RF Membrane

It seems to me that the first issue is to establish a reasonable specification for the scientific properties. It comes as a bit of a shock to discover that there isn't one and I wonder whether this means that nothing has been included in the system performance estimates for the effects of this membrane. The main issues seem to me to be RF loss, with the associated increase in system temperature, and instrumental polarization. Effects on stability, calibration, sidelobes, etc., should also be born in mind.

RF Loss

We will presumably be using a dielectric material which means that most of the loss will be due to reflection rather than absorption, but since the reflection is back into the receiver cabin it is terminated at ambient and the effect is therefore the same as an absorptive loss. The effect of such a loss L on system temperature is to add roughly $L^*(300 + T_{\mathrm{sys}})$ to the system temperature. (I think this approximation is good enough for small L.) I don't know what loss would be regarded as acceptable. One measure is that an increase in system temperature of 2% causes roughly the same loss in overall sensitivity as dropping one antenna, i.e. if point source sensitivity is the key criterion, we would be justified in spending several million dollars to reduce the loss in sensitivity due to the membrane from say 3% to 1%.

If we take 1% increase in system temperature as the goal, then the allowed membrane loss is $L \sim 1/(300/T_{\mathrm{sys}}+1)$ %. For T_{sys} = 50K this is only 0.14%, while at T_{sys} = 150K it is 0.33% and for T_{sys} = 500K it is 0.63%. (I have forgotten what our expected system temperatures are, but I imagine that these values might correspond to something like 100, 300 and 700GHz.) These are very low figures as will be seen from the estimates for reflection losses of dielectrics below. We might well have to settle for something more like 2% for the increase in system temperature.

There are three strategies that I can think of:
1) use a very thin continuous film of a relatively strong dielectric material;
2) use a thicker film of dielectric material that has been expanded in some way to make it have a lower effective refractive index;
3) use a film with some surface coating to give better matching to free space.

Case 1)

Any dielectric film will have alternating maxima and minima of transmission, with the maxima occurring when the round trip path through the film and back again corresponds to a whole number of wavelengths. For the thin film option we would try to have the first minimum at a shorter wavelength than our highest operating frequency, which means that we are talking about thicknesses of less than ~25 microns.

The reflective loss is then set by the refractive index n and the thickness t in wavelengths. I get the following approximate formula, for small t and near to normal incidence:

$$L = [(n^2 - 1).\ \pi\ \ t / \lambda\ ]^2\ \ .$$

The material with the lowest dielectric constant that I know of is PTFE (Teflon) with n = 1.44. There are a number of other plastics with $n \sim 1.5$ (polyethylene, polypropylene, etc.). Mylar (PETP) is stronger than any of these but has $n \sim 1.8$ and a significant loss tangent too – see James Lamb collection of data[1].

As examples of the maximum thickness we can allow to have a reflective loss of 0.33% at a wavelength of 1mm, the formula above gives about 17.5 microns of Teflon or 8 microns of Mylar. Unfortunately the absorptive loss does contribute significant extra emission in the case of Mylar so that, if I have the right figure for that (loss tangent ~ 0.014), the maximum thickness allowed would be more like 5 microns.

I will discuss whether this seems feasible later on, but note that since the loss goes as roughly the square of frequency, these thicknesses will give losses of over 1% at 700GHz which is above the target suggested above.

Case 2)

There are various ways of expanding the plastics to reduce the effective refractive index. One option is to make a woven fabric and another is to make a foam. Somewhere in between are materials made of fibres with essentially random orientation and location – a "felt". (Is this the right expression?).

The effective refractive index will be ~ $n_{\mathrm{eff}} = (n_{\mathrm{solid}}-1) / f + 1$, where f is the volume filling factor. The biggest problem here is likely to be scattering due to the in-homogeneities in the material, but if we assume for the moment that it does act like a uniform slab there will still be maxima and minima in the loss. If the loss tangent is insignificant, the loss at the maxima is given by $L \sim (n_{\mathrm{eff}}{}^2 -1)^2 / 4\, n_{\mathrm{eff}}{}^2$ and at the minima it is ~ 0. For the maxima to have a loss of say 1% we need to get n_{eff} down to about 1.11, i.e. a filling factor of about 0.25 in the case of Teflon. If the thickness is really large (several wavelengths) then the maxima and minima will be spread all the way across the wavebands and in some sense the loss averaged over frequency would be the relevant value – this is just half that at the maxima. With some luck we might be able to get the peaks in the loss to coincide with frequencies where the atmospheric losses are large and put the minima at the most critical frequencies for high sensitivity observations.

The location and the depth of minima in the transmission curve of the material specified for ALMA (Goretex Type: RA 7956) suggests that it has an n_{eff} of about 1.15 and a thickness of ~ 460 microns. There is a general increase in the loss at high frequencies which may be due to scattering, but which can be modelled by including a loss tangent of ~0.0007. This is within the rather large range of values quoted for Teflon in James's compendium. As commented by Peter Schilke, this is really pretty good performance and comes quite close to meeting our loss requirements. It is not clear to me whether this is a woven material or some other form of expanded Teflon.

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[1] Miscellaneous data on materials for millimeter and submillimeter optics, J. W. Lamb, *Int. J. IR and Millimeter Waves*, vol. 17, no. 12, pp. 1997-2034, Dec. 1996.

Case 3)

To make transparent windows with modest bandwidth, one can make multilayer dielectrics which can have very low loss. In the case of solids one can also cut grooves, etc., into the surfaces to make a matching layer. It seems to me very unlikely that either of these techniques can be used for the very wide fractional bandwidth that we need to cover all the ALMA bands. (I assume that we do not wish to contemplate a set of membranes which are changed by some mechanism when we change observing band!)

If one had total control over making materials with different degrees of expansion then it is just conceivable that one could make a multi-layer sandwich starting with very low effective dielectric on the outside and gradually working up to a denser and presumably stronger material in the middle. This also seems too ambitious to me.

Polarization

It seems to me that the goal has to be for this to be low and reproducible. I don't have the figures for other parts of the system to hand but I would have thought that we should keep the contribution to the instrumental polarisation from this source to a few tenths of a percent at the most and any variations in it (over say a 20GHz range of frequency or as a function of time, temperature, etc) to well under 0.1%.

In the case of continuous films there is probably not much problem. The materials are somewhat anisotropic as a result of the way they are manufactured, but probably only at the level of a few percent of their total values for things like refractive index, so if the total loss in transmission is less than 1% the polarisation effects should be less than the values above. The transmission does become polarized for non-zero angle of incidence, but the ALMA design calls for an angle of incidence of only 5 degrees – this was no doubt done to avoid standing waves. The actual angle of incidence will be slightly different for the different receiver locations and at different points in the aperture but will always be less than about 10 degrees (but see comments below about curved membranes). For comparison a 20 micron thick film with n = 1.5 gives a loss of ~0.6% at 300GHz but the difference in transmission for the perpendicular and parallel components does not reach 0.1% until the angle of incidence is about 14 degrees. The resulting instrumental polarization would be only 0.05% if it is defined as difference/sum.

Woven cloths are definitely more of a problem because it is very difficult to get the threads in the two directions – the warp and the weft – to have the same properties. Even if they have the same spacing and thickness they don't lie equally flat after weaving. We did some work on this during the JCMT development[2] and chose the best weave we could get (a "2 by 2 basket weave") but we still ended up with an instrumental polarization of (from memory) nearly 1%. What is more, this changes sign between the 350 and 700GHz windows. I have always assumed that this indicates that diffraction effects are becoming important here – the spacing of the threads is ~ 0.3mm – but I do not understand the details at all. Clearly we will have to pay close attention to this if we use a woven material.

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[2] See Birch et al. Applied Optics, **22**, 2947 (1983).

I don't know anything about the polarization properties of foams or what I am calling felts. In foams one probably requires that the bubbles are sufficiently round and in felts that the fibre orientations really are random, or at least evenly distributed. I imagine that these things depend on the processing steps involved.

Other transmission properties that one might need to specify

The remaining point that occurs to me is that it is possible to have good power transmission but still mess up the phase.

This is not likely to be a problem in the case of a continuous film. If we have a 20 micron thick film with $n = 1.5$, the added path is only 10 microns so a 10% rms variation adds only 1 micron rms of path, which is equivalent to ~0.5 microns rms of surface error.

For the much larger thicknesses that one might use for expanded materials irregularities could be a problem. The specification appears to contemplate thickness of up to 1.5mm of a material that appears to have $n_{eff} \sim 1.15$. The added path is ~225 microns, so one would be asking for this to be uniform to ~2% to keep the path length errors to ~5 microns. Remember that a 5 micron rms path error would scatter ~1% of the signal at 900GHz. This might well be hard to achieve, but I doubt very much that we would really be using such a thick membrane.

I suggest we set a limit of 5 microns rms on the path errors for scales between 0.3mm and say 300mm.

Mechanical and related properties

The first question seems to me to be, what we want the membrane for? There is a separate shutter which is closed in the case of storms, rain and snow. One therefore assumes that is needed to allow the temperature in the receiver cabin to be controlled. It is however my understanding that when the receiver system is in place, the volume in front of the receiver (the "widget space") is effectively isolated from the cabin. That is at least my recollection of how the EIE design was arranged. If so then this suggests that the only function of the membrane is to keep the calibration devices and the external optics in a comfortable environment. Is this really right and if so how tight is the requirement on that? Given that the loads we are planning to use have their own temperature regulation, this may in fact not be very critical. Good insulation around the calibration loads is probably needed anyway.

One is tempted to speculate that the membrane may not be necessary at all. The space we are talking about is down the bottom of a reasonably long tube and if it is sealed then there will not be a real flow of air – just eddies resulting from wind flows around the antenna plus the convection arising when the widget space is warmer than the outside air. I can imagine that an air blower producing a "curtain" of air across the aperture might be enough to limit those to an acceptable level.

Assuming that this is not so and that a real barrier is needed, then it appears to me that it does not need to provide a real hermetic seal. Clearly it does have to be water-proof so long as we can rely on the shutter and being somewhat porous to air might be an advantage since it would allow the mean air pressure inside the widget space to come into balance with that outside, due to example to steady winds.

Wind Forces

The membrane only needs to withstand the operational wind speeds of v ~10ms^{-1}. As a very crude estimate of the dynamic pressure we can just take ρv^2 with the air density ρ as 1 kgm^{-3}, which gives 100Pa. This is not much – the force on a diameter of 0.8m is only ~ 50N (11 pounds).

My strong belief is that a flat membrane is basically hopeless even if it is tensioned up. It will flap around, which is bad for stability and soon causes it to get slack and eventually to break from fatigue. The essential step is to put some curvature into it.

It is easy to show that for a single curvature, radius R, and with a tension in the membrane of T per unit width, the pressure difference across the membrane is T/R. As suggested by Peter Schilke, it is possible use a positive internal pressure to produce a spherically curved surface giving a pressure of $2T/R$. If one uses two layers with increased pressure between them, the thickness of the individual layers would have to be reduced still further to meet our requirements. If the widget space is sufficiently well sealed we could pump air into the whole volume to provide a pressure in excess of the 100Pa of dynamic pressure so only a single layer would be needed in the aperture.

It is however almost as effective to use a saddle shape with two equal and opposite curvatures. This is how the membrane on the JCMT works. The saddle shape can be produced simply by shaping the frame that supports it. One option is to use a square frame with two diagonally opposite corners raised up and the other two lowered. The alternative is to have a circular frame with the sin(2*phi) variation in height cut into it. The net pressure force is $T_1/R_1 - T_2/R_2$, which is zero when the tensions and radii are equal, but when the wind pushes on the membrane the tensions and radii will change until the pressure is balanced. The order of magnitude will be right if we simply set T/R to our pressure estimate of 100Pa. For the curvature we can take $R \sim 4$m, which gives a sag of 20mm across the 0.8m aperture. The tension required is therefore $T \sim 400$Nm^{-1}.

The stress in the material is then $S = T/t$, with t the thickness, and we can see how this comes out for the various thicknesses we discussed before. For Mylar we had $t \sim 5$ microns, giving $S = 80$MPa. This can be compared with tensile strengths which I found quoted[3] as 190 to 260MPa. This probably does not give us a large enough safety margin, but it shows that such a thin membrane is not out of the question. Remember that the 100Pa estimate for the dynamic pressure is probably rather high and also that we may be able to use a considerably smaller radius of curvature than the 4m assumed here. (One problem, however that if we use too much curvature we get significant changes in the angle of incidence, which may cause polarization effects and might also mean that the membrane is at normal incidence at some point in the aperture, which could cause standing waves.)

For Teflon we had $t \sim 17.5$ microns, so the stress is $S = 23$MPa. The tensile strength of the normal material is given as 10-40MPa, so this is no good. In addition Teflon

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[3] I looked in http://www.goodfellow.com/csp/active/gfHome.csp and searched under Material Properties.

normally creeps more or less continuously making it unusable in this sort of application. The trick discovered by Gore is a method (which is I believe secret) of making the polymers lock up so that it is much stronger and doesn't creep. Thus the material used in the JCMT membrane operates with stresses of up to ~30MPa and has not stretched appreciably in 20 years of operation. This is however a woven fabric and I don't know if such material is available as a continuous sheet.

Some other materials with intermediate dielectric constant, such as polypropylene which has n ~ 1.52, can apparently be prepared with strength comparable to that of Mylar. If so, then these would be good candidates in terms tensile strength.

Of the expanded materials, we know that woven Teflon can be made strong enough, but we will probably have to pay Gore's prices. I note that their original development of the woven materials was to make filters for use in the food industry. We (JCMT) then got them to put a continuous Teflon film on the front to make it completely impermeable (i.e. to keep out water and dust) and they started selling it as a radome material. It may be that we can go back to a filter material and in particular we might be able to get one with a lower filling factor than the radome materials but with smaller and more closely spaced fibres to get away from scattering effects.

I have no knowledge about the strength of foams or felts. I suspect that they are quite weak, but since they can be much thicker than the solid films it would be worth investigating them further.

UV resistance

This is a critical requirement and one that may be difficult to meet. I believe that all the simple hydrocarbon polymers fall apart quite rapidly when exposed to UV light at the sort of levels found on mountain sites. The exception is Teflon, which is apparently not affected at all and for this reason it is the most worthwhile candidate to investigate. It is however possible to get UV-protective coatings on other materials. We have used coated Mylar for windows on the systems in Tenerife with no signs of problems from UV. The problem then is of course what are the loss properties of the coatings at the short wavelengths we are working with.

Conclusions

The first thing to check is whether a membrane is really needed at all.

If it is, then the next thing to do is agree a detailed set of specifications on losses, polarization, scattering, etc.

My suggestion is that we should mount the membrane on a frame that provides a doubly curved shape and the ability to tension it. Materials to be investigated should include:
1) thin films of Mylar, polypropylene or similar materials, with UV resistant coating,
2) the Gore form of Teflon, in either film, woven or perhaps "felt" form,
3) foams with small and uniform bubble size, with perhaps a very thin Teflon coating for UV protection.

Richard Hills 17th July 2005