Comment on amt-2022-236

Anonymous Referee #1
Referee comment on "Drone-based meteorological observations up to the tropopause" by Konrad Benedikt Bärfuss et al., Atmos. Meas. Tech. Discuss.,
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The Authors would like to thank the referee for taking the time to review our work – which is highly appreciated in such busy times.

The manuscript "Drone-based meteorological observations up to the tropopause" by Konrad Bärfuss, Holger Schmithüsen, and Astrid Lampert, presents the development and first results of an uncrewed aircraft system (UAS)capable of sounding the atmosphere up to 10 km. This is an outstanding achievement and can have a major impact on improving in-situ atmospheric measurements for a future use in the operational network of a met service. The content gives a valuable contribution to the community, however some major changes have to be implemented before publication. I am going to explain why below:

Thank you for your appreciating general comment.

General comment:
The manuscripts present the use and first deployment of a novel UAS for atmospheric sounding up to 10 km. The airborne platform is introduced and discussed, including the design envelope of the aircraft.

This is the main goal of the article, and we now emphasize more this purpose.

Measuring up to 10 km is challenging as the sensors have to handle and withstand a wide range of environmental conditions. The authors explained this in much detail in Section 2.2 in their manuscript. The sensor package is mentioned, but a proper sensor introduction, or the methodology of wind measurement including an adequate error discussion, is missing. However, due to the harsh conditions the sensors are exposed to, a detailed discussion is essential. The authors give some information in the caption of Table 1. Still, it remains unclear what is the temporal, thus the spatial or vertical resolution of the sensors or the absolute uncertainty depending on the flight trajectory or how well the sensors perform in e.g. very low temperatures, high humid conditions etc. Also, the methodology of the wind estimation remains unclear. Although the author claims that calibration and removal of installation errors are an own branch of science, validating the LUCA system with commonly used systems such as a met tower or a validation in a climate chamber is required. The authors show a comparison with radiosondes, but due to a time differences of several hours between the radiosonde and the aircraft measurement, the comparison remains insufficient and shows large deviations.

We agree with you, that presenting a validated measurement system would need a detailed introduction into sensors, sensor placement, data processing and validation techniques. Within the presented work, the ability of carrying sensors up to the tropopause on board small UAS is the key content. Besides, we show low-quality measurements to demonstrate what the system is intended for.
Similar sensor packages have been deployed on other UAS and validated with well-established methods in the atmospheric boundary layer.

Based on your comment, we added more information on the simplistic sensor setup as well as the postprocessing algorithms including wind vector retrieval and humidity sensor handling. Furthermore, we included a new subsection within "Results" and intercompare data (LUCA vs radiosonde) as a case study "deploying a simple sensor setup" in the similar way data quality is assessed in Wagner and Petersen, 2021 [1].

However, the focus of the article is to present the platform as a re-usable carrier for measurements in the entire troposphere.

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Specific comments:
4: What do you mean by environment friendly additional data?

Compared to the environmental impact of radiosondes (waste not collected, but left in the environment) as well as aircraft powered by fossil energy (increasing the atmospheric carbon dioxide), the data is gathered in an environmentally friendly way using the UAS LUCA, that is without emitting greenhouse gases and without leaving waste in the environment.

84: Usually UAS stands for uncrewed aircraft system

Indeed, we altered the abbreviation by mistake.

102: Authors could add this citation:
Jensen, Anders A., et al. "Assimilation of a coordinated fleet of uncrewed aircraft system observations in complex terrain: Observing System Experiments."
Monthly Weather Review 150.10 (2022): 2737-2763.

Thank you for the suggestion, we implemented the reference in the revised version.

165: Does this also account for take-off and landing?

Yes, there is no need for a lower limit than 28 m/s during take-off and landing. We clarified this, and stated that operators have to be aware of wind gusts which could affect the UAS during these mission phases. Crucial for operations under such conditions is the automatic alignment with the main wind direction, based on the real-time measurement data.

203: Is 13:00 UTC or local time. Does LUCA have a real-time downlink and can provide data during the flight at 12 UTC? This is not clear here.

All times in the manuscript are provided in UTC, which is local time minus 2 h in the presented cases, we added “UTC” in the text.
Indeed this depends on the data link and possibly reserved frequency bands. The system is able to link down real-time data, but as temperature and humidity measurements are quality checked and processed using post-priori information, the data is not available in real time up to now. However, the wind speed and wind direction is available at a frequency of up to 100 Hz, which is crucial for surveying the mission. In case of high wind speed exceeding the aircraft limitations, the mission is abandoned. The wind direction is of high importance for the landing phase, as the aircraft trajectory is oriented against the wind direction for landing.

Section 2.2: A clearer description of the aircraft system is missing. What kind of engine, autopilot, C&C link etc. is used ?

Some more information on technical details is provided. For a more detailed overview of the technical questions regarding the system, the reader is referred to Bärfuss et al., 2022 [2], as the technical implementation is not the focus of this study.

Section 2.2: Why does the aircraft not perform a normal landing with a flare? Common open-source autopilots such as the one used in LUCA can handle this.

These technical questions regarding the system are now addressed in Bärfuss et al., 2022 [2] and are not in focus for this study. However, we added a short note that in case of high near-surface wind speed, as occurs frequently in the Antarctic, the system would be blown away and cannot be found in low visibility conditions of drifting and blowing snow. Besides the harsh surface in the Antarctic, a soft belly landing with a flare would require a reliable altimeter, working in conditions such as snow drift, and would increase system weight and cost.

Section 2.3 How is the measured data stored?

The data is stored directly in the autopilot system.

218: ‘closed sensing path’. An illustration or a picture of the sensor system would be very helpful. What is the mass flow around the sensor?

In the revised version we provide an illustration. The flow speed around the sensor is around 5 m/s (see Bärfuss et. al., 2018 [3]).

219: For what errors are they corrected?

The data is corrected for dynamic sensor response – in the case of the humidity sensor including a variable “time constant” of the assumed (simplified) underlying transfer function G(s)=1/(1+Ts). The basic method using a constant “time constant” is explained in detail in Bärfuss et al., 2018 [3], which is now referred to in the revised manuscript.

221: How does the flight trajectory of a mission look like? The authors should show the flight trajectory at least of one flight mission.

A good idea! We now included the flight trajectory of a mission.

221: What do you mean by heading output? How is the horizontal wind, using the heading information, calculated? Please explain the method of your wind estimation in detail and please elaborate on:

- How does the flight trajectory impact the wind estimation, and how does this effect the measurement error?
- How does the wind speed influence the wind speed uncertainty?
- Is the wind measured during turns or during the ascent or descent in straight flight?
- During which trajectories is the wind estimation bad?
- What is the overall error of the wind estimation, and how do you calculate it?

The calculation of the wind speed is now mentioned briefly:
The wind is calculated similar to the wind estimation of AMDAR/TAMDAR – as a difference between the inertial trajectory vector and the wind vector. Similar simplifications as for (T)AMDAR are applied and consist of:
- Zero angle of sideslip
- Zero vertical wind
In the AMDAR/TAMDAR wind retrieval, measurements during bank of more than 5 degrees are excluded. For UAS flying at much lower air speed (one order of magnitude lower airspeed), the sensitivity of angular errors are no that crucial, as all three vectors (wind, airspeed, ground speed) are on the same order of magnitude (note that airliners operate at higher airspeed and therefore the vector difference of two large vectors is more sensitive to angular errors).
The flight trajectory has an impact mainly on two measurements: Heading (as calculated within the inertial navigation system) and sideslip angle. Both have an impact on the resulting vector difference and are heavily system-dependent. Elaborating the quantity of the error would require system identification of the aircraft and INS-filter simulations – both are regarded as an inadequate effort with respect to the main statement of the article (“small UAS are capable of sounding the complete troposphere”). Qualitative considerations instead should be implemented along with a description of the wind calculation.
In stationary flight just after dynamics (to feed the INS algorithm to compute a useful heading - on straight legs, the heading usually is tied more or less slowly towards the vector over ground), the wind estimation is expected to perform best. Spiralling might be regarded as a quasi-stationary flight state, but still provides dynamic input to the INS filter. In increasing wind speed, the spiral is deformed into a short-time curved and a long-time straight trajectory. This might lead to reduced absolute quality of the wind vector components in high wind speed, but stable relative quality.

Up to now, we do not calculate the wind error in flight and rather estimate/observe the error during intercomparison/assimilation. We included the method for the wind estimation in the manuscript and added an assessment of the wind error within the section “Results”.

224: In addition, magnetic vector measurements to be fused in the attitude estimation might be deteriorated. Is the magnetic sensor fused or not?

The magnetic sensor is fused – but as you mention, one has to be careful using it. While the distortion can be eliminated to some extent, we rather use information from the magnetic sensor during the descent, where the generated electromagnetic fields through the power train (including cables) are minimal.

225: How can a camera be a reliable ice detector? Please explain in more detail.

The phrase is written misleading. The camera is not an ice detector, but a physical replacement for the cut out in the wing, which is usually used for the ice detector. The cut out is foreseen for the sensor, but other instruments can be fitted into it.

Table 1: A real discussion of the sensor error in the text is missing. The authors give some information in the caption of Table 1, however this is hard to follow and mainly cites further publications using similar sensor but on different platforms. It remains unclear what is the temporal, thus the spatial or vertical resolution of the sensors during the ascent and descent, the absolute uncertainty depending on the flight trajectory and the relative error (see also my comment for line 221). Although the author claim that calibration and removal of installation errors are an own branch of science, at least a comparison of the LUCA system with commonly used systems such as a met tower should be performed to enable a real sensor error estimation or a validation in a climate chamber. Also, it is not clear what is meant by calibration and removal of installation errors.

The focus of the article is on the development of the platform and the technical achievement, and not a detailed discussion of the sensor error. Nevertheless, we included an assessment of the data quality as part of a case study "Assessment of data quality using a simplistic sensor setup on the platform LUCA" within the results section.

257: '... which equals the minimum horizontal component of the true airspeed during the ascent.' Why minimum?

As the dynamic pressure to stay airborne limits the true airspeed at higher altitudes (due to the decreasing air density), the horizontal component of the true airspeed is higher at the ceiling than close to the ground. Therefore we used the wording "minimum" to state that we never fly at a lower horizontal airspeed component during the mission – which subsequently gives us the wind resistance up to this true airspeed.

265 ff: Part of this has been mentioned also earlier in the text. I would recommend skipping this and refer at an earlier stage to the aerospace journal, e.g., in Section 2.2.

Thank you for recommending so – we agree that we should clarify this point at an earlier stage ad should not double information at this point.

261: Where did the flight take place? An overview of all analysed flights described in this study should be presented.

That is a good hint; we implemented more information on the flights.

283: The word simultaneous is misleading, as even the authors claim that there is a time gap up to three hours between the flights and the radio sonde ascent.

Thank you for the hint. We will make reference to a study, where TAMDAR data was compared to radiosoundings and apply the metrics therein to determine whether the spatiotemporal gap is low enough to compare data [1]. The flight with a time difference of three hours is not used for intercomparison.

294 and 301: Plots in Fig. 5 are too small to identify the ABL structure and follow the explanation in this paragraph. I would suggest increasing the resolution at least for the lower part of the atmosphere.

As the study does not focus on the ABL in contrast to most previous UAS measurements, we choose the standard representation for radiosonde data – although the ABL structure cannot be identified by this plot type.

305: 'multiple times' What is the frequency? See also comment for Table 1.
Thank you for the hint – we implemented information about how turbulence can be represented independent of the measurement frequency (Eddy Dissipation Rate) and added the current measurement frequency.

Fig 6. Part of the caption belong to the Section. It is not clear what is meant by 'on decomposing the time signal in sinusoids with differing frequencies (cycles per day), and higher harmonics (natural products of the fundamental frequency) reveal the non-sinusoidal waveform of the diurnal cycle' A more detailed explanation should be already implemented in the Method Section of the study. Also, it remains somehow unclear to me, what the benefit of Section 3.3 in relation to LUCA is. For instance, the sentence ‘Interestingly, temperature variability at a cycle of 6 per day is low below 5 km altitude, pronouncing the importance of profiling the atmosphere to higher altitudes’, which only appears in the caption of Fig. 6 should be stressed more in the text.

The benefit of the section is the representation of the intensity of changes within the atmosphere on diurnal timescales. We added more information about the decomposition/transformation of the atmospheric variables from time- into frequency-domain and moved the subsection into discussion/outlook.

350: Minor drawbacks in the measurements occurred as expected due to the simple sensor setup. What are these? This is not clearly described in the previous Sections.

We included more information on the drawbacks such as heat transfer from the fuselage.

354ff: ‘Using a more sophisticated measurement package, standard radiosonde accuracy is expected to be reached or even surpassed. By design, the UAS technology bears the pivotal advantage of re-using sensors and the possibility of pre- and post-flight calibration....’ This is very speculative and should be addressed as an outlook.

We agree with the author, and put the statement into the outlook.

367: I disagree with this to claim a camera a ‘dedicated sensor’ (see also comment above)

The sentence is indeed misleading, so we changed it.

Technical comments:
2: In the ABL, above the oceans and in polar regions
146: ... the UAS of type LUCA

We implemented these comments in the revised version.

Thank you for the attentive reading and your valuable comments which enabled us to further improve the manuscript!

[1] Wagner, T. J., & Petersen, R. A. (2021). On the Performance of Airborne Meteorological Observations against Other In Situ Measurements, Journal of Atmospheric and Oceanic Technology, 38(6), 1217-1230. Retrieved Jan 10, 2023, from https://journals.ametsoc.org/view/journals/atot/38/6/JTECH-D-20-0182.1.xml

[2] Bärfuss K, Dirksen R, Schmithüsen H, Bretschneider L, Pätzold F, Bollmann S, Panten P, Rausch T, Lampert A. Drone-Based Atmospheric Soundings Up to an Altitude of 10 km-Technical Approach towards Operations. Drones. 2022; 6(12):404. https://doi.org/10.3390/drones6120404

[3] Bärfuss K, Pätzold F, Altstädter B, Kathe E, Nowak S, Bretschneider L, Bestmann U, Lampert A. New Setup of the UAS ALADINA for Measuring Boundary Layer Properties, Atmospheric Particles and Solar Radiation. Atmosphere. 2018; 9(1):28. https://doi.org/10.3390/atmos9010028