



A log-domain method for decoupling environmental interference from hardware response in multi-filter calibration of forward-scatter visibility sensors

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Abstract. Accurate calibration of forward-scatter visibility sensors remains challenging because their response depends on instrument geometry and scattering conditions, while field calibration is additionally perturbed by background atmospheric extinction. Existing indoor multi-filter protocols can characterize sensor response under controlled conditions, but their transfer to outdoor operation is hindered by environmental contamination during reference measurements. Here, we propose a log-domain calibration framework that separates a hardware-dependent calibration factor, f_{cal} , from an environment-dependent interference term, f_{env} , by comparing paired darkroom and outdoor regressions of measured versus reference meteorological optical range (MOR). In this formulation, the darkroom intercept represents the hardware baseline, whereas the outdoor intercept contains both hardware and environmental contributions. The framework was evaluated using two forward-scatter sensor families, the Vaisala PWD22 and Biral SWS-200, with neutral-density filter sets and an LT31 transmissometer used to define model-specific reference meteorological optical range (MOR) values and monitor outdoor background visibility. The PWD22 exhibited near-unit darkroom slope and stable intercept transfer, allowing modest f_{env} contributions to be resolved under relatively clear outdoor conditions, whereas the SWS-200 was more sensitive to slope instability and filter-seating effects. In both cases, calibration improved bias more than scatter, so the framework is best viewed as a practical field-transfer method for suitable forward-scatter sensors that does not replace transmissometer-based traceability and remains conditional on sufficiently high background visibility and stable sensor slope.

1 Introduction

1.1 MOR measurement and the calibration challenge

Accurate observation of the Meteorological Optical Range (MOR) is a foundational requirement for aviation safety, synoptic meteorology, and autonomous transport systems (WMO, 2021; ICAO, 2010). Two optical instrument architectures dominate modern observing networks: transmissometers, which measure light attenuation directly across a fixed path (typically 30 m), and forward-scatter sensors, which infer visibility from the intensity of light scattered into a small receiver volume (~ 0.1 L) at a defined angle (WMO, 2021; Burnham, 1982) (Fig. 1). Transmissometers provide a path-integrated reference traceable to the



Bouguer–Beer–Lambert law, but their cost, infrastructure requirements, and alignment sensitivity limit their deployment density. Forward-scatter sensors are therefore the instrument of choice for dense synoptic networks worldwide (Crosby, 2003; Gultepe et al., 2019).

WMO (2021) does not prescribe a universal $\pm 10\%$ MOR accuracy across the full range; rather, the required uncertainty is 50 m below 600 m, 10 % from 600 to 1500 m, and 20 % above 1500 m. KMA (2023) adopts a broadly similar operational specification framework, while WMO (2021) indicates that the best transmissometers and forward-scatter meters may achieve errors of about 10 % over limited operating ranges under favourable conditions.

Ensuring the accuracy of forward-scatter sensors is, however, a persistent metrological challenge. Their response depends on both the fixed transceiver geometry and the wavelength- and size-dependent aerosol scattering phase function, which varies with meteorological conditions (WMO, 2021; Guo et al., 2021). As a result, forward-scatter sensors are not routinely calibrated on an absolute physical scale for field operation; in practice, their readings are generally referenced to a co-located transmissometer or equivalent traceable standard (Kim et al., 2015; Kim et al., 2021). A further complication arises during field calibration: any procedure that compares sensor output against a reference MOR is perturbed by background atmospheric extinction present at the time of the test. In an indoor darkroom, background scatter is negligible; outdoors, it contributes to the optical signal and displaces the apparent MOR reading. Without a principled framework for separating this environmental contribution from the hardware response, field calibration results remain ambiguous.

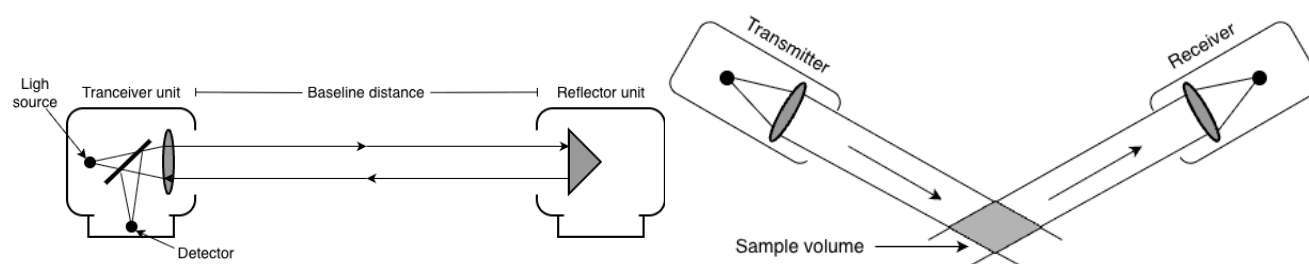


Figure 1: Left: transmissometer integrating optical attenuation across a 30 m baseline. Right: forward-scatter sensor interpreting pseudo-visibility from angular scattering within a ~ 0.1 L optical volume. Schematics adapted and redrawn from WMO (2021), *Guide to Instruments and Methods of Observation* (WMO-No. 8), Vol. I, Chapter 9, Figs. 9.2–9.5.

1.2 Existing calibration protocols and their limitations

The conventional field approach for forward-scatter sensor calibration uses Single Check Unit (SCU) plates — physical targets that intercept the optical beam and produce a reproducible signal. SCU plates offer operational simplicity but suffer from mechanical aging, optical drift, and contamination, and characterise only a single point on the sensor's response curve (Spitzer et al., 1997). WMO guidance places SCU use within a transmissometer-linked traceability chain, but because they sample only one operating point, maintaining defensible calibration across the full atmospheric dynamic range (fog through clear air) is practically difficult (WMO, 2021; Crosby, 2003; Spitzer et al., 1997).



To address this limitation, the Korea Research Institute of Standards and Science (KRISS) developed a comprehensive indoor protocol using calibrated neutral-density (ND) filter combinations to simulate atmospheric extinction across the full dynamic range (Kim et al., 2015; Kim et al., 2021). By inserting filter sets into the sensor's optical sampling volume in a darkroom and comparing the pseudo-MOR output against a transmissometer reference established at the Boseong Standard Observatory, NIMS (National Institute of Meteorological Sciences), the KRISS protocol produces a model-specific calibration curve for each sensor family (Park et al., 2015).

The KRISS protocol is, however, inherently a laboratory procedure. Transferring darkroom-derived calibration factors to field deployments requires that background extinction during outdoor testing be negligible relative to the filter-equivalent MOR — a condition that cannot be guaranteed in practice. No systematic framework currently exists for quantifying and correcting the environmental contamination that occurs when filter tests are conducted outdoors, and this gap limits the operational transferability of laboratory calibration results.

1.3 Objectives and scope

This study introduces a log-domain calibration framework that explicitly separates f_{cal} from f_{env} by operating in the logarithmic domain consistent with WMO multiplicative uncertainty conventions. The key insight is that background atmospheric extinction and hardware bias enter the forward-scatter measurement multiplicatively; in log-space they therefore appear as additive intercept terms distinguishable through paired darkroom and outdoor regression. This separation allows f_{cal} to be established reliably indoors and f_{env} to be estimated and corrected for during outdoor deployments.

The framework is evaluated using the Vaisala PWD22 and Biral SWS-200 with KRISS-assigned filter sets (Sets B and E) and an LT31 transmissometer as the metrological reference. Darkroom tests characterise the hardware baseline; outdoor filter tests under varying background conditions demonstrate the environmental decoupling; and a six-month continuous deployment at the NIMS Seogwipo testbed (August 2023 – February 2024) assesses long-term calibration performance.

The framework inherits the KRISS traceability architecture (Kim et al., 2015; Kim et al., 2021) and does not replace transmissometer-based referencing; its scope is a principled field-transfer mechanism for laboratory-derived calibration parameters, conditional on near-linear sensor behaviour, mechanically repeatable filter placement, and adequately clear outdoor background conditions. The novelty of the present study lies in using paired indoor and outdoor regressions to create a conditional field-transfer mechanism that separates a darkroom-defined hardware baseline from an environment-dependent outdoor intercept, while keeping the analysis within the existing transmissometer-based KRISS traceability framework.

2 Theoretical Framework

2.1 Log-domain multiplicative error model

The percentage-based MOR uncertainty framework used in WMO guidance motivates a multiplicative interpretation of calibration error, since a fixed proportional bias produces different absolute deviations across the MOR range: a sensor with



bias factor f over- or under-estimates all MOR values by the same proportional amount. The relationship between measured MOR (V_{meas}) and reference MOR (V_{ref}) is therefore $V_{meas} = f \cdot V_{ref}$. Taking natural logarithms linearises this relationship is $\ln(V_{meas}) = \ln(f) + \ln(V_{ref})$ (Fig. 2).

90 This log-linear form has two practical advantages. First, a single additive intercept in log-space corresponds to a percentage bias that is constant across the full dynamic range. The linear form in Eq. (1) is expected only when the sensor response can be approximated by a power-law relationship over the fitted MOR range; the method therefore treats log-linearity as an empirical property to be verified rather than assumed universally. Over the limited pseudo-MOR range studied here, such behaviour is physically plausible because the forward-scatter signal is governed by fixed transceiver geometry, approximately
 95 linear detector/electronic response, and firmware scaling that can often be approximated locally by a power-law mapping between pseudo-MOR and reference MOR. Second, the log transformation tends to reduce heteroscedasticity in visibility calibration data and provides a more stable basis for linear regression across a wide MOR range (Crosby, 2003).

For a multi-filter calibration sequence in which V_{ref} is varied by inserting filter combinations of known optical density, the log-linear relationship becomes:

$$100 \quad \ln(V_{meas}) = a_{ln} \cdot \ln(V_{ref}) + C. \quad (1)$$

where a_{ln} is the log-domain slope (ideally unity for a geometrically linear sensor) and C is the log-domain intercept representing the cumulative multiplicative bias. Departure of a_{ln} from unity indicates a range-dependent response that cannot be corrected by an intercept shift alone; the validity of the decoupling framework therefore rests on the sensor exhibiting $a_{ln} \approx 1$. In the present study, “sufficient log-linearity” is judged operationally by near-unit darkroom slope together with a confidence
 105 interval that remains close to unity; in practice, slopes within approximately ± 0.05 of unity were found to retain interpretable intercept separation, whereas larger departures degraded physical identifiability.

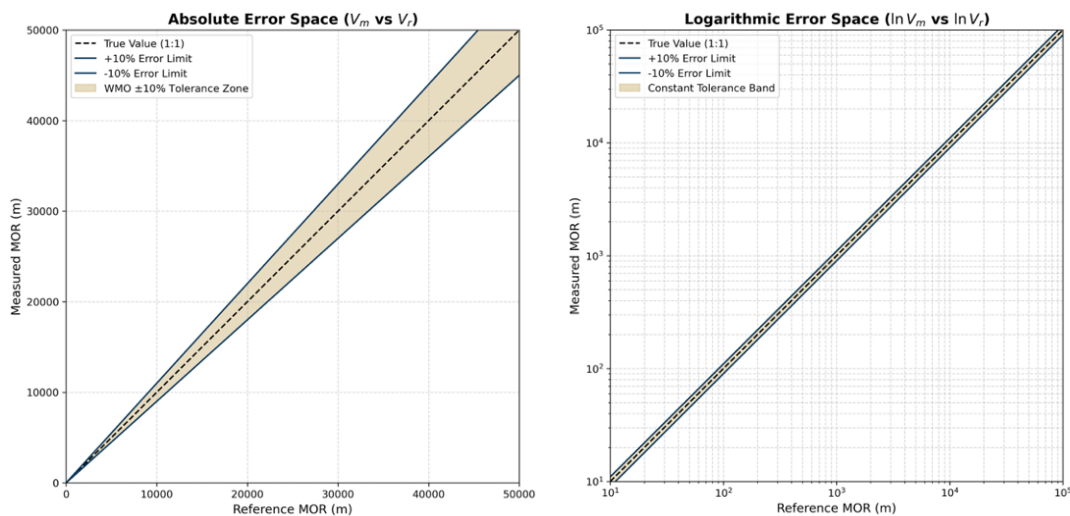


Figure 2: Comparison of measurement error structure in linear (left) and logarithmic domains (right). The multiplicative bias f appears as a constant proportional offset in linear space and as an additive shift in log-space, regardless of absolute MOR.



110 2.2 Separation of f_{cal} and f_{env}

The cumulative log-intercept C in Eq. (1) has two physically distinct contributions. In a darkroom where background scatter is zero ($V_{bg} \rightarrow \infty$), no environmental interference is present and the intercept reflects only the hardware optical response of the sensor:

$$C_{dark} = \ln(f_{cal}). \quad (2)$$

115 Outdoors, background atmospheric extinction adds to the measured signal, introducing an environment-dependent term:

$$C_{out} = \ln(f_{cal}) + \ln(f_{env}). \quad (3)$$

where $f_{env} = 1$ when background scatter increases the apparent scattering coefficient. The environmental interference is then isolated as:

$$\ln(f_{env}) = C_{out} - C_{dark}. \quad (4)$$

120 In the present formulation, environmental contamination enters the regression primarily as an additive intercept shift in log space, because background extinction superposes on the calibration signal as a multiplicative bias factor f_{env} ; by contrast, the hardware slope a_{ln} is treated as an intrinsic property of the sensor response and is not assumed to change under the short-duration outdoor filter tests themselves (Fig. 3). When the slope remains stable, the vertical offset between the darkroom and outdoor regressions corresponds directly to $\ln(f_{env})$, so Fig. 3 can be read as a graphical representation of the intercept-based
 125 environmental correction. In this formulation, $\ln(f_{env})$ is treated as approximately constant across a given filter set, although the exact harmonic-sum relation implies weak dependence on V_{cal} ; the intercept-based separation is therefore a first-order approximation whose validity improves as V_{bg}/V_{cal} becomes large over the full filter range. The separation is practically identifiable only when three conditions are satisfied: (1) the darkroom slope remains close to unity, so that intercept and scale are not strongly entangled; (2) the darkroom baseline is effectively free of environmental extinction, so that the indoor intercept isolates hardware response; and (3) filter placement is mechanically repeatable, so that intercept shifts reflect optical response rather than sequence artefacts. Violation of condition (1) couples intercept and scale and can produce apparent environmental
 130 corrections with the wrong magnitude; violation of condition (2) inflates the inferred f_{cal} ; and violation of condition (3) can bias either f_{cal} or f_{env} upward or downward depending on the sign of the filter-placement error.

This subtraction is exact when the same sensor unit is used in both regressions. When a second unit is used, it requires separate
 135 evidence that the darkroom baseline is transferable between units of the same model. Given estimates of $\ln(f_{cal})$ and a_{ln} from the darkroom regression, the corrected MOR for any raw field observation V_{meas} is:

$$\ln(V_{corrected}^{out}) = \frac{\ln(V_{meas}) - C_{out}}{a_{ln}}. \quad (5)$$

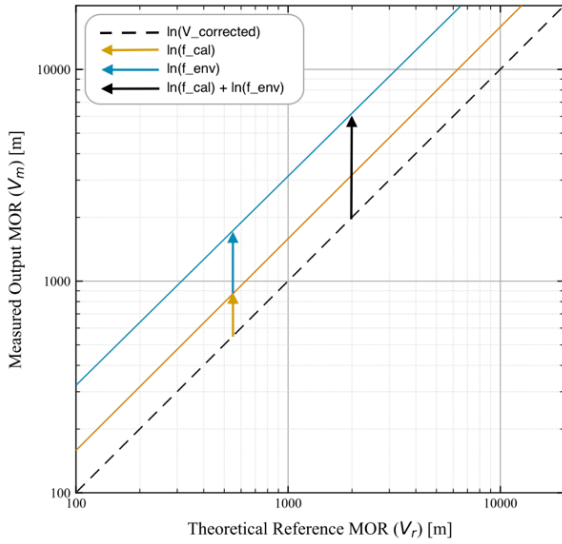


Figure 3: Schematic decomposition of the log-domain intercept. The darkroom intercept isolates f_{cal} ; the outdoor intercept captures the combined $f_{cal} \cdot f_{env}$; their difference yields f_{env} .

2.3 Sensor geometry and filter model variance

Different forward-scatter sensor families use distinct transceiver intersection angles (typically 35° – 45°), so the same ND filter produces different pseudo-MOR values on different instrument models. The reference MOR values (V_r) associated with each filter combination are therefore established model-by-model during the KRISS operated outdoor cross-calibration at the Boseong Standard Observatory, NIMS, rather than computed from filter optical density alone (Kim et al., 2021). Traceability is maintained through the geometry-specific V_r values, not through a universal MOR assignment per filter (Boudala et al., 2021).

2.4 Background constraint

Because forward-scatter visibility is inversely proportional to the optical scattering coefficient, the measured field MOR (V_{meas}) during a filter test is related to the filter-equivalent calibration MOR (V_{cal}) and the ambient background visibility (V_{bg}) by:

$$\frac{1}{V_{meas}} = \frac{1}{V_{cal}} + \frac{1}{V_{bg}}. \quad (6)$$

The fractional contamination of the calibration signal by background scattering is approximately V_{cal}/V_{bg} . If a 10 % tolerance is adopted as a practical benchmark for contamination control, then the tolerance threshold:

$$V_{bg} > 10 \times V_{cal}. \quad (7)$$

From Eq. (6), setting $V_{bg} = 10 \cdot V_{cal}$ makes the background term contribute 10 % of the calibration extinction in the simple additive-extinction model used here. A less restrictive criterion would permit larger contamination, whereas a stricter one



would reduce it at the cost of fewer usable outdoor calibration opportunities. This $10\times$ rule is adopted here as a practical criterion for limiting background contamination during outdoor filter tests. It does not make the environmental contribution exactly constant across all filter combinations, but bounds it to a first-order level that is small enough for intercept-based approximation.

For a filter producing $V_{cal} \approx 5,000\text{ m}$, a background exceeding $50,000\text{ m}$ is required — achievable only under very clear conditions at most sites. The constraint is more easily satisfied by higher-OD filters that produce lower V_{cal} values, and explains why reliable outdoor decoupling requires conditions substantially clearer than the filter-equivalent MOR.

A separate limitation arises at the clear-range end of the filter set. When the filter-equivalent reference MOR becomes very large, the induced optical extinction becomes weak, so both the transmissometer and the forward-scatter sensor approach their practical low-signal open-range regime and the variance of the log-domain fit increases. In the present dataset, this effect became appreciable for $V_r < 8,000\text{ m}$; accordingly, extraction of f_{cal} and f_{env} was restricted to $V_r < 8,000\text{ m}$. This threshold is empirical and study-specific rather than universal.

2.5 SI Traceability Chain

Executing the log-decoupling protocol requires confidence in the reference MOR values assigned to each filter combination. WMO treats transmissometers as the closest practical instrumental realization of atmospheric optical extinction measurement and as the reference class for scatter-meter traceability (WMO, 2021; Park et al., 2015). The traceability chain leading to the certified V_r values used in this study proceeds through five sequential stages:

1. SI traceability — the physical transmittance hierarchy defines the absolute optical scale through calibrated radiometric reference values. WMO provides the observational framework for MOR definition and uncertainty classification, but is distinct from the SI traceability chain.
2. Cross-calibration at the MOR standard site — prior to the present study, KRISS established model-specific reference MOR values by co-locating a reference transmissometer and reference scatterometers at the Boseong Standard Observatory under clear, spatially homogeneous conditions; the reference scatterometer was aligned to a transmissometer baseline, such as the Vaisala LT31.
3. Multi-filter and zero calibration in darkroom — the calibrated reference scatterometer is moved indoors; zero background is verified; KRISS assigned OD filter sets are inserted sequentially into the optical sampling volume.
4. V_r certification — the pseudo-MOR recorded by the reference instrument under each filter combination is certified as V_r for that specific filter set and sensor geometry.
5. Field deployment — V_r anchors traceability; f_{cal} and f_{env} decoupling resolves hardware and environmental contributions.

Stages 1–4 constitute the established KRISS architecture (Kim et al., 2015; Kim et al., 2021). Stage 5 — the principled field-transfer mechanism — is the contribution of the present study.



190 **3 Method**

3.1 Instruments and filter sets

The framework was evaluated using two forward-scatter sensor families: the Vaisala PWD22 (units A01 and B01) and the Biral SWS-200 (unit B03). All three sensors are single-axis forward-scatter instruments with manufacturer-specified transmitter–receiver intersection angles in the range 42°–45°, namely 45° for the Vaisala PWD22 and 42° for the Biral SWS-200. A Vaisala LT31 transmissometer, operating over a 30 m total optical path, served as the field reference for background MOR and for the outdoor cross-calibration chain (Snyder et al., 2024). The overall experimental context is summarized in Fig. 4, which shows the Seogwipo outdoor observation site, the locations of the NIMS-operated Seogwipo and Boseong facilities, and the indoor and outdoor multi-filter measurement configurations used in this study.

Although the original KRISS protocol includes filter sets A–E, only sets B and E were used here, as they span the low-to-middle pseudo-MOR range most relevant to the present darkroom-to-field transfer experiment (Table 2). Each set comprises combinations of individual ND glass filters mounted on the transmitter and receiver apertures to produce pseudo-MOR values spanning approximately 200–5,000 m. Model-specific reference MOR values (V_r) for each filter combination were assigned by KRISS through outdoor cross-calibration at the Boseong Standard Observatory, NIMS (Sect. 2.3; Kim et al., 2021).



205 **Figure 4: Experimental setting and site context of the present study. Top left: aerial view of the NIMS outdoor visibility-instrument**
test site at Seogwipo, Jeju Island, South Korea, showing the reference transmissometer (“Ref”) and the forward-scatter sensor
positions used in the broader observation array. Right: map of South Korea showing the locations of the NIMS headquarters and
test site at Seogwipo (orange marker) and the Boseong standard observation site (blue marker), both operated by the National
Institute of Meteorological Sciences (NIMS), Korea Meteorological Administration (KMA). Map data © 2026 Google. Bottom left:
210 **indoor darkroom configuration of a forward-scatter sensor equipped with the multi-filter mount used for controlled calibration**
measurements. Bottom centre: outdoor configuration of the same multi-filter mounting concept used during field filter tests.



3.2 Darkroom protocol

Darkroom measurements used in this study were conducted in the NIMS optical laboratory in Jeju under optically controlled conditions, following the protocol of Kim et al. (2015) (Table 1). Opaque light-blocking fabric shrouded the optical assembly and all ambient illumination was extinguished to establish an effectively zero-background baseline for the purpose of filter calibration ($V_{bg} \rightarrow \infty$ in the idealized formulation).

Table 1: Decoupling dataset acquisition schedule.

Instrument Model	Filter Set	Test Environment	Acquisition Date
Vaisala PWD22 (A01)	Set B	Indoor (Darkroom)	19 & 23 July 2024
	Set E		18 & 23 July 2024
Vaisala PWD22 (B01)	Set B	Indoor Darkroom	07 & 08 August 2024
	Set E		09 August 2024
	Set B	Outdoor Field	04 & 05 September 2024
	Set E		06 & 07 September 2024
Biral SWS-200 (B03)	Set B	Indoor Darkroom	05 August 2024
	Set E		02 August 2024
	Set B	Outdoor Field	10 & 11 September 2024
	Set E		12 & 13 September 2024

Operationally, this condition was confirmed when the unfiltered darkroom reading reached the instrument's open-range maximum (approximately 20,000 m for the sensors used here), indicating negligible residual background extinction relative to the calibration signals. Zero calibration was performed before each filter sequence to verify the baseline state. ND filter combinations from Sets B and E were then inserted sequentially into the optical sampling volume (Table 2). Each sequence comprised a full repetition of the complete filter-combination series for the relevant set and sensor unit. The pseudo-MOR recorded under each filter combination, referenced against the corresponding V_r , constitutes the darkroom dataset for log-domain regression.

When two units of the same sensor model exhibit nearly identical darkroom multi-filter regression properties, they may be treated as sharing the same effective optoelectronic response, so that one unit can serve as a field-transfer proxy for the other, subject to subsequent validation under operational conditions.

Table 2: Multi-Filter Combination and Reference MORs

Instrument model	Filter combination	
	Set B	Set E



	Transmitter	Receiver	Reference MOR (V_r) [m]	Transmitter	Receiver	Reference MOR (V_r) [m]
Vaisala PWD22	None	ND1.0	209	None	ND1.0	252
	ND0.5	ND1.0	471	ND0.5	ND1.0	620
	ND0.6 + ND0.3	ND1.0	810	ND0.6 + ND0.3	ND1.0	1,056
	ND1.0	ND1.0	1,222	ND1.0	ND1.0	1,440
	ND1.3	ND1.0	1,619	ND1.3	ND1.0	1,783
	ND2.0	ND1.0	4,895	ND2.0	ND1.0	4,921
Biral SWS200	ND0.3	ND0.6	230	ND0.3	ND2.0	240
	ND0.3 + ND0.5	ND0.6	640	ND0.3 + ND0.5	ND0.6	720
	ND1.3	ND0.6	1,630	ND1.3	ND0.6	1,440
	ND1.3 + ND0.4	ND0.6	3,460	ND1.3 + ND0.4	ND0.6	2,860
	ND2.0	ND0.6	5,800	ND1.3 + ND0.4	ND0.6	4,600

230 **3.3 Outdoor filter testing**

Outdoor filter tests were conducted at the NIMS Seogwipo testbed on Jeju Island, South Korea. Sensors were mounted at manufacturer-specified heights and orientations to minimise structural reflections and direct solar blinding. The identical filter combinations used in the darkroom were applied in the field (Table 1); the sun was physically blocked during filter exchanges to prevent solar interference. Session-specific LT31 background MOR statistics for the adopted outdoor calibration events are summarized in Table 4 and interpreted against the 10× criterion in Sect. 4.2.

235 **3.4 Long-term deployment and data processing**

Continuous MOR observations from PWD22 A01 and SWS-200 B03 were recorded alongside the LT31 reference at the NIMS Seogwipo testbed (33°15'34"N, 126°31'04"E, altitude 176 m MSL) from 17 August 2023 through February 2024. This start date corresponds to the earliest point at which both sensors were simultaneously operational, ensuring all comparisons span an identical window. The darkroom and outdoor calibration campaigns described in Sect. 3.2–3.3 were conducted in 2024, after the long-term deployment period analysed here; the correction is therefore applied retrospectively and assumes that the relevant hardware response remained stable over that interval.

Raw 1-minute data were processed with a 10-minute trailing rolling average prior to log-domain regression. This integration interval reduces the effect of spatial inhomogeneity between the ~0.1 L point-sampling volume of the scatter sensors and the



245 30 m path-integrated transmissometer baseline (WMO, 2021; Griggs et al., 1990; Waas, 2008); a 10 min window was adopted as a practical compromise: short enough to preserve low-visibility event structure, but long enough to increase the likelihood that advecting fog or haze filaments influence both instruments within the same comparison interval. Secondary interference sources specific to unshielded forward-scatter receivers — transient solar glare, localised reflections, and biological contamination — are also attenuated by time-averaging.

250 *NaN* masking was applied uniformly: PWD22 A01 readings equal to exactly 7,999 m or exceeding 19,500 m were excluded (saturation and open-range flags); SWS-200 B03 readings equal to exactly 20,000 m were excluded (saturation); Vaisala LT31 readings exceeding 14,000 m were excluded as open-range values, because above this level the reference transmissometer approaches its practical clear-air operating ceiling and the analysis becomes dominated by weak-extinction cases in which calibration differences are both less stable and less informative. No additional smoothing or manual event classification was

255 applied beyond the stated masking and rolling-average procedure. After applying the instrument-specific masking rules, only timestamps for which the PWD22, SWS-200, and LT31 all returned simultaneous MOR values greater than zero were retained for analysis. For f_{cal} and f_{env} extraction, data were further restricted to $V_r < 8,000$ m to maintain adequate optical SNR (Sect. 2.4).

4 Results

260 4.1 Darkroom characterisation

This section evaluates the stability and linearity of the indoor darkroom regressions that define the baseline hardware calibration term f_{cal} . Table 3 summarises the log-domain regression statistics for each instrument, filter set, and sequence using Eq. (1). Although Table 3 includes both indoor and outdoor regressions for completeness, the present subsection discusses only the indoor darkroom results; the outdoor regressions are interpreted in Sect. 4.2. Reported slope and intercept

265 values are given as estimate $\pm$ standard error, with 95 % confidence-interval half-widths listed separately as $Cl_{a_{in}}$ and Cl_C ; the *Point CV*(%) column represents the mean pointwise measurement coefficient of variation computed from the 1-minute statistics and is not a regression-residual metric.

PWD22 units A01 and B01 produced consistent darkroom regressions across both filter sets: indoor slopes ranged from $a_{in} \approx 0.964$ to 1.001 and all R^2 values exceeded 0.999. For filter set B, intercept confidence intervals were tightly constrained

270 ($Cl_C \approx 0.014 \sim 0.015$) for both units, and the close agreement between A01 and B01 indoor intercepts is consistent with the possibility of intercept transfer between nominally identical hardware. Filter set E of A01 showed wider intercept confidence intervals (up to $Cl_C \approx 0.061$), consistent with the smaller number of high-optical-density reference points at the upper end of the fitted range. This broadening mainly affects confidence in the fitted intercept rather than the basic monotonicity of the darkroom response. The SWS-200 B03 darkroom regressions were more variable. Set B retained near-unit slopes but with

275 broader slope and intercept confidence intervals than PWD22 ($Cl_{a_{in}} \approx 0.029$, $Cl_C \approx 0.065 \sim 0.066$). In set E, Sequence 1



returned an anomalous slope ($a_{ln} \approx 1.113$) and a strongly shifted intercept ($C \approx -0.804$), inconsistent with other sequences. Sequence 2 recovered a near-unit slope ($a_{ln} \approx 0.982$) with a positive intercept ($C \approx 0.163$), suggesting that the Sequence 1 result was more likely caused by mechanical variation in filter seating than by a stable intrinsic nonlinearity of the sensor. Accordingly, the Sequence 2 parameters are adopted for subsequent SWS-200 corrections.

280 **Table 3: Log-domain regression statistics for indoor darkroom and outdoor filter tests. Slopes and intercepts are reported as estimate $\pm$ standard error; $CI_{a_{ln}}$ and CI_C denote 95 % confidence-interval half-widths, and CV denotes the mean pointwise coefficient of variation derived from the 1 min observations.**

Environment	Instrument	Filter set	Sequence	Slope (a_{ln})	$CI_{a_{ln}}$ (95 %)	Intercept (C)	CI_C (95 %)	R^2	Point CV (%)
Indoor	PWD22_A01	B	1	0.993 ± 0.002	0.006	-0.007 ± 0.014	0.014	0.999	0.546
		B	2	0.992 ± 0.002	0.006	0.005 ± 0.015	0.015	0.999	0.643
		E	1	0.965 ± 0.008	0.023	0.147 ± 0.061	0.061	0.999	0.472
		E	2	0.964 ± 0.006	0.017	0.146 ± 0.045	0.045	0.999	0.546
	PWD22_B01	B	1	0.996 ± 0.001	0.002	-0.024 ± 0.005	0.005	1.000	0.796
		B	2	1.001 ± 0.002	0.005	-0.068 ± 0.012	0.012	1.000	0.478
		E	1	0.996 ± 0.002	0.006	-0.075 ± 0.016	0.016	1.000	0.703
		E	2	0.996 ± 0.002	0.007	-0.075 ± 0.017	0.017	1.000	0.711
	SWS200_B03	B	1	0.998 ± 0.009	0.029	-0.057 ± 0.065	0.065	0.998	0.221
		B	2	0.999 ± 0.009	0.029	-0.064 ± 0.066	0.066	0.998	0.297
		E	1	1.113 ± 0.017	0.055	-0.804 ± 0.101	0.101	0.995	0.224
		E	2	0.982 ± 0.009	0.029	0.163 ± 0.069	0.069	0.999	0.267
Outdoor	PWD22_B01	B	1	0.968 ± 0.005	0.015	0.125 ± 0.039	0.039	0.999	1.174
		E	1	0.973 ± 0.007	0.020	0.097 ± 0.053	0.053	0.999	1.637
	SWS200_B03	B	1	0.995 ± 0.005	0.017	0.017 ± 0.039	0.039	0.999	0.220
		E	1	1.003 ± 0.004	0.013	0.033 ± 0.029	0.029	1.000	0.258

4.2 Environmental decoupling: darkroom vs. outdoor

Figure 5 presents the six-panel comparison between indoor darkroom and outdoor filter-test regressions for sensor units A01, B01, and B03 under filter sets B and E. Each panel compares the regression obtained in the indoor darkroom with its
 285 corresponding outdoor regression for the same sensor unit and filter set, so that environmental interference appears primarily as a relative shift between the fitted lines. For the PWD22 units, the outdoor regression lines are consistently displaced from their darkroom counterparts by $\Delta C = C_{out} - C_{dark}$ (Eq. 4), indicating that the environmental contribution $\ln(f_{env})$ is resolvable and broadly consistent with the relatively clear background MOR monitored by LT31 during each test day. Under



the relatively clear conditions sampled here ($V_{bg} \approx 15,000$ m), the recovered f_{env} remained close to unity for the PWD22, consistent with the expectation that background interference should be small when the background MOR substantially exceeds the lower- V_r filter combinations. This interpretation is consistent with the theoretical interference relation shown in Fig. 6, which indicates that calibration events conducted near $V_{bg} \approx 15,000$ m should lie in a low-interference regime for the lower- V_r filter combinations. For the SWS-200 B03, the outdoor intercepts were closer to the darkroom baseline, consistent with the session-specific LT31 background MOR values summarized in Table 4; however, because the SWS-200 also exhibited weaker slope stability, this smaller offset should not be interpreted as stronger overall calibration robustness. Taken together, these results are best viewed as a consistency check showing that the observed outdoor regression shifts are compatible with the expected low-interference regime, rather than as a full empirical validation of the interference model over a wide range of background MOR.

Table 4: Summary of adopted indoor and outdoor regression intercepts for the decoupling experiments and the corresponding inferred environmental factors. For the PWD22, the B01 outdoor sequence was used as the field-transfer proxy for A01, as discussed in Sect. 4.2 and Sect. 5.3. LT31 MOR values are based on 1 min measurements averaged over the period 10:00–14:00 local time on the day of each outdoor calibration session. The LT31 maximum reported MOR in this dataset is 15,000 m. The final column indicates whether the resulting f_{env} is interpreted as a physically meaningful environmental contribution or only as an empirical correction coefficient.

Sensor unit	Filter set	Darkroom seq.	Outdoor seq.	C_{dark}	C_{out}	f_{env}	LT31 MOR (mean $\pm$ SD)	Interpretation
PWD22	B	1	1	-0.024	0.125	1.161	15,000 $\pm$ 0 m	Physical
A01: baseline								
B01: outdoor	E	1	1	-0.074	0.097	1.187	13,281 $\pm$ 2,140 m	Physical
SWS-200 B03	B	1	1	-0.057	0.017	1.077	14,407 $\pm$ 2,057 m	Physical, but sensitive
	E	2	1	0.163	0.033	0.878	14,975 $\pm$ 194 m	Empirical only

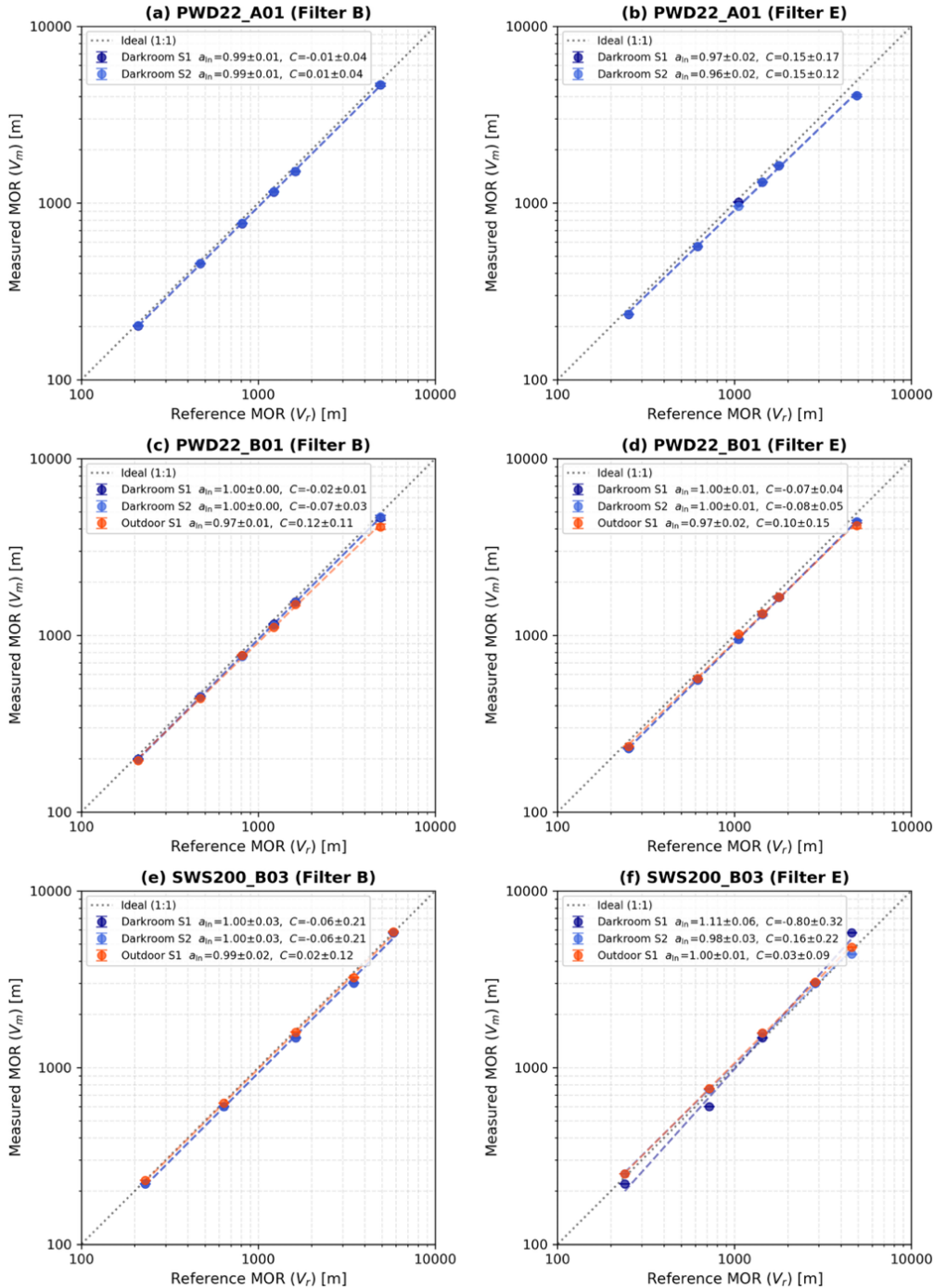


Figure 5: Six-panel comparison of darkroom and outdoor log-domain regressions for sensor units A01, B01, and B03 under filter sets B and E. Blue lines denote indoor darkroom regressions and red lines denote outdoor regressions. For PWD22, outdoor lines are primarily displaced through intercept shifts, consistent with resolvable environmental contamination; for SWS-200, one sequence also exhibits slope instability, indicating that intercept-based decoupling is less robust when the hardware response is not repeatably linear.

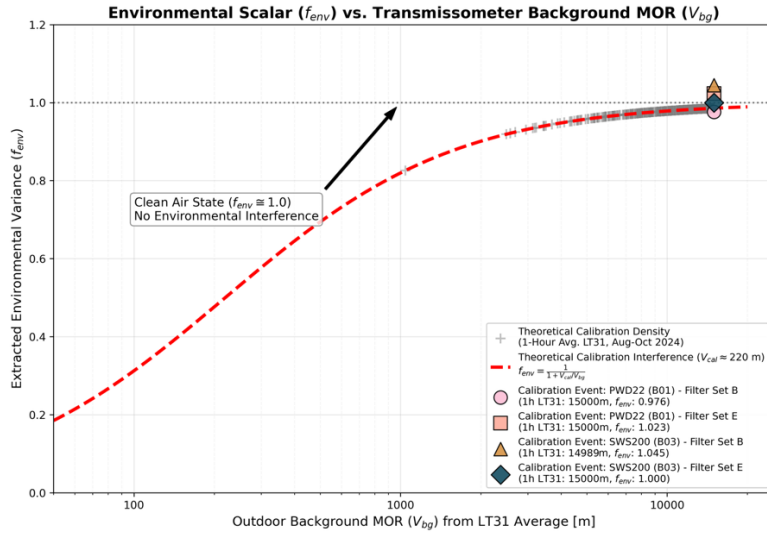


Figure 6: Effect of background visibility on the fractional contamination of the calibration signal. The $10\times$ rule ($V_{bg} > 10 \times V_{cal}$) defines the practical threshold below which background scattering remains within WMO tolerance. Session-specific calibration conditions are summarized in Table 4 and described in Sect. 3.3.

4.3 Long-term field validation (17 Aug 2023 – Feb 2024)

4.3.1 Temporal overview

The calibration correction applied to continuous outdoor data derives from the intercept-decoupling procedure of Sect. 4.2.

For each sensor and filter set, the darkroom regression yields $\ln(f_{cal})$ and a_{ln} (Table 3); the corresponding outdoor field intercept $C_{out} = \ln(f_{cal}) + \ln(f_{env})$ is obtained from measurements taken under relatively clear background conditions and interpreted against the $10\times$ criterion of Sect. 2.4.

The correction applied to each raw MOR observation V_m follows Eq. (5). For the PWD22, the adopted hardware baseline $\ln(f_{cal})$ and a_{ln} were taken from the A01 darkroom calibration, while the outdoor intercept C_{out} was taken from the B01 field-transfer sequence; for the SWS-200 B03, Set B uses Seq. 1 and Set E uses the mechanically stable Seq. 2 values. This mixed indoor–outdoor pairing for the PWD22 reflects the same-model transfer assumption discussed in Sect. 5.3, under which the A01 darkroom baseline and the B01 outdoor field-transfer intercept are treated as compatible realizations of the same sensor family.

Under the stated masking rules, 73,608 valid A01 records, 49,135 valid B03 records, and 59,709 valid LT31 reference records were retained over the deployment period. Figure 7 presents the temporal evolution of MOR observations as log-scale dot plots for both sensors against the LT31 reference.

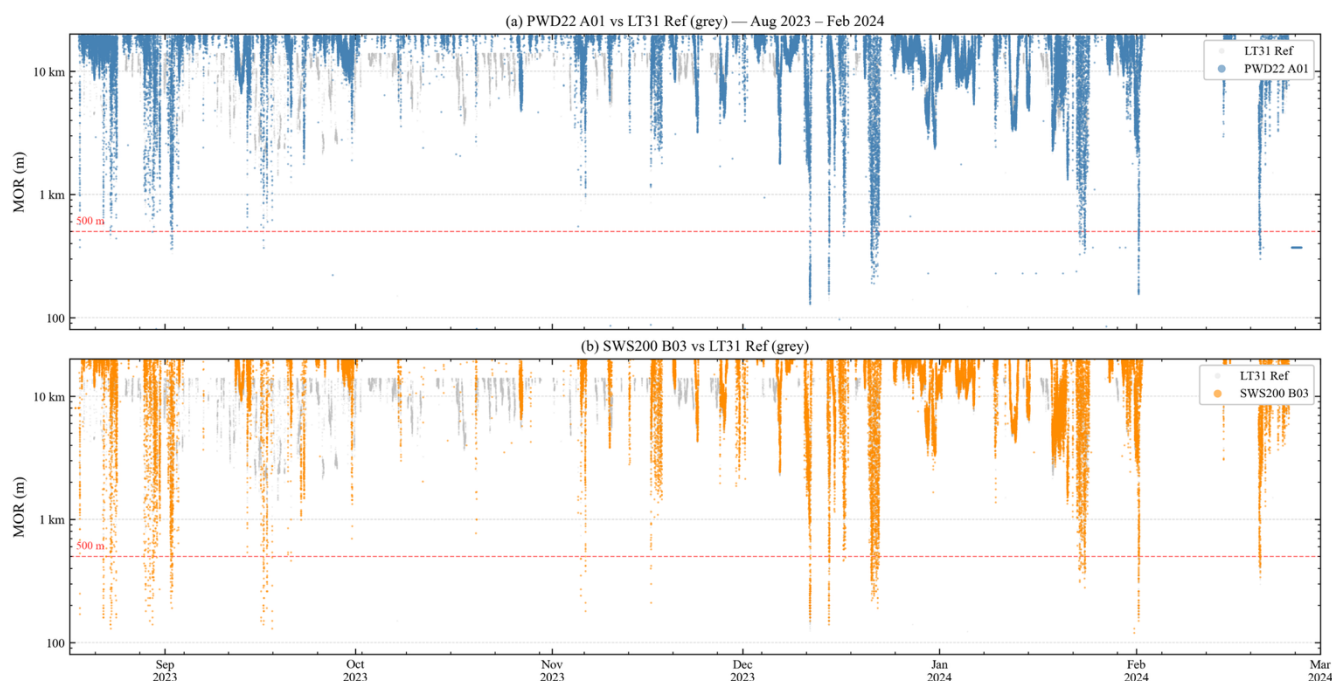


Figure 7: Log-scale dot plots comparing (a) PWD22 A01 (blue) and (b) SWS-200 B03 (orange) against LT31 reference (light grey) from 17 August 2023 to February 2024. Dashed red line marks the 500 m fog-aviation threshold. Valid data counts: LT31 = 59,709; A01 = 73,608; B03 = 49,135.

A clear asymmetry is evident in the sub-500 m regime. The PWD22 A01 tracks the LT31 closely throughout the record, crossing below 500 m only during episodic events simultaneously confirmed by LT31 depression — genuine fog or dense haze. In contrast, the SWS-200 B03 exhibits persistent sub-500 m readings scattered across the entire record, including extended intervals where the LT31 remains well above 1,000 m. This is consistent with a tendency of the SWS-200 to over-report scattering at low MOR, consistent with its sub-unit long-term OLS (ordinary least squares) slope (~ 0.94) that amplifies small-signal responses relative to the 1:1 reference.

4.3.2 PWD22 A01: scatter analysis and calibration performance

Figure 8 presents the 2×3 panel analysis for PWD22 A01 ($n = 33,152$ valid pairs). In the raw state (panel a), the OLS slope in log space is 0.90, with Pearson $r = 0.843$, log-RMSE = 0.190, and global log-bias $\mu = -0.010$. Direct outdoor filter calibration of PWD22 A01 could not be performed during the campaign because the instrument was committed to concurrent observational use in other projects. The outdoor calibration parameters derived from PWD22 B01 were therefore transferred to A01, under the assumption — supported by their nearly identical darkroom multi-filter regressions — that the two units were optoelectronically equivalent realizations of the same sensor model. Accordingly, the improved long-term performance obtained for A01 should be interpreted as conditional on the assumption that its relevant hardware response remained stable between the deployment interval and the later 2024 calibration campaign.



The sub-unit slope indicates a compressed response in log space, corresponding to overestimation at low MOR and underestimation at high MOR relative to the LT31 reference. Only 16.7 % of observations fall within the WMO ± 10 % tolerance. Applying the Set-B correction shifts the global log-bias to $+0.020$ and improves WMO compliance to 22.4 % (Fig. 8e), with little change in RMSE (0.192). Because this correction acts primarily through an intercept shift, the long-term OLS slope remains essentially unchanged at 0.90. Applying the Set-E correction produces a stronger improvement in WMO compliance to 37.1 % (Fig. 8f). However, it also yields a more positive residual bias ($\mu = +0.062$) and a slightly larger RMSE (0.204). This behaviour is consistent with the non-unit darkroom slope of the Set-E fit, which modifies both intercept and effective scaling rather than acting as a pure translation. Although the outdoor calibration sessions were conducted under relatively clear conditions, the fitted outdoor–indoor intercept differences still imply modest positive environmental contributions, with $f_{env} \approx 1.161$ for Set B and $f_{env} \approx 1.187$ for Set E. Thus, the PWD22 outdoor calibrations were carried out in a low-interference regime, but not in a strictly interference-free one. The stacked residual histograms confirm that the residual distribution is dominated by the $> 10,000$ m LT31 bin, consistent with the predominantly clear-sky conditions at this coastal site.

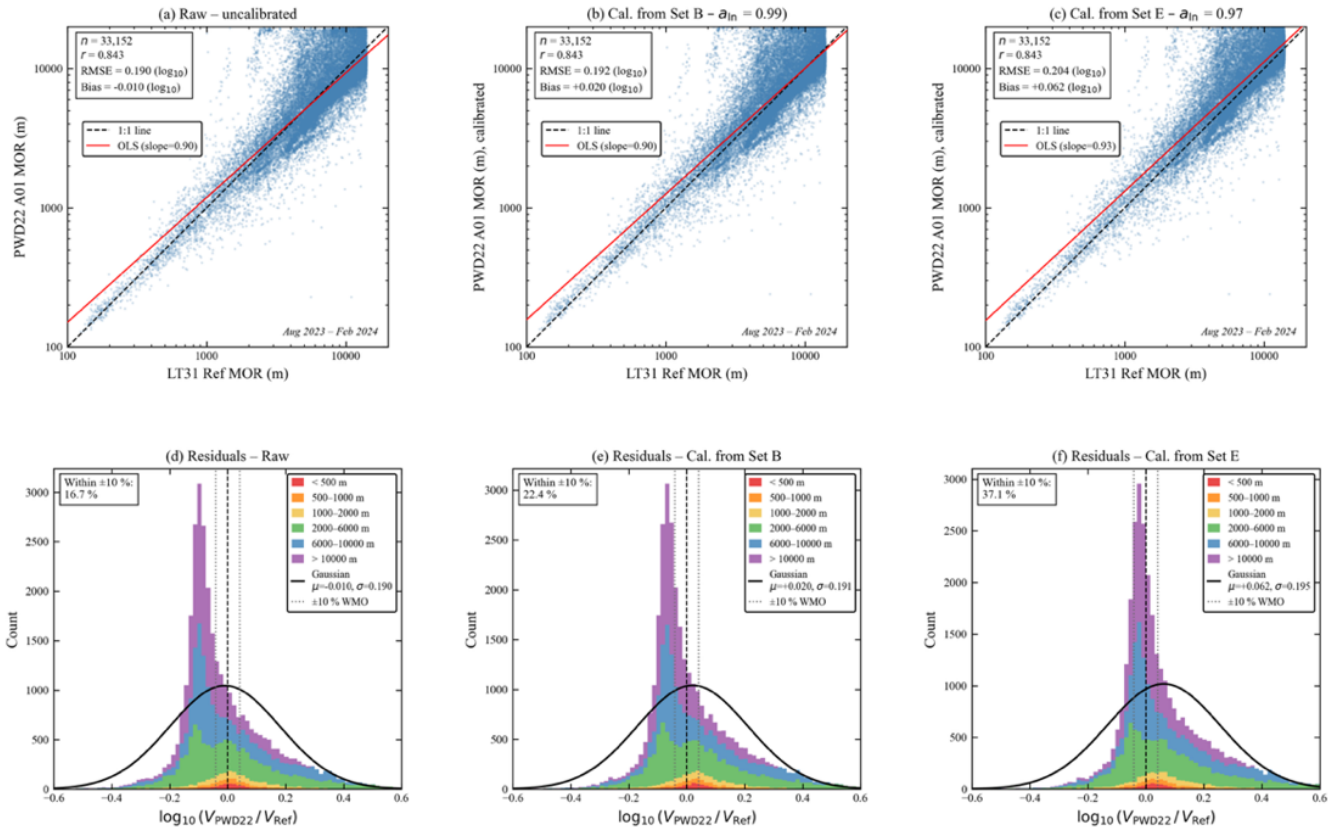


Figure 8: Top row: log–log scatter plots for (a) raw Vaisala PWD22 A01 (17 Aug 2023 – Feb 2024), (b) Set-B calibrated, and (c) Set-E calibrated MOR against LT31. Bottom row: histograms of residuals in $\log_{10}(V_{meas}/V_{ref})$, coloured by LT31 MOR bin, with Gaussian envelopes and vertical WMO ± 10 % bounds.



4.3.3 SWS-200 B03: scatter analysis and calibration performance

Figure 9 presents the equivalent analysis for SWS-200 B03 ($n = 32,018$ valid pairs). The raw state shows OLS slope 0.94, Pearson $r = 0.820$, log-RMSE = 0.217, and global log-bias +0.030. Relative to the PWD22, the SWS-200 exhibits larger scatter, consistent with its greater sensitivity to filter-seating variability and phase-function dependence, while retaining a higher apparent raw WMO compliance (34.4 %) because the aggregate global bias remains close to zero. In other words, the broader SWS-200 residual spread is centred more symmetrically around the 1:1 relation, so its raw WMO compliance is higher than that of the PWD22 despite its visibly larger scatter.

Applying the Set-B correction worsens WMO compliance to 27.4 % and shifts the global log-bias to +0.042, with RMSE increasing slightly to 0.220. This outcome is consistent with the Set-B outdoor calibration having been performed under conditions where background contamination was still embedded in the recovered intercept: the corresponding outdoor–indoor difference gives $f_{env} \approx 1.077$, indicating that the adopted correction did not represent a purely hardware-isolated baseline. By contrast, the Set-E correction yields near-zero global log-bias ($\mu = +0.004$), the best WMO compliance of all tested SWS-200 configurations (41.9 %), and a slightly reduced RMSE (0.215). However, the corresponding intercept difference formally gives $f_{env} \approx 0.878$, which is not physically consistent with the idealized additive-background interpretation of Sect. 2.2. Accordingly, for the SWS-200 Set E case, the decoupled f_{env} should not be interpreted as a physical environmental diagnostic. Instead, it should be treated as an empirical correction coefficient influenced by sequence dependence, slope–intercept coupling, and residual mechanical variability between darkroom and outdoor filter applications. Thus, the improvement obtained with Set E should be interpreted operationally — as the most effective correction configuration in this dataset — rather than as evidence that the environmental term itself was fully or uniquely isolated. As with the PWD22, the long-term OLS slope remains 0.94 after correction, showing that the intrinsic geometric non-linearity of the sensor is not removed by intercept adjustment alone.

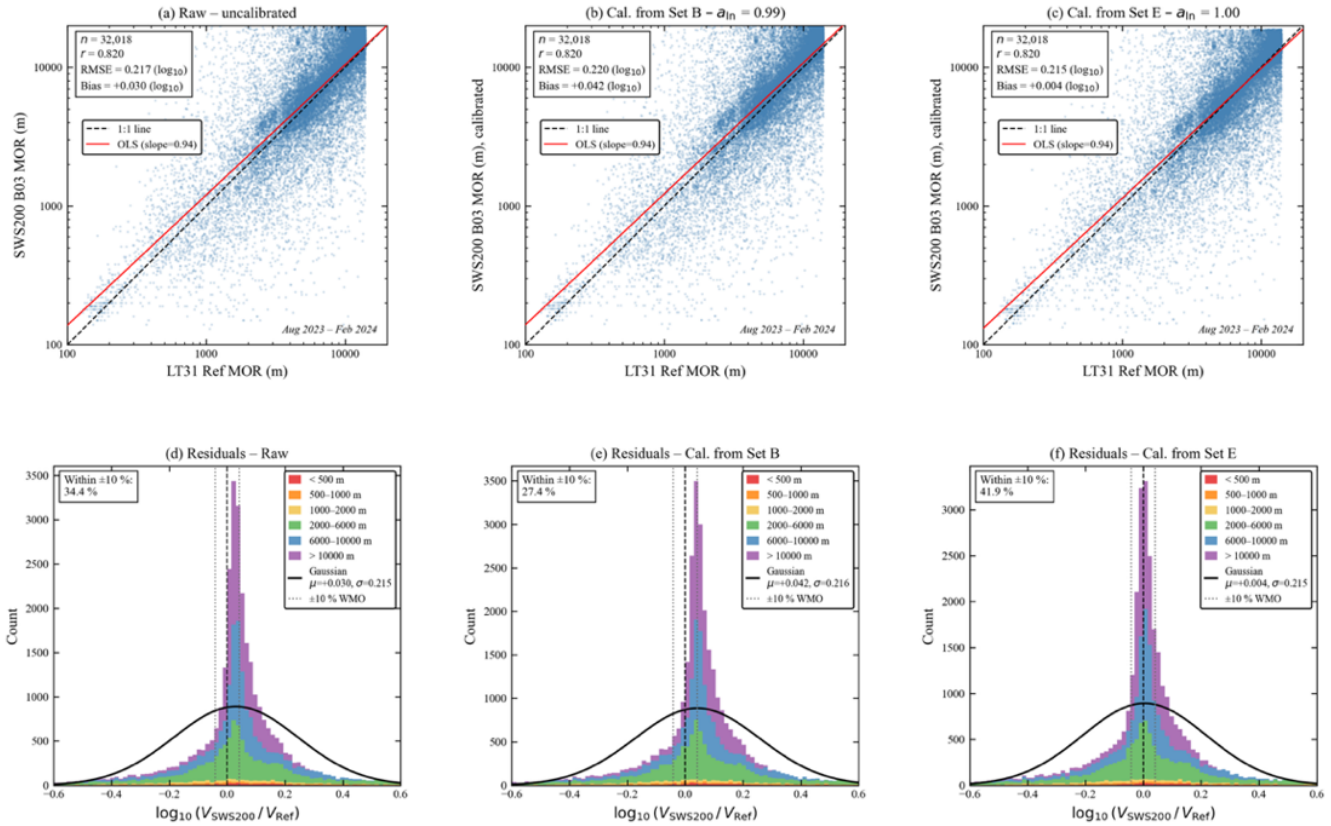


Figure 9: Top row: log–log scatter plots for (a) raw Biral SWS-200 B03 (17 Aug 2023 – Feb 2024), (b) Set-B calibrated, and (c) Set-E calibrated MOR against LT31. Bottom row: histograms of residuals in $\log_{10}(V_{meas}/V_{ref})$, coloured by LT31 MOR bin, with Gaussian envelopes and vertical WMO $\pm 10\%$ bounds.

4.3.4 Comparative assessment

Table 5 summarizes the long-term validation statistics for both sensors under the raw, Set-B, and Set-E correction states.

For the PWD22 A01, the Set-B correction improves the proportion of data within the WMO $\pm 10\%$ tolerance from 16.7 % to 22.4 %, but shifts the global log-bias from -0.010 to $+0.020$ with essentially no reduction in RMSE (0.190 to 0.192).

By contrast, the Set-E correction increases WMO compliance more substantially to 37.1 %, but also produces a more positive residual bias ($+0.062$) and a slightly larger RMSE (0.204), consistent with the fact that the non-unit darkroom slope modifies both intercept and effective scaling. For the SWS-200 B03, the Set-B correction degrades WMO compliance from 34.4 % to 27.4 % and increases both bias ($+0.042$) and RMSE (0.220), indicating that the adopted intercept still contained environmental contamination. The Set-E correction performs best for this sensor, reducing the global log-bias to $+0.004$, slightly lowering RMSE to 0.215, and increasing WMO compliance to 41.9 %. Overall, these results show that the proposed framework is more effective as a bias-correction and compliance-improvement tool than as a scatter-reduction method, and that the higher-OD Set-E configuration is the more effective calibration strategy in this dataset, including for the SWS-200 boundary case.



405 Although the post-correction WMO ± 10 % compliance remains below 50 %, this should be interpreted in the context of field intercomparison between a point-sampling forward-scatter sensor and a 30 m path-integrating transmissometer. Published visibility intercomparison studies similarly show that residual disagreement remains substantial even after careful calibration, particularly when instrument geometry, obscurant type, and representativeness differ (Griggs et al., 1990; Boudala et al., 2021; Zhuang et al., 2022).

410 **Table 5: Long-term field validation performance summary (17 Aug 2023 – Feb 2024).**

Metric	PWD22 A01			SWS-200 B03		
	Raw	Set B	Set E	Raw	Set B	Set E
Valid pairs (n)	33,152			32,018		
Pearson r	0.843			0.820		
OLS slope (log-space)	0.90	0.90	0.93	0.94	0.94	0.94
Log-bias (μ , $\log_{10}$)	-0.010	+0.020	+0.062	+0.030	+0.042	+0.004
Log-RMSE (δ , $\log_{10}$)	0.190	0.192	0.204	0.217	0.220	0.215
Within WMO ± 10 %	16.7 %	22.4 %	37.1 %	34.4 %	27.4 %	41.9 %

Note: Pearson r and OLS slope are invariant to intercept-only correction; slope change under Set E reflects the slope-rotation component of the non-unit a_{ln} correction.

5 Discussion

5.1 Slope stability and filter-seating effects

415 The log-log regression slope a_{ln} must remain sufficiently close to unity for the intercept-decoupling framework to retain a clear physical interpretation. In the present darkroom dataset, the most plausible mechanism for large departures of a_{ln} from unity is mechanical filter-seating variation rather than stable intrinsic hardware non-linearity. In log-log space, a single mis-seated filter measurement near either end of the fitted MOR range can exert strong leverage on the regression, tilting the fitted line away from unity even when the underlying hardware response is otherwise close to linear.

420 This interpretation is consistent with the SWS-200 B03 Set E Sequence 1 result ($a_{ln} = 1.113$, intercept CI ± 0.101), which contrasts sharply with the recovery in Sequence 2 ($a_{ln} = 0.982$). The 95 % confidence intervals in Table 3 quantify this vulnerability: the SWS-200 intercept uncertainty is substantially wider than the corresponding PWD22 uncertainty across comparable filter sets, suggesting greater sensitivity to filter-seating mechanics in the present setup. More generally, previous intercomparison studies have shown that forward-scatter sensor performance depends strongly on obscurant regime and instrument characteristics (Zhuang et al., 2022). Earlier climatic-chamber studies similarly showed that visibility-sensor

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behaviour can depend strongly on obscurant regime and comparison geometry, even under controlled conditions (Burnham, 1983).

A practical implication is that the number of filter points and their distribution across the MOR range matters as much as the number of repeated sequences. A regression anchored at both ends of the dynamic range by stable filter placements is more robust to individual outliers than one with points clustered in a narrow range. When the fitted slope departs materially from unity or when the associated confidence interval becomes unusually broad, the sequence should be treated as unstable and repeated before the intercept is adopted for field correction.

5.2 Identifiability conditions and method limits

Section 2.2 defined three identifiability requirements for the intercept-decoupling framework: slope stability, zero-baseline anchoring, and filter-placement repeatability. The purpose of this section is not to restate those conditions, but to assess how departures from them affect interpretation of the present results.

Uncertainty in the decoupled terms arises mainly from uncertainty in the fitted slopes and intercepts of the indoor and outdoor regressions. To first order, uncertainty in $\ln(f_{cal})$ is given directly by the indoor intercept uncertainty, whereas uncertainty in $\ln(f_{env})$ combines the indoor and outdoor intercept uncertainties through Eq. (4). Uncertainty in corrected MOR depends additionally on the adopted slope a_{in} , so that slope uncertainty contributes increasingly toward the ends of the fitted MOR range.

When one or more of these conditions is not satisfied, the framework fails in a predictable way: the inferred f_{cal} may be biased upward or downward, but the method no longer provides unambiguous attribution between f_{cal} and f_{env} . The confidence intervals in Table 3 should therefore be interpreted as diagnostic indicators; wide intercept confidence intervals signal conditions under which one or more identifiability requirements were not adequately met. In the present dataset, the PWD22 satisfied these conditions sufficiently for the framework to yield a physically interpretable field correction, whereas the SWS-200 illustrates how violations of the slope-stability and filter-repeatability assumptions limit the physical interpretability of the decoupled terms.

5.3 Transferability of f_{cal} across nominally identical hardware units

In this study, the outdoor filter decoupling experiment was conducted on PWD22 unit B01, whereas the long-term validation used data from unit A01. This substitution was made for practical reasons: direct outdoor filter calibration of A01 could not be performed during the campaign because that unit was committed to concurrent observational use in other projects. This transfer is therefore retrospective not only across hardware unit, but also in time, because the long-term A01 deployment predates the 2024 calibration campaign; its validity consequently assumes that the relevant hardware response remained stable over that interval. The transfer was justified by the close agreement between the A01 and B01 darkroom regressions — for Set B, the fitted darkroom values of $\ln(f_{cal})$ differ by less than 0.08 between the two units (Table 3) — indicating that the intrinsic hardware bias is reproducible at the model level.



Because the darkroom baseline is established under conditions where $f_{env} = 1$, the intercept difference between the two units can be interpreted primarily as a difference in hardware optical response rather than as an environmental effect. The assumption that f_{cal} is transferable between units of the same model is therefore a working approximation rather than a guaranteed property, and is most defensible when optical alignment and mechanical reproducibility are high; whenever intercept differences approach or exceed the instrument's stated MOR tolerance, independent darkroom verification remains advisable. For exploratory deployments or cross-model generalisations, establishing f_{cal} directly on the sensor unit to be deployed outdoors remains preferable.

In the present study, the close darkroom agreement between PWD22 A01 and B01 was sufficient to justify transfer of the outdoor-derived correction parameters from B01 to A01, but the same assumption should not be extended automatically to other units or sensor families without equivalent verification.

5.4 Operational implications

The long-term validation demonstrates that intercept-decoupling provides meaningful bias correction for both sensor families: WMO $\pm 10\%$ compliance increases by 20.4 and 7.5 percentage points for PWD22 A01 and SWS-200 B03 (Set E), respectively. However, the log-RMSE changes only marginally after correction, indicating that the framework primarily removes systematic bias rather than reducing scatter. The irreducible scatter floor is set by spatial inhomogeneity between the ~ 0.1 L point receiver and the 30 m transmissometer path (Sect. 3.4) and cannot be addressed by any hardware calibration procedure. The reported compliance fractions are also conditioned by the masking strategy used in Sect. 3.4, which excludes open-range clear-air values and therefore emphasizes the lower-MOR regime where calibration differences are more consequential.

The consistent superiority of Set E over Set B in WMO compliance for both instruments points to a practical recommendation: higher-OD filter sets that span a wider MOR range produce more stable slope estimates and more faithfully isolate the hardware intercept. Where sensor linearity is uncertain, the higher-OD configuration is preferable.

The contrasting outcomes for the two instruments also illustrate the method's dependence on operator execution. The SWS-200 Set-B degradation in compliance after correction (34.4 % $\rightarrow$ 27.4 %) is consistent with the outdoor test having been conducted under background conditions that did not satisfy the $10\times$ rule, leaving f_{env} embedded in the recovered f_{cal} . Adherence to the background constraint during outdoor testing is therefore as important as the darkroom protocol itself.

Operationally, the framework is most defensible when three conditions are satisfied: (i) the darkroom slope CI is narrow and centred on unity; (ii) outdoor filter tests are conducted under $V_{bg} > 10 \times V_{cal}$; and (iii) filter placement repeatability has been verified through repeated darkroom sequences. Where these conditions cannot be guaranteed — for instance, at remote sites where darkroom access is infrequent — the method provides a useful diagnostic but should be combined with regular transmissometer cross-checks to monitor evolving field bias and the stability of the inferred environmental contribution over time (Roggenstein et al., 2009).



6 Conclusion

490 Calibration of forward-scatter visibility sensors is complicated by the need to transfer laboratory-derived hardware characterization into field environments where background atmospheric extinction perturbs the calibration reference. This study presented a log-domain framework for separating a hardware calibration factor (f_{cal}) from an environmental interference term (f_{env}) through paired darkroom and outdoor multi-filter regressions, evaluated on the Vaisala PWD22 and Biral SWS-200 using KRISS-assigned filter sets and a Vaisala LT31 transmissometer reference.

495 For the PWD22, near-unit darkroom slope and stable intercept transfer yielded reliable f_{cal} and modest f_{env} estimates, increasing long-term WMO ± 10 % compliance from 16.7 % in the raw state to 37.1 % under Set E correction; for the SWS-200, elevated sensitivity to filter-seating variability and slope instability limited the physical interpretability of the decoupled terms, although the mechanically stable Set E sequence still achieved the highest compliance of all tested configurations (41.9 %). In both cases, log-RMSE changed only marginally after calibration, confirming that the framework addresses systematic

500 bias rather than the scatter arising from spatial inhomogeneity between point and path-integrating instruments. The method operates within the KRISS traceability architecture and does not modify the transmissometer-based reference chain. Its operational value lies in providing a principled mechanism for diagnosing and correcting hardware bias under field conditions, subject to three practical constraints: background visibility should exceed roughly $10\times$ the filter-equivalent MOR during outdoor tests; filter placement must be mechanically repeatable; and the sensor must exhibit stable near-unit log-domain

505 slope. When these conditions are satisfied, log-domain intercept separation offers a reproducible and traceability-consistent route for extending laboratory calibration into field application for suitable forward-scatter networks. Future work should test the framework on additional forward-scatter geometries and evaluate whether independent environmental diagnostics, such as aerosol backscatter or lidar-based extinction, can help constrain the environmental term more directly.

510 Code and data availability

Non-sensitive analysis scripts used to generate the regression statistics and figures can be made available by the corresponding author upon reasonable request, subject to permission from the National Institute of Meteorological Sciences (NIMS). The observational data used in this study are not publicly archived and may be made available for non-commercial research use upon reasonable request, subject to institutional approval by NIMS/KMA.

515 Supplement link

No supplement is associated with this manuscript.



Team list

Not applicable.

Author contributions

- 520 R. Choi conceived the study, designed the methodology, conducted the experiments, analysed the data, and wrote the manuscript.

Competing interests

The author declares that there are no competing interests.

Disclaimer

- 525 The views expressed in this article are those of the author and do not necessarily reflect the official position of the National Institute of Meteorological Sciences or the Korea Meteorological Administration.

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