

Correlative comparison of two optoelectronic carbon monoxide measuring instruments

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In this paper, a correlative comparison of two carbon monoxide (CO) measuring instruments is presented. Implementing different principles, the point source device and the open path optical remote sensing instrument do actually not measure the same quantity. Taking the random character of the CO-concentration signals into account, a statistical comparison of the two instruments is still possible. After low-pass and high-pass filtering of the CO-concentration signals there correlation coefficients to some meteorological parameters are calculated. The correlative analysis leads to the expected conclusion that the open path instrument is more suitable for monitoring the pollution level in a large area than the classical point source device.

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1. Introduction

In the frame of European research projects, several air quality measuring campaigns in cross roads, streets, parks as well in a non ecological waste deposit near Timișoara city were realized (** [2003-04]; ** [2001-04]). Some of the conclusions of these projects are already reported (Bisorca D., Ionel Ioana, Hanna L.,Cooke K., 2003; Bisorca D., Ionel Ioana, Popescu Fr., Ionel S., Ungureanu C., 2003; Ionel Ioana, Ionel S., Bisorca D., 2004; Ionel Ioana, Ionel S., 2004).

In this paper a correlative comparison of two optoelectronic carbon monoxide measuring instruments is presented. The analyzed signals were measured in the non ecological waste deposit.

Section 2 contains a short description of the utilized measuring systems. The measured CO-concentration signals and meteorological parameters as well as signal conditioning procedures are presented in section 3 of the paper. A correlative analysis allowing a statistical comparison of the measuring instruments and conclusions are the purposes of sections 4 and 5, respectively.

2. The optoelectronic measuring instruments

One of the utilized instruments was the a specialized HORIBA APMA-350E CO monitor, which furnishes the local pollution level. Fig.1 presents a bloc diagram of this instrument working on the classical Non-Disperse Infrared (NDIR) method. The APMA-350E represents a generation of ambient CO monitors designed to eliminate routine calibration cycles and to provide long-term stable

measurements and unattended continuous operation. It features a newly developed cross-flow modulation (CFM) technique which results in remarkable improved zero drift performance and sensitivity. The cross-flow modulated analyzer incorporates the basic design features of the conventional NDIR analyzer.

The essential new element in this design, according to Fig.1, is a rotary valve that alternately directs the sample gas and a reference gas to the one cell of the analyzer. By this method, the distinction between the sample and the reference optical path is eliminated and each path alternately functions as a reference and a sample path. The requirement for an optical chopper to modulate the detector output is thereby eliminated. In the cross-flow analyzer design, sensitivity is inherently increased because the amount of IR energy absorbed and translated into the output signal is theoretically doubled for any concentration at the given modulation frequency. In addition, the signal-to-noise ratio is significantly better because the optical chopper which tends to introduce noise in the conventional NDIR instrument is removed in this CFM design. In the CFM scheme, gas flow rates and cell configuration can be selecting providing very smooth modulation. To minimize interference, dual detector system employing a compensating detector located behind the main detector is adopted in this instrument. The two detectors are charged in such a way that response to the interference gas in the second detector is compared to that of the measured gas. The signal from this detector is amplified and subtracted from the main detector signal, in the electronic part of the analyzer.

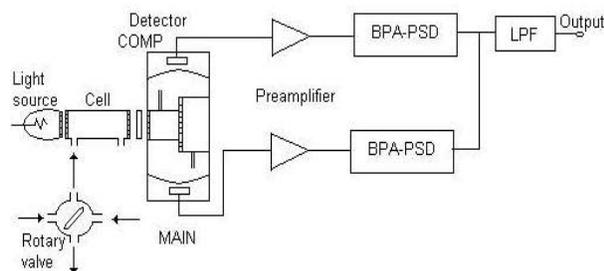


Fig. 1. Bloc diagram of the HORIBA APMA-350E CO monitor.

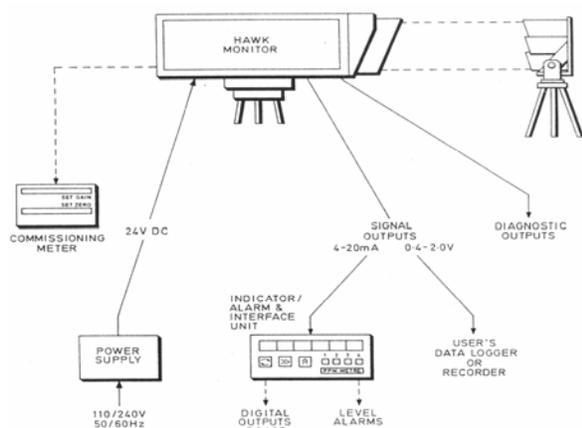


Fig. 2. A schematic diagram of the IR DOAS HAWK instrument.

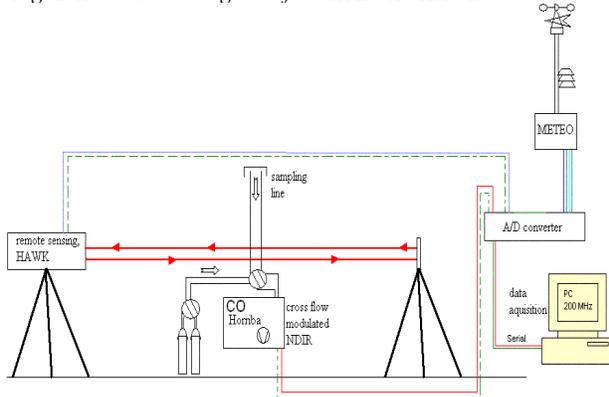


Fig. 3. Measuring setup with the two instruments: SIEMENS-HAWK and HORIBA-APMA 350E

The second utilized instrument was an IR HAWK system from Siemens Environmental Systems, with the schematic diagram presented in Fig.2. This instrument is an IR (infrared) DOAS (Differential Optical Absorption Spectroscopy) apparatus, which can be configured to detect several species of pollutants including carbon monoxide. The beam path can be up to 400m and detection is typically better than 50ppb. The HAWK system works by measuring the absorption of infrared radiation passing along the instrument beam path by the gas to be measured. The system consists of a monitor,

which contains the source and the detector unit, and a reflector. The total path length is therefore twice the distance between monitor and reflector. The source emits over a range of wavelengths and the beam is modulated after generation. The beam is reflected back to the monitor where it is filtered at a wavelength specific to gas of interest. The filtered beam is focused onto a detector which compares filtered and unfiltered reflected light in order to measure the concentration of the target gas.

Open path techniques have an advantage over the point source detectors: the sample volume is much greater, the non-uniformity of the sample is eliminated and a more representative value of the concentration to be measured is obtained. Under field conditions, the degree of mixing is affected by the local environment, primarily, wind and thermal gradients.

Fig. 3 shows a typical relative setup for the HAWK and HORIBA analysers. One should observe also the meteorological mast, which continuously sent data (15 minutes mean values) to the general data acquisition system.

3. Measured and conditioned signals

3.1. The measured signals

The CO-concentration signals were measured with both HAWK open path monitor and the HORIBA point monitor at a sampling period of 6 seconds. This corresponds to a sampling frequency $f_s = 600$ cycles/hour and a maximal (Nyquist) frequency of $f_{max} = 300$ cycles/hour. Each signal contains 4950 samples expressed in $[mg/m^3 N]$ as represented in Fig.4. The total registration length covers 8 hours and 15 minutes. Obviously, both signals have a nonstationary random character.

During the same time interval of more than 8 hours, some meteorological parameters were also measured. Two of them, namely temperature, in $[^{\circ}C]$, and wind velocity, in $[m/s]$, are represented in Fig.5. The direction of the wind were measured and utilized in the determination of the wind component parallel to the optical axis of the HAWK open path monitor as well the component perpendicular to this axis. The two wind components, in $[m/s]$, are also represented in Fig.5. However, the sampling period for the meteorological parameters was 15 minutes, so that each of the meteorological parameters is determined through 33 values. The corresponding sampling frequency of 2 cycles/hour is a good choice for a slowly varying quantity like temperature, but can become critical in a turbulent environment with rapid changing wind direction or intensity. One can appreciate that, in our case, the sampling frequency was great enough for temperature and for wind velocity as well.

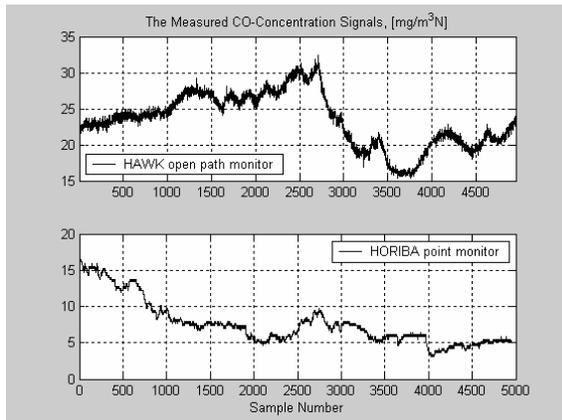


Fig. 4. CO-concentration signals measured with the HAWK open path and the HORIBA point monitor, respectively.

Certainly, in a routine measurement choosing very different sampling frequencies for CO-concentrations and meteorological factors is not justified. In our case, the high sampling frequency of the CO-concentrations allows a characterization of the noise associate with these measurements. On the other side, choosing a higher sampling rate for the slowly varying meteorological parameters could be equivalent with storing a large amount of redundant data.

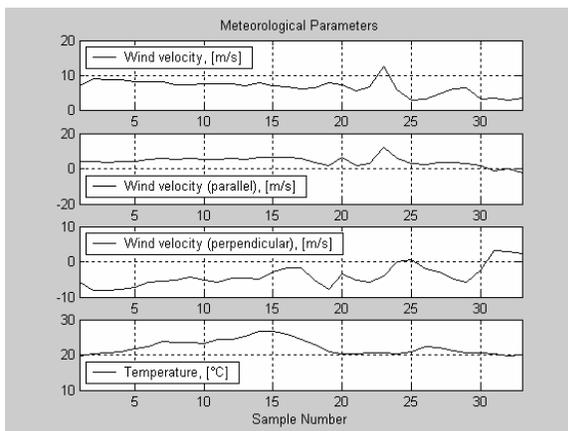


Fig. 5. Meteorological parameters measured with 15 minutes sampling period: wind velocity and temperature.

3.2. Preprocessing of the measured signals

In order to separate the stable local mean value of the CO-concentration from the measurement noise, an ideal low-pass (LP) and high-pass (HP) filtering of the signals were performed. The two components of the signal measured with the HAWK instrument are represented in Fig.6. By “ideal filtering” we mean the infinitely sharp frequency characteristic at the cut-off frequency so that the

sum of the HP and LP components gives exactly the values of the original unfiltered signal.

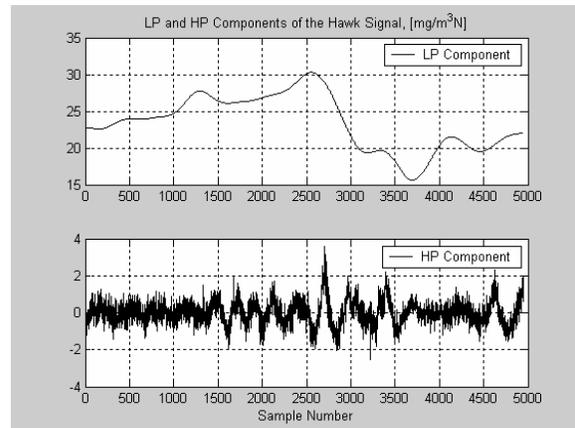


Fig. 6. HP and LP components of the CO-concentration signal measured with the HAWK instrument.

Practically, the ideal filtering was implemented through a direct fast Fourier transform (FFT) followed by a windowing the obtained spectrum with the desired filter characteristic and finally a reverse FFT to obtain the time domain representation of the LP or HP component of the CO-concentration signal.

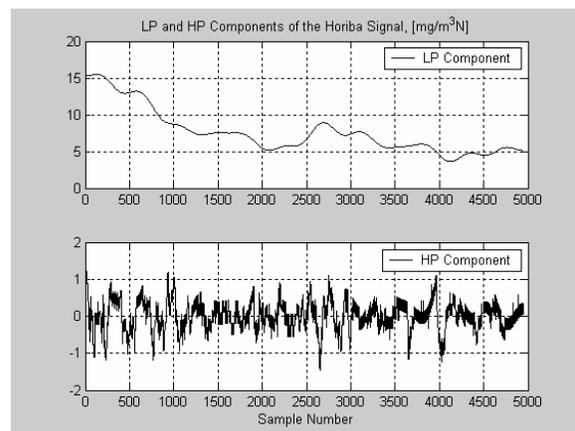


Fig. 7. HP and LP components of the CO-concentration signal measured with the HORIBA instrument.

The cut-off frequency of the LP filter representing also the corner frequency of the HP filter, was empirically chosen to be 2 cycles/ hour. So the LP component contains frequencies between 0 and 2 cycles/hour while the HP component covers the range from 2 cycles/hour to 300 cycles/hour. Similar observations are valid for the LP and HP components of the CO-concentration measured with the HORIBA instrument. These are represented in Fig.7.

Other signal processing techniques, like wavelets or short-time spectra can be used to separate the HP and LP components of the pollution level signals. However ideal filtering based on Fourier transformation is simpler and very efficient.

The power of the measurement noise, calculated as the mean value of the HP components of the CO-concentration proves to be greater in the case of the HAWK instrument, than for the HORIBA device: $P_{HAWK} = 0.4151$ in comparison with $P_{HORIBA} = 0.1455$. This relation can be observed also in the graphical representation of the unfiltered signals, in Fig. 4. Experiments show that measurement noises may introduce an up to 5% error in the determination of the correlation coefficients. This effect could be neglected. However, the separation of LP and HP components of the CO-concentration signals can be a very useful signal conditioning step which allows a simple elimination of possible artifacts in the measured pollution levels.

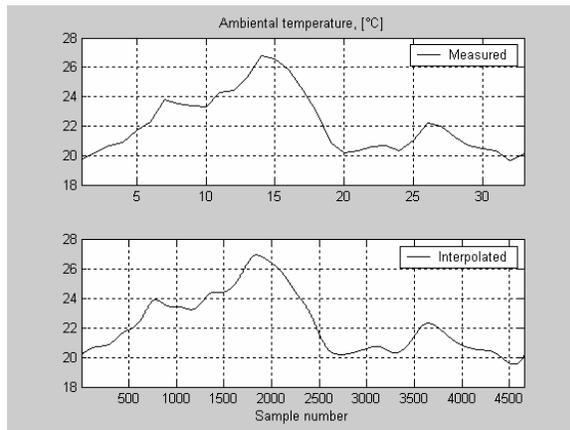


Fig. 8. Ambient temperature: measured and interpolated.

Another pre-processing step is concerning the measured meteorological parameters. In order to calculate the correlation coefficients between CO-concentration signals on one side, and the meteorological parameters on the other, we must have the same number of samples in every signal. Therefore, the temperature and wind velocity signals were interpolated using a cubic spline procedure; the number of samples was increased from 33 to 4950. Due to the great interpolating errors at the beginning and the end of the signals, the first 150 and the last 150 samples of the interpolated signals were rejected. For example, Fig.8 presents the ambient temperature signal in both forms, measured and interpolated. The first and the last 150 samples from the LP components of the CO-concentration signals were also eliminated. Finally, all signals, representing the pollution level, as well as the meteorological factors have the same length: 4650 samples.

4. Correlative analysis

The sample Pearson product-moment correlation coefficient, r , (Papoulis, 1991) was computed for the following signals: LP component of the CO-concentration signal measured with the HAWK instrument (HAW), LP component of the CO-concentration signal measured with the HORIBA device (HOR), the wind velocity (W), the wind velocity component parallel with the optical axis of the HAWK instrument (Wpar), the wind velocity component perpendicular to the optical axis of the HAWK instrument (Wper), and the ambient temperature (T). Table 1 presents the approximate values (with only two decimals) of the correlation coefficients.

In order to facilitate the interpretation, a diagram of the correlation coefficients is represented in Fig.9. One can see a positive but small correlation coefficient between the two CO-concentration signals ($r \cong 0.23$). Related to the maximal possible value ($r \cong 1.00$), this is evaluation of the fact that the two instruments do actually not measure the same quantity. The poor correlation proves the fundamental difference between a local pollution level (measured with HORIBA instrument) and spatial averaged CO-concentrations (from the HAWK system), not only as absolute values but also as variations tendencies.

Table 1. Approximate correlation coefficients.

HAW	HOR	W	Wpar	Wper	T
1.00	0.23	0.45	0.33	-0.40	0.62
0.23	1.00	0.56	0.11	-0.68	-0.09
0.45	0.56	1.00	0.75	-0.73	0.23
0.33	0.11	0.75	1.00	-0.35	0.49
-0.40	-0.68	-0.73	-0.35	1.00	0.15
0.62	-0.09	0.23	0.49	-0.15	1.00

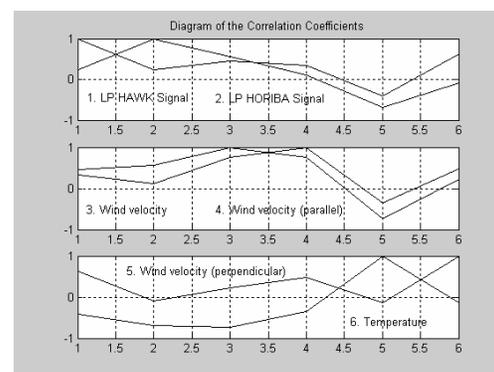


Fig. 9. Graphical representations of correlation coefficients.

The averaged signal measured with the open path remote sensing instrument is strongly positive correlated with the temperature ($r \cong 0.62$), while this meteorological parameter has practically no influence on the local pollution level ($r \cong -0.09$). This can be explained by the intensification of the activities in the non ecological waste deposit by daytime, fact clearly sensed by the open path

instrument but not by the Horiba device which measures the pollution in a certain point, at soil level. The CO-concentrations measured with both instruments are moderate positive correlated to the magnitude of the wind velocity ($r \cong 0.45$ and $r \cong 0.56$ with the HAWK and HORIBA signals respectively). However, the component of the wind velocity perpendicular to the optical axes is negative correlated with both measured pollution levels. Due to the geometrical arrangement of the measuring systems this wind component tends to clean the air. As a global conclusion, the HAWK CO-concentration signal is better correlated with the meteorological parameters than the HORIBA signal.

Table 2. Exact values of the correlation coefficients and their confidence intervals.

HAWK -95%	HAWK	HAWK +95%
1.0000	1.0000	1.0000
0.2039	0.2313	0.2583
0.4260	0.4492	0.4719
0.3085	0.3343	0.3596
-0.4281	-0.4043	-0.3800
0.6006	0.6187	0.6361

The 95% confidence intervals of the correlation coefficients were computed using a procedure based on the Fisher transformation (Shen, 2006). Exact values of the correlation coefficients between HAWK CO-concentration and the other five signal are given in Table 2, together with their confidence intervals. Due to the great number of samples in each signal, the confidence intervals are narrow around the calculated correlation coefficients. Fig.10 gives a graphical image of the narrowness of these intervals.

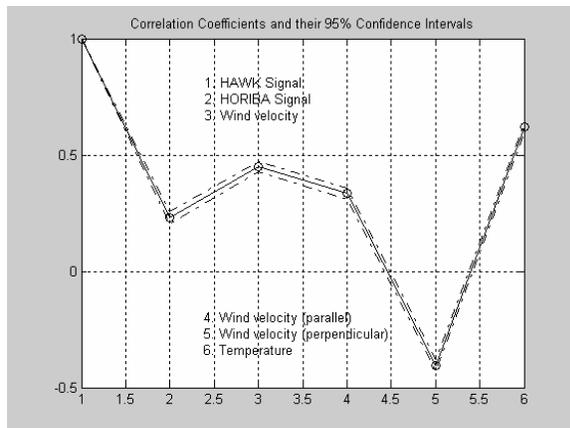


Fig. 10. Correlation coefficients of the HAWK signal (o) and their 95% confidence intervals (-).

5. Conclusions

Two CO-concentration optoelectronic measuring instruments, working on different principles can be compared using a statistical correlative analysis. Ideal

filtering based on fast Fourier transform is an useful preprocessing step allowing a simple rejection of measurement noise and possible artifacts of the pollution level signals. Interpolation can be used to increase the number of samples of the slowly varying meteorological parameters, avoiding redundant measurements.

The correlation coefficient is an useful tool in analyzing the dependencies between the pollution levels and the meteorological factors. The open path remote sensing instrument measures spatial averaged values presenting better correlation to the meteorological parameters. Thus, the open path instrument is better suited for monitoring the pollution level in a large area than the classical NDIR device.

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