

# Response to Reviewer Comments

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*Ground-Based Validation of Sentinel-5P TROPOMI Cloud Fraction Products  
using Calibration-Informed Low-Cost Multi-Spectral Sensors*

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We thank the reviewer for their careful and constructive reading of our manuscript. The comments are well-founded and will substantially improve the clarity and scientific integrity of the paper. We address each point in the order presented. All line numbers refer to the revised manuscript.

## General Comments

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### GC1

*The approach is well-considered; my primary concern is that there is too little quantitative information to draw meaningful conclusions, resulting from the relatively short sampling period and the limited precision of the derived cloud fraction. My main recommendation is that the paper be revised and resubmitted after a longer data collection period.*

**Response:** We fully agree. Continued data collection is ongoing at the DG2MCM-15 station, and we intend to incorporate an extended dataset in the revised manuscript. More importantly, the paper will be repositioned clearly as a methodology demonstration and proof-of-concept rather than a statistically mature validation study. The abstract, introduction, and conclusions will be revised to reflect this framing consistently throughout.

### GC2

*Cloud fraction conclusions are stated too strongly. The strong correlation reported is driven entirely by two points (Figure 2b); without these, correlation would be 0. Though noted in the discussion (lines 288–292), the message could be clearer throughout, especially in the abstract.*

**Response:** This is the most important criticism and we agree entirely. The revised abstract will remove the phrase 'strong agreement' and replace it with language that accurately reflects the quasi-categorical nature of the measurement: the method reliably discriminates between clear, partly cloudy, and overcast conditions, but the reported  $R = 0.879$  is driven by two high-cloud-fraction observations and the correlation near zero without these points. This caveat will be reinforced in the Introduction, Results, and Conclusions — not only in the Discussion as currently written.

### GC3

*I would suggest a binning approach for Figure 2: divide TROPOMI cloud fractions into 3 bins centered on the MLX90614 cloud fraction clusters (< 38%, 38–63%, > 63%) and produce a confusion matrix plot showing when measurements fell into the same broad bins vs. when TROPOMI and MLX90614 disagreed.*

**Response:** An excellent and well-suited suggestion. A confusion matrix based on the three bins proposed by the reviewer (< 38%, 38–63%, > 63%), aligned with the natural clustering of MLX90614 cloud fraction values, is a far more appropriate representation of the method's actual capabilities. We will implement this as a new panel in Figure 2, which will more clearly and honestly convey what the temperature-ratio approach can and cannot do for operational cloud screening.

## Specific Comments

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### SC — Title

*Suggest specifying 'cloud fraction product' rather than 'atmospheric products' in the title.*

**Response:** Agreed. The title will be revised to: "Ground-Based Validation of Sentinel-5P TROPOMI Cloud Fraction Products using Calibration-Informed Low-Cost Multi-Spectral Sensors". This more accurately reflects the scope of the validation results presented, since the aerosol index and trace gas products could not be meaningfully validated with the current sensor configuration.

### SC — Line 37

*Suggest adding reference to the Pandonia Global Network for trace gases.*

**Response:** A reference to the Pandonia Global Network ([pandonia-global-network.org](http://pandonia-global-network.org)) will be added at Line 37 alongside the existing AERONET and NDACC references, as an example of an established ground-based network for trace gas column validation relevant to TROPOMI NO<sub>2</sub> and O<sub>3</sub> products.

### SC — Lines 40–43

*The cited references (Schneider et al., 2019; Lewis et al., 2016) refer to in-situ air quality sensors, not low-cost remote sensing. Müller et al. (2020) is a PTR-TOF-MS instrument, which is not a low-cost method. More directly comparable prior work would include the GLOBE network and the Maritime Aerosol Network.*

**Response:** The reviewer is entirely correct — we apologise for these citation errors. The references at Lines 40–43 will be replaced with: the GLOBE citizen science network ([doi:10.1175/BAMS-D-19-0295.1](https://doi.org/10.1175/BAMS-D-19-0295.1)) as an established example of citizen-science satellite validation, and the Maritime Aerosol Network ([doi:10.1029/2008JD011257](https://doi.org/10.1029/2008JD011257)) as an example of low-cost handheld sun photometry for aerosol satellite validation. The Müller et al. (2020) reference will be removed as PTR-TOF-MS is a high-cost laboratory technique unrelated to the low-cost context of this study.

### SC — Lines 49–55

*Suggest moving instrumentation details into Section 2.*

**Response:** Agreed. The sensor specifications currently at Lines 49–55 will be moved to Section 2.1. The Introduction will retain only a brief characterisation of the station without technical specifications.

### SC — Section 2.1.2

*It might be useful to note the approximate cost of the instrumentation.*

**Response:** Thank you — this is directly relevant to the paper's low-cost focus. Approximate retail costs will be added in Section 2.1 when each sensor is introduced: MLX90614 infrared pyrometer (~€19), AS7341 11-channel spectrometer (~€30 per unit, ~€60 for the dual configuration), and the RAK4631 LoRa microcontroller with RAK19007 base board (~\$25 combined). The complete DG2MCM-15 station hardware costs approximately €150–200 including all sensors and GNSS module — contrasting sharply with the \$50,000–100,000 cost of professional reference sun photometers noted in Section 4.2.

### SC — Line 188

*Noting 348 overpasses is potentially misleading; Figure 1 indicates ~21 overpasses. This should be revised to distinguish between satellite overpasses and paired observations across different products.*

**Response:** The reviewer correctly identifies a terminological inconsistency. The 348 figure refers to satellite data product retrievals (observation pairs across four TROPOMI products), not distinct satellite overpasses (orbital passes of the spacecraft). Since cloud, ozone, and NO<sub>2</sub> products are retrieved on the same orbital pass, the 89 cloud product retrievals correspond to 89 distinct overpasses. The text will be revised throughout Section 3.1 to clearly distinguish these two quantities.

### SC — Lines 211–213

*The low precision of the measurements practically allowed only a few values of cloud fraction to be output. This can be emphasized more.*

**Response:** Agreed. Lines 211–213 will be strengthened to make clear that quasi-discrete clustering is a fundamental limitation of the temperature-ratio approach with a broadband 90° FOV thermometer: under Central European winter conditions, the instrument effectively produces only three distinguishable cloud fraction states and is better described as a three-state classifier (clear / partly cloudy / overcast) than as a continuous cloud fraction retrieval.

### SC — Line 221

*There do not seem to be examples of cloud fraction < 10% in the results.*

**Response:** Correct. Line 221 will be revised; the minimum observed cloud fraction in the dataset is approximately 20–25%. The absence of near-zero cloud fraction observations reflects the predominantly cloudy January–February conditions at the Kempten site combined with the positive spatial-mismatch bias of the method, and this will be noted explicitly.

### SC — Section 3.3

*Suggest moving this (and Table 1) earlier to Section 3.1, when the discussion of data matching takes place.*

**Response:** Agreed. Section 3.3 and Table 1 will be integrated into Section 3.1, establishing sample sizes before presenting the validation results.

### SC — Section 3.6

*This discussion can be moved earlier, to motivate the discussion in other sections.*

**Response:** Agreed. Section 3.6 (Trace Gas Products: Data Context) will be repositioned directly after Section 3.1, clearly establishing at the outset why trace gas products were co-located but not directly validated, avoiding confusion in later sections.

### SC — Lines 344–348

*These are important considerations for future work. The recommendation to use inter-sensor differences to constrain measurement uncertainties is an attractive approach that can be expanded on further.*

**Response:** Thank you. We will expand Section 4 to connect the dual-AS7341 strategy explicitly to the broader challenge of low-cost network calibration: in regions lacking formal calibration infrastructure, systematic inter-sensor differences at closely-spaced co-located instruments can serve as a field-deployable proxy for measurement uncertainty, enabling data quality control without laboratory reference standards. This approach is directly scalable to the type of citizen science network described in Section 4.2 and represents an important design principle for future network expansion.

### SC — Lines 352–354

*Also the Sentinel-4 mission, recently launched.*

**Response:** Thank you for this update. Sentinel-4 will be added to Lines 352–354. As a geostationary mission providing continuous daytime monitoring over Europe, Sentinel-4 is particularly relevant to the DG2MCM-15 station location and will require continuous ground-based validation that autonomous low-cost stations are well positioned to provide.

## Summary of Revisions

Reviewer Comment	Action
Reframe as proof-of-concept throughout	Abstract, Introduction, Conclusions revised
R=0.879 caveat — driven by two points	Explicit statement added to abstract
Confusion matrix for Figure 2	New panel (3-bin) implemented
Title: 'cloud fraction product'	Title revised
Pandonia Network reference (L37)	Added
Replace L40–43 references	GLOBE + MAN added; Müller (2020) removed
Move L49–55 instrumentation to Sect. 2	Done
Sensor costs in Sect. 2.1.2	MLX €19 · AS7341 €30 · RAK \$25 added
'348 overpasses' terminology	Revised: retrievals vs. overpasses clarified
Cloud fraction precision (L211–213)	Language strengthened
L221: no <10% observations	Line corrected
Sect. 3.3 + Table 1 → Sect. 3.1	Restructured

Sect. 3.6 moved earlier	Repositioned after Sect. 3.1
Inter-sensor uncertainty discussion	Expanded in Section 4
Sentinel-4 (L352-354)	Added

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*We are grateful for the reviewer's thorough and constructive engagement with this manuscript. The revisions will substantially improve the scientific rigour and practical value of this paper for the satellite validation community.*