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Title: A lightweight broadband cavity-enhanced spectrometer for NO_2 measurement on uncrewed aerial vehicles
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The article by Womack et al. describes the development of a compact, portable, lightweight, and low power field instrument for *in situ* detection of NO_2, based on incoherent broadband cavity-enhanced absorption spectroscopy (IBBCEAS). The spectrometer is based on a high optical power LED at around 457 nm and a standard dispersive spectrometer of medium resolution (0.9 nm), which are used in conjunction with a high finesse 22 cm cavity (R=0.999963). The instrument's weight (3050 g) and power consumption (~35 W) enable its employment on an unmanned aerial vehicle (UAV), in the current case a standard commercial hexacopter with <6 kg payload.
The instrument's technical specifications are characterized in the laboratory in good detail with very few shortcomings. The instrument's applicability and initial performance on a UAV have been demonstrated successfully in this proof-of-principle study in Boulder, CO, for mixing ratios of NO_2 at sub-ppbv levels in vertical measurements at altitudes of up to 110 m. Based on the instrument's 1σ (laboratory-)precision of 43 pptv of NO_2 for an integration time of 1 s, and the stated accuracy of ~4.5%, it will be a very useful tool for airborne and other highly flexible monitoring of NO_2 and potentially other atmospheric species in the future.
The miniaturization of ultra-sensitive cavity enhanced absorption spectrometers (like this IBBCEAS device) enables the deployment on all sorts of highly mobile platforms, not only copter drones like in the current case. Conventional ground-based monitoring networks that typically use established standards, such a chemiluminescence detection for NO_2, are static and do not provide the spatial resolution required to characterize sources and/or sinks in a way that allows the advancement or validation of existing atmospheric chemistry mechanism or transport models. Innovative developments of the kind outlined by Womack et al. will clearly help to advance trace gas monitoring efforts and the investigation of the lower planetary boundary, whose spatial and temporal complexity requires the most sensitive and flexible technology to tackle current scientific questions. As far as I am aware this is the first report of an IBBCEAS instrument being employed on a drone. The merit of this innovation is that, in contrast to other alternative techniques like the more compact, lighter, and cheaper wet chemical sensors, IBBCEAS is capable of delivering reliable NO_2 mixing ratios at most typical atmospheric scenarios. However, subsequent campaigns will be necessary to further investigate the robustness and environmental adaptability of the new instrument - further characterization of its capabilities in the context of field monitoring is thus desirable.

In my opinion this article is basically publishable in its present form, subject to some small technical revision and some clarifications as follows:

(1) The way the spectrometer was mounted to the UAV should be explained in more detail in section 4 or in section 2.6. Only a mounting kit is mentioned. Especially the position of the inlet with respect to the rotors is of interest here. In line 104 it is merely stated that a quarter inch Teflon line extended directly above the UAV. In section 2.5 more detail on the mechanical system should be given, or put into an appendix or supplementary material.

The information in lines 236-241 cannot be put into perspective with more detail on the position of the inlet.

(2) An argument should be made in Line 104 why mirror purges are unnecessary in this case. Without mirror purges the area of applications of this compact spectrometer will be somewhat limited to not heavily polluted areas, which should be mentioned.

(3) A few more details should be given on the fitting procedure of the spectra. If this has been published earlier, then a reference should be included here. The items of interest are (i) the correlation of the fit parameters in the Levenberg-Marquardt approach, which can be an issue in comparison to other analysis methods, (ii) the dependence of the results and their error on the fit range, and (iii) the choice and justification of the wavelength-dependent weighting factors mentioned in the text. How were these factors chosen, what criteria were applied?

(4) The error estimation in section 5.1 is not very conservative and has gaps. Nonetheless the overall accuracy is stated as 4.5% in the summary and Table 1. I recommend to be a bit more cautious here. I have my doubts that the instrument will really live up to this accuracy in field campaigns.

Minor suggestions and comments:

Line 15: … has a power consumption of less …

Line 83: The authors state a temperature of 22.5±0.05 °C. The number of significant figures is inconsistent here. How was this temperature accuracy established?

Line 84: Acronym TEC = ThermoElectric Cooler?

Line 131/132: It would be good to also state the information given in form of a duty cycle time.

Line 147: "…38 min minus (3.6 min kg^{-1} × payload mass)" may be nicer expressed in form of a proper equation.

Line 169: What is a typical time for the zero air calibration measurements?

Line 180: The number of publication of the NO_2 cross-section is large. What is the reason for using the values by Vandaele et al. (1998) in this case?

Line 224: Where is the optical extinction shown in Figure 3?

Line 230: "…0-120 m…" Figure 4 only shows 0-110 m. If data are available for only up to 110 m altitude, then this should be corrected; also in the abstract and throughout the text where 120 m are stated.

Line 236: "… have been completed by McKinney et al. 2019". Include the reference here directly in the text.

Line 246: "The mACES inlet was located vertically above the UAV, in the region that is modeled to have approximately laminar flow." This should be shown – see also item (1) above. More detail required here.

Line 251: "The measurement precision of 43 ppt NO_2 in 1 s suggests that the observed variability within the vertical profile represents real NO_2 variation,…". I agree that the precision of 43 pptv would suggests that, however, it is not quite clear how meaningful this measurement is. On the descent (blue trace in Fig. 4) the data points represent averages over a vertical distance of 0.5 m. On the ascent (red trace) it is not quite clear how the measurement were performed in between altitude steps of 10 m (see also paragraph starting Line 196 ff.). Please discuss in some more detail

Comment: The hovering at 10 m intervals and estimating the error as given by the error bars in Figure 4 is meaningful appear the most meaningful.

Tables 1: precision → Precision (1 sigma)
Figure 1: (b) - Acronym MFM is not defined. (c) & (d) - The size scale of the instrument cannot be made out appropriately.
Figure 3 caption: "…of fitted NO_2…   . … of fitted NO_2" is too casual. Please rephrase.
Throughout the manuscript (incl. Figures) mixing ratios should be stated parts per number by volume: ppm → ppmv, ppb → ppbv etc.
Figure 4: The measurement conditions on the descent (continuous at constant speed) should also be stated in the figure caption.