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Review of the manuscript „The TropoPause Composition TOwed Sensor Shuttle (TPC-TOSS): A new airborne dual platform approach for atmospheric composition measurements at the tropopause“

by Bozem et al.

Reply to referee #2

We appreciate the kind words on our manuscript and thank the referee for the constructive comments and proposed suggestions which helped to improve the manuscript. We will answer to all comments of referee #02 below point by point. Referee comments are given in standard, answers in red, and changes to the manuscript in blue font.

The article presents a very interesting new platform for airborne measurements at the tropopause altitude range. It is well-written, and fully fits in the range of the journal AMT. In my opinion it can be published after some minor revisions. Suggestions for improvement and small typos are specified below.

Suggestions for improvement:

- I would suggest to introduce the method earlier, e.g. the first figure should be a sketch of how it works, with the Lear Jet, the rope and the payload. In my opinion it takes too long for the reader to get a first impression in Fig. 3/ on page 8. This should also include a clear statement if there is only a mechanical connection, or also power supply

  Following this suggestion, we added Fig. 1b showing a schematic of the concept of the dual platform approach and extended the caption of Fig. 1 as follows:

  (b) Schematic of the concept of the dual platform approach with TPC-TOSS attached to the Learjet aircraft with a steel wire rope allowing for simultaneous measurements at two levels. Colors in the background represent an arbitrary air mass property changing from low to high values at the tropopause. This property can be measured simultaneously by the two platforms. Modified from Emig et al. (2025).

  Furthermore, we added the following sentence in Sect. 1: The TPC-TOSS was attached to the aircraft via a purely mechanical connection using a steel wire rope.

- Please state on the swinging behaviour of the system, e.g. show statistics on pitch/roll/yaw angles during one flight, mention critical situations, describe more in detail how the tethered system is handled, e.g. with a winch. There is some information in the summary (900 m behind, 200 m lateral) – how constant is this?

The TPC-TOSS is flying quite stable during undisturbed flight conditions (without turns and altitude changes). During these conditions the following statistics are given as mean values and standard deviation over flight F10 (see figure below):

- Altitude difference between Learjet and TPC-TOSS: 152.3 +- 8.3 m
- Pitch angle: -0.02 +- 0.60 °
- Roll angle: -2.52 +- 2.35 °
- Horizontal distance between Learjet and TPC-TOSS: 877.2 +- 3.1 m
- Lateral distance between Learjet and TPC-TOSS: 88.7 +- 8.2 m

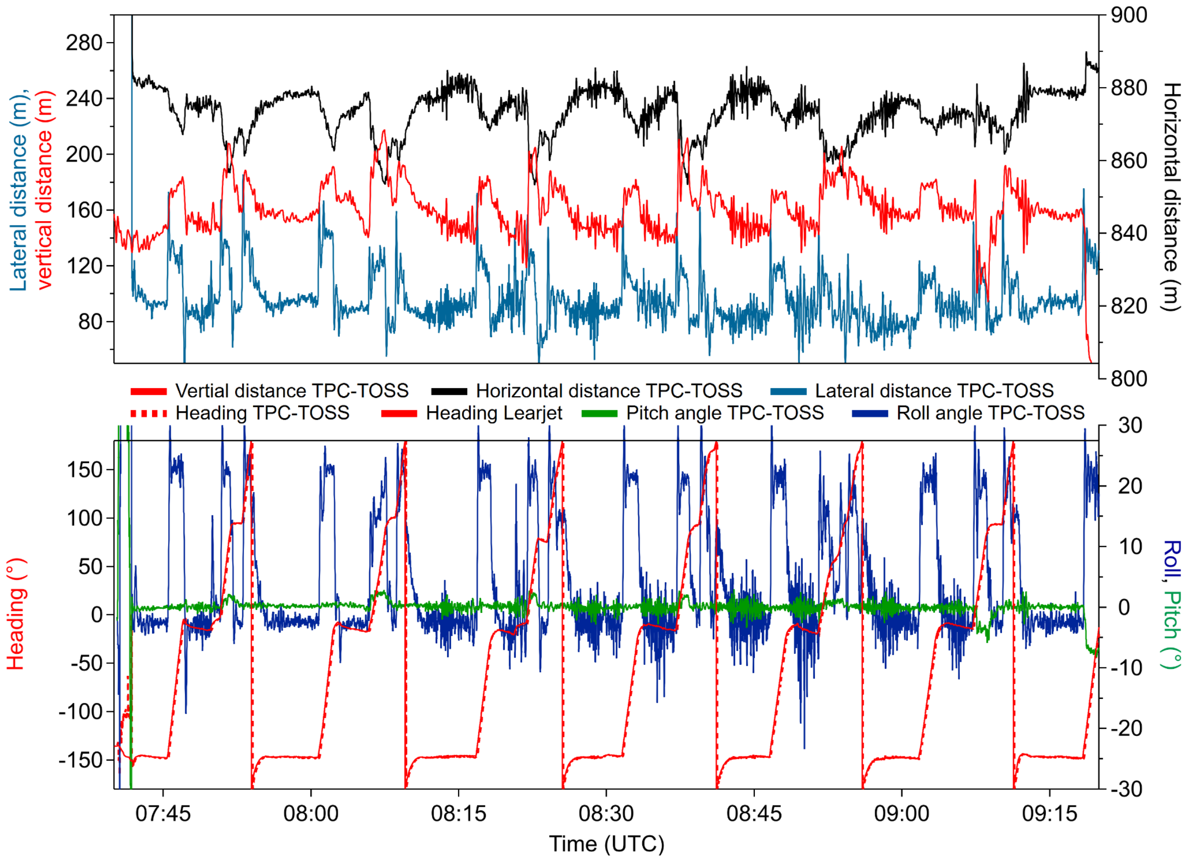

Figure 1: Time series of different attitude and position parameters during research flight F10 on 20 June 2024 during TPEX I. The upper panel shows relative positions of the TPC-TOSS to the Learjet. The lower panel shows heading (red), roll (blue) and pitch (green) angles of TPC-TOSS and Learjet (only heading) during the flight.

Deviations from these undisturbed flight conditions occur during altitude changes and turns. Altitude changes of Learjet and TPC-TOSS are indicated by a higher pitch angle during climb or a lower pitch angle during descent in Fig 1., turns are indicated by a change in the Learjet and TPC-TOSS heading. These are accompanied by significantly higher roll angles of the TPC-TOSS following the turn until it is in stable flight mode after a few seconds. For the particular flight larger variations in the roll angle along part of the horizontal flight sections are visible. These are mainly caused by turbulence occurrence during the flight. Notably, none of these deviations from undisturbed flight conditions significantly affect trace gas and aerosol measurements as discussed in Fig 14 in the preprint.

Critical situations during the flight in general arise from turns as these add additional force to the rope and too sharp turns might lead to a rupture in the wire rope.

To further analyse the oscillating behaviour of the TPC-TOSS we performed frequency analysis of the attitude parameters of TPC-TOSS but could not identify regular oscillations in these parameters. There are some flight intervals for which the frequency analyses indicate oscillations with a period of around 20 s of unspecific origins. However, measurements were not affected by these oscillations.

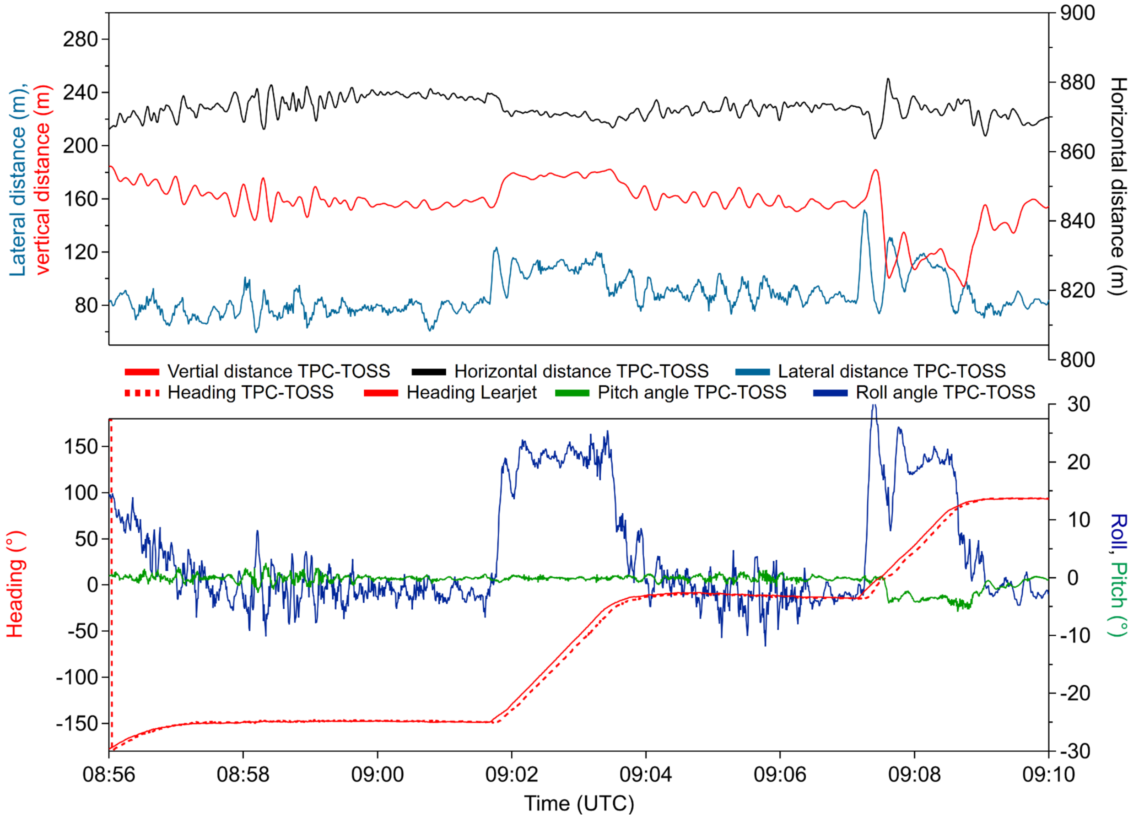

Figure 2: Same as Fig. 1 with a zoom on a specific time interval.

With respect to the handling of the towed sensor shuttle we added the following paragraph in Sect. 3:

The TPC-TOSS is attached to a winch under the right aircraft wing that is equipped with a steel wire of a maximum length up to 4 km. The pilots operate the winch to release the drag body to the desired wire length and retract it after the measurements. For certification reasons the operation of the winch is only allowed below 25000 ft (7.6 km) while the maximum flight altitude with the TPC-TOSS deployed is 41000 ft (12.5 km). During the TPEX I flights with the TPC-TOSS a wire length of 3000 ft (914 m) was used. The main reason for not using a longer wire length was the military controlled restricted air space with a maximum side length of 50-80 km in which we were only allowed to fly with TPC-TOSS due to safety constraints. The small area resulted in multiple turns during aircraft operation. Based on the experience from earlier campaigns in the same airspace, the chosen wire length was a compromise between a maximum reachable vertical distance between Learjet and TPC-TOSS and safe and feasible Learjet operation (Klingebiel et al. (2017, and references therein). With this wire length a vertical distance between Learjet and TPC-TOSS of 152 ± 8 m was reached during stable flight conditions (no turns or climbs/descents). The maximum range of vertical distance was between 95 m and 220 m including turns and altitude changes. Further details on the relative position of TPC-TOSS and Learjet are discussed in Sect. 5.1.

And we added the following sentences to Sect. 5.1:

Line 437 ff.: Due to the limited operational area, the wire rope length was set to 914 m as mentioned in Sect. 3. This resulted in a horizontal distance between TPC-TOSS and Learjet of 877 +- 3 m on average during undisturbed flight conditions (no turns and no climb or descent). The resulting vertical distance was on average 152 +- 8 m.

Line 444 ff.: The lateral distance between TPC-TOSS and Learjet was on average 89 +- 8 m based on flight F10.

- There are different informations about altitude, e.g. in the intro it says 6-12 km. This is a contradiction to l. 69, studying vertical transport form the PBL into the UTLS. Then in l 84 it states that the maximum altitude with the TPC-TOSS was only 9700 m.

  We corrected inconsistent altitude information given in the paper. In general, during the TPEx I mission 8 scientific measurement flights were performed. During 4 out of these 8 flights the TPC-TOSS was deployed. It is important to note that the Learjet allows for a high flexibility for operating the TPC-TOSS or not. The drag body including the winch system can be removed between flights. Depending on scientific questions for a specific research flight the winch system including TPC-TOSS was attached to the aircraft or not. Therefore, half of the scientific flights were flown without the TPC TOSS and the others with the dual platform. For the flights without the TPC-TOSS, we probed the atmosphere from ground levels up to an altitude of 12 km and with the TPC-TOSS deployed we covered altitudes between 6.4 and 10.9 km.

- Different informations about aerosol sizes: 95 nm-1 µm in l. 77

  The information given in line 77 refers to the size range of the UHSAS instruments operated on both platforms, Learjet and TPC-TOSS. The optical particle counter measuring up to 3 µm was only operated on the Learjet.

- Please motivate more in detail the 200 m rope length. Was this a choice based on technical constraints or scientific scales? In both cases please explain more in depth. L. 343 states that the rope was only 200 ft – is this flexible? Can it be chosen for each flight?

  To derive gradients of trace species, aerosol and meteorological parameters, we equipped the Learjet and the TPC-TOSS partly with similar instruments for which we did intercomparison measurements in the lab and in between research flights on the ground as discussed in Sect. 4. To have an in-flight comparison of the redundant instrumentation on TPC-TOSS and Learjet we aimed for a part of the flight with a minimum distance between TPC-TOSS and Learjet. For safety reasons, the TPC-TOSS is switched off while attached to the aircraft and the winch system. During release of the TPC-TOSS it takes a few minutes until all instruments are working properly and thus the distance between Learjet and TPC-TOSS is already large. On research flight F10 we took the opportunity to stop retracting the TPC-TOSS at a minimum safe distance to fly for four minutes in that configuration. This minimum safe distance corresponded to a wire length of 200 ft (61 m) which in turn resulted in a vertical distance of 43 m and allowed for a quasi colocated performance test of the instrumentation as described in Sect. 4.4.5.

  In general, the rope length is flexible between the minimum length allowed to safely operate the aircraft and the maximum length of 4 km. As discussed in the additional and new paragraph in section 3 the rope length of 914 m during the research flights was a compromise between a maximum reachable vertical distance between Learjet and TPC-TOSS and feasible operation of the dual platform configuration in the small, restricted air spaces. In addition, operating the winch is only allowed below 25000 ft so that the length of the rope is once set at the beginning of the research flight and cannot be changed during TPC-TOSS operation at higher altitudes. For all flights with TPC-TOSS deployed we kept the rope length at 914 m.

- If relevant, please explain quickly the Mission Support System, or omit.

The Mission Support System (MSS) is an important tool for detailed flight planning, in particular for flights with TPC-TOSS deployed. We extended the section on MSS as follows:

For operational planning of the flights we used the Mission Support System (MSS, Bauer et al. (2022)) with meteorological and chemical data from ECMWF from the IFS and CAMS forecast models. MSS as a server client application allows to interactively plan flight trajectories based on current four dimensional forecast data. Additionally, we used high resolution data from the ICON-D2 for forecasts of convection as well as from ICON for WCB forecasts.

- Please include technical details on temperature management. The aerosol sensors are for sure temperature stabilized? How cold does it get in the TPC-TOSS without heating, how much heating power is applied? Is it actively controlled depending on measured inside temperatures? L. 231 only mentions that the system is thermally isolated

For the TPC-TOSS there is no active temperature management of the drag body itself or any instrument inside due to limitations in available power from the battery pack. Instruments and the drag body are only heated from the heat the instruments produce during operation which in turn results in a higher temperature within the drag body in comparison to environmental temperatures outside. We did not measure the temperature of the drag body volume itself but had temperature measurements inside the ozone instrumentation for example. Based on former measurement campaigns minimum temperatures inside the drag body reached -20 to -25 °C at the time instruments were switched on. The ozone instrument was certified to operate only above -20°C, all other instruments and components are certified for lower temperatures. Therefore we installed BASOTECT foam around the ozone instrument for a passive insulation to reduce the cooling rate of the instrument during the flight time before switching on the TPC-TOSS when all instrumentation inside the TPC-TOSS had to be switched off. Details on the temperature evolution of the ozone instrument are discussed in Sect. 4.4.3.

- 150/151: the uncertainty is 1.25 and 2 m. Is this good enough? Please comment.

The uncertainty of 1.25 m (horizontal position) and 2 m (vertical position) for the determination of the position based on the GNSS/INS instrumentation resulted in relative errors of 0.1 % (horizontal) and 1.3 % (vertical) taking into account the average horizontal and vertical relative distance between Learjet and TPC-TOSS. The error of the position is included in the uncertainty of the gradients discussed in Fig. 16 (shaded region for the respective parameter) by applying Gaussian error propagation. Since relative errors of the position are in the same order of magnitude or even smaller than instrument uncertainties for the respective parameters this uncertainty allows to determine ozone or temperature gradients of a few 100 ppbv / km.

- 167/168: what is the temporal resolution of the humicap in the UTLS? A few minutes would be too much for the scientific questions, I suppose? Why not complement with an optical hygrometer?

  Thank you for bringing up this point. The data output frequency of the humicap as part of the ICH sensor regularly operated within the IAGOS framework since 2011 is 1 Hz. However, the response time of the humidity measurement of 1 s (altitude region 0-3 km) is reduced to 15 s (altitude region 3-6 km) and up to 180 s (altitude region 6-12 km) based on Rolf et. al. 2024 (and references therein). During TPEX I, in the Learjet cabin, the FISH instrument was operated serving as a reference instrument for humidity measurements in particular in the UTLS as shown during previous campaigns (DENCHAR, AIRTOSS I + II) with the Learjet (Rolf et al., 2024). Based on humidity intercomparisons during these campaigns the agreement between FISH and the ICH sensor is 9 % for water vapor concentrations in the range 30-300 ppmv and better in the range 300-1000 ppmv. It will of course depend on the scientific question in which way the humidity data from the ICH sensor can be used. While small scale fluctuations of humidity in the UTLS might not be resolved with the ICH data, a valuable insight in the water vapor distribution in the UTLS using the two-platform approach is still possible but outside the scope of this paper.

  For the TPC-TOSS measurements an additional humidity instrument would of course be beneficial but almost impossible to realize due to limitations in space and weight.

- In general, how do you address the issue of response time? What corrections are applied? Maybe compare to the correction methods applied in Bärfuss et al., 2023 (https://amt.copernicus.org/articles/16/3739/2023/amt-16-3739-2023.html), who performed temperature and humidity measurements up to 10 km altitude based on a drone

  There are no corrections applied to the humidity data of the ICH sensor with respect to the response time. The aforementioned increased response time of ICH humidity with decreased temperature/altitude was derived for the data quality assurance of ICH operation during MOZAIC and IAGOS by Neis et al. (2015), who applied an exponential moving average (EMA) to the reference data from the Fast In-situ Stratospheric Hygrometer (FISH), which was measuring in parallel to the ICH sensor on earlier Learjet field campaigns. As noted in the reply to the last comment, the ICH sensors are a compromise made to observe the horizontal distribution of humidity at stable flight levels and possibly the vertical difference in water vapour concentration/humidity between two platforms. The small-scale fluctuations of humidity, especially during the ascent and descent legs, if necessary, might be seen in ICH by trying numerically deconvolution of the measured signal based on the response time, which is beyond the scope of this paper.

- Explain colours of figures only in captions, do not use in text, e.g. l. 297-299, 330, 346, 413

  Thank you for the hint. We changed it accordingly.

- 7: were temperature corrections applied, similar to Bärfuss et al.? If yes, please explain method in text. If not, why? What error does this imply?

  The time lag of Pt1000 clarified in Bärfuss et al. (2023) is an interesting point. After careful consideration, we don't think it has a big impact on the temperature readings of the Pt100 (1 Hz) and therefore, a similar spectral correction was not applied here given the scope of the TPEx I campaign and the application cases of the ICH sensors. However, the adiabatic heating in the Rosemount inlet housing, which causes a substantial temperature increase by about 30°C subjected to aircraft Mach number compared to ambient temperature, is corrected. Similar to Bärfuss et al. (2023), an additional recovery factor dependent on ICH sensor specifics and aircraft Mach number is also applied to account for an incomplete adiabatic process. And the ICH sensors are regularly calibrated under cruise temperature conditions in the atmospheric simulation chamber against a dew/frost point mirror. The overall error introduced by the temperature corrections is about 0.1-0.15 °C.

- 16: include vertical lines for better overview, e.g. for begin of climb?

  Thank you for the suggestion. We included a box indicating the time interval of the climb to the next level.

Minor details:

- 24: according to THE World Meteorological Organization
  Correct. We changed it accordingly

- aircraft is also aircraft in the plural form, please adapt throughout the manuscript, e.g. l.40, 54
  Correct. We changed it accordingly

- put references in chronological order, e.g. l. 51/52, 406
  Thank you for the hint. We changed it accordingly

- 75: deploy IT during...
  Correct. We changed it accordingly
- 125: modificationS
  Correct. We changed it accordingly
- caption of Fig. 3: bracket missing
  Correct. We changed it accordingly
- 185: ThereforeE
  Correct. We changed it accordingly
- 231 thermalLy isolated
  Correct. We changed it accordingly
- 245: in Section 4.4
  Correct. We changed it accordingly
- 246: instrument output frequency of the ozone instrument
  We changed this part of the sentence as follows: "...the output frequency of the ozone instrument..."
- explain all acronyms, e.g. l. 263 NIST
  We added the explanation for NIST (National Institute of Standards and Technology)
- use „laboratory" instead of „lab" throughtout the text, e.g. l. 328
  Correct. We changed it accordingly
- 344 AT a distance
  Correct. We changed it accordingly
- 373: brackets
  Correct. We changed it accordingly
- change order of Fig. 15 and 16, as mentioned in text?
- 482 dot missing
  Correct. We changed it accordingly
- 483 2 dots
  Correct. We changed it accordingly
- 500: AT two altitudes
  Correct. We changed it accordingly
- 504/505: rephrase

  We rephrased this part as follows:

In addition to trace species measurements, two UHSAS instruments deployed on TPC-TOSS and the Learjet provide, for the first time, the opportunity to study the impact of small-scale dynamical features on aerosol concentration and size distribution in the UTLS. A recent study by Joppe et al. (2025) further exploited the potential temperature gradient derived from the dual-platform measurements to analyze the radiative impact of biomass-burning aerosol transported into the UTLS by warm conveyor belt transport.

- 524: all authors
  Correct. We changed it accordingly

References:

Neis, P., Smit, H. G. J., Rohs, S., Bundke, U., Krämer, M., Spelten, N., Ebert, V., Buchholz, B., Thomas, K., and Petzold, A.: Quality assessment of MOZAIC and IAGOS capacitive hygrometers: insights from airborne field studies, Tellus B: Chemical and Physical Meteorology, 67, https://doi.org/10.3402/tellusb.v67.28320, 2015.

Rolf, C., Rohs, S., Smit, H. G. J., Krämer, M., Bozóki, Z., Hofmann, S., Franke, H., Maser, R., Hoor, P., and Petzold, A.: Evaluation of compact hygrometers for continuous airborne measurements, Meteorologische Zeitschrift, 15–34, https://doi.org/10.1127/metz/2023/1187, 2024.