We would like to thank both reviewers for the careful reading of the manuscript and the very constructive comments and suggestions, and we hope to have addressed them satisfactorily.

We have provided our answers to the comments and questions below in line in blue color.

Review of "Accurate humidity probe for persistent aviation-contrail conditions" by Christoph Dyroff et al., MS No.: egusphere-2025-3972

Summary:

This manuscript reports on a humidity sensor for the application of persistent aviation contrail conditions (i.e., humidity levels so high that contrails of condensed ice will remain persistent and not evaporate). It presents a novel optical design featuring optical fibers and a short-path absorption path. Two nearly identical prototypes are compared to each other (the only difference being electronics). The two prototypes show good agreement with each other over a large range of water volume mixing ratios.

Overall:

Overall, this manuscript is well-written and appropriate for the scope of AMT, presenting a new sensor prototype to measure humidity from aircraft. The title, abstract, presentation, use of language, and references are all good. The novelty of this sensor is both low-noise performance and optical design (optical fibers and a short-path absorption path). One issue is that the manuscript is lacking a connection between the scientific motivation of accurate humidity measurements at aircraft cruising altitudes and performance requirements for parameters including but not limited to: the desired range of water volume mixing ratio, pressures, temperatures, time resolution, accuracy and precision.

Another issue is that the description is not complete enough for subject matter experts to assess this new sensor. The manuscript is missing important details in the description of the instrument design and operation (the flow system), electronics, spectroscopic fitting, data processing, experimental validation, and how the results relate to the performance requirements. If the authors provided more details, then this would be an important contribution to the scientific literature. I recommend that this manuscript should be considered for publication only after substantial revisions to provide more details as addressed in the science comments below.

General comments:

1. First, early in the paper, the connection is not described between persistent contrails and the detailed range of water mixing ratios, pressures, temperatures expected. All that is said is that the "relevant H2O range below 200 ppm" is appropriate (page 15, line 274

and repeated elsewhere). This is missing detail such as: what is the lower limit of H2O mixing ratio expected in contrail-producing regions? What accuracy of measurement is required for this application of predicting persistent contrails? What is the spatial scale in the atmosphere of high humidity / low humidity regions that would drive a requirement of how fast measurements need to be? For instance, are 1-Hz measurements sufficient?

We have added a paragraph in the introduction to provide context for the expected humidity range for contrail conditions.

We have also provided context for the time response and linked spatial resolution.

The required accuracy is difficult to quantify other than better than the lowest expected humidity relevant to the question, here << 30 ppmv.

2. What are the performance requirements for sufficiently accurate water measurements at aircraft cruising altitudes? Specifically, what is the requirement measurement dynamic range of water volume mixing ratio, pressures, temperatures? What are the required time response, accuracy and precision?

See point 1 above.

3. Given that there are existing commercial instruments (WVSS-II and IAGSO ICH) and scientific-grade TILDAS hygrometers, what is the motivation for developing a new humidity probe? How is this probe novel? This not made very clear, but it is implied in the abstract that the novelty is single-mode optical fiber (and two channels). Could the authors please state why is the novelty important (compared to existing state-of-the-art sensors) for this application of measuring humidity in persistent contrail-forming conditions?

We have changed the wording from novel to new.

We have provided context for other commercially available technology and their benefits and limitations in the introduction.

4. For the readers, it is important to know hardware details, including material of the optical cell, and what electronics were used.

This information is now given in sections Optics and Electronics.

> 4a. In the lab measurements presented in this manuscript, what pressures and temperatures were used? Were these measured? Pressure and temperature are essential inputs into fitting spectra (as the water mixing ratio is dependent on them).
>
> This information is provided (160 Torr, 213 hPa, unstabilized room temperature).
>
> 4b. If these prototypes were deployed in an aircraft, how would design change? H would the air be sampled on an aircraft? How would the sensor be packaged?

What would be the pressure and temperature in the sample cell? How do gas control, temperature and pressure control affect the measurements?

We have added this information in the Outlook section, which has been added to the manuscript.

Specific Comments:

5. Spectroscopy: page 3, line 57-58: “an isolated absorption line of H2O”. It is important to the readers to know specifically which H2O line? What is the wavelength of the isolated line? Can you show a synthetic spectrum of the expected absorbance versus wavenumber (or wavelength) (for the sensor pathlength)? Can you give some rationale for why this particular water absorption line was selected?

We have added Table 1 with parameters and their uncertainties in brackets if available from the HITRAN2016 database.

The fits in Figure 4 are essentially synthetic spectra. The figure now also indicates fractional absorption and noise metrics.

The rationales for choosing this line are provided in section Optics.

6. Detail is lacking on optical cell, such as the pathlength, how the detector is mounted. Specifically on page 3, line 65, “The beam is aligned through a pinhole target onto a detector at 300 mm.” Is this (300 mm) the optical pathlength?

Figure 2 has been updated and now shows the cell dimension.

The text in section Optics was clarified to better describe the build process using a production jig with pinhole preceding the cell assembly.

7. In the Spectroscopy section, pages 4 and 5, can you provide more spectroscopic details, such as:

7a. In lines 88-89: please clarify how the baseline spectrum is used to normalize the sample spectrum. E.g., does this provide the incident/background intensity for the absorption calculation? Is it possible that trapped water in the laser diode or baseline detector could cause the low bias in the accuracy measurements (section 3.2)?

We have addressed this in more detail in the Optics (trapped water) and Spectroscopy section (fit).

7b. In lines 106-107: what is the motivation for the two different electronics in prototypes 1 and 2? Are there pros and cons of the different implementations?

We have clarified the choices in Section 2.2 Electronics.

We have used the NI system because it is a very matured system developed at ARI and provides the lowest-noise benchmark. The RedWave system was chosen for its compact size and integration of up to 3 low-noise laser drivers.

7c. In line 111, “2666 Hz (334 Hz)”: why were these scan rates selected for prototypes 1 and 2?

This has been addressed in the Spectroscopy section.

7d. How many scans are averaged? Are scans fitted in the electronics or in software?

This is now better described in Section Spectroscopy.

7e. What is the sampling rate?

See 7c. for scan rate. The rate of H2O measurements was 1 Hz as described in 2.3 Spectroscopy.

7f. In line 114: how is 50 seconds of spectral averaging (followed by 10 s of averaging baseline) relevant to airborne measurements? Can the prototypes deliver 1-Hz data at the required accuracy and precision? (see comment #1 above)

The prototypes always deliver 1 Hz data. With prototype 1 we recorded 50 seconds of 1-sec sample spectra (not averaged) followed by a 10-second averaged baseline spectrum. The duty cycle was 50/60=83%. We have discussed the consequence of the duty cycle in the Outlook section.

7g. In line 103 “Upon pre-averaging of the spectra, they were fit in TDLWintel” and line 118 “we recorded spectra on the device and then fit them offline using the same fitting engine”– can you please say more about how the spectra are fitted? How many spectra are “preaveraged”?

This info is now provided in 2.3 Spectroscopy.

8. Page 5, lines 121-122: “glass rod” – please call this an etalon.

We have added that the glass rod “served as etalon” as it is not specifically designed to be an etalon.

9. Page 6, lines 130-134: discussion is completely lacking on how the spectroscopic absorption line is fitted. Can you please say more? Are you using the Beer-Lambert Law? How is pressure broadening treated?

We have extended the description in Section 2.3 Spectroscopy to include a better explanation of the treatment of sample and baseline spectra as well as the fit.

10. Page 6, line 133-134: "the noise is low enough to not significantly affect the overall measurement uncertainty" – this raises several questions:

This statement was vague and was removed.

We have moved the noise quantification to new section *3.2 Noise* and the following sections are re-numbered.

> 10a. What is the uncertainty of the spectral line strength (and other properties) for the water absorption line selected?
>
> See new Table 1. Linestrength uncertainty < 1%.
>
> 10b. If noise does not significantly affect the overall measurement uncertainty, what is the dominant factor contributing to overall measurement uncertainty?
>
> See above: This statement was vague and was removed.
>
> We have added a paragraph in the discussion regarding measurement uncertainty sources.
>
> 10c. Please provide more detail about how the electronics achieve exceptionally low noise? Please quantity the noise on the spectra.
>
> Figure 4 was updated. The noise in the baseline of the spectra is 1.8E-5 (1-sigma) in units of fractional absorption compared to a signal of 2.4E-4 (peak to peak) of the H2O line at 13 ppmv.
>
> We have added a discussion about how we achieved low noise in the new Section 3.2 Noise.

11. Page 7, Figure 5 caption: what are the details of this data? Which data went into making this plot? Can you please define the acronym ADEV (please say "Allan Variance").

We used the 1-sec data of Figure 7 (now Figure 6) as basis for the noise comparison. We used the Allan deviation because the deviation provides a more comprehensible unit (ppbv) than the variance. This is now defined in the text.

12. Figures 7, 8,10, 13: this manuscript jumps back and forth between ppm and "ppbv times 103". For better clarity, please consistently plot in the same units, ppmv.

We have changed all plots to units of ppmv.

13. Section 3.5 – how would the additional attenuation affect the accuracy and precision of the low-ppm measurement regime? It would also be valuable for the reader to have quantitative information on incident power limits for linear performance.

We have added a paragraph to Section Extended humidity range that discusses the noise increase due to attenuation.

We don't have enough statistics to quantify the incident power limits. The non-linearity was different for the two prototypes (two sets of detectors). This requires further experiments on a larger sample size to be quantitative.

14. Figure 3: Consider adding etalon peaks to subplot to show how the peak locations translate to wavenumber curve

We don't think it is necessary as the tuning rate curve is given.

15. Figure 7 and Figure 9 show the quick response time of the instrument in lab setting with the test configurations. Could you comment on the cadence / delay times expected when integrated with an aircraft and the associated sampling system?

We have added the response time of our prototypes to Figure 7 (now Figure 6). It was derived from a double-exponential fit to the H2O measurement on the falling edge from 50 ppmv to 0 ppmv at 1 slpm flow rate.

We have added a new Section 3.2 Response to humidity changes and included a brief paragraph regarding time response in the outlook section.

16. Will the sensors still be non-temperature controlled when integrated on aircraft? How will the range of temperatures and rapid fluctuations in temperature affect the instrument hardware and spectroscopic fitting?

We have added more specifics of the anticipated pre-production instrument in a new Section Outlook.

17. Section 3.5: Please elaborate on how the non-linearities affect the accuracy and the detection limits mentioned.

See point 13.

18. Page 15, Line 278-280: Please provide details of all items listed: "spectroscopic fit, including the laser-dependent tuning rate, the baseline characteristics as well as position and width of the fit." How do these contribute to the accuracy?

This has been addressed in the discussion.

Editing Comments:

1. Please check grammar. Several commas are missing where needed.

2. Consistently use ppmv (not ppm or ppbv) and define ppmv the first time as "parts per million by volume".

Done.

3. Page 10, line 201: replace "is" with "in".

Done.

4. References: please cite references in consistent EGU format.

Done.