Performance Evaluation of Low-cost Carbon Dioxide Sensors

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Abstract – ***The present work is dedicated to the performance evaluation of commercial, off-the-shelf non-dispersive infrared (NDIR) carbon dioxide sensors. These sensors are very promising candidate for the new generation air monitoring tools, but some of their basic characteristics are not sufficient for scientific and control applications. In this study the sensors were tested and evaluated for the assessment of their uniformity, repeatability, linearity, accuracy, atmospheric pressure, temperature and humidity sensitivity. Possibilities for the sensor calibration and accuracy improvement are discussed.***

Keywords – ***Carbon dioxide, Correlation, Linear regression, NDIR gas sensors, Repeatability, Uniformity***

I. Introduction and Motivation

Carbon dioxide (CO_2) is a major greenhouse gas, with fundamental significance to Earth's climate. Since measurements started at the Mauna Loa Observatory in the early 1950s, the global mean concentration of CO_2 has steadily risen from levels of approximately 280 parts per million (ppm) of dry air, to levels today exceeding 400 ppm [1]. So far, urban CO_2 has been monitored in many cities. Most of the urban CO_2 data were obtained using fixed observation stations or vehicles. However, most of the studies provide CO_2 concentration data only for a small number of fixed points or characteristic points on the vehicle route [2].

For the CO_2 concentration, data acquisition with high temporal and spatial resolution is necessary to use a multi-point observation methods based on many fixed stations or observation vehicles are needed. Therefore, low-cost CO_2 sensors with sufficient accuracy are required.

There are different new technologies for CO_2 concentrations measurement. In recent years, CO_2 sensors based on solid electrolytes, laser diodes, optic fibers, and non-dispersive infrared (NDIR) detectors have been developed [3].

One of the most promising near-term technologies for atmospheric CO_2 concentration measurements are the commercially available non-dispersive infrared (NDIR) sensors. This sensor technology has a lot of advantages such as linear response to concentration, fast response, low fabrication cost, light-weight and low power consumption, all of which are desirable for the so-called "next generation" of air monitoring tools.

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NDIR sensors are widely employed since they are very robust and stable against other air pollutant gas components interferences. Low-cost NDIR carbon dioxide gas sensors find increasingly application not only in environmental monitoring, indoor air quality control & energy conservation in buildings and greenhouses but also in portable deployment for safety, industrial and medical applications [2, 4].

A number of studies and analyzes of carbon dioxide sensors show levels of accuracy that do not meet the requirements for scientific studies and for control applications [5, 6]. The output of NDIR sensors is affected by temperature, atmospheric pressure, and length of use [7]. To improve the accuracy and precision of NDIR sensors, an extensive use of correction algorithms is needed. In the present study, an approach based on successive linear regression for the accuracy and precision improvement of recently developed cost effective CO_2 sensors is presented.

II. Instrumentation and Methods

A. Essential Characteristics

This paper presents evaluation of low-cost NDIR CO_2 gas sensors performance under varying gas concentrations at different temperature, relative humidity (RH) and pressure conditions. Alongside the impact of the temperature, RH and pressure changes, we have studied the accuracy, the precision, (especially the uniformity and the repeatability) of the low-cost NDIR sensors. Some studies do not use those concepts in accordance with their accepted definitions [8]. In the present paper we look at uniformity as a systematic error which refers to the consistency of a measured value, usually compared to another sensor taking the same measurement. Repeatability is similar to uniformity but it deals with the problem how consistent a particular sensor is against itself. It is used to describe the ability of a sensor to provide the same result, under the same conditions again and again [9].

For the uniformity assessment the normalized Root Mean Square Error (nRMSE) between two sensors ($S1$ and $S2$) of the same type measuring the same gas concentration was used:

$$\text{nRMSE} = \frac{\sqrt{Mean(CO_{2s1} - CO_{2s2})^2}}{Mean(CO_{2s1} + CO2_{s2})/2}, \quad (1)$$

where CO_{2s1} the PM concentration is detected by sensor $S1$ and $CO2_{s2}$ is the concentration detected by sensor $S2$ for a defined time interval. Mean $(CO_{2s1} + CO_{2s2})$ is the average concentration of both sensors over the all measurements. Smaller nRMSE values correspond to better uniformity between the sensors [10].

B. CO_2 and atmospheric Sensors

To test the validity of using low-cost sensors for different monitoring, control and scientific applications four off-the-shelf models of NDIR CO_2 sensors were preevaluated (K30, SenseAir; IRC-A1, Alphasense; S100, ELT Sensor; MinIR, GSS). Their all have warrantied measurement ranges of 0–5.000 ppm and weight under $20\ g$.

TABLE 1. DATASHEET INFORMATION FOR THE USED CO_2 SENSORS.

Sensor	K30	IRC-A1	S100	MinIR
Manufacturer	SenseAir	Alphasense	ELT Sensor	GSS
Accuracy	±30ppm+3% of reading	1% FS	±30 ppm ±5% of read.	±70 ppm ±5% of read
Warranty range, ppm	0–5,000	0–5,000	0–5,000	0–5,000
Response time, t_{90}, s	< 60	< 40	60	10
Operating voltage	4.5–14	2–5	5	3.25–5.5
Weight, g	17	15	10	16

Accuracy is usually specified at the so called "standard conditions" but defining these conditions is already a serious problem. Many different definitions of standard reference conditions are currently being used by organizations all over the world. Some of these organizations used other standards in the past [7].

The K30 sensor module from SenseAir is the low-cost NDIR CO_2 sensor that was tested for this study. The K30 was chosen because of its highest manufacturer specified accuracy and high reliability and consistency when compared to higher-quality instruments. It is a device with on-board signal averaging and temperature correction. It has a measurement range of 0 to $10\,000\ ppm$, and resolution of $1\ ppm$. The manufacturer's stated accuracy of the K30 sensor is $\pm 30\ ppm \pm 3\ \%$ of reading for the $0.5\ Hz$ raw output [11].

For the atmospheric temperature and relative humidity measurements the SHT11 sensor which is integrated in a K33 data logger is used (accuracies $\pm 0.4\ K$ at $25°C$ and $\pm\ 3\%\ RH$).

For the atmospheric pressure measurement, the MPL115A1 sensor (absolute accuracy $\pm 1\ hPa$) from NXP was chosen.

C. Test Chamber and Reference Instrument

An experimental set-up was built for the detailed performance study of the low-cost NDIR sensors (Fig. 1). The control of the set-up and the measurement procedures is executed in the LabVIEW environment of graphical programming.

The studied CO_2 sensors (K30 $10{,}000\ ppm$) and the K33 data logger are mounted in the test chamber. An external cooling/heating device is used to maintain the needed temperature.

To evaluate the performance of the K30 sensors in research instrumentation, a gas analyzer based on dual wavelength infrared sensor was used as reference instrument. The CA-10 Carbon Dioxide Analyzer from Sable Systems provides barometric pressure compensated CO_2 concentration measurements with response time of $0.5\ s$ and has an un-calibrated uncertainty of < 1% [12].

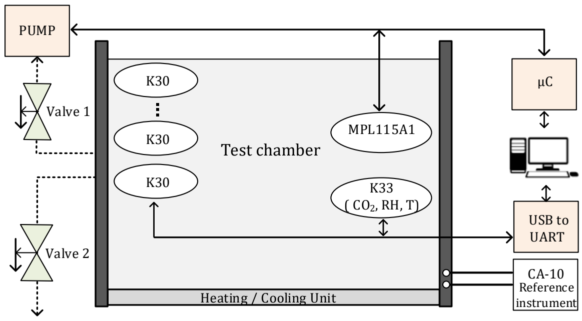

Fig. 1. Experimental set-up

For the initial reduction of humidity, we have used silica gel. The desired RH was adjusted by flowing dry air through a deionized water bubbler and then into the chamber before the test. After the RH reached the set values, the feeding of water vapor was discontinued. The decrease of RH was found to be less than 5 % during the test.

Outlets for pumping air in and out are included to keep the pressure within the desired limits and for connection of the reference instrument (Fig. 1).

III. EXPERIMENTAL EVALUATION

For the calibration of air quality sensors several protocols have been developed. This section presents the experimental results on evaluating the CO_2 sensors using the revised protocol provided by European Commission JSR Protocol of evaluation and calibration of low-cost gas sensors [13, 14].

A. Allan deviation

Allan deviation is a measure of the time-averaged stability between consecutive measurements or observations, often applied to clocks and oscillators. It is a common way to quantify sensor noise and can be used to determine the optimal averaging interval for a dataset to minimize noise [15]. Fig. 2 shows the Allan deviation analysis for one of the tested K30 sensors.

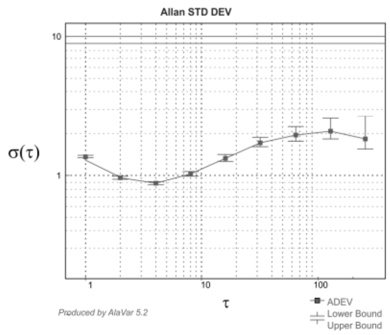

Fig. 2. Allan deviation analysis

For the analysis, the raw 30 s data of the sensor exposed to a known CO_2 concentration (of about 555 ppm) is used. Averaging for even one minute drops the deviation significantly. According to this analysis, the Allan deviation is at a minimum, when averaging time is approximately 4 min. Extended averaging times do not contribute for noise reduce. Allan variance was computed for the other five sensors and was found that they perform similarly. For the subsequent analysis, an averaging time of 4 min is used.

B. *Uniformity and Repeatability*

The results of the nRMSE explained in Section 2 indicates a very good *uniformity* of the 5 sensors. Table 2 shows the results for a relative low gas concentration of 500 ppm.

TABLE 2. nRMSE VALUES OF THE FIVE EXAMINED SENSORS

Sensor A	Sensor B	nRMSE
1	2	0.066
1	3	0.116
1	4	0.054
1	5	0.084
2	3	0.050
2	4	0.013
2	5	0.019
3	4	0.063
3	5	0.032
4	5	0.031

The repeatability of the sensor responses was calculated using the repeatability standard deviation (of sensor values for at least 3 consecutive hourly averages (at 0 ppm and at about 80 % of full scale) [13]. We found an average standard deviation s_{LV} of $12 - 14\,ppm$ and relative standard deviation $s_{R_{rel}}$ of 2.73 %.

The repeatability limit is calculated using the expression

$$r = \sqrt{2} \cdot t \cdot s_R, \qquad (2)$$

where t is the two-sided Student's t value for the required level of confidence and the appropriate number of degrees of freedom.

C. *Calibration and Linearity*

For the purposes of this study, the measurements with the tested low-cost CO_2 K30 sensors were correlated with the CA-10 CO_2 Analyzer as a reference.

Fig. 3 shows 24 hours of measurements of CO_2 from 2 pcs K30 in the lab chamber including a calibration period when low (near 100 ppm) and high (near 5000 ppm) has been reached by introducing zero gas and, respectively CO_2, in the test chamber.

During this time, the data from each K30 was collected every twenty seconds and then averaged over each minute. Because the chamber is not perfectly sealed, there is a slow diffusion from the air inside the room into the container, leading to some indoor influences in addition to the natural outdoor diurnal variation. For the calibration, first the synthetic zero air, containing only nitrogen, is pumped into the chamber. Then, CO_2 gas for 20 min before returning to the ambient air.

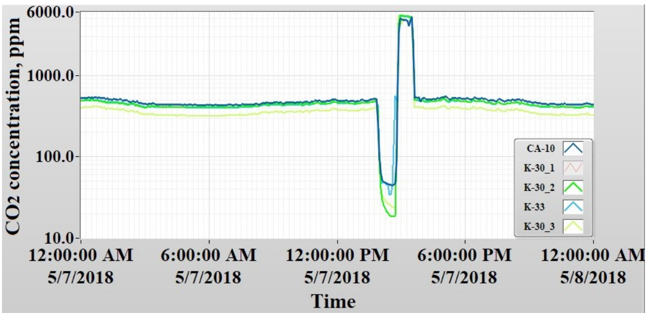

Fig. 3. 24 hours of measurements of carbon dioxide mixing ratios from two K30 NDIR sensors and the CA-10 CO_2 Analyzer

For the tested sensors, a calibration function was computed by assumption of linearity between the sensor outputs and the reference measurements. The calibration functions were of the type $y = a + bx$ where y represents the sensor responses and x the corresponding reference measurement. The reverse equation (measuring function), $x = (y - a)/b$ was applied to all sensor outputs for the calculation of CO_2 concentration levels. For the calculations a conventional least square regression and Reduced Major Axis (RMA) regression was used. Prior to RMA, the outliers are removed from the data set because they can cause significant changes to the model parameter estimates.

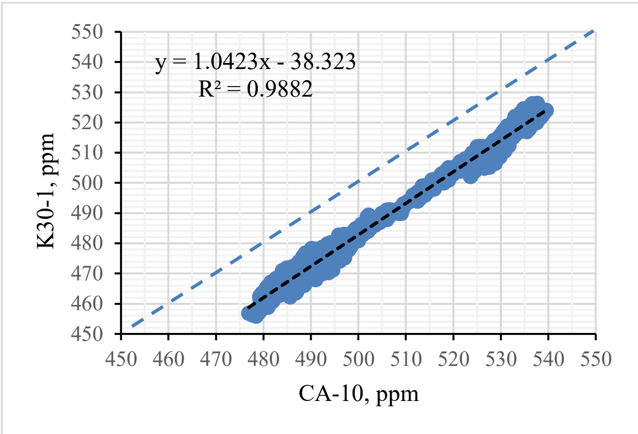

Fig. 4. Calibration function of K30-1 Sensor vs CA-10 CO_2 Analyzer

Table 3 shows the result for the linear regression of an averaged value for all five sensors against the reference instrument.

TABLE 3. LINEAR CORRELATIONS BETWEEN K30 GAS SENSOR OUTPUTS AND CA-10 CO_2 ANALYZER MEASURED CONCENTRATION

	Least squares $(0 - 5000\,ppm)$	RMA $(0 - 5000\,ppm)$	Least squares $(450 - 550\,ppm)$
Slope	1.060	0.987	1.032
Intercept	7.38	-3.87	-19.23
R^2	0.974	0.979	0.983

The coefficient of determination between the CA-10 CO_2 Analyzer and the sensor average is very high with $R^2 \approx 0.98$ (Fig. 4).

The results in the table are used to assess the accuracy with the help of linear regression. Although the results vary slightly, the very high R^2 value indicates the good performance of the low cost sensors. The small differences between the least square and RMA regression indicate minor influence of the variation of CA-10 CO_2 analyzer measurements.

D. The Impact of Pressure, RH and Temperature Changes

Based on the equation of ideal gas and the formula of the density a relatively accurate estimation of the deviations in measuring CO_2 concentration is achieved when there are changes in pressure as compared with the 'standard' pressure for which the sensors are usually calibrated.

Clear dependence of the K30 sensor outputs of about $1.5\ \%/kPa$ of the measured concentration by deviation from standard pressure $(100\ kPa)$ can be observed.

Relative humidity affected the performance of the gas sensors in different ways. Water molecules absorb the infrared radiation and often cause overestimation of gas concentrations, due to the reduced light intensity received by the photo receiver [16].

In the tests performed under different RH levels $(20, 40, 60\ and\ 80\%)$ and at low CO_2 concentrations near the target values of about $800/1000\ ppm$ significant correlation was found between the RH and the sensor responses. The impact of the temperature changes on the sensor outputs has been studied by gas concentration of about $550\ ppm$, at pressure of $950\ hPa$ and RH of $60\ \%$. The temperature in the chamber was changed from $15\ °C$ to $50\ °C$ with a step of $5\ °C$.

The sensor module K30 shows a very good built-in temperature compensation and the reading deviations in the temperature range from $15\ °C$ to $50\ °C$ do not exceed $20\ ppm$.

CONCLUSION

The K30 is a small, low-cost NDIR CO_2 sensor designed primary for industrial OEM applications. Each of the tested sensors falls within the manufacturer's stated accuracy range of $\pm 30\ ppm\ \pm 3\%$ of the reading when compared to a high-accuracy CO_2 analyzer. However, once correcting for a zero-offset, and performing a regression analysis, the practical accuracy of these sensors is less than ten parts per million, or approximately $1\ \%$ of the observed value, with final root mean square errors of each K30 being $10 - 14\ ppm$. With errors in this range, these sensors could be used in variety of control and scientific applications.

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