

CoURAGE KAZR b1 Processing: Corrections, Calibrations, and Processing Report

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March 2026



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Acronyms and Abbreviations

AGL	above ground level
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
BNL	Brookhaven National Laboratory
BSEC	Baltimore Social-Environmental Collaborative
CoURAGE	Coast-Urban-Rural Atmospheric Gradient Experiment
DOE	U.S. Department of Energy
DQR	Data Quality Report
DSD	drop size distribution
GE	general mode
KAZR	Ka-band ARM Zenith Radar
LDR	linear depolarization ratio
MD	moderate mode
PNNL	Pacific Northwest National Laboratory
<i>R</i>	rain rate
RWP	radar wind profiler
SNR	signal-to-noise ratio
TRACER	Tracking Aerosol Convection Interactions Experiment
TWTA	traveling wave tube amplifier
UIFL	Urban Integrated Field Laboratory
UTC	Coordinated Universal Time
VDISQUANTS	Video Disdrometer Value-Added Product
WRA	wet radome attenuation
<i>Z_e</i>	reflectivity

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1.0 Introduction

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) User Facility supports atmospheric and earth system research through a comprehensive network of fixed and mobile observatories. These facilities provide long-term and intensive campaign-based observations of clouds, aerosols, precipitation, radiation, and meteorological state variables. ARM observations are designed to improve the physical understanding and numerical representation of atmospheric processes in earth system models, with particular emphasis on cloud-radiation interactions and precipitation processes.

The Coast-Urban-Rural Atmospheric Gradient Experiment (CoURAGE) deploys one of the ARM Mobile Facilities (AMF) to the Mid-Atlantic region surrounding Baltimore, Maryland, for the period 1 December 2024 through 30 November 2025. This deployment focuses on characterizing atmospheric structure, cloud properties, and precipitation processes across strong land-use and surface heterogeneity gradients associated with urban, rural, and coastal (Chesapeake Bay) environments.

The CoURAGE deployment complements the Baltimore Social-Environmental Collaborative (BSEC), a DOE Urban Integrated Field Laboratory (UIFL), by providing high-quality atmospheric observations needed to connect urban surface processes, emissions, and meteorology to cloud and precipitation responses. In addition to the central urban site, ancillary observing sites were deployed to rural Maryland northwest of Baltimore and to an island site in Chesapeake Bay. These measurements further complement a long-term atmospheric observatory operated in Beltsville, Maryland, by Howard University in collaboration with the Maryland Department of the Environment.

Together, these assets form a four-node regional atmospheric observatory network representing Baltimore and its three primary surrounding environments—urban, rural, and coastal/bay. This coordinated observational strategy enables investigation of spatial gradients in boundary-layer structure, cloud occurrence, precipitation evolution, and aerosol-cloud interactions across complex surface regimes. Within this network, vertically pointing cloud radars play a critical role by providing continuous, high-resolution measurements of cloud and precipitation vertical structure.

1.1 Overview of the CoURAGE KAZR (Ka-band ARM Zenith Radar)

A cornerstone of the CoURAGE observational strategy is the Ka-band ARM Zenith Radar (KAZR), a vertically pointing cloud-profiling radar operating at 35 GHz (Ka-band). The KAZR is designed to provide high-sensitivity, high-temporal-resolution measurements of hydrometeors in the atmospheric column above the site, making it particularly well suited for observing clouds, drizzle, and light precipitation.

The KAZR deployed during CoURAGE is equipped with a traveling wave tube amplifier (TWTA). The radar operates in two configurable operational modes, each optimized for different altitude ranges and atmospheric conditions. Both modes include linear depolarization ratio (LDR) capability, which provides additional information on hydrometeor shape, phase, and orientation.

- General (GE) mode

GE mode uses short-pulse transmission to achieve high vertical and temporal resolution, particularly within the lowest 1-2 km above ground level (AGL). This mode is optimized for observing shallow clouds, fog, drizzle, and near-surface hydrometeor returns, and is especially valuable for studying boundary-layer cloud processes and cloud-surface interactions common in urban and coastal environments.

- Moderate (MD) mode

MD mode employs chirped-pulse (frequency-modulated) transmission, which increases sensitivity at higher altitudes while maintaining reasonable vertical resolution. This mode is optimized for observing deeper cloud systems and mid-to-upper-tropospheric cloud layers. The use of chirped pulses introduces a near-radar blind zone, which is a known and documented trade-off between sensitivity and minimum usable range. After the MD sidelobe leakage filter is updated around the end of January and early February, the minimum range is adjusted to about 1.8 km from 0.8 km.

During the CoURAGE deployment, the KAZR alternates between GE and MD modes to provide continuous coverage of both near-surface cloud processes and deeper cloud structures. This dual-mode strategy ensures robust sampling across a wide range of meteorological conditions encountered throughout the annual deployment cycle.

The KAZR b1 datastream represents the quality-controlled, calibrated, and processed radar moments, including reflectivity (Z_e), Doppler velocity, spectral width, and depolarization parameters, derived from the raw radar measurements. This report documents the processing steps, calibration considerations, and quality-control procedures applied to the CoURAGE KAZR data to support scientific analysis and long-term archival use.

1.2 Radar Performance

Radar performance was continuously monitored throughout the CoURAGE deployment to ensure data quality and long-term measurement stability. Key performance metrics include instrument uptime, transmitter power output, and calibration constant stability for both operational modes (GE and MD). These parameters directly affect the accuracy and consistency of measured Z_e and are therefore critical for downstream scientific analysis.

1.2.1 Data Availability and Operational Continuity

The data availability of the CoURAGE KAZR observations is summarized in Figure 1, which shows hourly data coverage over the deployment period. Overall, the KAZR achieved excellent temporal coverage, with data availability exceeding 99% across most hours.

Periods of missing data are limited and primarily associated with:

- Planned radar hardware adjustments or maintenance, and
- Local power outages, occasionally occurring during severe weather events.

Data gaps lasting longer than 24 hours were formally documented through ARM Data Quality Reports (DQRs). The small number and short duration of these interruptions demonstrate a high level of operational reliability. This degree of data continuity supports robust analyses of diurnal and seasonal variability in clouds and precipitation, which are central to CoURAGE science objectives.

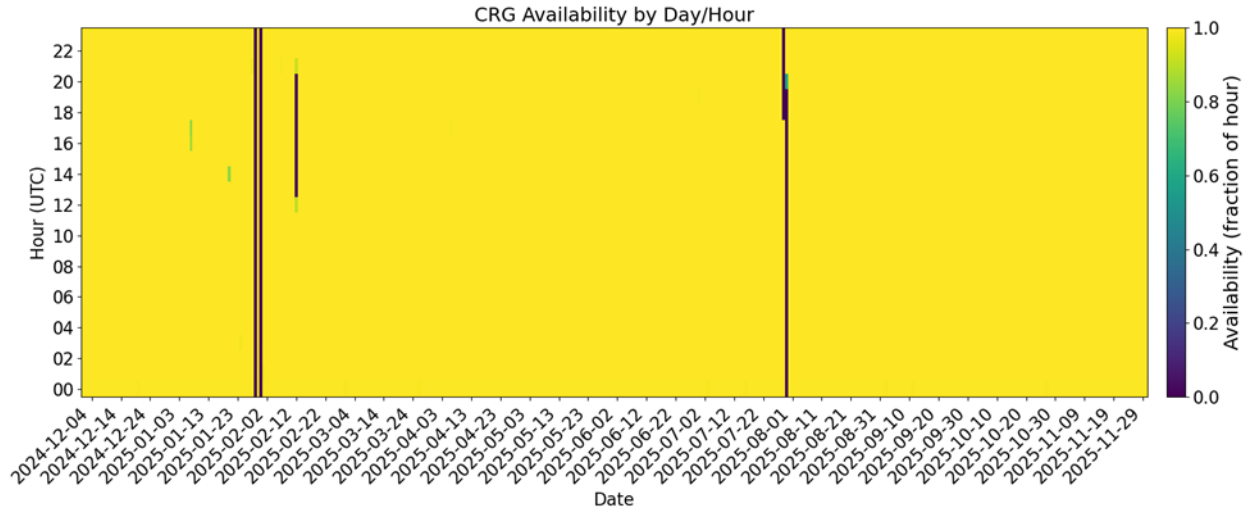


Figure 1. CoURAGE KAZR operation and data availability by hours in the day.

1.2.2 Transmitter Power and Calibration Constant Stability

Figure 2 presents the time series of transmitter power output and radar calibration constants for both GE and MD operating modes. These diagnostics provide critical insight into radar system stability, potential transmitter degradation, and periods of system intervention or self-adjustment.

Throughout the deployment, the transmitter power output remains stable, with no notable long-term trend or degradation. The transmitted power is consistently maintained at approximately 52 dB, indicating stable transmitter performance over the full campaign duration.

The calibration constant exhibits mode-dependent behavior:

- In MD mode, the calibration constant shows an abrupt increase of approximately 2 dB on February 2, 2025.
- In GE mode, the calibration constant remains relatively stable near -8 dB, with modest fluctuations observed in early June, late July, and early November.

These variations in calibration constants are interpreted as system-level adjustments, likely associated with radar self-calibration processes or compensations for minor changes in hardware response or transmitted power. Importantly, these adjustments act to preserve consistency in Z_e rather than introducing spurious trends.

The observed calibration constant variability underscores the importance of continuous performance monitoring and provides the basis for time-dependent calibration corrections, which are described in later sections of this report. Overall, the stability of both transmitter power and calibration constants confirms

that the CoURAGE KAZR operated within expected performance bounds and produced scientifically reliable reflectivity measurements throughout the deployment.

Variations in the radar calibration constant directly translate to systematic offsets in measured equivalent radar reflectivity (Z_e) if not properly accounted for. Even modest, mode-dependent changes on the order of 1-2 dB can introduce artificial temporal shifts in Z_e that may be misinterpreted as physical variability in cloud or precipitation intensity. Consequently, continuous monitoring of calibration constants provides a critical diagnostic for identifying periods when time-dependent Z_e offsets may occur. In the CoURAGE KAZR b1 processing, these calibration constant variations are explicitly incorporated into the reflectivity calibration framework to ensure consistency across operating modes and over the full deployment period. The methodology used to apply these corrections and evaluate their impact on Z_e stability is described in subsequent sections of this report.

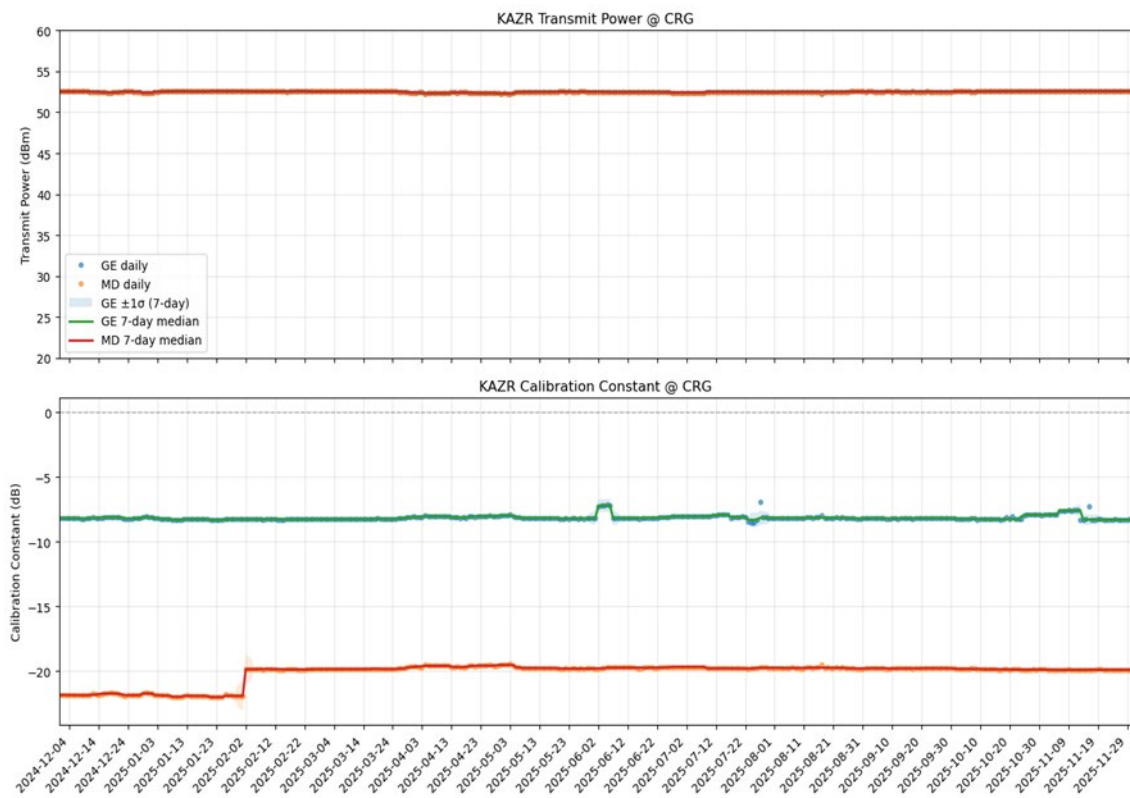


Figure 2. CoURAGE KAZR transmitted power and radar calibration constants for GE and MD operating modes.

2.0 Calibrations and Connections

Accurate calibration of KAZR reflectivity is essential for producing high-quality radar moments suitable for quantitative analysis of cloud and precipitation microphysics. At Ka-band frequencies, reflectivity measurements are particularly sensitive to instrument calibration stability and signal attenuation, especially during precipitation. Surface-based disdrometer observations provide an independent reference for near-surface hydrometeor properties and, when combined with appropriate attenuation corrections, offer a robust framework for evaluating and correcting radar reflectivity biases.

During CoURAGE, reflectivity calibration is primarily assessed using disdrometer-based comparisons, with particular emphasis on the GE operating mode. GE mode provides frequent sampling of shallow precipitation and near-surface returns, making it well suited for surface-referenced calibration approaches. A critical component of this calibration strategy is explicit correction for wet radome attenuation (WRA), which can otherwise introduce large, rain-rate-dependent biases in measured reflectivity.

2.1 KAZR GE-Mode Calibration Using Disdrometer Observations with WRA Correction

The WRA calibration technique applied in this study follows the methodology developed by Deng et al. (2024). This approach accounts for the two-way attenuation caused by a thin film of water accumulating on the radar radome during rainfall events. At Ka-band, this effect is substantially more pronounced than at lower radar frequencies due to stronger microwave absorption and scattering by liquid water on the radome surface. If uncorrected, WRA can bias radar reflectivity measurements by several decibels, particularly during moderate to heavy rain.

The WRA calibration method is based on direct comparison between:

- Radar-measured reflectivity (Z_{e_radar}) at a fixed height near the surface (typically around 0.5 to 1 km AGL), and
- Disdrometer-derived reflectivity ($Z_{e_disdrometer}$), calculated from surface-measured drop size distributions (DSDs) provided by ARM's Video Disdrometer Value-Added Product (VDISQUANTS).

The reflectivity difference is defined as:

$$\Delta Z_e = Z_{e_disdrometer} - Z_{e_radar}$$

During rainfall, ΔZ_e is expected to increase systematically with rain rate (R) due to enhanced radome wetting. Empirically, this relationship is well described by a log-linear function of rain rate in light or moderate rain, such that:

$$\Delta Z_e = a + b \log_{10}(R)$$

where R is the rain rate (mm hr^{-1}), b represents the WRA sensitivity, and a represents a constant radar calibration offset. A log-linear regression is applied to stratiform rain events to estimate these parameters. Evaluation of this method against independent calibration approaches during the ARM Tracking Aerosol Convection Interactions Experiment (TRACER) demonstrated an overall calibration uncertainty of approximately ± 3 dB (Deng et al. 2024).

An example stratiform precipitation event observed on 12 April, beginning at 13 UTC, is shown in Figure 3. This event features a well-defined bright band near 2 km AGL, indicating melting-layer precipitation suitable for calibration analysis.

In Figure 4b, radar-measured Z_e at 500 m AGL (green points) is compared with disdrometer-estimated Z_e from VDISQUANTS (blue points). The uncorrected KAZR reflectivity is generally biased low relative to the disdrometer reference. Figure 4a shows that the reflectivity difference increases from approximately 0 to 15 dB as rain rate increases from 0 to 5 mm hr⁻¹, consistent with increasing WRA behavior in Deng et al. (2024).

Applying the WRA correction using a log-linear fit with flexible b (yellow points in Figure 4a) effectively removes the rain-rate-dependent bias. After correction, the mean Z_e offset relative to VDISQUANTS is reduced to approximately 0.77 dB, and the corrected radar reflectivity exhibits a strong agreement with the disdrometer reference (correlation coefficient $r_r = 0.95$, Figure 4b). This example demonstrates that explicit WRA correction is essential for accurate estimation of Z_e offsets during precipitation.

Figure 5 shows the time series of GE-mode Z_e offsets relative to disdrometer-derived reflectivity for rainy periods during the CoURAGE deployment. Day-to-day variability is observed, reflecting a combination of WRA fitting uncertainty, rain-type variability, and sampling limitations.

Despite this variability, two distinct offset regimes are evident:

- Before 2 February 2025, the average Z_e offset is approximately -1.5 dB.
- Beginning on 2 February 2025, the average Z_e offset changed to approximately 0.1 dB.

This shift closely coincides with engineering work performed on the radar, providing independent confirmation that the observed Z_e offset variability is instrument-related rather than meteorological in origin. This consistency reinforces the interpretation that time-dependent calibration constants must be incorporated into the reflectivity calibration framework to ensure long-term Z_e stability.

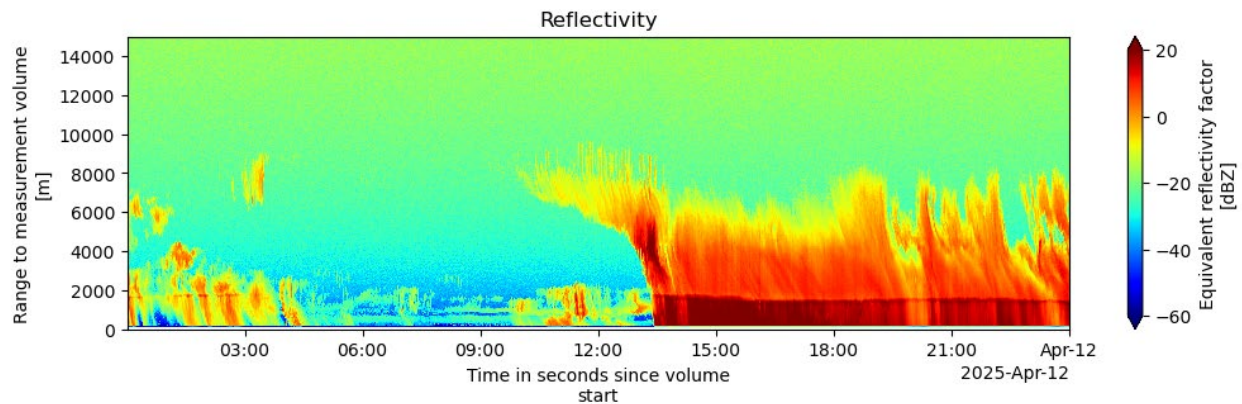


Figure 3. CoURAGE KAZR-observed Z_e in stratiform precipitation event on 12 April 2025.

KAZR_Ze_offset 2025-04-11

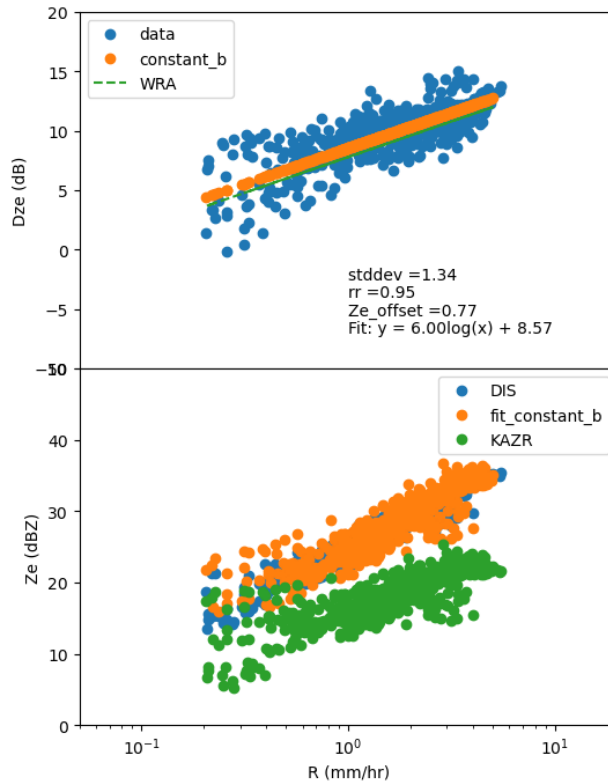


Figure 4. Ze offset calculation in KAZR GE mode with disdrometer-derived Ze on 12 April, 2025 with the WRA correction method.

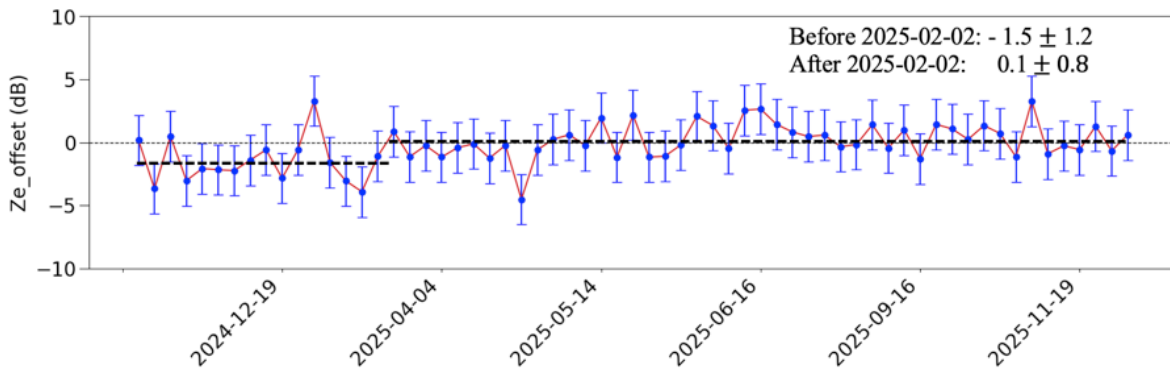


Figure 5. CoURAGE KAZR GE-mode Ze offset in respect to disdrometer measurement with wet-radome attenuation calibration method.

2.2 KAZR Intermode Comparison (GE versus MD)

The MD operating mode employs pulse compression to enhance sensitivity at higher altitudes, which results in a larger minimum usable range compared to GE mode. As a consequence, MD-mode

reflectivity measurements have limited overlap with near-surface precipitation and exhibit reduced correlation with surface-based disdrometer observations. For this reason, direct disdrometer-based calibration is not applied to MD mode. Instead, the MD-mode Z_e offset is estimated through intermode comparison with the GE mode, which has been independently calibrated using the WRA correction approach described in Section 2.1.

Intermode calibration relies on the assumption that, above a common height range and under sufficiently strong signal conditions, both modes sample the same atmospheric volume and should produce consistent reflectivity measurements. To ensure a robust comparison, only data exceeding a common signal-to-noise ratio threshold ($\text{SNR} > 0$ dB) are included.

Figure 6 shows the time series of the mean reflectivity difference (GE-MD) at the CoURAGE site, along with daily values and a 7-day running median. The intermode reflectivity difference remains relatively stable within two distinct periods separated by February 2, 2025, consistent with the MD-mode calibration shift identified earlier.

Specifically:

- Before 2 February 2025, GE-mode reflectivity is approximately 1.2 dB higher than MD-mode reflectivity.
- After 2 February 2025, GE-mode reflectivity becomes approximately 2.0 dB lower than MD-mode reflectivity.

These stepwise changes in intermode bias are temporally collocated with the MD-mode calibration constant adjustment discussed in Section 1.2 and reflected in the disdrometer-based Z_e offset analysis in Section 2.1. This agreement confirms that the observed intermode differences are dominated by instrument calibration changes rather than meteorological variability.

A smaller fluctuation of less than 1 dB is observed around early June, which coincides with a period of GE-mode calibration constant variability (Figure 2). This correspondence further supports the interpretation that intermode reflectivity differences provide a sensitive diagnostic of mode-specific calibration stability.

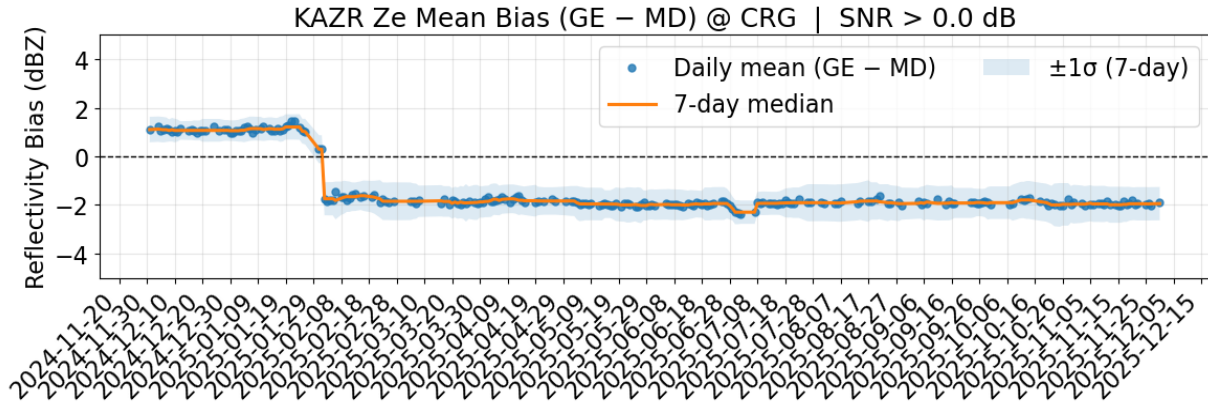


Figure 6. Time series of KAZR reflectivity differences between GE and MD modes at the CoURAGE site for data with $\text{SNR} > 0$ dB. Shown are daily mean differences and a 7-day running median.

Overall, the intermode comparison demonstrates that the relative calibration between GE and MD modes is stable within well-defined periods, and that step changes in reflectivity bias can be reliably attributed to documented calibration constant adjustments. These results form the basis for applying time-dependent intermode Ze offset corrections in the b1 data processing to ensure consistency between GE and MD reflectivity products.

2.3 Additional Evaluation with KAZR and RWP Cross-Comparison in Rain

In addition to the disdrometer-based calibration, an independent cross-comparison using the radar wind profiler (RWP) is applied to estimate the KAZR reflectivity (Ze) offset during rain events.

Cross-comparison with an independently calibrated radar is a commonly used approach for monitoring and evaluating Ka-band radar calibration performance.

During the CoURAGE campaign, the RWP reflectivity measurements were not absolutely calibrated. Therefore, a two-step calibration strategy is adopted. First, the RWP Ze is calibrated through direct comparison with surface disdrometer measurements during light stratiform rain, when attenuation due to rain and wet-radome effects is minimal for the RWP. Owing to its longer wavelength, the RWP is substantially less affected by wet-radome attenuation and rain attenuation than the Ka-band KAZR, making it a suitable intermediate reference.

Two stratiform rain events in December 2024 are selected for this analysis (Figure 7). These events are characterized by steady precipitation, weak vertical variability, and minimal convective influence, providing favorable conditions for both radar-disdrometer and radar-radar comparisons. For each event, the disdrometer-derived Ze is first used to estimate the RWP Ze offset. The calibrated RWP Ze is then compared with collocated KAZR GE-mode Ze at overlapping heights within the rain layer.

The resulting KAZR-RWP Ze differences provide an independent estimate of the KAZR reflectivity offset during rain. For these two cases, the mean KAZR-RWP Ze differences are close to 0 dB, indicating good agreement between the two radars after calibration. This result supports the consistency of the KAZR Ze calibration under precipitation conditions and complements the direct KAZR-disdrometer

calibration, particularly when wet-radome effects are expected to be strongest. The RWP operated reliably on and off from December 2024 through mid-April 2025. Time series of the RWP calibration offset (blue dots) and the corresponding KAZR Ze offset (orange dots) relative to the calibrated RWP during rain are shown in Figure 8. There is a strong variation of RWP Ze offset, especially before March 2025, though the KAZR Ze exhibits very good agreement with the calibrated RWP measurements over this period, further confirming the stability of the derived KAZR reflectivity offsets.

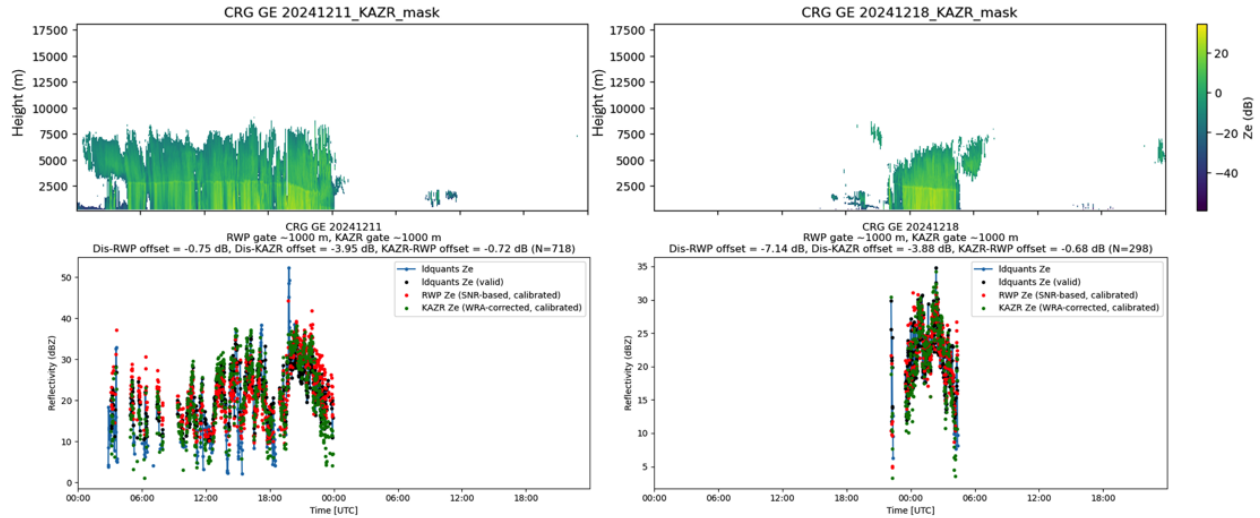


Figure 7. Examples of two stratiform rain events in December 2024 used for RWP-disdrometer calibration and subsequent KAZR-RWP Ze comparison.

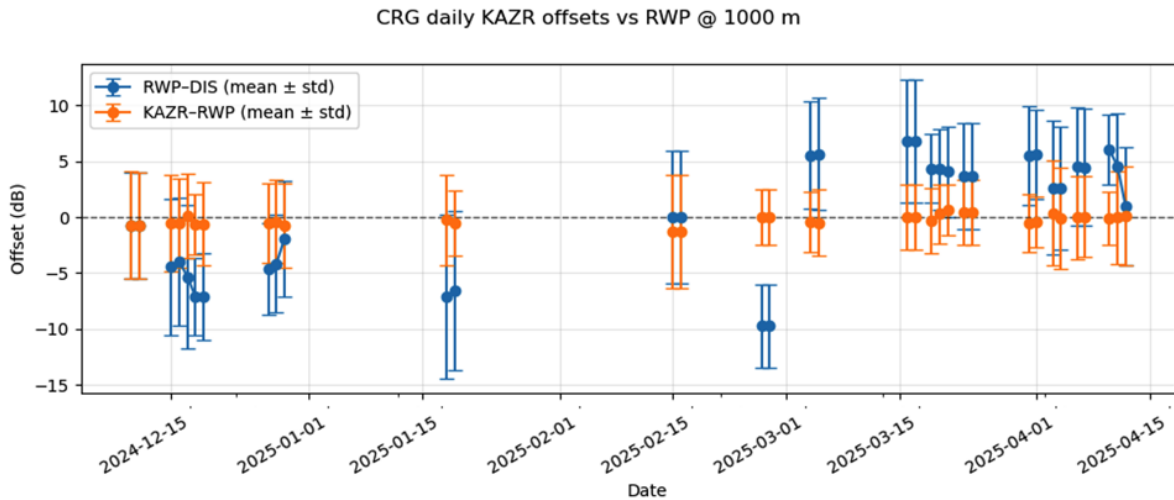


Figure 8. CoURAGE KAZR GE-mode Ze offset relative to calibrated RWP measurements during rain.

2.4 Implementation of GE and MD Ze Offsets in b1 Processing

Based on the disdrometer-referenced calibration analysis for GE mode (Section 2.1) and the intermode comparison between GE and MD modes (Section 2.2), time-dependent Ze offsets were derived and applied during the b1 processing to ensure consistent reflectivity calibration throughout the CoURAGE deployment.

The GE-mode Ze offsets are determined directly from the WRA corrected comparison with disdrometer-derived Ze, while the MD-mode Ze offsets are obtained by combining the GE-mode offsets with the relative MD-GE intermode reflectivity differences. This approach leverages the strengths of each mode: GE mode provides reliable surface-referenced calibration, while intermode comparison ensures consistency for MD mode where direct surface calibration is not feasible.

Analysis of both disdrometer-based offsets and intermode reflectivity differences reveals two distinct and internally consistent calibration periods, separated by February 2, 2025 when the MD-mode sidelobe filter was upgraded, corresponding to a documented shift in the MD-mode calibration constant (Section 1.2). Accordingly, piecewise-constant Ze offsets are applied for each period in the b1 processing.

These offsets are applied as additive corrections to Ze in the b1 datastream and are held constant within each time period. This implementation ensures:

- Consistency between GE and MD reflectivity products,
- Alignment of GE-mode reflectivity with surface-based disdrometer observations, and
- Removal of artificial step changes in Ze associated with instrument calibration constant adjustments.

By explicitly accounting for time-dependent calibration behavior, the b1 processing produces a homogeneous reflectivity record suitable for long-term statistical analysis, intercomparison with other ARM radars, and evaluation of cloud and precipitation processes across the CoURAGE observing network.

Table 1. Time periods and corresponding Ze offsets applied in the CoURAGE KAZR b1 processing.

Time Period	GE Offset (dB)	MD Offset (dB)
2024-12-01 – 2025-02-02	-1.5	-0.3
2025-02-02 – 2025-11-30	-0.1	-1.9

3.0 Masks

As in past ARM field campaigns, a censor mask is developed using the velocity texture (spatial standard deviation of mean Doppler velocity). For the CoURAGE KAZR, a velocity texture threshold of 2.0 m s^{-1} distinguishes background noise from signals. An example of the censor mask applied to KAZR for the 29 March 2025 case is shown in Figure 9.

While velocity texture can be used to identify signals from background noise, it cannot alone distinguish between non-meteorological signals such as clutter, insects, and range sidelobes versus meteorological signals like clouds and precipitation. Thus, to help users further identify these signals, an additional classification mask is included in the b-level data. The linear depolarization ratio is the primary variable used to identify biota (most likely insects) which are prevalent in both GE and MD modes during CoURAGE. The MD mode also occasionally has range sidelobes that show up as false echoes above strong, shallow clouds. The sidelobes are a result of the pulse compression filter. On 30 January 2025, the sidelobe filter was upgraded and little to no sidelobe artifacts were detected afterwards. This filter

upgrade did result in the first few gates of the MD mode showing a clutter-like signal with near-zero Doppler velocity and spectral width, though. The classification mask successfully identifies these gates as clutter.

The resulting combination of methodologies to identify non-meteorological signals is shown in Figures 9d, h for the 29 March 2025 case. The four non-meteorological categories are background noise, clutter, sidelobe, and biota. Pixels that do not meet criteria for these categories are considered hydrometeors. If users are only interested in meteorological data, they can use this mask to filter out the data of interest.

CRG KAZR b1 Masks for 20250329

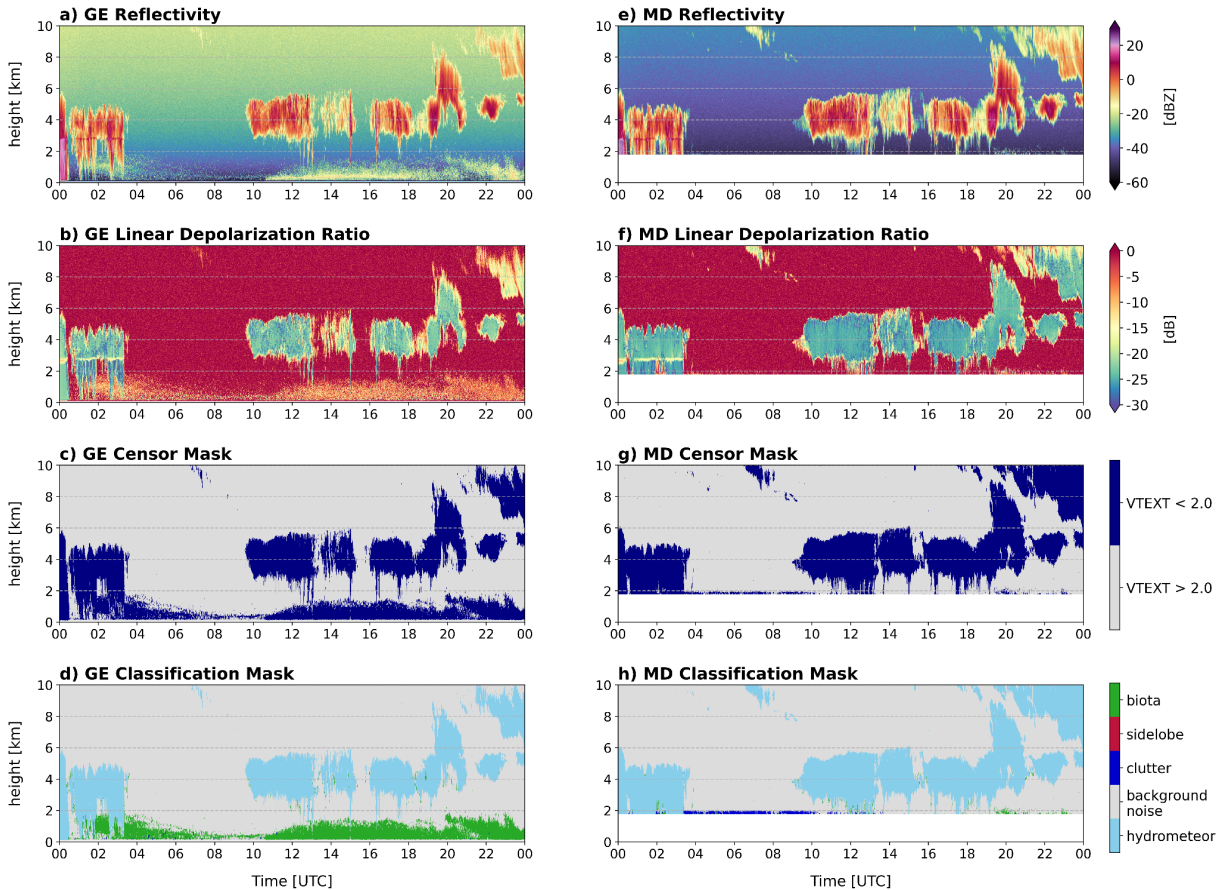


Figure 9. Time-height CoURAGE KAZR observations on 29 March 2025 showing (a) reflectivity (dBZ), (b) linear depolarization ratio (LDR), (c) velocity-texture censor mask (texture $> 2 \text{ m s}^{-1}$: light gray; $\leq 2 \text{ m s}^{-1}$: navy), and (d) non-meteorological signal classification (hydrometeor: light blue; background noise: light gray; clutter: blue; sidelobe: red; biota: green) for the GE mode. Panels (e-h) show MD-mode observations, respectively.

4.0 Description of Data Files

Some of the key variables in the b1-level radar datastreams for CoURAGE are listed below. The reflectivity fields have corrections applied to them (Table 1), and new masks detailed in Section 3 are included in the b1 data.

KAZR File Contents	
(crgkazrcfrgeqcM1.b1 and crgkazrcfrmdqcM1.b1)	
Moments	
linear_depolarization_ratio	linear depolarization ratio, channel unspecified
mean_doppler_velocity	radial mean Doppler velocity, positive for motion away from the instrument
mean_doppler_velocity_crosspolar_v	Doppler velocity, cross-polar for vertical channel
reflectivity	equivalent reflectivity factor with offset applied
reflectivity_crosspolar_v	equivalent reflectivity factor, cross-polar for vertical channel
signal_to_noise_ratio_copolar_h	Signal-to-noise ratio, horizontal channel
signal_to_noise_ratio_crosspolar_v	Signal-to-noise ratio, cross-polar for vertical channel
spectral_width	spectral width
spectral_width_crosspolar_v	spectral width, cross-polar for vertical channel
Masks	
sensor_mask	Bit mask 0: no mask 4: velocity_texture_above_threshold
classification_mask	Non-meteorological echo classification mask 0: hydrometeor 1: background noise 2: ground clutter 3: sidelobe 4: biota

5.0 References

Deng, M, SE Giangrande, MP Jensen, K Johnson, CR Williams, JM Comstock, Y-C Feng, A Matthews, IA Lindenmaier, TG Wendler, M Rocque, A Zhou, Z Zhu, E Luke, and D Wang. 2025. “Wet-radome attenuation in ARM cloud radars and its utilization in radar calibration using disdrometer measurements.” *Atmospheric Measurement Techniques* 18(7): 1641–1657, <https://doi.org/10.5194/amt-18-1641-2025>



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