We would like to thank the referee for the review and comments to improve the quality of this work. Following these comments, we have made major modifications and point-by-point responses. Please find our response below (in blue).

General Comments:

This manuscript details a low-cost, lightweight and portable humidification system for calibrating trace gas analyzers. In short, the system uses a combination of "wet" (produced by humidifying air through a Nafion membrane in a water bath) and "dry" (dry standard gas) air streams to produce stable water vapor levels comparable to ambient levels for trace gas analyzers in an automated fashion using pre-programmed Raspberry-Pi control. Currently, maximum water vapor levels achievable are dependent upon water bath temperature and mass flow of air through the system. The system is lightweight enough and has a low enough footprint that it can be efficiently moved from one observations site to another for deriving dry mole fractions of trace gases using empirically-derived water vapor corrections with this system.

The system was tested on both Aeris MIRA and Picarro CRDS systems, and indicates lower errors in corrected dry mole fraction measurements of trace gases relative to instrument-provided water vapor corrections, in addition to general adherence to recommended WMO compatibility goals for specific trace gases. The system is generally well-documented here and presents a worthwhile contribu9on to AMT over current methodologies; I provide some comments below to mainly clarify the description, potentially additional testing involved, and some additional details for consideration before publication.

Thank you for your time and expertise in reviewing and thus improving this paper. We appreciate your comments.

1. Figure 1 and the main text description could use some expansion for clarity. First, please state whether there is any temperature control at all within the system at present. My understanding is that the water bath is not temperature-controlled. In L87, the stability of the water vapor levels is controlled by the stability of the water bath, so if this changes due to room temperature, etc., how does this affect the stability of the water calibration steps?

The reviewer is correct in that the system is not temperature-controlled at all and we have clarified this in the manuscript (Line 102). We note in the discussion that temperature control is a possible future improvement (Line 380). This reviewer comment prompted us to examine whether temperature variability could account for the observed short-term H_2O variability during the calibration steps. We compared the standard deviation of the H_2O during the calibration steps to the standard deviation of

the enclosure inlet temperature (T2, see below). The correction coefficient (R^2) was 0.006 for the 313 windows from the 3-5 min tests. Thus, variation in enclosure inlet temperature explains essentially none of the observed short-term H_2O variability, which may be caused by Aeris H_2O measurement noise, MFC flow-control variability, and/or analog mass flow controller setpoint-voltage stability. We added this figure to the supplement (Figure S5) and added the description text to Lines 257-262.

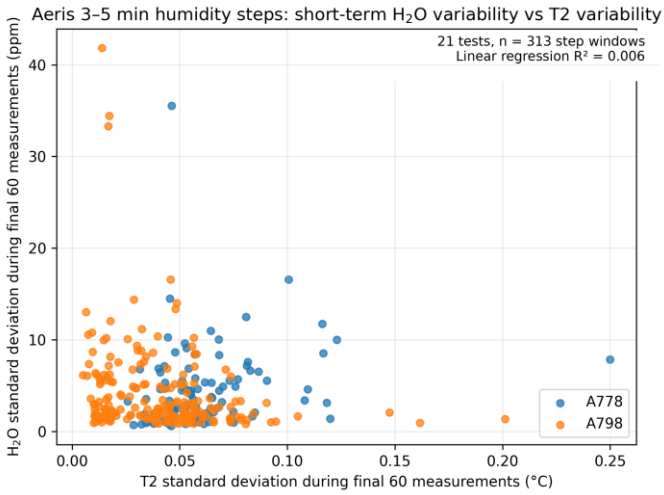


Figure S5. Standard deviation of the H_2O during the calibration steps to the standard deviation of the enclosure inlet temperature (T_2) of 21 tests (313 windows) for Aeris MIRA analyzers (serial number A778 and A798). The correction coefficient (R^2) was 0.006 for these 3-5 min tests.

Please specify tubing composition – is this stainless steel (and which diameter)?

The system uses 1/8-inch outer-diameter (OD) stainless-steel tubing and we apologize for the oversight in not including this important detail. Added to the manuscript (Line 103).

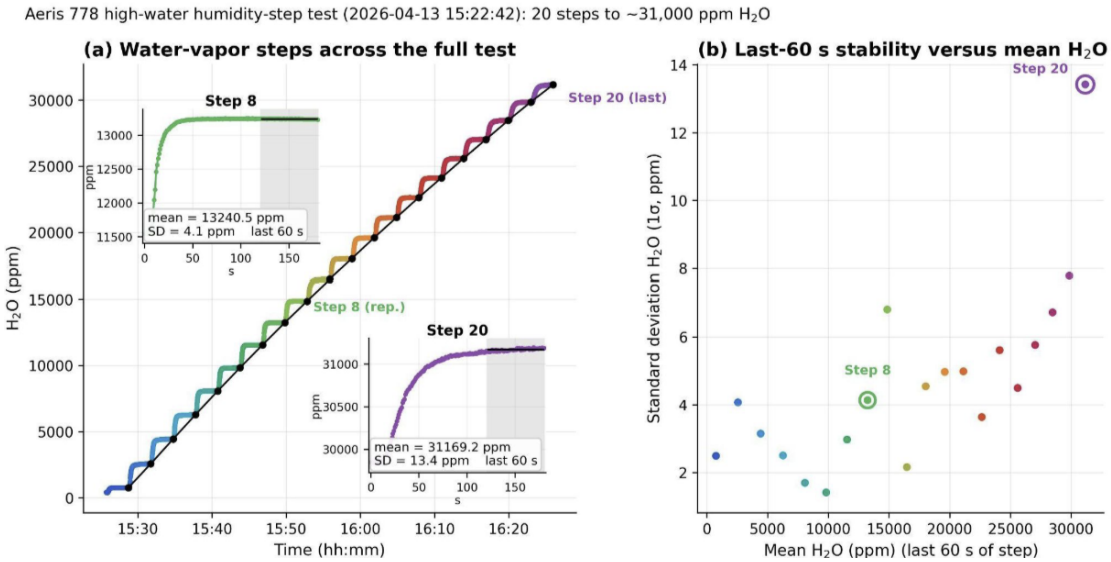
Please describe the purpose of the overflow in Figure 1 for the reader (presumably for analyzer pressure stability).

Thank you for the comment. The text "An overflow line was included downstream of the system to maintain a stable flow and pressure at the analyzer inlet." was added to Lines 97-98.

2. Figure 2: it is difficult to see in a) how stable the water actually us at the end of the 3-5 min step – can you zoom in on a few of these steps to show that the H_2O mole fraction equilibrates relatively quickly to a stable value? As you describe tests with both the Picarro (up to 1.7% H_2O) and the Aeris instrument later in the text (up to 3% H_2O) and as it looks as if the precision of the water vapor mole fraction degrades at higher H_2O, can you provide results in b) that substantiate your claim for stability and

repeatability in the humidity control up to these H_2O mole fractions? The example of only stepping up to 0.7% in Section 2.1 seemed somewhat incomplete given that the rest of the manuscript describes system tests to higher H_2O levels.

Thank you for this comment. We added representative insets for two steps to Fig. 2. It is now more clear that the water vapor levels off quickly (see below – which is the updated Fig. 2). We also agree that we should show steps up to as high as possible. You can see that indeed the stability does degrade at the higher water vapor levels. In particular, Step 20 doesn't appear to have leveled off at all. Previously we had focused our efforts on the lower water vapor levels because with our system in the field, we dry (albeit not completely, hence the need for water vapor calibration), and thus quoted 3 ppm H_2O SD. But in fact, the stability is more like 10 ppm H_2O for water vapor up to 3% and even higher above. We adjusted the text to reflect these nuances (Lines 135-141).



We also added a figure (below) to the supplement (Figure S1) to more carefully address the water vapor variability at various levels during the steps used to develop water calibration curves for the instruments. The variability increases with increasing water vapor for the completed tests. Across 29 humidity-step tests comprising 368 individual steps and two Aeris analyzers, the median final-60-s H_2O variability was 2.8 ppm (1σ), with typical variability of ~2-3 ppm below 20,000 ppm H_2O and ~7-10 ppm at the highest H_2O levels.

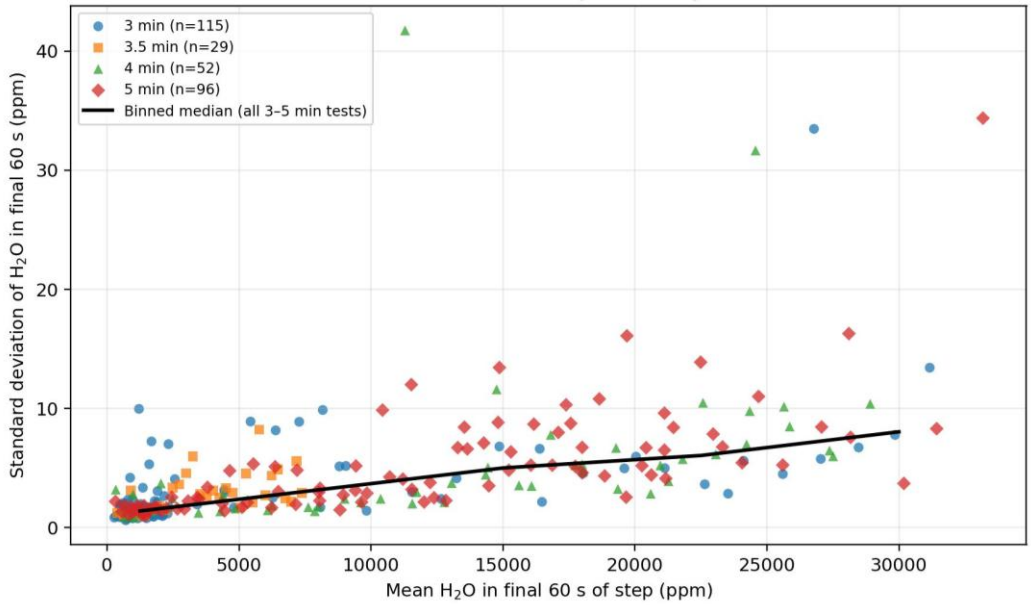


Figure S1. Variability of generated H_2O as a function of water vapor concentration and step duration. Each symbol represents the standard deviation of H_2O during the final 60s of an individual concentration step. Different symbols indicate step durations of 3, 3.5, 4, and 5 min. The black line represents the binned median across all 3-5 min tests.

3. Describe which MFCs would be needed to achieve higher water vapor levels comparable to those observed for the Picarro analyzer.

Thank you for the comment. We just need both the wet and dry MFCs to have a maximum flow rate slightly in excess of the flow that the instrument needs. For example, the Picarro draws about 250 sccm so each MFC needs to have a max control value of about 275 sccm, assuming we are using an overflow method.

4. L294-295 states that the Nafion-based system should minimize solubility-related effects from the water bath since there is no direct air-to-gas interaction, and before this, that permeability effects are somewhat negligible. However, have you tested this for CO_2 (and potentially also CH_4) when the water bath is not acidified? It is still somewhat unclear to me whether deionized or more basic water baths could still create issues with the Nafion system at higher water vapor levels > 1.5%.

Thank you for raising this issue, prompting us to do additional testing. As shown in the figure below, a calibrated reference cylinder (424.4 ppm CO_2 and 1977.2 ppb CH_4) was measured with Picarro analyzer CFKADS2025 under three configurations: directly after the humidity generator, after the humidity generator followed by a downstream Nafion dryer, and through the Nafion dryer with the humidity generator bypassed. The external downstream Nafion dryer was a 144-inch Perma Pure Nafion tube (MD-070-144S-2), with counterflow provided by a zero cylinder (0.4 ppm CO_2, 17.6 ppb CH_4, 14 ppb CO). In (a) we see the water vapor, as measured by the Picarro during these

three tests. In (b), the Generator only line indicates the CO_2 changing by up to 0.175 ppm for water vapor of 1.4%. After drying with the Nafion, there is a possible permeation effect from the external Nafion of up to 0.075 ppm, essentially the same as when only the Nafion was used (no water generator). Since the Generator plus Nafion line is essentially the same as the Nafion only line, this indicates that the Generator itself did not affect the CO_2 of the air sample. In (c), there is possibly a slight water vapor dependence for the Generator only test, but no evidence of permeation effects caused by the Generator or the external Nafion. In (d), we see a large water vapor effect for CO, and again no evidence of permeation effects. We have added this figure to the supplement (Figure S8) and text to the Results section (Lines 320-332).

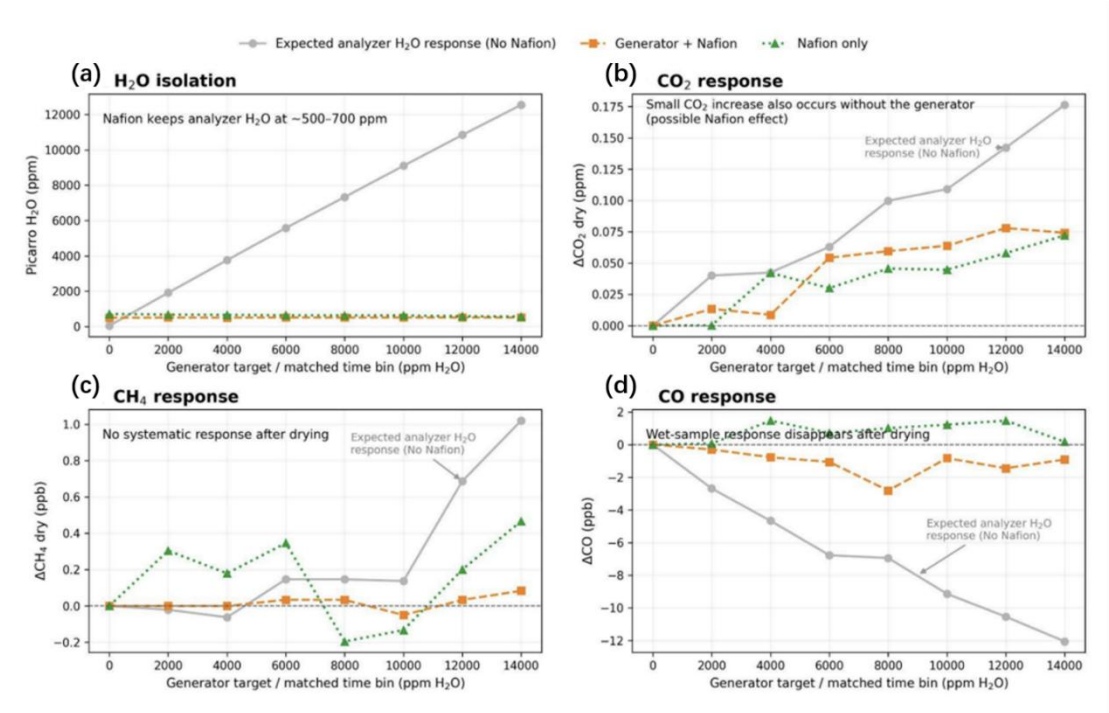


Figure S8. (a) water vapor mole fraction measured by Picarro (CFKADS2025), for three tests (calibration cylinder gas through the water generator (Generator only), calibration cylinder gas through the water generator and an external Nafion (Generator + Nafion), and calibration cylinder gas through an external Nafion (Nafion only). (b) CO_2 mole fraction (corrected to the dry mole fraction using the manufacturer correction). (c) CH_4 mole fraction (corrected to the dry mole fraction using the manufacturer correction). (d) CO mole fraction.

Specific Comments:

- Title: you might consider renaming to something more general like “Portable system for characterizing trace gas analyzers for sensitivity to water vapor” as you describe water vapor corrections for CO in the main text.

This is a good idea, thank you for the suggestion. “Portable system for characterizing trace gas analyzers for sensitivity to water vapor: Application to cavity ring down and mid IR sensors” to emphasize that our purpose is the application.

- L44: Please provide a citation for the stated WMO compatibility goals. These are often found in WMO annual meeting reports.

Thank you for the comment. The reference (WMO, 2025) has been added to Line 44.

References

WMO (2025): Measurement guidelines for the observations of carbon dioxide, methane, and nitrous oxide at global atmosphere watch stations, GAW Report No. 318, World Meteorological Organization, Geneva, Switzerland.

- L47: “500 ppm H2O potentially resulting in significant measurement errors” – Rella et al. 2013 state that there are CO2 measurement biases from 500 ppm H2O, so you could cite this paper here for reference.

Thank you for the comment. The reference (Rella et al., 2013) has been added to Line 48.

- L90: Specify maximum and/or average power draw to better substantiate the potential for portable operation under battery power.

Reviewer CC1 also requested this, which was an overcite on our part. Thank you for pointing this out. The text “During normal operation, the P-WAVES system consumes approximately 10 W of electrical power. A 24 h deployment would therefore require approximately 240 Wh of energy. As a representative example, a commercially available 12 V, 30 Ah $LiFePO_4$ battery has a nominal capacity of approximately 360 Wh and could provide sufficient energy for more than 24 h of operation, depending on power-conversion efficiency and usable battery capacity. A representative battery of this size measures approximately 16.5 × 16.3 ×8.6 cm, weighs about 3.2 kg, and could be accommodated within the enclosure used for the current P-WAVES configuration.” was added to Lines 112-117.

- L102 “…requires longer steps” – Do you have a sense for how long?

Thank you for the comment. The text “(about 10 min)” was added to Line 123.

- L139: Please also state value of CO dry mole fraction for completeness.

Thank you for the comment. The text “For CO, the value of the calibration cylinder was estimated to be 123.8 ppb.” was added to Line 173.

- L142: It would perhaps be useful to state how long it takes for the H_2O mole fraction to equilibrate (also see comment for Figure 2 above) to provide justification for 3-5

minute time steps.

Thank you for the comment. As mentioned for the previous comment, Figure 2 has been updated and Figure S1 was added to supplement. The text "The short-term within-step stability gradually decreased at higher water vapor levels. Across 29 humidity-step tests comprising 368 individual steps and two Aeris analyzers, the median final-60-s H_2O variability was 2.8 ppm (1σ), with typical variability of ~2-3 ppm below 20,000 ppm H_2O and ~7-10 ppm at the highest H_2O levels (Fig. S1)." was added to Lines 139-141.

- L215: It is somewhat surprising that there was no water vapor dependence for CO for the CKADS2025 as these analyzers in the past have shown a water vapor dependence (Chen et al., 2013). You may note or comment for the reader that this is somewhat unexpected.

As we noted on Page 12, Lines 241-243, two of the Picarros indicated significant CO dependence but CKADS2025 did not. The text "For these instruments, the measured CO mole fraction is commonly observed to depend on water vapor (Chen et al., 2013)." was added to Lines 311-312.

- Figure 8: It may be useful to provide the same y-axis scale for Figures 8(a-c) to compare variability between tests.

Thank you for the comment. Figure 8 was updated as suggested.

- L338: "if a linear dependence is assumed" – but we know that the CO bias is non-linear (Chen et al., 2013); perhaps caveat this statement in some way?

Thank you for the comment. The sentences were rewritten as "This study showed that without analyzer-specific water correction for CO, the mean CO bias reached about 12 ppb for the CFKADS2025 and CFKADS2218 analyzers for up to 17000 ppm H_2O. A linear extrapolation would yield an estimated bias of about 22 ppb at 30000 ppm H_2O, however, this extrapolation should be interpreted cautiously because the CO response to water vapor is nonlinear (Chen et al., 2013)."

Technical Comments:

- L41 and others: please list citations in ascending order by year

Thank you for the comment. We have revised the citations throughout the manuscript to list them in ascending order by year.

- L82: please define acronym 'MFC' here as it is used in Figure 1 below.

Thank you for the comment. We have defined the acronym "MFC" at Line 82.

- L128 – please punctuate the end of this sentence with a period after Eq. 1.

Thank you for the comment. We have added a period after Eq.1 as suggested.

- Figure and Table appearance: For Figs 3-10 in general, it is difficult to differentiate between the triangles and circles for different dry vs. corrected values. One suggestion may be to use filled vs unfilled shapes for dry vs. corrected values. Shapes in Figures 5-10 are somewhat small, as is the text in Table 2 (maybe this can be rotated 90 degrees).

Thank you for the comment. Figure 3-10 and Table 2 were updated.

- L241: “Picaro” ⟶ Picarro

Thank you for the comment. “Picaro” was corrected to “Picarro” at Line 241.