Designing and testing an ultra-wideband receiver for the Green Bank Telescope

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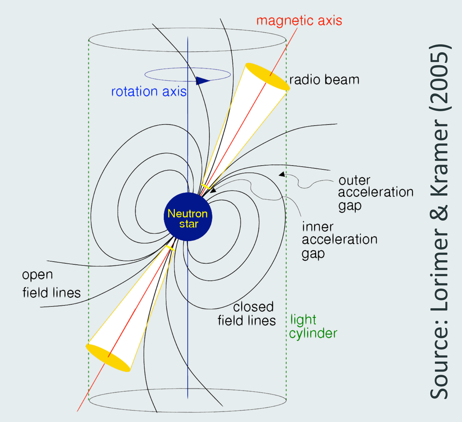
Abstract

We determined the predicted efficiency and basic circuit characteristics of a new ultra-wideband (UWB; 0.7 to 4.2 GHz) receiver for the Green Bank Telescope (GBT). The UWB receiver has been in development for several years and it represents a movement towards new-age receiver technology for Green Bank Observatory. The design features a quad-ridged, flared feed horn and utilizes a corrugated skirt and a quartz spear to extend the receiver's bandwidth. We find the predicted efficiency of the receiver to be around 60 to 70% at lower frequencies and above 50% at higher frequencies. The S_{11} values for the UWB receiver are better than –10 dB across the entire bandwidth, and performance is only predicted to degrade slightly at 2.8 GHz with the inclusion of a waveguide window. The UWB receiver will be used by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) to perform pulsar timing experiments using the GBT with greater sensitivity than before. Secondary science drivers for the receiver include the detection of broadband fast radio bursts and other radio transients as well as the study of radio recombination lines.

Motivation

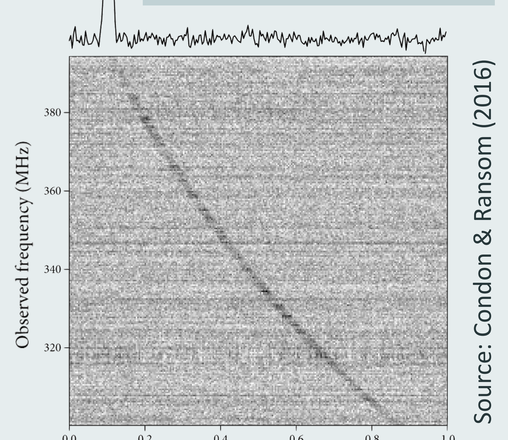
Pulsars are radio-bright, rapidly rotating neutron stars. NANOGrav's mission is to time the rotation of pulsars and detect gravitational waves using variations in their rotational periods. Radio signals from pulsars are subject to frequency-dependent **dispersion** on their path to the Earth.



Above: a cartoon picture of a pulsar's anatomy.

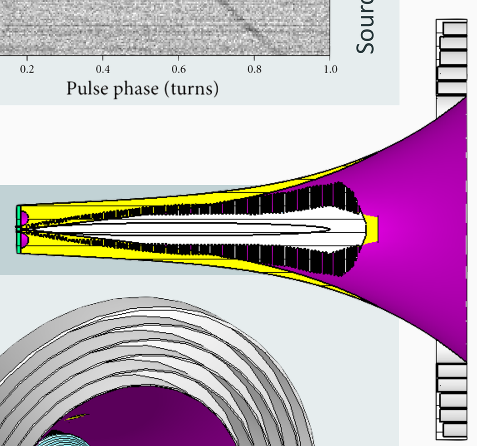
Thus, pulsars must be observed using a wide range of radio frequencies to accurately measure their periods. The GBT currently uses its 800 MHz and L-band receivers at different times to observe a single pulsar, which reduces timing accuracy. The sensitivity of pulsar timing observations for the GBT can be improved by a new receiver that can perform wide-band pulsar observations **simultaneously.**

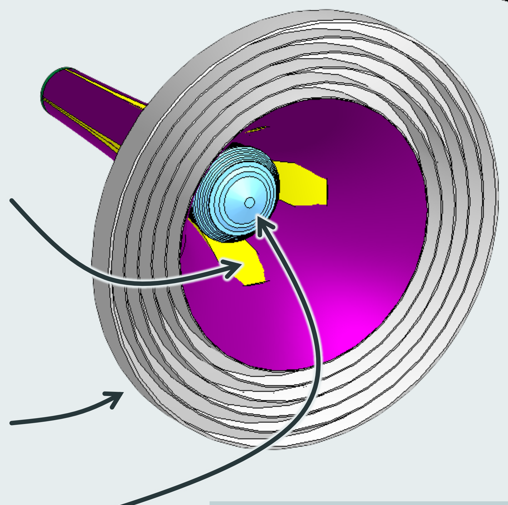
Below: an observation of a pulse spread out in frequency.

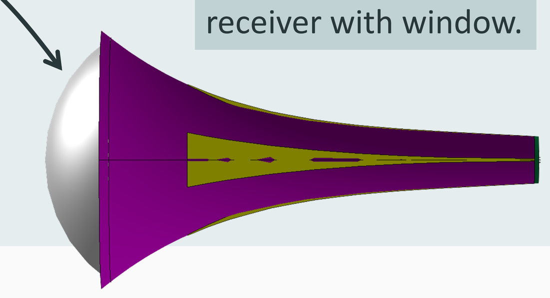


Specifications

- Frequency range: **0.7 – 4.2 GHz**
  → Bandwidth: **3.5 GHz (6:1)**
- Dimensions: **1.5 m × 1 m**
- Four symmetrically-spaced **ridges** lower the cutoff frequency of the dominant mode in the horn.
- To reduce spillover at lower frequencies, a **corrugated skirt** encircles the receiver's aperture.
- In the throat, a **dielectric spear** reduces under-illumination at high frequencies.
- A quartz fabric **window** will allow radiation into the receiver.
- Designed in CST Microwave Studio by Steve White.







Above: side (above) and isometric views of the UWB receiver. **Below:** side view of receiver with window.

References

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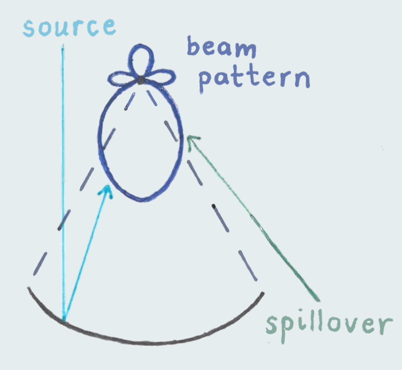
Results

Efficiencies

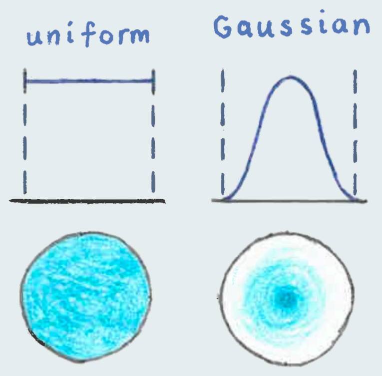
The total **feed efficiency** (e_{tot}) of an antenna is the proportion of the radiation incident on the telescope which gets received and recorded. e_{tot} depends on the shape of the receiver's radiation pattern, which depends on the receiving frequency. The feed efficiency can be divided into **sub-efficiencies** due to spillover (e_{sp}), inefficient dish illumination (e_{ill}), phase errors (e_{ph}), and cross-polarization (e_{xp}). The **balance** between spillover and illumination is the primary predictor of the receiver's efficiency. e_{tot} is the product of its sub-efficiencies:

$$e_{tot} = e_{sp} \cdot e_{ill} \cdot e_{ph} \cdot e_{xp}$$

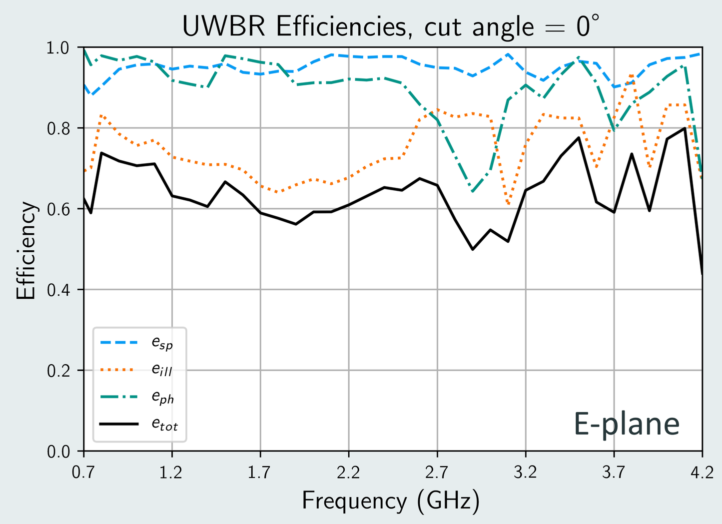


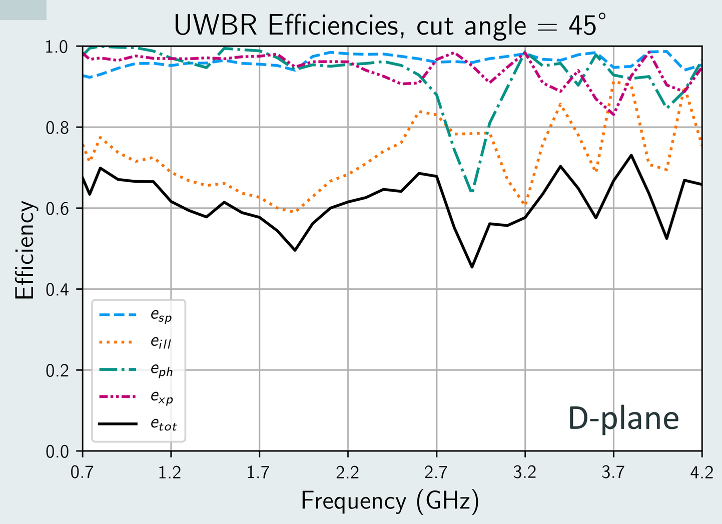
Above: a depiction of how both source and spillover radiation reach a receiver.

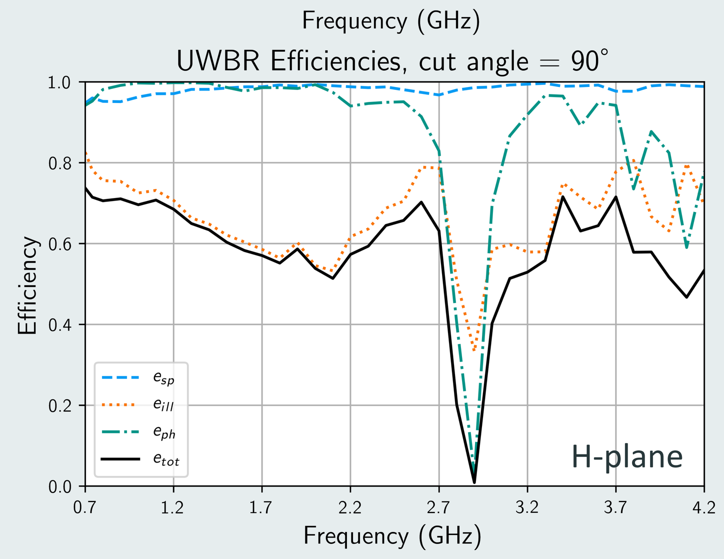
The resulting total feed efficiency will be between zero and one. The design goal for the UWB receiver was to achieve e_{tot} between 60 and 70% at the lower end of the frequency range and above 50% at higher frequencies. We calculated each sub-efficiency as a function of frequency given far-field radiation patterns from our CST model. Since radiation patterns are three dimensional, we sliced through them at three standard azimuthal angles to calculate e_{tot}. Our design goals mentioned above are close to being achieved across the entire frequency band for all cut angles, as can be seen in the efficiency plots below.



Left: a drawing of uniform and Gaussian illumination patterns in 1D and 2D. Designing a radiation pattern to perfectly edge-match its reflector is not possible, so the balance between spillover and illumination is important.

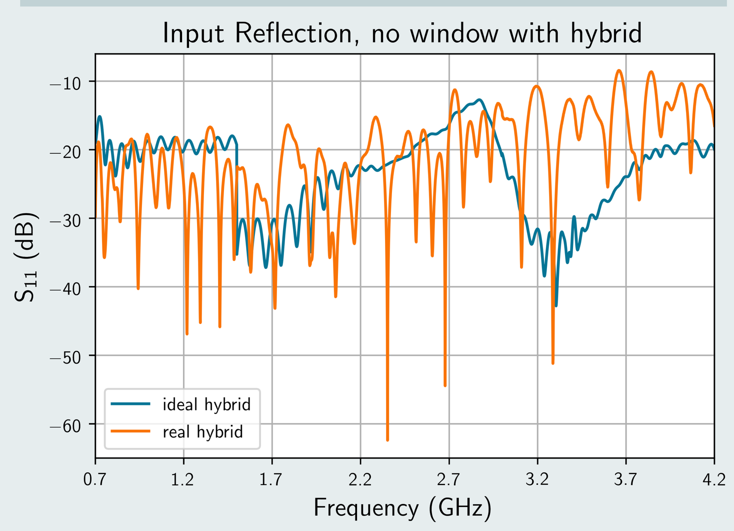






Above and left: total efficiency (solid line) and sub-efficiencies (non-solid lines) for the receiver at three far-field cuts. A large dip in phase efficiency causes reduced performance (e_{tot} = 0.03) at 2.9 GHz in the 90° cut.

Below: the S_{11} parameters for the receiver and hybrid combiner without the window included.

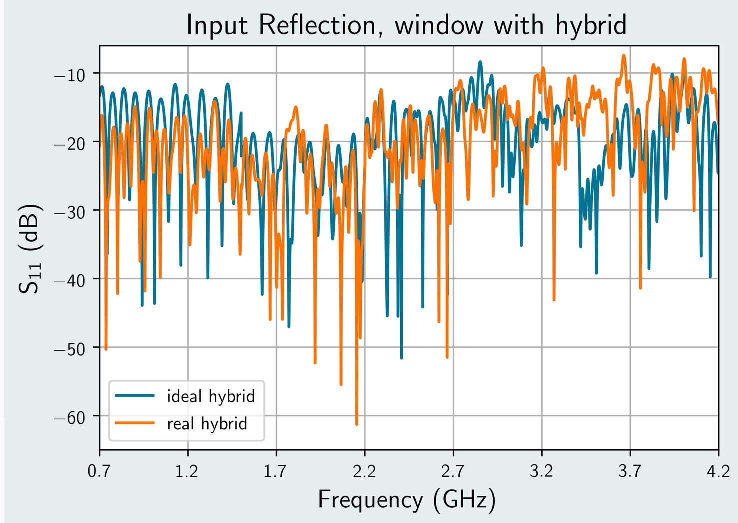


Reflection

The UWB receiver will be housed in a metal dewar and cooled with helium to 15 K. A radio-transparent quartz fabric window will be placed on the front of the feed horn to ensure that radiation can still reach the receiver. Because of the receiver's large size, the window must be **curved** in order to withstand the vacuum force. We modeled the nonstandard window shape with the receiver in CST, along with real data for an additional feed component (a hybrid combiner), to measure the performance of the receiver with the window included.

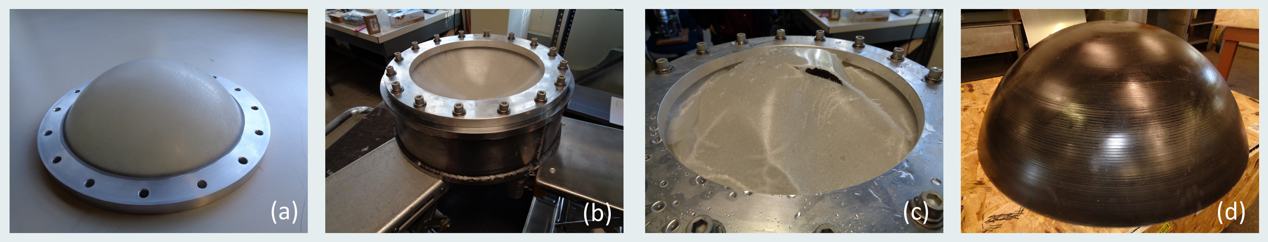
Results (continued)

Treating the receiver as a transmitter, the **S_{11} parameter** for the window represents the fractional amount of signal reflected back from the window. Our design goal for the S_{11} parameter of the feed with a window included was –10 dB or better. A signal that is 10 dB lower than another signal is one-tenth as powerful. The S_{11} parameter across the bandwidth is not degraded significantly when the window is included with the receiver in the model.



Left: the S_{11} parameters for the receiver and hybrid combiner with the window included. Note the near compliance with the design guideline (less than –10 dB).

Since the window must withstand large forces due to vacuum pressure in the dewar, **destructive tests** must be performed. The latest prototype burst at 66 psi, as expected.



Above: (a) shows the 8" diameter prototype. (b) shows the prototype in the pressure vessel. (c) shows the prototype after bursting. (d) shows a 40" diameter spinned dome which will be the mold for the final window. Images courtesy of Bob Simon.

Conclusions

- ➤ The ultra-wideband receiver **meets its efficiency design goals** in its "frozen" design state.
- ➤ The waveguide window **has only a minor effect** on the circuit properties of the feed horn.

Future Work

Current Project Status

- ✓ All **mechanical drawings** for the feed and its components are complete. Fixtures have been fabricated for holding the components in place while they are machined.
- ❑ The ridges will be the first components to be fabricated.
- ⇢ Mechanical drawings have been sent to Art Symmes at NRAO Charlottesville for **thermal modeling** of the feed and the dewar that will house it.
- ⌛ The software development for the UWB receiver **backend** is also progressing. The control software for the receiver will be an extension of the existing VEGAS backend. Prototyping is beginning on the manager for the receiver and physical upgrades to the server room are in progress.

Modal-Based Receiver Design

- Even though the effect of the reduced efficiency at 2.9 GHz can be mitigated, its origin still sparks curiosity. All the undesirable radiation pattern characteristics that stem from the UWB receiver's geometry are most likely related to the **imbalance of higher-order mode excitation** in the feed horn.
- Beukman et al. (2016) present a design technique focused on understanding the modal content of the feed horn to determine the ideal parameters for the horn geometry without brute-force optimization. As my senior honors thesis, I will determine the modal makeup of the radiation patterns for the UWB receiver to inform GBO's receiver design process.

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