https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Estimating Beam Pointing of Vertically Pointing Cloud Radars Using Radiosonde Measurements

Min Deng[1], Scott E. Giangrande[1], Adam K. Theisen[2], Karen Johnson[1], Iosif A. Lindenmaier[3], Timothy G. Wendler[3], Jennifer Comstock[3], Marquette Rocque[3], Zeen Zhu[1], and Alyssa Matthews[3].

[1]Brookhaven National Laboratory,

[2]Argonne National Laboratory,

[3]Pacific Northwest National Laboratory

Correspondence to: Min Deng (mdeng@bnl.gov)

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Abstract

Accurate beam pointing is essential for vertically pointing cloud radars, as even small tilting off zenith introduces projections of horizontal wind into Doppler velocity measurements. These effects can bias the interpretation of vertical air motion and hydrometeor fall speeds, leading to systematic errors in cloud and precipitation retrievals.

We present a method to estimate and validate radar beam pointing angle using collocated radiosonde observations. When the radar beam is tilted, the observed Doppler velocity exhibits a cosine dependence on wind direction due to projection of horizontal wind onto the beam, with an amplitude proportional to wind speed. By normalizing Doppler velocity with horizontal wind speed, this geometric dependence can be isolated, enabling quantitative retrieval of off-zenith beam pointing estimation.

The method is applied to the Ka-band ARM Zenith Radar (KAZR) and the Marine W-band ARM Cloud Radar (MWACR) during the Cloud and Precipitation Experiment at kennaook (CAPE-k). Results show a clear wind-direction dependence consistent with small but measurable beam pointing offsets. Differences in Doppler velocity between KAZR and MWACR further reduce the influence of hydrometeor fall velocity and vertical air motion, providing an independent constraint on relative pointing errors. Application to KAZR observations at ARM fixed sites and recent field campaigns further demonstrates that the method is robust across a range of atmospheric conditions. This approach provides a practical and scalable tool for evaluating radar beam pointing using routinely available radiosonde data, with direct implications for improving the accuracy of ARM cloud and precipitation products.

Short Summary

Cloud radars are used to measure air motion, clouds, and precipitation, but even very small pointing errors can affect their accuracy. We developed a method to detect these pointing offsets using routine weather balloon observations. The method was tested on several radar systems deployed in different environments and successfully identified small but important pointing biases. This approach provides a practical way to improve the quality and long-term consistency of cloud and precipitation measurements used in weather and climate research.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

1. Introduction

Vertically pointing cloud radars have become essential tools for observing cloud structure, microphysics, and atmospheric dynamics at high temporal and spatial resolution. Measurements of radar reflectivity and Doppler velocity from these systems provide key information for studies of cloud processes, precipitation formation, and vertical air motion. Doppler velocity observed by vertically pointing radars is commonly interpreted as the sum of hydrometeor fall velocity and vertical air motion, forming the basis for numerous retrieval techniques for in-cloud vertical velocity, turbulence, and microphysical properties. These measurements have been widely used to investigate boundary layer clouds, mixed-phase and ice cloud processes, and precipitation dynamics (e.g., Kollias et al., 1999; Deng et al. 2006, 2008, Shupe et al., 2008; Kollias et al., 2014).

The United States Department of Energy (DOE) Atmospheric Radiation Measurement user facility (ARM) has continuously deployed vertically pointing cloud radars at fixed and mobile observatories since 1996 (Kollias et al., 2016). Initially, the Ka-band Millimeter Cloud Radar (MMCR) was deployed, then in 2011, ARM transitioned to the Ka-band ARM Zenith Radar (KAZR) and the Marine W-band ARM Cloud Radar (MWACR). Both KAZR and MWACR were recently deployed to kennaook Tasmania to support the Cloud and Precipitation Experiment at kennaook (CAPE-k).

A fundamental challenge in Doppler radar analysis is the separation of vertical air motion from hydrometeor fall velocity. Techniques based on Doppler spectra and Doppler moments, including spectral decomposition and identification of Mie scattering signatures, have been developed to isolate the air motion component in cloud and precipitation systems (e.g., Lhermitte, 1988; Kollias et al., 2002; Kollias et al., 2007; Shupe et al., 2008; Deng and Mace, 2006 and 2008; Kalesse and Kollias, 2013). These studies demonstrate that millimeter-wavelength Doppler spectra and moments contain detailed information on particle fall velocities, turbulence broadening, and vertical air motion, although retrieval accuracy depends on assumptions regarding particle size distributions and scattering regimes. Complementary observations, such as lidar identification of liquid cloud layers and thermodynamic constraints from radiosonde measurements, can provide additional context for interpreting Doppler spectra and reducing uncertainty in vertical velocity estimates (e.g., Shupe et al., 2008;

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Kollias et al., 2014; Zhu et al., 2021). Together, these studies highlight the capability of vertically pointing cloud radars to resolve fine-scale atmospheric motions in clouds.

A fundamental assumption underlying these applications is that the radar beam is accurately aligned with the local vertical. However, even small deviations from zenith can introduce systematic biases in Doppler velocity through projection of horizontal wind onto the radar beam. For a perfectly vertical beam, horizontal wind does not contribute to the measured Doppler velocity. In contrast, a small zenith angle offset produces a wind-direction-dependent Doppler signal, which can introduce bias in retrieved vertical air motion and turbulence estimates. This sensitivity is particularly important for millimeter-wavelength cloud radars such as the KAZR and MWACR, which are designed to detect small velocity perturbations associated with weak cloud motions and boundary layer turbulence. As a result, even sub-degree pointing uncertainties can lead to measurable biases in Doppler velocity and derived geophysical products.

Despite the importance of accurate beam alignment, relatively few studies have directly quantified beam pointing errors for vertically pointing cloud radars. Existing approaches have primarily relied on engineering alignment procedures, statistical characteristics of Doppler velocity, or comparison with independent wind measurements. The systematic evaluation of the Doppler velocity–wind direction relationship for beam pointing estimation remains limited. In particular, the sensitivity of the approach to atmospheric variability, wind speed magnitude, and instrument characteristics has not been extensively assessed across different radar systems and observational environments. In addition, the consistency of pointing estimates derived from multiple co-located cloud radars operating at different frequencies has not been thoroughly examined. Understanding these uncertainties is important because pointing biases can propagate directly into retrievals of vertical air motion and cloud microphysical properties.

Radiosonde observations provide a particularly valuable reference because they offer high-resolution vertical profiles of horizontal wind speed and direction that are independent of radar calibration assumptions. In this study, we develop and apply a monitoring method to estimate and validate the beam pointing of vertically pointing cloud radars using collocated radiosonde wind measurements. The method exploits

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

the cosine dependence of Doppler velocity on wind direction to retrieve off-zenith pointing angle and to quantify their impact on Doppler velocity observations. The approach is applied to observations from the KAZR and the MWACR collected during multiple ARM field campaigns and fixed sites, enabling cross-instrument comparison and evaluation of relative pointing differences. The results provide new insight into the magnitude and variability of beam mispointing and demonstrate a practical framework for monitoring the vertically pointing radar measurements and evaluating the related retrieval products.

2. Data Description

2.1 Cloud radar observations

Observations from the CAPE-k KAZR (~35 GHz) and the MWACR (~94 GHz) are used in this study. KAZR and MWACR were sited to each other within 200 meters. KAZR has an antenna diameter of 1.8 m and a one-way half-power beam width (HPBW) of approximately 0.3°, while the MWACR operates with a smaller antenna diameter of about 0.5–0.6 m and a broader HPBW of approximately 0.8°.

They provide high-sensitivity measurements of cloud and precipitation properties (Kollias et al. 2007; Widener et al. 2012; Bharadwaj et al. 2013). They are designed primarily for vertically pointing observations to provide continuous time–height retrieval products of cloud properties and air motion (Kollias et al. 2014; Isom et al. 2013).

Radar reflectivity (Ze) and Doppler velocity (Vd) are derived from Doppler spectra obtained by the cloud radar signal processor. Radar moments are computed from the Doppler spectrum following clutter filtering and noise removal (Doviak and Zrnić 1993; Kollias et al. 2002). Radar reflectivity factor is proportional to the sixth moment of the particle size distribution, while Doppler velocity is calculated as the power-weighted mean radial velocity of scatterers within the radar sampling volume. Under the assumption of vertical beam pointing, Doppler velocity primarily represents the combined contribution of hydrometeor fall velocity and vertical air motion (Kollias et al. 2001; Shupe et al. 2008).

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

In this study, vertically pointing observations from KAZR and MWACR are analyzed to assess the consistency of Doppler velocity measurements and to diagnose potential beam mispointing of each instrument. The use of two independent cloud radars at the same site also provides an opportunity to do cross comparison for evaluating systematic differences in Doppler velocity between them.

2.2 Radiosonde observations

Radiosonde observations provide independent measurements of atmospheric state variables, including temperature, pressure, horizontal wind speed, and wind direction. Wind profiles from radiosondes are derived from GPS tracking of balloon position, providing estimates of the horizontal wind vector as a function of height (Dirksen et al. 2014; Nash et al. 2011, Keeler 2025). These measurements serve as an external reference for evaluating the relationship between Doppler velocity and horizontal wind direction observed by vertically pointing cloud radars. Typical uncertainties in radiosonde wind measurements are approximately 0.5–1.0 m s^{-1} for wind speed and 5–10° for wind direction, depending on atmospheric conditions and instrument type (Nash et al. 2011; Dirksen et al. 2014).

A known limitation in radar–radiosonde comparisons is the horizontal displacement of the radiosonde during ascent. As the balloon ascends through the atmosphere, it drifts with the ambient wind, resulting in spatial separation between the radiosonde measurement location and the radar sampling volume. Previous studies have shown that radiosonde drift distances typically range from 5 to 30 km by the time the balloon reaches 10 km altitude, depending on wind conditions (Seidel et al. 2011; Nash et al. 2011). This spatial displacement introduces uncertainty when comparing radiosonde winds with vertically pointing radar measurements, particularly in environments with strong horizontal wind shear or spatial variability in cloud structure.

Despite this limitation, radiosonde wind measurements have been widely used as a reference for validating radar-derived wind and Doppler velocity observations because they provide reliable estimates of the large-scale wind field (May and Rajopadhyaya 1999; Kollias et al. 2007). In this study, the horizontal wind speed (U) and wind direction (ϕ) derived from radiosonde observations are combined with radar Doppler velocity measurements to evaluate the contribution of horizontal wind to the observed

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Doppler velocity. The comparison assumes that horizontal wind variability over the radiosonde drift distance is relatively small compared to the wind direction dependent Doppler velocity signal associated with radar beam mispointing.

2.3 Case study of the Vd contribution from horizontal wind

Figure 1 shows time–height cross sections of radar reflectivity (Ze) and Doppler velocity (Vd) from KAZR and MWACR at the CAPE-k site on 6 September 2024. Both radars observe an extensive cloud layer between approximately 5–8 km, indicating consistent detection of the cloud structure. Within this layer, KAZR reflectivity is comparably larger than MWACR reflectivity, which may reflect calibration differences or frequency-dependent scattering effects between the Ka-band and W-band radar measurements.

The Doppler velocity fields show a systematic difference between the two radars. MWACR Doppler velocities are generally weakly downward, with magnitudes around 0–0.5 m s^{-1}, consistent with expected fall speeds of small ice particles in stratiform cloud conditions. In contrast, KAZR Doppler velocities increase from near 0 m s^{-1} at cloud base at 5 km to values approaching 2 m s^{-1} upward toward cloud top at about 8 km, which is unlikely to result from persistent upward air motion over such an extended layer. The Doppler velocity difference between KAZR and MWACR shows a consistent positive bias in KAZR measurements, suggesting a possible contribution from beam pointing offsets through projection of horizontal wind onto a slightly tilted KAZR beam.

Figure 2 shows the schematic illustration of the geometric relationship between Vd, horizontal wind (U), particle fall velocity (Vf), and vertical air motion (W). When the radar beam is vertically pointing, the measured Vd is a summation of Vf and W. When the radar beam deviates from the vertical direction, the measured Vd has three main components from the projection of U, Vf, and W as in following equation:

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

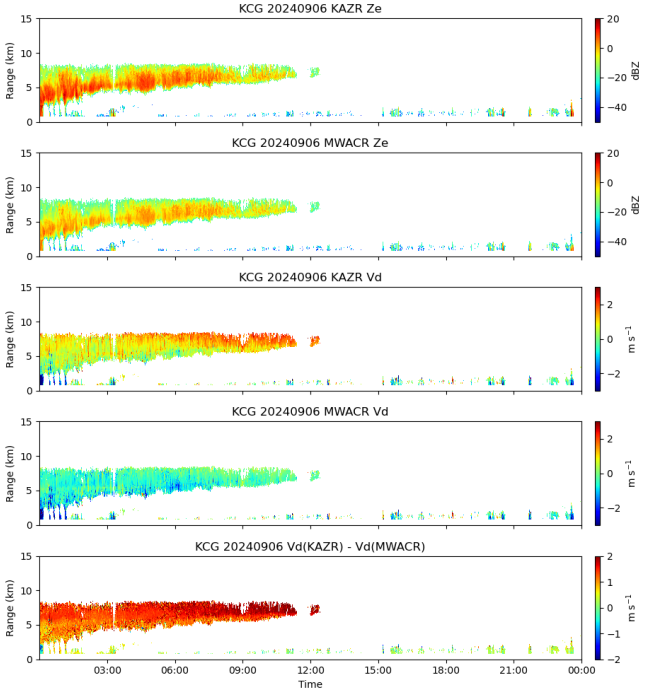

Figure 1. Time–height cross sections of radar reflectivity (Ze) and Doppler velocity (Vd) observed by KAZR and MWACR at the CAPE-k site (KCG) on 6 September 2024. Panels show (a) KAZR reflectivity, (b) MWACR reflectivity, (c) KAZR Doppler velocity, (d) MWACR Doppler velocity, and (e) Doppler velocity difference Vd(KAZR) − Vd(MWACR).

225

226

$$v_{d,ka} \approx \boldsymbol{U}\, cos(\boldsymbol{\phi} - \boldsymbol{\phi_{0,ka}})\, cos(\boldsymbol{\theta_{0,ka}}) + w sin(\boldsymbol{\theta_{0,ka}}) - v_{f,ka} sin(\boldsymbol{\theta_{0,ka}}) + C_{ka}, \quad (1)$$

$$v_{d,w} \approx \boldsymbol{U}\, cos(\boldsymbol{\phi} - \boldsymbol{\phi_{0,w}})\, cos(\boldsymbol{\theta_{0,w}}) + w sin(\theta_{0,w}) - v_{f,w} sin(\boldsymbol{\theta_{0,w}}) + C_{w}, \quad (2)$$

227

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

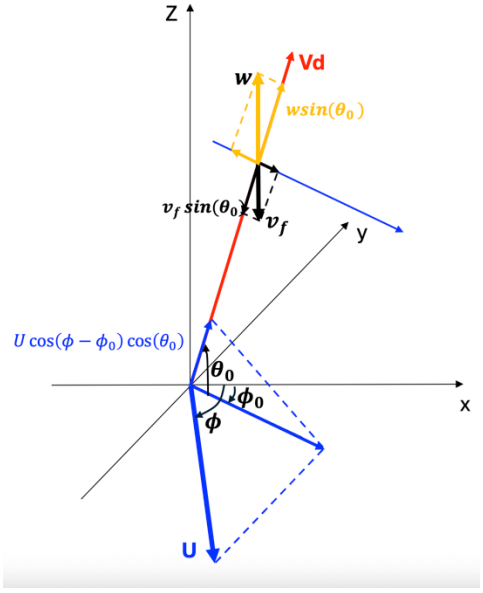

Figure 2. Schematic illustration of the geometric relationship between Doppler velocity (Vd), horizontal wind (U), particle fall velocity (Vf), and vertical air motion (*w*). The radar beam pointing is defined by zenith angle θ_0 and azimuth angle ϕ_0. The horizontal wind direction is denoted by ϕ. The projection of U, Vf, and *w* onto the radar beam contributes to Doppler velocity when the radar beam deviates from the vertical direction.

The radar beam pointing is defined by zenith angle θ_0 and azimuth angle ϕ_0. In this study, the horizontal wind direction ϕ is defined differently from current radiosonde convention. It is defined using the vector direction convention, measured clockwise from north as the direction toward which the wind flows rather than the direction from which it originates, such that 0° indicates northward flow and 180° indicates southward flow. The projection of U, Vf, and W onto the radar beam contributes to Doppler velocity when the radar beam deviates from the vertical direction. The C_{ka} and C_w are the corresponding offsets for KAZR and MWACR, which should be close to zero.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

3. Beam Pointing Estimation Method

3.1 Sensitivity of Doppler Velocity to Horizontal Wind and Beam Pointing Angle

The contribution of horizontal wind to Doppler velocity increases with both horizontal wind speed and radar beam off-zenith angle. To illustrate this sensitivity, Doppler velocity was simulated as a function of wind direction for different horizontal wind speeds and radar zenith pointing angles, assuming zero particle fall velocity and zero vertical air motion in order to isolate the contribution of horizontal wind. The azimuth angle of the radar beam is assumed to be constant at 135°.

The results are shown in Figure 3. When the radar beam is perfectly vertical ($\theta_0 = 90°$), Doppler velocity shows no dependence on horizontal wind speed or wind direction because the horizontal wind vector is perpendicular to the radar beam. When the radar beam deviates slightly from vertical pointing, Doppler velocity exhibits a cosine dependence on wind direction, with maximum magnitude occurring when the horizontal wind direction is aligned with the radar azimuth angle.

For a small pointing offset of 0.5° ($\theta_0 = 89.5°$), the contribution of horizontal wind produces a weak but detectable Doppler velocity signal. For example, when horizontal wind speed is 10 m s^{-1}, the resulting Doppler velocity magnitude is approximately 0.05 m s^{-1}. For stronger winds of 40 m s^{-1}, which are commonly observed in upper-level jet conditions, the maximum Doppler velocity contribution increases to approximately 0.3 m s^{-1}.

As the off-zenith angle increases, the magnitude of the wind-induced Doppler velocity increases approximately proportionally to $\cos(\theta_0)$. Increasing the beam offset from 0.5° to 1° approximately doubles the amplitude of the wind-induced Doppler velocity signal, while increasing the offset to 2° produces an approximately fourfold increase relative to the 0.5° case. This strong sensitivity to small pointing offsets demonstrates that the wind-direction dependence of Doppler velocity provides an effective method for estimating and validating radar beam pointing.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

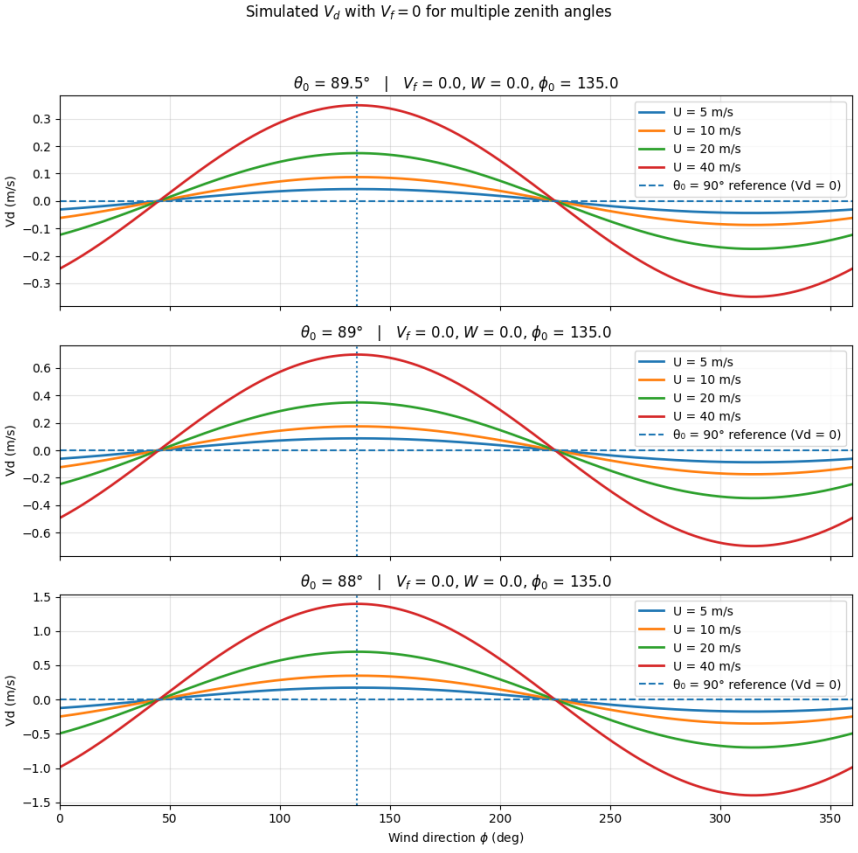

Figure 3 Simulated Doppler velocity (Vd) as a function of wind direction for different horizontal wind speeds (U) and radar zenith pointing angles (θ_0), illustrating the dependence of Vd on beam mispointing, assuming zero fall velocity and air motion. a) θ_0 =89.5° b) θ_0 =89° and c) θ_0 =88°

3.2 Normalization of Doppler Velocity by Horizontal Wind Speed

Equation (1) and Figure 3 show that the contribution of horizontal wind to Doppler velocity depends on both wind speed and radar beam pointing geometry. Because horizontal wind speed varies with height and time, direct comparison of Doppler velocity between radar and radiosonde measurement can be influenced by variability in wind magnitude. To isolate the geometric contribution of beam pointing to Doppler

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

velocity, the observed Doppler velocity is normalized by horizontal wind speed obtained from radiosonde measurements.

Dividing Eq. (1) by horizontal wind speed U yields

$$\frac{V_d}{U} \approx \cos(\phi - \phi_0)\cos(\theta_0) + \frac{W - V_f}{U}\sin(\theta_0) + \frac{C_{ka}}{U}. \quad (3)$$

For sufficiently strong horizontal wind speeds, the second and third terms become small compared to the first term and less of wind direction dependence, especially in upper-level ice clouds where particle fall velocities are small and vertical air motion is weak relative to synoptic-scale horizontal wind. Under these conditions, the normalized Doppler velocity can be approximated as

$$\frac{V_d}{U} \approx \cos(\phi - \phi_0)\cos(\theta_0) + C \quad (4)$$

where C represents a small constant offset that accounts for the combined contribution of mean particle fall velocity, mean vertical air motion, and potential calibration bias.

This normalization removes the dependence of Doppler velocity magnitude on wind speed and highlights the cosine dependence on wind direction. As a result, the normalized Doppler velocity primarily reflects radar beam pointing geometry rather than atmospheric variability in wind magnitude. Because both KAZR and MWACR observe the same horizontal wind field, the ratio V_d/U provides a consistent framework for comparing beam pointing characteristics between the two radars. The amplitude of the cosine relationship is proportional to $\cos(\theta_0)$, while the phase shift provides an estimate of the azimuth pointing offset ϕ_0. In addition to the cosine dependence of V_d/U associated with off-vertical pointing, atmospheric vertical air motion and hydrometeor fall velocity contribute additional variability that can introduce scatter or bias in the expected relationship.

3.3 Wind dependence of Vd using Radiosonde Observations

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

To evaluate radar beam pointing using the relationship between Doppler velocity and horizontal wind, Doppler velocity profiles are compared with collocated radiosonde wind measurements. For each radiosonde launch, radar Doppler velocity profiles (Vd) are averaged within a time window centered on the radiosonde launch time (typically from ±30 to ±150 minutes). The temporal averaging reduces variability associated with turbulence and short-term cloud evolution while maintaining consistency with the large-scale wind profile measured by the radiosonde.

Radiosonde temperature profiles are used to identify atmospheric layers above the melting level in order to minimize the contribution of precipitation fall velocity. Above the melting layer, ice-phase particles generally exhibit smaller fall velocities and reduced variability, making these regions more suitable for isolating the horizontal wind contribution to Doppler velocity.

The averaged Doppler velocity profiles are then examined together with radiosonde wind speed and wind direction profiles. According to Eq. (1), when the radar beam deviates slightly from vertical pointing, Doppler velocity exhibits a dependence on horizontal wind speed and wind direction through the geometric projection of the wind vector onto the radar beam. The normalized quantity V_d/U is therefore expected to follow a cosine dependence on wind direction.

Figure 4 shows an example of this processing procedure for the case in Figure 1. In this case, the wind direction is relatively uniform between approximately surface and 15 km altitude, with winds primarily from the northwest. Wind speed increases substantially with height, from approximately 10 m s^{-1} near surface to nearly 90 m s^{-1} near 11 km altitude, consistent with the presence of strong upper-level flow. KAZR measures two layers of clouds, and the upper layer is our focus here. The Doppler velocity measured by KAZR exhibits a corresponding increase with height, increasing from approximately 0.5 m s^{-1} near 6 km to about 2 m s^{-1} near 8 km. In contrast, MWACR Doppler velocity exhibits weaker vertical variation, with general downward motion ranging from 0 to 0.5 m s^{-1}.

Because the contribution of horizontal wind to Doppler velocity depends primarily on wind direction rather than altitude, observations from multiple heights within ice cloud layers can be combined to improve statistical robustness. In individual radiosonde

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

cases, wind direction may not vary sufficiently with height to clearly reveal the cosine dependence predicted by Eq. (2). Therefore, observations from multiple radiosonde launches throughout the field campaign are combined to obtain a broad sampling of wind directions. This aggregation allows identification of the expected cosine dependence of normalized Doppler velocity on wind direction and enables estimation of radar beam pointing offsets.

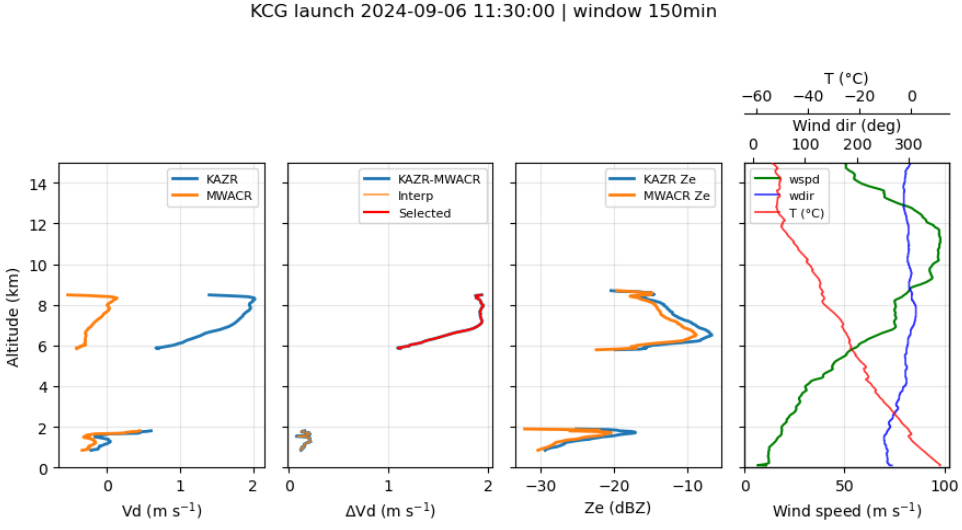

Figure 4 Profiles of KCG KAZR and MWACR Doppler velocity (Vd) averaged over a time window centered on the radiosonde launch, together with collocated radiosonde profiles of temperature, wind speed, and wind direction.

4. Method Application and Results

4.1 KAZR Observations from the CAPE-k

The CAPE-k campaign was deployed from April 15, 2024, to October 15, 2025. The dominant wind in cloud from radiosonde measurement in Figure 5a is in 50 to 150 degrees, which are south-westerly, westerly to north-westerly wind. The corresponding Doppler velocity as a function of wind direction Figure 5b shows a baseline Vd at approximately −0.8 m s^{-1}, consistent with typical fall velocities of ice particles. Superimposed on this baseline Vd, a wind-direction-dependent modulation

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

is evident, with maximum positive Doppler velocity at 1.5 m s^{-1}, occurring near a wind direction of approximately 140°, approximate in the radar azimuth angle.

The Doppler velocity exhibits substantial variability, especially around 50-150 degree, due to the combined influence of hydrometeor fall velocity, vertical air motion, and projection of horizontal wind onto a slightly tilted radar beam as shown in Fig. 5a. The magnitude of the Doppler velocity variation reaches values close to 1.5 m s^{-1}, comparable to the simulated wind-projection component shown in Fig. 3c.

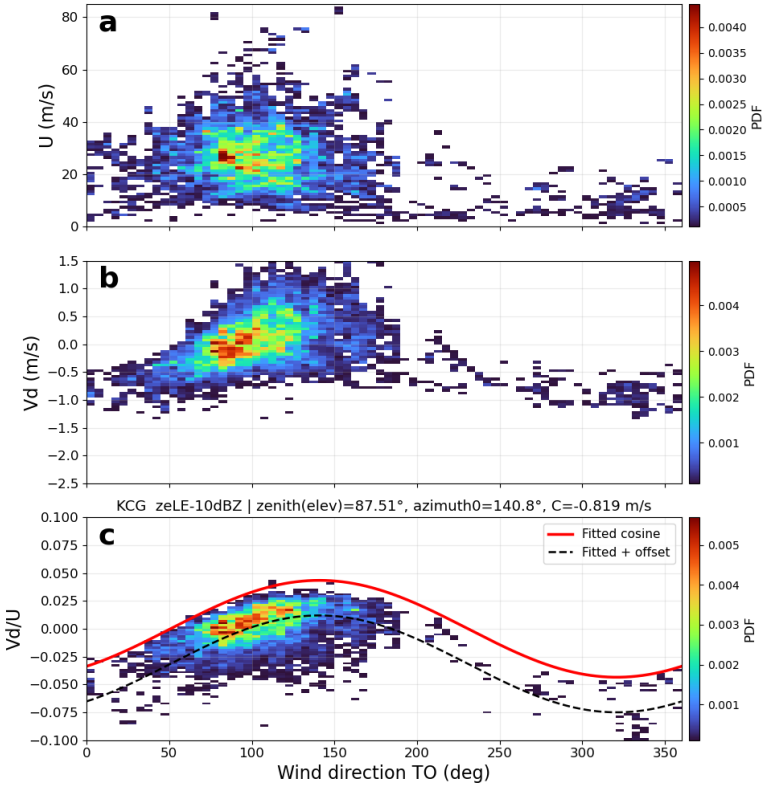

Figure 5. KAZR pointing validation at CAPE-k. (a) Horizontal wind speed (U), (b) Doppler velocity (Vd), and (c) normalized Doppler velocity (Vd/U) as functions of wind direction toward the angle, rather than from the angle as in radar coordinate. In panel (c), cosine fits to Vd/U are shown with and without a constant offset; the offset (−0.819 m s^{-1}) represents the combined contribution of mean particle fall velocity and vertical air motion.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Figure 5c shows the normalized Doppler velocity (V_d/U) as a function of wind direction. After normalization by horizontal wind speed, the dependence of Doppler velocity on wind direction becomes more clearly defined. The normalized observations exhibit a cosine variation consistent with the cosine dependence predicted by Eq. (2). A cosine function is fitted to the observations to estimate the radar beam pointing parameters. The amplitude of the fitted cosine function corresponds to a zenith pointing angle θ_0 of approximately 87.5°, indicating an off-zenith pointing of about 2.5°. The phase shift provides an estimate of the azimuth pointing direction ϕ_0 of approximately 140°, indicating the direction of beam tilt relative to geographic north.

4.2 MWACR Observations from the CAPE-k

The same analysis procedure is applied to MWACR observations collected during the CAPE-k field campaign to evaluate beam pointing characteristics and provide an independent comparison with KAZR. Figure 6 summarizes the MWACR observations using data from the full campaign period. Figure 6b shows Doppler velocity as a function of wind direction. The MWACR Doppler velocity exhibits variability associated with changes in horizontal wind speed, superimposed on a mean Doppler velocity of approximately −0.7 m s^{-1}, consistent with expected fall speeds of ice particles. Compared with KAZR, the MWACR Doppler velocity shows a smaller wind-direction-dependent modulation, indicating a weaker influence of horizontal wind projection.

Figure 6c shows the normalized Doppler velocity (V_d/U) as a function of wind direction. After normalization by horizontal wind speed, the MWACR observations exhibit a relatively weak cosine dependence on wind direction compared with KAZR. The fitted cosine function yields a zenith pointing angle of approximately 89.4°, corresponding to an off-vertical pointing of about 0.6°. The fitted azimuth angle indicates the direction of the small residual beam tilt. The fitted constant offset of approximately −0.69 m s^{-1} represents the combined contribution of mean particle fall velocity and vertical air motion within the analyzed ice cloud layers.

The weaker cosine dependence of V_d/U on wind direction suggests that the MWACR beam is closer to vertical than the KAZR beam during this campaign period. Besides the beam width difference in radars, differences in the amplitude of the fitted cosine

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

relationship indicate that the stronger wind-direction dependence observed in KAZR Doppler velocity is likely associated with a larger beam pointing offset.

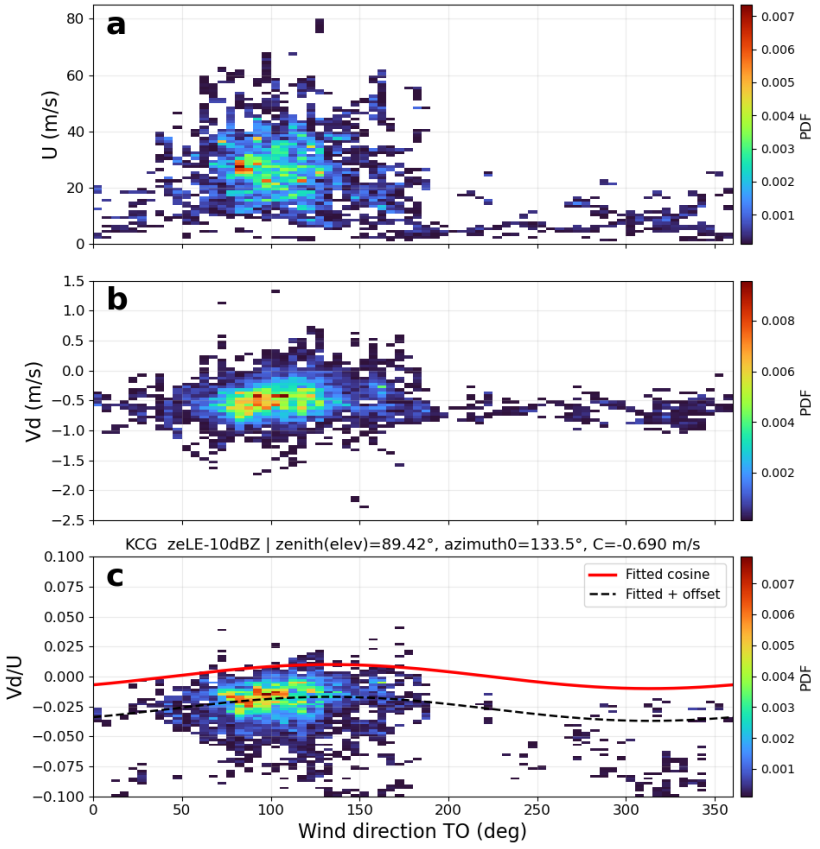

Figure 6. Same as Figure 5, but for MWACR at CAPE-k.

4.3 Difference Between KAZR and MWACR Doppler Velocity

To further validate the beam-pointing estimation method, the Doppler velocity difference between KAZR and MWACR is examined. Because the two radars observe nearly the same atmospheric volume, the contributions from particle fall velocity (V_f) and vertical air motion (W) are expected to be similar. Taking the Doppler velocity difference therefore reduces the influence of these atmospheric contributions and emphasizes differences associated with radar beam pointing.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

The Doppler velocity difference is defined as

$$\Delta v_d = v_{d,\mathrm{KAZR}} - v_{d,\mathrm{MWACR}}.$$

Assuming that the contributions from particle fall velocity and vertical air motion largely cancel, the Doppler velocity difference can be approximated as

$$\Delta v_d \approx U\cos(\phi - \phi_0)\cos(\theta_0) + C,$$

where U is horizontal wind speed, $\phi$is wind direction, $\phi_0$is the effective azimuth angle of the relative beam pointing offset, $\theta_0$is the effective zenith angle of the relative pointing offset, and C is a constant offset term. After normalization by horizontal wind speed,

$$\frac{\Delta v_d}{U} \approx \cos(\phi - \phi_0)\cos(\theta_0) + \frac{C}{U}.$$

For sufficiently strong winds, the second term becomes small, and the normalized Doppler velocity difference is approximately described by a cosine dependence on wind direction.

Figure 7 shows the Doppler velocity difference between KAZR and MWACR for all radiosonde cases during the field campaign. Panel (a) is identical to Figs. 5a and 6a. Panel (b) shows the Doppler velocity difference as a function of wind direction. The mean $\Delta v_d$is close to zero, indicating that the contributions from particle fall velocity and vertical air motion largely cancel, as expected. The Doppler velocity difference exhibits a systematic wind-direction dependence, with maximum values of approximately 1–1.5 m s^{-1} occurring near a wind direction of about 140°.

Panel (c) shows the normalized Doppler velocity difference, $\Delta v_d/U$, as a function of wind direction. Compared with the individual radar results, the normalized difference exhibits a clearer cosine dependence and a much smaller constant offset. The fitted cosine relationship indicates an effective elevation angle of approximately 88.5°, corresponding to a relative off-vertical pointing of about 1.5°, and an azimuth direction near 140°. The near-zero offset term indicates that differencing largely removes the

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

mean contributions from particle fall velocity and vertical air motion that appear as offsets in the individual radar analyses.

This result provides an important validation of the method. Because the differencing approach suppresses the common atmospheric contributions to Doppler velocity, the remaining wind-direction-dependent signal more directly reflects the relative beam pointing difference between the two radars. The consistency between the individual-radar fits and the difference analysis supports the interpretation that the observed cosine dependence of Doppler velocity on wind direction primarily results from radar beam mispointing.

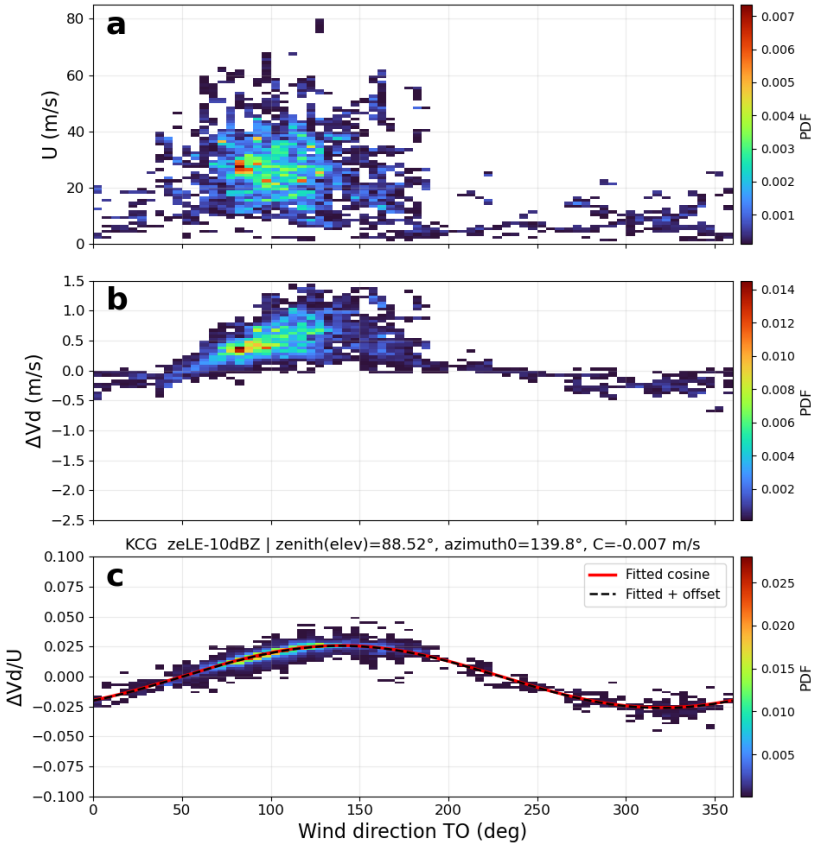

Figure 7 Same as Figures 5 and 6, but for the difference in Doppler velocity (ΔVd) between KAZR and MWACR.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

4.4 Application to the recent campaigns and fixed sites

To assess whether the proposed beam-pointing validation method is applicable beyond the CAPE-k campaign, the same analysis was applied to KAZR observations collected during the Bankhead National Forest (BNF, Kuang et al., 2026) and other field campaigns. As in the CAPE-k analysis, Doppler velocity observations were paired with collocated radiosonde wind profiles. Only data from ice cloud layers above the melting level were retained to reduce the influence of precipitation fall velocity. The normalized Doppler velocity, V_d/U, was then analyzed as a function of wind direction to identify the expected cosine dependence associated with radar beam pointing offsets.

Figure 8 summarizes the KAZR observations from the BNF campaign. Panel (a) shows horizontal wind speed as a function of wind direction derived from radiosonde measurements. Similar to CAPE-k, the BNF dataset includes a broad range of wind speeds, typically between 10 and 60 m s^{-1}, with occasional stronger winds exceeding 80 m s^{-1}, providing sufficient variability for evaluating the wind-projection component of Doppler velocity. Panel (b) shows the corresponding KAZR Doppler velocity observations. The mean Doppler velocity is approximately −0.5 m s^{-1}, consistent with expected fall speeds of ice particles. The wind-direction-dependent variability in Doppler velocity is weaker than that observed for KAZR at CAPE-k and is comparable in magnitude to the MWACR results shown in Fig. 6. Panel (c) shows the normalized Doppler velocity, V_d/U, as a function of wind direction. The normalized observations exhibit a weak but systematic cosine dependence consistent with the cosine relationship predicted for small beam pointing offsets.

The cosine fit shown in Fig. 8c yields a retrieved elevation angle of approximately 89.5°, corresponding to an off-vertical pointing offset of about 0.5°, and an azimuth angle near 130°. The fitted constant offset is approximately −0.5 m s^{-1}, reflecting residual contributions from mean particle fall velocity and vertical air motion. Compared with the CAPE-k KAZR result, the weaker cosine signal at BNF indicates a smaller beam pointing offset during this campaign period.

The estimated off-vertical pointing angle of about 0.5° is relatively small and is comparable to expected uncertainties associated with both instrument characteristics and the retrieval method. Several factors can contribute to this level of uncertainty.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

First, the effective beam direction can be influenced by the radar beam width and sidelobe structure. Even if the radar container and antenna mount are mechanically aligned with the local vertical, slight asymmetries in the antenna radiation pattern or sidelobe contamination may introduce a small effective tilt in the zenith beam. Second, partial beam filling near cloud boundaries or horizontal inhomogeneity in ice cloud layers can introduce variability in the observed Doppler velocity that is not related to beam pointing. Third, spatial separation between the radar sampling volume and radiosonde wind measurements introduces representativeness uncertainty, particularly in environments with strong wind shear or horizontal variability.

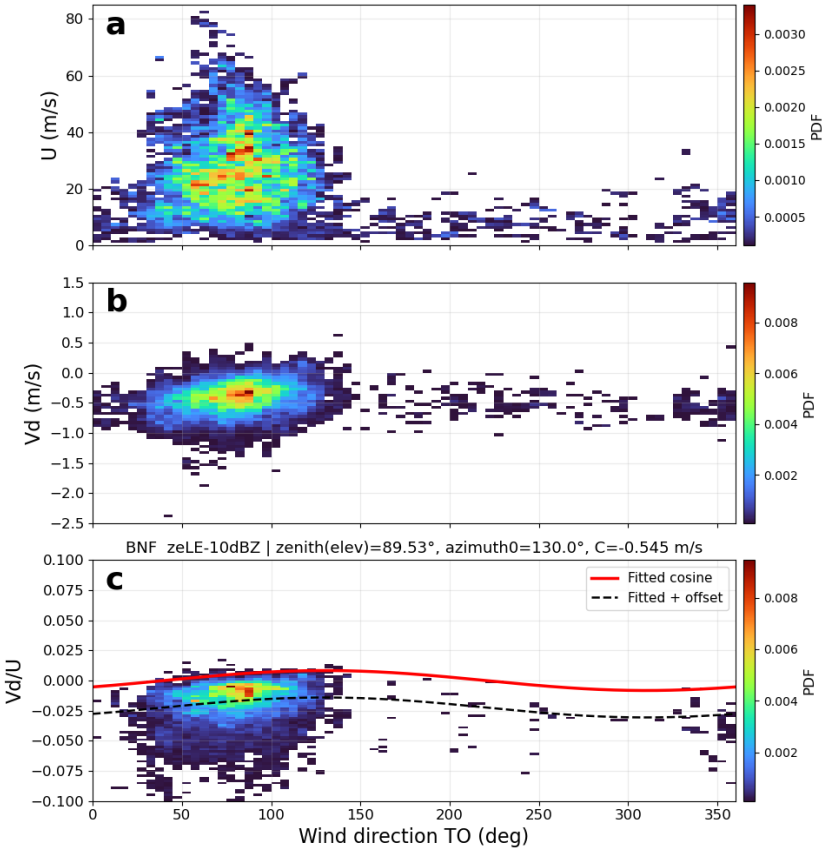

Figure 8. Same as Figure 5, but for KAZR at BNF

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Additional uncertainty arises from methodological choices used in the Doppler velocity averaging and fitting procedure. Sensitivity tests using averaging windows of 30, 50, 90, 120, and 150 minutes show that the retrieved elevation angle varies by less than 0.3°. Sensitivity tests to particle fall velocity effects were performed by applying reflectivity thresholds of −30, −20, −10, and 0 dBZ to select ice cloud layers with different particle size characteristics. The fitted elevation angle varies by less than 0.25° across these thresholds. Considering these factors together, the overall uncertainty in the estimated beam pointing angle is on the order of 0.5°.

These results indicate that the proposed method provides stable and physically consistent estimates of beam pointing across different field campaigns. The relatively small pointing offsets retrieved at BNF, together with the larger offset identified at CAPE-k, demonstrate that the method is capable of detecting both small and moderate deviations from vertical pointing while maintaining uncertainty within approximately 0.5°.

The estimated beam-pointing offsets for recent ARM field campaigns, including the Surface Atmosphere Integrated Field Laboratory (SAIL), TRacking Aerosol Convection interactions ExpeRiment (TRACER), Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE), Coast-Urban-Rural Atmospheric Gradient Experiment (CoURAGE), CAPE-k, and BNF, are summarized in Table 1. Long-term results for the fixed ARM sites—the Southern Great Plains (SGP), North Slope of Alaska (NSA), and Eastern North Atlantic (ENA)—from 2011–2025 are presented in Figure 9. Overall, the retrieved pointing offsets for most field deployments are within approximately 0.5°, indicating generally good mechanical alignment of the radar antenna relative to the local vertical despite challenges associated with instrument transport, installation, and variable environmental conditions encountered during field operations. Two campaigns show larger deviations: CoURAGE exhibits a moderate offset (~1.2°), while CAPE-k shows the largest offset (~2.5° for KAZR). These results demonstrate that most ARM field deployments maintain near-vertical pointing within the expected uncertainty range, and that the proposed method is sufficiently sensitive

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Table 1. Estimated KAZR and MWACR Beam Pointing tilting from vertical for fixed sites and recent field campaigns.

	Site / Campaign	Time Period	Tilt from Vertical (°)
Fixed Sites	SGP	2011-2025	Figure 9
	NSA	2011-2025	Figure 9
	ENA	2016-2025	Figure 9
Field Campaigns	BNF (BNF)	2024-10-01-current	~0.5
	CoURAGE (CRG)	2024-12-01-2025-11-30	~1.2
	CAPE-k (KCG)	2024-04-15-2025-10-15	~2.5 (KAZR) ~0.6 (MWACR)
	EPCAPE (EPC)	2023-02-15-2024-02-14	~0.3
	TRACER (HOU)	2021-10-01-2022-09-30	~0.1
	SAIL (GUC)	2021-09-01-2023-06-15	~0.4

to identify significant alignment deviations when they occur.

For the long-term fixed sites, the results indicate stable pointing performance at SGP and NSA, with typical offsets near 0.5° throughout the 2011–2025 period. This consistency reflects the effectiveness of routine maintenance and periodic instrument levelling performed by ARM radar mentors. A notable deviation is observed at ENA during 2017–2018, where the retrieved pointing offset increases relative to other periods, which resulted increased Doppler velocity as reported by ARM data quality report (https://adc.arm.gov/ArchiveServices/DQRService?dqrid=D190321.8). ARM corrective maintenance (CM) records document a radar leveing procedure conducted in January 2019, after which the estimated pointing offset decreased to approximately 0.1°, indicating restoration of near-vertical alignment. The improved pointing stability following this maintenance activity highlights the importance of periodic mechanical

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

verification and adjustment of radar alignment, particularly after instrument relocation, exposure to severe environmental conditions, or extended operational periods.

Together, Table 1 and Figure 9 demonstrate that the proposed method can be applied consistently across both short-term field deployments and long-term operational sites, providing a unified and quantitative framework for evaluating radar pointing performance across the ARM KAZR network. The results also illustrate how beam pointing diagnostics can complement routine instrument maintenance records by identifying periods of potential misalignment and providing an independent observational constraint on radar mechanical stability.

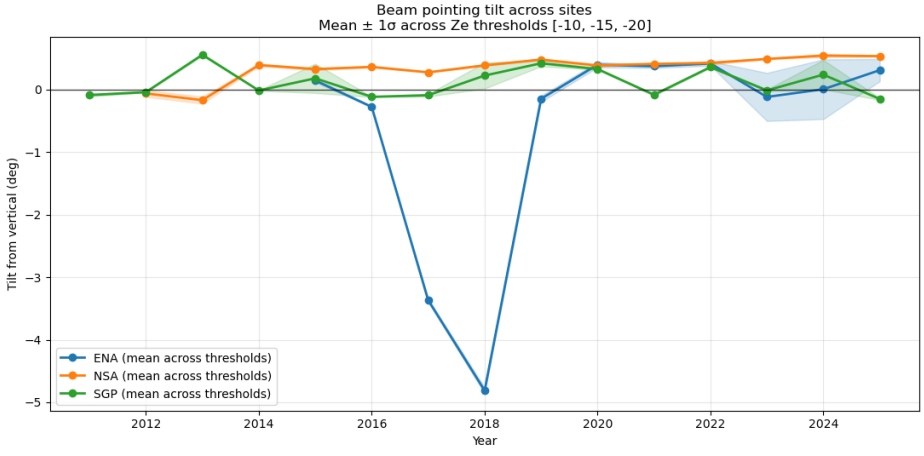

Figure 9. Time series of the mean KAZR beam-pointing tilt from vertical at the ENA, NSA, and SGP sites during 2011–2025. Tilt estimates are derived using multiple radar reflectivity (Ze) thresholds (−10, −15, and −20 dBZ) to filter the observations used in the pointing estimation. Shaded regions represent the standard deviation of the tilt estimates obtained using the different Ze thresholds, indicating the sensitivity of the retrieval to reflectivity-based data selection. The results show generally stable pointing within approximately 0.5° at NSA and SGP over the analysis period, while a larger deviation is evident at ENA during 2017–2018.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

5 Summary

Accurate beam pointing is essential for vertically pointing cloud radars because Doppler velocity measurements are widely used to infer vertical air motion and hydrometeor fall velocity. Even small deviations from vertical pointing introduce a horizontal wind contribution through geometric projection onto the radar beam, potentially biasing the interpretation of cloud dynamical and microphysical processes. In this study, we developed and evaluated a method to estimate and validate beam pointing offsets of vertically pointing cloud radars using collocated radiosonde wind measurements.

The method is based on the cosine dependence of Doppler velocity on horizontal wind direction when the radar beam deviates slightly from the vertical direction. By normalizing Doppler velocity by horizontal wind speed, the dependence on wind magnitude is reduced and the remaining variability primarily reflects radar beam pointing geometry. The normalized Doppler velocity (Vd/U) exhibits a cosine variation with wind direction, allowing quantitative estimation of radar zenith and azimuth pointing offsets through cosine fitting. Sensitivity tests indicate that the uncertainty in the retrieved pointing angle is on the order of 0.5°, demonstrating that the method can detect both small and moderate deviations from vertical pointing.

Application of the method to observations from the CAPE-k field campaign shows detectable pointing offsets for both KAZR and MWACR, with KAZR exhibiting a larger off-vertical deviation than MWACR during this period. Analysis of the Doppler velocity difference between the two radars reduces the influence of particle fall velocity and vertical air motion, resulting in a clearer wind-direction-dependent signal and providing an independent constraint on relative beam pointing differences.

The method was also applied to observations from the BNF field campaign to evaluate its applicability under different atmospheric conditions. Results from BNF indicate very small off-vertical pointing offsets, demonstrating consistency with expected radar alignment and confirming the stability of the retrieval approach. The successful application of the method across multiple field campaigns demonstrates its robustness and general applicability.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Overall, small beam pointing offsets produce measurable Doppler velocity signals through projection of horizontal wind onto the radar beam. Normalization using Vd/U isolates radar beam pointing geometry from variability in wind magnitude. Cosine fitting of the wind-direction dependence provides quantitative estimates of radar zenith and azimuth pointing angles. Differencing Doppler velocity between co-located radars reduces uncertainty associated with particle fall velocity and vertical air motion. The method is applicable across multiple field campaigns and atmospheric conditions.

Because radiosonde observations are routinely available at many atmospheric measurement sites, the proposed method provides a practical and independent approach for monitoring and validating beam pointing of vertically pointing cloud radars. The approach can improve interpretation of Doppler velocity observations and support long-term consistency of radar-derived cloud and vertical velocity products.

Data availability

The Atmospheric Radiation Measurement Climate Research Facility KAZR and MWACR data used in this study, including observations from the CAPE-k, BNF, CoURAGE, EPCAPE, SAIL, and TRACER campaigns, as well as the fixed ARM sites SGP, ENA, and NSA, are available as ARM a1-level data products. The radiosonde data are obtained from the calibrated ARM sondewnpn.b1 datastream, and all datasets are publicly accessible through the ARM Data Discovery portal at ARM Data Discovery.

The beam-pointing estimation algorithm has been implemented at the ARM Data Quality Office for long-term monitoring applications. The code is available from the lead author, Dr. Min Deng, upon request via email (mdeng@bnl.gov).

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Acknowledgement

Contributions from Brookhaven National Laboratory co-authors were supported by the Atmospheric Radiation Measurement (ARM) Facility and the Atmospheric System Research (ASR) program of the Office of Biological and Environmental Research in the U. S. Department of Energy, Office of Science, through Contract No. DE-SC0012704. Pacific Northwest National Laboratory (PNNL) is operated by Battelle for the U. S. Department of Energ. The authors from PNNL are also supported by ARM through Contract No. DE-SC0015990.

References

Dirksen, R. J., Sommer, M., Immler, F., Hurst, D. F., Kivi, R., and Vömel, H.: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde, Atmos. Meas. Tech., 7, 4463–4490, https://doi.org/10.5194/amt-7-4463-2014, 2014.

Deng, M., and G. G. Mace, 2006: Cirrus Microphysical Properties and Air Motion Statistics Using Cloud Radar Doppler Moments. Part I: Algorithm Description. J. Appl. Meteor. Climatol., 45, 1690–1709, https://doi.org/10.1175/JAM2433.1.

Deng, M., and G. G. Mace, 2008: Cirrus microphysics properties and air motion statistics using MMCR Doppler moments: Water content, particle size and sedimentation relationships. GRL, 35, L17808, doi:10.1029/2008GL035054 (13)

Doviak, R. J. and Zrnić, D. S.: Doppler Radar and Weather Observations, Academic Press, San Diego, USA, 1993.

Kalesse, H., and P. Kollias, 2013: Climatology of high cloud dynamics using profiling ARM Doppler radar observations. J. Climate, 26, 6340–6359, doi:10.1175/JCLI-D-12-00695.1.

Keeler, E. Balloon-Borne Sounding System (SONDE) Instrument Handbook. U.S. Department of Energy, Atmospheric Radiation Measurement user facility, Richland, Washington. DOE/SC-ARM-TR029.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

622 Kollias, P., Albrecht, B. A., and Marks, F.: Why Mie? Accurate observations of vertical
623 air velocities and raindrops using a cloud radar, Bull. Amer. Meteor. Soc., 83,
624 1471–1483, https://doi.org/10.1175/BAMS-83-10-1471, 2002.

625 Kollias, P., Bharadwaj, N., Widener, K., Jo, I., and Johnson, K.: Scanning ARM cloud
626 radars. Part I: Operational sampling strategies, J. Atmos. Ocean. Technol., 31,
627 569–582, https://doi.org/10.1175/JTECH-D-13-00044.1, 2014.

628 Kollias, P., and Coauthors, 2016: Development and Applications of ARM Millimeter-
629 Wavelength Cloud Radars. Meteor. Monogr., 57, 17.1–
630 17.19, https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0037.1.

631 Kollias, P., Clothiaux, E. E., Albrecht, B. A., Miller, M. A., Moran, K. P., and Johnson,
632 K. L.: The Atmospheric Radiation Measurement Program cloud profiling radars:
633 Second-generation sampling strategies, processing, and cloud data products,
634 J. Atmos. Ocean. Technol., 24, 1199–1214,
635 https://doi.org/10.1175/JTECH2033.1, 2007.

636 Kollias, P., Szyrmer, W., Luke, E., & McFarquhar, G. (2007).
637 On the estimation of vertical air motion using cloud radar Doppler spectra.
638 Journal of Atmospheric and Oceanic Technology, 24, 1805–1821.
639 https://doi.org/10.1175/JTECH2081.1

640 Kollias, P., Szyrmer, W., Luke, E., & McFarquhar, G. (2007).
641 On the estimation of vertical air motion using cloud radar Doppler spectra.
642 Journal of Atmospheric and Oceanic Technology, 24, 1805–1821.
643 https://doi.org/10.1175/JTECH2081.1

644 Kuang, C., and Coauthors, 2026: The U.S. DOE ARM User Facility Establishes a New
645 Site for Studies of Land–Aerosol–Cloud Interactions in the Southeastern United
646 States. Bull. Amer. Meteor. Soc., 107, E1–E8, https://doi.org/10.1175/BAMS-
647 D-25-0072.1.

648 Luke, E. P. and Kollias, P.: Separating cloud and drizzle radar moments during
649 precipitation onset using Doppler spectra, J. Atmos. Ocean. Technol., 30,
650 1656–1671, https://doi.org/10.1175/JTECH-D-11-00195.1, 2013.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

Mather, J. H. and Voyles, J. W.: The ARM Climate Research Facility: A review of structure and capabilities, Bull. Amer. Meteor. Soc., 94, 377–392, https://doi.org/10.1175/BAMS-D-11-00218.1, 2013.

Moran, K. P., Martner, B. E., Post, M. J., Kropfli, R. A., Welsh, D. C., and Widener, K. B.: An unattended cloud-profiling radar for use in climate research, Bull. Amer. Meteor. Soc., 79, 443–455, https://doi.org/10.1175/1520-0477(1998)079<0443:AUCPRF>2.0.CO;2, 1998.

Nash, J., Oakley, T., Vömel, H., and Wei, L.: WMO intercomparison of high quality radiosonde systems, WMO Instruments and Observing Methods Report No. 107, World Meteorological Organization, Geneva, Switzerland, 2011.

Shupe, M. D., Kollias, P., Matrosov, S. Y., and Schneider, T. L.: Deriving mixed-phase cloud properties from Doppler radar spectra, J. Atmos. Ocean. Technol., 21, 660–670, https://doi.org/10.1175/1520-0426(2004)021<0660:DMCPFD>2.0.CO;2, 2004.

Shupe, M. D., J. M. Comstock, D. D. Turner, and G. G. Mace, 2016: Cloud Property Retrievals in the ARM Program. Meteor. Monogr., 57, 19.1–19.20, https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0030.1.

Shupe, M. D., Kollias, P., Poellot, M., and Eloranta, E.: A focus on mixed-phase clouds: The status of ground-based observational methods, Bull. Amer. Meteor. Soc., 89, 1549–1562, https://doi.org/10.1175/2008BAMS2378.1, 2008.

Shupe, M. D., Kollias, P., Poellot, M., & Eloranta, E. (2008). On deriving vertical air motions from cloud radar Doppler spectra in mixed-phase Arctic clouds. Journal of Atmospheric and Oceanic Technology, 25, 547–557. https://doi.org/10.1175/2007JTECHA1007.1

Zhu, Z., Kollias, P., Yang, F., & Luke, E. (2021). On the estimation of in-cloud vertical air motion using radar Doppler spectra. Geophysical Research Letters, 48, e2020GL090682. https://doi.org/10.1029/2020GL090682

Zhu, Z., Kollias, P., & Yang, F. (2023). Particle inertial effects on radar Doppler spectra simulation.

https://doi.org/10.5194/egusphere-2026-3304
Preprint. Discussion started: 12 June 2026

682 Atmospheric Measurement Techniques, 16, 3727–3737.
683 https://doi.org/10.5194/amt-16-3727-2023