DEVELOPMENT OF AN OPTIMIZED ANTENNA AND OTHER ENHANCEMENTS OF A SPECTROMETER FOR THE STUDY OF OZONE IN THE MESOSPHERE

Sai N. Tenneti
University of Massachusetts, Amherst MA
Summer REU Student

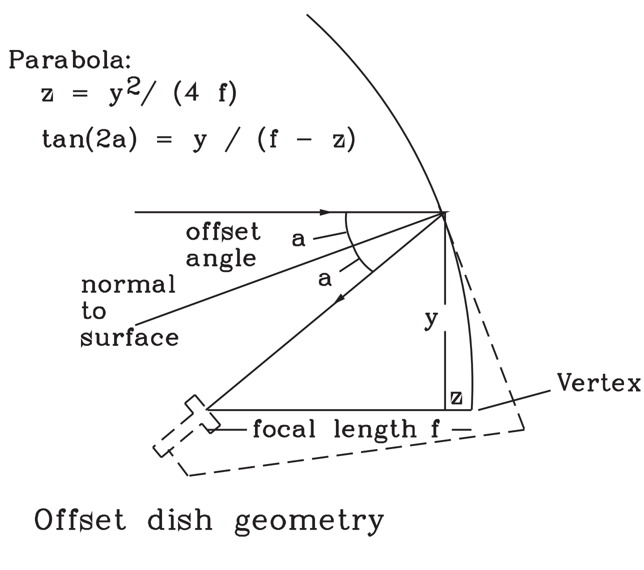
Alan E. E. Rogers
MIT Haystack Observatory, Westford MA
REU Mentor

ABSTRACT

The goal of this project was to optimize the performance of a spectrometer at Haystack that measures the amount of ozone in the mesosphere. This required searching and testing for compact, inexpensive low noise block converters (LNBs) that can perform efficiently in the X-band of the electromagnetic spectrum. Various devices were tested such as the Fortec FSKUVN 0.2 dB, Invacom SNF-031 0.3 dB Horn, Invacom SNF-031 0.3 dB C120 flange, and the Smart 0.1 dB. Software was used to estimate the "sky noise" as a function of azimuth and elevation, and in turn was used to calculate the antenna response. Numerous calibration techniques were used to obtain accurate values for the noise figure, such as the use of various absorbers to measure the "Y-factor", liquid nitrogen calibration, and also calibration with a fluorescent lamp that periodically turns on and off. Some possible solutions to reduce spillover from the ground and further optimize the antenna performance, were also tested.

INTRODUCTION

The setup to observe the ozone line of 11.072 GHz consists mainly of a "Direct TV" offset parabolic dish and an LNB away from the dish at a distance equal to its focal distance and looking up at an angle equal to its offset angle. For the Winegard DS-4047, the focal distance is 10.6" and the offset angle is 24 degrees. A mirror is located at the center of the dish for alignment, and the antenna beam approaches the dish at 8 degrees elevation.



Offset dish geometry

The probe periodically injects a frequency calibration signal consisting of harmonics of 10 MHz derived from a calibrated 10 MHz oscillator in a temperature controlled oven. The harmonic at 11.072 GHz is used to correct the frequency error of the 9.75 GHz local oscillator. The signal then gets amplified and passes through a bias tee, gets attenuated, passes through a high pass filter, and gets attenuated again before the desired frequencies are obtained and then down converted and digitized. The ozone spectrum is derived by Fourier transforming the time samples to the frequency domain.

It is important to measure the noise performance of the ozone spectrometer, because a low noise performance means a more efficient antenna with reduced spillover. One way of measuring the ozone spectrometer's noise performance is by placing an absorber over the feed and measuring the increase in total power.

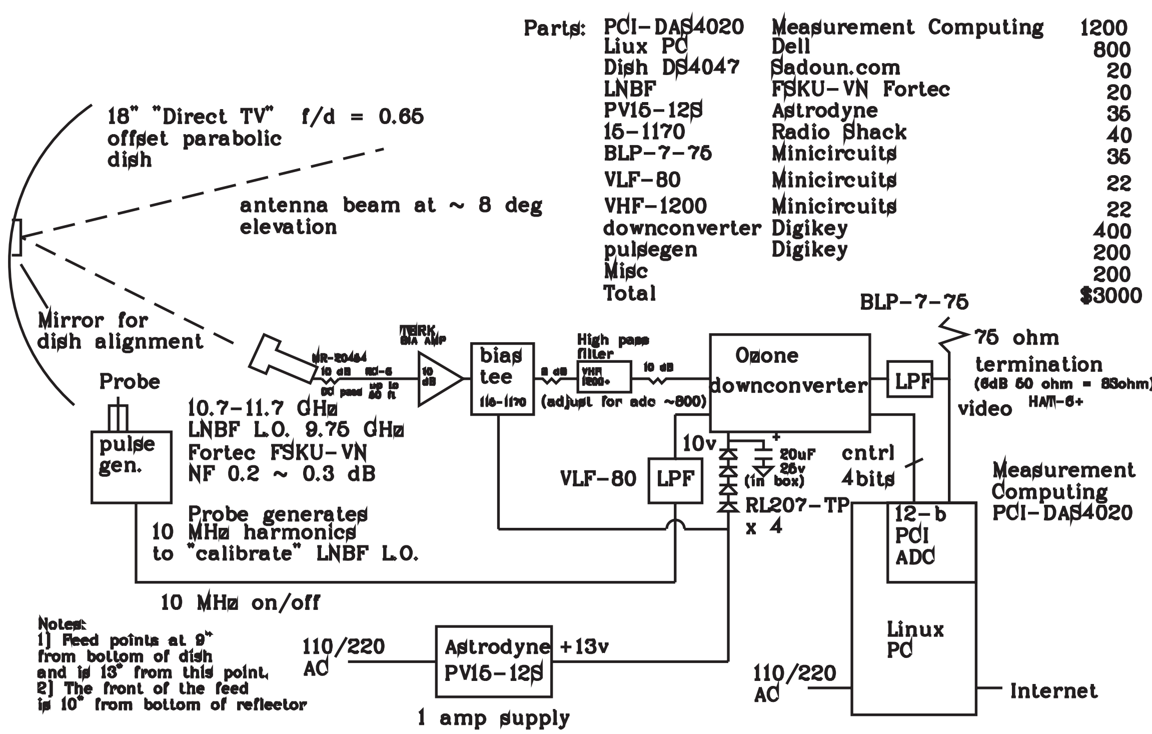
The "Y" factor or ratio between the absorber in place and with the absorber removed is

$$Y = \left(T_{amb} + T_{LNA}\right) \Big/ \left(T_{sky} + T_{LNA}\right)$$

T_{sky} depends on a variety of factors, like the atmospheric weather, the spillover from the antenna feed, and the cosmic microwave background of 3K. T_{amb},the ambient temperature, is assumed to be about 295 K. Using these values, and the measured Y-factor, T_{LNA}, the noise temperature of the low noise amplifier, can be solved for. The noise figure is then calculated based on the following equation:

$$NF = 10*\log10(T_{LNA}/290 + 1.0)$$

A high Y-factor leads to a low T_{LNA}, and consequently a low noise figure and better efficiency. Therefore, the aim is to obtain as large of a Y-factor as possible.



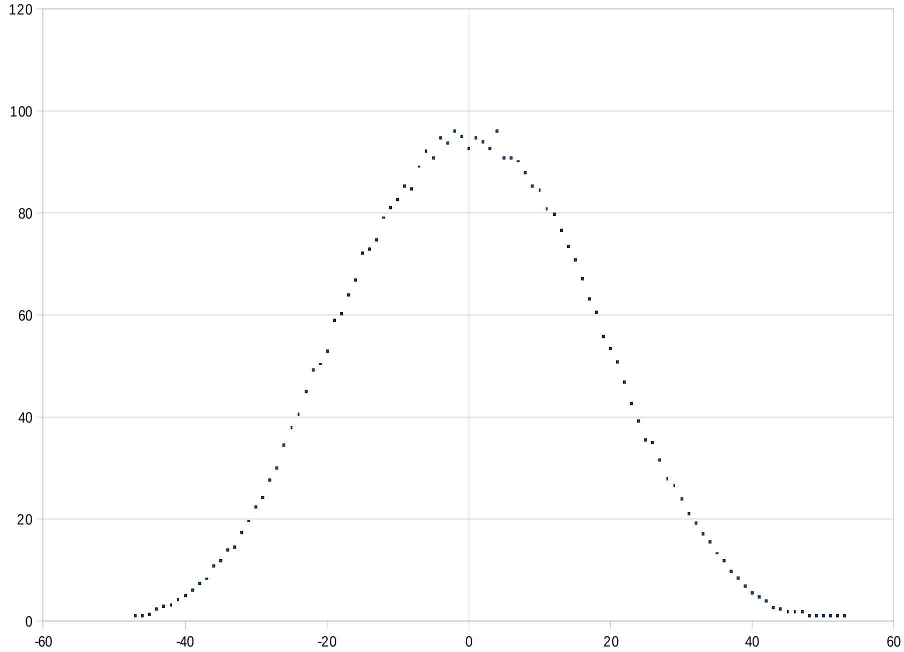
11.0724545 GHz ozone line spectrometer 4 Mar 09

ANTENNA BEAM PATTERNS

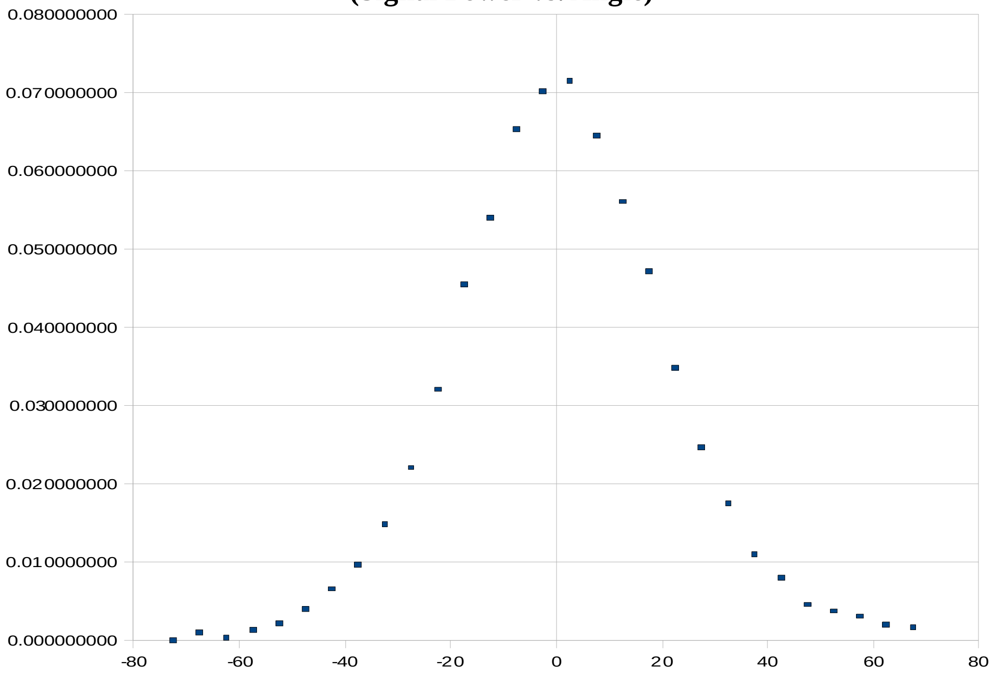
The first task was to obtain the beam pattern for the Fortec Star FSKUVN Universal Single LNB. The LNB was connected to a signal generator which produced a frequency of 11 GHz, closest to the microwave ozone line frequency.
The LNB was clamped to a small stand on a rotary table and the direction of the LNB was manually controlled by rotating a small crank located at the front of the device. A power detector faces the device, and is also connected to a spectrum analyzer to measure the received power. The power is therefore measured as a function of the offset angle between the LNB and the detector. The beam pattern turns out to be similar to a Gaussian, with the ends somewhat broader. Several variations of measuring the beam pattern were tested. For example, two LNBs positioned side-by-side and clamped were both rotated to see if there was any significant difference in the beam pattern. The same measurements were carried out with LNBs positioned one above another, and both rotating. Then, the response was measured with the top LNB staying steady and the bottom LNB rotating as the user cranks the device. After several tests, it was deduced that the beam pattern can be described by a Gaussian equation added to a constant.

Beam Pattern Measured with LNBFs positioned vertically with each other

(Signal Power vs. Angle)



Beam Pattern measured with LNBFs positioned vertically with each other, but one LNB stays steady while the other moves.
(Signal Power vs. Angle)



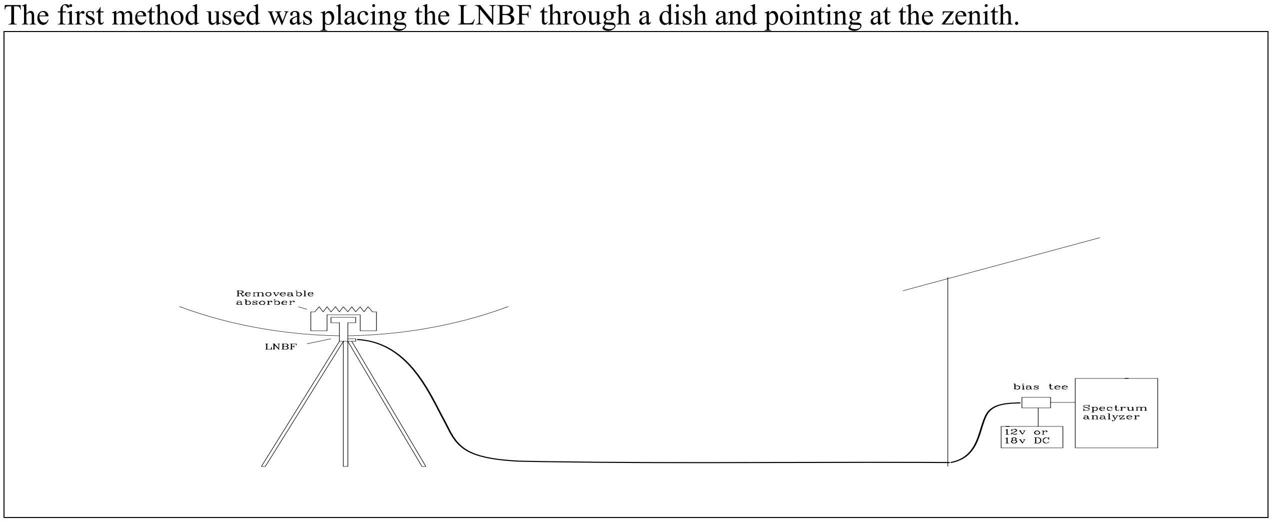
The equation for a Gaussian equation is of the form

The beam width was calculated to be 21.5 degrees, and the constant was roughly 0.002.

$$B(\theta) = e^{-0.693(\theta\ /\ 21.5)^{\wedge}2}+0.002$$

SKY NOISE CALIBRATION

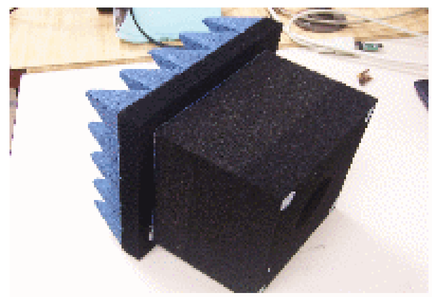
In order to look into the potential for lower system noise, measurements were made on the LNBF assemblies. The first method used was placing the LNBF through a dish and pointing at the zenith.



A “Y factor” measurement was made by calculating the ratio of the power from the LNBF covered by a microwave absorber and the power with the LNBF without the absorber and looking at the “cold sky”. The dish and LNBF were placed atop a tripod, and the LNB was connected to a bias tee located inside a trailer, which in turn was connected to a spectrum analyzer to calculate the power.

It was observed that using the dish improved noise figure by about 0.2 dB, rather than having the LNB alone without the dish supporting it. Different types of absorbers were used, to provide consistency in results, and also to test whether some absorbers work better than others. Two different Fortec Star Universal Single LNBFs which claimed to have a performance of 0.2 dB were tested. Two different types of Invacom LNBs were also tested. One had an integrated feed, and one came with only an LNB unit, and a circular, ringed feed was added. Both units claimed a noise figure of 0.3 dB. Finally a Smart LNB imported from UK was tested, which claimed to have a noise figure of 0.1 dB. The antennas were tested at different frequencies (800 MHz, 1300 MHz, 1800 MHz), and two different voltages (13V and 17.5V).

These are photos of the two main absorbers used. The absorber on the right consists of ETS-Lindgren EMC-03PCL cut into a 7.5” x 7.5” square, glued to an ETS-Lindgren 4500CL cut to a 6” x 6” x 4” block and drilled on the bottom is a hole 2” in diameter and 3” deep. It has proven to be quite effective in Y-factor measurements.

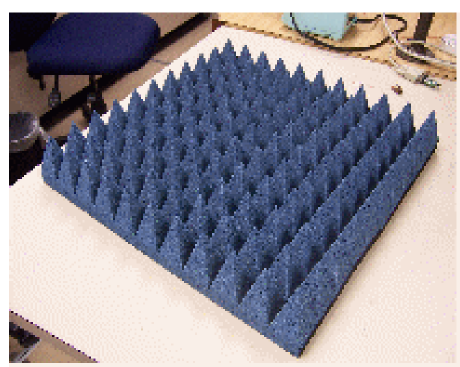


Drawing 1: Absorber #1

The absorber on the left is ETS-Lindgren EMC-03PCL cut into a 22.5” by 9” rectangle, bent and maintained with tape, and covered by plastic wrap. This absorber is not as effective as the one above, because it does not shield the entire sky as viewed by the antenna. However, this absorber was used extensively, especially for feeds which did not fit through the hole in the above absorber.

Drawing 2: Absorber #2

The absorber on the right is also made up of ETS-Lindgren EMC 03PCL cut into a 16.5” by 16.5” square. This is ideal for those antennas which sport a feed or a shield that is too big to fit into the hole of absorber #1, because unlike absorber #2, this covers the whole top of the antenna feed from the sky.



Drawing 3: Absorber #3

LOW NOISE BLOCK CONVERTERS THAT WERE TESTED

Fortec Star FSKUVN Universal Single LNB 0.2 dB

Invacom SNF-031 0.3 dB Horn

Invacom SNF-031 0.3 dB Flange

SMART 0.1 dB

Feed associated with the Invacom Flange

Ratio of Absorber on/absorber off power in dB, for each particular voltage, LNB, absorber, and frequency

13 V voltage

	Absorber 1			Absorber 2		
	800 MHz	1300 MHz	1800 MHz	800 MHz	1300 MHz	1800 MHz
Fortec #1*	6.3	6.4	5.7	5.8	6.1	5.4
Fortec #2*	5.9	6.6	6.4	5.6	6.3	6.2
Invacom	4.4	6.5	6.4	4.0	6.2	6.5

**Two different LNBs of the same type were tested in case of defective equipment*

17.46 V voltage**

	Absorber 1			Absorber 2		
	800 MHz	1300 MHz	1800 MHz	800 MHz	1300 MHz	1800 MHz
Fortec 1	5.9	6.6	6.0	5.5	6.4	5.7
Fortec 2	5.8	6.5	6.6	5.4	6.2	6.2
Invacom	5.5	6.5	6.3	5.1	5.9	5.9

***The voltage changes the polarization of the LNBF*

It was concluded from this data that the Invacom LNB is quite inefficient at low voltage and low frequency. As for the Fortec Star LNB, the largest Y-factor measured is 6.6 dB, which converts to 0.42 dB noise figure using the following equations:

$$\text{Y-factor} = (T_{lnbf} + 290) / (T_{lnbf} + T_{sky}) \Rightarrow T_{lnbf} = 290(10^{0.1*lnbfdb} - 1)$$

lnbfdb is equal to the noise figure, and T_{sky} is calculated using computer software integration with respect to azimuth and elevation, as will be explained below. Though the noise figure is promising, it is nowhere near the advertised figure of 0.2 dB.

As for the Invacom LNB unit joined with the separate ringed feed, the highest difference obtained was still about 6.6-6.7 dB, when a value over 7 dB was expected.

SMART 0.1 dB

The Smart 0.1 dB LNB did not look as promising as the Fortec Star LNB at first. However, experimenting with the reference level of the spectrum analyzer proved otherwise. Using the frequency of 1300 MHz, the high voltage of 17.6 V, and absorber #1, the Smart 0.1 dB was able to produce Y-factors up to 7.3 dB! This would convert to a noise figure of about 0.23 dB, which is a much bigger improvement.

USE OF MOUTH OF A METALLIC FUNNEL TO FURTHER REDUCE SPILLOVER

In the objective of reducing spillover from the antenna feed, the stem of a metallic funnel was cut, so that the mouth would serve as a shield around the feed. The addition proved to be slightly effective, increasing the Y-factor up to 0.2 dB.

SKY NOISE

The "sky" noise is calculated from the 2-D integral of the antenna response pattern weighted by the sky temperature as a function of azimuth and elevation and normalized by the integral of the antenna response pattern $D(az,el)$. That is

$$T_{sky} = \iint D(az,el)T(az,el)el\Omega \Big/ \iint D(az,el)d\Omega$$

The temperature $T(az,el)$ is taken as the sum of the 3K from the cosmic microwave background plus the temperature contribution from the atmosphere at 11 GHz which was assumed to be 5K/sin(el). When the sky was blocked by a building or the ground the ambient temperature of 295K was assumed.

The model assumes the horizon at 25 degrees from the horizontal, and the sun at 89.75 degrees from the horizontal. Any point lower than the horizon is assumed to have ambient temperature, and any point between 89.75 and 90 degrees near the sun has a large temperature approximated as 1e4 K. For all other points, the sky temperature varies with the elevation angle based on the equation:

$$T_{sky} = 295.0*(-10^{-0.007/\sin(elev)}+1)+3.0$$

295.0 K is assumed to be the ambient temperature, and 3.0 K as stated before is the cosmic microwave background.

LIQUID NITROGEN CALIBRATION

Another method used to measure the Y-factor was to perform a hot/cold measurement on an Invacom SNF-031 LNB. Since the LNB has a C120 flange, a circular to rectangular waveguide transition and a waveguide to coax adapter were used. In this case, the Y-factor is

$$Y = (T_{amb}+T_{LNA}) / (T_{cold} + T_{LNA})$$

where T_{cold} is the effective temperature seen by the LNA when the load in the Styrofoam container is cooled with liquid nitrogen.

However, when the nitrogen is boiled at 80 K, there are losses in the coaxial line from the container, in the coax adapters, and in the coax to waveguide adapter.

The loss in the coax and adapters from S_{12} was measured from a network analyzer and the coax to waveguide loss was estimated by measuring S_{11} with the LNB end of the waveguide shorted with a metal plate. In this case S_{11} should give twice the loss since the wave travels to the short and returns.

Using 1300 MHz as the center frequency, 3MHz as the resolution frequency, and 10 MHz as the span, the trial results for a hot/cold Y-factor measurement on an Invacom SNF-031 LNB were as follows:

	Hot	Cold	Y-factor
Trial 1	-62.90	-65.56	2.66 dB
Trial 2	-61.20	-64.84	3.64 dB
Trial 3	-62.54	-65.70	3.16 dB
Trial 4	-61.82	-65.54	3.72 dB

The highest Y-factor obtained from this data is 3.72 dB.

The coax to waveguide loss was thereby estimated. Listed are the numbers obtained from several trials measuring the loss.

0.445 dB, 0.693 dB, 0.396 dB, 0.838 dB, 0.466 dB, 0.438 dB, 0.48 dB, 0.313 dB, 0.445 dB, 0.477 dB, 0.482 dB, 0.347 dB, 0.260 dB, 0.531 dB, 0.397 dB

Averaging these gives a value of 0.445 dB. The loss from S_{11} gives a loss of 0.2 dB, so one way would give a loss of 0.1 dB. So putting the two together gives an overall loss of 0.545 dB.

To calculate T_{cold}, the following formula was used:

$$T_{cold} = T_{boil}*L + T_{amb}*(1- L) \quad (5)$$

T_{boil} is from boiling the nitrogen and is nominally set to 80K. L is found by using the formula

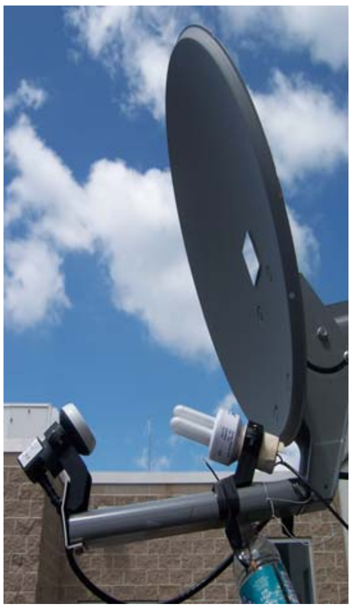
loss = - 10*log(L), and 0.545 dB is plugged in for the loss. This gives L = 0.8821.

T_{amb} is assumed as 295 K. So plugging the appropriate values into equation 5 gives a temperature T_{cold} = 105.3 K.

Plugging this value of T_{cold} into equation 4, and using a Y-factor of 3.72 dB that converts to 2.355, T_{LNA} turns out to be 34.7 K, which only comes to about 0.5 dB.

There are several sources of error in this experiment. For example, the orientation and tightness of screws mattered on the coaxial line on the container, and variations resulted in a discrepancy in results. If the LNB ideally had a 0.3 dB noise figure, then losses should have been about 0.780 dB. In the above data, only one number is about 0.7 dB, and the rest fall into a much lower range.

FLUORESCENT LAMP CALIBRATION



A fluorescent lamp was placed near the calibrator oriented towards the LNB and at an angle with respect to the horizontal, slightly lower than the feed angle. The lamp periodically turns on and off, and the Y_{lamp} is calculated as the ratio between the power when the lamp is on and when it is off. Y_{lamp} also equals

$$Y_{lamp} = (T_{lamp} + T_{sky} + T_{LNA}) / (T_{sky} + T_{LNA})$$

The sensitivity is equal to $1/ (T_{sky} + T_{LNA}) = (Y_{lamp} -1)/ T_{lamp}$

The sensitivity can also be written a different way, in terms of Y_{load}, which is assumed at the start to be 4.5 dB.

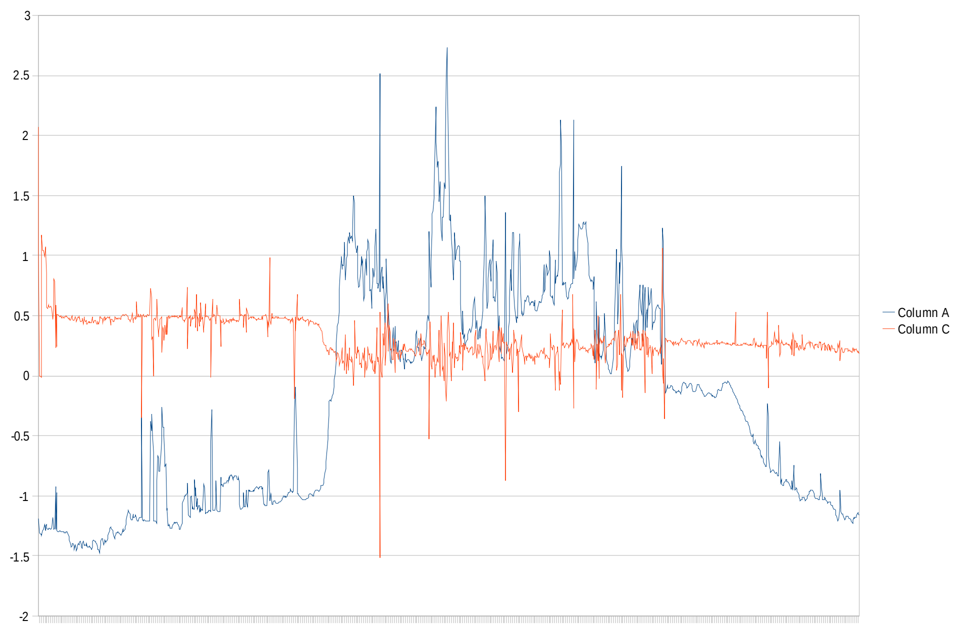
Since $Y_{load} = (T_{load} + T_{LNA}) / (T_{sky} + T_{LNA})$

and the sensitivity is $1/ (T_{sky} + T_{LNA})$, in terms of Y_{load}, the sensitivity is equal to $Y_{load} / (T_{load} + T_{LNA})$

T_{load} and T_{LNA} have estimated noise figures of 2.5 dB and 0.7 dB respectively. With this information, the sensitivity can be calculated, and from this information, the power that the lamp receives can be estimated.

Based on calculations, the noise temperature from the lamp was predicted to be about 7.33 K.

Below is a graph showing power readings with respect to time. The Column A variable represents the power when the lamp is off, and Column C represents the ratio between the power when the lamp is on to when it is off.



Note: Spikes are likely due to interference from Haystack radar

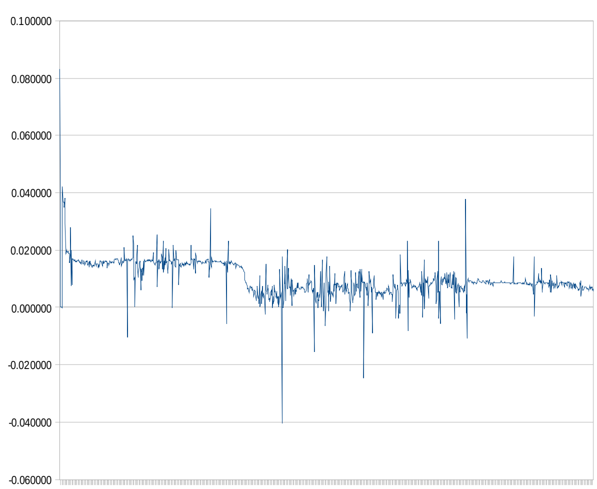


Illustration 1: This is a graph of sensitivity with respect to time. As expected, the sensitivity graph has a very similar pattern to the Y_{lamp} graph.

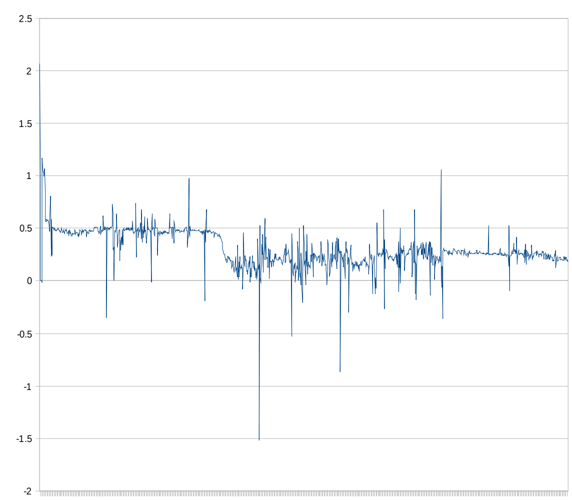


Illustration 2: The following is a graph of Y_{lamp} with respect to time.

GROUND SCREEN

Adding a ground screen was foreseen as a potential solution to reducing spillover from the feed for the ozone spectrometer. Without the ground screen, the Smart 0.1 dB on the ozone spectrometer showed to have a y-factor of about 4.7 dB. Adding the ground screen bumped it up to 5.1 dB. Furthermore, there appeared to be a slight difference in keeping the ends of the ground screen loose and taping the ends to the dish of the spectrometer. However, the difference only was about 0.1 dB.

CONCLUSION

The object of the research project was to investigate whether the signal for the spectrometer could be better optimized. This highly depended on increasing the signal to noise ratio, by either increasing the signal or decreasing the noise. This investigation focused almost entirely on reducing the noise figure. The first and most important step that needs to be taken to reduce the noise figure is to search for an LNB which claims to have a low noise figure, because most likely it will, and that will reduce the amount of complexity in calibrating the antenna and using other tools to reduce the noise. That is why several LNBs were tested of different ranges, and from the various antenna feeds that were tested out, the Smart 0.1 dB LNB clearly outperformed all the other ones. Using the mouth of a metallic funnel increased the signal to about 7.5 dB, which converts to a noise figure very close to 0.2 dB.

There was some effort to reducing the spillover from the antenna for the ozone spectrometer. Adding a ground screen was once again experimented with. Results have shown that the ground screen is in fact effective. However, a better solution needs to be examined, since the screen cannot practically withstand snow buildup in the wintertime. Now that LNB noise figure has been reduced, future research must focus on modifying the setup such that the spectrometer acquires as much signal from the sky as possible and as little of the spillover from the ground as possible.

ACKNOWLEDGEMENTS

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