We thank the reviewers for their insightful comments, which have allowed us to produce a stronger manuscript. Our responses to the general and specific comments are given below. Reviewer comments are provided in italics and our responses are given in plain text. Line number references pertain to the revised manuscript with no tracked changes. Quoted text from the revised manuscript is given in blue in this response document.

Reviewer 2:

Reviewer 2 general comments

Comment: *The authors present improvements in AMOD sensing device for concurrent PM2.5 and AOD measurements. They describe a sample deployment of 10 AMODv2s for 2.5 days during a wildfire smoke event, and they present a 7-day validation campaign of the AMODv2 that was co-located with a AOD reference device. The results indicate close agreement between AMODv2s and the reference instrument although they identified some intra-device variability. They conclude that the AMODv2 is well suited for citizen science and other high-spatial-density deployments due to its low cost, compact form, user-friendly interface, and high measurement frequency of AOD and PM2.5. The paper addresses an important topic, a cost-effective strategy for improving satellite estimates of PM2.5 concentration. They present results to support their statements about measurement accuracy. However, it presents rather limited data to support many of the authors' other conclusions. The paper would be strengthened with additional data. It also requires some clarification regarding real-time presentation of PM2.5 concentrations as well as some date inconsistencies. If additional results are not possible, the manuscript may be more suitable as a technical note.*

Response: Thank you for your suggestions. Since our initial submission, we have added several new results and analyses that address concerns outlined in this review. The specific details are provided in our responses to the relevant reviewer comments. We feel that this work is sufficient to qualify for a standalone research paper, as per the aims and scope of *Atmospheric Measurement Techniques*. However, if the managing editor for AMT feels that this work is better suited as a technical note, we will be pleased to have it considered as such.

Reviewer 2 general comments

Significant weaknesses

1. ***Comment:*** *Limited scope of data. The website presented in the paper illustrates that the AMODv2s are collecting and presenting measurements to the public, which is great. It is puzzling why the authors present only 2.5 days of measurements (2 days of AOD measurements)*

from 14 devices. This limited data set also makes it difficult to support the authors statements that the system is autonomous.

Response: Field campaigns are currently ongoing and results from those studies will be presented in separate papers. The original section 3.1 was included solely as a demonstration of the AMODv2 capabilities (apart from lab testing). That section has now been moved to the supplement in favor of new results and analyses (field deployments were put on hold in 2020 due to the COVID-19 pandemic). The measurements taken by participants require more context and analysis that we felt was outside the goals of this paper. However, we have added additional data to the manuscript as detailed in our subsequent responses.

2. ***Comment:*** *Presented longer-term measurements, which is one of the key motivations for this developing autonomous measurements. The paper would be greatly strengthened if they:*

Response: In Section 3.3, we present a summary of samples collected between January and March of 2021, for the purpose of analyzing the ability of the AMODv2 to complete its intended sample consistently. Specifically, this section includes failure rate analysis on 76 test runs conducted on the roof of our laboratory building. Measurements were taken on three separate weeks. We describe this experiment in the manuscript on lines 317-325 as follows:

"We tested the reliability of AMODv2 instruments in a series of 5-day, outdoor samples on the roof of a Colorado State University laboratory facility (430 N College Avenue, Fort Collins, Colorado, USA). All units were co-located within a 10 m radius. We started tests on January 16, 2021, January 30, 2021, and March 31, 2021, which included 34, 27, and 15 unique AMODv2 units respectively, for a total of 76 samples. We assessed the reliability of the AMOD according to the rate at which samples terminated prematurely. Samples that failed to reach at least 115 hours of the intended 120 hour sample duration were designated as premature terminations. We specifically assessed the mechanical robustness of AMODv2 units by visually inspecting failed units for evidence of water ingress and electrical component damage. We also analyzed the AOD data from these samples to evaluate the automatic solar alignment procedure and quality control algorithm."

To clarify, automation in this article refers specifically to AOD measurement and data transfer. The AMODv2 is not autonomous in the sense that it can be left unattended for longer than than the programmed five-day sample. After each sample, an operator needs to replace the gravimetric filter cartridge and charge the unit for ~8 hours. In other words, each discrete five-day sample is completed unsupervised, as described in Figure 2. However, after the device is fully charged, it can be re-deployed, enabling sampling in consecutive weeks. At the time of writing, 31 AMODv2 units are currently deployed across the USA in a citizen-science network. Our participants are starting samples every Tuesday for a span of 8 weeks starting in mid-June

2021. The results of this study are outside of the scope of this article and will be detailed in a future work.

3. ***Comment:*** *Co-located a few AMODv2s to understand intra-device variability, and have long-term validation measurements by co-locating the AMODv2s with AOD reference devices for a long time period (seasons to a year). The manuscript provides some evidence that device to device variability could be important.*

Response: The final portion of what is now Section 3.2 includes calibration stability analysis of 16 AMODv2 units. The description of this experiment is given on lines 312-316 as follows:

"We evaluated the long-term stability of the AOD sensors by re-calibrating a set of 16 AMODv2 units 15 months after their initial calibration. Original calibrations for the units tested were conducted at the MAXAR-FUTON site in Fort Lupton, Colorado, USA (40.036 N, 104.885 W) on February 21, 2020. Re-calibrations were conducted at the NEON-CVALLA site on May 27, 2021 (The MAXAR-FUTON site was indefinitely unoperational at the time of the second calibration)."

The results of this experiment are provided on lines 418-444 as follows:

Previous work has noted the tendency for optical interference filters to degrade over time, changing the accuracy of the most recent calibration (Brooks and Mims, 2001; Giles et al., 2019). We quantified the long-term stability of the AMODv2 AOD sensors by re-calibrating 16 AMODv2 units 15 months after their initial calibration. Summary statistics quantifying the change calibration constant (V0) changes are provided in Table 3.

Table 3: Summary statistics for AMODv2 calibration stability test. All summary statistics refer to the change in V_0 (Eq. 2). Note that the absolute value of the maximum change refers to the single unit with the highest percent change for each wavelength.

Wavelength (nm)	Average absolute value of change (%)	Median change (%)	Absolute value of maximum change (%)
440	13.84	-7.14	62.72
500	11.80	-9.64	37.08
675	6.66	-0.75	29.40
870	14.63	-2.80	50.72

A plot illustrating the voltage change undergone by each of the 16 AMODv2 units is provided in Fig. 6.

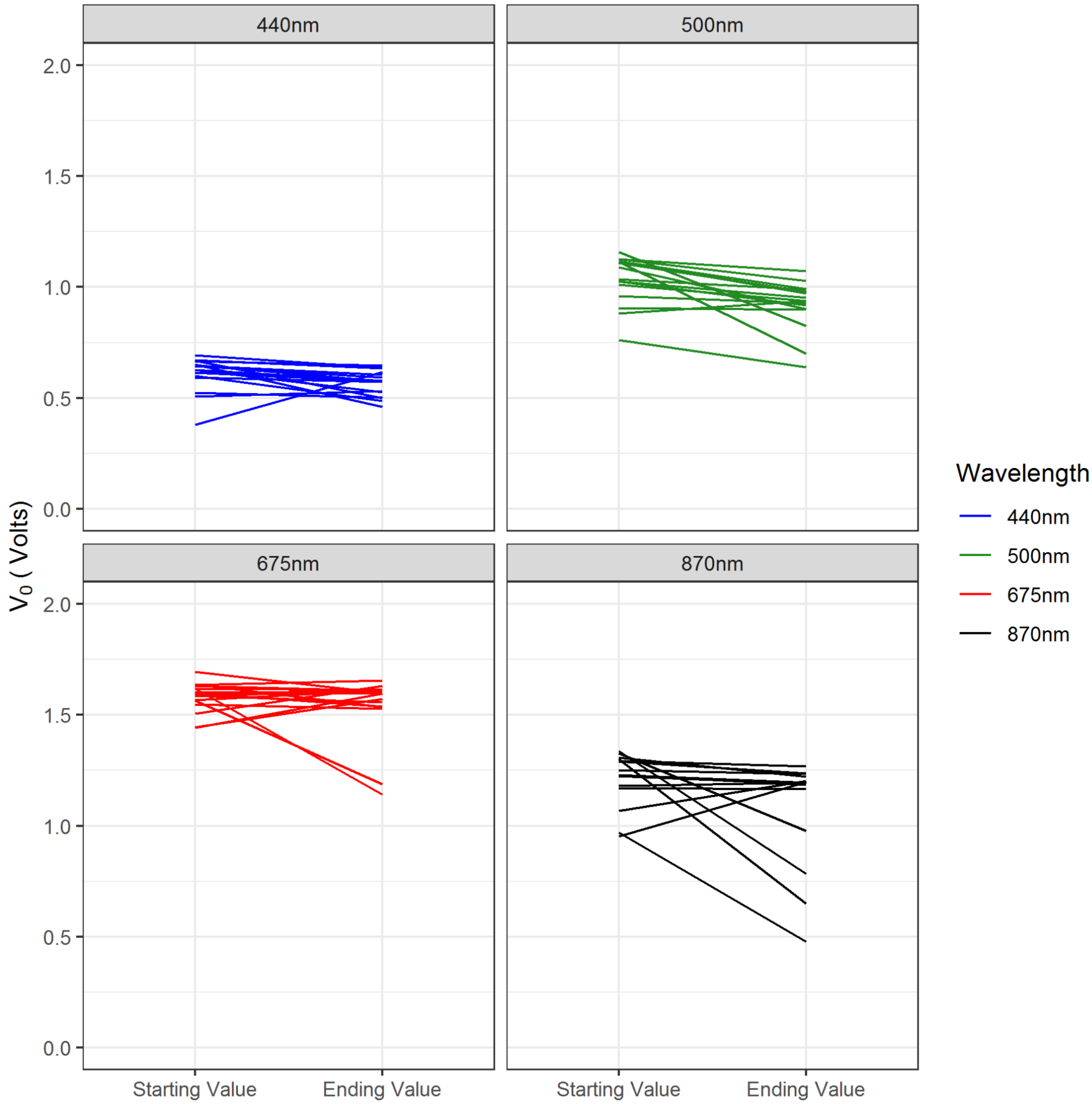


Figure 6: Linear change plots illustrating the change in calibration voltage, V_0 (Eq. 2), from the initial calibration to a follow up test calibration of 16 AMODv2 units. Each instrument is represented by a separate line with starting and ending calibration voltage values delineated on the vertical axis. Panels are separated by wavelength. Each line represents the change after 15 months of a single wavelength channel of an AMODv2 unit.

The results presented in Fig. 6 illustrate that the calibration constants (V0 in Eq. 2) remained relatively stable (changes of 5% or less) for most AMODv2 units over the course of 15 months. However, several units exhibited relatively large changes (in excess of 30%) in their calibration constants, indicating calibration changes may vary considerably by unit. Boersma and de Vroom (2005) present theoretical analyses and conclude that the calculation of AOD is most sensitive to errors in the calibration constant, V0. (Boersma and de Vroom, 2006). Their theoretical analyses combined with the results in Fig. 6, point to drift in V0 as a likely source for large, unit specific errors in AOD AMODv2 measurements. To limit errors due to calibration drift, we recommend that AMODv2 V0 values be re-calibrated on an annual basis. Determining the source of changes to the calibration constants of some AMODv2 units is the subject of ongoing investigation. Potential sources include changes in sensitivity or drift of the photodiode sensor element, degrading of the optical interference filters, and/or clouding of the protective glass window element in the light path of the sensors.

4. ***Comment:*** *Presented data that indicates the autonomous nature of the device, % of device up time, and number of valid AOD measurements (quality control described with triplicate measurements), number of AOD measurements excluded for cloud cover, etc. This needs to be done for weeks or months of measurements to begin to support the autonomous claims in the manuscript.*

Response: In what is now Section 3.3 we have added an analysis that includes 76 samples (each 5 days in duration) completed at our laboratory rooftop. There we provide failure, and AOD quality control results as follows:

"AMODv2 sensor validation results from this work and prior work indicate that the instrument can accurately measure AOD and PM2.5 when operating properly. However, for effective large-scale deployments, AMODv2 units must reliably complete their intended sampling protocol when deployed outdoors for 120 hours. Potential causes of premature sample failure included, premature battery drainage, damage to mechanical or electrical components (e.g. water ingress into motors or sensors), and firmware related crashes (e.g. memory overflow errors). In a series of reliability tests on the rooftop of our laboratory facility, we found that of 76 attempted samples, 75% were successfully completed, 16% failed due to premature battery drainage, 8% failed due to water damage, and 1% (one unit) failed due to a firmware crash. To address failures due to premature battery drainage, we replaced batteries that would not fully charge and replaced motors that were drawing excess current. To address failures due to water damage, we replaced damaged boards and applied additional sealant to key mechanical interfaces. We addressed the firmware crash issue by reconfiguring the memory allocation to grant more memory to the wireless data push functionality, which proved to be the most memory intensive sub-system. Overheating was not an issue in the testing discussed here, as the testing was conducted in winter months. We will test the AMODv2 under warmer conditions to evaluate heating effects on the performance of the instrument.

We also verified that AMODv2 units were attempting AOD measurements and applying the prescribed data screening protocols. In the 76 test samples, AMODv2 units attempted 22,419 AOD measurements per wavelength. Units detected the sun and took at least one measurement toward forming a triplet 4,763 times per wavelength. The results partitioned by quality control designation are provided in Table 3. Instances where an AMODv2 reported a numerical AOD value were considered valid AOD measurements. Instances where an AMODv2 failed to acquire three AOD measurements for a single measurement sequence (Fig. S6) were designated as incomplete with a unique error code. Cloud-screened measurements were those where the solar alignment is achieved for 3 measurements but the triplet failed to meet the acceptance criteria (Fig. S6).

Table 3: Results from the AMODv2 quality control algorithm from 4.763 AOD measurements taken in laboratory rooftop testing. Attempts where zero measurements were logged for a triplet attempt are omitted from the table.

Wavelength (nm)	Proportion of valid AOD measurements	Proportion of invalid AOD measurements	
		Incomplete AOD triplets	Cloud-screened measurements
440	33%	20%	46%
500	34%	20%	45%
675	35%	20%	44%
870	33%	20%	46%

The results of this study indicate the AMODv2 automatically acquired solar alignment for a complete measurement triplet on 80% of attempted measurements. However, among the completed triplets, approximately 45% of measurements were identified as cloud-contaminated and subsequently screened. The screening algorithm did not reach consistent results across all wavelengths, as evident by slight deviations in the proportion of screened data across wavelengths. In this work, we applied the same exclusion criteria to each wavelength (Fig. S6). These results indicate unique exclusion criteria may be necessary for each wavelength to achieve consistent results, particularly when there is substantial deviation in magnitude between two measurement wavelengths (e.g. 440 nm AOD much higher than 870 nm AOD for a single measurement)."

5. *Comment:* *The validation measurements of AMODv2 are also limited. The authors state that their validation measurements cover a range of conditions, which is important. If the AMODv2 is capable of autonomous measurement, it is unclear why the validation results are so limited. It is also unclear how the authors came to 426 data paired points. I would encourage them to include a table in the supplementary materials that presents the device ID, the number of valid AOD measurements each day, the number and % of excluded measurements (if any), % of missing data and the cloud and PM2.5 conditions of the day. I struggled with understanding how 426 paired data points were achieved. If the sampling rate was 2.5 to 3 minutes, are they presenting* *the results of each test (one every two to three hours, this would get closer to 426 data points were the samples averaged?) or samples selectively included.*

Response: We respectfully disagree that the AOD validation data set is limited. Compared with our AMODv1 work, our AMODv2 work includes 296 more measurement pairs per measurement wavelength (Wendt et al., 2019). We also had limited opportunities to measure at high AOD due to the transient nature of wildfire smoke and the generally clean air in Colorado. Therefore, most additional data we could have collected would have been at low AOD. We had already shown in the AMODv1 paper that our AOD system performs well at low AOD (Wendt et al., 2019). Additional data at low AOD would have left the two ends of the AOD spectrum unbalanced, in terms of the number of measurements, affecting our regression analysis in particular.

There were also logistical challenges that limited our access to AERONET monitors. Owing to the high cost (>$55,000) of AERONET Cimel sun photometers we cannot purchase one of our own to perform AOD validation. We traveled one hour by car to reach an AERONET site at Vance Brand Airport in Longmont, Colorado. We could not access the private area where the AERONET photometer is kept due to COVID-19 restrictions. Instead, we set up our units at a public table outside the fence but still relatively near the monitor, where it was not safe to leave the units unattended for extended periods of time.

The device-specific AOD data requested by the reviewer are available in the data set associated with the article (amod_v2_validation.csv) available at the following link: https://hdl.handle.net/10217/225291. There were no measurements excluded due to clouds. We selected days with no cloud cover to perform our validation experiments. Also, a team member was always there to observe that none of the measurements were cloud-contaminated.

As for the 426 number, the AERONET instrument measured at a lower frequency (1 measurement every 15 minutes) than AMODv2 units, which were custom-configured to sample at the higher rate of 2.5 to 3 minutes specifically for validation. This means that many AMODv2 measurements were omitted from the data set because they lacked an accompanying coincident AERONET measurement. We have added lines 308-309 to the manuscript to clarify this point.

"The AERONET reference monitor sampled at a frequency of one sample approximately every 15 minutes."

6. ***Comment:*** *With less than 10 days of data total (2.5 of sample deployment and 7 days of validation), it is difficult to see how this annual calibration recommendation is reached. Line 408: "To mitigate unit specific errors, we recommend re-calibrating instruments at least one time per year." PM2.5 concentrations. The paper presents PM2.5 measurements from the Plantower PMS5003. The authors need to clarify if they are presenting measurements that were*

corrected with their on-board filter measurements (or if these are raw measurements or corrected using some other strategy). They should provide these filter-based correction factors in the supplementary material. If they are using some other method, they should describe this. They should also describe if they are applying corrections to Plantower's raw ATM or CF=1 measurements. Also, in several places in the manuscript, the authors discuss real-time visualization and data access. However, as the authors and others have published previously the Plantower PMS 5003 raw measurements are biased. They require a correction factor for the aerosol conditions of interest. Reasonably accurate real-time PM2.5 concentration estimates would not be possible if the filter cartridges require one week of sampling, must be mailed in, and weighed. These corrections would only be possible weeks after the PM2.5 measurements are posted. The authors need to clarify what they are presenting and if the measurements are corrected how they are corrected.

Response: As a minor correction, we conducted nine, co-located AOD evaluation experiments, not seven. We have provided this detail in lines 305-307 as follows:

"We co-located our instruments within 50 m of the reference instrument (and within 5 m of each other) on nine separate days with varying atmospheric conditions (e.g. wildfire smoke and clean air) using a total of 14 unique AMODv2 units."

The statement regarding re-calibration is now supported by the analysis presented at the end of Section 3.2 (see response to comment 3).

We have moved this discussion of the wildfire event and the plots to the supplement. In Figure S8, we show the Plantower PMS5003 PM25_CF1 rather than the PM25_ATM, following Tryner et al. (2020) and our Ford et al. (2019, Part 2 of this series). However, both the CF1 and ATM values are output and stored on the internal log file. The Plantower has a widely known bias, and many groups have developed correction factors for the Plantower. These correction factors are applied in post-processing and have generally been developed for longer averaging periods (i.e., the Barkjohn et al. 2020 was developed for 24-hour average concentrations) rather than 5-minute averages. The application of the correction factor is an open area of research (by our group and others); thus, we have decided to display the raw values in real-time on our website as does the PurpleAir website (purpleair.com), whose sensors include the same Plantower model. All participants are informed that the data displayed on the website is preliminary (AOD values have a simple cloud screening applied for the website, but, as in Part 2, we perform more QA/QC in post-processing). From our multiple deployments this year, we plan to further investigate developing correction factors from our concurrent filter and Plantower measurements that could be applied in real-time for future AMOD deployments (our datasets now cover a wider range of locations and atmospheric conditions). We have edited the text to state that these values are the raw CF1 values in Figure S8. "$PM_{2.5}$ measurements are from the Plantower PMS5003 and are the

CF = 1 values. These values have not been corrected using the PMS5003 atmospheric correction factor, but were not corrected relative to the filter mass concentrations."

We have moved Section 3.1 to the supplement and clarified that $PM_{2.5}$ measurements were not corrected using the PMS5003 atmospheric correction factor, and are not corrected relative to the filter.

Moderate weaknesses

7. ***Comment:*** *Table 1. What types of conditions are being presented here. All 7 days or a subset? How do the statistics vary by condition?*

Response: Table 1 summary statistics include the full data set with no separation by condition. Partitioned data are provided in supplementary Table S1, which is also replicated below. Briefly, the AOD mean absolute errors of the AMODv2 were found to be largely independent of the AOD magnitude.

Table S1: AMODv2 validation summary statistics calculated separately for elevated-AOD days and clear days. Elevated-AOD days were defined as days in which the average AERONET AOD was greater than or equal to 0.15. Clear days were defined as days in which the average AOD at 500 nm was less than 0.15. In total, five days were identified as clear and four days were identified as elevated-AOD.

Wavelength (nm)	AERONET 500 nm AOD magnitude	Number of samples	Mean absolute error (AOD)	AOD Precision (AOD)
440	All included	426	0.046	0.023
500	All included	426	0.056	0.027
675	All included	426	0.026	0.0089
870	All included	426	0.033	0.017
440	> 0.15 (elevated)	115	0.054	0.019
500	> 0.15 (elevated)	115	0.051	0.019
675	> 0.15 (elevated)	115	0.027	0.006
870	> 0.15 (elevated)	115	0.031	0.007
440	< 0.15 (clear)	311	0.043	0.024
500	< 0.15 (clear)	311	0.059	0.030
675	< 0.15 (clear)	311	0.025	0.010

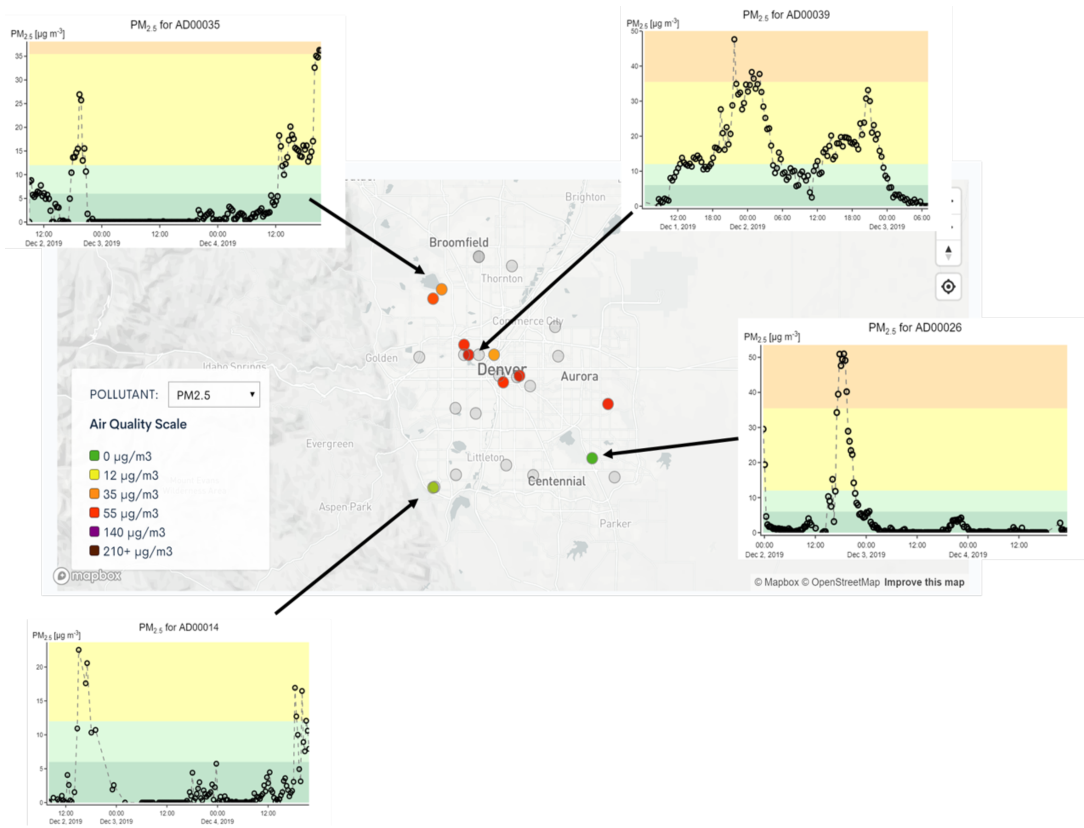
870	< 0.15 (clear)	311	0.034	0.021

8. ***Comment:*** *The manuscript in places reads a little like an advertisement for the AMODv2. The authors should focus on statements that are supported by their results (i.e., the terms autonomous, realtime, user friendly, use for citizen science). See comments about autonomous and real-time in the previous section.*

Response: We have identified and altered or removed portions of the manuscript that read like an advertisement. Specifically, we have removed the discussion section and moved statements of current and future applications into the conclusions.

9. ***Comment:*** *Figure S7 does not occur during either the sample deployment (October 2021 or maybe 2020, see comment on date inconsistencies below) or during the co-location validation testing. It is unclear why the authors would select a time other than the sample deployment described in the paper. If there is a good reason, they should provide it. They should also discuss the causes of the PM2.5 concentration peaks. Also, this figure illustrates that more than one half of the AMODv2s are offline (see comment about autonomous).*

Response: The snapshot in Figure S7 was taken at a time when AMODv2 units were located at different locations in Colorado for test deployments, for purposes of illustrating the web interface. The validation data were taken with the samplers located together. With co-located samplers, points on the map would overlap and obscure what information is available on the web interface. We have clarified the purpose of the figure and the presence of inactive circles in the caption as follows:



"Sample live map from sampler website csu-ceams.com overlaid with time series of $PM_{2.5}$. This snapshot was taken at a time when AMODv2 units were located at different locations in Colorado for test deployments, for purposes of illustrating the web interface. Colored circles represent active AMODv2s. Grey circles represent inactive AMODv2 units. Inactive circles are typically units that have been assigned a location on the map, but are at a location with poor Wi-Fi connectivity, in between samples, or recently sent back by the operator. The color scale is determined by the current Air Quality Index (AQI) calculated based on the $PM_{2.5}$ measurement. The four sample $PM_{2.5}$ time series plots are linked to specific participant locations with arrows. Time series plots can be accessed by clicking on an active circle. Users may select the option to view AOD from a drop-down menu for both the map and the time series plot. Note: that this figure has been edited to show map and time series plots on the same page. On the actual website selecting a point displays only one simplified time series on the map itself. Detailed time series shown here are available on a separate page which can be accessed through selecting a unit on the map."

10. ***Comment:*** *Given that the AMODv2 requires WiFi, wouldn't it be reasonable to have a plug in option, which would likely increase up-time, see comment regarding figure S7.*

Response: We are currently testing a plug in option as part of a collaboration with NASA's Jet Propulsion Laboratory, as they are interested in long-term deployment of the AMOD to support future satellite remote sensing missions. The intention is to achieve longer runtimes with less operator interaction. Depending on the success of these tests, we may transition the standard operation protocol to support continuous line power. However, for now, five day samples on battery power remain the default mode of operation.

11. ***Comment:*** *It is unclear why the authors present only 2.5 days of results when the devices are capable of 5 days of measurements.*

Response: Note that this section has been moved to the supplement. The units deployed were not fully charged before the sample. We did not realize this until after the samples terminated. We chose to include this test due to the broad range of air pollution levels covered in a short period of time. The original intention of this section was to highlight the advantages in automatic AOD data collection compared with the one-sample-per-day paradigm of the AMODv1. We analyze the ability of AMODv2 units to complete five-day samples in Section 3.3.

12. ***Comment:*** *This may be just my eyes, but Figure 4 doesn't look like it contains 426 data points.*

Response: We have verified that each panel in what was formerly Figure 4 contains 426 data points. Due to close agreement of AMODv2 units with other AMODv2 units, there is a high level of overlap of the data points, particularly at low AOD. We direct the reviewer to our open-access dataset that will be archived with the manuscript (https://hdl.handle.net/10217/225291).

13. ***Comment:*** *The Figure 2 shows one sampling interval rather than continuous sampling. The filter cartridge needs to be replaced and the instrument restarted. This should be included in the figure.*

Response: We have updated the caption to clarify the flowchart applies to a single sample as follows:

"Figure 2: Overall device operation flow diagram for a single sample. After each sample, the AMODv2 must be recharged for at least eight hours before a new sample can be started. Manual inputs require operator intervention. Automatic processes are executed with no operator intervention. Predefined processes are detailed in Supplemental Figs. S1-S6. Parallel processes are executed pseudo-simultaneously using a real-time operating system."

14. ***Comment:*** *Line 288 The authors discuss their sample deployment of co-located 10 AMOD units during a wildfire smoke event in Fort Collins, Colorado in October of 2021. I believe that they mean October 2020 since October 2021 has not yet occurred.*

Response: We have corrected the dates in the relevant supplementary material text.

15. ***Comment:*** *Line 374 The authors should clarify how they derived their expected error equations.*

Response: We have added lines 385-389 to further describe the equations:

"We derived expected error (EE) equations to constrain the error of AMODv2 measurements relative to AERONET as a function of AOD (following the form used in the validation of satellite AOD products compared to AERONET AOD). We derived the equations iteratively by adjusting the constant and linear terms until the bounds defined by Eqs. (4) through (7) each contained 85% of the co-located measurement pairs for each wavelength."

16. ***Comment:*** *Line 427. The authors are not comparing apples to apples here. First, they are comparing their component costs to commercial instruments, which are likely 5 to 10X the component costs.*

Response: We have removed this cost comparison.

17. ***Comment:*** *Further the GRIMM EDM is a Federal Reference Method. A more reasonable comparison would be a low-cost particulate matter sensor, i.e., Purple Air at $250 or something like the TSI DustTrak $5000 with a cyclone cut point and filters that can be weighed.*

Response: We have removed this cost comparison.

<u>Minor</u>

Comment: *Line 395 "by wavelength" is repeated*

Response: We have removed the repeated text.

Response Bibliography

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