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Ionospheric Neutral Mass Spectroscopy

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Abstract

Understanding neutral masses in the ionosphere, especially in the E- and D-regions, is a very challenging endeavor. This is due to the high density of neutral masses at this height and the speed at which sounding rockets travel. These factors limit the ability to understand the quantity and quality of neutral masses in these regions; the density of these masses and the percentage of different masses present is not well resolved. Therefore, there exists a need to further investigate neutral mass in the ionosphere, and this research aims at presenting a possible instrument for doing so. We conducted experiments to evaluate whether a residual gas analyzer (RGA) could be used as a neutral mass spectrometer for application in the E- and D-region ionosphere. The basic experimental configuration was a roughing vacuum pump attached to a turbo vacuum which together brought the configuration to a pressure between 5×10^{-9} to 2×10^{-8} Torr. With the RGA within the vacuum, data was collected on the trends found, accuracy, and scanning speed of the instrument. Ultimately, the RGA was able to collect at a rate of 9 seconds per AMU studied with a deviation of around $\pm 10^{-10}$ Torr when running in secondary electron multiplier mode (SEM). The results did not support the potential flight of a RGA on future sounding rocket campaigns for studying neutral masses within the ionosphere, however solutions around the limitations of the device are offered.

1 Introduction

The current literature surrounding the study of neutral masses within the ionosphere, approximately 50 to 1000 km above the Earth's surface, is lacking [NAS]. The main reason behind this is due to the difficulty in studying this region; the ionosphere is difficult to reach from ground based instruments yet is not high enough for top down methods utilizing satellites to be vey useful. However, both sounding rockets and balloons have proven as useful vessels for studying this region. Both of these carry instruments into the ionosphere and therefore allow for in-situ study of its components [SN09].

Figure 1: A picture of the residual gas analyzer (RGA) outside of the vacuum chamber.

Some of these components are neutral masses in the ionosphere. Neutral masses are of relatively great density in this region and are key in the formation, energetics, and dynamics of the ionosphere. Therefore understanding their quantity and quality is important for understanding atmospheric behavior. Neutral masses have been studied utilizing sounding rocket instrumentation in the past, however this is difficult due to their speed, which is typically around 1 km per second. Therefore, in order to better study neutral masses utilizing a sounding rocket, the proposed instrument must quickly collect data, at least at a rate of 0.1 seconds in order to get 100 m resolution [SN09].

This research is focused on one of these proposed instruments, specifically the use of a residual gas analyzer (RGA) as a neutral mass spectrometer for application within the E- and D-region ionosphere. The RGA in use is the Partial Pressure Transducer Quadrupole RGA produced by MKS Instruments. This device utilizes quadrupole mass spectrometry in order to process gas analysis and allows for filtering in order to detect distinct constituents surrounding the device. As shown in Figure 1, the RGA was approximately 0.3 meters long, supporting that its size and weight, two important components for instruments that might be flown on sounding rocket missions, would not be an issue [Ins95]. However, in order to determine if the device would be useful for studying neutral masses in the ionosphere through a sounding rocket mission, the accuracy and speed of the device would need to be determined.

2 Methodology

The hardware configuration consisted of a Partial Pressure Transducer (PPT) Quadrupole residual gas analyzer (RGA) placed within a vacuum chamber created by two roughing and turbo pumps working in conjunction. At one end of the vacuum chamber was a valve for leaking nitrogen gas into the system at some set rate. The vacuum chamber was brought down to a total pressure between 5×10^{-9} to 2×10^{-8} Torr at the beginning of all of the experiments by allowing the pumps to run over the course of a couple days. The RGA was then connected to an electronic control unit (ECU) which communicated with the computer through serial pins. Finally, a PKR Full Range Gauge was located next to the RGA in order to compare the output of the two devices to further confirm the accuracy of the RGA. This configuration is presented below in Figure 2.

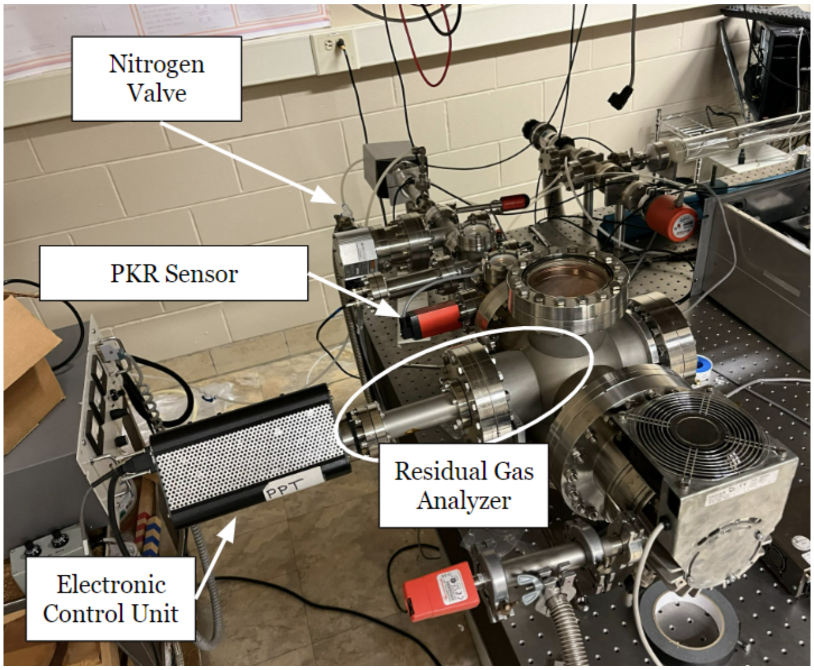

Figure 2: This is the basic experimental configuration vacuum chamber used.

The MKS-PPT software utilized to receive and interpret the data collected through the ECU from the RGA was the MKS-PPT software accessed through DOSBOX. In order to run the MKS-PPT software, the following lines of code were inputted into DOSBOX

```
mount c folder_path/black_RGA_content
C:
cd PPT430
PPT
```

This allowed for serial communication with the ECU. Overall, the MKS-PPT software allows for data collection through several modes: Analog, Bar, Table, Pressure vs Time, Leak, Split, and Tune. In order to study the speed and accuracy of the RGA, the experiments done here were conducted in the Pressure vs. Time mode, as this mode was useful for collecting trend data along multiple channels in order to compare different input conditions, such as differences in Dwell times which would impact the rate of data collection. The Dwell variable, which establishes the "desired rate of filtering needed for making each measurement", as well as the Volts variable, which sets the SEM voltage, were altered across different channels [Ins95]. The equation for the Dwell time's effect on the scanning time is presented in Equation 1 presented below for the Pressure vs. Time mode.

$$\text{Scan Time} = (\text{Dwell} \times 20 \text{ ms}) + 10 \text{ ms per channel} \tag{1}$$

The Dwell value's range is 1 to 1000. When in Pressure vs. Time mode, the MKS-PPT software collects data on the partial pressures from all the channels synchronously, and it plots these pressures over the course of a scan. The duration of a scan is in the range of 6 to 100 hours. The Dwell time determines the scan time it will collect data over to produce one data point. For example, if data is collected from two channels at the same atomic mass unit (AMU) and one has a Dwell of 1 and the other a Dwell of 8, the same amount of data points are produced by both channels. However the accuracy of the larger Dwell will provide more consistent data points since more raw data points were used to create each one of those output data points. In contrast, the DataLog feature may be switched on and this will store continuous ASCII data, however the range for this feature is 0.1 to 120 minutes, allowing for at best a speed of collection at every 6 seconds. The limitations of the current MKS-PPT software, as well as suggested improvements, will be discussed in the **Discussion and Conclusion** section.

The RGA can also be operated in two different detector modes: Primary Mode and Secondary Electron Multiplier (SEM) Mode. These signify the operation pressure range for the sensor, with Primary Mode being in the range of 10^{-4} to 10^{-9} Torr and SEM Mode 10^{-4} to 10^{-12} Torr and experiments were conducted on the capabilities of both of these modes [Ins95]. In total 10 experiments were conducted, 5 in Primary Mode and 5 in SEM mode. To begin ever session of data collection, the sensor's degas feature was utilized to decrease residual gas around the device.

In addition to controlling the RGA, the valve attached to the chamber was controlled in order to leak nitrogen gas into the system. Ultimately, data was collected from both the MKS-PPT software and a PKR Full Range Gauge placed near the RGA (as seen in Figure 2) in order to compare the pressure readings from both of these instruments. In addition, note that the PKR Full Range Gauge collected data on the total pressure of the system while the RGA was set to collect data specifically at 28 AMU, since N_2 was available and therefore used for testing. However, when the valve was opened an increase in both the total pressure and pressure at 28 AMU was expected.

Within the folder titled "black_RGA_content" are .txt files that explain how to navigate and use the other files found within the folder. The data collected from the RGA was saved out as a binary file saved within the "PPT430" folder. In order to process the binary files outputted by the MKS-PPT software, the files must be placed in the "430DATA" folder. Next within DOSBOX, the user must input the following lines of code

```
mount c folder_path/black_RGA_content/PPT430/430DATA
C:
DATASCAN <NG45PV.H Dfilename Doutname >outname
```

This will save the input file to a .CSV file if specified in "outname" and this will be placed within the "PPT430" folder as well. Once this was completed, the data from both the RGA and PKR were plotted using python. These plots are presented in the **Results** section and they are discussed further.

3 Results

3.1 Primary Mode

In total 5 experiments were run in the Primary Mode of the RGA over different Dwell times, different time intervals, and with different valve conditions. All experiments were focused at an AMU of 28, which corresponds to N_2. First, Experiment 1 and 2 were conducted over a single Dwell time for 12 minutes. Experiment 1, as plotted in Figure 3, was done at a Dwell time value of 1 and Experiment 2, as shown in Figure 4, was done at a Dwell time value of 8.

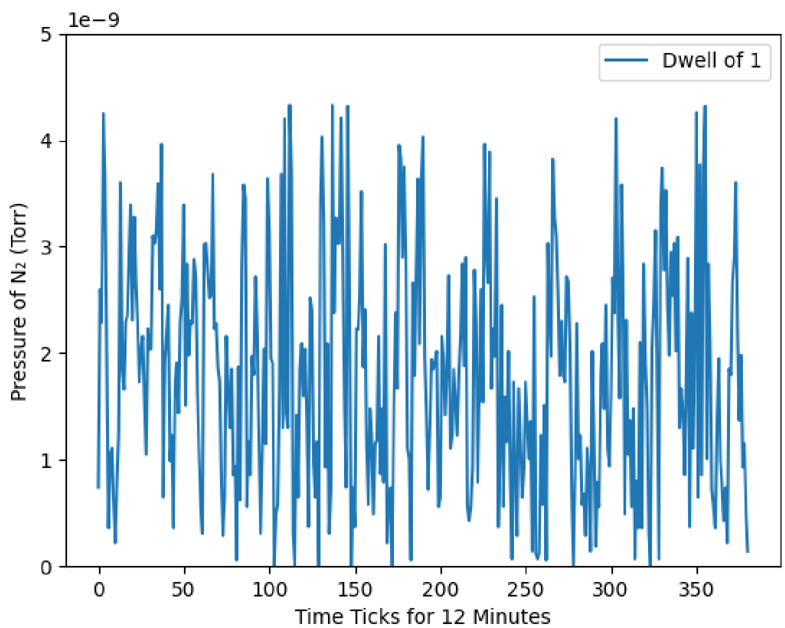

Figure 3: The Primary Mode was run for 12 minutes at a Dwell time value of 1.

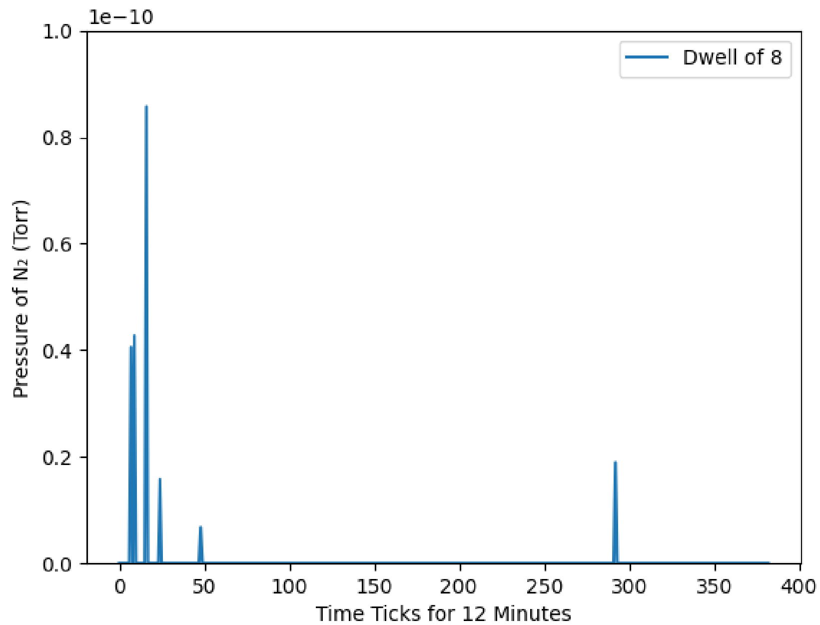

Figure 4: The Primary Mode was run for 12 minutes at a Dwell time value of 8.

Comparing the two figures, it is clear that the Dwell time value of 1 compared to 8 is much noisier. In addition, because the Primary Mode has an operating pressure range of 10^{-4} to 10^{-9} Torr and no nitrogen was being actively pumped into the system, the values found in Experiment 1 are mostly due to noise. However, the values in Experiment 2 are mostly zero which is expected since the pressure of N_2 in the system is expected to be below the lowered range of this mode when not pumped into the system. Since the Dwell time gives the integration time and not rate of collection, both the Dwell 1 and Dwell 8 experiments outputted the same number of data points over the 12 minute periods, however with the Dwell 8 channel being much more consistent.

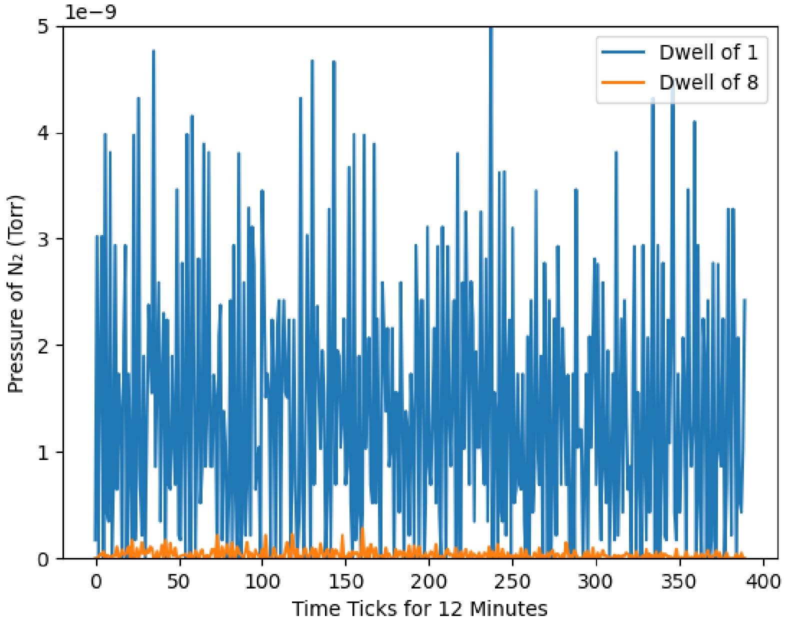

Figure 5: The Primary Mode was run for 12 minutes at Dwell time values of 1 and 8.

Following this, Experiment 3 ran both the Dwell time values of 1 and 8 simultaneously over 12 minutes. The results are shown below in Figure 5. As was seen in Experiments 1 and 2, here both Dwell time value curves experienced noise with the Dwell of 1 curve being much noisier and inaccurate with expected values for the pressure of N_2. It is also clear here that running both Dwell times in the same scan made the Dwell 8 data less consistent overall, but also the data had less outliers.

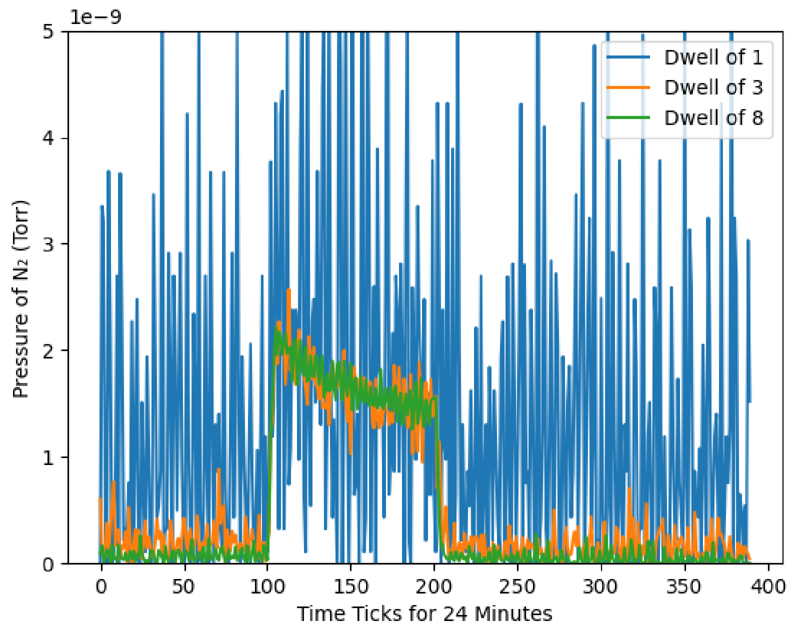

Figure 6: The Primary Mode was run for 24 minutes at Dwell times values of 1, 3, and 8. From around 100 to 200 time ticks, the N_2 valve was opened to 62% and then closed.

Next, for Experiment 4 data was collected at the Dwell time values of 1, 3, and 8 simultaneously for 24 minutes. Then at approximately the 6 minute mark (around the 100th time tick), the valve value was set to 62% open in order to allow nitrogen gas to enter the system. This was left open for approximately 6 minutes and then was fully closed at approximately the 12 minute mark (around the 200th time tick), as seen in Figure 6. Since the Primary Mode of the RGA has a lower end for detection at 10^{-9} Torr, the RGA was capable of seeing the increase in nitrogen gas, as shown in the elevated region within the center of Figure 6. This increase was also seen across all Dwell times, although the Dwell 3 and Dwell 8 channels were much less noisy and accurate to the change.

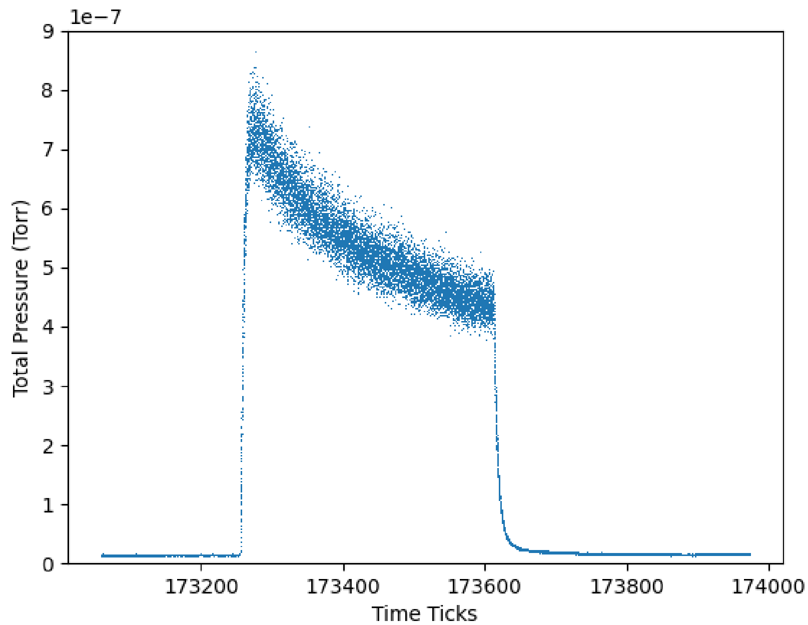

Figure 7: The PKR Full Range Gauge total pressure output during Experiment 4

An additional thing to note is the downward slope of the elevated region, showing that following the initial spike in N_2, the turbo pump was capable of bringing the system down in pressure once again, although this is done very slowly since it is fighting the nitrogen entering the system. This is noticeable in Figure 7, which is a plot of the total pressure as collected by the PRK Full Range Gauge which is located next to the RGA (see Figure 2. The RGA was able to see this as well and comparing the two they are very similar plots, further confirming the accuracy of the RGA at larger Dwell times, as the Dwell 1 still is very noisy and shows the trend less visibly.

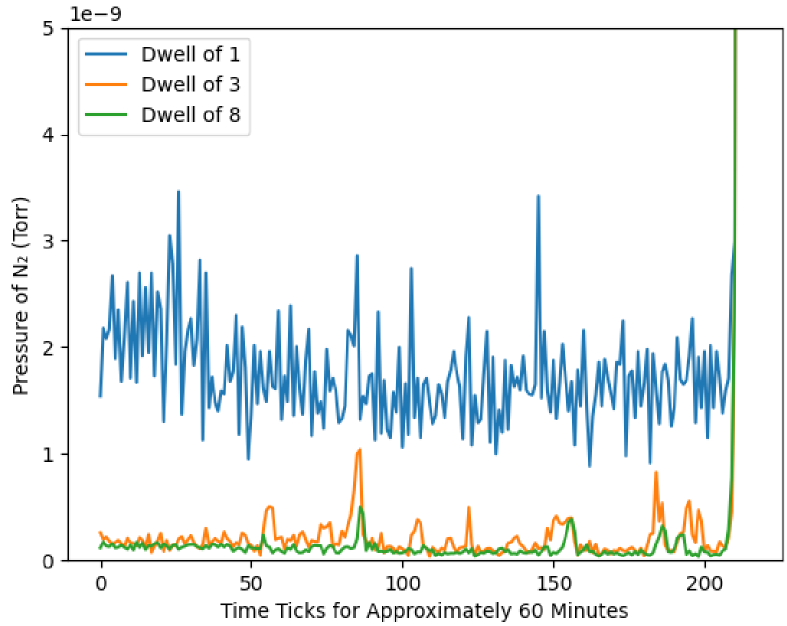

Figure 8: The Primary Mode was run for approximately 60 minutes for channels with a Dwell of 1, 3, and 8. Both the turbo pump and roughing pump were turned off at approximately the 12 minute (40th time tick) and 60 minute mark (200th time tick) respectively.

Finally in Experiment 5, the RGA collected data over the Dwell 1, 3, and 8 channels for approximately 60 minutes as shown in Figure 8. During this experiment at around the 12 minute mark (40th time tick), the turbo pump was turned off and the system was allowed to increase in pressure freely. Once the turbo pump had stopped rapidly spinning, at around the 1 hour mark (200th time tick), the roughing pump was turned off. This quickly increased the pressure of the system and engaged the RGA sensor's pressure protection which automatically turned it off at 10^{-4} Torr. This function can also be disengaged if desired. During this experiment, the data appears more consistent, especially for the Dwell 1 channel. This is most likely due to the pressure being at a higher level allowing for the sensor to more accurately get a reading on the pressure of N_2 within the system.

Again the RGA values were compared with the PKR Full Range Gauge total pressure values, as shown in Figure 9. Its output is similar to that found by the RGA as expected, although since it measure the total pressure it did see a somewhat more gradual increase

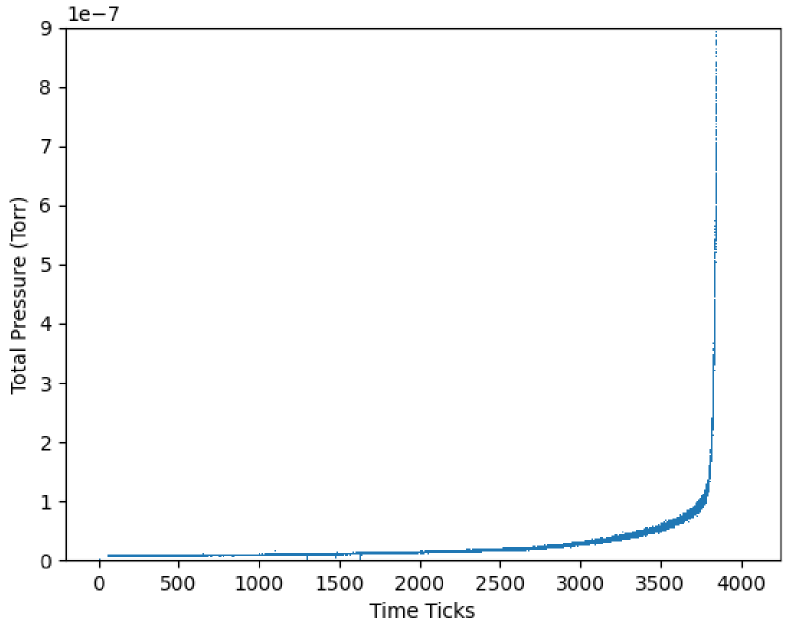

Figure 9: The PKR Full Range Gauge total pressure output over the course of Experiment 5.

compared to the sudden sharp spike seen from the RGA in Figure 8.

3.2 Secondary Electron Multiplier Mode

In total 5 experiments were run in the Secondary Electron Multiplier (SEM) Mode of the RGA over different Dwell times, different time intervals, different SEM voltages, and with different valve conditions. All experiments were focused at an AMU of 28, which corresponds to N_2.

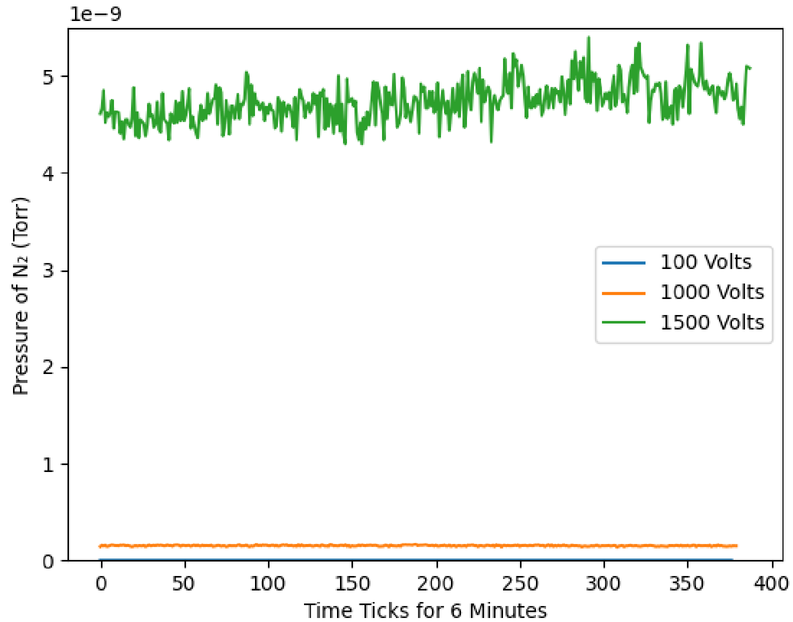

Figure 10: The SEM Mode was run for 6 minutes for 100, 1000, and 1500 volts.

First in Experiments 6, 7, and 8, different SEM voltages were compared (Figure 10). Here the Dwell was held constant at 1 and the experiments were run for 6 minutes each. When the SEM voltage was set to 1500 volts, the output had some noise, however it was much more consistent than the noise seen at Dwell 1 in the Primary Mode. At 100 volts, the output was too low and is seen at the value of 0 over the entire time. At 1000 volts, the data was the most consistent, and this voltage was used in the experiments that follow. In addition, for the 1000 volts Dwell 1 experiment, the data was collected the quickest and most accurate out of all the experiments, with a rate of one data point every 9 seconds. This is further explained in the **Discussion and Conclusion** section.

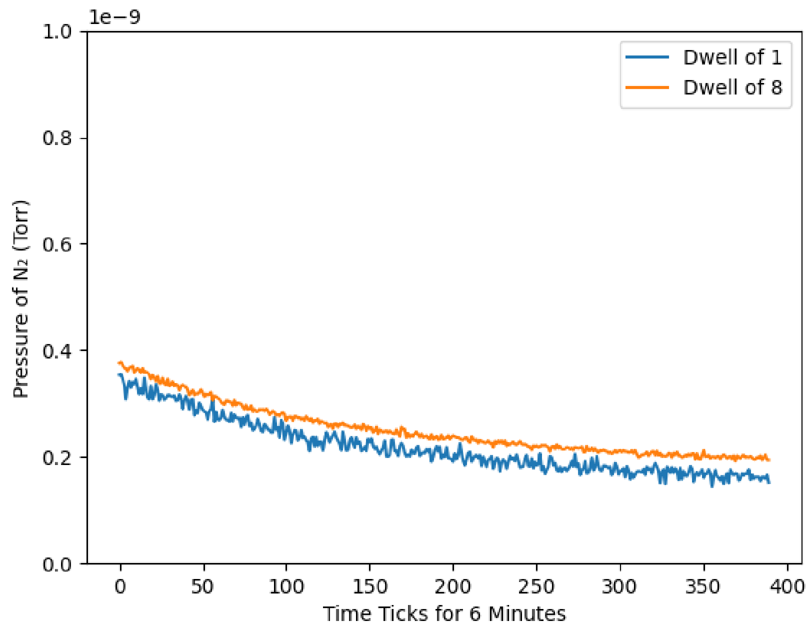

Figure 11: The SEM Mode was run for 6 minutes at 1000 volts for Dwell 1 and 8 channels.

Next Experiment 9, displayed in Figure 11, compared Dwell of 1 and 8 over two channels at 1000 volts and over 6 minutes. Here it is clear that the Dwell 8 is more consistent than the Dwell 1, however not to a very noticeable extent. For the SEM Mode, the consistency of the data is less drastic over different Dwell values as compared to the Primary Mode.

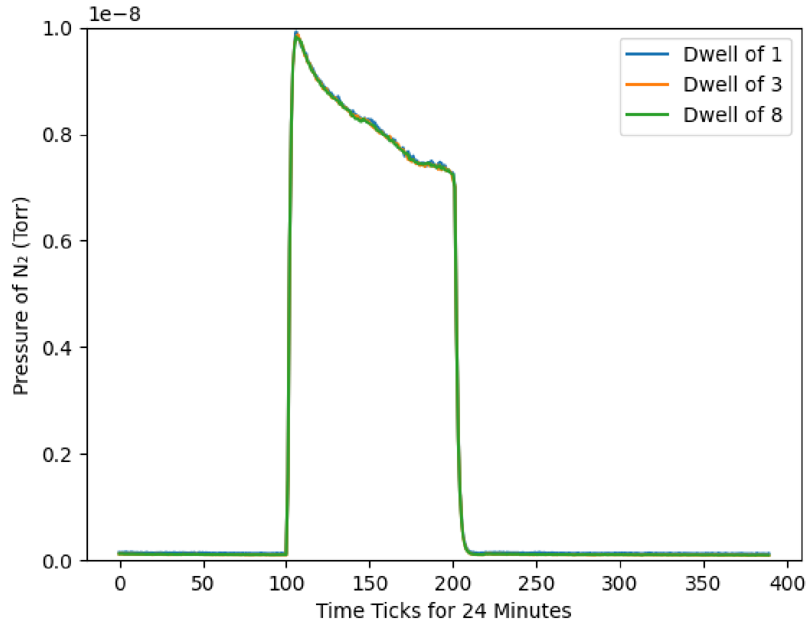

Figure 12: The SEM Mode was run for 24 minutes at 1000 volts over the channels of Dwell 1, 3, and 8. The N_2 valve was opened to 62% at around 6 minutes (100th time tick) and was closed at around 12 minutes (200th time tick).

Finally Experiment 10 tested Dwell 1, 3, and 8 over 24 minutes at 1000 volts. Here, the N_2 valve was opened to 62% at approximately 6 minutes (100th time tick) and was closed at around 12 minutes (200th time tick). This experiment is presented both in Figure 12 and in more detail in Figure 14. Here due to the greater scanning range of the SEM Mode, the peak in the pressure of N_2 was more apparent.

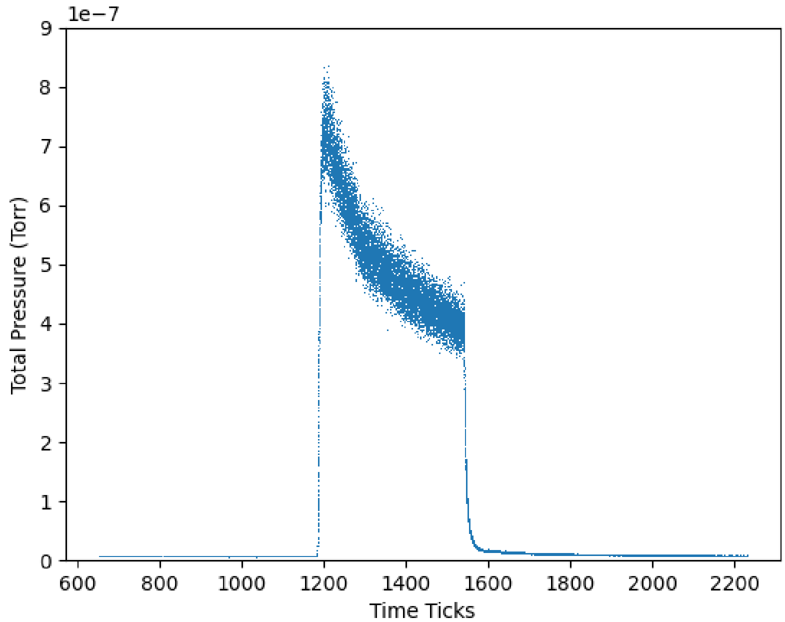

Figure 13: The PKR Full Range Gauge total pressure output over the course of Experiment 10.

In addition, it was clear that the curves for Dwell 1, 3, and 8 were very consistent with one another, with only some small variations in Dwell 1 compared to Dwell 8. Again it was also seen that the pressure decreased over the 6 minutes that the N_2 valve was open as the turbo pump continued to pump out the nitrogen gas that was entering the system following the inital spike. In Figure 14, the PKR Full Range Gauge's output is shown and it follows the same curve expected and seen in the RGA's output.

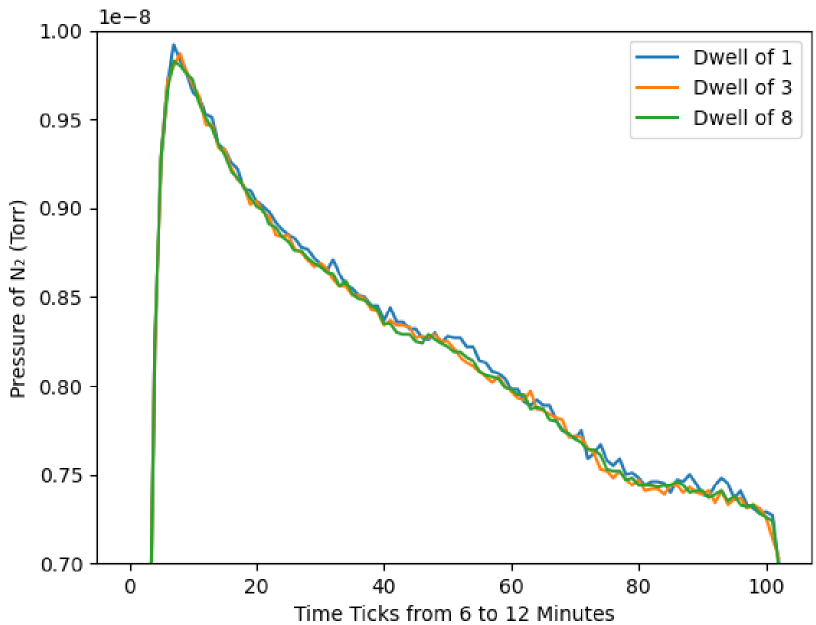

Figure 14: The zoomed in portion of Experiment 10 at its peak in pressure. Here the Dwell values of 1, 3, and 8 are compared.

4 Discussion and Conclusion

To begin, comparing the two modes used for collecting data, the Primary Mode and SEM Mode, it is clear that the SEM Mode is more versatile, since it can collect data over the range of 10^{-4} to 10^{-12} Torr. In addition, the data it collected was much more consistent and less noise was present, even when comparing Dwell values of 1 and 8. The SEM voltage of 1000 volts was also found to be the best at producing consistent data out of the three SEM voltages tested. Currently, the accuracy of the device would make it viable for flight on a sounding rocket assuming the SEM Mode was viable for this campaign. As shown in the **Results** section, the device can reach a deviation of around $\pm 10^{-10}$ Torr when utilized in the SEM Mode with a SEM voltage of 1000 volts.

Now discussing the MKS-PPT software of the RGA. it has two methods for collecting and saving data. The first is the regular saving mode which produces a scan over the predetermined amount of time (at least 6 minutes) and then produces 400 data points utilizing the

Dwell time set. The Dwell gives the integration time and this is the largest limiting factor in the rate of collect using this method. This means that when comparing a Dwell 1 and Dwell 8 scan over the course of 6 minutes, the RGA will only save 400 data points. Those points will be more consistent, as shown in the **Results** section, however this limits the speed of the device. Therefore, it is advised that the MKS-PPT software must be adapted to save a larger number of points depending on the length of the scan. In addition, if the Dwell condition could be lowered through an adaptation of the MKS-PPT software's code or even removed so that the user was reading every data point that came from the RGA without any integration of points, this would provide a much faster scan.

The second is utilizing the DataLog mode. This mode allows for continuous data saving, instead of waiting until the end of a scan to save the data. However, this mode was not tested since the lower limit possible is data collection every 6 seconds. This is a hard limit within the MKS-PPT software, however if this could be lowered within the software's code. then this mode would be ideal for flight. Therefore, edits to the MKS-PPT software's code must be made in order to better this mode and bring down the time between data points.

All in all, given the current MKS-PPT software limitations, the RGA device would not be viable for flying on a sounding rocket campaign. At its current state, the MKS-PPT software has a lower bound for the Dwell of 1 and has a lower bound for the DataLog mode of 6 seconds. Therefore assuming the sounding rocket was traveling at about 1 km per second, the best resolution the RGA could currently achieve would be 9 km in the regular saving mode and 6 km in DataLog mode. Both of these would not provide useful data and it is advised that the code behind the MKS-PPT software be edited to greatly lower these times and therefore the resolution of the device.

Testing must continue following this to then see how accurate the data is compared to what was collected here using the device under the stock, unedited MKS-PPT software. Assuming the changes offered here were possible and made within the MKS-PPT software's code and the device could then reach a resolution of around 100 m, then it would be viable for flight to support the future study of neutral masses within the E- and D-regions of the ionosphere.

References

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