Evaluation of the KCD-HP-1001 CO_2 sensor

Abstract

The KCD-HP-1001 CO_2 sensor probe was found to respond linearly to carbon dioxide concentration according to V_{out} = 8.0371*C - 891.23 and linearly to temperature according to V_{out} = 0.057786*T + 1.9743, where C is the concentration of carbon dioxide in ppm and T is the temperature in °C. A linear response to pressure was not confirmed. The comparison between the KCD-HP-1001 and the Carbocap GMP343 failed because of trouble with the CIO's weather station. It was concluded that the operation of the KCD-HP-1001 is promising because of it linear response to carbon dioxide concentration and temperature and its small mean deviation. It is recommended that its response to humidity is tested and that a field test be conducted to compare the device with the Carbocap GMP343 and the Li-cor before a final conclusion can be given on replacing the Carbocap GMP343 with the KCD-HP-1001.

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Introduction

Global warming due to the enhanced greenhouse effect is the biggest environmental threat the world faces today. It is widely accepted that the main cause of the increased greenhouse effect is the anthropogenic carbon dioxide gas in the atmosphere. For research towards climate and climate change it is therefore recommended to monitor the atmospheric carbon dioxide concentration.

Several projects that do this use Vaisala Carbocap GMP343 sensor (From now on referred to as Vaisala). Unfortunately the Vaisalas are not satisfying. The Vaisalas have an internal correction that is quite complicated. This correction was found to be wrong and had to be improved.[1] Also the price of a Vaisala has increased drastically, from €1541- in 2005 to €2255- in 2012.[2] Besides, most sensors wear out after 5 years and need to be repaired, costing another €600-. These are reasons to look for a sensor that can replace the Vaisala. A possible alternative is the KCD HP1001 CO2 sensor (from now on referred to as Catec). With a price of €364 the Catec costs less than one sixth of the price of the Vaisala. If the Catec's accuracy and precision is comparable to that of the Vaisala, it can be considered to replace the Vaisalas with Catecs. The goal of this research is to find whether or not the Catec is a good replacement for the Vaisala.

The Catec's quality was tested in the following way. Firstly the Catec's response to different carbon dioxide levels and changing temperature was tested in the lab. After that a field test was conducted by placing the Catec next to a Vaisala, a LI-COR and the CIO's weather station. This way the Catec's reaction to pressure and humidity could be tested and its output could be compared with the output from the Vaisala and the LI-COR that were operating under the same weather conditions.

2 Operation of the Catec

The Catec's operation principle relies on absorption of radiation by carbon dioxide molecules. Molecules of one type can absorb photons of only a very specific set of wavelengths. (Figure 1) A molecule's absorption spectrum depends on the molecule's rotational and vibrational modes, which in turn are caused by the molecule's structure.[3] A molecule in a gas at a certain temperature has a specific transition either occupied or unoccupied. According to Boltzmann the ratio between the number of molecules with the specific transition occupied and the number of molecules with the transition unoccupied depends on the temperature.[4] The absorption spectrum of the gas will also change under the influence of pressure.[1] Thus, the absorption coefficient of a gas depends on the type of molecules in the gas, the temperature and the pressure.

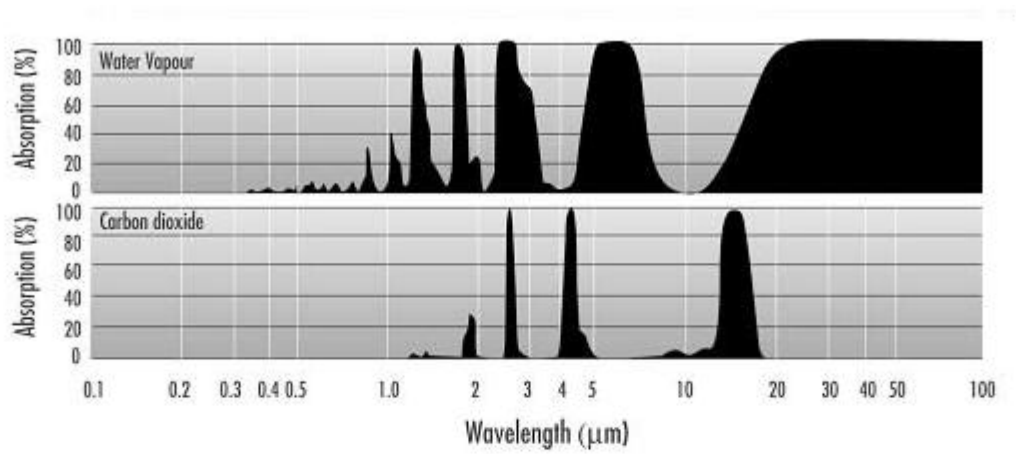

Figure 1. *An example of the absorption spectrum of carbon dioxide and water vapor in the infrared spectrum.[5]*

The heart of the Catec's operation is basically a small chamber with an infrared lamp on one side and two light sensors on the other side. (Figure 2) One of the sensors is covered with a 4.3 µm filter. Of all the abundant gasses in the atmosphere, carbon dioxide is the one that most strongly absorbs light with this wavelength. The intensity measured by the first light sensor must be compared with the intensity that would have been measured if there were no carbon dioxide particles in the chamber. This way the influence of aerosols in the chamber and intensity fluctuations of the lamp can be filtered out. To do this a second light sensor was placed. The second light sensor is covered with a 3.9 µm filter. This wavelength is not absorbed by carbon dioxide, and it is sufficiently close to 3.9 µm to assume that the influence of aerosols and intensity fluctuations of the lamp are the same as for the 4.3 µm wavelength. From the ratio between the two intensities the carbon dioxide concentration in the chamber can be calculated.

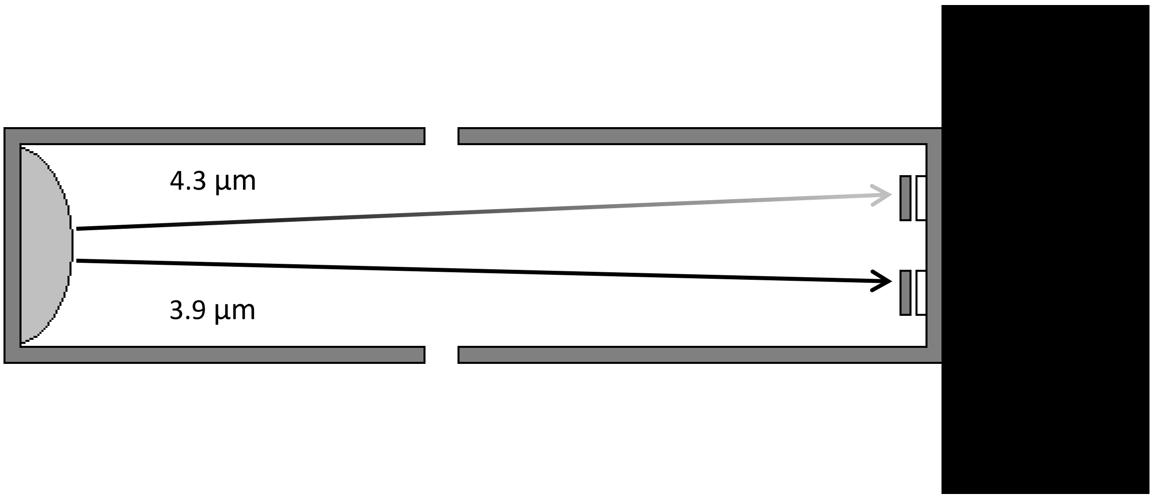

Figure 2. *Schematic overview of the inside of the Catec. The 4.3 µm light is partly absorbed by the carbon dioxide molecules inside the chamber, while the 3.9 µm light is not absorbed by carbon dioxide molecules.*

3 Theory

The Catec measures the intensity of 4.3 µm light and compares it with the intensity of the 3.9 µm light. The Beer-Lambert law gives:

$$\frac{I}{I_0} = \exp(-\varepsilon l C)$$

In which I is the intensity of the 4.3 µm light, I_0 the intensity of the 3.9 µm light, ε the molar absorption coefficient of carbon dioxide, l the length the light has traveled through the chamber (i.e. the length of the chamber) and C the molar concentration of carbon dioxide.

The molar concentration is given by:

$$C = \frac{n}{V}$$

Where n is the number of moles carbon dioxide molecules in the volume en V the volume.

If air is treated as a perfect gas, we find for N:

$$N = \frac{pV}{RT}$$

Where p is the pressure, T the temperature in Kelvin and R the gas constant. The variable N in this formula is the total number of particles, while the only interesting molecules are the carbon dioxide molecules. More specifically: the wanted variable is the concentration of carbon dioxide in in units of ppm: n_{ppm}. This is solved by stating:

$$N = \frac{n * 10^6}{n_{ppm}}$$

Where n is then the total number of carbon dioxide molecules in the chamber in moles, and n_{ppm} is the concentration of carbon dioxide in ppm. Rewriting the ideal gas law:

$$n = n_{ppm} \frac{pV}{RT * 10^6}$$

Now, the Beer-Lambert law becomes:

$$\frac{I}{I_0} = \exp(\frac{-\varepsilon l n_{ppm} p}{RT * 10^6})$$

Where ε is not a constant, but depends on temperature and pressure.

The description above assumes that the output from the Catec only depends on the conditions of the air in the chamber. However, its operation might also react on another way to the indicated factors. For example, if the surrounding air gets warmer the internal light sensors will become warmer too. Most light sensors are sensitive to changes in temperature, and since there is no internal thermometer the Catec cannot correct for this influence. Also the lamp might get hotter in a warm environment and thus emit a different spectrum.

4 Comparison between the Catec and the Vaisala

The Vaisala also estimates the number of carbon dioxide molecules in an internal chamber by looking at its absorption of 4.3 µm light. Just like the Catec it compares this with the absorption of 3.9 µm light to find the carbon dioxide concentration. A schematic overview of the inside of the Vaisala can be seen in Figure 3. The infrared lamp and the sensor are protected by a window. The light from the lamp reflects from a gold coated mirror, passes through a Fabry-Perot interferometer and is then measured by the light sensor. The Fabry-Perot interferometer is used as a filter that can be tuned to change back and forth between filtering 4.3 and 3.9 µm light. The window and the mirror are heated to avoid water to condensate on them. The Vaisala also has an internal temperature sensor. The Vaisala then corrects for the internal temperature, pressure and humidity and gives a voltage output that is linearly proportional to the carbon dioxide concentration. As noted before this correction needed to be improved.[1]

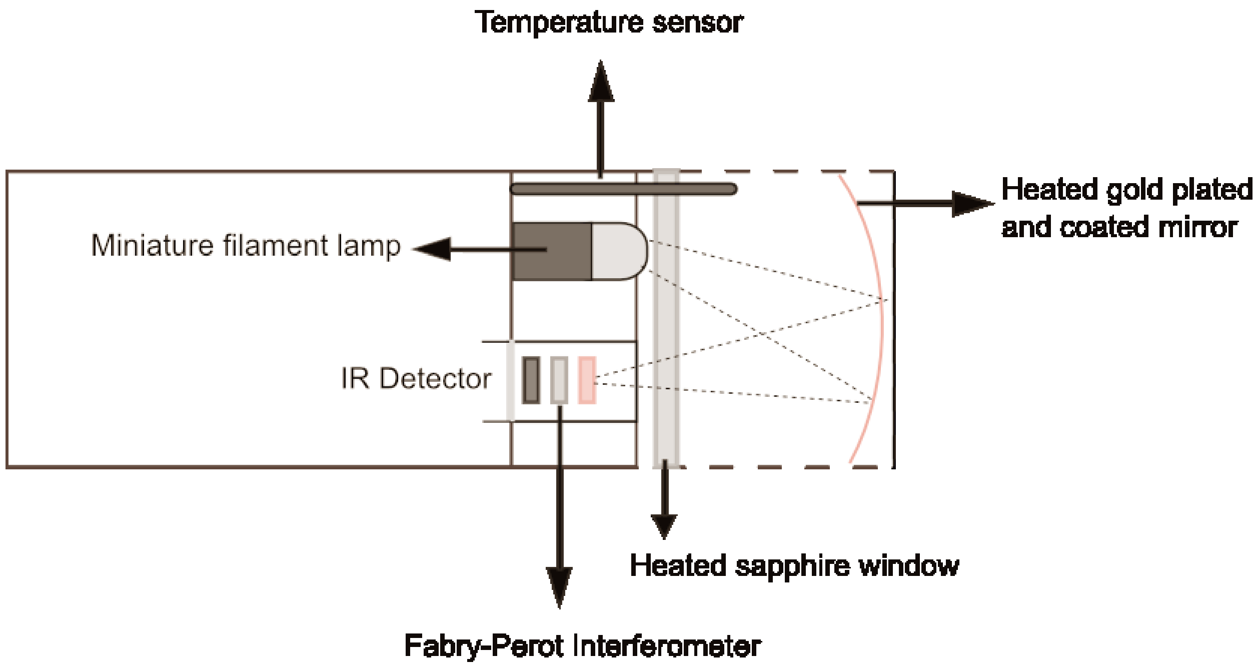

Figure 3. *Schematic overview of the inside of the Vaisala.*[1]

5 Experimental Setup

5.1 Lab setup

The Catec's current output will be used. According to the manufacturer the Catec will give an output between 4 and 20 mA for carbon dioxide concentrations between 0 and 1000 ppm. Because the interesting part lies roughly between 200 and 500 ppm it is expected that the Catec will give current outputs below 12 mA. A resistor is put between the Catec's current output and the ground. A Campbell CR1000 data logger is set to measure the voltage over the resistor. This data logger can measure voltages up to 5 V so a resistance of 270 Ω is used. The final output then is a voltage, that is linear to the Catec's current output, that is in turn a measure for the carbon dioxide concentration. The voltage over the resistor will be considered the output of the Catec.

The setup that was already used for calibrating the Vaisala was used.[1] The setup exists from a pvc pipe in which the Catec is placed. The pvc pipe also has a temperature sensor and a heating element in it. The pipe is connected to two cables and two tubes. One of the tubes is connected to a mass flow controller that is connected to a gas cylinder filled with air with a known carbon dioxide concentration and no water vapor. The other tube serves as an air outlet. The cables are connected to power sources for the Catec, the heater and the temperature sensor. They also serve to send data from the Cated and the temperature sensor to either a computer or the data logger. And finally, the cables are also used by the computer to turn the heater on and off. A schematic overview of the pipe can be seen in figure 6.

After the Catec is placed inside the pipe, all the cables and tubes are connected and the pipe is placed inside a freezer. A computer program, originally created for testing the Vaisala, but later adapted to work with the Catec, can be set to keep the inside of the pipe at a certain temperature. The program will turn the heater on when the temperature gets below the desired temperature, and turns the heater off when the temperature gets too high. This way the temperature in the tube will oscillate around a temperature that is slightly lower than the desired temperature. The average of the actual temperature inside the pipe can then be calculated from the output of the temperature sensor. The standard deviation of the average temperature is less than 0.1 degree. The program can also be set to follow a more complicated time scheme of temperatures, for example to raise the temperature in steps of 5 degrees, and to keep each step stable for 2 hours.

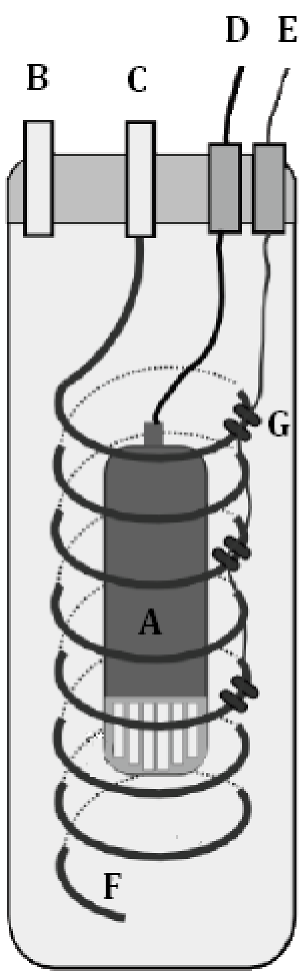

Figure 6. *An overview of the PVC pipe. Adapted from [1].*
A. The Catec.
B. Air outlet.
C. Air inlet (Connected to copper tube in the shape of a spiral.)
D. Cable for power and data.
E. Another cable for power and data.
F. A spiral copper tube.
G. A heater element that is curled all around the copper tube.

5.2 The experiments

The sensitivity of the Catec to temperature was determined as follows. First, a gas cylinder with a carbon dioxide concentration of 405.50 ppm was connected to the mass flow controller and opened. Then the temperature was changed a few times to find how much time the Catec needs to warm up. It was found that the Catec needs at most one and a half hour to warm up. The computer was set to maintain the temperature in the tube at 1 °C for two hours, then to maintain a temperature of °6 C for two hours, then to maintain a temperature of 11 °C for two hours, and so on until 31 °C. Then it had to lower the temperature with the same step size until the temperature was back at 1 °C. Then the cycle had to start again. During this cycle, the temperature sensors output is logged by the computer and the data logger measures the average voltage over the resistor every 10 seconds. The step size of two hours gives the Catec enough time to warm up, and gives sufficient time to do reliable measurements after that. At the end of the experiment this resulted in two sets of data, namely the temperature versus the time and the voltage versus the time. These where coupled to each other to find how the voltage depends on the temperature.

In the second experiment the temperature was held constant at 6 °C. Then three cylinders with air with different carbon dioxide concentrations were measured. The cylinder's concentrations, also for some other gasses are found in table 1.

	Cylinder nr 9570	Cylinder nr 4827	Cylinder nr 9563
CO_2 (ppm)	382.03 ± 0.31	405.50 ±0.63	457.58 ± 0.05
CO (ppm)	138.6 ± 3.6	234.6 ± 2.1	140.9 ± 1.2
CH_4 (ppm)	1891.9 ± 2.0	1964.1 ± 2.4	2194.8 ± 0.9

Table 1. *The cylinders and their concentrations.*

The third experiment was the field test. The Catec was placed at the roof of the CIO building, next to the Vaisala. The Catec was in position for about 10 days. After these 10 days the Catec's output first had to be compared with the pressure and humidity measurements from the CIO's weather station. After calibrating for the pressure and humidity it was intended to compare the final, corrected Catec output with the measurements from the Vaisala, and the even better LI-COR carbon dioxide sensor. The results from the LI-COR would then be considered perfectly accurate and the comparison would exist from checking whether the Catec approaches the output from the LI-COR better or worse than the Vaisala. However this approach failed because the weather station and the Vaisala were offline during the field test, and the LI-COR was not into place. To compare the Catec's output with the pressure, the measurements from the the KNMI was downloaded. The closest KNMI station to Groningen is Eelde, roughly 10 kilometers from the CIO.

6 Results and discussion

6.1 Temperature correction

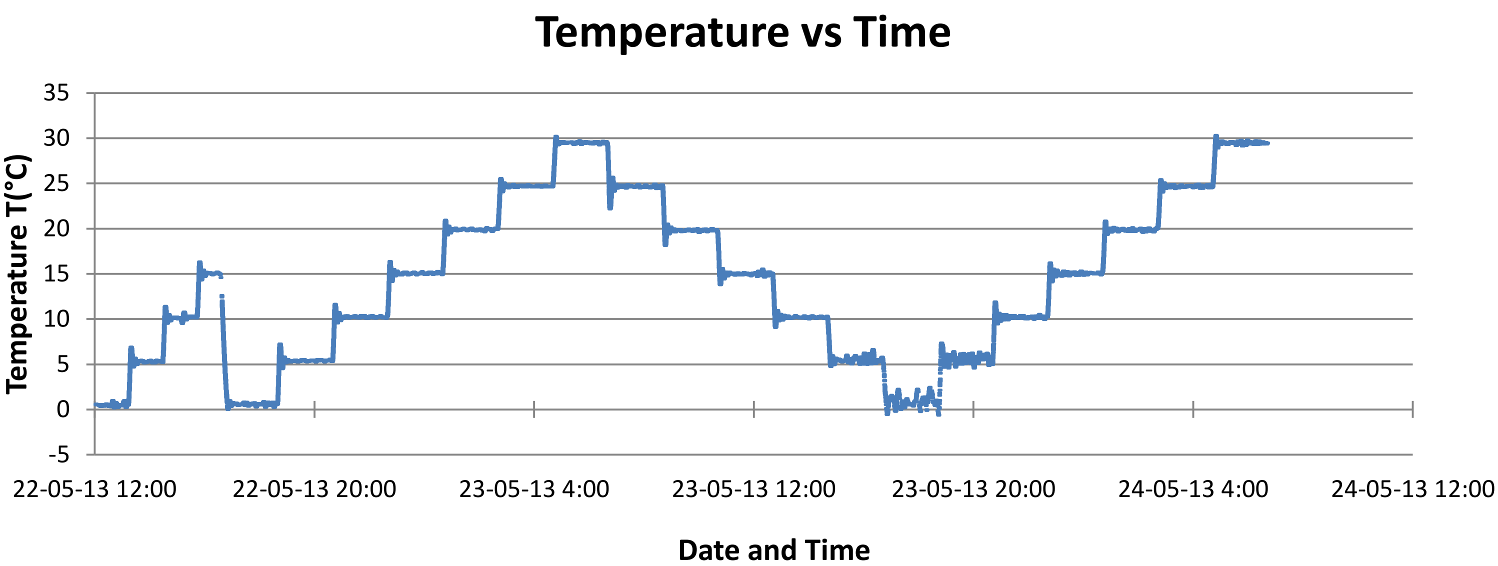

Figure 7. *The temperature measured inside the pipe.*

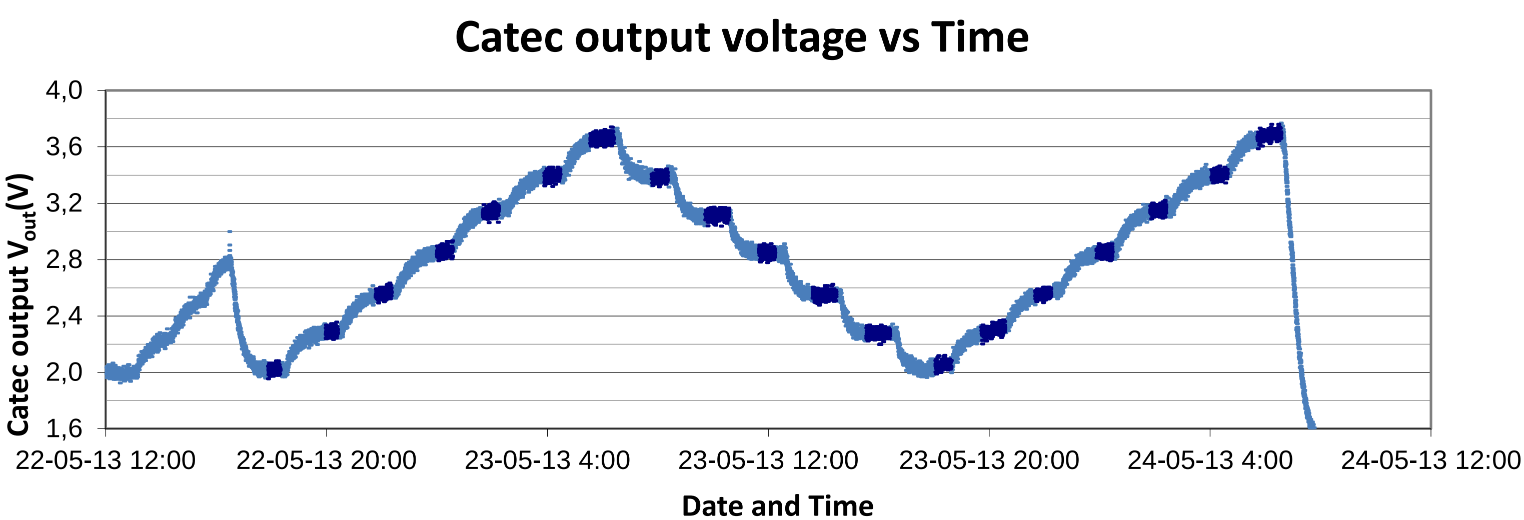

Figure 8. *The Catec's output. The averages of the dark parts were used for the calibration in figure 9. The slopes in the dark parts are at some points positive. This is not because the Catec is still warming up since the same can be observed when the temperature goes down.*

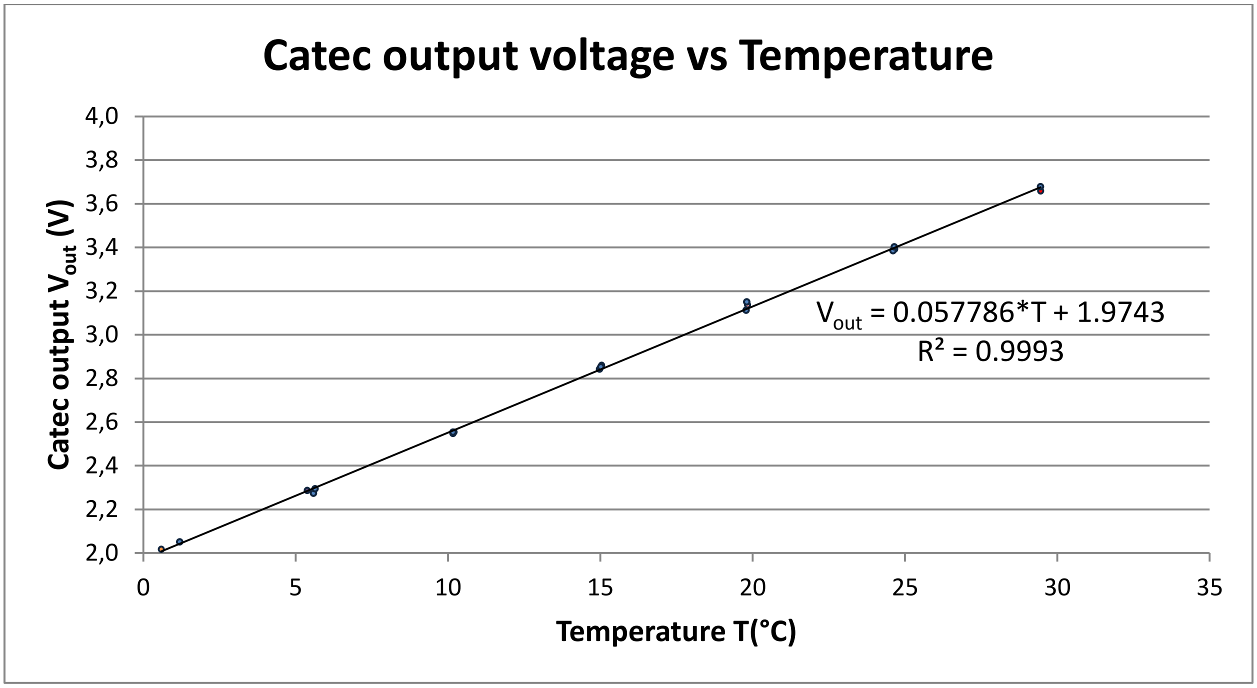

Figure 9. *The dependence of the Catec's output on the temperature. This plot has 19 data points in it, but some of them overlap so much they cannot be distinguished on the printed version of this report.*

The temperature experiment was conducted with a concentration of 405.50 ±0.63 ppm. From the plot in figure 9 it is clear that the Catec's response to a change in temperature is linear. During the experiment the pressure in the lab fluctuated between 0.9848 and 0.9895 bar. The observed slope is roughly 7 times as steep than the one found in earlier research.[2] The average of the standard deviations of the dark parts in figure 8 is 25.17 mV.

The fitted linear function has a positive slope. This means that the Catec's reaction to temperature cannot be attributed to the expected behavior according to the ideal gas law. Other temperature dependent factors have a bigger effect than the lower number of carbon dioxide molecules that result from a higher temperature.

This behavior is not expected to be caused by the light sensors temperature response. If both the light sensors respond to changes in temperature in the same way the ratio I/I_0 does not change.

The influence of the temperature on the IR-lamps spectrum can be ruled out as the main cause for the positive temperature respond. If the surrounding air is cold, the lamp will be slightly less hot than when the surrounding air is warm. If the lamp is less hot its peak wavelength will be shifted more towards larger wavelengths according to Wien's law, and a logical consequence of that is that slope to the right of the peak wavelength will become less steep, as seen in figure 10. This means that the ratio between emitted 4.3 µm light and 3.9 µm light will change. This will cause the ratio I/I_0 and thus the Catec's output to become lower at lower temperatures, which is exactly what is observed in figure 9. However the maximum temperature difference in the experiment is 35 degrees, while the typical operation temperature of an infrared lamp is 1000 K. The spectral radiance coming from the lamp can be described with Planck:

$$B(T) = \frac{2kc^2}{\lambda^5}\frac{1}{\exp(\frac{hc}{\lambda kT}) - 1}$$

The influence of this external temperature difference is so small that it cannot be the main cause of the temperature dependence.

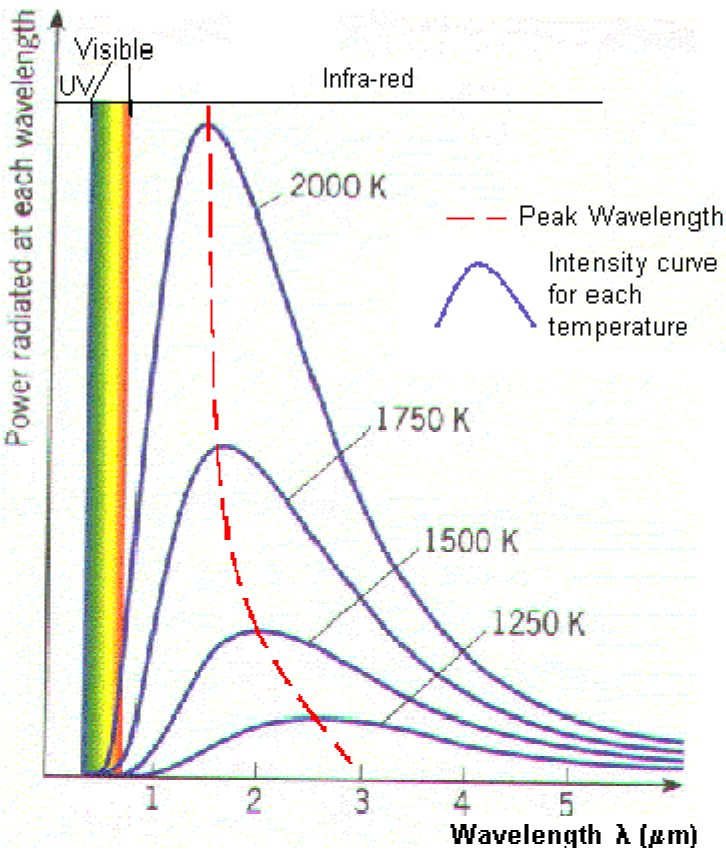

Figure 10. *If the lamp becomes colder, its emitted spectrum will change and as a result the ratio between emitted 3.9 µm light and 4.3 µm light will change. Image taken from a website on black body radiation.*[6]

The strongest factor is that the value of the absorption spectrum depends on temperature.[2][4] When the temperature changes, also the ratio between carbon dioxide molecules with unoccupied and occupied 4.3 µm transitions will change. Because of this the absorption will change too.

6.2 Calibration for carbon dioxide concentration

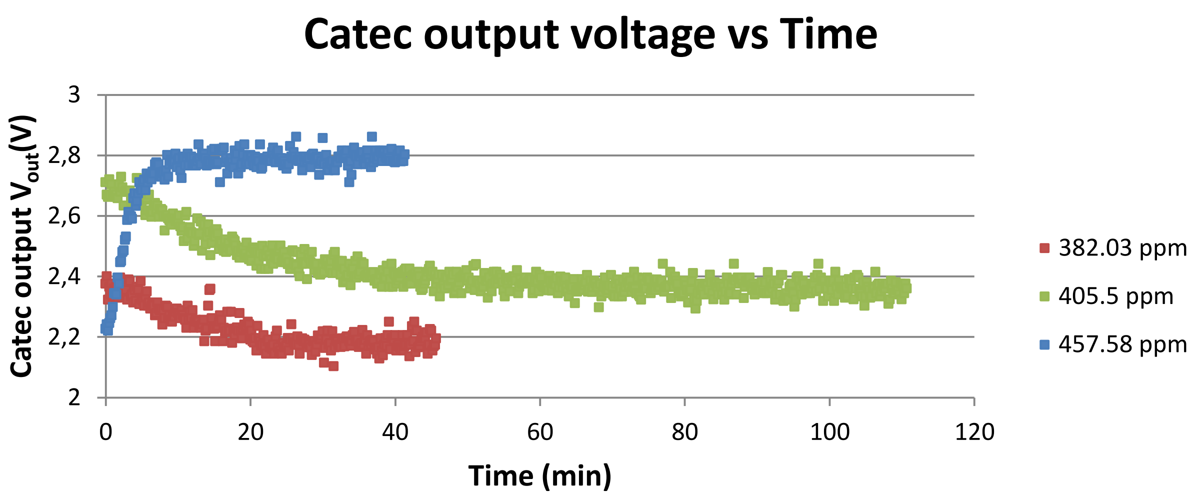

Figure 11. *The output voltage from the Catec versus the time. The cylinder with 405.50 ppm was measured first. After the 405.50 ppm measurement the cylinder with 383.03 ppm was measured, and after that the cylinder with 457.58 ppm. The 457.58 ppm test approaches its final value faster than the others because the mass flow controller was set higher. These measurements where made with an average temperature of 5.5 °C and an average pressure of 0.9983 bar.*

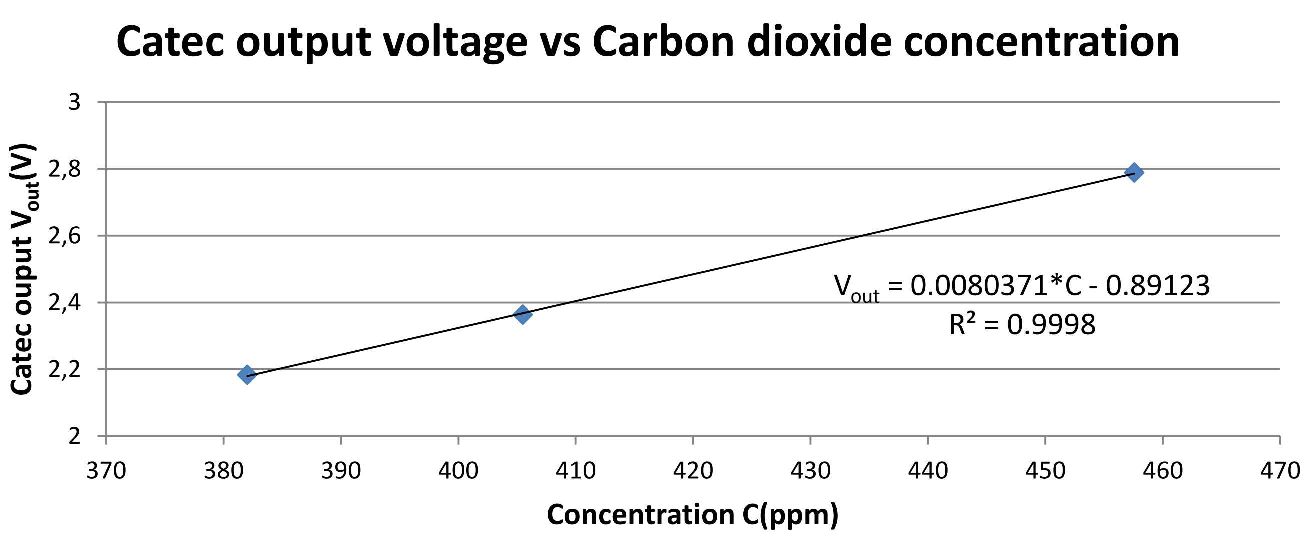

Figure 12. *The output voltage from the Catec versus the concentration.*

The Catec's output increases linearly with carbon dioxide concentration. (Figure 12) The standard deviations of the parts of the graphs where the outputs became constant are shown in table 2. The atmospheric carbon dioxide concentrations in the atmosphere will nearly always be in the measured range.

	Cylinder nr 9570	Cylinder nr 4827	Cylinder nr 9563
CO_2 (ppm)	382.03 ± 0.31	405.50 ±0.63	457.58 ± 0.05
Stdev (mV)	25.25	25.52	23.09
Stdev (ppm CO2)	3.13	3.17	2.87

Table 2. *The standard deviations of the constant parts of the graphs.*

6.3 Field test

The Catec was placed on the roof of the CIO, Groningen and ran for almost 10 days, from 31-05-2013 17:30 to 10-06-2013 16:30. Unfortunately it was found that the entire CIO weather station, including the Vaisala had been logging exactly the same temperature, pressure, humidity, carbon dioxide concentration, wind speed and wind direction at every logging point for at least ten days. Also the LI-COR was not in position. Therefore the necessary data about temperature, pressure and humidity was downloaded from the closed KNMI station, Eelde, which is about 10 kilometers from the CIO. It was not possible to compare the Catec's output with that of other nearby carbon dioxide sensors.

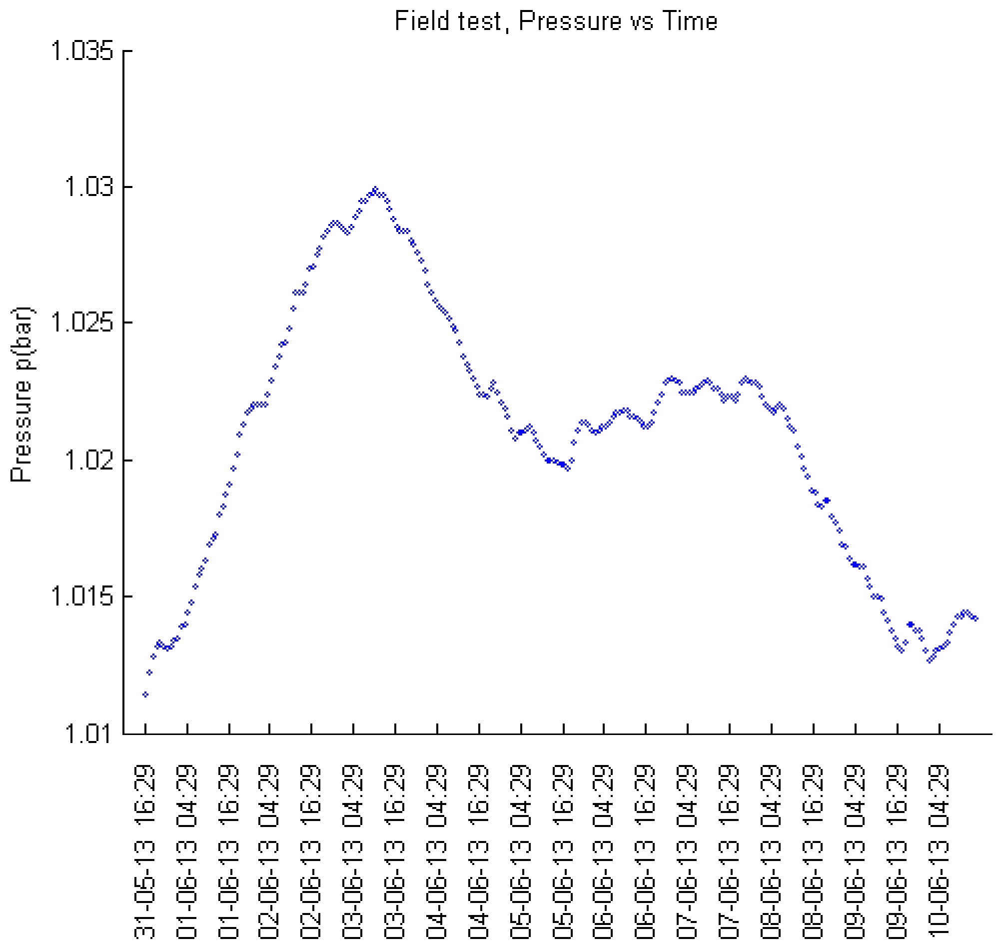

Figure 13. *The hourly average of the pressure versus the time since the start of the first experiment at KNMI station Eelde. During the field test the outside pressure varied significantly. This data, just like the other data about the weather conditions, comes from KNMI Eelde.*

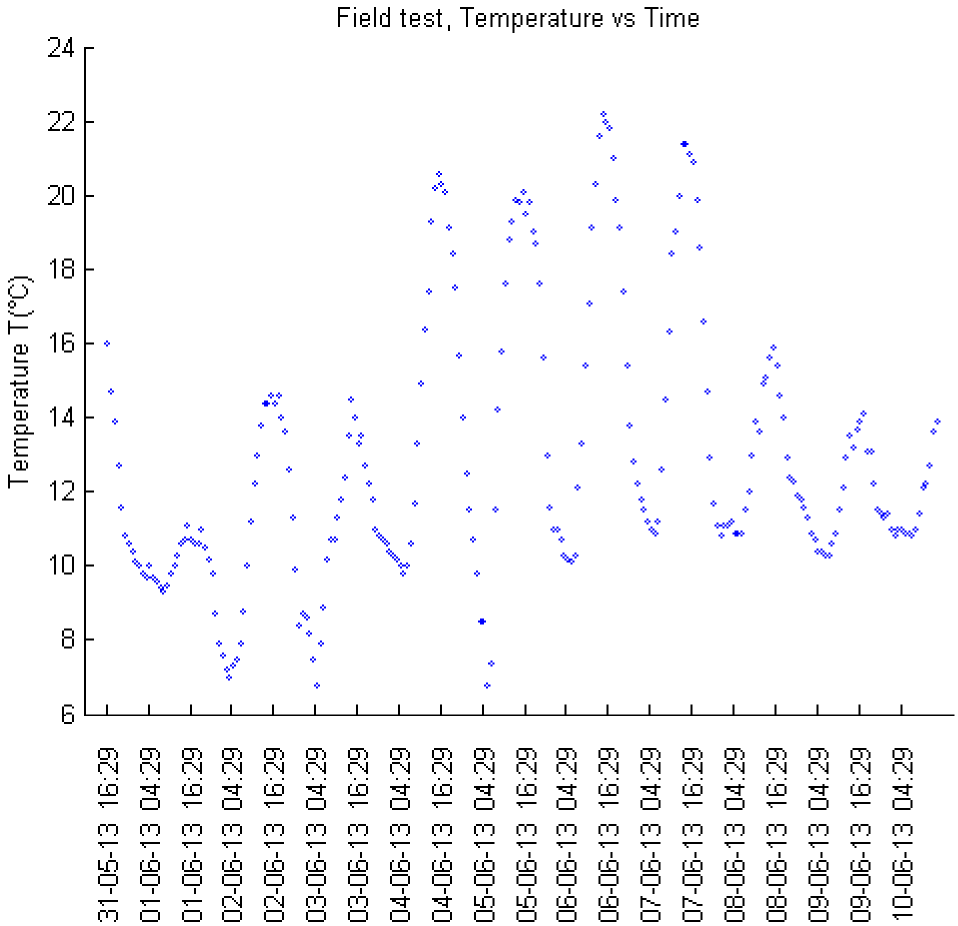

Figure 14. *The temperature data from KNMI Eelde. This graph has been moved 10400 seconds to the left to take the Catec's response time into account.*

There was a time difference between the peaks of the temperature and the peaks of the Catec's output. (Figure 15) This time difference can be explained by the Catec's warm up time and the fact that the temperature is measured 10 kilometers from the Catec. A time difference of 10400 seconds was found between the peaks of the temperature plot and the Catec output plot. To relate the Catec's output to the temperature 10400 seconds were substracted from the last one.

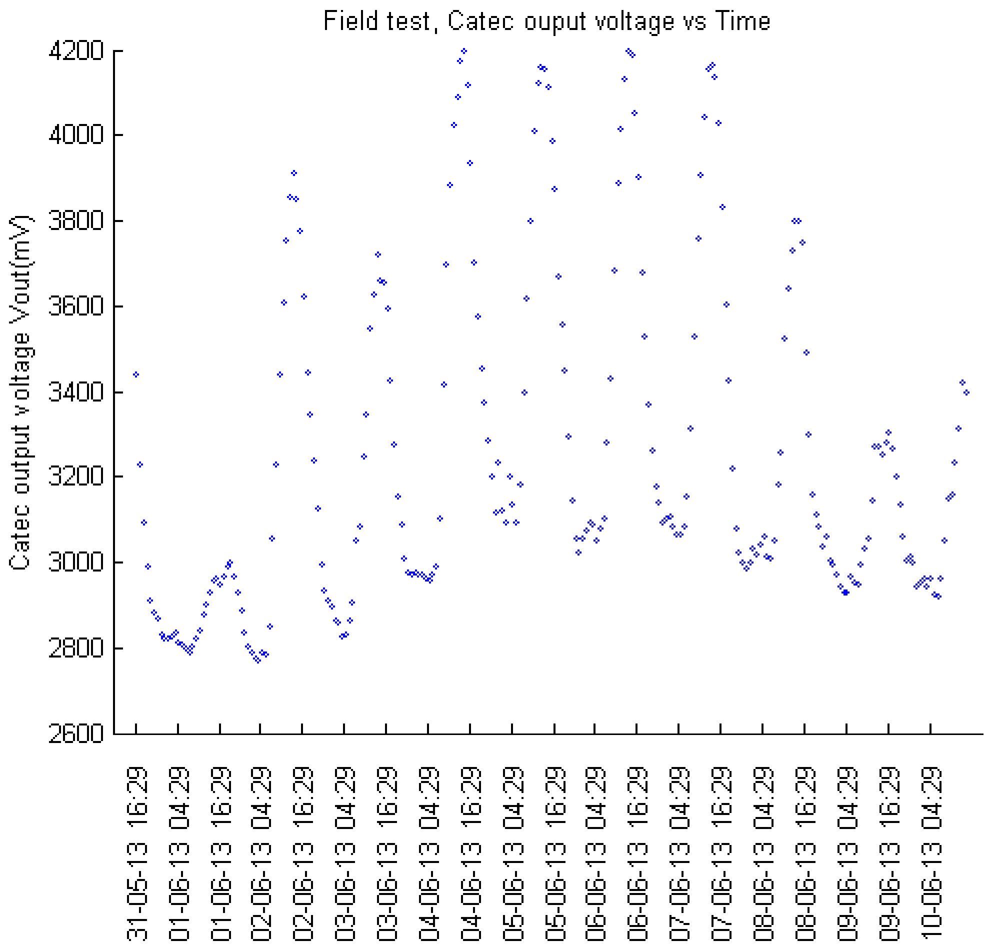

Figure 15. *The output from the Catec.*

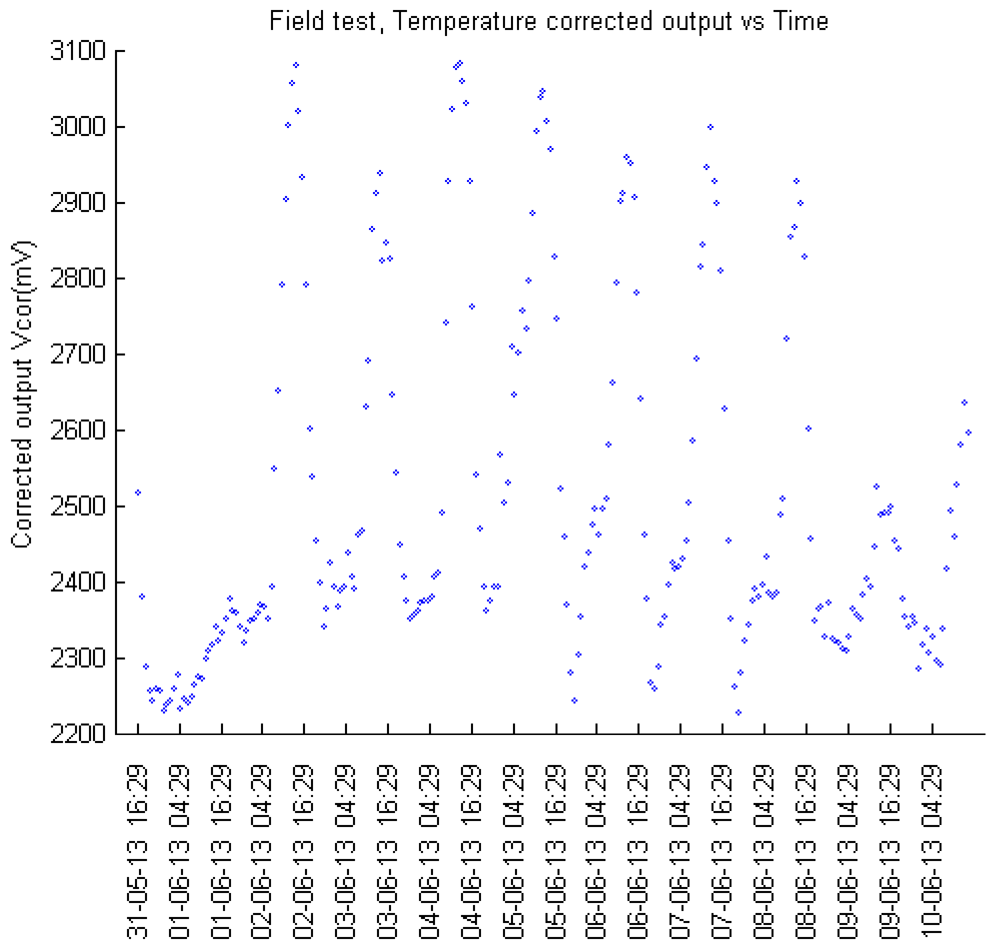

Figure 16. *The output from the catec corrected for temperature using the laboratory calibration:* $V_{cor} = V_{out} - 57.786*T$.

During daytime the carbon dioxide concentration are lower because trees absorb carbon dioxide under influence of light. The output from the Catec shows the opposite. It can be seen in figure 16 that the Catecs output is much higher when the temperature is high, during daytime. It is argued that this is because of the placement of the Catec, rather than the correction for temperature being insufficient. The Catec was positioned right next to the Vaisala so they could be compared later. Unfotunately this is on the south of the building, on a dark metal plated wall, under a thin metal sheet. When there is little wind and no clouds, the Catec tends to get much hotter that the average outside temperature measured in Eelde. The Vaisala can correct for this with its internal temperature sensor. The Catec has no internal temperature sensor and cannot do this.

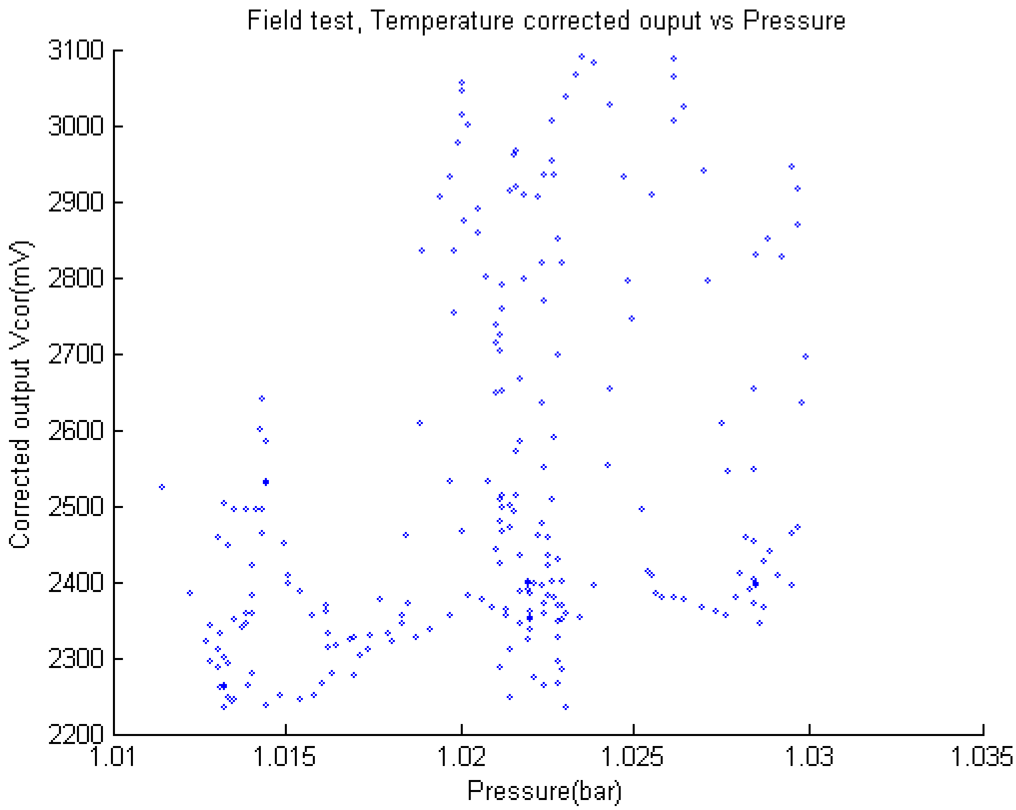

Figure 17. *The corrected output from the Catec versus the pressure during the compete field test. No obvious relation could be found because of the huge spread in the data.*

The placement of the Catec was somewhat awkward. But a part of the collected data might still be useful to find the output's dependence on pressure. The most obvious selection would be to cut out all the daytime data. A somewhat different approach was used. First, it was decided to concentrate only on the data before may 6, 10:30. This way the big pressure peak from figure 13 was inside the remaining data, and only two big day time peaks needed to be filtered out. Second, all data points with a temperature higher than 12 °C where deleted. This was done under the assumption that if the temperature was below 12 °C it would be either night or a cloudy day, and thus overheating of the Catec would not take place. Finally, all the data points where the Catec's corrected output was over 2700 mV, or its difference with the previous point was higher than 50 mV where cut out. This resulted in the next five plots.

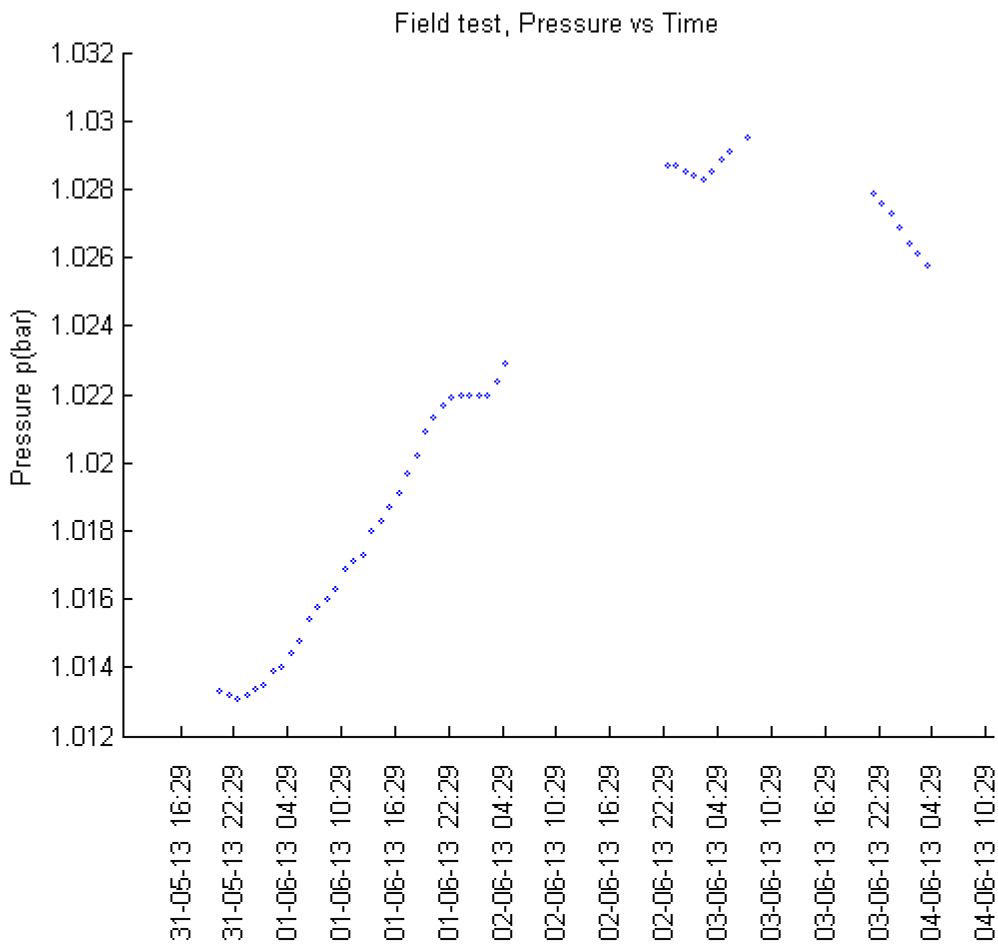

***Figure 18**. Again the pressure versus the time. As can be seen, only the first big peak was selected. The gaps origin from the fact that at those times the temperature was higher than 12 °C.*

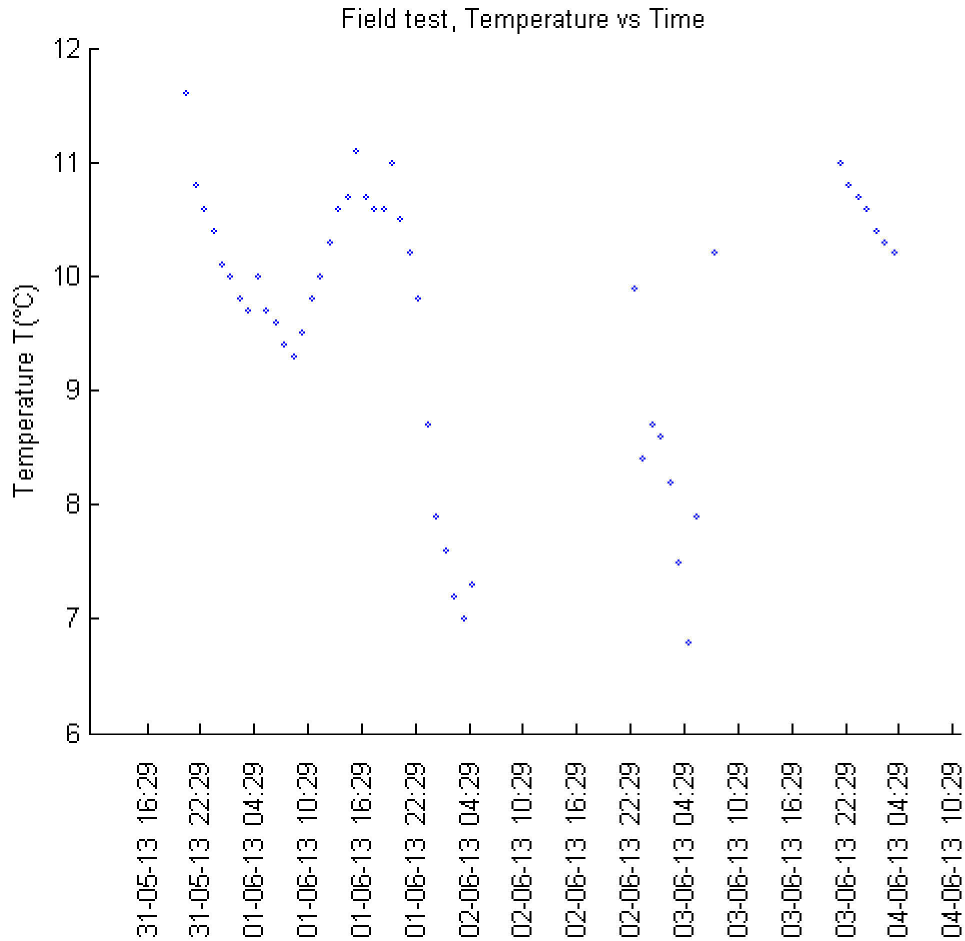

Figure 19. *Again the temperature versus the time. As can be seen, there are no points with a temperature higher than 12 °C in the selection.*

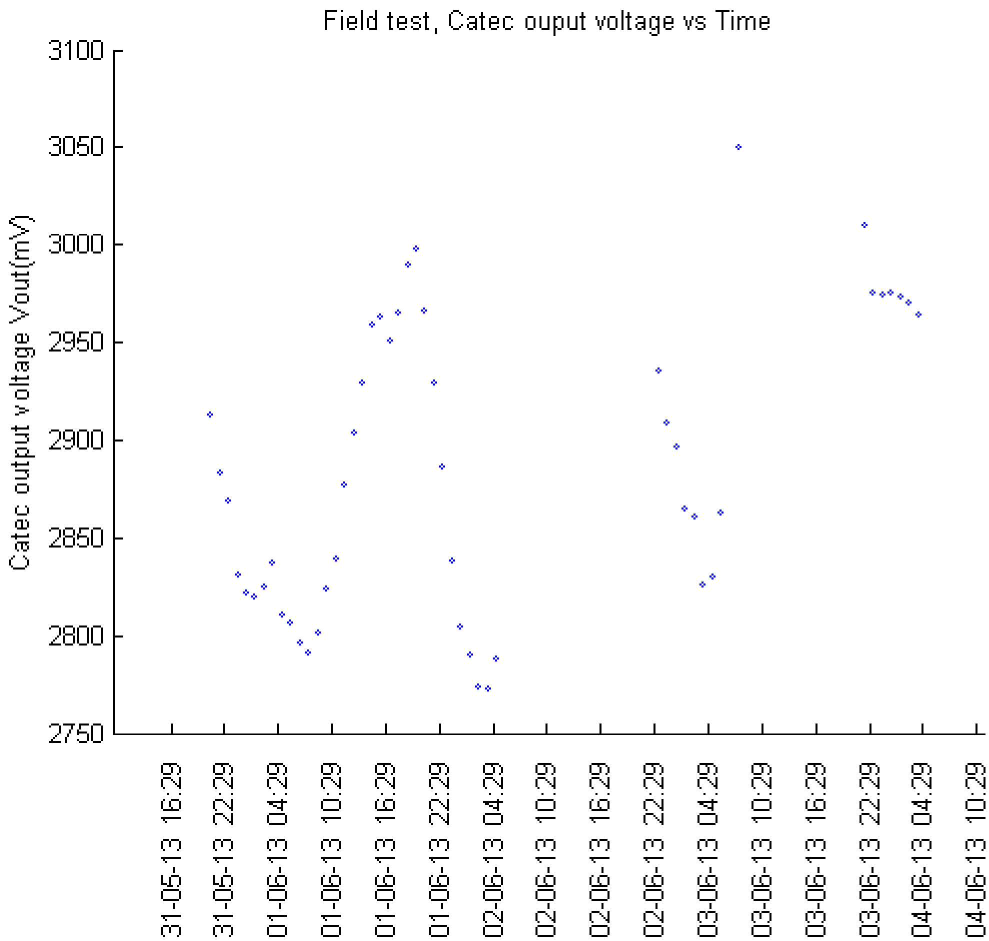

Figure 20. *The part of the Catec's output that meets the specified selection rules.*

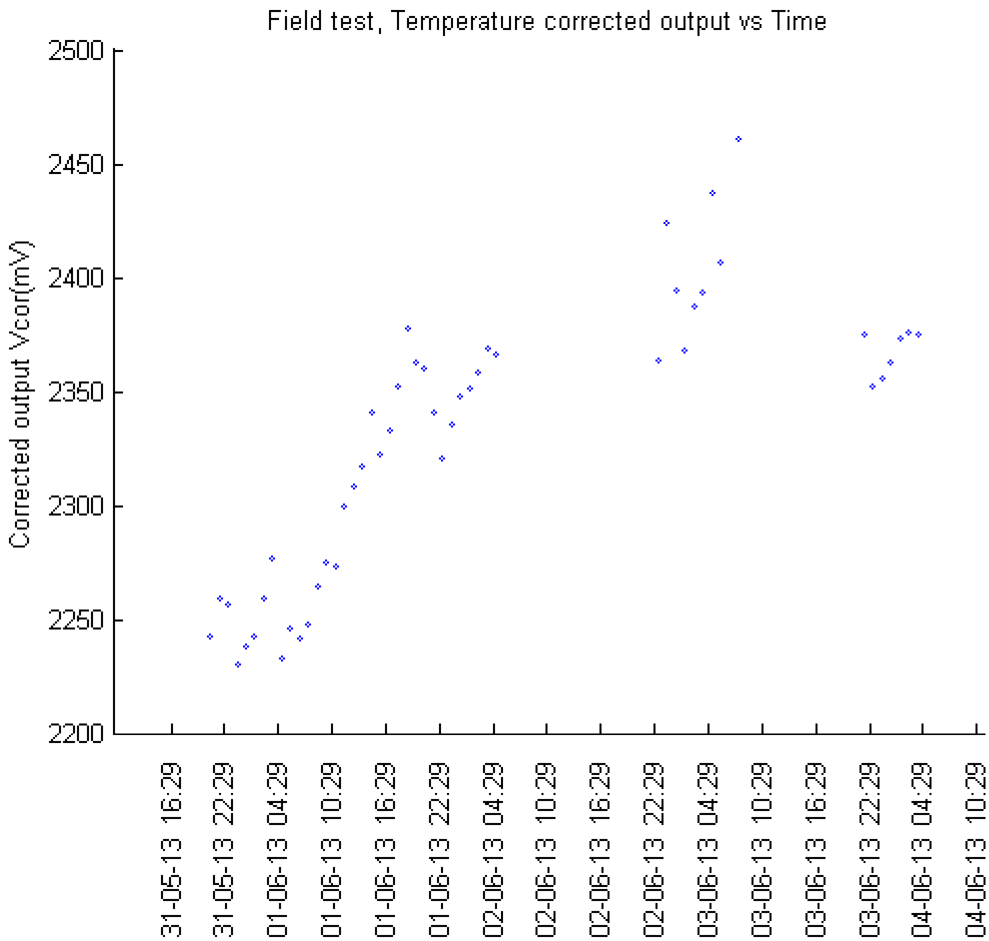

Figure 21. *The Catec's output corrected for temperature.*

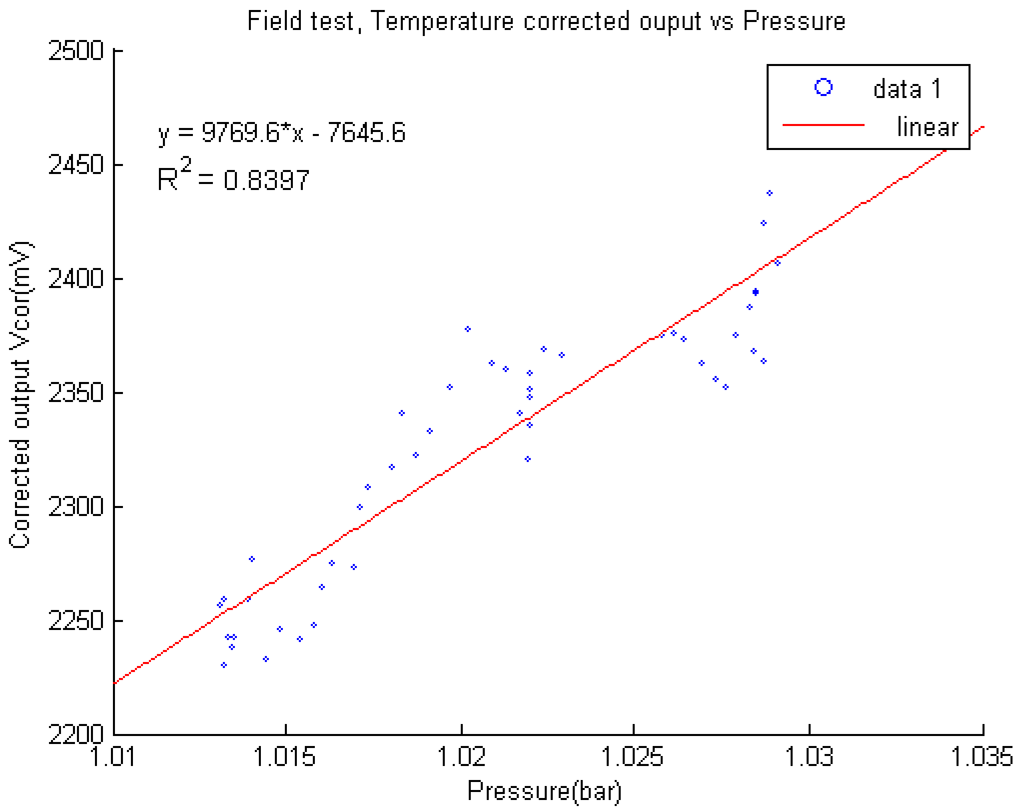

Figure 22. *Again the Corrected output from the Catec versus the Pressure. The linear relation was found with Matlab's basic fitting tool that uses the least squares method.*

The relation found in figure 21 does not have an R-squared value close to 1, and the observed slope is almost 5 times as large as the one found in previous research to this type of sensor.[2]

The humidity test was skipped because it could not be reasonably assumed that the humidity measured in KNMI Eelde is representative for the humidity at the roof of the CIO. Eelde and the CIO are separated by a distance of about 10 km.

7 Conclusions

The Catec's response to temperature is linear. The relationship for the tested sensor is:

$$Vout = 0.057786 * T + 1.9743$$

Where T is the temperature in °C. The found R-squared value for this approximation is 0.9993.

The Catec's response to carbon dioxide concentration is also linear. The found relation is:

$$Vout = 0.0080371 * C - 0.89123$$

Where C is the concentration carbon dioxide in ppm. The found R-squared value for this approximation is 0.9998.

From previous research[2] it is known that the outputs dependence on pressure must be linear, but the observed linear correlation in this research has a too small R-squared value to conclude that the output really is linear with the pressure. A qualitative conclusion can be made though. It is found that a higher pressure will result in a higher output, and a lower pressure in a lower output.

The influence of humidity on the Catec's operation couldn't be found because there was no data about the humidity available. Also the Catec could not be compared with the Vaisala or the LI-COR since those devices were offline or gone.

It could not be confirmed that the Catec is a good replacement for the Vaisala. This is because the influence of humidity and pressure were not found qualitatively and because the devices could not be compared. However the linear response to carbon dioxide concentration and temperature, and the small mean deviation (25.17 mV) are promising. More research is recommended.

8 Recommendations for future research

In last year's research to the Catec a different method to find the Catec's response to changing pressure was used and the result is linear over a large range.[2] This year the Catec's reaction to changing temperature was found with a higher accuracy than last year. [2] The most important missing parameter is the humidity. Therefore it is recommended that next year's research puts a larger focus on finding a reliable way to test the influence of the humidity.

The weather station needs to be repaired, and the LI-COR should be placed back before next year's student can perform a field test. The use of KNMI data is not recommended if there is a weather station right next to the sensor.

If the Catec is completely calibrated, it is useful to find whether or not its operation changes over time.

9 Acknowledgements

The author of this report would like to thank the following people for their help during the research:

- Dr. W. Klaassen for his supervision and feedback during the research.

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- B. Kers for explaining how to work with cylinders and to take me to the roof of the CIO.

- M. de Vries for helping in repairing the cable setup that broke a few times.

10 References

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