Development of a Low Cost Multichannel Spectrometer for the Study of Ozone in the Mesosphere

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Abstract

Previously, Haystack Observatory has developed a low cost spectrometer for detecting ozone in the mesosphere using a satellite TV dish and a low noise block down converter feed (LNBF). While these spectrometers have contributed greatly to our understanding of the ozone at 100 km altitude, they require at least twelve hours to attain a significant signal-to-noise ratio (SNR). By using three dual polarization LNBFs, we are able to decrease the time to obtain a significant SNR by a factor of 6 or to about two hours. The increased sensitivity also can provide a fine enough resolution to provide data about wind speeds and the temperature of the ozone in the mesosphere. The modest cost of the system is maintained by using inexpensive digital TV tuners and demodulators. This system will enable scientists to gain continued understanding of the atmosphere at a fraction of the cost of other methods.

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1 Introduction

Global Warming is an international concern. Every year humans produce emissions that add to the carbon dioxide already in the environment. This results in steady incremental increases in the global temperature. This can have drastic consequences for individual climates in ways that scientists are still not able to predict [1]. In order to understand the way that the environment is changing, it is essential to understand the dynamics of greenhouse gases and how they impact climates. The gases in the atmosphere can be studied by looking at the electromagnetic radiations that are scattered, reflected, and emitted from the atmosphere. These radiation spectra can be used to infer the structure and composition of the atmosphere [2]. Since the chemistry of the ozone in the mesosphere is closely coupled with the chemistries of other oxygen and hydrogen containing molecules, studying ozone can provide unique insight into the composition and dynamics of the atmosphere [3]. It is important to understand how the atmosphere is changing over time in order to minimize our effect on the environment as a whole. In the Mesosphere there is a thin layer of ozone that radiates at 11.072 GHz.

Previously, Haystack Observatory developed a low cost way of measuring this layer of ozone using a Direct TV offset parabolic dish and and a single LNBF at a focal distance away. The system was pointed at about 8° of elevation and measures the power level at 11.072 GHz. It then calibrated out any ambient noise and Fourier transformed the time samples to the frequency domain [4]. From this data, We are able to view and analyze the diurnal cycle as well as the change over time of ozone. This gives the opportunity to study the processes which create and destroy ozone in more detail [4]. However, as beneficial as this system is, it lacks in sensitivity and resolution. In order to obtain a significant signal-to-noise ratio (SNR) the device must collect data for at least twelve hours. Also, for a significant measurement of the mesospheric ozone at this resolution, we were unable to provide data about wind speeds and the temperature of the ozone in the mesosphere, which would be helpful for continued understanding of the dynamics of the atmosphere. In order to surmount these challenges, We designed the system described in the paragraphs below.

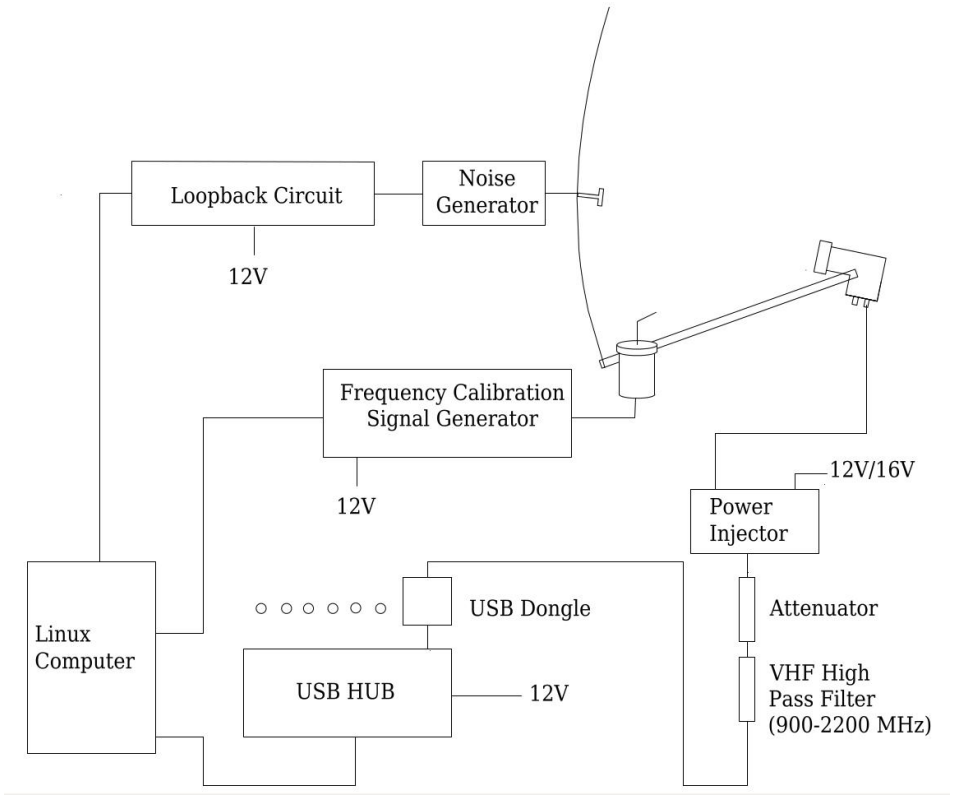


Figure 1: Full System

2 Hardware

The system is made up of a satellite dish with three LNBFs. The LNBFs are powered using a power injector. They are then used to collect the electromagnetic signal at 11.072 GHz and transfer it to the Linux computer via USB SDRs. In order to maintain accurate frequency, a signal is generated every 90 seconds and picked up by the LNBFs to compare their frequencies to. A noise calibrator is used to correct for changes in the system noise due to weather and drifts in the LNA. A program is run from the computer which controls the frequency and noise calibration and collects and processes the data into a user friendly format. Figure 1 shows how the components are interconnected.

We used a frequency switching pattern to remove receiver bandpass and systematics. The ozone line spectrum is extracted by subtracting the spectrum from an adjacent frequency band which acts as a comparison and then dividing by the comparison. A first order calibration is then obtained by multiplying this fractional spectrum by the system temperature to convert the units to degrees kelvin. This enabled us to more accurately separate the ozone signal from the noise. The comparison spectrum is smoothed using a low order polynomial to remove the noise in the reference spectrum without affecting the bandpass. This improved the SNR by a factor of $\sqrt{2}$

2.1 Low Noise Block Feedhorns and Satellite Dish

Secondly, we added two additional LNBFs. Similarly to the first system the set of LNBFs are placed a focal distance away facing the center of the dish. Figure 2 and 3 show the set up of the LNBFs. These additional channels allow us to minimize the data collection time by a factor of $\sqrt{6}$ to obtain the same SNR as the single channel spectrometer. These two LNBFs are placed on either side of the first one with their centers about 2.25 in. apart. The addition of the LNBFs introduces the challenge of minimizing the spillover in the outrigger ones, since most dishes are not optimized for multiple LNBFs. The spillover is the part of the feed antenna radiation which misses the reflector. It can be calculated by:

$$1 - P_{dish}/P_{total}, \tag{1}$$

The power on the dish is found by modeling the power as a Gaussian function and integrating over the surface of the dish. The total power is found by integrating over a dish of comparatively infinite radius.

Initially we intended to use the DirecTV Slimline elliptical Dish since it appeared to be better suited for multiple LNBFs. However, it had a focal length of about 19 in. Due to this large focal length only about 80% of the signal



(a) LNBF Geometry



(b) LNBF Orientation

Figure 2

power that was picked up was from the dish. The other 20% came from other sources such ambient radiation and ground. This poses a significant problem because we only collect about 80% of the available ozone power and even if only 10% of the excess energy comes from the ground it can raise the entire system temperature by 30 K. After discovering the inadequacy of the Slimline dish, we opted to use the 60 cm Winegard DS-4060 dish, with a focal distance of 13.87 in. This provided a much more reasonable spillover ratio of about 5% for the central LNBF.

It is important to measure the actual noise performance of the ozone spectrometer to evaluate the efficiency of the antenna. One way of quantitatively measuring the noise performance of the spectrometer is by measuring the Y factor. The Y-factor is the ratio of the Ambient Temperature and the LNA temperature to The sky temperature and the LNA temperature.

$$Y = (T_{amb} + T_{LNA})/(T_{sky} + T_{LNA}), \tag{2}$$

A high Y-factor implies a low T_{LNA} which leads to a lower noise figure and a more efficient antenna. The easiest way to find the Y factor is to measure the signal with an absorber in place and divide it by the signal with the absorber removed. I ran the Y-factor three times for each LNBF at both orientations and obtained the results contained in table 1.

Table 1: Y-Factor Values (Dbi)

LNBF	Middle	Middle	Left	Left	Right	Right
	Voltage		Voltage		Voltage	
	12 V	16 V	12 V	16 V	12 V	16 V
Without Absorber	53.2	56.2	53.1	55.1	54.6	56.1
With Absorber	58.1	60.9	57.6	59.9	59.2	60.8
Without Absorber	53.3	55.8	52.9	54.9	54.6	56.0
With Absorber	58.1	60.7	57.4	59.8	59.4	60.7
Without Absorber	53.2	55.6	52.8	54.8	54.7	55.9
With Absorber	58.0	60.7	57.4	59.8	59.4	60.6
Y Factor	4.8	4.9	4.5	4.9	4.7	4.7

For the LNBFs, We used Star Com's SR-3602 Mini digital KU-band Universal LNBFs with dual polarizations. Each LNBF has two channels which switch between the two polarizations based on the input voltage. For a voltage of 11.5 V to 14 V it is polarized vertically and for a voltage of 16 V to 19 V it is polarized horizontally. Three of the LNBF channels were powered with 16 V to get a horizontal polarization and three of the LNBF channels were powered with 13 V to get the vertical polarization.

Ideally we wanted the spectrometer to be pointed at an elevation of 8° to get the strongest signal possible. However, at that elevation, the trees near the current spectrometer location, would block some of the signal. As a result, an elevation of 12° was used. Figure 3 shows the orientation of the dish.

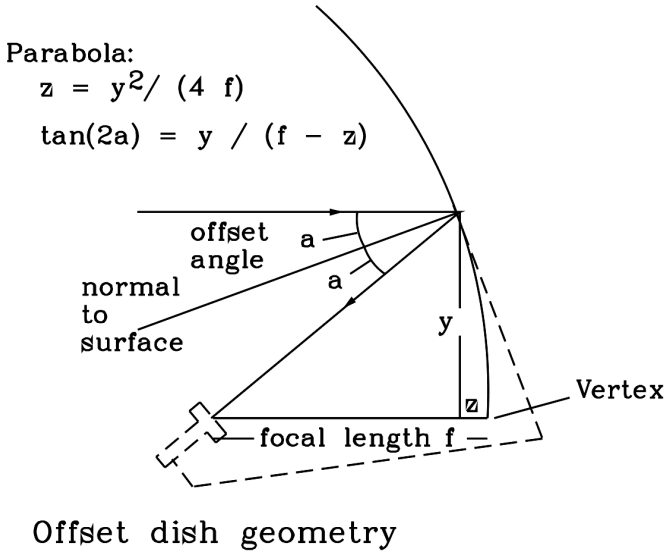


Figure 3: Orientation and Geometry of the Dish

2.2 Noise Calibrator



Figure 4: Noise Calibrator Dipole Antenna

One design consideration is that the system needs to be able to correct for changes in the system noise due to weather and drifts in the LNAs. The previous spectrometer relied on changes in the total power to correct for the added noise and loss from the atmosphere. This depends on the assumption that the gain and LNA noise temperature are constant. However, this approximation fails if there are large changes in the ambient temperature. In order to achieve more accurate correction for the added noise and loss from the atmosphere which changes with the weather, we used a noise calibrator. If we assume a constant LNA noise temperature,

$$P_{off} = g(T_{LNA} + T_{atmos} + T_{spill}) = gT_{sys}, \tag{3}$$

$$P_{on} = g(T_{LNA} + T_{atmos} + T_{spill}) + gT_{cal}, \tag{4}$$

Where:

P_{off} = total of power with noise calibration off

P_{on} = total of power with noise calibration on

g = gain

T_{LNA} = LNA noise temperature

T_{atmos} = noise contribution from the atmosphere

T_{spill} = noise from spill over of LNBF

T_{cal} = calibration noise temperature

T_{sys} = system noise temperature

Attenuation in the atmosphere adds to the system noise as well as reducing the observed strength of the ozone line. By the theory of radiative transfer:

$$T_{atmos} = (1 - e^{-\tau})T_{abs}, \tag{5}$$

$$T_{obs} = T_{ozone}e^{-\tau}, \tag{6}$$

Where:

τ = The opacity of the atmosphere

T_{abs} = Physical temperature of the absorbing region

T_{ozone} = noise temperature from the ozone line

T_{obs} = observed temperature

if T_{LNA}, T_{spill}, and T_{cal} are measured with separate tests and assumed constant equations 1 through 4 can be used to measure and calculate T_{atmos}, g, and the system noise temperature.

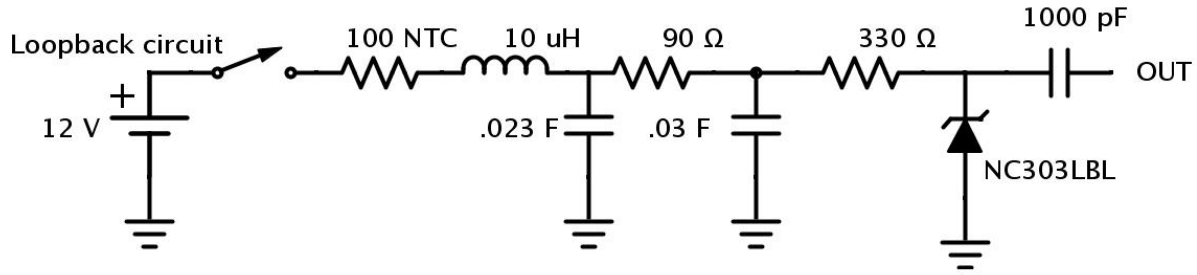


Figure 5: Noise Calibration Circuit

In order to generate the signal for the noise calibrator, we designed a custom circuit, shown in figure 5. This circuit supplied a constant 8.6 V to NoiseCom's NC303LBL noise diode to generate the calibration signal. The signal was radiated with a half-wave-dipole antenna, shown in figure 6, that was mounted 3/4 wavelengths above the ground plane at the dish center approximately 14 in away from the LNBFs. A ferrite toriod was added the antenna to act as a balun to increase the uniformity of the output. It was coated with several coats of hydrophobic epoxy in order to make it more rugged.

The expected path loss can be found using:

$$\frac{G_1 G_2 \lambda^2}{2(4\pi)^2 r^2} \tag{7}$$

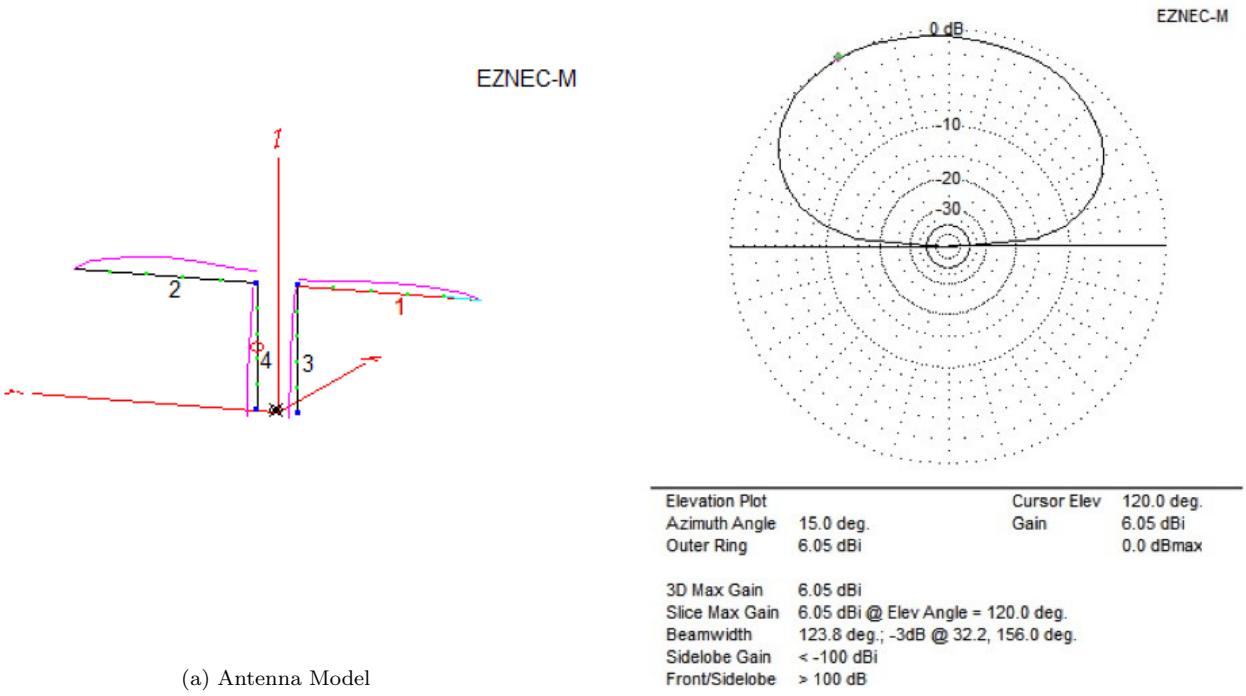
Where:

G_1 = LNBF gain relative to isotropic in the direction of the noise source

G_2 = Antenna gain in the direction of the LNBF

r = distance from LNBF and antenna

The factor of 2 in the denominator comes from the fact that the polarizations are oriented 45° from each other. For G_1 = 11 dBi, G_2 = 6 dBi, r = 14 in, λ = 1.1 in the loss is 30 dB. For a noise diode output of 30 dB ENR the expected cal T_{cal} is about 300 K which will result in 4.8 dB increase in power when the calibrator is turned on for $T_{sys} \approx 100$ K



(a) Antenna Model

(b) Simulation of Antenna Beam Pattern

Figure 6

2.2.1 Testing

The next step was to determine if the system was working properly. Since the power of the antenna is calculated from the power measured at each of the LNBFs and the output of the antenna is theoretically constant, we can compare the calculated value over time to evaluate the system. Variation in the antenna strength can be caused by interference from other signal sources or weather events. Figure 7 shows the system with varying levels of interference. While some of the interference came from rain, the main source of interference came from the HAX radar system. In order to eliminate these faulty segments from the data, a simple filter was applied. If the power of the dipole antenna deviates widely from the expected value, that segment of data was omitted. This however limits the amount of data able to be collected in a given time frame and it is recommended to move the system to a quieter location, such as behind the Moran building.

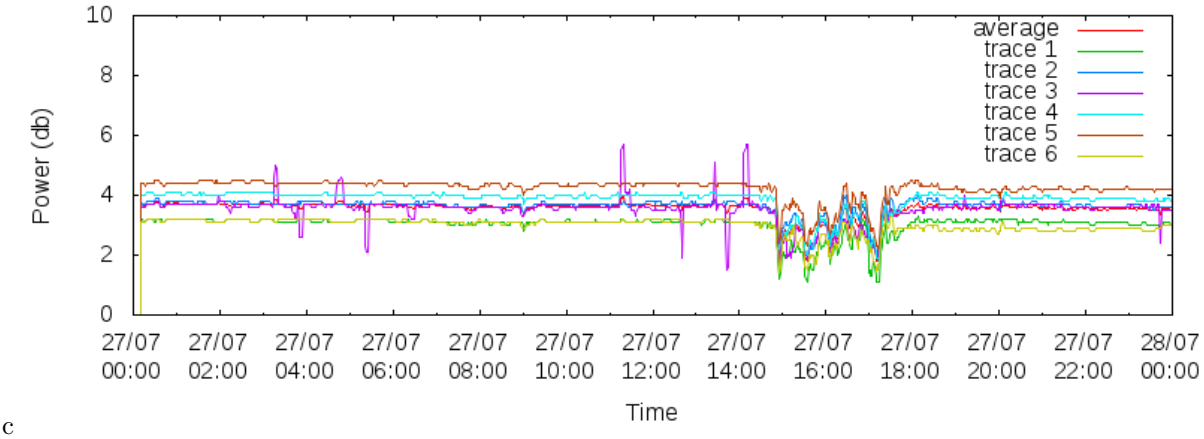
The slight variations in the measured power levels in each of the channels is due to differences in path length and orientation of the LNBF.

2.3 USB TV SDR dongles

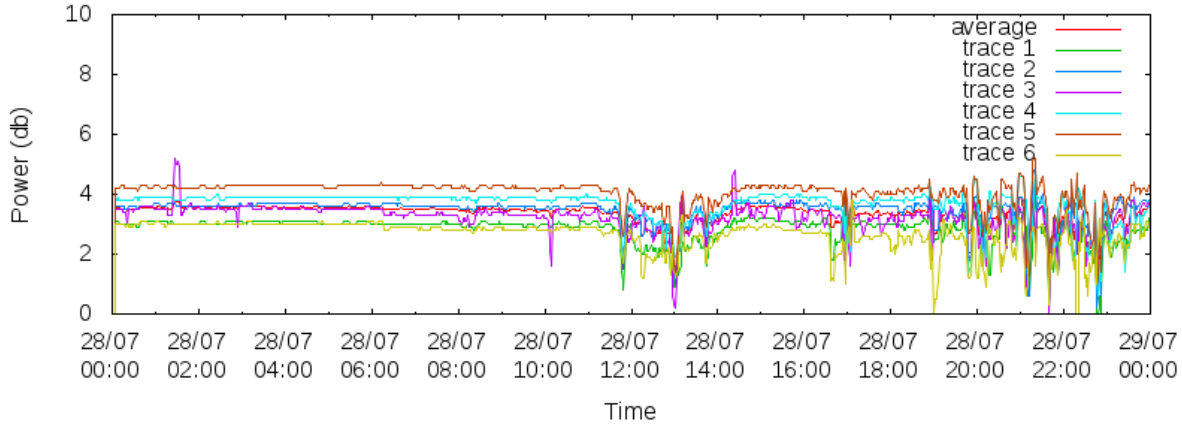
USB TV SDR dongles are low cost receivers which have found many applications outside their original purpose of TV reception via computer. In order to collect and correlate the data from the LNBFs we needed to transfer it to the computer. The multichannel ozone spectrometer uses six dongles to connect each channel to the computer. The dongles connected the LNBFs to the computer via a 7 port USB 3.0 HUB with a 12 V external power supply. However under this configuration, the USB digital TV tuner RTL-SDR dongles were overheating to a temperature of 55°C as measured at the RF input connector. At a temperature around 55°C and above the local oscillator synthesizer fails.

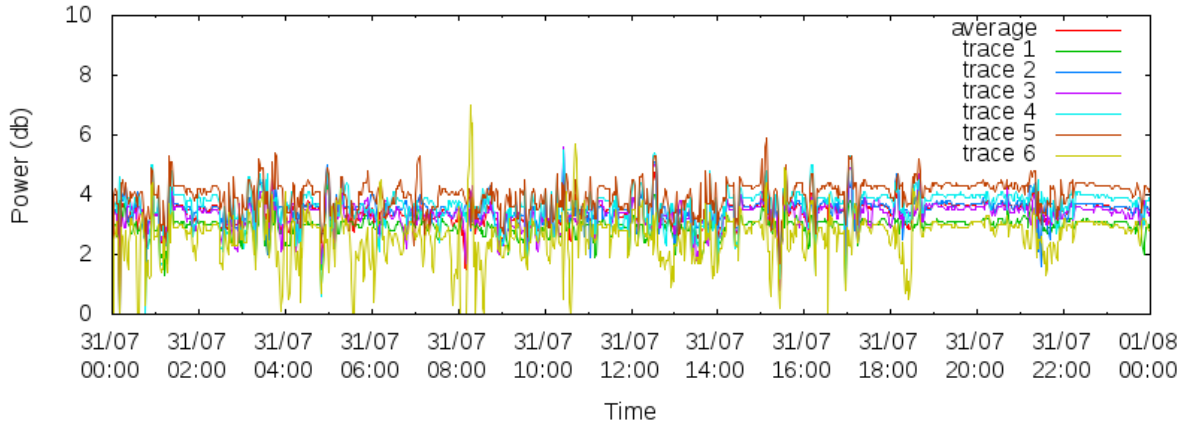
In order to address this problem we created a heat sink to dissipate the power. The heat sink consisted of a 11.75 in. by 5.5 in. metal plate. We extended the dongles out away from the USB hub and fastened them to the plate by screwing a metal piece over them. The top metal piece was 8.75 in. in length and extended up by 4.25 in.

Since the current drawn by the Hub was 840 mA supplied from a 12 V source about 10 W was dissipated in the circuit. Assuming that the majority of the power dissipated was in the dongles, we can assume that about 10 W will need to be dissipated by the heat sink. To find the power dissipated due to radiative transfer we can use the



c





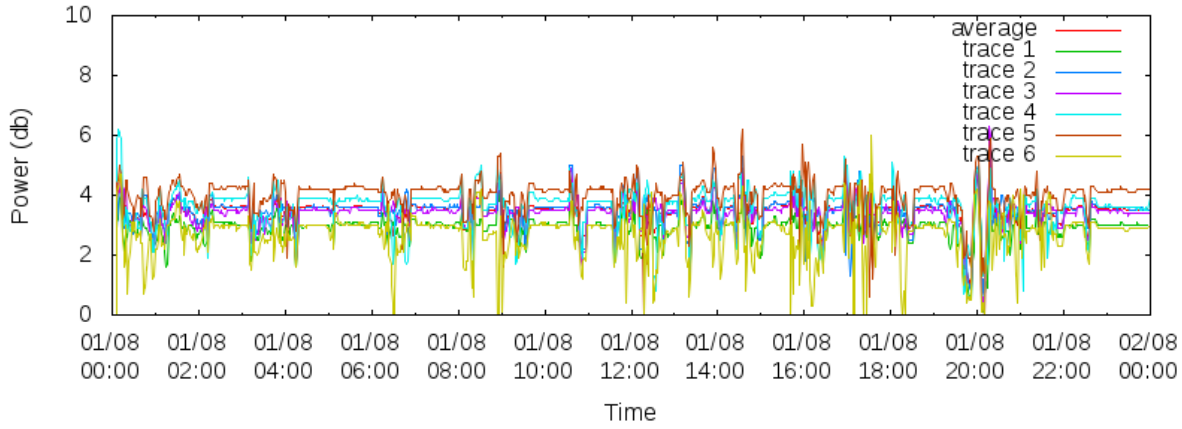


Figure 7: Noise Calibration Testing

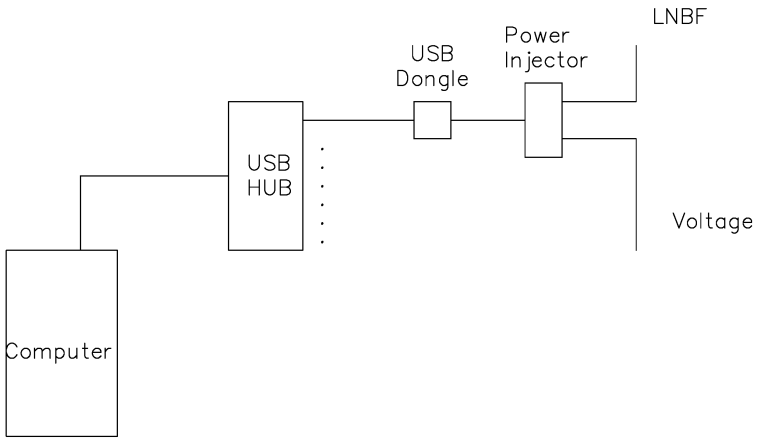


Figure 8: Circuit Diagram

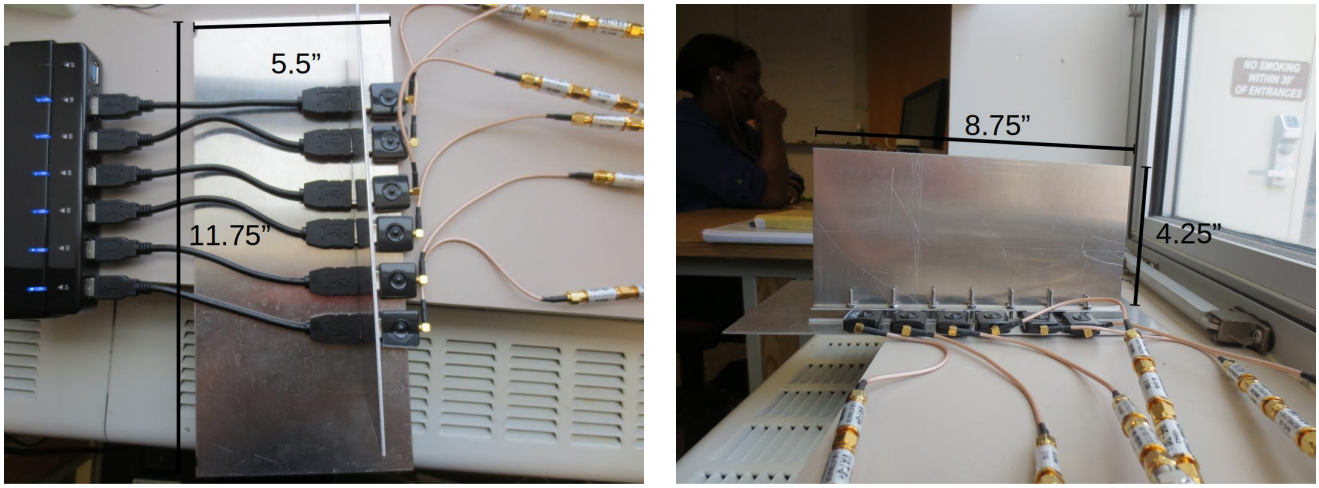


Figure 9: Images of Heat sink

equation.

$$P = 2A\epsilon\sigma(T_{metal}^4 - T_{atm}^4) \tag{8}$$

Where:

P = Power

A = area

T_{metal} = Temperature of the metal

T_{atm} = Temperature of the atmosphere

σ = Stefan-Boltzman Constant

ϵ = emissivity of the heat sink material

Since:

$$T_{metal} = T_{atm} + \delta \tag{9}$$

Then equation (1) becomes

$$P = 2A\sigma((T_{atm} + \delta)^4 - T_{atm}^4) \tag{10}$$

By using the approximation for b $\ll$ a

$$(a + b)^4 = a^4 + 4ba^3 \tag{11}$$

then equation (4) simplifies to

$$P = 2A\epsilon\sigma(4\delta)T_{atm}^3 \tag{12}$$

Solving with $\delta = 28$ since the measured value of 55°C is approximately 28°C above the room temperature of 27°C, $\epsilon = 0.1$ for aluminum and A = 0.0417 m^2 for the bottom plate The power dissipated on the bottom plate = 1.43 W. The area of the vertical piece is 0.0240 m^2 so the power dissipated on the vertical piece is 0.823 W. Total Power dissipated due radiation is 2.253 W

The heat sink was also erected in an upright position, so additional cooling occurs due to convection. The heat transfer due to convection can be calculated by solving the equation:

$$P = hA(T_{metal} - T_{atm}) \tag{13}$$

Where h is a constant depending on the material and orientation of the heat sink. For a vertical plane:

$$h = \frac{k}{L}(.825 + \frac{.387Ra_L^{1/6}}{(1 + (.492/Pr)^{9/16})^{8/27})^2} \tag{14}$$

Where:

k = Thermal conductivity of the material

L = Height of plane

Ra_L = Rayleigh Number with respect to height of plane

Pr = Prandtl Number

For L = 0.10795 m and Ra = 3.42 * 10^6 and Pr = 4.94 * 10^6, h = 5.76 and the power dissipated from convection is 6.73 W. This brings the total heat dissipated to about 9.26 W. Since this value is lower than the needed value of 10 W, we considered painting the heat sink black to increase the rate of heat dissipation. Painting the heat sink black would result in an increase in emissivity and, as a result, the heat dissipated due to radiation. Using $\epsilon = 0.8$ then the power dissipated on the lower plate would be 11.44 W and on the vertical piece it would be 6.58 W. As a result additional margin could be gained to keep the dongles well below 55°C.

2.4 Frequency Calibrator

Since the LNBF module uses a free running oscillator and the frequency of this type of oscillator drifts with changes in temperature it has to be calibrated every 90 seconds. This is done by injecting harmonics of 10 MHz from a crystal oven oscillator to detect and correct for changes in frequency. Also, by comparing the detected frequency and power distribution of the ozone to the known frequency of ozone, one can determine the wind velocities in the mesosphere from the Doppler shift. However a very precise comparison frequency must be used in oder to obtain accurate wind velocities.

The ozone spectrometer uses an OX200-SC 10 MHz VCOCXO oven crystal. During testing, we noticed that when a signal was inputted exactly at the frequency of 11.0724545 GHz the program was outputting a non-zero wind velocity.

We measured the 10 MHz frequency of the oven crystal against a calibrated signal of 5 MHz. This revealed that the oven crystal was off by a value of about 100 ppb. According to the data sheet, aging the crystal by 5 years can result in a 60 ppb frequency shift. The crystal is also very sensitive to tuning frequency and can shift by 0.3 ppm/V. Since we are not using a voltage regulator to power the crystal this may also be causing shifts in frequency. A frequency error of 1 ppb corresponds to an error of 0.3 m/s in velocity As a result, we are unable to get accurate wind velocities.

The recommendation for a short term fix is measure the frequency deviation and to hard code into the program a correction for it. In the long term, it is recommended to get a more accurate oscillator such as an atomic clock to calibrate for shifts in frequency. The Chip Scale Atomic Clock SA.45s has an accuracy, upon shipment of $\pm$ 5.0*10^{-11} and less than 3.0*10^{-10}/month aging rate which translates to 0.05 ppb error on shipment with a decay of 0.3 ppb/month. This would meet our needs for accuracy.

2.5 USB to RS232 converter

Both the frequency and noise calibrators use a USB to RS232 converter to turn on and off. Therefore, there need to be some form of positive identification for the computer to differentiate between the two of them. So the USB to RS232 for the noise calibrator was wired in a loop back mode. Pins 2 and 3 were soldered together and a symbol was sent to pin 2 and then pin 3 was probed to determine if the pins were connected. If so it would identify it as the noise calibrator; if not it would identify it as the frequency calibrator.

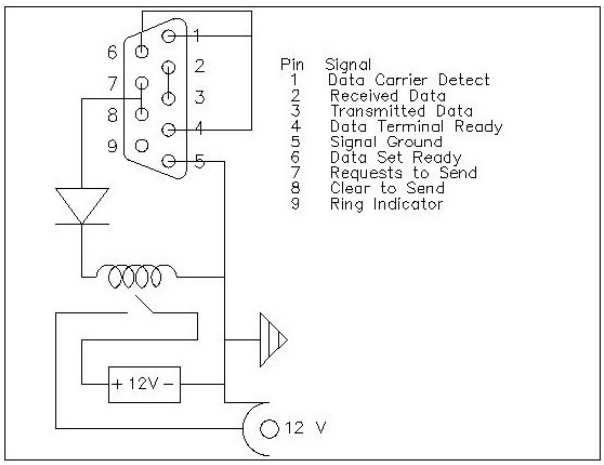


Figure 10: Loopback Circuit

3 Execution

The system was set up behind one of the buildings and run remotely by SSHing into the computer to access the collected data.

3.1 Conclusion

The ozone spectrometer is able to detect the ozone line with greater resolution and less time is needed to detect the signal than the previous system. Figure 11 shows the ozone line as detected by the previous system (right) and the current one (left) over the same time period. Even though we had to filter out almost half of the data due to interference the current system detects the signal at almost twice the strength of the previous system. However, the wind velocity measurements are still not good enough to attain a significant wind figure unless we replace the oven crystal oscillator with the Chip Scale Atomic Clock. In the future we should replace the oven crystal oscillator with the Chip Scale Atomic Clock to attain wind velocities and move to Moran Building to minimize interference from HAX radar.

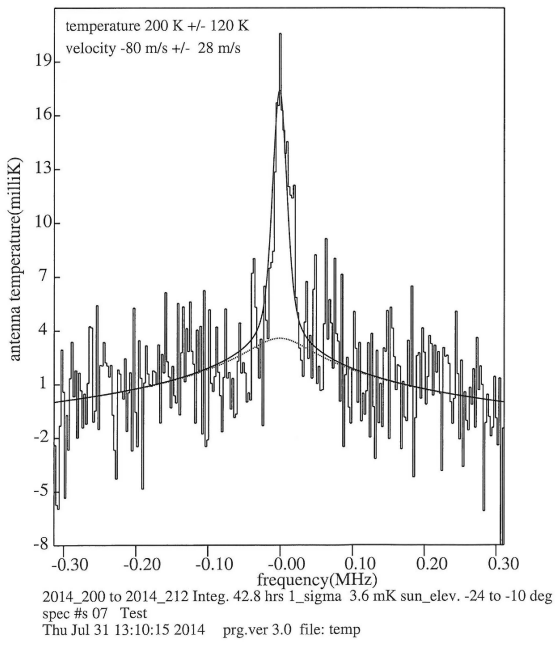
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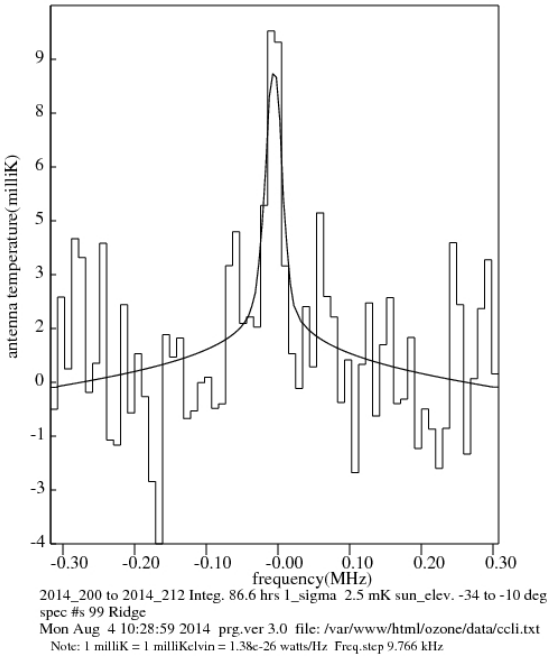
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(a) Current System



(b) Previous System

Figure 11