GAYRARD Tristan

Université de Toulouse

Development of a Drone-Based Methane Quantification Method for Oil and Natural Gas Production Facilities

University of Wyoming
1426 E Flint St, Laramie, WY 82072

Internship completed from April 3rd to June 21st, 2024

Tutors : Jeff Nivitanont - Shane Murphy
Supervising Professor : Yingjie Wang

IUT Paul Sabatier – University of Toulouse

BUT2 APPLYED PHYSICS - MCPC

Abstract

The Site Aerial Basin Emissions Reconciliation (SABER) project aims to address the gap between top-down and bottom-up emissions accounting in the oil and natural gas industry. Top-Down accounting is done through direct measurements, whereas Bottom-Up accounting is calculated by applying component-based emissions factors to component inventory. Top-Down accounting for SABER will be done by utilizing drones equipped with advanced spectrometers to measure greenhouse gas emissions from oil and natural gas midstream and production facilities.

This internship focused on the development of this new drone-based quantification system and the calibration of its individual components, ensuring accurate methane, ethane, nitrous oxide and carbon dioxide quantification. The testing methodology involved stability characterization of the instruments, calibration of mass flow controllers, and assessment of GPS accuracy to enhance data precision. Key tasks included creating applications for data analysis and calibration verification, incorporating humidified calibration setups, and updating the drone's firmware to comply with new regulations.

System testing demonstrated successful calibrations and enabled the development of reliable field deployment protocols for this drone-based technique. We concluded that this system has a maximum measurement uncertainty of 5% attributed to the measurement components. These results support accurate greenhouse gas emissions reporting, contributing to improved environmental accountability in the oil and natural gas sector.

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An introduction with a brief presentation of the internship topic

The SABER project

Site Aerial Basin Emissions Reconciliation (SABER) is a project funded by the US Department of Energy to reconcile the historically persistent gap existing between top-down and bottom-up emissions accounting [1]. Top-down (TD)/bottom-up (BU) intercomparison studies attempt to compare two disparate scales of measurements in order to provide an accurate-as-possible emissions estimate for a given region. TD quantifies the system as a whole, such as entire facilities or regions. While the spatial coverage is greater, TD methods do not always provide mechanistic causes for emissions. TD may overestimate emissions due to the relatively short timescale most TD measurements are taken over or incorrect source attribution. BU may underestimate emissions by missing equipment failure rates or incorrect emissions factors. For these reasons, comparisons of the emissions estimates from TD/BU have historically disagreed. For the SABER project, Colorado State University will be modeling BU emissions using component emission factors and failure rates gathered from field observations. University of Wyoming will be taking TD facility-scale measurements of methane emissions for comparison.

The measurement efforts for SABER consists of measuring greenhouse gases emissions from well sites thanks to a drone hexacopter equipped with two on-board spectrometers. This is coupled with the released gas next to the well site is used to verify the plume's position and emission rate [2]. Here is an example of the method :

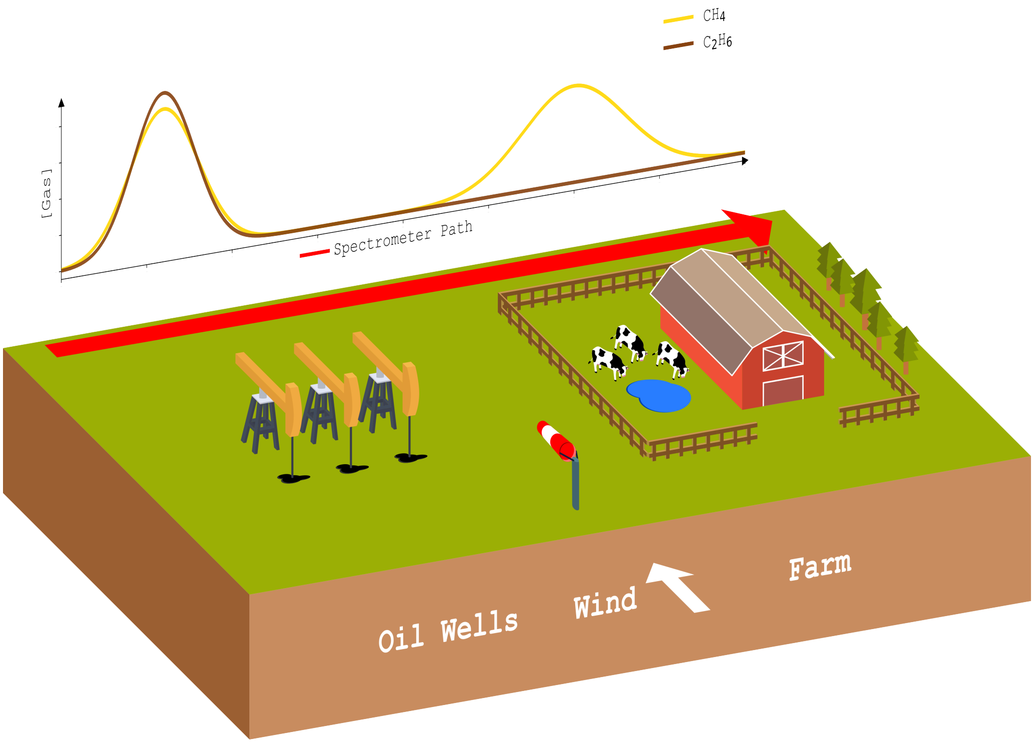


Figure 1: Tracer Gas method

The two tracer gases released are acetylene (C_2H_2), which is typically found near construction and industrial sites, and nitrous oxide (N_2O) which is naturally occurring from soil microbes. Neither of these two gases are naturally occurring in large quantities, so they are excellent tracers.

Presentation of the Host Institution

The University of Wyoming (UW) [3] is a public research university in Laramie, Wyoming. It was founded in March 1886, four years before the territory was admitted as the 44th state and opened in September 1887. The university also offers outreach education in communities throughout Wyoming and online. The University of Wyoming consists of seven colleges: agriculture and natural resources, arts and sciences, business, education, engineering and applied sciences, health sciences, and law[3].

Presentation of the Host Department

The Department of Atmospheric Science [4] at the University of Wyoming offers excellent opportunities in graduate education and research, and is world-renown for using both observations and numerical modeling to understand natural phenomena in the atmosphere [4]. The Department of Atmospheric Science provides a rigorous graduate program that allows students to compete for top-level careers in the field. The students have direct access to three unique training facilities, an atmospheric research aircraft, one of the most powerful supercomputers in the world and a mobile research lab. Graduates of this department go on to have careers that cross many boundaries, many of which have landed careers with the National Weather Service and state air quality agencies.

Precise Definition of the Internship Subject

The main advantage of having a drone for measuring gas plumes coming out of well sites is accessibility. In order to measure gas emissions using the tracer release method, only the downwind concentrations of the gas and tracer are needed. These are typically measured with sensors aboard a vehicle, but vehicles require developed roads. Since oil and natural gas facilities are typically located in remote locations, developed roads are not guaranteed. The drone ameliorates this issue and also gives vertical information on emission plumes.

Not only are the tracer gases are used to verify the plume's position, but it's also an indispensable step to use for calculating the emissions from well site because of the following :

$$C_X = \alpha_X F_X$$

$$\frac{C_X}{C_T} = \frac{\alpha_X}{\alpha_T} \cdot \frac{F_X}{F_T}$$

$$F_X = \frac{C_X}{C_T} \cdot F_T$$

With C_X the concentrations of the measured gases, from the Tracers and well site's, F_T the flow in mass per time of the Tracer gas and α, a variable considering wind, turbulences, irradiance, etc. All very complicated values to measure for α. Since both the concentrations are measured at the same place and time, $\alpha_X = \alpha_T$ thus the variables are cancelling themselves out.

The goal of the internship is to characterize and calibrate instruments used for the drone-based tracer system and to help set the system up for the field deployment.

Method

Stability testing of the instruments

Introduction of the spectrometer

Figure 2: A picture of the Strato Spectrometer

The strato is the lightest part-per-billion precision gas analyzer sensor on the market. It is a closed-cell spectrometer meaning that it measures energy absorption across a laser path to calculate gas concentrations. For this method, we work with two of them, one measuring methane (CH_4) and ethane (C_2H_6) and another measuring nitrous dioxide (N_2O) and carbon dioxide (CO_2). In addition to the gas analytes of interest, water vapor concentrations are also measured and play a crucial role in fitting absorption spectra. Because water vapor is always present in the atmosphere, the water vapor absorption peak is used to normalize the absorption spectrum, and an expectation-maximization algorithm is used to calculate gas concentrations.

Instrument Characteristics to Analyze

Data Collection and Initial Analysis: To ensure the reliability of the data, stability testing involved continuous operation of the spectrometers, over a 24-hour period. This extended data collection period allows us to perform meaningful statistical analysis and draw trustworthy conclusions about the system's performance.

Stability Analysis Using Allan Deviation Plot: First, I will assess the stability of the Stratos by making an Allan Deviation Plot. This graphical representation is crucial for analyzing the stability or noise characteristics of the system over time. It illustrates how the variance of the signal changes with increasing averaging time facilitating comparison with other error sources.

Rolling Statistics for Stability and Consistency: To further analyze the stability and consistency of the Stratos, I will use rolling statistics. This involves calculating statistical metrics over a moving window of data points. The main metrics I will calculate are:

Rolling Standard Deviation: This measures the variation or dispersion within the dataset, providing us on how the system is stable by ignoring small variations. By using the standard deviation as an indicator of noise, we are assuming that the noise is distributed normally around a single observation. This assumption is later supported by our Allan deviation analysis.

Rolling Mean: Plotting the rolling mean helps smooth out minor fluctuations, offering a clearer view of underlying trends.

By varying the window size for these calculations, we can observe how different segments of the data behave over time.

Next, I will calculate the Rolling Relative Standard Deviation (RSD%), defined as the ratio of the Rolling Standard Deviation to the Rolling Mean. This percentage metric indicates the degree of dispersion relative to the mean, with higher values signifying greater variability. Finally, I will compute the Root Mean Square Error (RMSE) to measure the average distance between the model's predicted values and the actual values in the dataset. A lower RMSE indicates a more stable and accurate dataset. If the Stratos measures gas concentrations in hundreds of ppm, we expect the RMSE to be tens of ppb. The RMSE is equivalent to the standard deviation if it is assumed that the instrument noise follows a Normal distribution (i.e., white noise). RMSE is reported because there is no assumption of constant variance in the noise distribution in the aggregate. This is because most instruments will drift over time.

Calibrations

I will start with the calibration of the spectrometer of verification, used to verify the position of the plume on the field, this spectrometer won't be on the drone.

The calibrations of the Stratos are done within their own software and only consists of a single-point measurement, plotted with a line going through zero. Therefore we verify the calibration by making a plot of theoretical dilutions concentrations values against red values by the Strato. In order to make this verification, we are required to calibrate any other instruments used for it.

First, the Mass Flow Controllers (MFC), two are used, one to control the volumetric flow of the measured gas by the Strato and another one, the air, both are mixed to dilute the measured gas with the air to obtain a range of concentrations and make a plot. Thus, we need to calibrate both, as the following:

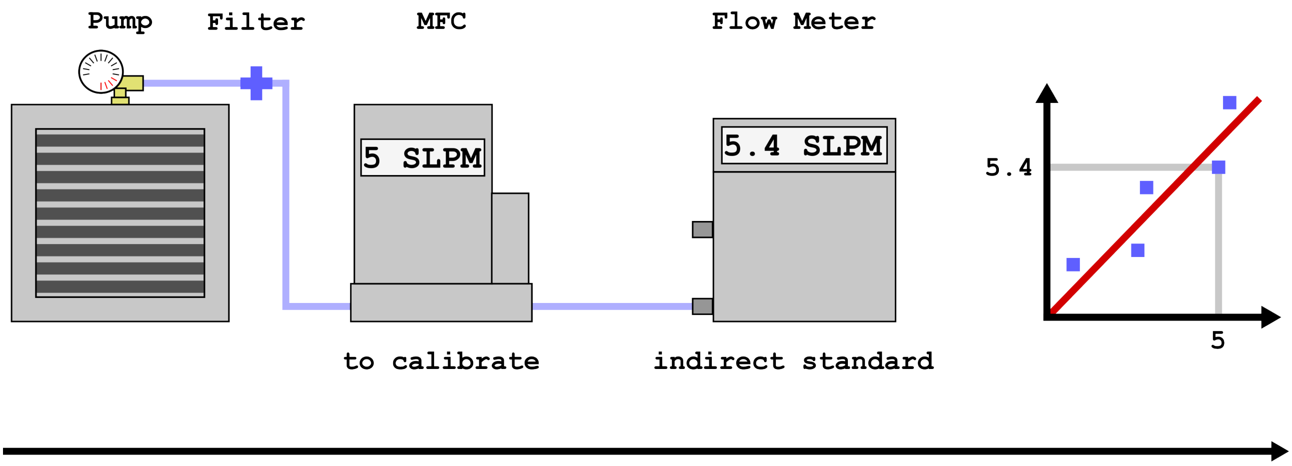


Figure 3: Calibration setup of a Mass Flow Controller

After gathering the data from the MFC, and plotting values given by a standard against the red values, the slope will be used to correct given by the instruments later on. Once the MFCs are calibrated, we can start by mixing gases thanks to them and verify the calibration of the Stratos. The formula for diluting gas is not the same as for liquid, because we measure gas standard concentrations as a mixing ratio (MR) in ppm or ppb,

$$C_X = \frac{MR}{1 + MR}$$

$$C_{dil} = \frac{C_X \cdot V_{air}}{V_{gas} + V_{air}}$$

With C_{dil} the concentration of the diluted calibration gas, C_X the concentration of the calibration gas, V_{gas} the volumetric flow of the calibration gas tank and V_{air} the volumetric flow of the air gas tank. The quantity we are varying in our calibration setup is the volume of dilution gas released,

$$V_{cal} = \frac{C_{dil}}{(C_{gas} - C_{dil}) \cdot V_{air}}$$

For practical reasons, we calculate the Volumetric Flow of the calibration gas to dilute the calibration concentrations to near ambient air concentrations. Typically, we can verify the calibration simply by sending the diluted gas in the instruments.

However, failure is expected because both of the gas tanks do not contain H2O, and we know that the Stratos are using the water peak to fit the spectrum. If the absorption spectrum cannot be normalized due to lack of water vapor, we will need to change the setup by incorporating a bubbler, which will humidify the gas, as show on the scheme:

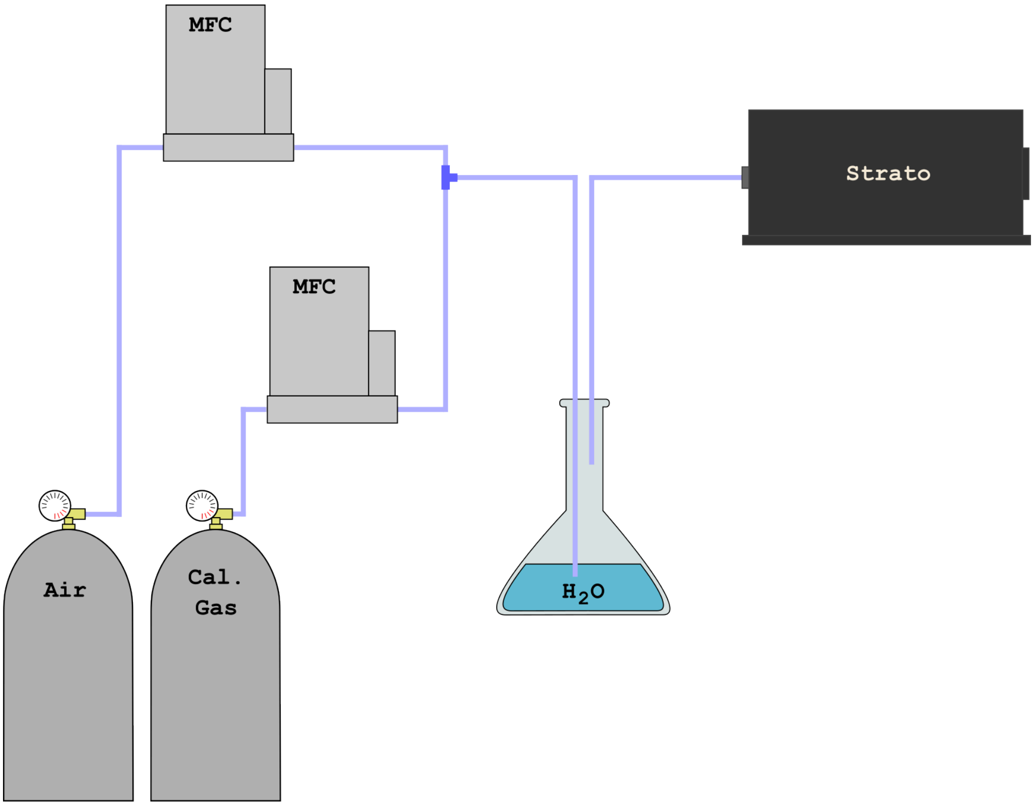


Figure 4: Calibration setup of the Strato Spectromters

When plotting the data gathered from this setup, we expect to obtain a slope of $m = 1.00 \pm 0.03$ because the range of uncertainty of the gas standard in the lab are within 2% and 1% for the Mass Flow Controllers.

GPS

A GPS module is needed to know the drone paths, for later on calculating the flow in mass per time of the plume's gases. Therefore, having a precise GPS is a must. A generic GPS receiver was furnished with Stratos but is not trustworthy because the uncertainty given by the manufacturer is unacceptable and in the range of tens of meters. We then ordered a more precise module, a Garmin USB GPS, oping the uncertainty on the given localization is less than the original one. When reading the Garmin's datasheet I noticed that the speed's uncertainty was $0.1 knots \approx 52 cm.s$-1 while the uncertainty on the position was said to be < 10m. So by integrating the speed, for having the position, the uncertainty on the calculated position would be better than the one from directly the position. When looking for other velocity information in the data sheet, I found that one of the possible NMEA sentence (National Marine Electronics Association), which is the standard type of information layouts given by GPSs, was giving the True East, North and Up velocity. That NMEA sentence is called $PGRMV. By multiplying the speed by the difference of time between each point received and adding the calculated position in the index before that point, I would get the position on X, Y and Z. The goal is to compare the data acquired from integrating the speed against the position calculated from the latitude and longitude. The method that I will use to compare these two data sets is the following :

Figure 5: Picture of the Garmin GPS system

$$df_1\ (m) = (X_1; Y_1; Z_1)$$

$$df_2\ (m) = (X_2; Y_2; Z_2)$$

$$df_\Delta\ (m) = df_1 - df_2 = (X_\Delta; Y_\Delta; Z_\Delta)$$

With df : DataFrame, the type used in Python to store the data sets, with df_1 the DataFrame storing the localisation derived from speed and df_2 the localisation from latitude and longitude.

$$Positional\ Error\ (m) : \|C\|_2 = \sqrt{C \cdot C} = \sqrt{(X_\Delta)^2 + (Y_\Delta)^2 + (Z_\Delta)^2}$$

Then with $\|C\|_2$we can plot a histogram to show the distribution of error.

This technique will be used to compare two data sets considered not really accurate.

However the localization data from the flight controller on the drone is really accurate but we cannot get it in real time due to hardware connection constraints. Once we have these three data sets, I will be able to compare individually the first two against the one from the drone by resampling the drone data to correspond to the frequency of the Garmin and plotting each variable, to compare the positions of noticeable values like the maxima or minima. A roll function of the Garmin data may be used in order to have the best correlation possible because both the drone and Garmin won't be turned on at the same time.

Battery tests

Knowing the time the battery of the Stratos takes to run down and charge up is crucial, for the purpose of scheduling our days out on the field. We could easily change the portable batteries in the Stratos, but we want to avoid having dust in the instruments as much as possible.

The data of the strato running on battery and running while charging can be found directly from instrument logs.

For estimating the time the Strato would take to charge while being shut off, I can note the value of the battery, turn the Strato off, plug it on for 10 minutes then turn it back on and note the state of charge.

Tracer gas

For the tracer gas release, a calibration of the Mass Flow Controller needs to be done, knowing the Flows released is a must because it's used in the formula to calculate the flow of the well's site gases.

The calibration of these Mass Flow Controllers will be the same as the ones for the calibration of the Stratos.

The drone

The drone used for this measurement system is a Vision Aerial Vector Hexacopter. It is a heavy-lift drone capable of carrying up to 5 kg of payload thanks to advancements in battery technology. Since our miniaturized spectrometers weigh 2 kg each, it is a suitable platform for this system.

As of September 2023, the Federal, the Federal Aviation Administration (FAA) rules have been updated and the drone now needs to send a user ID and goal of flight. We will have to either update the firmware of the flight controller on the drone or order a remote ID module made to meet FAA rules.

Figure 6: Picture of the hexacopter

As well as knowing the characteristics of the batteries and of the spectrometers, knowing those of the drone is as important. The drone has the functionality to return to its take off position when reaching a setup threshold. We will test it with different dummy loads even if the drone should be only flown with 2 loads, the spectrometers.

New parts have been ordered to change the polymer studs holding the spectrometers' cage to aluminum ones and I will need to install them and applying Loctite on the screw to minimize the chances of the studs getting loose.

Results

Tests and statistics on spectrometers

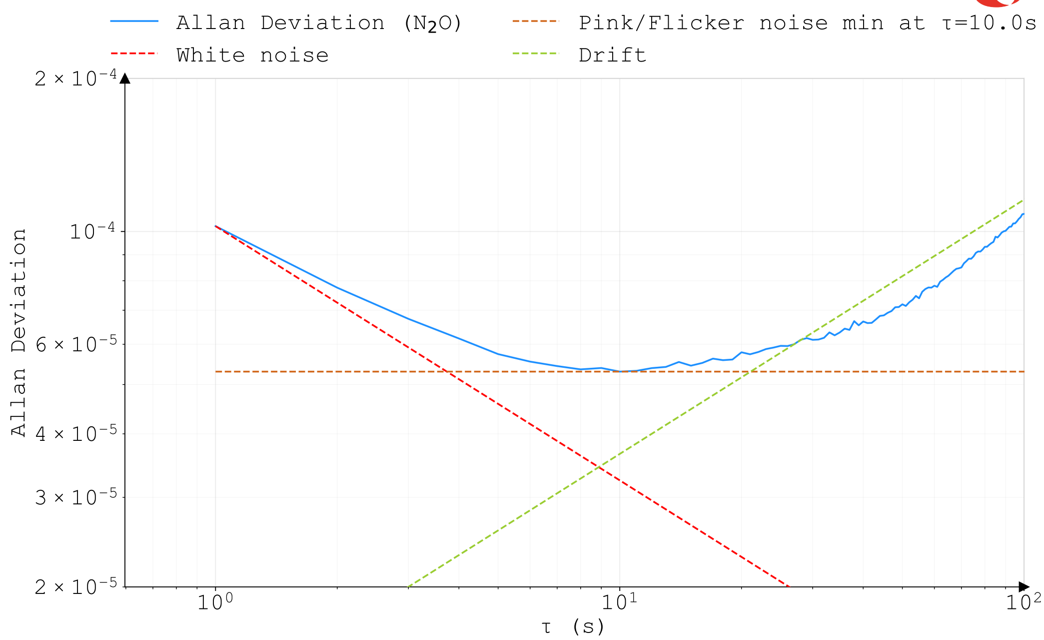


Figure 7: Allan Deviation Plot of N_2O measurements

On the Allan's deviation plot we can see that Optimal Frequency Stability and measurement time for N_2O is at 10.0 s for the CO_2 the optimum time is 45.0 s. This is where the deviation curve reaches its minimum and indicates the averaging time length when instrument drift begins to influence the variance.

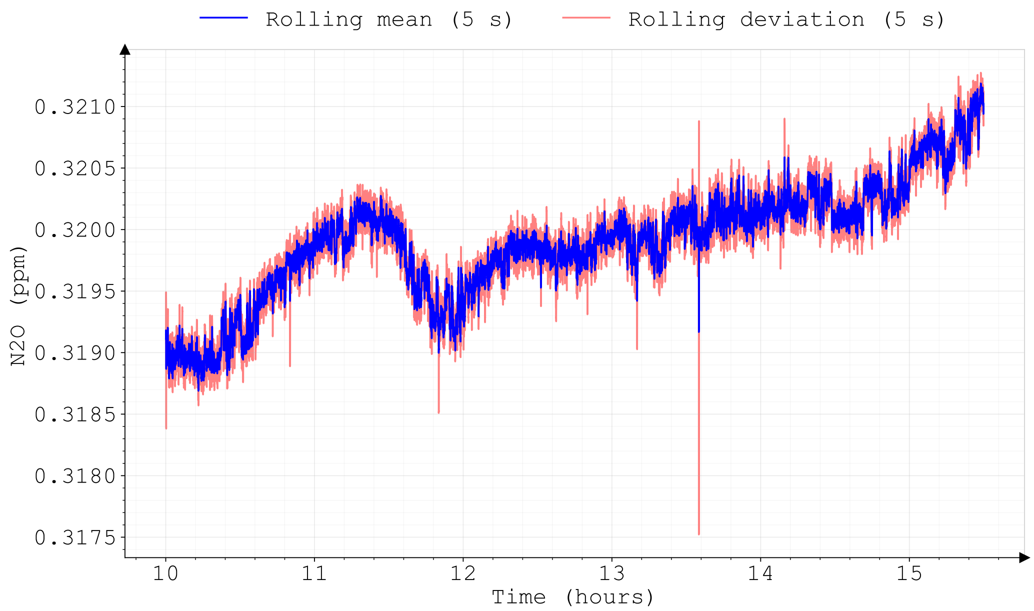


Figure 8: Rolling Statistics Plot of N_2O measurements

On this plot we can see in blue the rolling mean smoothing out the variations from the instrument noise with in red, the uncertainty on these values, which is just the rolling standard deviation ± the rolling mean.

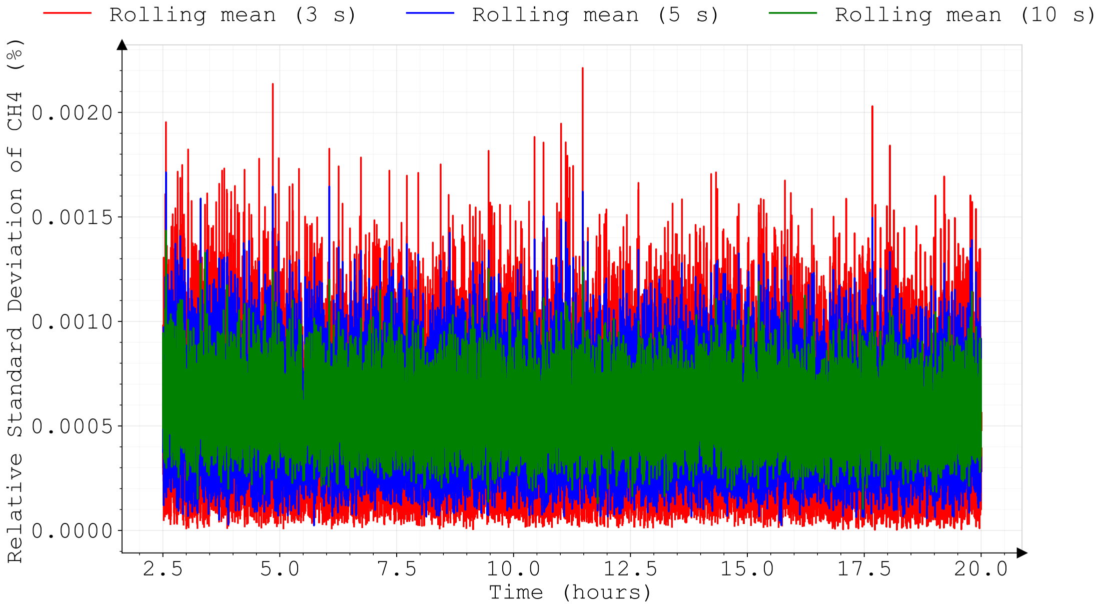


Figure 9: Relative Statistics Plot of CH_4 measurements

On this plot the relative standard deviation is around 0.05 % which tells us that the general of the instrument is spread 0.05 % away from the mean, which is more than sufficient

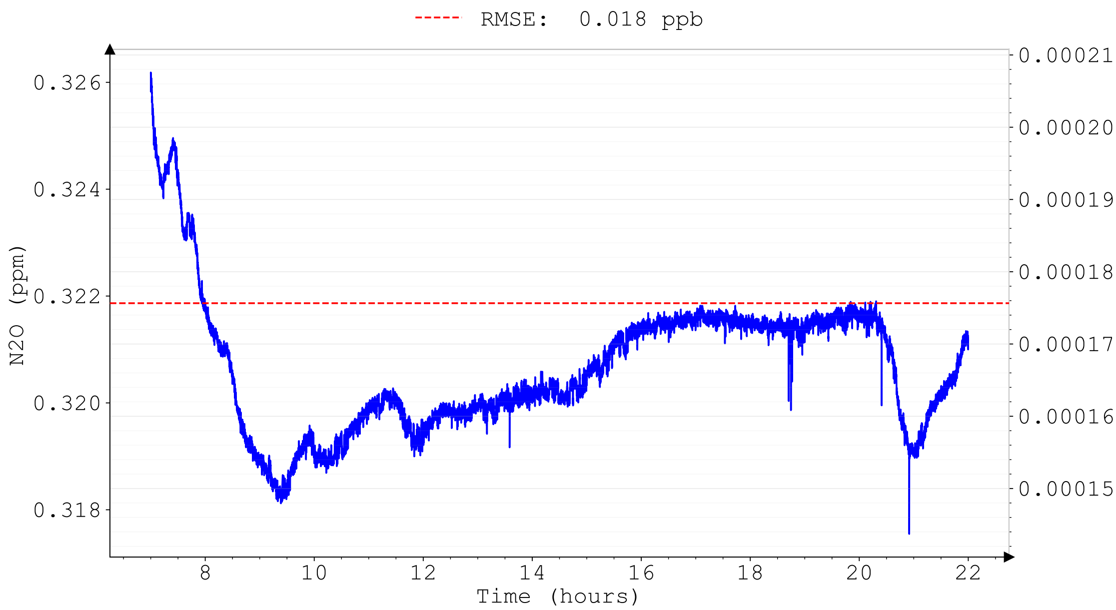


Figure 10: Root Mean Square Error of the N_2O measurements

A RMSE of ≈ 1 *ppb* in the context of an average of 322 ppb of N_2O concentrations suggests that the model or measurement system is capable of detecting and predicting N_2O concentrations with high precision. Small deviations like this are minor compared to the overall mean concentration.

After making all these plots, I knew that I would still have to make a lot more in the future, so instead of losing more time making each of these again, I decided to create an application with Python that all persons working with the Stratos and I could use later on, to analyze new data sets from the spectrometers.

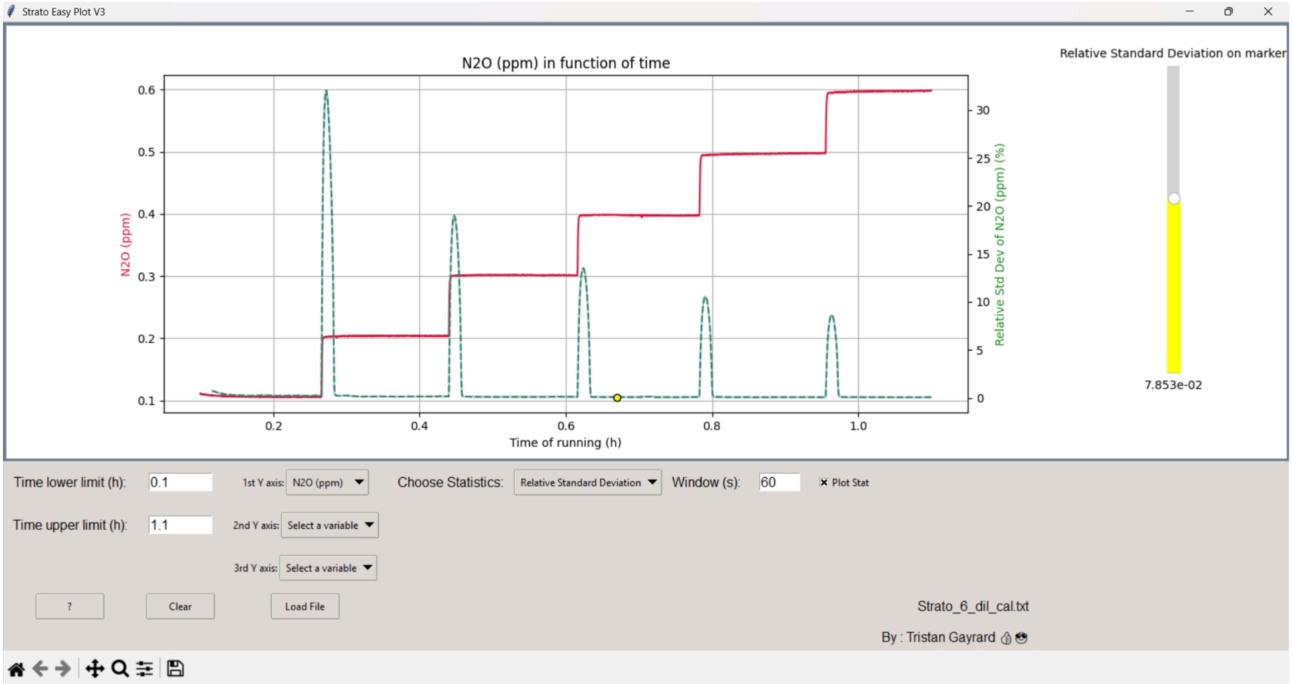


Figure 11: Screenshot of the "Strato Easy Plot" application

The application works by loading a raw data file from the Strato, then selecting any variable to plot of the 3 axes. In addition, there is a statistics option with its rolling window to calculate all of the statistics made earlier. When plotting a statistic, a slider appears and can be used to move a point on the plotted statistics to analyze the average of the statistic on its window.

I noticed downwards peaks starting at around 10 hours of running time from the N_2O/CO_2 Strato and decided to investigate these anomalies. These peaks are one data point wide, and we may be suspecting the instrument computer to struggle when processing data and giving use these values. Before plotting every variable in the data file to find which one is correlating the most with these peaks, I used a correlation matrix, plotted as a heatmap.

The greater the correlation is, the redder the color will be in the heatmap. At this point I knew which variables fitted the peaks the most so I could start making plots.

When plotting the variable that correlated the most, it was clear why it did. But we don't have any information on what really is win0fit7 because this is proprietary information for the instrument manufacturer. Although, we suspect this is directly related to the absorption window of N_2O.

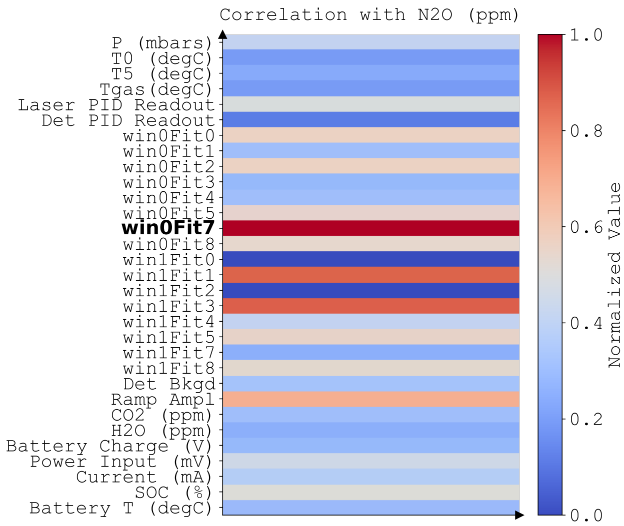


Figure 12: Heatmap of the correlation matrix

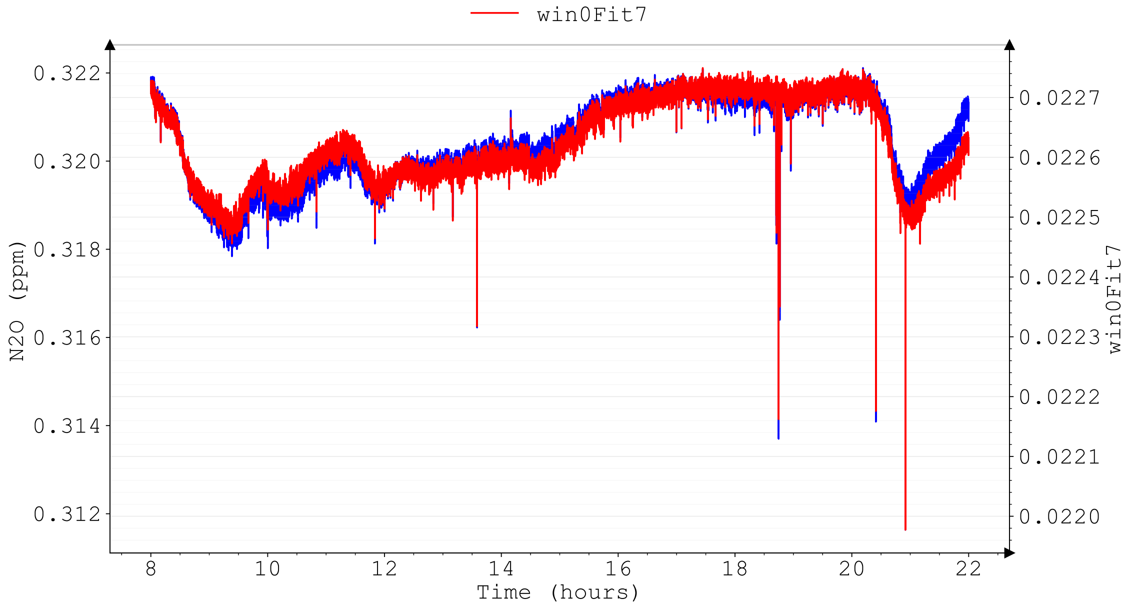


Figure 13: win0Fit7 data plotted on top of the N_2O measurements

At this point the only thing we could do is send the instrument to the company and tell them that we think these peaks are correlated with the variable win0fit7.

After making more tests on the CH_4/C_2H_6 Strato, it started to read negative values, which is physically impossible. We addressed these two issued to the manufacturer at the same time and suggested that the laser had died because of an Electrostatic Discharge, if it was the case we should see the Laser Readout near 0 in the data file.

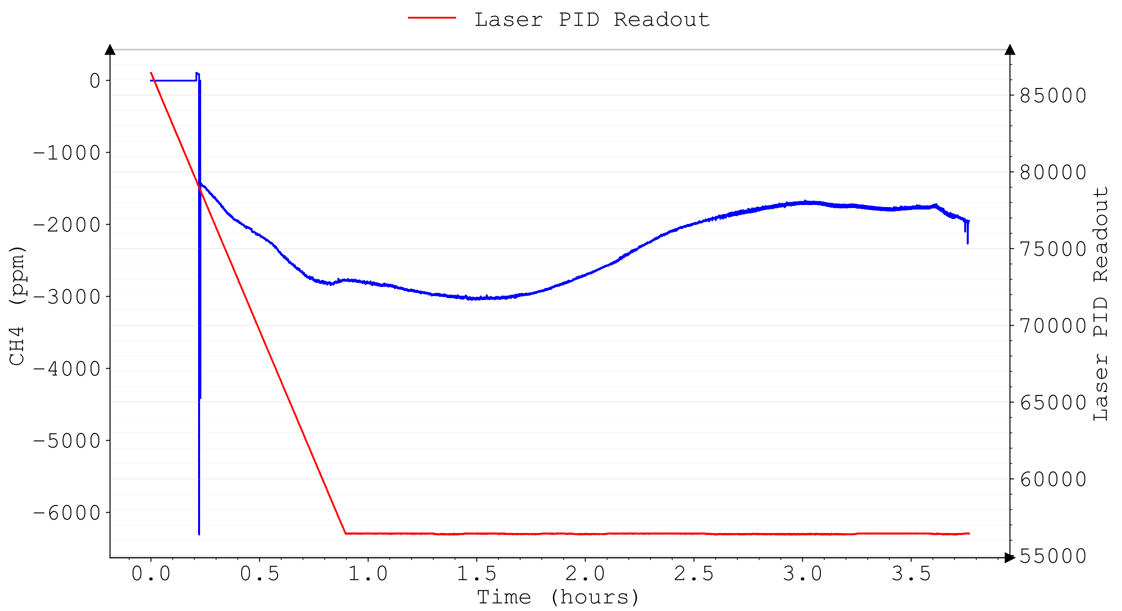


Figure 14: Laser PID Readout on top of the CH_4 measurements

Unfortunately we can see that it's nowhere near zero. We decided to send the instrument to the company so then could repair it.

Calibrations

Calibration of the verification's spectrometer

I was provided with a MATLAB code, to make the plot of the calibration but the code wasn't optimized because we had to manually change a lot of lines of code to make the plots. I then decided to convert the code to a python one and semi-automatize it by making an application, so we won't lose time on changing code on other calibrations later on. The application consists of choosing manually where to calculate the average of point on each dilution steps thanks to color sliders and entering the theoretical values of these dilution steps, then the calibration plot appears with its slope.

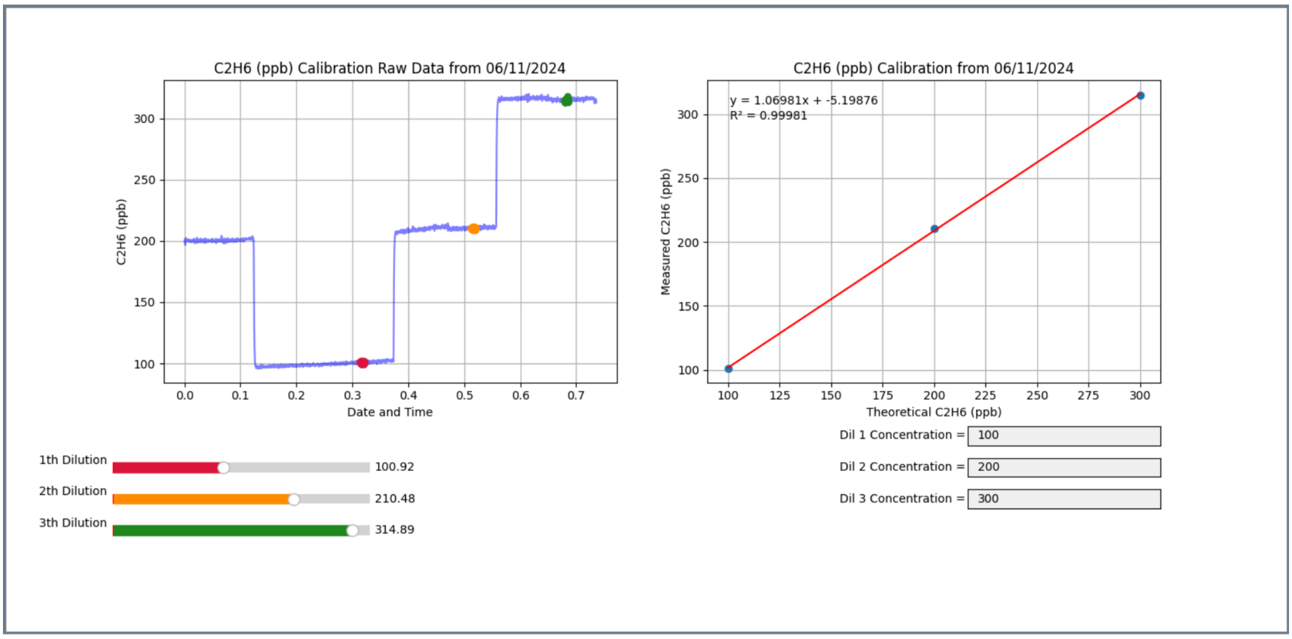


Figure 15: Screenshot of the calibration application

Calibration of the Mass Flow Controllers

After gathering and plotting the data gathered for the calibration, slopes of the C_2H_6 Mass Flow Controllers is only 0.5 % off, while the N_2O Mass Flow Controllers is 9% off but the R^2 is still near 1 so we can conclude that the instrument has drifted over time and would need to be send to the manufacturer for an intern calibration.

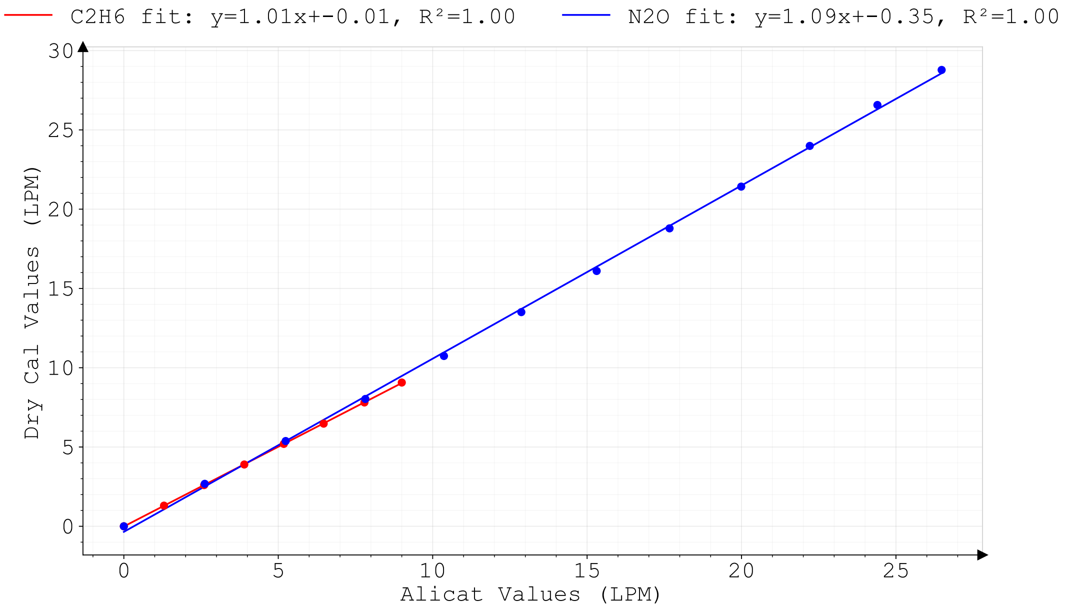


Figure 16: Calibration plot of the Mass Flow Controllers

Calibration of the Stratos

For calculating the volumetric flow of the calibration gas tank to make points around the ambient concentration of gas I decided to make an application thanks to Python to easily calculate these Volumetric Flow instead of losing time later, when doing other calibrations.

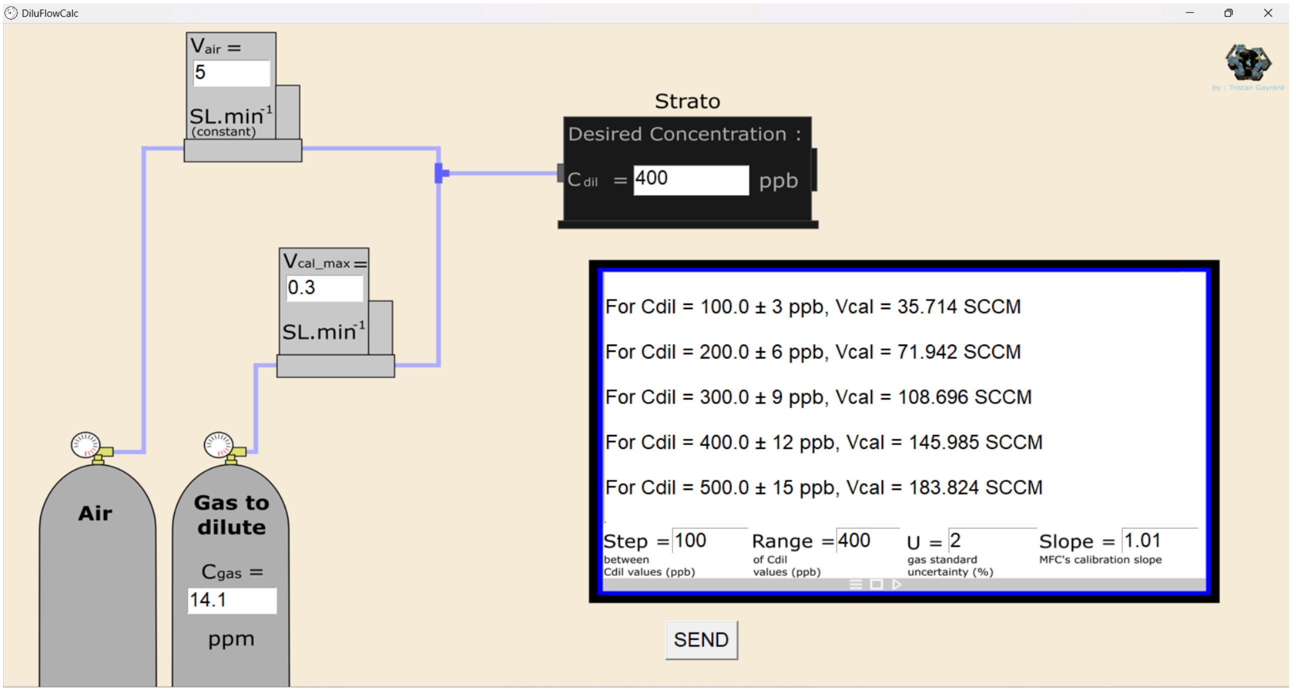
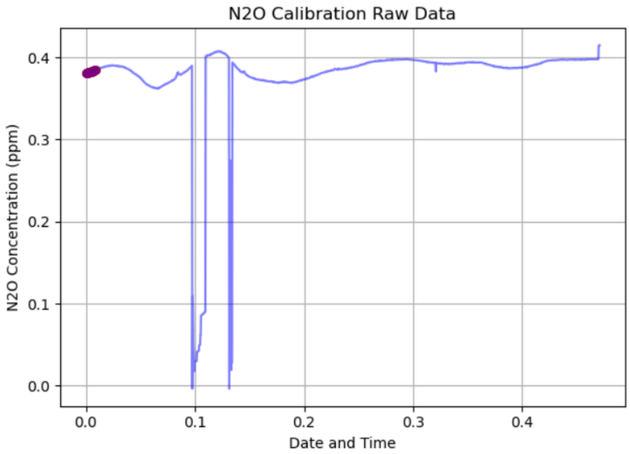


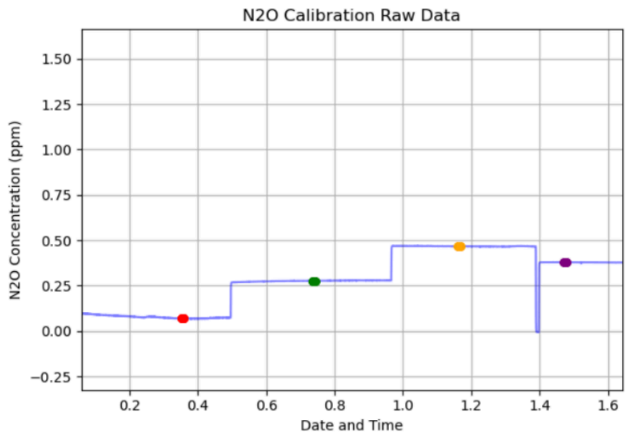
Figure 17: Screenshot of the "DiluFlowCalc" application

The application works by entering the constant values of the formula to calculate the Volumetric Flow but also entering the step and range of gas dilution we want to make, the uncertainty of the gas given by the manufacturer and also the slope of the calibration of the Mass Flow Controller, to calculate the uncertainty on the concentration of the dilutions.

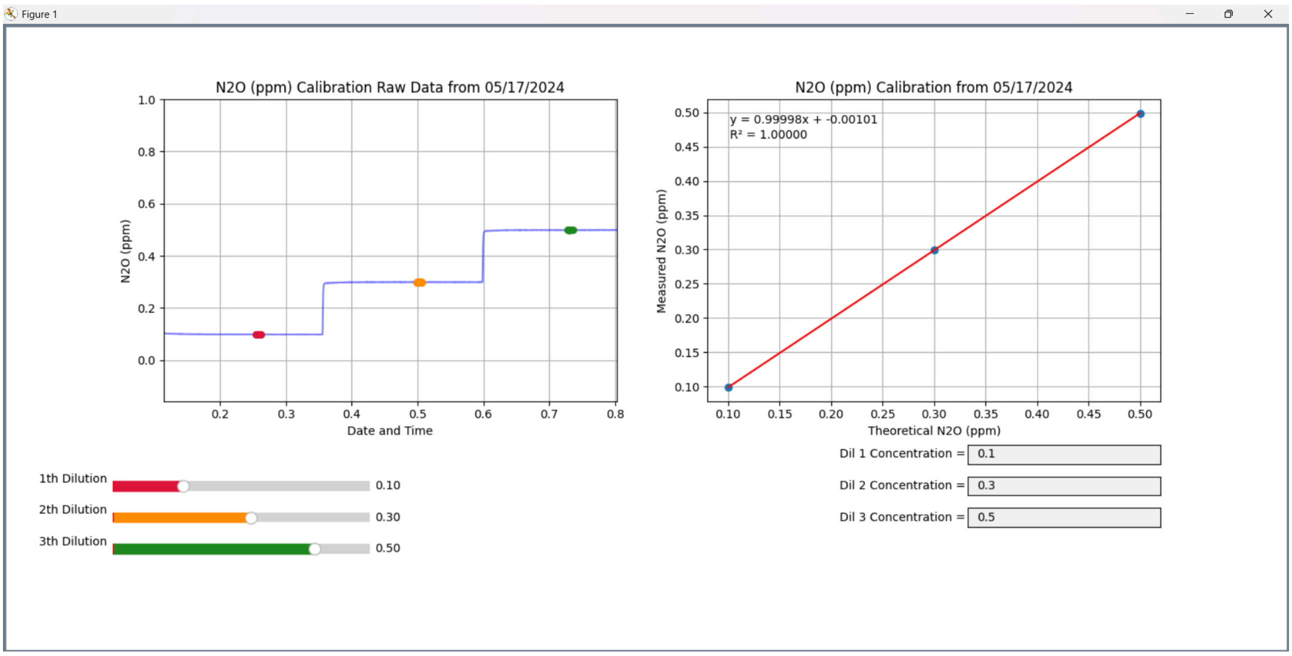
After verifying the calibration of the Stratos without humidifying the air thanks to the bubbler, the gathered data wasn't great, we decided to let the instruments stabilize for longer, but the red values were still out of the uncertainty range given by the application.

After these 2 failed verifications we incorporated the bubbler in the setup. Water concentrations went from 0 ppm to 20,000 ppm. Which helped the instrument to stabilize on the water peak and therefore, give precise and stable concentration values.

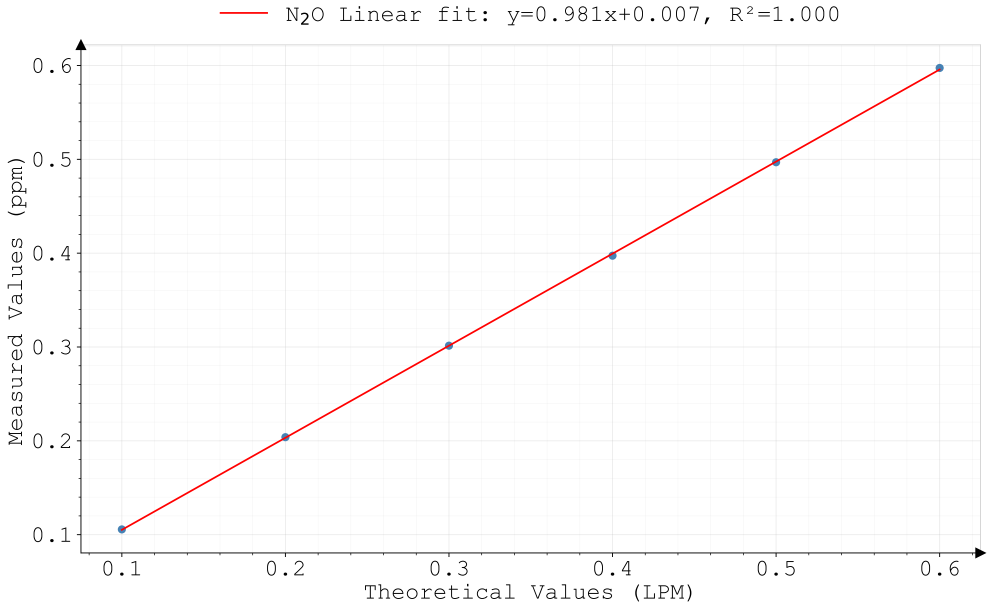




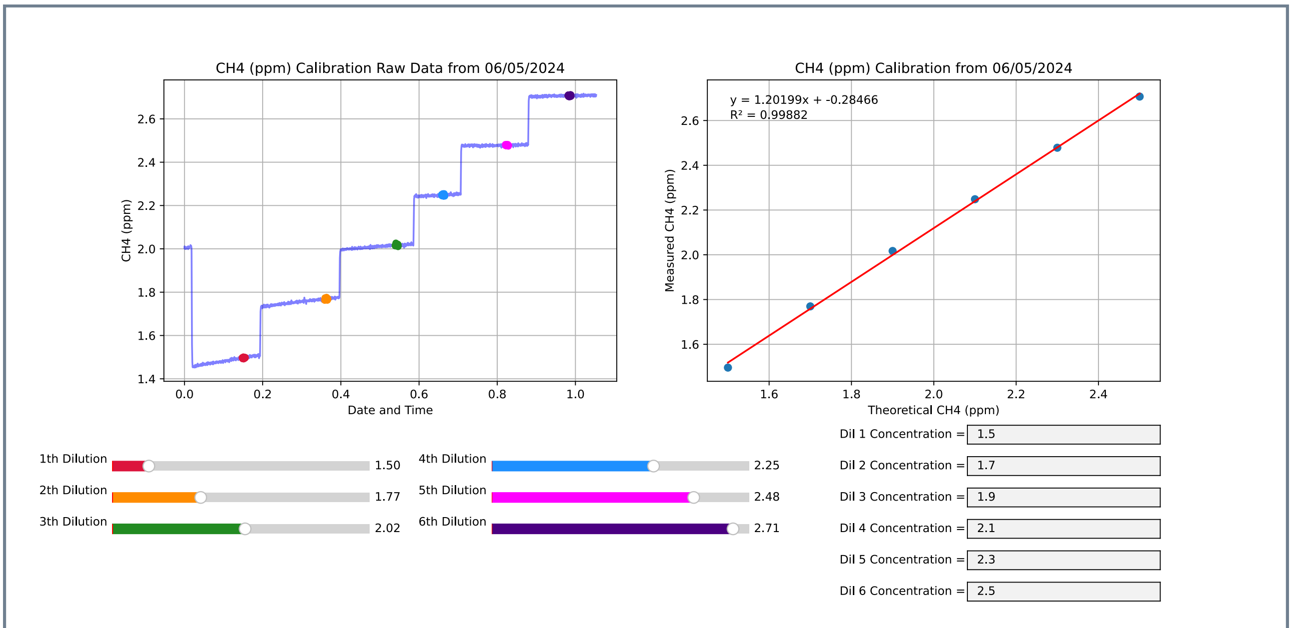
After only making 3 points because of a lack of time, we decided to make the plot the see the results that this new setup gave us. I modified to calibration application that I made earlier to work with the Stratos and added functionalities such a choosing the calibration gas and number of dilutions.



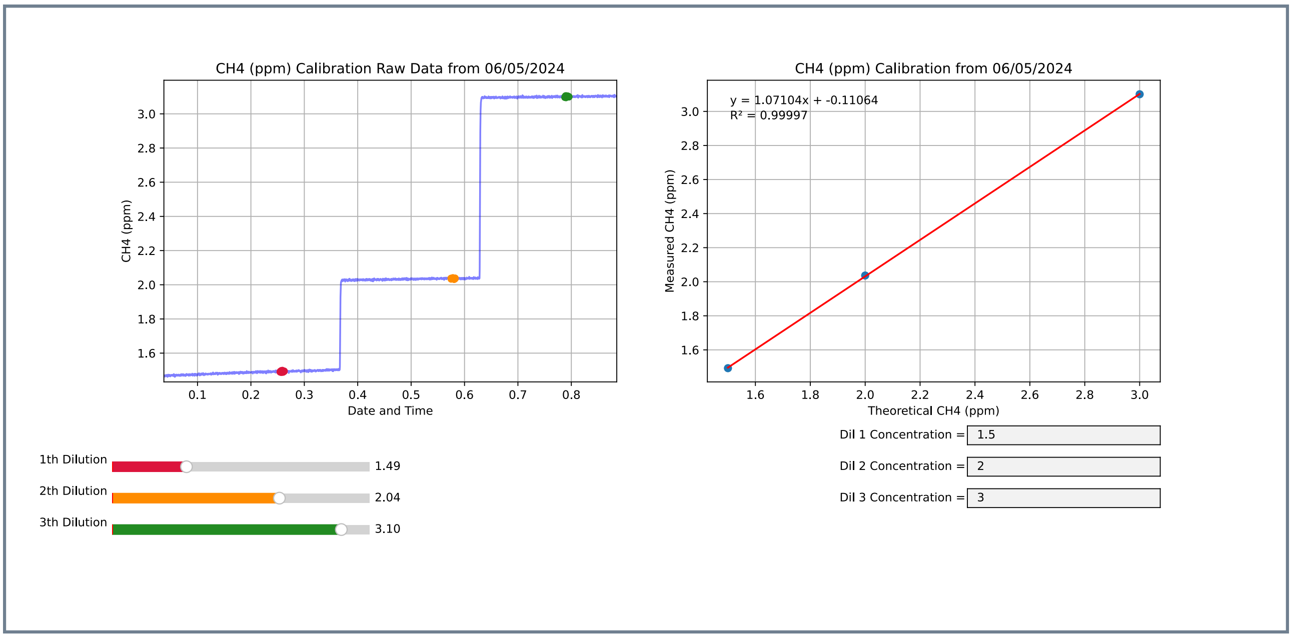
The slope is only 0.005 % off, and $R^2 \approx 1$, which indicates us that the calibration was successful. Calibration with the bubbler setup improved water vapor absorption lines, resulting in accurate measurements. But we still wanted to remake a verification of the calibration with more points for repeatability. For the second verification, I sent 6 concentrations in the Strato. The slope is less than 2 % off, which is in the range of uncertainty of the gas standards and flow controllers, therefore the calibration is successful.



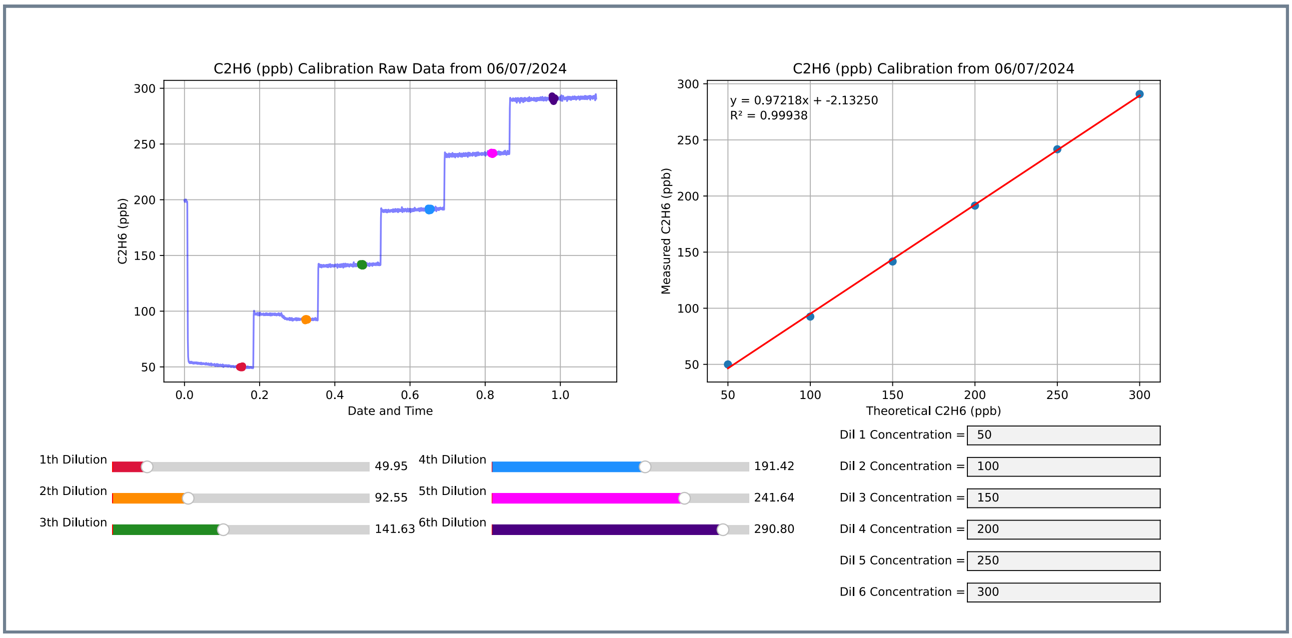
We didn't receive the CH_4/C_2H_6 Strato since FedEx lost the package it was shipped in. Therefore, we had to borrow one from another research lab.



After the verification off the calibration, we can see that the R^2 is good, but the slope is ≈ 20 % off and we can see on the Raw data plot that the first dilution steps took a long time to stabilize. We thought that it was because the instrument wasn't fully warmed up, but I turned it one hour before doing the verification. I then decided to remake a calibration plus verification but with less points to see if it was doing the same.



We let the dilutions steps for a longer time, and we can see that the first step at $1.5\ ppm$ took a long time to stabilize but once it was at $1.5\ ppm$ it stayed within the range of uncertainty. There is still a systematic error, but the slope is now just $\approx 7\ \%$ off.

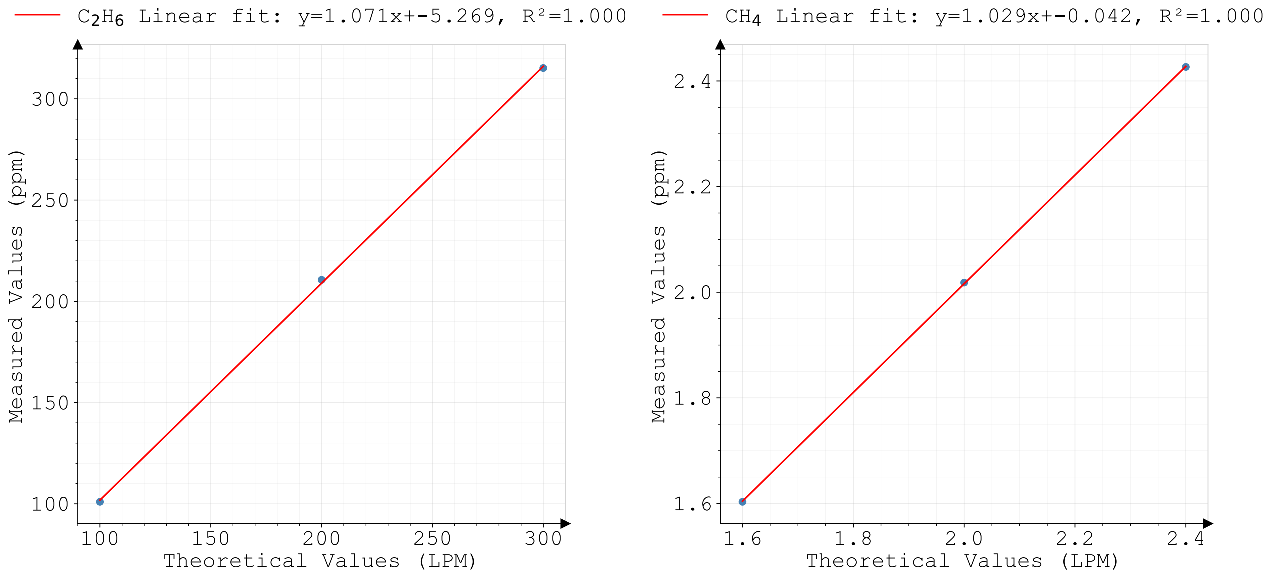


As for the calibration of the ethane part on the spectrometer, we can see that on the two first dilution steps, the sensor took a long time to stabilize, like for the methane. Here, while the concentrations were stabilizing, they were within the range of uncertainty.

These stabilization concentrations are due to the Mass Flow Controllers being in their low range. For example, the first dilution is made with a Volumetric Flow Rate of C_2H_6 of $\approx 5\ SCCM$, if the uncertainty is $3\ SCCM$, the Flow Rate oscillating around the $5\ SCCM$ position will be more impactful than if the Flow Rate would be $100\ SCCM$. We need to let the Mass Flow Controllers slowly adjust their position over time. That's why the first dilutions steps are taking some time to adjust.

The calibration slope is R^2 are still satisfying.

We received our original Strato just in time and decided to use this one, calibration results were even better than those from the borrowed one, and dilutions steps were drifting a lot less too.



If the slopes of these plots are greater than 2 % off, then we will correct the values post-measurement with the fitted equation.

Battery Tests

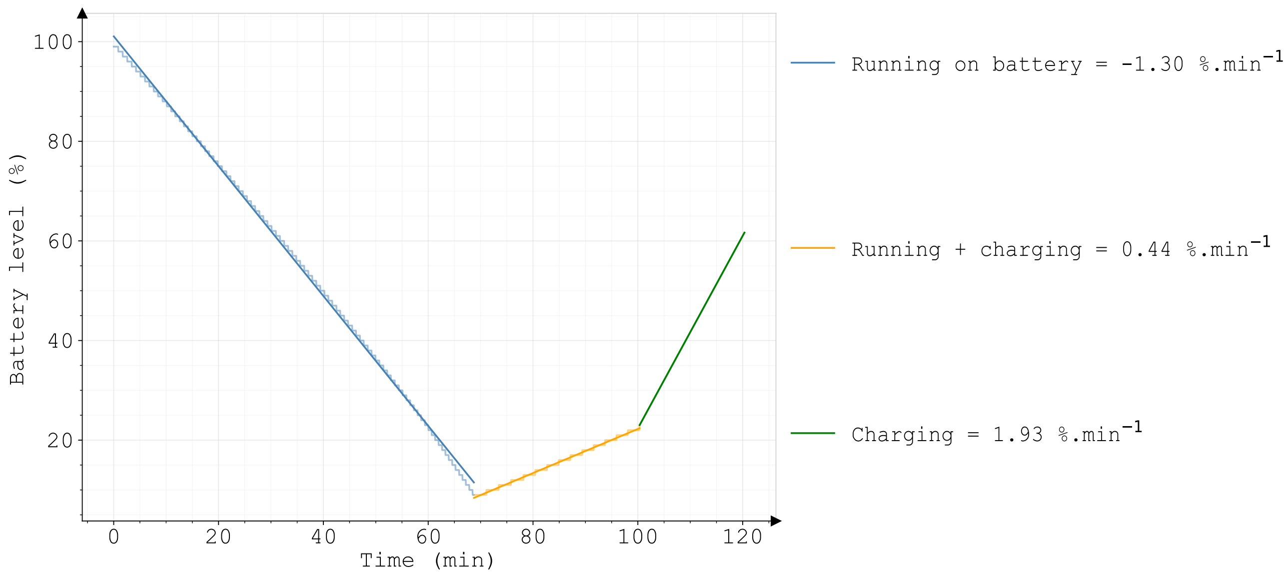


Figure 22: Battery Tests of the Strato

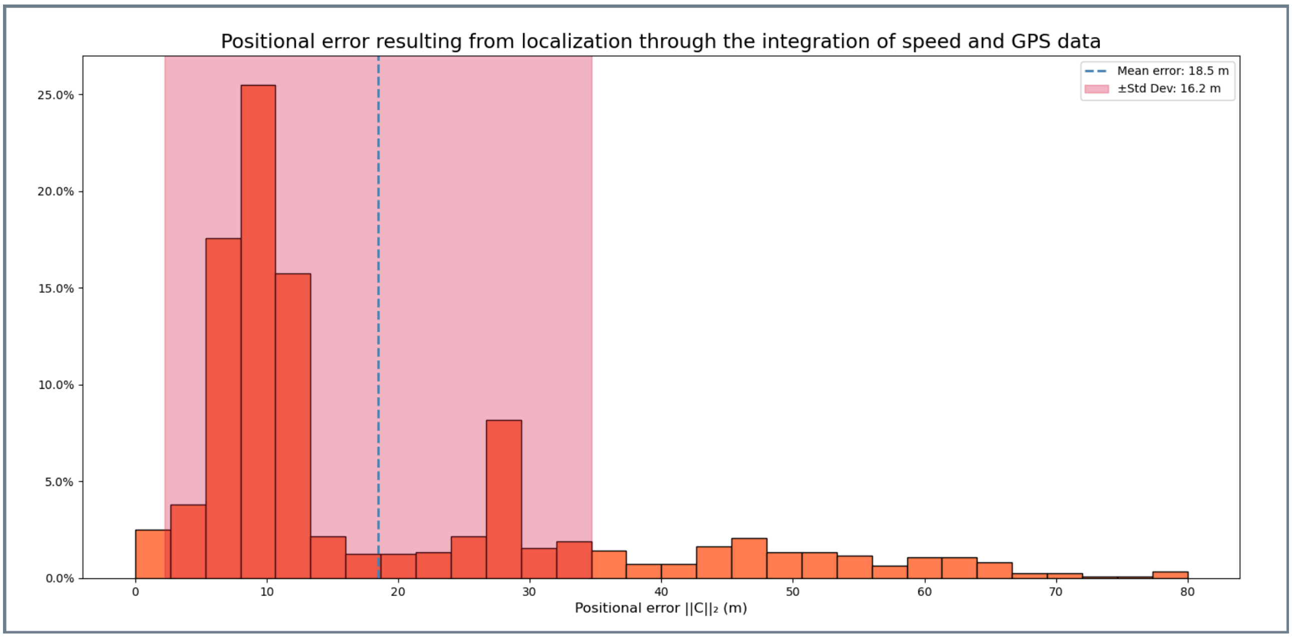
The first two lines are coming from the data file of the Strato.

For the Strato off and charging, in 10 minutes it went from 44 % to 63 % which is $\approx 1.9\ \%.min^{-1}$. Then I plotted a line this slope next to the others to easily compare.

Tests of the GPSs

After tests, the localization given by the GPS module that came with the Strato was within a range of $\pm$ 60 m $(k = 2)$, which is an unacceptable uncertainty.

For the Garmin GPS module, when plotting the Positional Error from calculated from the speed and localization data, we that a quarter of the time they are 10 meters apart of each other's, with an average of 18.5 meters, which isn't good.



To decide if we will use one data set or the other, I've plotted and compared these data sets against the localization from the drone's flight controller.

The Drone

Update of the firmware: After making the update of the firmware, we realized that the update didn't provide us with the FAA specifications, so we ordered the module for this purpose. Doing the update reinitialized the flight controller parameters, we had to re-make the calibration of the controllers' joysticks and setup the retractable landing gear with a Pulse Width Modulation Signal (*PWM*), which is just a square signal with a varying width and an amplitude of 1.

Battery of the drone

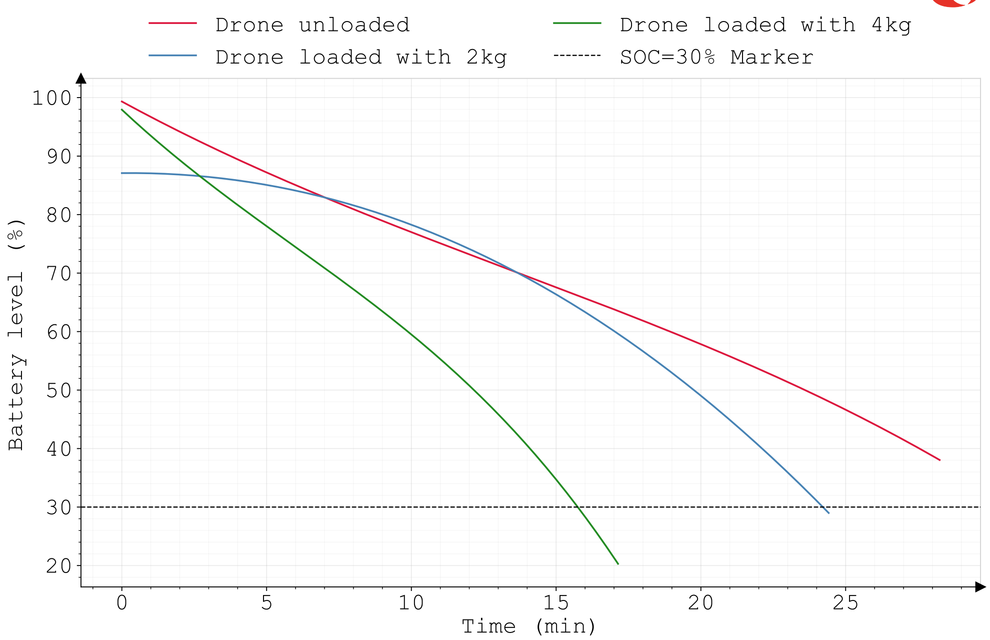


Figure 24: Polynomial Fitting of Drone Battery Data with different loads

During the deployment field, the drone will always carry two loads, so we should reference the green line. The drone will automatically come back to its take-off spot at 30% of battery, so if it's far away from this spot it will have enough battery to come back.

This plot also tells us that we will need to make at least one flight pattern in under 15.8 minutes

Stratos cage's holders

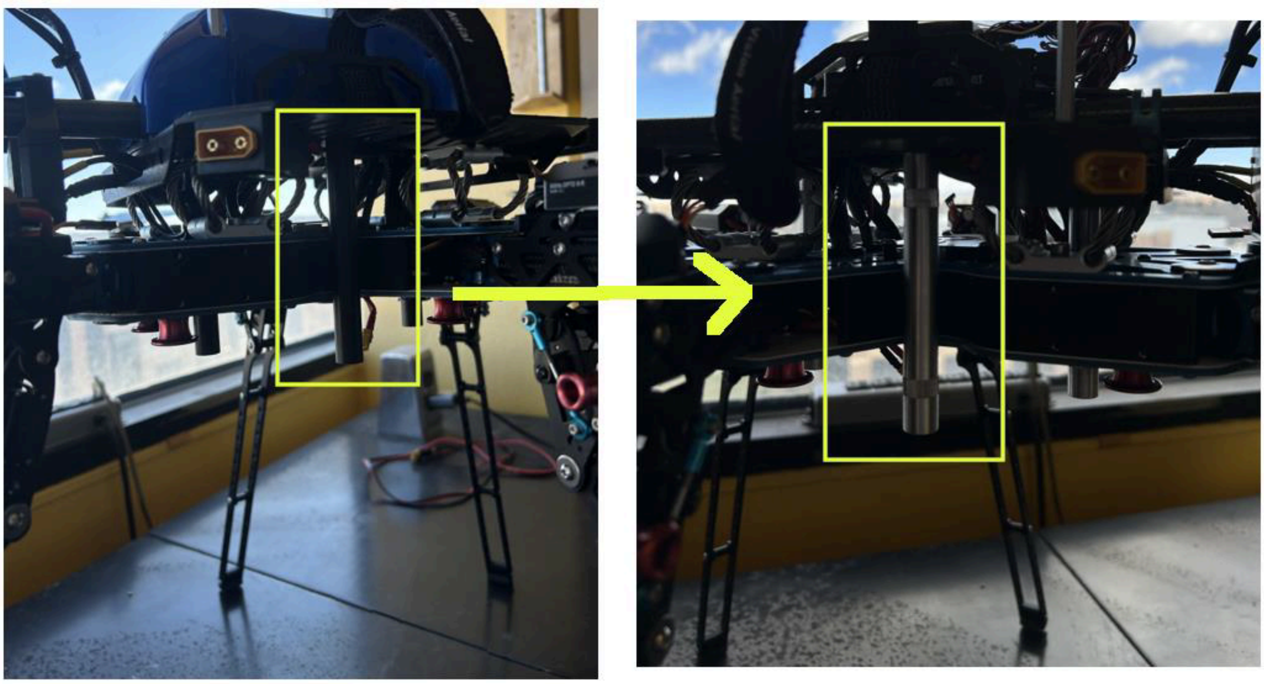


Figure 25: The Stratos Cage's holder

I installed the new studs to hold the Stratos' box with Loctite and without any difficulty. Loctite threadlocker solution are primarily designed to prevent fasteners from leaking or loosening due to vibration.

Conclusion

As of writing this report, the field deployment is scheduled for next week. It has been delayed one week because the drone was sent for repairs and upgrades.

Thanks to the work I have done, I can make an estimate of the uncertainty of the gas measurements that will be measured during the field campaign. By adding the uncertainties known of the instruments that will be used, spectrometers ($U = 1$ %), Mass Flow Controllers ($U = 2$ %), Tracer Gases ($U = 2$ %), I estimate that the uncertainty of the gas measurements coming from a well site of 5% of its reported values.

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GAYRARD Tristan