Noise Performance of the New ATA Cooled Feed

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We describe recent noise tests of the new upgraded ATA feed. The goal has been to develop a feed that has both more bandwidth and substantially lower noise temperature than the current ATA feeds. The new feed succeeds very well in both of these properties. For context, we begin with a brief description of the ATA antenna and the current feed and Low Noise Amplifier.

The ATA Antennas:

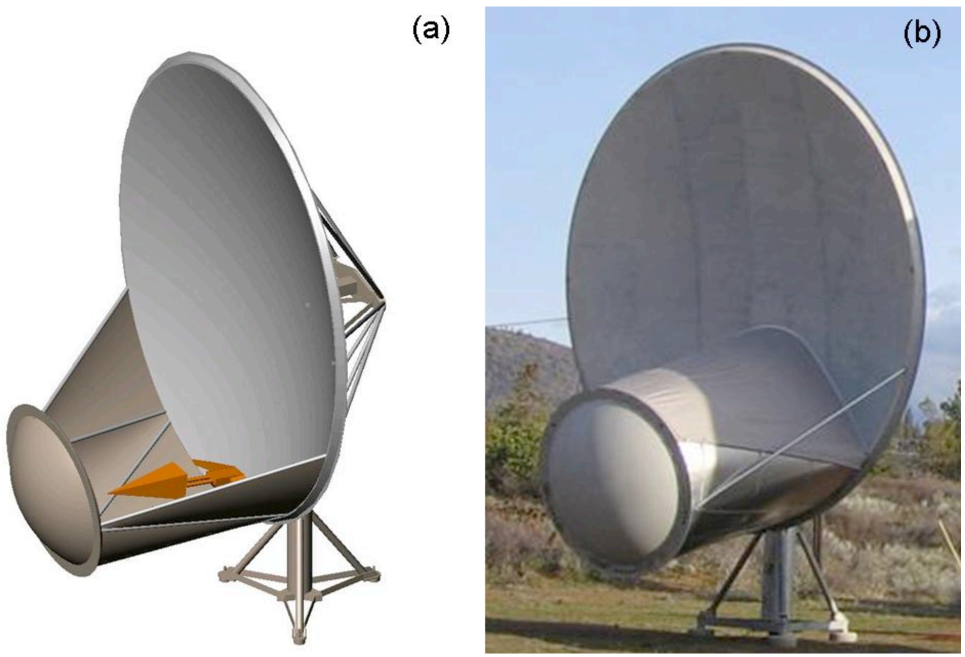


Figure 1 shows the offset Gregorian ATA antenna. The drawing on the left shows the two mirrors of the Gregorian with the log-periodic feed at its focus. Also shown is the approximately cylindrical aluminum shroud that lies between both mirrors and insures that the feed does not see the ground (and its ambient radiation) at any elevation of the antenna. The photograph on the right shows one of the antennas with the Sunbrella® fabric radome cover in place. The material is very transparent to radio waves but is also tough and resistant to weather. The feed can be moved along its axis for accurate focusing at any one frequency, but because of the long focal ratio of the feed and hence its large depth of focus, accurate focusing is not critical. For example, if the new feed is located for a 12 GHz focus, the antenna gain is only 1 dB down at 1 GHz and at 15 GHz.

The Current Feed System:

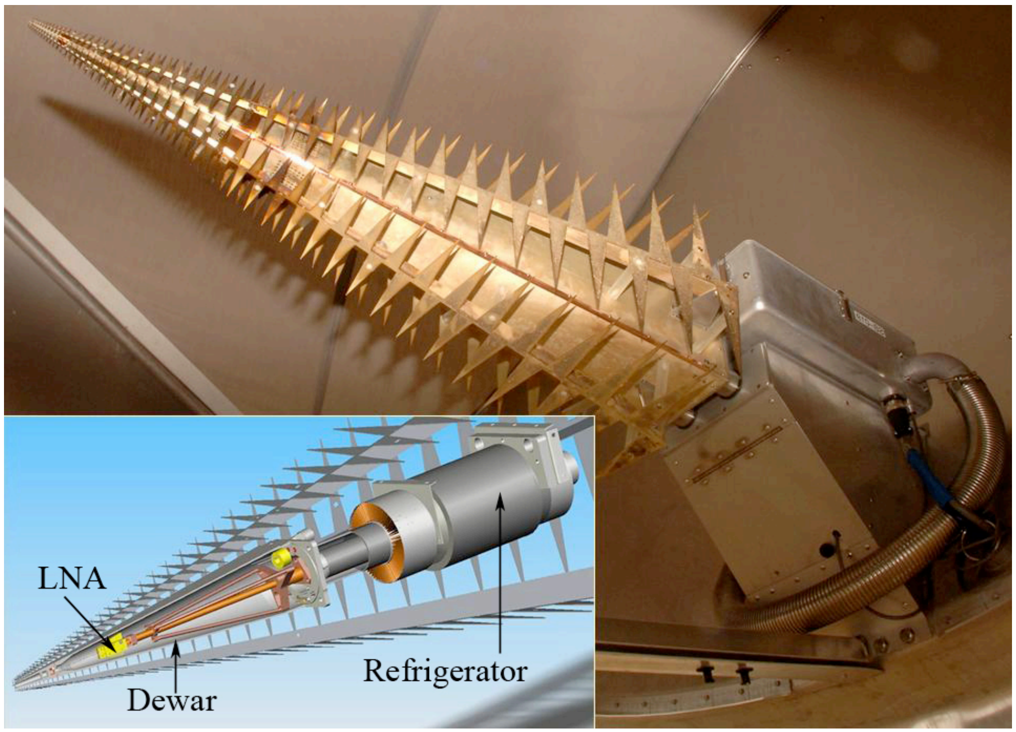


Figure 2 shows a photograph of a current ATA feed in place and also, in the lower left corner, a drawing of the feed without all of its pyramid and with just one of its linear polarizations. The cooler lowers the temperature of the LNA in its dewar to about 70K. The feed connecting leads outside of the dewar and the feed are at room temperature which leads to noise temperatures higher than desired. The log-periodic feed has a scaling factor of 0.96. It has a nearly constant gain, pattern, and impedance over that period, and so its properties are nearly constant over a frequency range that is limited on the short-wave end by the size of the structure at its small end and on the long-wave end by the structure size at its large end.

Gain of the LNA WBA13 by Sandy Weinreb:

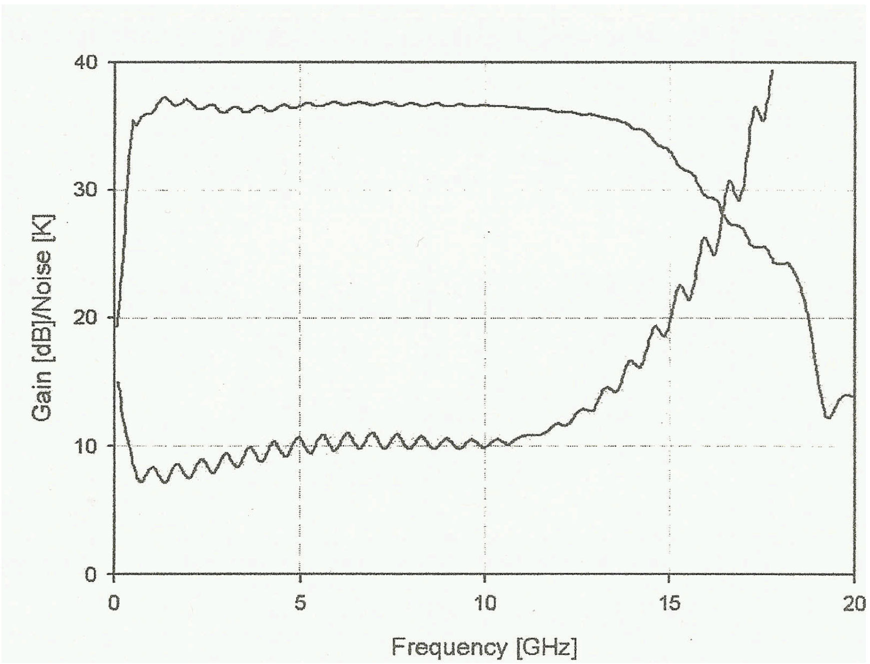


Figure 3 shows both the gain and the noise temperature of the WBA13 input amplifier as a function of frequency. The left hand scale is both gain in dB and noise temperature in degrees Kelvin of the amplifier. The small scale ripple is the result of a -10 dB mismatch in the circuit coupled to the amplifier.

Measurement of Performance of the Cooled Feed in the Lab:

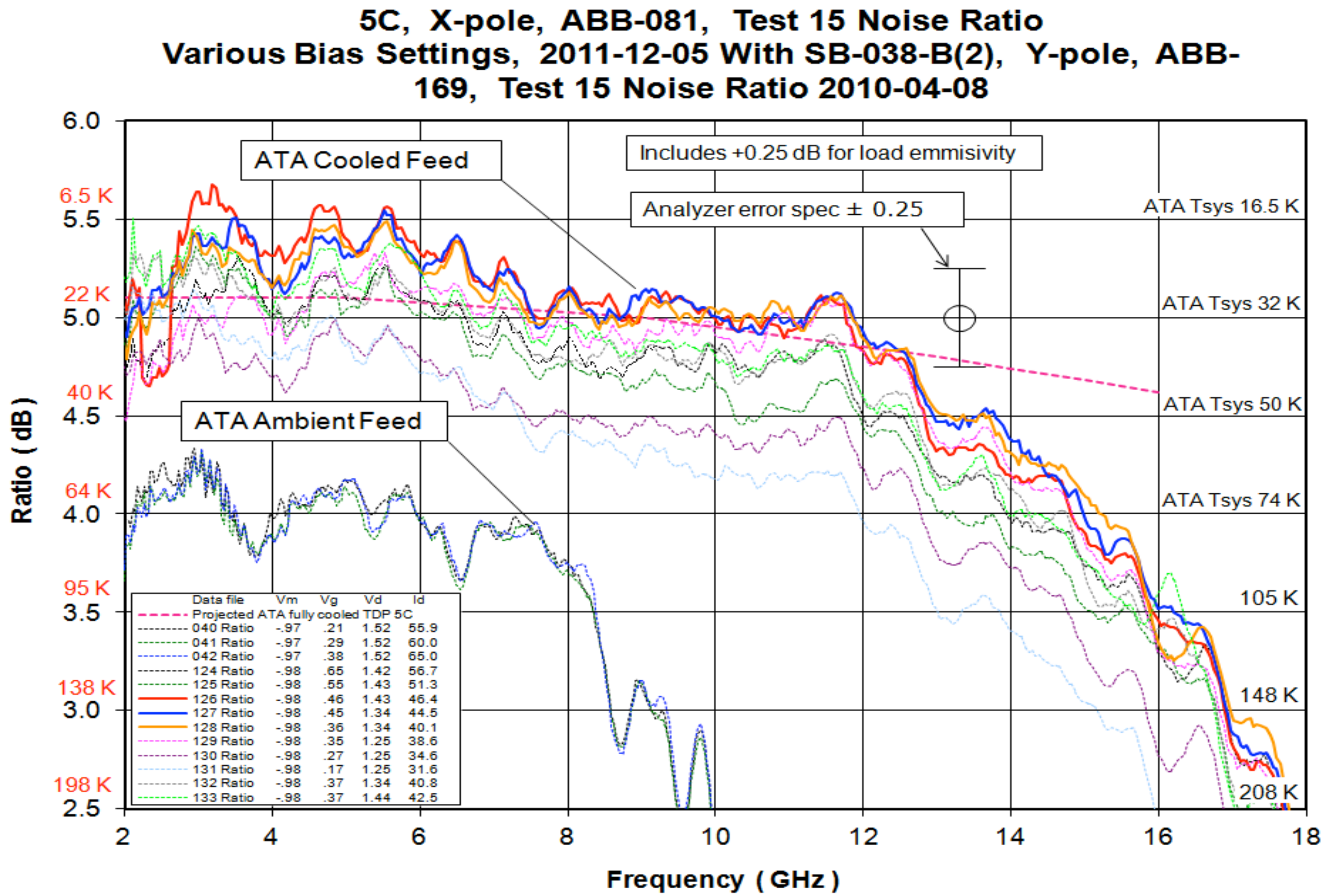


Figure 4 shows plots of Y-factor curves as a function of frequency. The Y-factor is the ratio of amplifier output power with the feed coupled to an ambient temperature load and with it coupled to a liquid nitrogen (LN) load. The plot is in dB and is the difference of the two measurements. The left side ordinate is shown in dB with the corresponding receiver temperature shown in red. The ATA Tsys numbers on the right hand ordinate are total system temperatures with approximately 10K expected, the antenna background temperature, added to the feed temperatures to produce the total system temperatures. The measurements of the Y-factor are only good for frequencies above about 2.5 GHz. This is because we are only able to immerse the tip part, the high frequency part of the feed, into the warm and cold loads. This is illustrated in Figure 12, in which we can see the feed being tested in the screen room as it is immersed into the ambient load. Considerable experience with the current ATA feeds shows that the system noise in L Band, 1-2 GHz , is always lower than what it is near 3 GHz, as one would expect for this kind of system. Thus, these measurements provide an upper limit on the L-band noise.

(a) The curve in the lower left corner is a typical result for one of the current ATA feeds. The slightly different plots there are for different LNA bias settings.
(b) The upper curves are for a feed and LNA that is cooled to about 70K. The different curves are with different bias settings with the ones near the optimum high-lighted. We discuss below how the cooling of the new feed was achieved.

There is a correction of .25 dB added to compensate for the emissivity of the plane surfaces of the LN load and for a small leakage of the pattern in the back direction toward ambient temperature surfaces. The dashed line is the result of an a priori calculation of the expected Y-factor. The agreement is quite good except that the measured value is a little lower for 14 – 15 GHz. The many faint lines are for different bias settings. The high-lighted lines are close to the optimum. The reproducibility is excellent. The main source of uncertainty is the specified uncertainty of the spectrum analyzer differential error across the screen. We show that as the +/- 0.25 dB error flags. As noted above, the measured values only begin at about 2.5 GHz because it is only possible to immerse the tip part of the feed in the hot/cold loads. With our expectation that the noise at L-band should be less than what we measure here at 3 GHz, we anticipate L-band total system noise temperatures of 20 – 25 K with the cooled feed.

An examination of the literature on the sensitivities of other cm wave systems in operation shows that present values for the cooled LP feed are very competitive.

The New Cooled Feed:

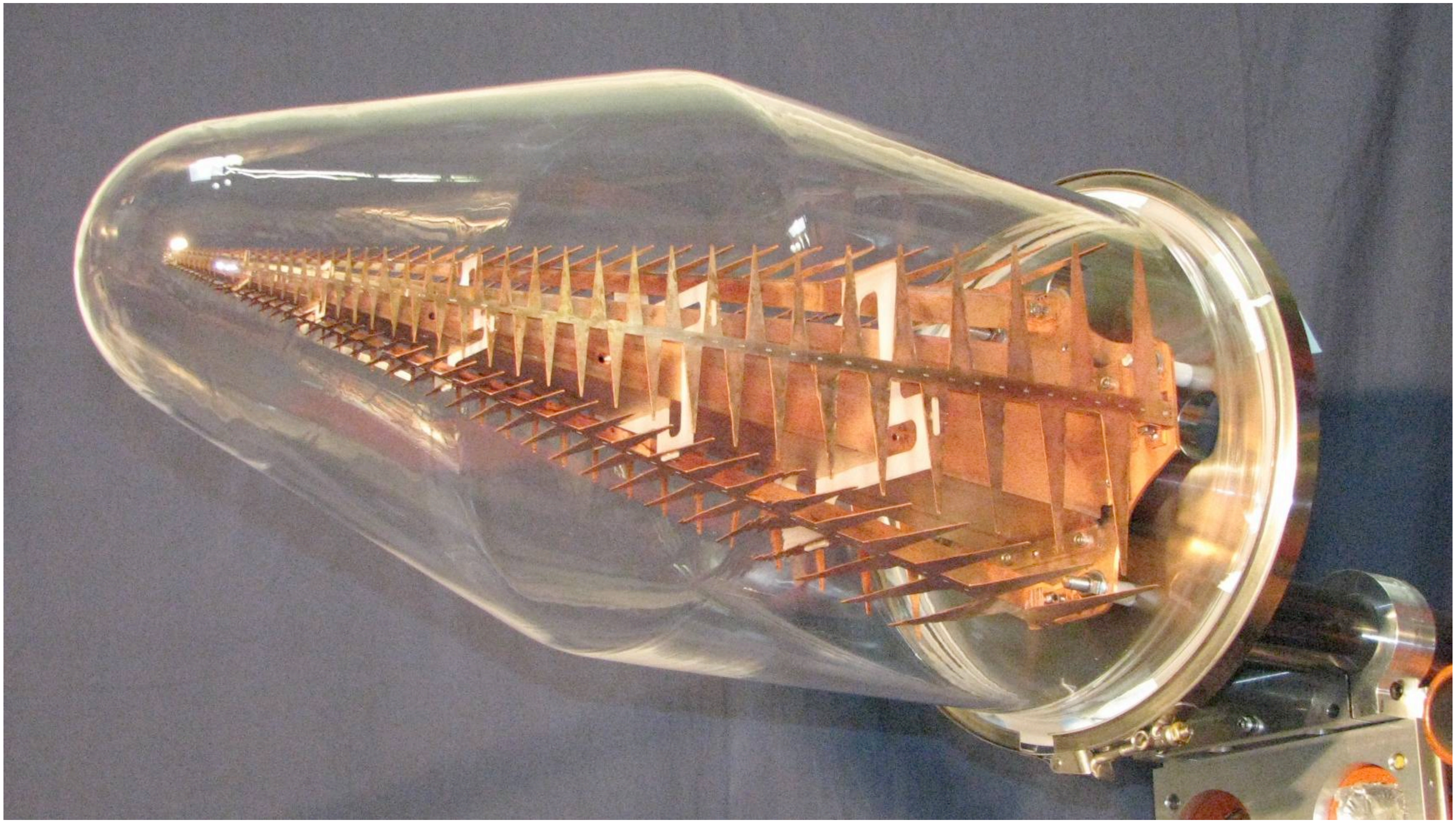


Figure 5 shows the new feed in an evacuated glass bottle with its bottom end coupled to a refrigerator (Sunpower Crystal GT cooler). Very clean copper with low infrared absorption (~2%) is used. The copper also has high thermal and electrical conductivity. The result is a total temperature rise from back end to tip of about 12K and a temperature of about 70K at the LNA location with about 5 watts of refrigerator power, as expected. The higher electrical conductivity as well as lower blackbody emission of the cold copper lowers the noise emission from the copper by more than an order of magnitude, just what is needed to lower the feed noise.

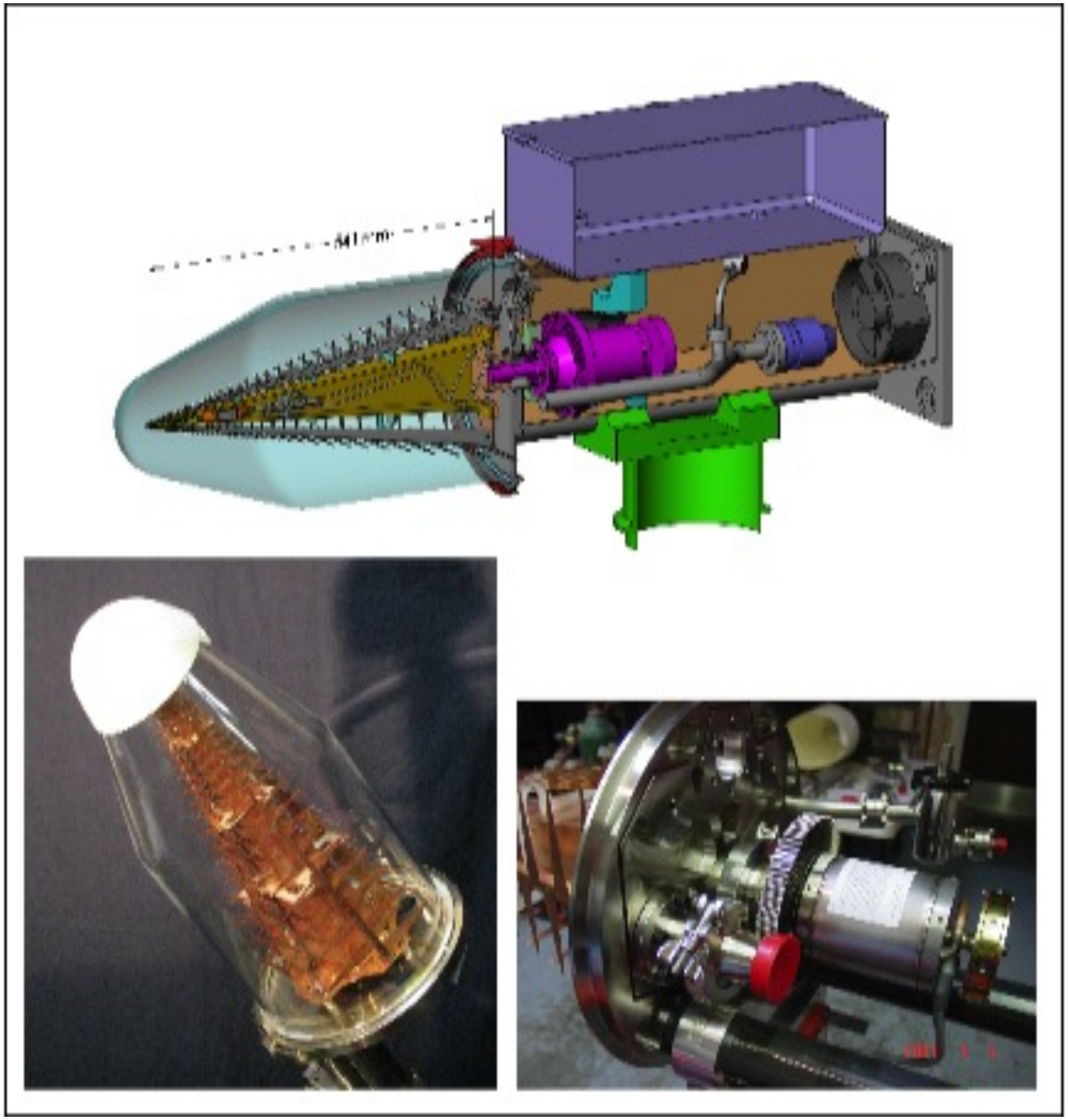


Figure 6 shows an overall system drawing, a photograph of the backend cryocooler, and another photograph of the feed in the glass bottle with a polyethelene cap. The cap is an antireflection cover to improve the radio transmission through the glass. The glass is 1 mm thick at its hemi-spherical tip, connects to a conical section that slowly expands toward its end, and connects to a cylindrical section that has thick walls. The thin part with its cap is over the high frequency part of the feed, and the low frequency part is covered by the cone and cylinder. The thicker parts add mechanical strength to the glass vessel without reflecting the low frequency radio waves.

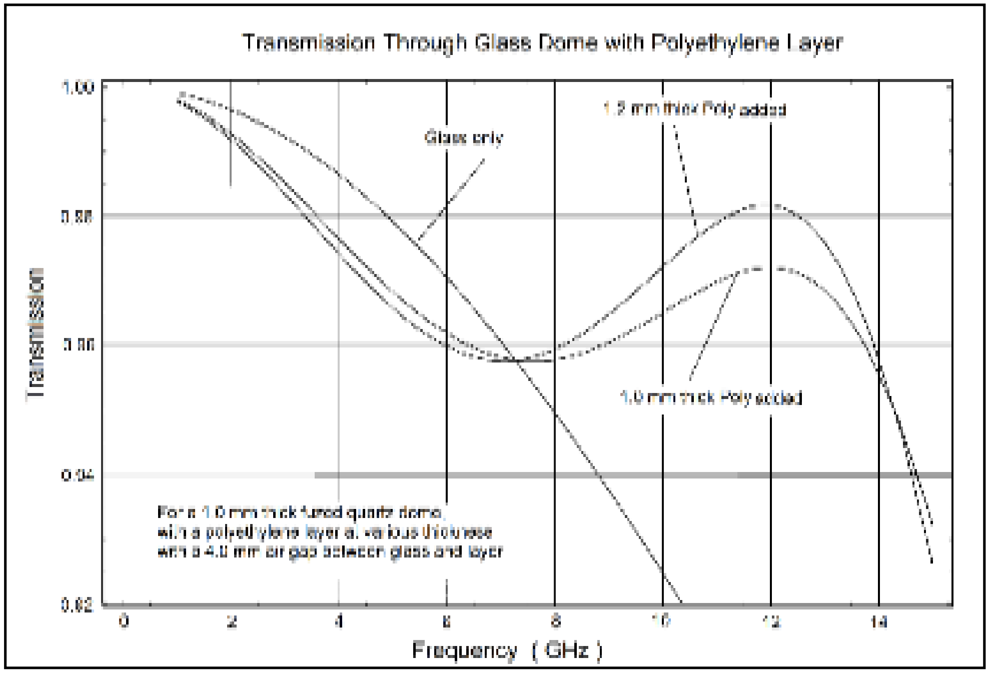


Figure 7 shows design curves for the hemispherical tip of the glass bottle and its polyethelene cap. The calculated transmission assumes that each frequency is emitted (or received) at the center of the sphere and is otherwise an exact EM calculation. The curve marked “Glass only” shows good transmission at low frequencies but substantially worse transmission at the higher frequencies. The other curves show the effect of the thin spherical layer of dielectric standing off from the glass. Only two of the many trial calculations are shown. The chosen curve, for 1.2mm of plastic at 4mm from the glass, gives the best overall transmission out to 15 GHz with the lowest residual transmission at midband, 5 to 7 GHz.

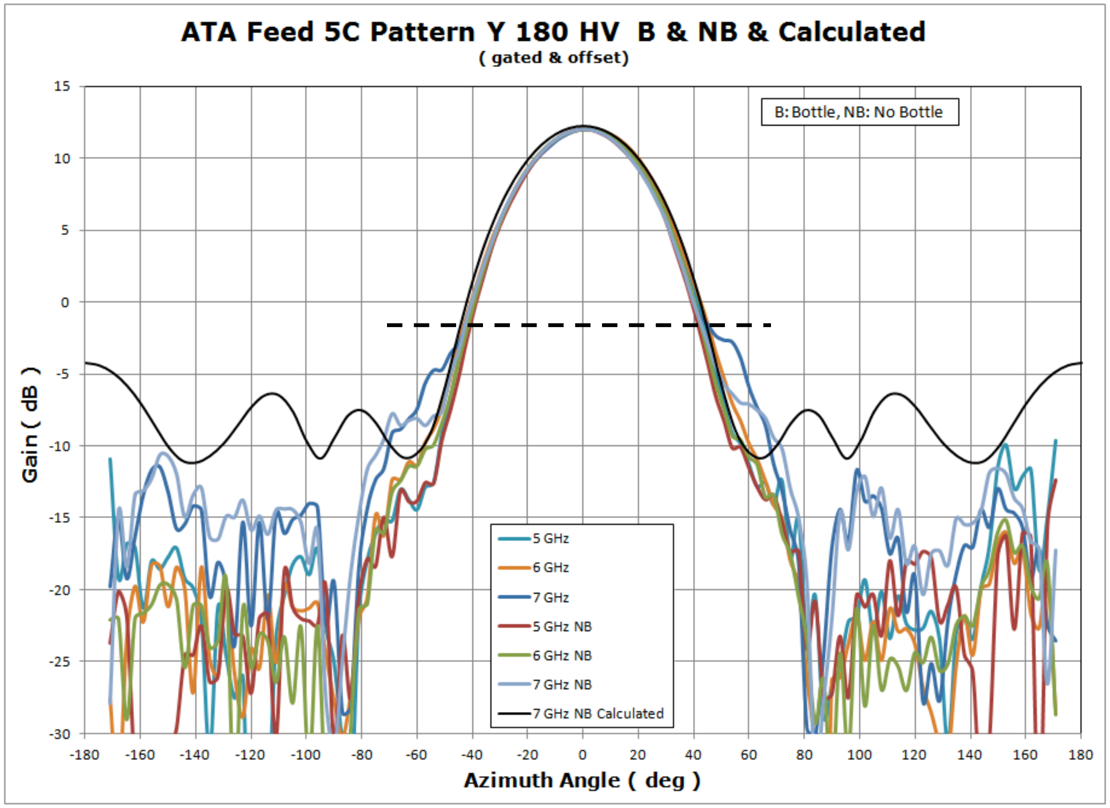


Figure 8 shows theoretical and measured patterns of the feed both with the bottle and plastic cap and without them for 5, 6, and 7 GHz. The patterns are for every azimuth at separations of 45 degrees. The dashed line shows the illumination level at the edge of the secondary. Both theoretically and measured the patterns are very symmetric at the secondary. Also there is little difference between patterns with and without the bottle and cap or between the measured and theoretical patterns. NB means no bottle.

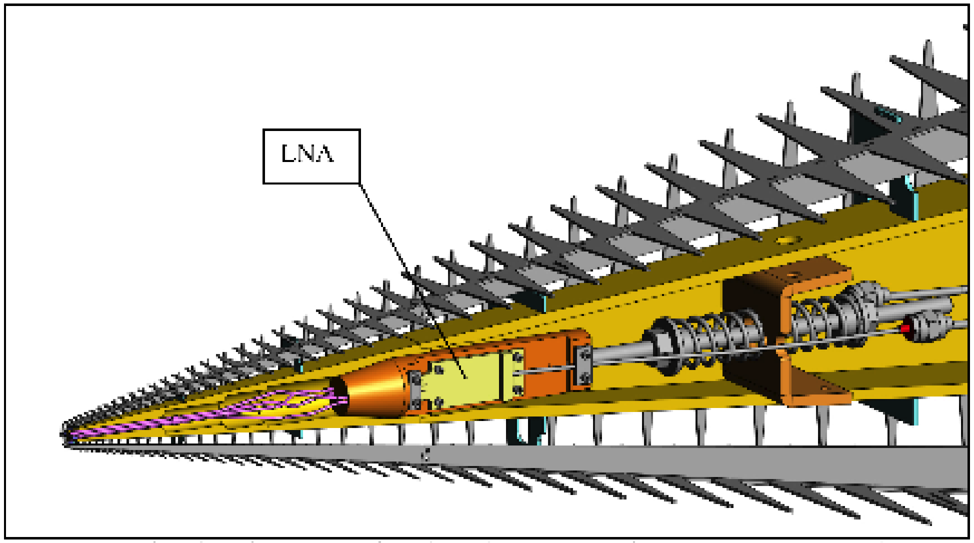


Figure 9 is a drawing of the new mounting of the LNA with small pairs of coaxial cables leading up to the feed input connections from the LNA for each polarization. These are small 95 ohm coaxial cables providing a 190 ohm balanced connection between the LNA and the feed. The feed impedance is expected to be close to 200 ohms.

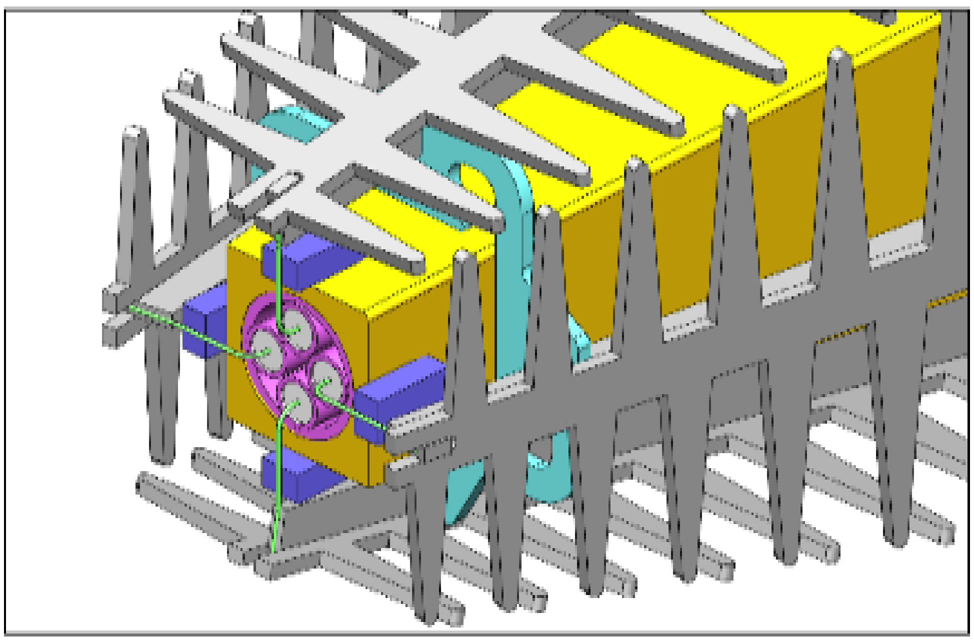


Figure 10 is a drawing of the connection to the feed. Simply connecting the coaxial center lines to the feed tips would leave a large inductance in series with the feed inputs. To eliminate that, we connect .05 pf capacitors (the blue blocks) between ground and the midpoint of each input lead. The two half leads are the input and output inductances which combine with the capacitor to produce a Tchebychev low pass filter. Even better, the capacitors are self resonant at about 30 GHz, and the effective series inductances are just about right for a 15 -16 GHz cutoff low pass filter on each arm.

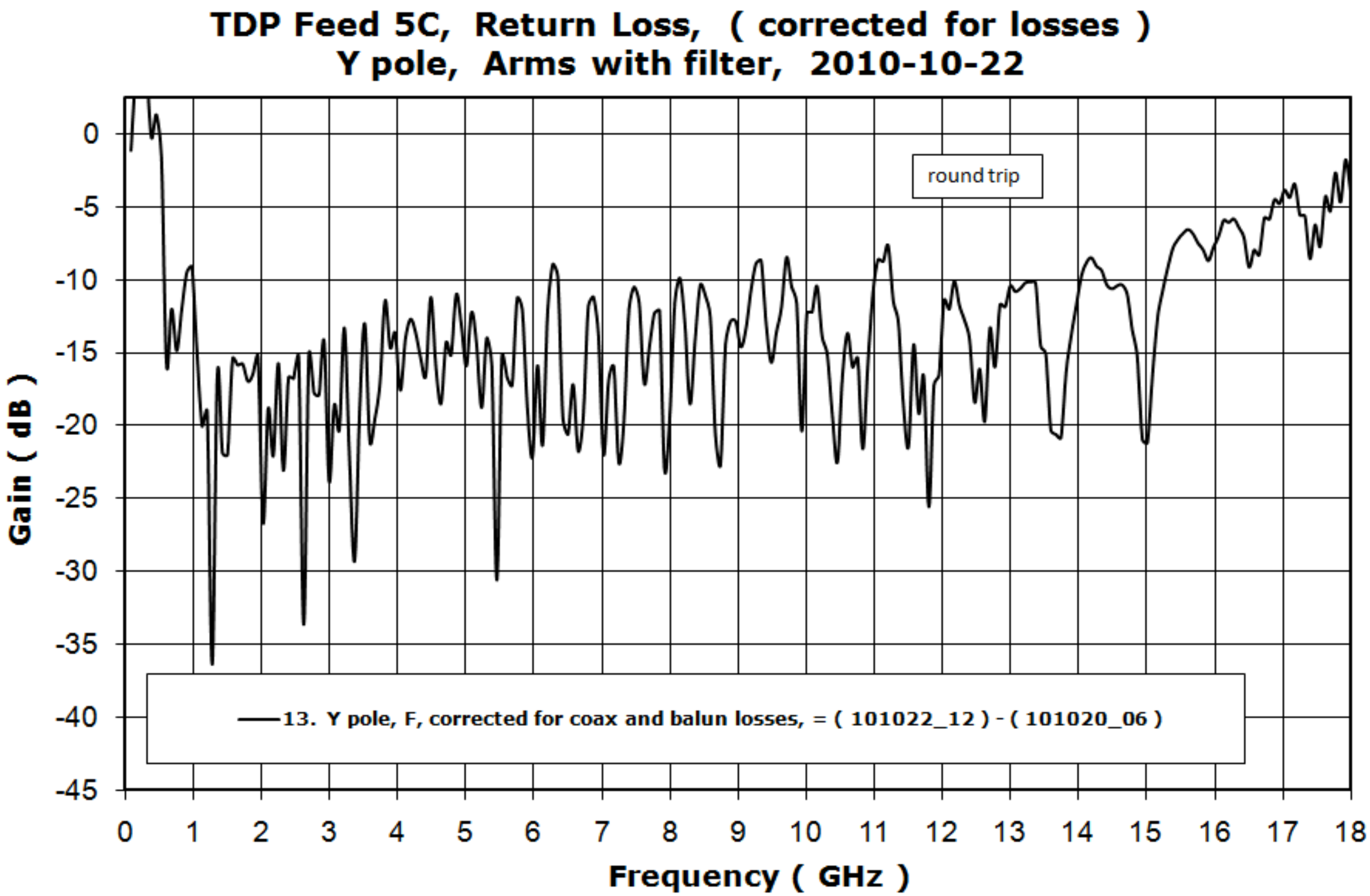


Figure 11 shows the input impedance measured at the coaxial cables at the location of the LNAs. This shows an input match that is -10 dB or better over the whole band .9 GHz out to 15 GHz. Good, low-noise operation is expected out to 15 GHz.

Laboratory Test chamber at Minex Engineering:

Figure 12 shows the cooled feed being tested in our screen room, where the local background interference is eliminated. The bottle is covered by the same material that we now use for the ATA radomes. The material is radio transparent, and it provides a safety net in case the bottle should be accidentally struck and it imploded

Experimental Test Setup at Hat Creek using ATA Antenna 3F:

To extend the noise temperature calibration to low frequencies and also estimate the total system temperature, we mounted the cooled feed on an ATA antenna at Hat Creek for the further noise measurements. Here we describe measurements of the receiver and system temperatures from about 4 GHz down to the low frequency limit of 900 MHz of the feed. This range overlaps the laboratory frequency range of about 2.5 GHz to 15 GHz.

The plan for the reference loads on the Hat Creek antenna was to use an ambient temperature load for the high temperature reference and the brightness of the sky for the cold reference. The ambient load consisted of a cylinder with end plate with absorber over both its cylindrical inner surface and its inner end plate.

Figure 13 is a photograph of the hot load. The cylinder with the inner absorber is placed over the feed to provide the known ambient reference. Its length is long enough to insure that all parts of the feed are covered. Its physical temperature is directly measured with a thermometer (= 304K). The absorbing material was tested and showed that its two way transmission is less than -44 dB at all relevant frequencies. It should be an essentially perfect black body at its measured temperature.

In order that the ambient load (cylinder) could be readily installed and removed by sliding it over the feed, the antenna was placed at its lowest elevation of 18° for the measurement.

Figure 14 shows a view of the antenna at this low elevation angle with the doors on the shroud closed.

Figure 15 shows the feed mounted near the Gregorian focal point. It is seen through one of the open shroud doors. For this special test it was not possible to mount the feed so that it could be set at various focal distances.

Since we were particularly interested in measuring its operation at low frequencies, we positioned it at the lowest frequency focal position. Note the effect of the choice of focal position on operation in Figure 16 below.

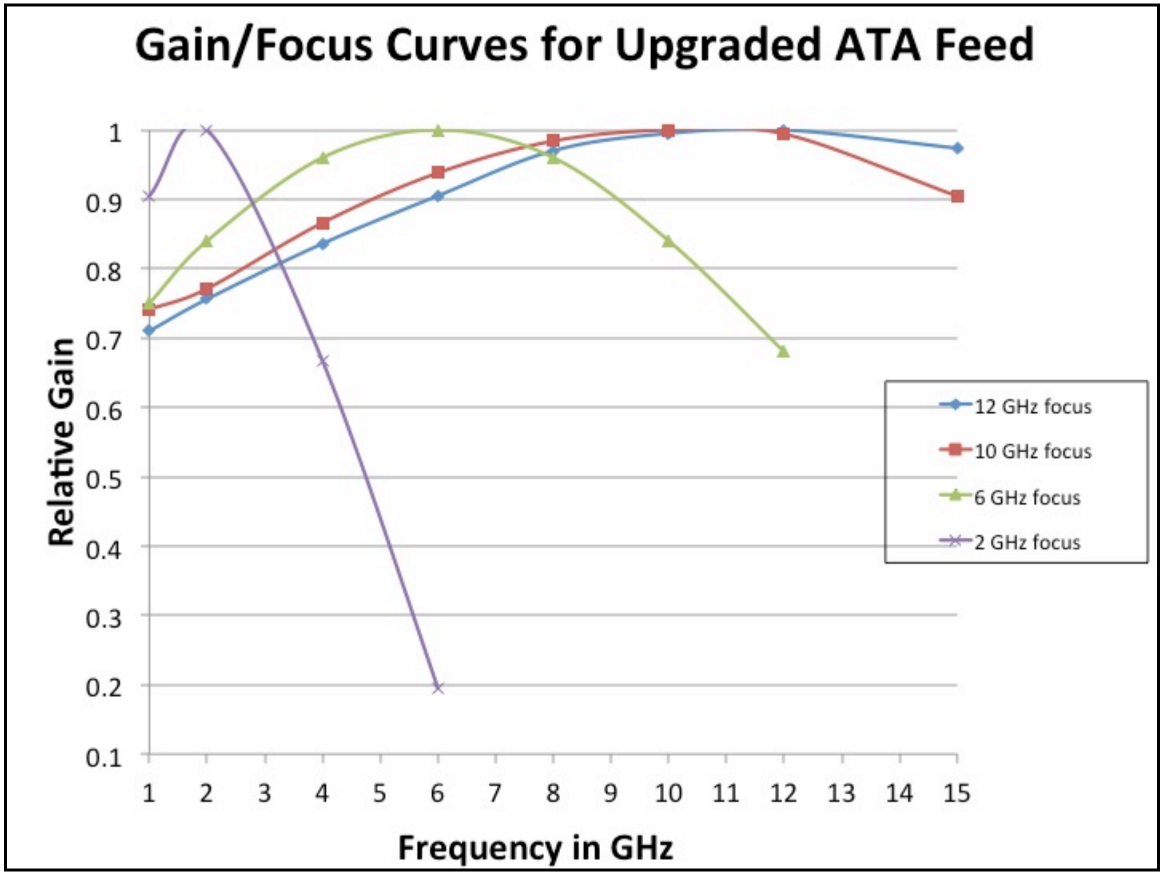
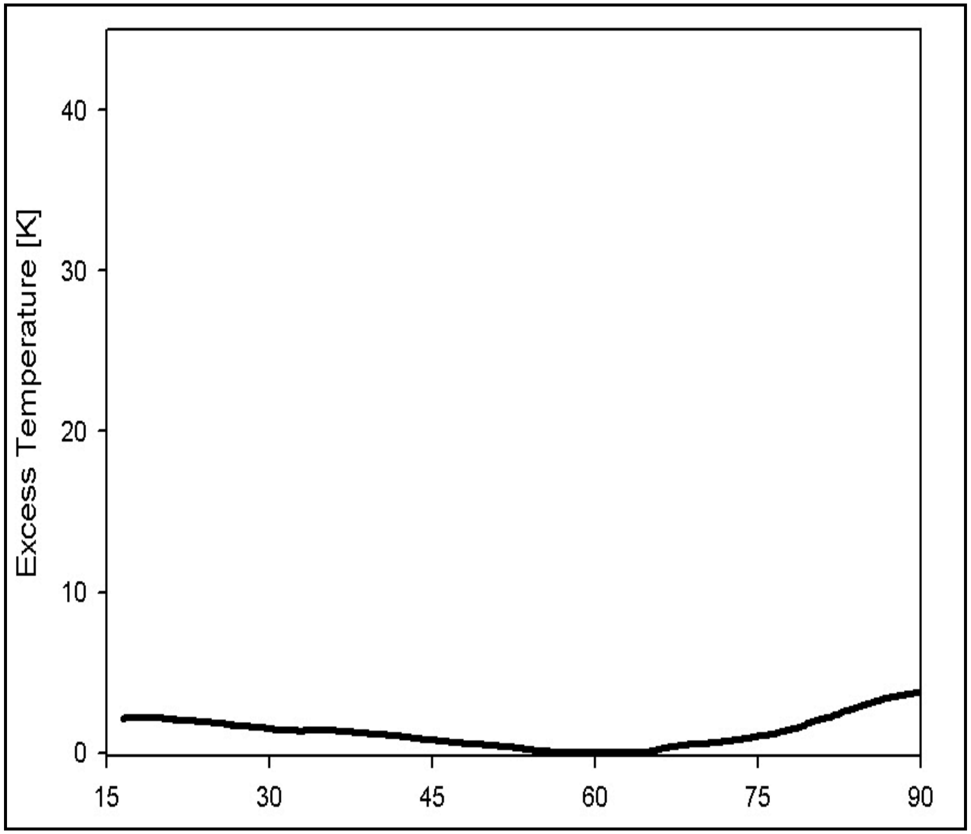


Figure 16 , these gain curves suggest that for normal operations, focusing at ~10-12 GHz is ideal. At the highest and lowest frequencies the resulting loss in sensitivity will be less than 1 dB. For observations demanding the greatest sensitivity at a particular frequency, the feed should be focused for that particular frequency.

The observations were as made at Hat Creek on 7/22/2012 during the interval 4PM – 7PM local time, 0-3 hrs GMT. The telescope was pointed due North, and at an elevation angle of 18°. This position corresponded to galactic coordinates l = 140°, and b = 10.6°. Though the observations were pointed away from the galactic center, they were at low latitude, so it will be necessary to include contributions from galactic synchrotron emission to the sky noise at low frequencies.

For conventional symmetrical antenna systems, such as the prime focus or symmetric Cassegrain systems, the antenna temperature pick-up from the ground is large at low elevation (high zenith) angles. For the ATA offset Gregorian with the shroud, on the other hand, the ground pick up is low at low elevation angles. This is an important advantage for mapping observations as well as for the present calibration. It is difficult to constrain elevation angles to be near zenith during a large mapping program.



Zenith Angle

Figure 17 shows the measured antenna temperatue as a function of zenith angle for the ATA antenna. The total ground pick-up actually decreases by a few degrees K as the antenna is tipped toward the horizon from the zenith. The curve of Figure 17 shows a minimum at mid range as the ground pick up is offset by the atmospheric emission due to increased atmospheric path length at higher zenith angles. As the tipping curve makes clear, it is a very small component.

When trying to measure the feed performance on the sky it is necessary to account for all the sources of noise emission coming from the sky and the instrumental set-up. The antenna background radiation has several small components at frequencies just above about 1 GHz. The first is the isotropic 2.7K Cosmic background (Penzias and Wilson, 1965, Ap.J,142) which is accurately known. There is also a small emission from the galactic synchrotron radiation that is a function of both frequency and galactic coordinates. Since this term is increases as frequency decreases by a strong power ($\sim\nu^{-2.7}$), it is only substantial for frequencies well below 1 GHz. During this experiment, the antenna was pointed away from the center of the Milk Way, but in the plane. The calculated contribution from galactic synchrotron emission was negligible. Then there are two other noise components from the ATA itself. One is the geometric optics term ~3K(1-z/90), discussed above (where z is the zenith angle), and the other is a somewhat uncertain, but small over most of the range, term $16K/(\sqrt{fg})$ which is a nearly isotropic diffracted term from the secondary, where f_g is frequency in GHz. Finally there is the atmospheric emission at18°elevation, which is proportional to the pathlength through the atmosphere and increases as the secant of the zenith angle. At the large zenith angle (low elevation) at which these measurements were made, it is important to include this atmospheric term. It is also possible that the radome cover on the antenna can absorb some of the incoming radiation, since it lies in the optical path of the signal. When the covers were new, we measured their radio transparency and could not detect any losses to a level of 0.1 dB. Nevertheless, since these covers are at ambient temperature, a 0.1db (~2.3%) could add as much as 7K to the background noise temperature. It is possible that over the years, as the radome covers accumulate dirt, their transparency may degrade. We have left a term in our analysis for the radome cover, and find that it is needed to align the receiver temperature T_{rec} derived from the measurements on the sky with the value of T_{rec} accurately measured against liquid nitrogen in the laboratory in the region of 3 GHz where the two sets of measurements overlap.

On the antenna, the basic observation is a Y-factor power measurement in which the reference spectrum is the blackbody (in this case a hot load) plus receiver $T_{ref} + T_{rec}$, and the test spectrum is an antenna temperature spectrum at 18° elevation plus receiver, $T_{amb} + T_{rec}$. T_{amb} contains all the different noise contributions from the sky and the antenna that are discussed above, and an accurate determination of T_{rec} and the system temperature of the new cooled feed on the ATA antenna requires careful attention to the environmental and astrophysical contributors.

$$Y = (T_{rec} + T_{ref})/ (T_{rec} + T_{amb})$$

For the reference observation, the shroud is opened and the ambient load is put in place over the feed. For the antenna temperature measurement, the load is removed from the feed and the shroud is closed for the observation through the atmosphere at 18° elevation. The measured spectra of the numerator and denominator are subtracted on the logarithmic scale of the spectrum analyzer, providing the logarithm of the Y-factor directly on the display. This Y-factor for the spectrum up to 4 GHz appears in Figure 18.

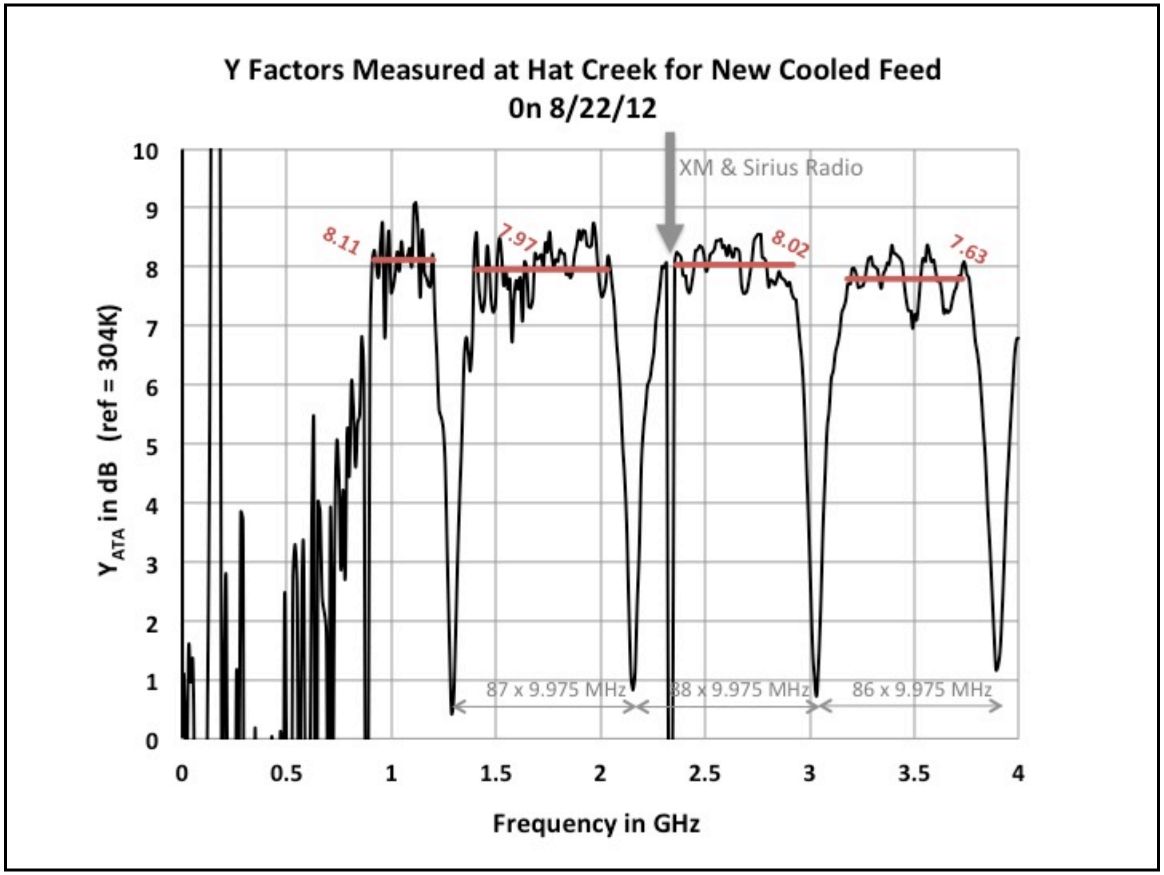


Figure 18 The Y-factor for the feed shows several features. It starts at 0.9 GHz, the lower limit of the feed with values of about 8 dB up to 4 GHz. In addition, there are several frequencies showing strong downward spikes. One of them, at 2.33 GHz, is due to interference from XM and Sirius radio at 2.33 GHz. These broadcast signals are so powerful that they are received in the antenna sidelobes. The other spikes are due to similar interference from the spectrum analyzer at intervals of about 0.9 GHz. In the laboratory it was possible to eliminate these interfering signals by placing the receiver in a shielded room. At the observatory we were not able to completely shield the receiver from this interference. Since these were strong at discrete frequencies, we were able to get useful data at the other frequencies.

In the laboratory, the reference temperature for the cold load is that of liquid nitrogen 77.2K, and the ambient temperature was measured to be 292K. There are no other confusing terms and it is straight forward to calculate Trec from the measured values of Y_{lab} shown in Figure 4, from the highest frequencies down to a few GHz.

$T_{rec} = (292 – 10^{Y_{lab}/10} * 77.2)/(10^{Y_{lab}/10} -1)$

It is not possible to extend the lab measurements to the lowest frequencies of the feed because its physical size precludes fully immersing the back end of the system (the large scale structures that respond to the longest wavelengths) in the liquid nitrogen bath. For low frequency measurements, the reference temperature would be ill defined, somewhere between 77.2 K and 292 K.

The physical temperature of the hot load on the antenna was continuously monitored and remained at 304K. Solution for T_{rec} looks like

$T_{rec} = (304 – 10^{Y_{ATA}/10} * T_{amb})/(10^{Y_{ATA}/10} – 1)$

$T_{amb} = T_{sky} + 3K(1\text{-}z/90) + 16K/(\sqrt{fg}\ ) T_{radome}$ and $T_{sky} = T_{atmosphere} + T_{CMB} + T_{Galaxy}$

Deboer has calculated T_{sky} as a function of frequency from a detailed model for an elevation angle of 18° and the Hat Creek site at an altitude of 3000 feet and that appears in Figure 19. Because it is the common practice to quote the system temperature T_{sys} for a facility as referenced to viewing cold, dry sky at the zenith, Figure 19 also contains a curve for elevation of 90°. Figure 20 shows the average values of Trec computed over the frequency ranges that were not affected by the spectrum analyser noise. Since the measurement error of the spectrum analyser traces is ± .25 dB, there is some uncertainty, particularly at the lowest values of the receiver temperature.

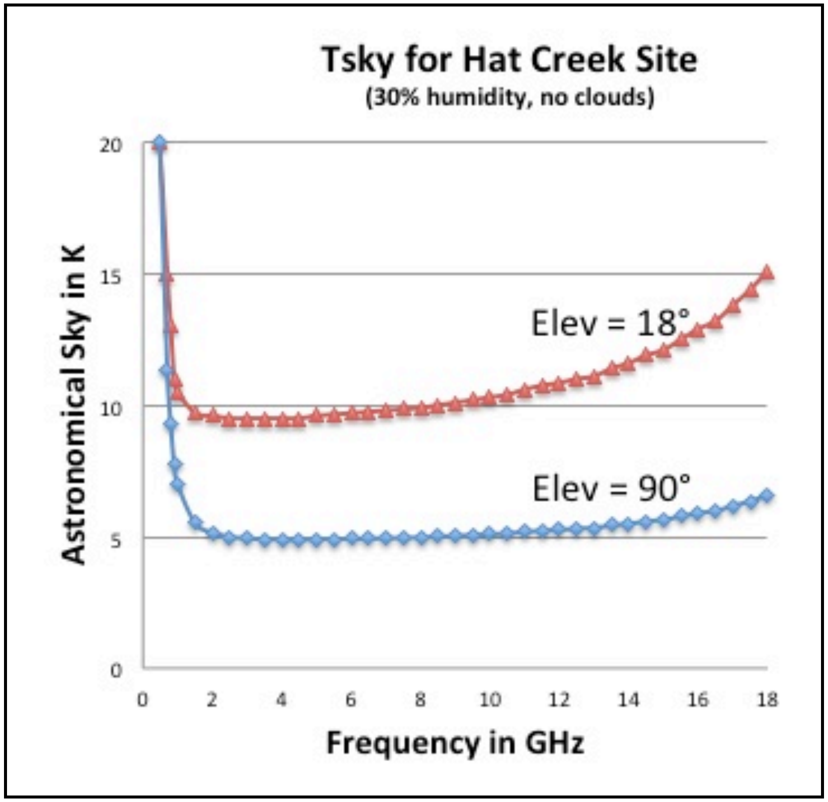


Figure 19 The contribution to the ambient temperature measurement due to the sky brightness at Hat Creek. The rise at lower frequencies is due to galactic synchrotron emission and must be included whenever looking through the galactic plane. At 0.9 GHz, the lowest frequency for the new cooled feed, the galaxy adds less than 3 K. The rise at the high frequency end is due to the water vapor line at 22 GHz, and the oxygen band at 50-60 GHz: the atmospheric contribution scales as the secant(z).

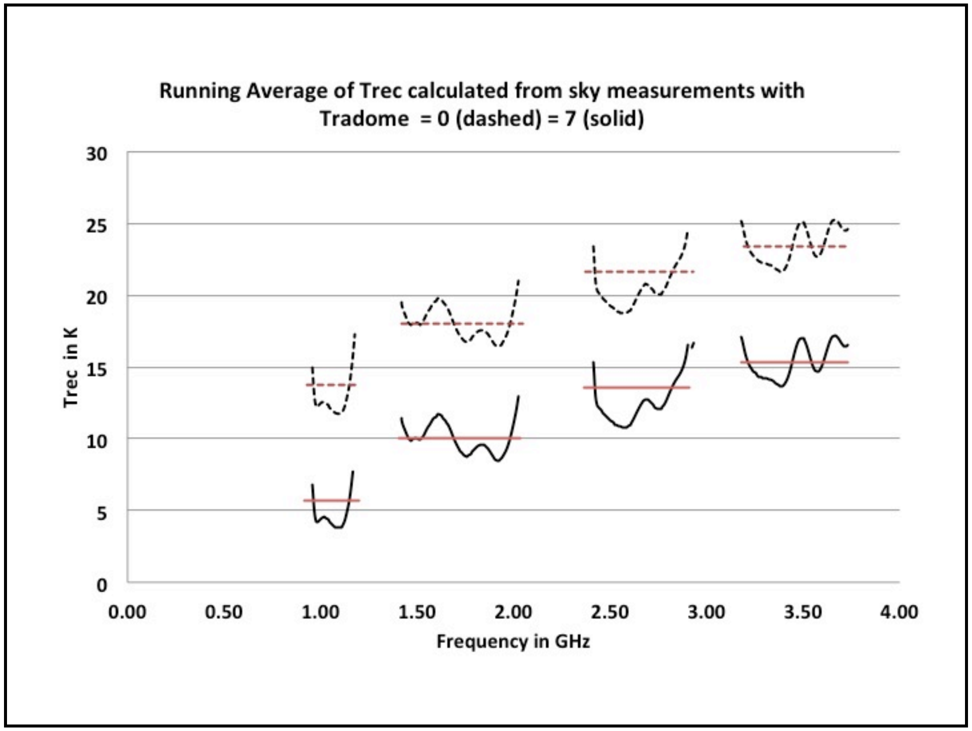


Figure 20 The calculated values for T_{rec} for assumed noise contributions from the radome cover of 0 K or 7 K. There is no direct measurement of this term, but in the area from 3 to 4 GHz where the laboratory measurements overlap with the measurements on the sky, an additional noise contribution helps to equalize the two measurements and force the values for Trec calculated from measurements on the antenna to align with the low values measured in the lab. The individual solutions as a function of frequency have been smoothed by a running average of width ~ 90 MHz for the purposes of this plot. The red lines represent the average results within each clean spectral region. Measurements were made up to 15 GHz, but because the positioning of the hot load made it impossible to adjust the focus for higher frequencies, it is best to rely on the straight forward lab measurements of higher frequencies. The data gathered at the ATA validate good performance at frequencies as low as 0.9 GHz that was predicted

Finally it is possible to place the measured and calculated values of Trec from 0.9 to 15 GHz on the same chart, and then add-on the effects of sky emission, geometric optics, and spillover to estimate the total system temperature of this new feed and receiver when pointed at cold sky at zenith. Figure 21 is our best estimate of the system temperature. The uncertainties are fairly large as the result of the use of the spectrum analyser as a detector (± 0.25 dB), the large atmospheric pathlength due to the low elevation, the non-standard observing configuration, and the varying orientation with respect to the galactic plane throughout the course of the measurement cycle. However it is very clear that this new cooled feed and receiver would substantially improve the sensitivity of the ATA at the frequencies currently covered while extending the useful range of observing frequencies up to 15 GHz.

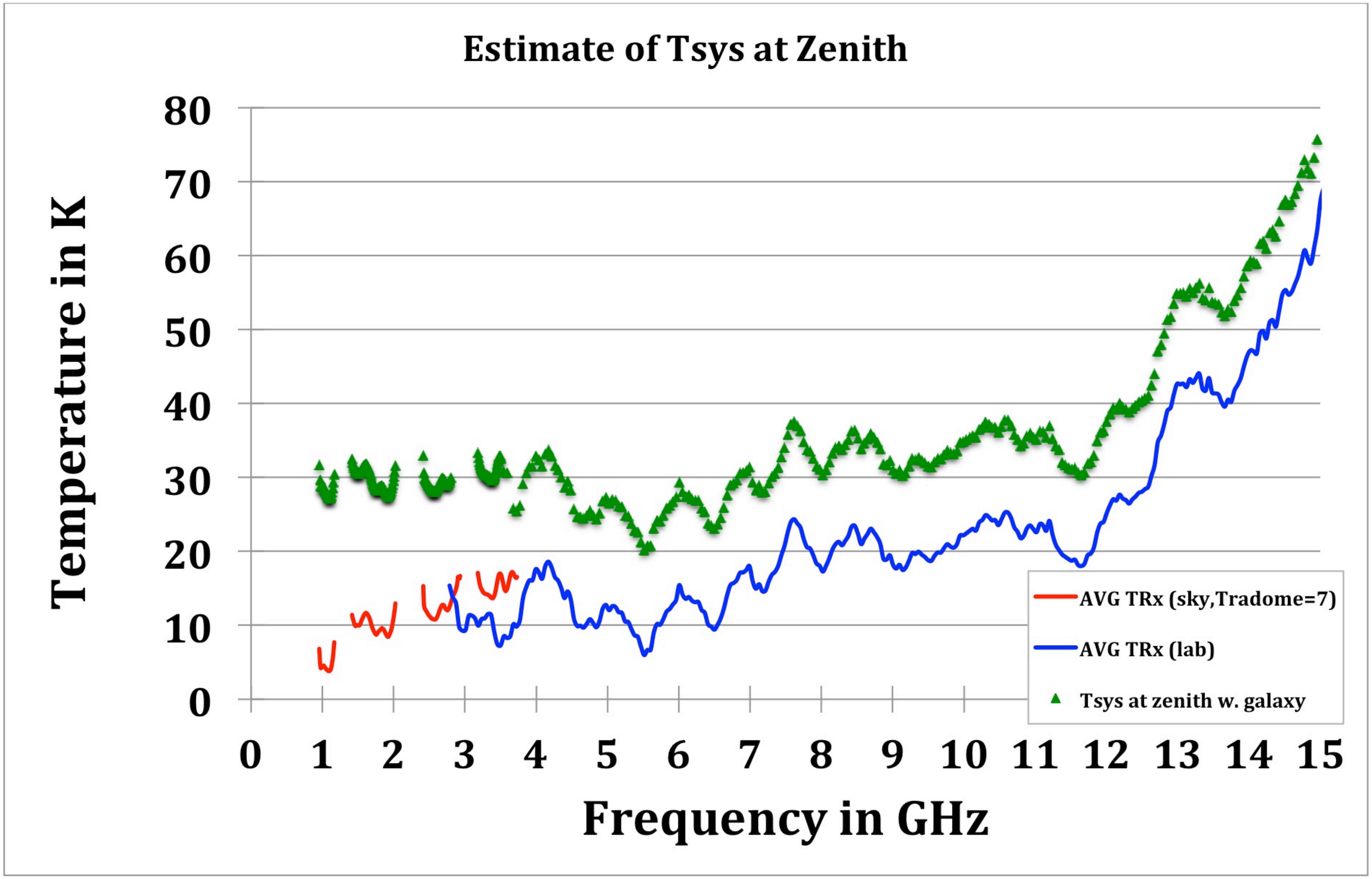


Figure 21 An estimate of the system temperature of the new cooled feed on the ATA when pointing at zenith. For values below 2.8 GHz, T_{rec} measured at the ATA have been used, for higher frequencies the laboratory measurements are used.

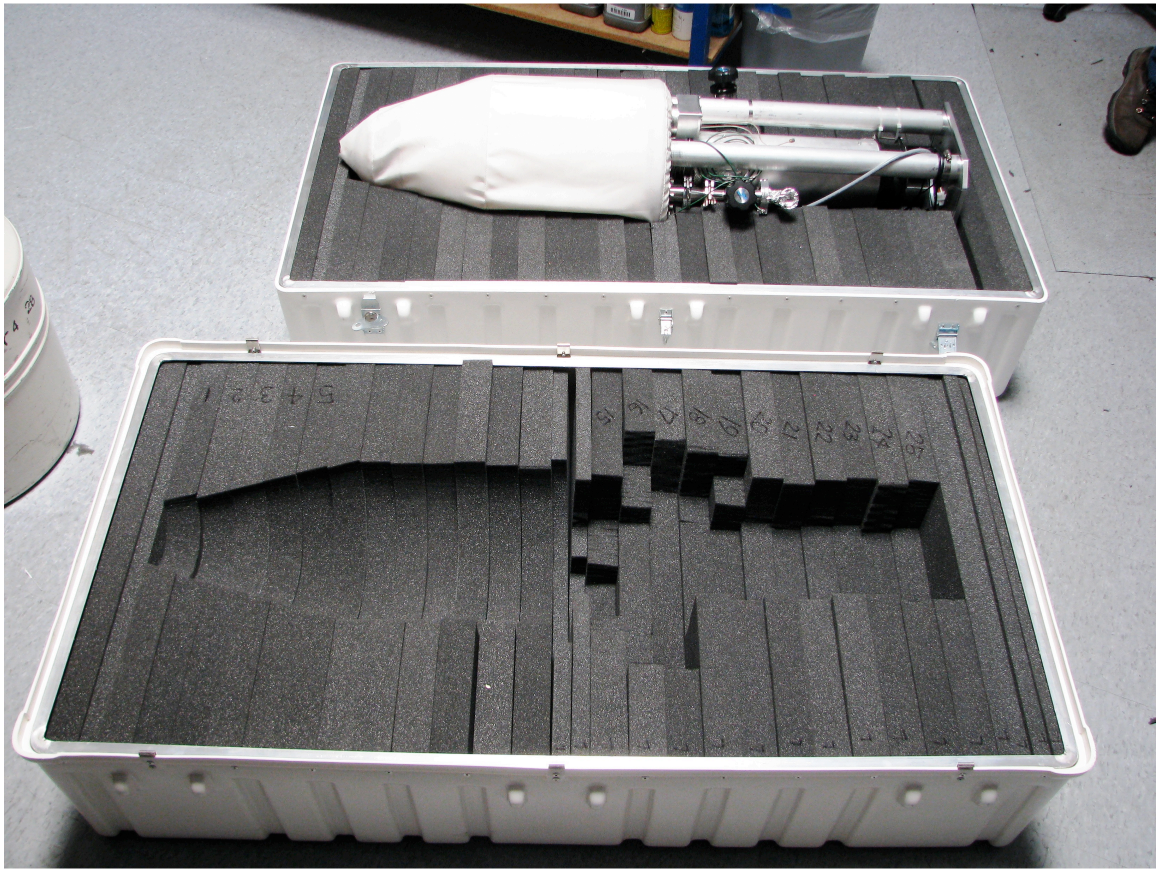


Figure 22 shows the foam-lined cases created to transport the new cooled feed to and from the observatory. Although the glass bottle surrounding the feed and receiver might appear fragile, this method of transport is considerably smoother and less stressful on the components than the current feed carrying structures.

The performance of this new cooled feed and receiver system is outstanding and the significant improvement in system temperature makes it very attractive to consider retrofitting all 42 ATA antennas and incorporating this new design into any future buildout of the array. The best estimate of cost for retrofitting the array and providing 6 spare units (including a 10% contingency appropriate to the current level of preparedness) is just under $5million.