Efficiency Modeling for an Ultra-wideband Receiver for the Green Bank Telescope

Maile Harris, Yale University Department of Applied Physics, GBO REU Summer Student
Steve White, Mentor, Green Bank Observatory

Abstract

This project simulates the S11 and efficiency of an ultra-wideband receiver for the GBT under various material conditions of the feed's quartz window. The goal was to improve the impedance match across the window by reducing the thickness of high-dielectric quartz needed to meet the strength requirements of the system. Instead, an intermediate layer of low-dielectric support foam sandwiched between two thin layers of quartz was used to improve power transmission without compromising feed efficiency. The support foam was tested at two thicknesses and two locations within the mouth of the feed horn, testing five values of the dielectric constant of the foam at each thickness and location. It was ultimately determined that the location of the window within the horn is a more significant factor than either the thickness or dielectric constant of the foam; a low dielectric foam at a thickness of two inches at the location of the feed's thermal gap provides comparably improved S11 results relative to a window with one inch thick foam under the same conditions, but a much greater and more stable improvement to the overall efficiency of the feed.

Introduction

The new ultra-wideband (UWB) receiver for the Green Bank Telescope will be used in high-accuracy pulsar timing experiments to predict gravitational waves by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav). This receiver also has applications in array technology with the potential to reduce the cost per antenna, as well as in very long baseline interferometry (VLBI) experiments to identify spectral lines with unknown redshifts (Bulatek 2020). The design for this receiver has been modeled in CST Microwave Studio and the efficiency has been optimized as the group has developed more understanding about the practicalities and limitations of the design, but there are still parts of the model that merit further investigation, such as the thermal gap and the size and thickness of the quartz window (White 2020), which has been the focus of this work.

The quartz window is a critical component that provides impedance matching across the thermal gap, a vacuum seal for the cryogenically cooled components, as well as protection against the weather for the sensitive components inside. The vast majority of the model was optimized before the project described here was started, but the quartz window can be further improved. The original model uses a single thick spherical cap of solid quartz laminate. This shape is a compromise between using a flat disc, which is easy to construct but weak against vacuum pressure, and a hemispherical dome, which provides the best strength against the vacuum, but is very difficult to construct (Simon 2019). Because the region inside the window is vacuum and cryogenically cooled with liquid helium, the quartz must be thick enough to withstand 20,000 pounds of pressure and capable of withstanding a 15 K thermal strain (Simon 2019). This is problematic, because the thick quartz laminate causes an impedance mismatch between the air, the window, and the vacuum. The air and vacuum both have a dielectric constant of 1, while the thick quartz has a dielectric constant of about 3.8 (White 2020). The proposed method to improve this mismatch is by sandwiching a strong, thick RF-transparent support foam between a thin inner and outer layer of quartz. The foam should have little to no effect on the transmission of radio waves, and the thinner quartz layers reduce the dielectric constant and improve the impedance match. This project models this proposed modification of the quartz window.

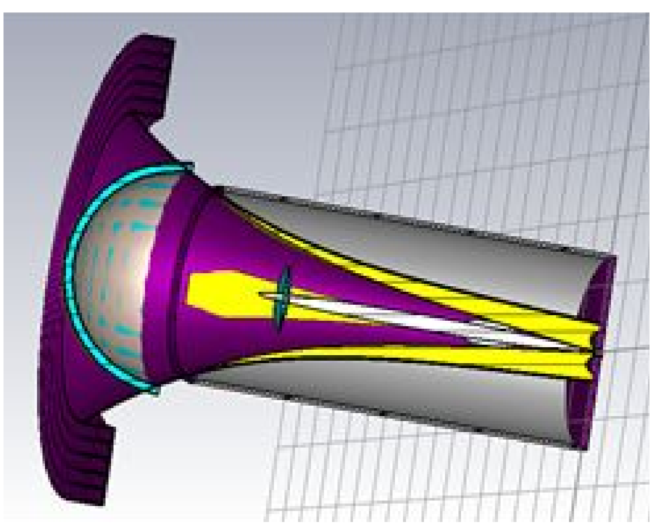

Figure 1. A cross sectional view of the feed horn as modeled in CST Microwave Studio. The full sized feed horn is approximately 1.5 meters long. The quartz window in question is the cyan and tan dome at the left of the model; all elements contained inside the window and grey can will be cryogenically cooled to 15 K, while external components will remain warm at ~290 K.

Methods

A new "sandwich" model for the window was created in CST Microwave Studio, and replaced the existing window in the model for the feed. The thick inner support foam was tested with dielectric constants of 1.0, 1.2, 1.4, 1.6, and 1.8, for each of three spatial configurations. The first configuration tested replaced the original window with a sandwich window using a one-inch thick support foam, in the original location of the window. The second and third configurations shifted the window 80 mm deeper into the feed, such that the inner quartz layer could be constructed to have its edge inside of the thermal gap[1], as reducing the width of the thermal gap is also expected to improve the impedance match. The second configuration tested a one inch thick foam layer at each of the dielectric constants, while the third configuration tested a two inch thick foam layer at each of the dielectric constants, because a thicker foam should be better able to withstand the required thermal and mechanical strain. For all simulations, both the inner and outer quartz layers were maintained at a 2 mm thickness. This was a somewhat arbitrary choice, based on previous experiences fabricating fiberglass-walled components.

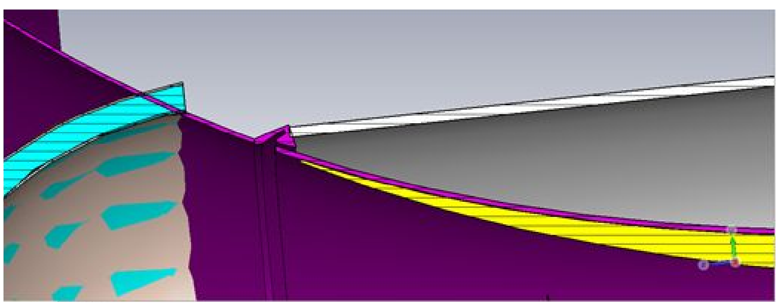

Figure 2a. The first condition under which the five dielectric constants were tested, with one inch thick support foam in the original window location shown in cyan,the inner quartz layer in tan, and the horn wall in purple.

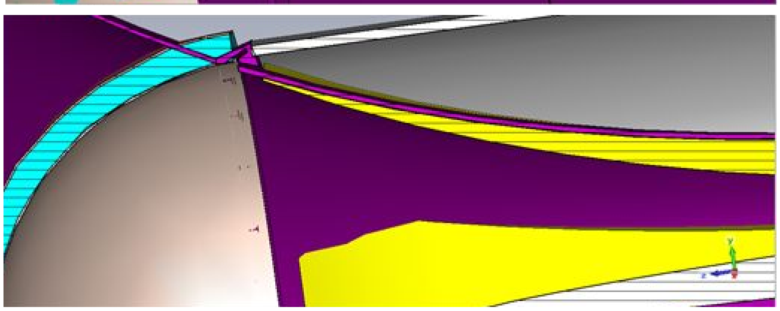

Figure 2b. The second condition under which the five dielectric constants were tested, with one inch thick support foam shown in cyan, where the entire window has been shifted into the thermal gap, shown in purple. The inner quartz layer is shown in tan.

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[1] Note that although the simulations placed the window in such a location so as to make it possible to have the inner quartz layer inside the thermal gap in practice, the inner quartz layer was not actually inside of the thermal gap in the simulations described here, because I could not figure out how to make the curvature of the window fit the curvature of the thermal gap in the model. Before proceeding with a prototype, I would recommend that someone with more experience in CST make the appropriate changes and verify that their results are in agreement with those presented here.

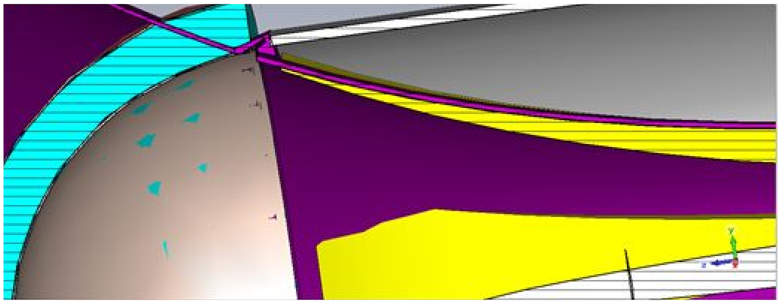

Figure 2c. The third condition under which the five dielectric constants were tested, with two inch thick support foam shown in cyan, where the entire window has been shifted into the thermal gap, in the same position as in Figure 2b.

The simulation was run in CST Microwave Studio, with farfield results exported to Matlab to calculate efficiency of different elements of the feed. Four types of sub-efficiencies were calculated, and the product of these values returns the overall efficiency of the feed. The results of the Matlab calculations[2] were then imported to Python to compare results across different simulations. Two metrics were used to evaluate results. First, the S11 results across the band were assessed to verify that the values were below -10 dB across the band. Above this value, too much power is reflected out of the feed, and standing waves are generated (White 2020). If the S11 values look good, then we proceed with efficiency calculations. The desired goal of the pulsar observation community is an average efficiency of 70% across the observation band, but with an observation band as wide as what we are designing for the GBT, this is not feasible (White 2020).

The four sub-efficiencies are calculated according to Collin (1984) and Kildal (1985). The illumination from equation 10 in Collin's paper describes the magnitude of the y-directed aperture field in relation to the magnitude that would be produced by a uniformly illuminated aperture radiating the same component of power. We also use equation 9 from the same paper to quantify how the phase error of the feed's copolar field contributes to the y-directed aperture field (Collin 1984). Kildal's work builds on Collin's, and provides our other calculations. Equation 23 accounts for losses due to light hitting the ground outside the beam, and not the dish itself, and describes the power within the subtended angle relative to the total power (Kildal 1985). Equation 24 describes the power of the copolar field relative to the total power within the subtended angle, and accounts for losses due to the cross-polarization of the beam, all for circular polarizations, and equation 25 modifies 24 to work for linear polarizations and agree

[2] Calculations done in Matlab were executed by a GUI written by Steve White.

with Collin (Kildal 1985). Finally, the illumination efficiency derived from both the copolar and cross-polar power output is calculated by equation 26, and becomes unity with a uniform aperture illumination (Kildal 1985). The product of each of the values these calculations produce at each interval tested results in the total estimated efficiency at that interval, allowing us to estimate the total efficiency across the band.

Results and Discussion

Figure 3 compares the results of each of the three window conditions against the original model for each dielectric constant tested. For each value of ϵ tested, the windows shifted in toward the thermal gap outperformed both the original model and the sandwich model with window in the original position in an S11 comparison. Consequently, the results of the sandwich window in the original position will be excluded from further analysis, as this model does not significantly achieve the goals of the project[3].

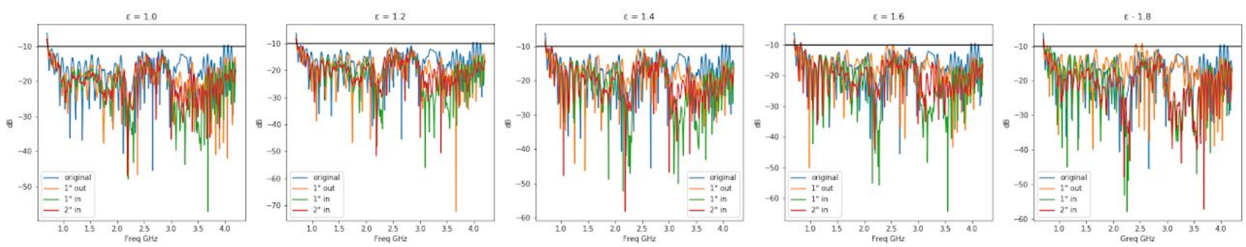

Figure 3. Each plot compares the effect of window condition at a given dielectric constant. For all plots, the original S11 spectrum is given in blue, the window in condition one is given in orange, the window in condition two is given in green, and the window in condition three is given in red.The upper limit target value of -10 dB is given in black. Across all plots, the window in condition one tends to track more closely with the original model, while windows in conditions two and three show marked improvement across the band for any dielectric constant tested.

In order to assess how the thickness of the support foam affects the impedance match, Figure 4a shows the S11 of all dielectric constants tested for the window in the second condition, while Figure 4b shows the S11 of all the dielectric constants tested for the window in the third condition. At higher frequencies, the one-inch foam performs better than the two-inch foam, though the two inch foam also shows a distinct decrease from the original model. At lower

[3] Note that the window in condition one does produce acceptable S11 results, but they do not deviate significantly from the original model, as the windows in conditions two and three do.

frequencies, the two-inch foam outperforms the one inch foam, and because the two inch foam significantly outperforms the original model at the high end of the band too, it is a strong indicator that a thicker support material of any dielectric constant from among those tested is ideal for both the mechanical strength and the impedance matching of the system. It is important to recognize, however, that both thicknesses of foam tested produce satisfactory S11 results.

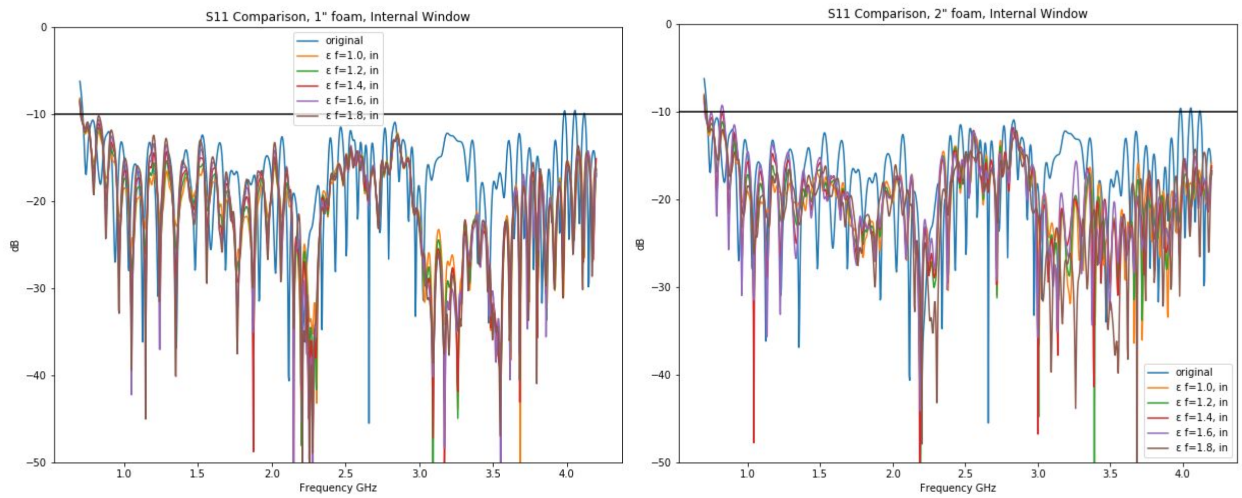

Figure 4. Figure 4a, at left, compares all dielectric constants tested in condition two, while Figure 4b, at right, compares all dielectric constants tested in condition three. Regardless of dielectric constant chosen, the performance of the window in each condition is notably improved from the original model (original results shown in blue). The window in condition two shows S11 results that are lower at the higher end of the band than those in condition three.

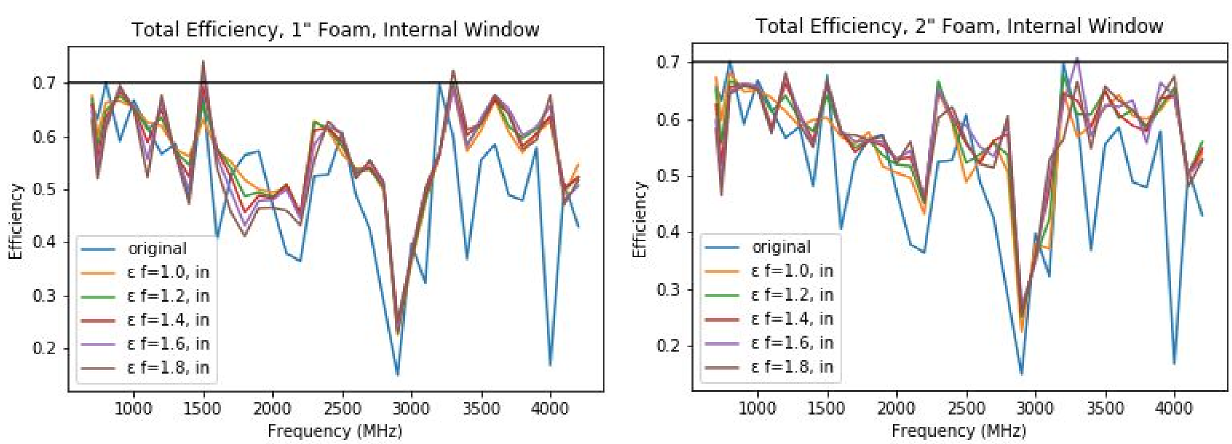

Figure 5. Figure 5a, at left, compares the total efficiency of the window in condition two for all dielectric constants tested, while Figure 5b, at right, compares the total efficiency of the window in condition three for all dielectric constants tested. In both plots, the efficiency of the original model is shown in blue. In both conditions, regardless of the dielectric constant chosen, the performance exceeds the original model, but condition three appears more stable at higher values across the band than is seen in condition two.

Figure 5a presents the total efficiencies calculated for each dielectric constant for the window in condition two, while Figure 5b does the same for the window in condition three. For all dielectric constants tested, the two inch foam has a more stable efficiency that trends higher across the band than either the one inch foam, or the original model, though the one inch foam does in two instances exceed the 70% goal of the pulsar community. However, a more stable efficiency that trends higher less erratically may be more favorable. Therefore, regardless of the dielectric constant chosen for the foam, the thicker foam has better performance.

Additional S11 and efficiency data not included in this discussion is included in the appendix.

Conclusions and Future Work

The results have demonstrated that it is possible to improve the impedance match across the window without compromising, and while even improving the efficiency performance. Moving forward, it will be important to simulate the feed with the window at thicknesses greater than two inches before beginning construction on a prototype to verify the trend shown in the results presented here, that thicker foam yields better S11 and efficiency results. A very small sample of only two thicknesses was utilized in this study, and in anticipating material failure under strain, it will be critical in designing the prototype to understand the upper limit on foam thickness. Following further simulations to find this upper limit, the next step is to construct prototypes to stress test different possible materials and thicknesses, as well as to optimize the fabrication technique.

The group at GBO has previously tried vacuum infusion techniques, whereby vacuum suction is used to uniformly draw epoxy through the quartz fabric, but they repeatedly found that all of the prototypes manufactured in this way had microleaks (Simon 2019). Instead, a hand-layup technique may be more effective, where the quartz fabric is stretched over a mold and the epoxy is painted on by hand, usually using several layers of fabric. This is a very labor-intensive process which requires practice to avoid holes, cracks, or air bubbles, but this method has generally been observed[4] to be much more reliable than vacuum infusion. It is also

[4] Observation based on research conducted external to the GBO/NRAO REU program.

possible to patch holes discovered after the epoxy has cured, by simply sanding the existing laminate, and then painting a new layer of fabric and epoxy over it. Patching a fabric-infused shell or hand-laying a few layers of fabric on a pre-built foam core may ease fabrication, but when adding more epoxy to patch holes, a piece of fabric should always be used with it, or else a thicker epoxy region will fail under both mechanical and thermal stress. Prototypes should be constructed on a small scale to solidify confidence in the fabrication technique and for preliminary stress testing, before transitioning to full scale variations. Testing must ensure that the window prototype is capable of withstanding the required 20,000 pounds of vacuum pressure and 15 K cooling. Once a satisfactory model is found, it will likely require additional external weatherproofing as well. Determining the necessary properties for such weatherproofing conditions is beyond the scope of this work.

Regardless of the foam thickness tested, both the S11 and efficiency results indicated that for all dielectric constants tested, there was an improvement over the original window design and location. Using the sandwich model, window thickness and location appears to have a more significant effect on feed performance than the dielectric constant, as five values were tested, and all performed comparably. This indicates that there is much flexibility in choosing a material to use as the foam support layer, especially as mechanical testing eliminates some options and necessitates others. Despite this flexibility in material parameters, there is clear evidence that the location of the window at the thermal gap is critical to improving performance. Changing the dielectric constant of the support foam demonstrates little deviation from the original model if the window location is not shifted deeper into the feed. Mounting the window to the feed at this location must therefore be an additional consideration for future construction efforts. It may also be worthwhile to investigate multiple layers of foam and fiberglass to further bolster the strength of the system.

Acknowledgements

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Works Cited

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Appendix

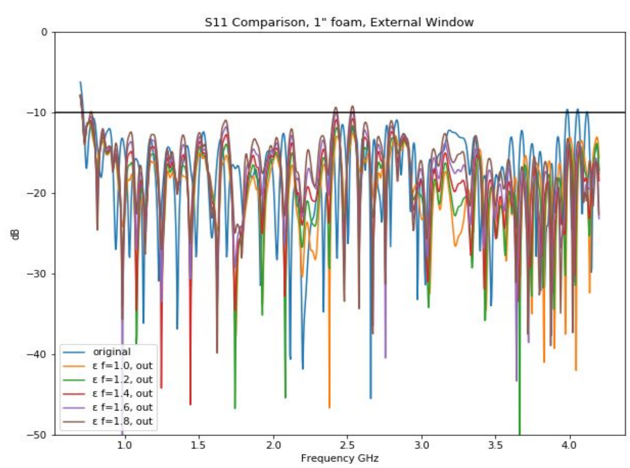

Figure A1 compares the S11 results of all dielectric constants tested for the window in condition one, with results of the original model shown in blue. At higher values of dielectric constant, the S11 performance is worse than the original model. This emphasizes that the location of the window is a more significant factor than either the foam thickness or dielectric constant, and the window should be placed inside the feed's thermal gap, instead of the location in the original model.

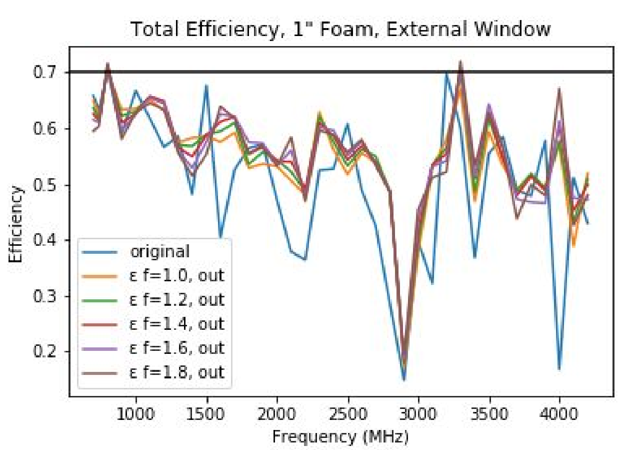

Figure A2 compares the total efficiency results of all dielectric constants tested for the window in condition one, with the result of the original model shown in blue. Although the efficiency of the sandwich window shows an improvement over the original model, regardless of the dielectric constant, and even exceeds the 70% goal of the pulsar community, the S11 results from Figure A2 are unsatisfactory enough to invalidate these efficiency results.