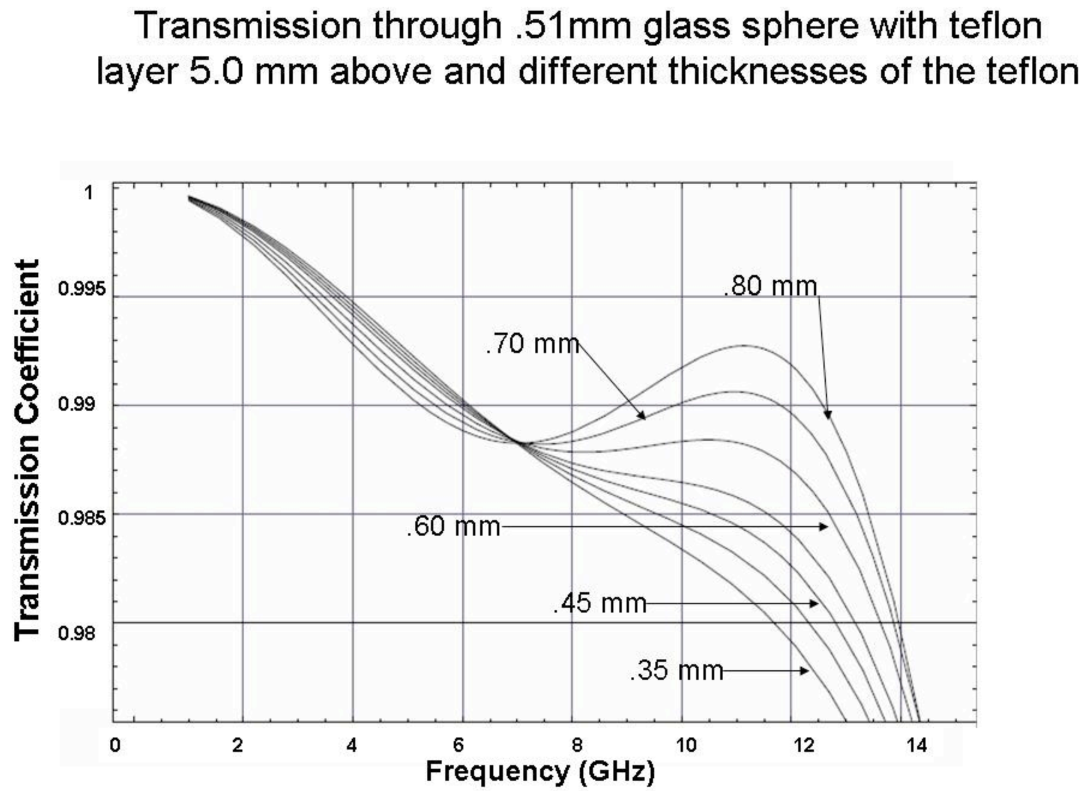

Figure 5: Glass and Teflon transmission with different Teflon thicknesses

IV. Transmission through the conical part of the glass cover.

This part covers the lower frequency part of the feed. The feed is about 24 inches long, and the 1 GHz sensitivity is at the back end. The 2 GHz zone is at 12 inches, the 4 GHz zone is at 6 inches, and the 8 GHz zone is at about 3 inches. This latter region is close to the tip, and is covered largely by the sphere. For the low frequency transmission from the large, low frequency, part of the feed, we use an approximate model which is plane parallel sheets of glass and Teflon. Since the transmission is expected to be high, this approximate model is plausible. For transmission through plane layers at approximately normal incidence, the spherical model which we have studied for the tip of the feed is the same EM problem. In equations (3) for the matching of the boundary conditions for the sphere, the 1/r factors drop out at each boundary, and the equations for the continuity of the tangential components of E and H in the plane parallel case are the same. Thus we can use the same results, equations (3), for the corresponding rectangular field components. What matters is the transmission through the double layer given by equation (4). The important parameters are the phase delays between the layers and the discontinuities of the field components at the glass and Teflon boundaries.

We can study the transmission through the conical part of the glass/Teflon dewar by examining Figure 6 or Figures 5 and 4. The first point to notice is that whereas the addition of the Teflon improves the transmission for frequencies above about 6 GHz it actually makes it slightly worse at the lower frequencies. This suggests that no Teflon be used over the conical part of the dewar. Because the thickness of the dewar is increasing toward the large end of the feed, it is necessary to include that effect in the scaling of the transmission to lower frequencies. Figure 6 shows large dots for the transmission at selected lower frequencies assuming that there is no Teflon and the thickness follows the dimensions of Figure 2. The model transmission is quite high at the lower frequencies which justifies the approximate model. Altogether the effect of the glass is small for the conical part of the dewar.

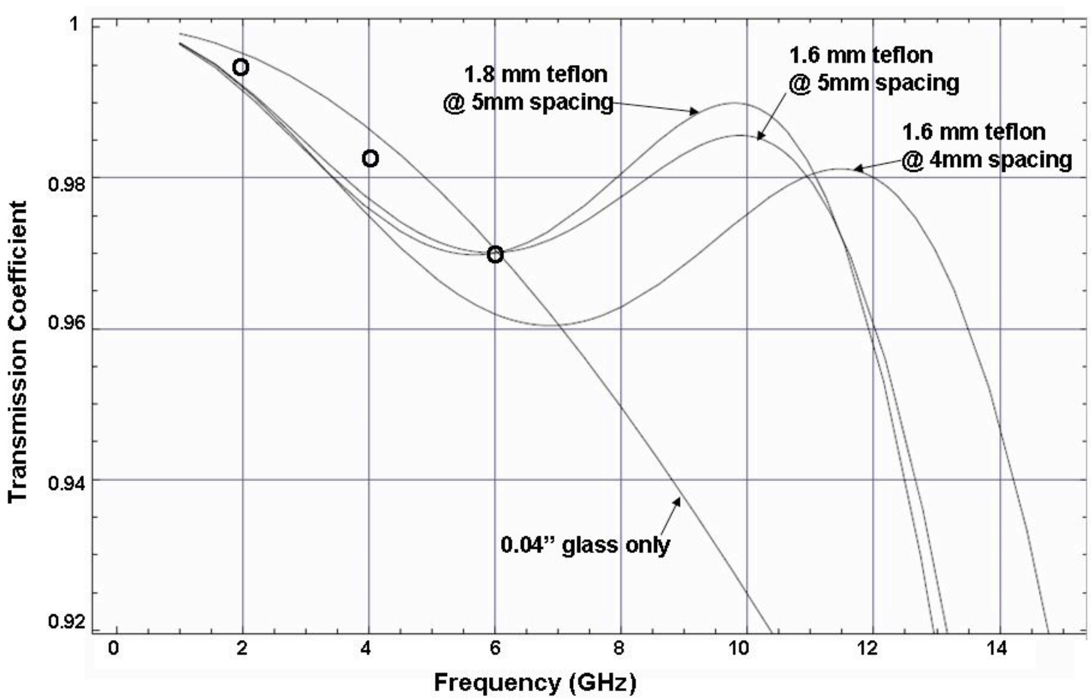

Figure 6: Transmission through the 1mm (.040") thick glass sphere and three different choices of Teflon thicknesses and separations. The three circles show the expected transmissions through the conical part of the feed with no Teflon at 2 GHz, 4 GHz, and 6GHz, where the cone and sphere thicknesses are the same.

V. Future Plans

We have found an experienced glass manufacturer who is confident about building the dewar. We have ordered two units for a good price and expect delivery in about a month. The glass thickness will be 0.04" corresponding to the second example above. In the meantime we will make a more detailed optimization of the required Teflon thickness and separation.