

1 **Estimating Beam Pointing of Vertically Pointing Cloud Radars Using**
2 **Radiosonde Measurements**

3 Min Deng¹, Scott E. Giangrande¹, Adam K. Theisen², Karen Johnson¹, Iosif A.
4 Lindenmaier³, Timothy G. Wendler³, Jennifer Comstock³, Marquette Rocque³, Zeen
5 Zhu¹, and Alyssa Matthews³.

6
7 ¹Brookhaven National Laboratory,

8 ²Argonne National Laboratory,

9 ³Pacific Northwest National Laboratory

10
11 *Correspondence to:* Min Deng (mdeng@bnl.gov)

12
13
14 Manuscript submitted to AMT publication.

Formatted: Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

Deleted: to be

Formatted: Font: Arial, Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

43 **Abstract**

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

49 We present horizontal wind U normalized velocity direction display (UN-VDD) method
50 to estimate and validate radar beam pointing angle using collocated radiosonde
51 observations. When the radar beam is tilted, the observed Doppler velocity exhibits a
52 cosine dependence on wind direction due to projection of horizontal wind onto the
53 beam, with an amplitude proportional to wind speed. By normalizing Doppler velocity
54 with horizontal wind speed, this geometric dependence can be isolated, enabling
55 quantitative retrieval of off-zenith beam pointing estimation.

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

67

68

69

70

Formatted: Font color: Text 1

Deleted: a

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

72 **Short Summary**

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

80 **1. Introduction**

81 Vertically pointing cloud radars have become essential tools for observing cloud
82 structure, microphysics, and atmospheric dynamics at high temporal and spatial
83 resolution. Measurements of radar reflectivity and Doppler velocity from these systems
84 provide key information for studies of cloud processes, precipitation formation, and
85 vertical air motion. Doppler velocity observed by vertically pointing radars is commonly
86 interpreted as the sum of hydrometeor fall velocity and vertical air motion, forming the
87 basis for numerous retrieval techniques for in-cloud vertical velocity, turbulence, and
88 microphysical properties. These measurements have been widely used to investigate
89 boundary layer clouds, mixed-phase and ice cloud processes, and precipitation
90 dynamics (e.g., Kollias et al., [2002](#); Deng et al. 2006, [2008a](#), Shupe et al., 2008, [2016](#);
91 Kollias et al., 2014).

92 The United States Department of Energy (DOE) Atmospheric Radiation Measurement
93 user facility (ARM) has continuously deployed vertically pointing cloud radars at fixed
94 and mobile observatories since 1996 ([Moran et al. 1998](#), Kollias et al., [2007 and 2016](#),
95 [Mather et al., 2013](#)). Initially, the Ka-band Millimeter Cloud Radar (MMCR) was
96 deployed, then in 2011, ARM transitioned to the Ka-band ARM Zenith Radar (KAZR)
97 and the Marine W-band ARM Cloud Radar (MWACR). Both KAZR and MWACR were
98 recently deployed to kennaook Tasmania to support the Cloud and Precipitation
99 Experiment at kennaook (CAPE-k).

100 A fundamental challenge in Doppler radar analysis is the separation of vertical air
101 motion from hydrometeor fall velocity. Techniques based on Doppler spectra and

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: systems

Formatted: Font color: Text 1

Deleted: 1999

Deleted: 2008

105 Doppler moments, including spectral decomposition and identification of [non-Rayleigh](#)
 106 scattering signatures, have been developed to isolate the air motion component in
 107 cloud and precipitation systems (e.g., Lhermitte, 1988; Kollias et al., 2002; Kollias et
 108 al., 2007; Shupe et al., 2008; Deng and Mace, 2006 and [2008a](#); Kalesse and Kollias,
 109 2013). These studies demonstrate that millimeter-wavelength Doppler spectra and
 110 moments contain detailed information on particle fall velocities, turbulence broadening,
 111 and vertical air motion, although retrieval accuracy depends on assumptions regarding
 112 particle size distributions and scattering regimes. Complementary observations, such
 113 as lidar identification of liquid cloud layers and thermodynamic constraints from
 114 radiosonde measurements, can provide additional context for interpreting Doppler
 115 spectra and reducing uncertainty in vertical velocity estimates (e.g., Shupe et al., 2008;
 116 Kollias et al., 2014; Zhu et al., 2021). Together, these studies highlight the capability
 117 of vertically pointing cloud radars to resolve fine-scale atmospheric motions in clouds.

118 A fundamental assumption underlying these applications is that the radar beam is
 119 accurately aligned with the local vertical. [For a perfectly vertical beam, horizontal wind](#)
 120 [does not contribute to the measured Doppler velocity.](#) However, even small deviations
 121 from zenith can introduce systematic biases in Doppler velocity through projection of
 122 horizontal wind onto the radar beam, [and this may introduce biases](#) in retrieved vertical
 123 air motion and turbulence estimates. This sensitivity is particularly important for
 124 millimeter-wavelength cloud radars such as the KAZR and MWACR, which are
 125 designed to detect small velocity perturbations associated with weak cloud motions
 126 and boundary layer turbulence.

127 Despite the importance of accurate beam alignment, relatively few studies have
 128 directly quantified beam pointing errors for vertically pointing cloud radars. [The radar](#)
 129 [beam alignment has traditionally been assessed through mechanical levelling and](#)
 130 [installation surveys. Observation-based methods infer mispointing from residual](#)
 131 [surface Doppler velocity or from systematic features of cloud Doppler-velocity](#)
 132 [distributions \(Haimov and Rodi, 2013; Battaglia and Kollias, 2015\).](#)

133 Radiosonde observations provide a particularly valuable reference because they offer
 134 high-resolution vertical profiles of horizontal wind speed and direction that are
 135 independent of radar calibration assumptions. [They can reveal horizontal-wind \(U\)](#)
 136 [contamination of nominally vertical Doppler velocities, although their use for](#)

Deleted: Mie

Deleted: 2008

Moved (insertion) [1]

Moved up [1]: For a perfectly vertical beam, horizontal wind does not contribute to the measured Doppler velocity.

Deleted: .

Deleted: In contrast, a small zenith angle offset produces a wind-direction-dependent Doppler signal, which can introduce bias

Deleted: As a result, even sub-degree pointing uncertainties can lead to measurable biases in Doppler velocity and derived geophysical products.

Deleted: 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....

quantitatively retrieving both pointing angles has remained limited. 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 the cosine dependence of U normalized Doppler velocity on wind direction display (UN-VDD) to retrieve off-zenith pointing angle and to quantify the impact of off-vertical titling on Doppler velocity observations. The cosine dependence of Doppler velocity is the established basis of velocity–azimuth display (VAD) wind retrievals for scanning Doppler radars (Browning and Wexler, 1968; Doviak and Zrnić, 1993). VAD method relates Doppler velocity to the scanning-beam azimuth to retrieve wind field, while UN-VDD relates wind-speed-normalized Doppler velocity to radiosonde wind direction to retrieve radar beam pointing.

The method 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 for the method development, which also provides an opportunity to perform cross comparisons for evaluating systematic differences in Doppler velocity and the beam pointing angle between them. KAZR and MWACR were sited to each other within 100 m. KAZR has an antenna diameter of 1.8 m and a one-way half-power beam width (HPBW) of approximately 0.3°, MWACR operated with a 0.6 m diameter antenna and an approximately 0.8° beamwidth during the early part of CAPE-k. In June 2024, the MWACR antenna was upgraded to a diameter of 1.2 m. Both KAZR and MWACR were operated with a range/gate resolution of 30 m during CAPE-k. KAZR had a Nyquist velocity of 7.95 m s⁻¹ and 256 FFT bins, corresponding to a Doppler-bin resolution of 0.06 m s⁻¹. MWACR had a Nyquist velocity of 5.59 m s⁻¹ and 128 FFT bins, corresponding to a Doppler-bin resolution of 0.08 m s⁻¹. Radar reflectivity (Z_e) and

Deleted: their

Deleted: approach

Deleted: ¶

Deleted: this study.

Deleted: 200 meters

Deleted: 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). ¶

Formatted: Font color: Text 1

213 Doppler velocity (V_d) are derived from Doppler spectra obtained by the cloud radar
214 signal [processo following clutter filtering and noise removal \(Doviak and Zrnić 1993\)](#)

215 2.2 [Radiosondes](#)

216 [Radiosondes](#) provide independent measurements of atmospheric state variables,
217 including temperature, pressure, horizontal wind speed, and wind direction. Wind
218 profiles from radiosondes are derived from GPS tracking of balloon position, providing
219 estimates of the horizontal wind vector as a function of height (Dirksen et al. 2014;
220 Nash et al. 2011, Keeler 2025). Typical uncertainties in radiosonde wind
221 measurements are approximately $0.5\text{--}1.0\text{ m s}^{-1}$ for wind speed and $5\text{--}10^\circ$ for wind
222 direction, depending on atmospheric conditions and instrument type (Nash et al. 2011;
223 Dirksen et al. 2014).

224 A known limitation in radar–radiosonde comparisons is the horizontal displacement of
225 the radiosonde during ascent. As the balloon ascends through the atmosphere, it drifts
226 with the ambient wind, resulting in spatial separation between the radiosonde
227 measurement location and the radar sampling volume. Previous studies have shown
228 that radiosonde drift distances typically range from 5 to 30 km by the time the balloon
229 reaches 10 km altitude, depending on wind conditions (Seidel et al. 2011; Nash et al.
230 2011). This spatial displacement introduces uncertainty when comparing radiosonde
231 winds with vertically pointing radar measurements, particularly in environments with
232 strong horizontal wind shear or spatial variability in cloud structure.

233 Despite this limitation, radiosonde wind measurements have been widely used as a
234 reference for validating radar-derived wind and Doppler velocity observations because
235 they provide reliable estimates of the large-scale wind field (May and Rajopadhyaya
236 1999; Kollias et al. 2007). In this study, U_v and wind direction (ϕ) derived from
237 radiosonde observations are combined with [collocated](#) radar Doppler velocity
238 measurements [within different window ranging from 30 to 150 minutes](#) to evaluate the
239 contribution of horizontal wind to the observed Doppler velocity. The comparison
240 assumes that horizontal wind variability over the radiosonde drift distance is relatively
241 small compared to the wind direction dependent Doppler velocity signal associated
242 with radar beam mispointing.

Deleted: 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).

Deleted: 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.

Deleted: Radiosonde observations

Deleted: Radiosonde observations

Deleted: These measurements serve as an external reference for evaluating the relationship between Doppler velocity and horizontal wind direction observed by vertically pointing cloud radars.

Deleted: the horizontal wind speed (

Deleted:)

271
272
273
274
275
276
277
278
279
280
281

282
283
284
285
286
287

288
289
290
291
292
293
294
295
296
297

2.3 Case study of the Vd contribution from horizontal wind

Figure 1 shows time–height cross sections of Z_e and V_d from KAZR and MWACR at the CAPE-k site on 6 September 2024. Both radars simultaneously observed an extensive ice-cloud layer between approximately 5–8 km, The vertical dashed line marks the launch time of the collocated radiosondes at 11:30 UTC. And the shaded regions indicate the 150- minutes radar averaging window used for comparison with the radiosonde profile. Within this cloud 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 of approximately 0–0.5 m s⁻¹. These values are comparable to typical fall speeds of small ice crystals, which are approximately 0.1–0.5 m s⁻¹, whereas larger particles and aggregates can fall faster than 1 m s⁻¹ (Deng and Mace 2008a and b; Protat and Williams 2011 Mitchell et al. 2011; Kalesse and Kollias 2013).

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 in figure 1e 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. This case is selected as a representative example signature occurred on many other days during CAPE-k, should not be considered exceptional and is used only to illustrate the analysis procedure.

•

- Deleted: radar reflectivity (
- Deleted:)
- Deleted: Doppler velocity (
- Deleted:)
- Deleted: observe
- Deleted: indicating consistent detection
- Deleted: cloud structure.

Deleted: around 0–0.5 m s⁻¹, consistent with expected fall speeds of small ice particles in stratiform cloud conditions.

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

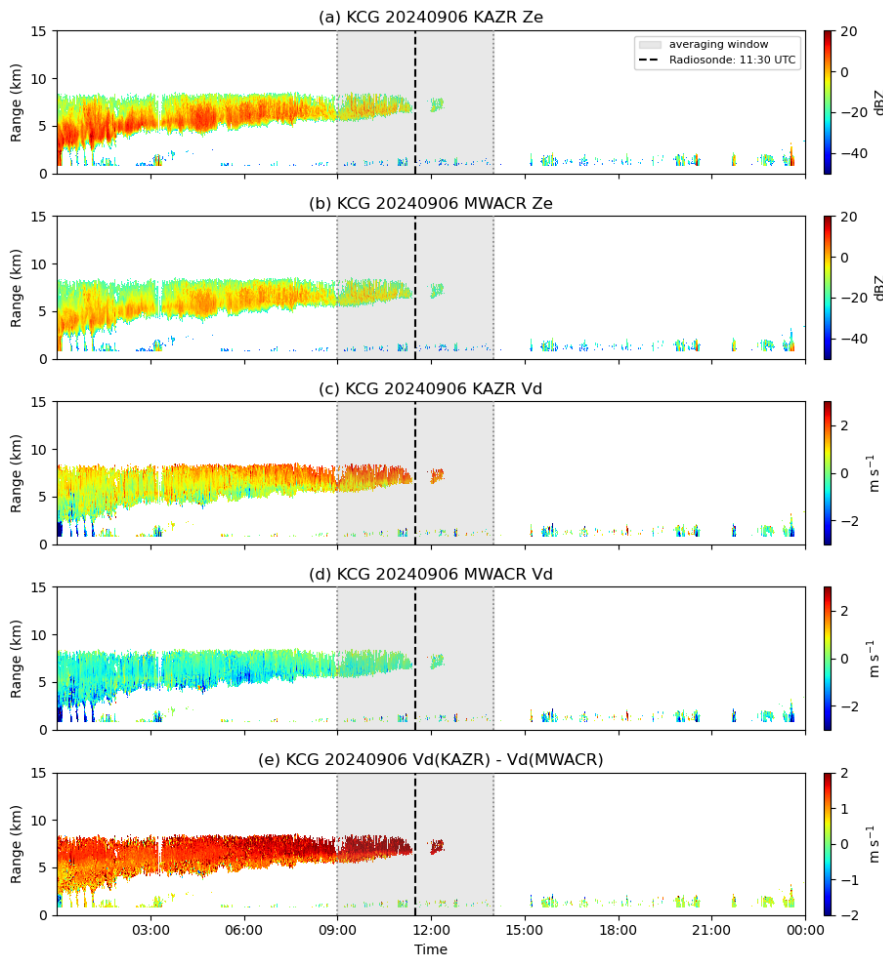


Figure 1. Time–height cross sections of radar reflectivity (Ze) and Doppler velocity (Vd) observed by KAZR and MWACR at the CAPE-k site (KCG) on 6 September 2024. Panels show (a) KAZR reflectivity, (b) MWACR reflectivity, (c) KAZR Doppler velocity, (d) MWACR Doppler velocity, and (e) Doppler velocity difference Vd(KAZR) – Vd(MWACR). The collocated radiosondes at 11:30 UTC is denoted in dashed line, and the shaded regions indicate the 150- minutes radar averaging window.

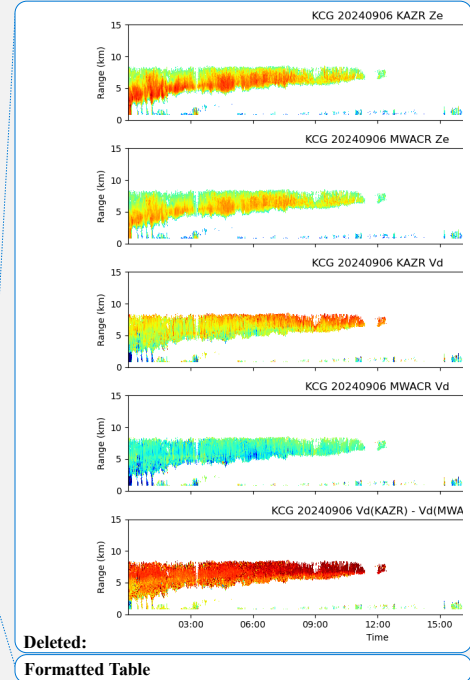


Figure 2 illustrates the geometric relationship between measured Vd, U, particle fall velocity (Vf), and vertical air motion (W). The radar beam pointing is defined by elevation angle θ_n , measured upward from the horizontal, and azimuth angle ϕ_n , measured clockwise from north. W is defined as positive upward, Doppler velocity is defined as positive along the radar beam away from the radar. The radar off vertical tilt angle, Is defined as $90 - \theta_n$. The horizontal-wind direction ϕ follows the vector-direction convention and is measured clockwise from north toward the direction in which the wind flows. This differs from the conventional radiosonde or meteorological wind direction, which indicates the direction from which the wind originates. Thus, $\phi = 0^\circ$ represents northward flow, whereas $\phi = 180^\circ$ represents southward flow. 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 Doppler velocities measured by the KAZR and MWACR are therefore expressed as:

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

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

In Eqs. (1)–(2), the first term is the projection of the horizontal wind onto the radar beam. The second and third terms are the respective projections of vertical air motion and downward particle fall velocity. The terms C_{ka} and C_w represent the small instrumental error for the KAZR and MWACR, respectively.

Moved (insertion) [2]

Deleted: ¶

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

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

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

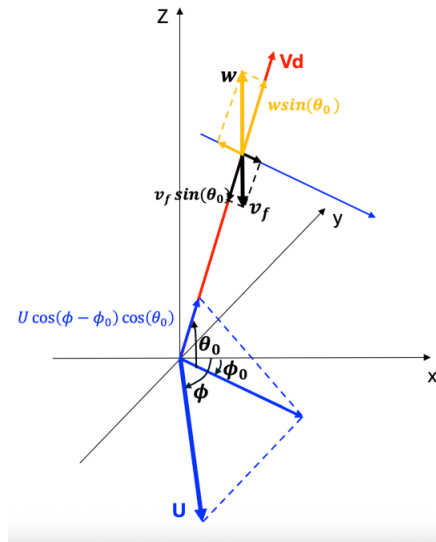


Figure 2. Schematic illustration of the geometric relationship between Doppler velocity (V_d), horizontal wind (U), particle fall velocity (V_f), and vertical air motion (w). The radar beam pointing is defined by elevation angle θ_0 and azimuth angle ϕ_0 . The horizontal wind direction is denoted by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

Deleted: zenith

Deleted: ¶

... [1]

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° .

356 The results are shown in Figure 3. When the radar beam is perfectly vertical ($\theta_0 = 90^\circ$),
357 Doppler velocity shows no dependence on horizontal wind speed or wind direction
358 because the horizontal wind vector is perpendicular to the radar beam. When the radar
359 beam deviates slightly from vertical pointing, Doppler velocity exhibits a cosine
360 dependence on wind direction, with maximum magnitude occurring when the
361 horizontal wind direction is aligned [along or opposite to](#) the radar azimuth angle.

Deleted: with

362 For a small pointing offset of 0.5° ($\theta_0 = 89.5^\circ$), the contribution of horizontal wind
363 produces a weak but detectable Doppler velocity signal. For example, when horizontal
364 wind speed is 10 m s^{-1} , the resulting [maximum](#) Doppler velocity magnitude is
365 approximately 0.1 m s^{-1} . For stronger winds of 40 m s^{-1} , which are commonly observed
366 in upper-level jet conditions, the maximum Doppler velocity contribution increases to
367 approximately 0.3 m s^{-1} .

Deleted: 05

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

375

376

377

Simulated V_d with $V_f = 0$ for multiple elevation angles

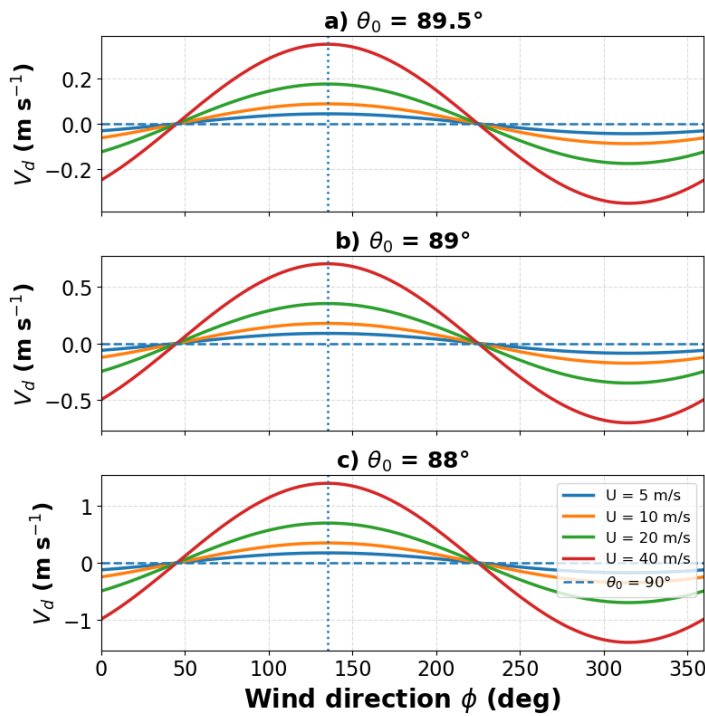
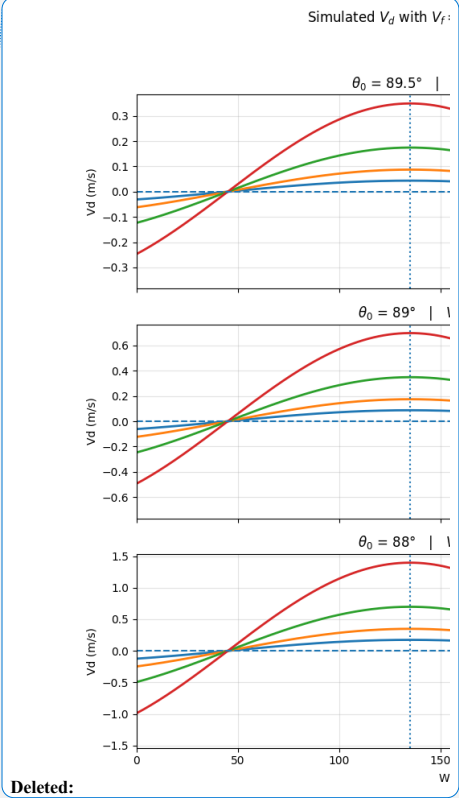


Figure 3 Simulated Doppler velocity (V_d) as a function of wind direction for different horizontal wind speeds (U) and radar zenith pointing angles (θ_0), illustrating the dependence of V_d on beam mispointing, assuming zero fall velocity and air motion. a) $\theta_0 = 89.5^\circ$ b) $\theta_0 = 89^\circ$ and c) $\theta_0 = 88^\circ$



Formatted: Font: Arial

Formatted: Font: Arial

Formatted: Font: Arial

Formatted: Font: Arial

Formatted: Font: Arial

Deleted: by Horizontal Wind Speed

Deleted: Equation

380

381 3.2 [Horizontal Wind U](#) Normalization of Doppler Velocity [Direction Display \(UN-VDD\)](#)

382 [Equations \(1\) and \(2\)](#) and Figure 3 show that the contribution of horizontal wind to
383 Doppler velocity depends on both wind speed and radar beam pointing geometry.
384 Because horizontal wind speed varies with height and time, direct comparison of
385 Doppler velocity between radar and radiosonde measurement can be influenced by
386 variability in wind magnitude. To isolate the geometric contribution of beam pointing to

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

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

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

395 For sufficiently strong horizontal wind speeds, the third terms in Eq. (3) become small
 396 compared to the first term of wind projection. The second term represents the
 397 contributions of particle fall velocity and vertical air motion. These contributions are not
 398 expected to vary systematically with wind direction; instead, they introduce scatter and
 399 an approximately direction-independent offset in the normalized Doppler velocity. This
 400 approximation is particularly appropriate for upper-level ice clouds, where particle fall
 401 velocities and vertical air motions are generally weak relative to synoptic-scale
 402 horizontal winds. Under these conditions, the normalized Doppler velocity can be
 403 approximated as

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

406 where C represents a small constant offset that accounts for the combined contribution
 407 of mean particle fall velocity, mean vertical air motion, and potential calibration bias.
 408 The amplitude of the cosine relationship is proportional to $\cos(\theta_0)$ and therefore
 409 increases with the off-vertical pointing angle, while its phase provides the beam-tilt
 410 azimuth ϕ_0 . Normalization reduces the dependence of Doppler velocity magnitude on
 411 wind speed and emphasizes its cosine dependence on wind direction. Consequently,
 412 V_d/U primarily reflects the radar beam-pointing geometry rather than variations in wind
 413 magnitude. Figure 4 presents the UN-VDDs for the simulated radar pointing offsets
 414 shown in Figure 3. As V_f and W are set to zero, the cosine relationship is centred at
 415 zero. In actual observations, particle sedimentation produces a negative bias and
 416 scatter in the fitted relationship, as demonstrated in the following section.

Deleted: ¶ ... [2]

Deleted: second and

Deleted: and less

Deleted: dependence, especially in

Deleted: are small

Deleted: motion is

Deleted: wind

Formatted: Font: Cambria Math

Deleted: 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. ¶

¶ Wind dependence of V_d

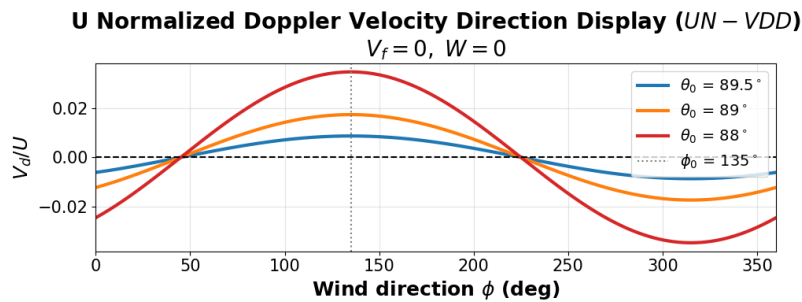


Figure 4. U-normalized velocity-direction displays (UN-VDDs) derived from the simulations in Figure 3 for $\theta_0 = 89.5^\circ$, 89° , and 88° .

3.3 UN-VDD Beam Pointing Estimation using Radiosonde Observations

To implement the UN-VDD for radar pointing estimation, for each radiosonde launch, radar Doppler velocity profiles (V_d) are averaged within a time window of 150 minutes centered on the radiosonde launch time. 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. The averaged Doppler velocity profiles are then interpolated to radiosonde data grid and examined together with radiosonde wind speed and wind direction profiles.

Figure 5 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,

Deleted: evaluate radar beam pointing using the relationship between Doppler velocity and horizontal wind, Doppler velocity profiles are compared with collocated radiosonde wind measurements. For

Deleted: (typically from ± 30 to ± 150 minutes).

Deleted: ¶

Deleted: 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

Deleted: 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. ¶

Deleted: 4

486 MWACR Doppler velocity exhibits weaker vertical variation, with general downward
487 motion ranging from 0 to 0.5 m s⁻¹.

488 Because the contribution of horizontal wind to Doppler velocity depends primarily on
489 wind direction rather than altitude, observations from multiple heights within ice cloud
490 layers can be combined to improve statistical robustness. In individual radiosonde
491 cases, wind direction may not vary sufficiently with height to clearly reveal the cosine
492 dependence predicted by Eq. (2). Therefore, observations from multiple radiosonde
493 launches throughout the field campaign are combined to obtain a broad sampling of
494 wind directions. This aggregation allows identification of the expected cosine
495 dependence of normalized Doppler velocity on wind direction and enables estimation
496 of radar beam pointing offsets.

497
498

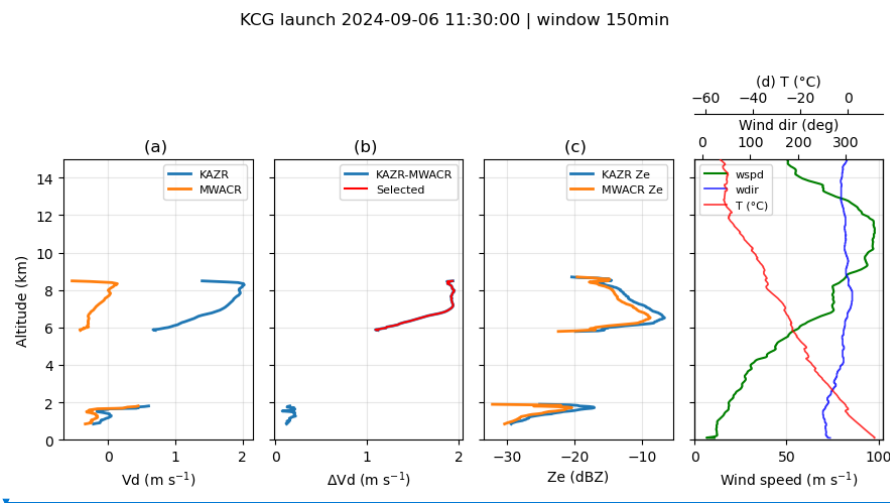


Figure 5 Profiles of KCG KAZR and MWACR Doppler velocity (Vd) averaged over a time window centered on the radiosonde launch, together with collocated radiosonde profiles of temperature, wind speed, and wind direction.

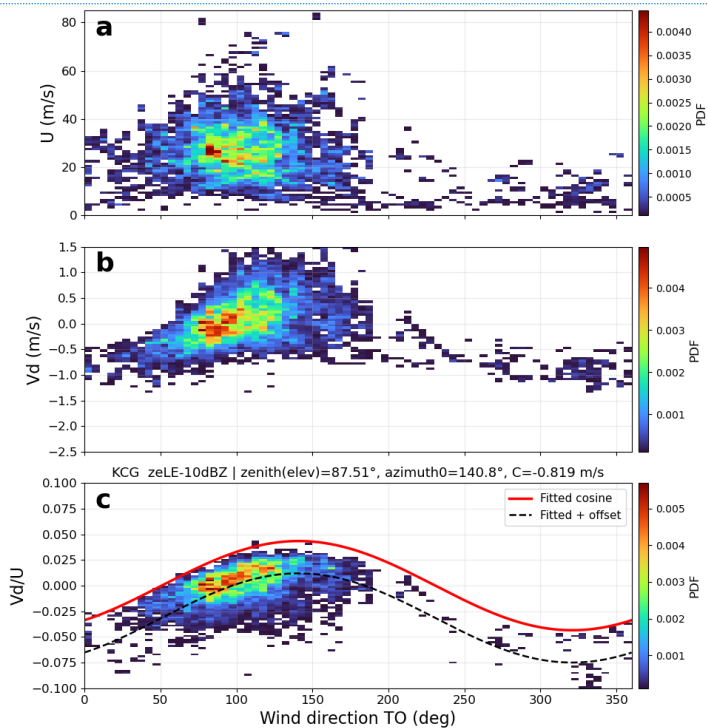
499
500

503 **4. Method Application and Results**

504 **4.1 KAZR Observations from the CAPE-k**

505 The CAPE-k campaign was deployed from April 15, 2024, to October 15, 2025. The
506 dominant wind in cloud from radiosonde measurement in Figure 6a is in 50° to 150°
507 degrees, which are south-westerly, westerly to north-westerly wind. The
508 corresponding Doppler velocity as a function of wind direction Figure 6b shows a
509 baseline Vd at approximately -0.8 m s^{-1} , consistent with typical fall velocities of ice
510 particles. Superimposed on this baseline Vd, a wind-direction-dependent modulation
511 is evident, with maximum positive Doppler velocity at 1.5 m s^{-1} , occurring near a wind
512 direction of approximately 140° , approximate in the radar azimuth angle, which is
513 comparable to the simulated wind-projection component shown in Fig. 3c.

Deleted: 5a
Deleted: 50
Deleted: 150
Formatted: Superscript
Deleted: 5b



Deleted: 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 6. 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

Deleted: 5

wind direction toward the angle, rather than from the angle as in radar coordinate. In panel (c), cosine fits to V_d/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.

Figure 6c shows the application of UN-VDD. 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° , a beam tilt of 2.5° from vertical. 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 7 summarizes the MWACR observations using data from the full campaign period. Figure 7b 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} . Compared with KAZR, the MWACR Doppler velocity shows a smaller wind-direction-dependent modulation, indicating a weaker influence of horizontal wind projection.

Figure 7c shows the corresponding UN-VDD. 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 is about 133° .

Deleted: 5c

Deleted: normalized Doppler velocity (V_d/U) as a function

Deleted: wind direction

Deleted: indicating an off-zenith pointing

Deleted: about

Deleted: $^\circ$.

Deleted: 6

Deleted: 6b

Deleted: $^{-1}$, consistent with expected fall speeds of ice particles.

Deleted: 6c

Deleted: normalized Doppler velocity (V_d/U) as a function of wind direction

Deleted: 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.

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

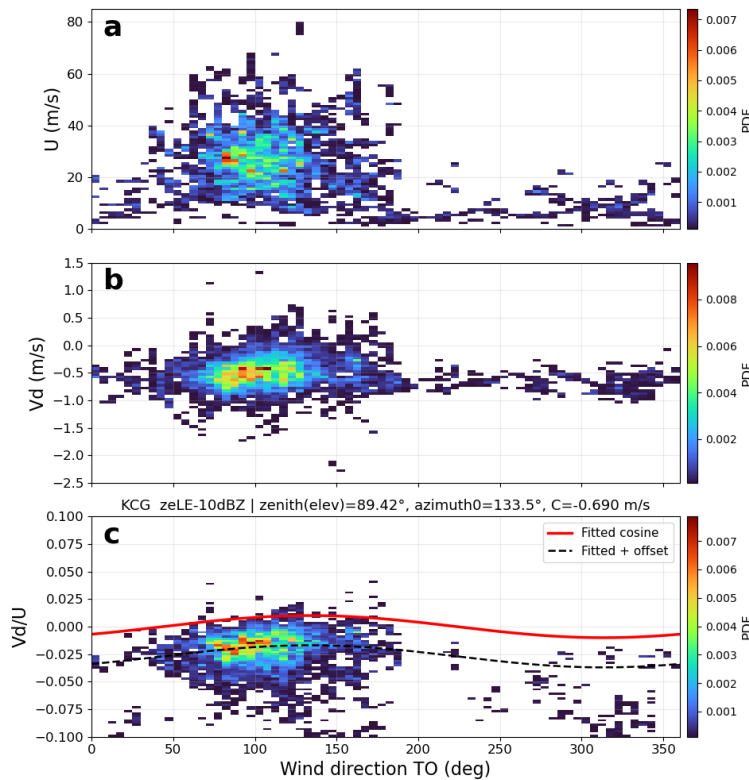


Figure 7. Same as Figure 5, but for MWACR at CAPE-k.

Deleted: 6

580

581 4.3 Difference Between KAZR and MWACR Doppler Velocity

582 To further validate the beam-pointing estimation method, the Doppler velocity
 583 difference between KAZR and MWACR is examined. Because the two radars observe
 584 nearly the same atmospheric volume, the contributions from V_f and W are expected
 585 to be similar. Taking the Doppler velocity difference therefore reduces the influence of
 586 these atmospheric contributions and emphasizes differences associated with radar
 587 beam pointing.

588 The Doppler velocity difference is defined as

589
$$\Delta v_d = v_{d,KAZR} - v_{d,MWACR} \quad (5)$$

Deleted: particle fall velocity (

Deleted:)

Deleted: vertical air motion (W)

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

$$\Delta v_d \approx U \cos(\phi - \phi_0) \cos(\theta_0') + C' \quad (6)$$

θ_0' is the effective zenith angle of the relative pointing offset, and C' is a constant offset term. After normalization by horizontal wind speed,

$$\frac{\Delta v_d}{U} \approx \cos(\phi - \phi_0) \cos(\theta_0') + \frac{C'}{U} \quad (7)$$

Figure 8 shows the Doppler velocity difference between KAZR and MWACR for all radiosonde cases during the field campaign. Panel (a) is identical to Figs. 6a and 7a. Panel (b) shows the Doppler velocity difference as a function of wind direction. The mean Δv_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 $1\text{--}1.5 \text{ m s}^{-1}$ 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 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.

Deleted:) + C,

Deleted: where U is horizontal wind speed, ϕ is wind direction, ϕ_0 is the effective azimuth angle of the relative beam pointing offset,

Deleted:) + $\frac{C'}{U}$.

Deleted: 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.¶

Deleted: 7

Deleted: 5a

Deleted: 6a

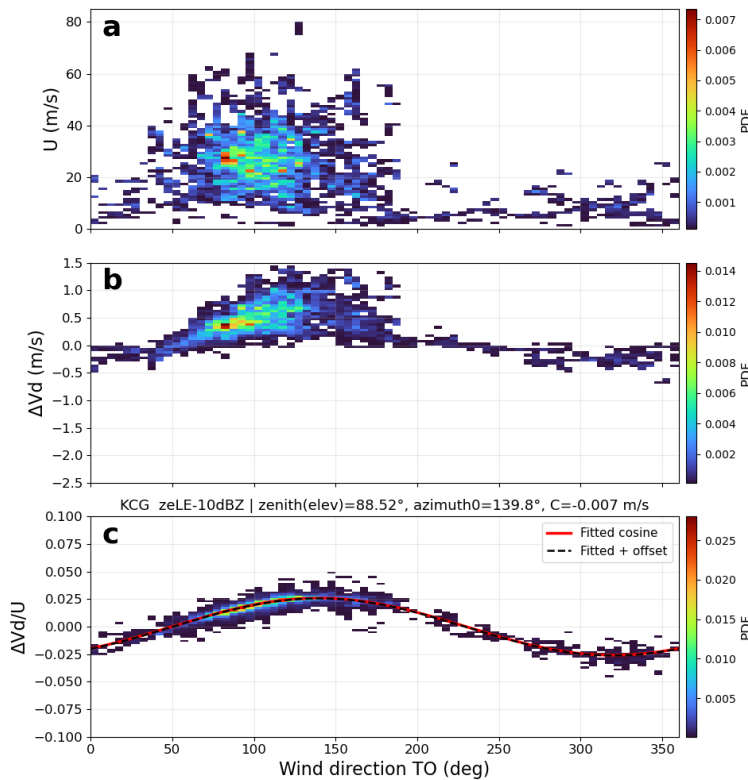


Figure 8 Same as Figures 6 and 7, but for the difference in Doppler velocity (ΔV_d) between KAZR and MWACR.

Deleted: 7

Deleted: 5

Deleted: 6

634

635 4.4 Application to the recent campaigns and fixed sites

636 To assess whether the proposed beam-pointing validation method is applicable
 637 beyond the CAPE-k campaign, the same analysis was applied to KAZR observations
 638 collected during the Bankhead National Forest (BNF, Kuang et al., 2026) and other
 639 field campaigns. Figure 9 summarizes the KAZR observations from the BNF campaign.
 640 Panel (a) shows horizontal wind speed as a function of wind direction derived from
 641 radiosonde measurements. Similar to CAPE-k, the BNF dataset includes a broad
 642 range of wind speeds, typically between 10 and 60 m s⁻¹, with occasional stronger
 643 winds exceeding 80 m s⁻¹, providing sufficient variability for evaluating the wind-
 644 projection component of Doppler velocity. Panel (b) shows the corresponding KAZR

Formatted: Font: Arial, 12 pt, Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

Formatted: Font: Arial, Font color: Text 1

Deleted: 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.

Deleted: 8

657 Doppler velocity observations. The mean Doppler velocity is approximately -0.5 m s^{-1} .
 658 The wind-direction-dependent variability in Doppler velocity is weaker than that
 659 observed for KAZR at CAPE-k and is comparable in magnitude to the MWACR results
 660 shown in Fig. 7. Panel (c) shows the normalized Doppler velocity, V_d/U , as a function
 661 of wind direction. The normalized observations exhibit a weak but systematic cosine
 662 dependence consistent with the cosine relationship predicted for small beam pointing
 663 offsets. The cosine fit yields a retrieved elevation angle of approximately 89.5° ,
 664 corresponding to an off-vertical pointing offset of about 0.5° , and an azimuth angle
 665 near 130° . Compared with the CAPE-k KAZR result, the weaker cosine signal at BNF
 666 indicates a smaller beam pointing offset during this campaign period.

Deleted: consistent with expected fall speeds of ice particles.

Deleted: 6

Deleted: ¶

Deleted: shown in Fig. 8c

Deleted: The fitted constant offset is approximately -0.5 m s^{-1} , reflecting residual contributions from mean particle fall velocity and vertical air motion.

Moved (insertion) [3]

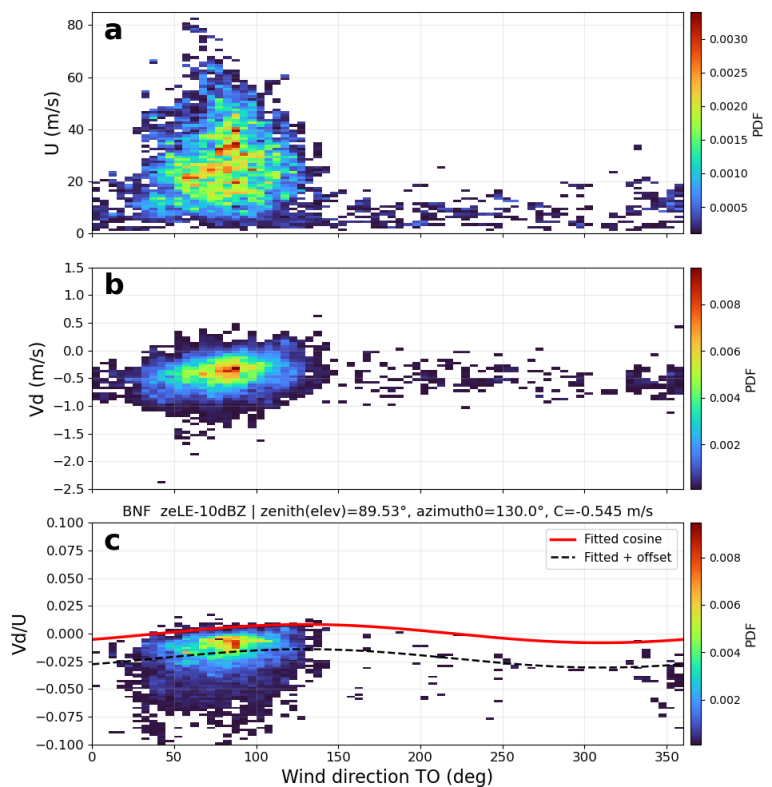


Figure 9. Same as Figure 6, but for KAZR at BNF

676

677 The estimated off-vertical pointing angle of about 0.5° is relatively small and is
678 comparable to expected uncertainties associated with both instrument characteristics
679 and the retrieval method. Several factors can contribute to this level of uncertainty.
680 First, the effective beam direction can be influenced by the radar beam width and
681 sidelobe structure. Even if the radar container and antenna mount are mechanically
682 aligned with the local vertical, slight asymmetries in the antenna radiation pattern or
683 sidelobe contamination may introduce a small effective tilt in the zenith beam. Second,
684 partial beam filling near cloud boundaries or horizontal inhomogeneity in ice cloud
685 layers can introduce variability in the observed Doppler velocity that is not related to
686 beam pointing. Third, spatial separation between the radar sampling volume and
687 radiosonde wind measurements introduces representativeness uncertainty,
688 particularly in environments with strong wind shear or horizontal variability.

690 Additional uncertainty arises from methodological choices in Doppler velocity
691 averaging and UN-VDD fitting. The averaging-window sensitivity tests quantify
692 uncertainty associated with radar-radiosonde collocation and temporal averaging.
693 Using windows of ± 30 , ± 50 , ± 90 , ± 120 , and ± 150 minutes, the retrieved elevation
694 angle varied by less than 0.3° . The sensitivity of the retrieval to particle fall velocity
695 was evaluated by applying reflectivity thresholds of -30 , -20 , -10 , and 0 dBZ, thereby
696 sampling ice-cloud layers with different particle-size and fall-speed characteristics.
697 The fitted elevation angle varied by less than 0.25° across these thresholds.
698 Considering both sources conservatively, the overall uncertainty in the estimated
699 beam-pointing angle is approximately 0.5° . This value is an empirical estimate based
700 on the sensitivity tests rather than a formal propagation of statistically independent
701 errors.

702 These results indicate that the proposed method provides stable and physically
703 consistent estimates of beam pointing across different field campaigns. The relatively
704 small pointing offsets retrieved at BNF, together with the larger offset identified at
705 CAPE-k, demonstrate that the method is capable of detecting both small and moderate
706 deviations from vertical pointing while maintaining uncertainty within approximately
707 0.5° .

Deleted: ¶

Deleted: Figure 8. Same as Figure 5, but for KAZR at BNF (... [3])

Deleted: used

Deleted: the

Deleted: procedure. Sensitivity tests using

Deleted: show that

Deleted: varies

Deleted: Sensitivity tests

Deleted: effects were performed

Deleted: to select

Deleted:

Deleted:

Deleted: varies

Deleted: these factors together

Deleted:

Deleted: order of 0.5° .

728 The estimated beam-pointing offsets for recent ARM field campaigns, including the
729 Surface Atmosphere Integrated Field Laboratory (SAIL), TRacking Aerosol
730 Convection interactions ExpeRiment (TRACER), Eastern Pacific Cloud Aerosol
731 Precipitation Experiment (EPCAPE), Coast-Urban-Rural Atmospheric Gradient
732 Experiment (CoURAGE), CAPE-k, and BNF, are summarized in Table 1. Long-term
733 results for the fixed ARM sites—the Southern Great Plains (SGP), North Slope of
734 Alaska (NSA), and Eastern North Atlantic (ENA)—from 2011–2025 are presented in
735 Figure 10. Overall, the retrieved pointing offsets for most field deployments are within
736 approximately 0.5°, indicating generally good mechanical alignment of the radar
737 antenna relative to the local vertical despite challenges associated with instrument
738 transport, installation, and variable environmental conditions encountered during field
739 operations. Two campaigns show larger deviations: CoURAGE exhibits a moderate
740 offset (~1.2°), while CAPE-k shows the largest offset (~2.5° for KAZR). These results
741 demonstrate that most ARM field deployments maintain near-vertical pointing within
742 the expected uncertainty range, and that the proposed method is sufficiently sensitive

Formatted: Font color: Text 1

Deleted: 9

Formatted: Font color: Text 1

743
744
745
Table 1. Estimated KAZR and MWACR Beam Pointing tilting from vertical for fixed
sites and recent field campaigns.

Formatted: Font color: Text 1

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

Formatted: Font color: Text 1

Formatted Table

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: 9

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: 9

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: 9

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Formatted: Font color: Text 1

▲	TRACER (HOU)	2021-10-01-2022-09-30	~0.1
▲	SAIL (GUC)	2021-09-01-2023-06-15	~0.4

Formatted: Font color: Text 1

Formatted: Font color: Text 1

Deleted: ¶

... [4]

to identify significant alignment deviations when they occur.

Formatted: Font color: Text 1

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/DQRSservice?dgrid=D190321.8>). ARM corrective maintenance (CM) records document a radar levelling 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 verification and adjustment of radar alignment, particularly after instrument relocation, exposure to severe environmental conditions, or extended operational periods.

Formatted: Font color: Text 1

Deleted: leveing

Formatted: Font color: Text 1

Together, Table 1 and Figure 10 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.

Deleted: 9

Formatted: Font color: Text 1

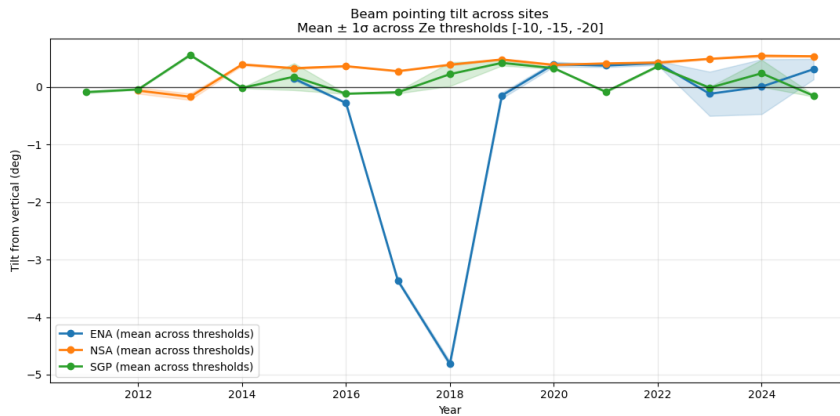


Figure 10. Time series of the mean KAZR beam-pointing tilt from vertical at the ENA, NSA, and SGP sites during 2011–2025. Tilt estimates are derived using multiple radar reflectivity (Z_e) thresholds (-10 , -15 , and -20 dBZ) to filter the observations used in the pointing estimation. Shaded regions represent the standard deviation of the tilt estimates obtained using the different Z_e 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.

Deleted: 9

Formatted: Font color: Text 1

Formatted: Font color: Text 1

5 Discussion and Summary

Deleted: 5

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.

This study developed and evaluated the U-normalized velocity–direction display (UN-VDD), which uses collocated radiosonde measurements to estimate the elevation and azimuth of a nominally vertically pointing radar beam. Normalizing Doppler velocity by horizontal wind speed reduces its dependence on wind magnitude and emphasizes the cosine variation with wind direction produced by beam mispointing. The amplitude and phase of the fitted cosine relationship provide estimates of the off-vertical angle and beam-tilt azimuth, respectively.

Deleted: 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

Application of UN-VDD to the CAPE-k observations identified pointing offsets in both KAZR and MWACR, with KAZR exhibiting the larger off-vertical deviation. The wind-direction dependence was clearer in the difference between the two radar Doppler velocities because differencing reduced the common contributions from particle fall velocity and vertical air motion. This result provided an independent constraint on the relative pointing difference between the two instruments. Application to BNF, other recent ARM campaigns, and long-term fixed-site observations produced generally small and stable pointing estimates, demonstrating that the method can be applied across different instruments, deployments, and atmospheric conditions.

Radiosonde measurement and sampling errors contribute to retrieval uncertainty. Wind-speed errors affect normalization by U , whereas wind-direction errors affect the independent variable in the cosine fit. These uncertainties can be propagated using weighted orthogonal-distance regression or Monte Carlo perturbations of radiosonde winds. Sensitivity tests involving radar averaging periods and reflectivity-based sampling suggest an uncertainty of approximately 0.5° in the retrieved off-vertical angle. This value should be considered an empirical estimate rather than a formal uncertainty bound unless radiosonde errors are explicitly propagated.

5.1 Operational beam-pointing monitoring

Radar pointing may change because of foundation settling, environmental loading, maintenance, scanner wear, or instrument relocation. A reference estimate established after installation, followed by reassessment after relocation, major maintenance, or severe environmental events, could help identify alignment changes. At sites with routine radiosonde launches, rolling UN-VDD estimates could also reveal gradual or seasonal variations.

The required sampling period should be determined by wind-direction coverage, atmospheric conditions, and retrieval uncertainty rather than by a fixed number of soundings. A small number of profiles may be sufficient when vertical wind shear provides broad directional sampling, whereas observations limited to two opposing directions constrain only one component of the tilt vector. Operational estimates should therefore include directional coverage, confidence intervals, and fit-stability

Deleted: 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 (V_d/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.

Deleted: the method

Deleted: from the CAPE-k field campaign shows detectable

Deleted: for

Deleted: a

Deleted: than MWACR during this period. Analysis of the Doppler velocity

Deleted: radars reduces the influence of

Deleted: , resulting in a clearer wind-direction-dependent signal and providing

Deleted: beam pointing differences.
The method was also applied to observations from the BNF field campaign to evaluate its applicability under different

Deleted: 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.

Deleted: Overall, small beam pointing offsets produce measurable Doppler velocity signals through projection of horizontal wind onto the radar beam. Normalization using V_d/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

Deleted: sites, the proposed method

metrics, with poorly constrained retrievals flagged rather than interpreted as physical pointing changes.

5.2 Doppler-velocity correction

The retrieved pointing angles can be used to remove horizontal-wind contamination from the measured Doppler velocity. Whether a correction is necessary should be determined from the expected velocity bias and the accuracy requirements of the intended radar product, rather than from a universal pointing-angle threshold. For a small off-vertical angle δ , the maximum horizontal-wind contribution is approximately $U\delta$, with δ expressed in radians. Thus, a 0.5° pointing offset can produce maximum Doppler-velocity biases of approximately 0.17 and 0.35 m s^{-1} at horizontal wind speeds of 20 and 40 m s^{-1} , respectively. A correction is most appropriate when the pointing offset is statistically distinguishable from zero, the tilt azimuth is adequately constrained, and the projected velocity bias exceeds the uncertainty acceptable for the intended application. Pointing estimates comparable to their uncertainty should generally be monitored or flagged rather than corrected deterministically.

Using the angle convention adopted in this study and the collocation wind field measurement, the corrected vertical Doppler velocity is calculated as:

$$V_{d,\text{cor}} = \frac{V_{d,\text{meas}} - U \cos(\phi - \phi_0) \cos \theta_0}{\sin \theta_0} = \frac{V_{d,\text{meas}}}{\sin \theta_0} - U \cos(\phi - \phi_0) \cot \theta_0. \quad (8)$$

After correction, the Doppler velocity contains the vertical contributions from particle sedimentation and air motion, along with any residual calibration error. Uncertainty in the wind field propagates directly into the corrected velocity, while spatial and temporal separation between the radar and wind measurement may introduce additional bias. Pointing estimates comparable to their uncertainty should therefore be monitored or flagged rather than corrected deterministically. Evaluation of the correction using independent wind and velocity constraints remains an important topic for future work.

Overall, UN-VDD provides a practical and independent method for estimating and monitoring the pointing of vertically oriented cloud radars, using routinely available radiosonde observations. The method detects the wind-direction-dependent Doppler

Deleted: approach

Deleted: and validating beam

Deleted: pointing

Deleted: . The approach can improve

signature produced by small pointing offsets, supports comparisons between collocated radars, and provides the information needed to estimate and correct the associated horizontal-wind contamination. Its application across field campaigns and fixed sites demonstrates its potential as a scalable quality-control tool for improving the consistency and interpretation of ARM cloud-radar Doppler velocity and related geophysical products.

Deleted: Doppler velocity observations and support long-term consistency of radar-derived

Deleted: and vertical

Formatted: Normal (Web), Space Before: 0 pt, After: 0 pt

Data availability

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

The Atmospheric Radiation Measurement Climate Research Facility KAZR and MWACR data used in this study, including observations from the CAPE-k, BNF, CoURAGE, ECAPE, 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).

Formatted: Font color: Text 1

Formatted: Font color: Text 1

940 **Acknowledgement**
941
942 Contributions from Brookhaven National Laboratory co-authors were supported by the
943 Atmospheric Radiation Measurement (ARM) Facility and the Atmospheric System
944 Research (ASR) program of the Office of Biological and Environmental Research in
945 the U. S. Department of Energy, Office of Science, through Contract No. DE-
946 SC0012704. Pacific Northwest National Laboratory (PNNL) is operated by Battelle for
947 the U. S. Department of [Energy](#). The authors from PNNL are also supported by ARM
948 through Contract No. DE-SC0015990.

Formatted: Font: Bold, Font color: Text 1

Formatted: Font color: Text 1

Deleted: Energ

Formatted: Font color: Text 1

951 References

- 952 [Battaglia, A. and Kollias, P.: Using ice clouds for mitigating the EarthCARE Doppler](#)
 953 [radar mispointing, IEEE Trans. Geosci. Remote Sens., 53, 2079–2085,](#)
 954 <https://doi.org/10.1109/TGRS.2014.2353219>, 2015.
- 955 [Browning, K. A. and Wexler, R.: The determination of kinematic properties of a wind](#)
 956 [field using Doppler radar, J. Appl. Meteor., 7, 105–113, https://doi.org/10.1175/1520-](#)
 957 [0450\(1968\)007%3C0105:TDOKPO%3E2.0.CO;2](https://doi.org/10.1175/1520-0450(1968)007%3C0105:TDOKPO%3E2.0.CO;2), 1968.
- 958 [Deng, M. and Mace, G. G.: Cirrus microphysical properties and air motion statistics](#)
 959 [using cloud radar Doppler moments. Part I: Algorithm description, J. Appl. Meteor.](#)
 960 [Climatol., 45, 1690–1709, https://doi.org/10.1175/JAM2433.1, 2006.](#)
- 961 [Deng, M. and Mace, G. G.: Cirrus cloud microphysical properties and air motion](#)
 962 [statistics using cloud radar Doppler moments: Water content, particle size, and](#)
 963 [sedimentation relationships, Geophys. Res. Lett., 35, L17808,](#)
 964 <https://doi.org/10.1029/2008GL035054>, 2008a.
- 965 [Deng, M. and Mace, G. G.: Cirrus microphysical properties and air motion statistics](#)
 966 [using cloud radar Doppler moments. Part II: Climatology, J. Appl. Meteor. Climatol.,](#)
 967 [47, 3221–3235, https://doi.org/10.1175/2008JAMC1949.1, 2008b](#)
- 968 [Dirksen, R. J., Sommer, M., Immler, F., Hurst, D. F., Kivi, R., and Vömel, H.: Reference](#)
 969 [quality upper-air measurements: GRUAN data processing for the Vaisala RS92](#)
 970 [radiosonde, Atmos. Meas. Tech., 7, 4463–4490, https://doi.org/10.5194/amt-7-4463-](#)
 971 [2014](https://doi.org/10.5194/amt-7-4463-2014), 2014.
- 972 [Doviak, R. J. and Zrnić, D. S.: Doppler Radar and Weather Observations, 2nd edn.,](#)
 973 [Academic Press, San Diego, CA, USA, 562 pp., 1993.](#)
- 974 [Giangrande, S. E., Luke, E. P., and Kollias, P.: Automated retrievals of precipitation](#)
 975 [parameters using non-Rayleigh scattering at 95 GHz, J. Atmos. Oceanic Technol., 27,](#)
 976 [1490–1503, https://doi.org/10.1175/2010JTECHA1343.1](https://doi.org/10.1175/2010JTECHA1343.1), 2010.

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Moved (insertion) [6]

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: <https://doi.org/10.5194/amt-7-4463-2014>.

Formatted: Font: 12 pt

Deleted: Deng, M., and G. G. Mace, 2006: Cirrus Microphysical Properties and Air Motion Statistics Using Cloud Radar Doppler Moments. Part I: Algorithm Description. J.

Deleted: .

Deleted: 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)

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: Kalesse, H., and

Deleted: .

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

992 [Giangrande, S. E., Luke, E. P., and Kollias, P.: Characterization of vertical velocity](#)
 993 [and drop size distribution parameters in widespread precipitation at ARM facilities, J.](#)
 994 [Appl. Meteor. Climatol., 51, 380–391, <https://doi.org/10.1175/JAMC-D-10-05000.1>,](#)
 995 [2012.](#)

996 [Haimov, S. and Rodi, A.: Fixed-antenna pointing-angle calibration of airborne Doppler](#)
 997 [cloud radar, J. Atmos. Oceanic Technol., 30, 2320–2335,](#)
 998 [https://doi.org/10.1175/JTECH-D-12-00262.1, 2013.](#)

999 [Kalesse, H. and Kollias, P.: Climatology of high cloud dynamics using profiling ARM](#)
 1000 [Doppler radar observations, J. Climate, 26, 6340–6359, \[D-12-00695.1, 2013.\]\(https://doi.org/10.1175/JCLI-

 1001 <a href=\)](#)

1002 [Keeler, E.: Balloon-Borne Sounding System \(SONDE\) Instrument Handbook, U.S.](#)
 1003 [Department of Energy, Atmospheric Radiation Measurement user facility, Richland,](#)
 1004 [WA, USA, DOE/SC-ARM-TR-029, <https://doi.org/10.2172/1020712>, 2025.](#)

1005 [Kollias, P., Albrecht, B. A., and Marks, F.: Why Mie? Accurate observations of vertical](#)
 1006 [air velocities and raindrops using a cloud radar, Bull. Amer. Meteor. Soc., 83, 1471–](#)
 1007 [1483, <https://doi.org/10.1175/BAMS-83-10-1471>, 2002.](#)

1008 [Kollias, P., Clothiaux, E. E., Albrecht, B. A., Miller, M. A., Moran, K. P., and Johnson,](#)
 1009 [K. L.: The Atmospheric Radiation Measurement Program cloud profiling radars:](#)
 1010 [Second-generation sampling strategies, processing, and cloud data products, J.](#)
 1011 [Atmos. Oceanic Technol., 24, 1199–1214, <https://doi.org/10.1175/JTECH2033.1>,](#)
 1012 [2007a.](#)

1013 [Kollias, P., Clothiaux, E. E., Miller, M. A., Albrecht, B. A., Stephens, G. L., and](#)
 1014 [Ackerman, T. P.: Millimeter-wavelength radars: New frontier in atmospheric cloud and](#)
 1015 [precipitation research, Bull. Amer. Meteor. Soc., 88, 1608–1624,](#)
 1016 [https://doi.org/10.1175/BAMS-88-10-1608, 2007b.](#)

Formatted: Font: 12 pt

Deleted: :

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Heading 1, Indent: Left: 0", First line: 0",
Space After: 0 pt

Deleted: .

Deleted: :

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: .

Deleted: .

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: ,

Formatted: Font: 12 pt

Deleted: Washington.

Deleted: TR029

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Moved down [10]: Bharadwaj, N., Widener, K., Jo, I.,
and Johnson, K.: Scanning ARM cloud radars. Part I:
Operational sampling strategies, J. Atmos.

Moved down [11]: Monogr.,

Deleted: Ocean. Technol., 31, 569–582,
<https://doi.org/10.1175/JTECH-D-13-00044.1>, 2013. [5]

Deleted: 57, 17.1– [6]

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: Ocean.

Deleted: <https://doi.org/10.1175/JTECH2033.1>, 2007

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: Szyrmer, W., Luke

Deleted: ., & McFarquhar

Deleted: (2007). [7]

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: radar Doppler spectra. [8]

Formatted: Font: 12 pt

Deleted: JTECH2081.1

Formatted: Font: 12 pt

Formatted: Font: 12 pt

1053 [Kollias, P., Bharadwaj, N., Widener, K., Jo, I., and Johnson, K.: Scanning ARM cloud](#)
 1054 [radars. Part I: Operational sampling strategies, J. Atmos. Oceanic Technol., 31, 569–](#)
 1055 [582, <https://doi.org/10.1175/JTECH-D-13-00044.1>, 2014.](#)

1056 [Kollias, P., Clothiaux, E. E., Ackerman, T. P., Albrecht, B. A., Bharadwaj, N., Mead, J.](#)
 1057 [B., Miller, M. A., Verlinde, J., Marchand, R. T., and Mace, G. G.: Development and](#)
 1058 [applications of ARM millimeter-wavelength cloud radars, Meteor. Monogr., 57, 17.1–](#)
 1059 [17.19, <https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0037.1>, 2016.](#)

1060 [Kuang, C., Giangrande, S. E., Serbin, S. P., Campbell, P., Elsaesser, G. S., Gentine,](#)
 1061 [P., Heus, T., Hickmon, N. L., Oue, M., Peters, J. M., Raghunathan, G. N., Ritsche, M.](#)
 1062 [T., Smith, J. N., Spychala, M., Steiner, A. L., and Theisen, A.: The U.S. DOE ARM](#)
 1063 [User Facility establishes a new site for studies of land–aerosol–cloud interactions in](#)
 1064 [the southeastern United States, Bull. Amer. Meteor. Soc., 107, E1–E8,](#)
 1065 [https://doi.org/10.1175/BAMS-D-25-0072.1, 2026.](#)

1066 Mather, J. H. and Voyles, J. W.: The ARM Climate Research Facility: A review of
 1067 structure and capabilities, Bull. Amer. Meteor. Soc., 94, 377–392,
 1068 [https://doi.org/10.1175/BAMS-D-11-00218.1, 2013.](#)

1069 [May, P. T. and Rajopadhyaya, D. K.: Vertical velocity characteristics of deep](#)
 1070 [convection over Darwin, Australia, Mon. Weather Rev., 127, 1056–1071,](#)
 1071 [https://doi.org/10.1175/1520-0493\(1999\)127%3C1056:VVCODC%3E2.0.CO;2, 1999.](#)

1072 [Mitchell, D. L., Mishra, S., and Lawson, R. P.: Representing the ice fall speed in climate](#)
 1073 [models: Results from Tropical Composition, Cloud and Climate Coupling \(TC4\) and](#)
 1074 [the Indirect and Semi-Direct Aerosol Campaign \(ISDAC\), J. Geophys. Res.-Atmos.,](#)
 1075 [116, D00T03, <https://doi.org/10.1029/2010JD015433>, 2011.](#)

1076 [Moran, K. P., Martner, B. E., Post, M. J., Kropfli, R. A., Welsh, D. C., and Widener, K.](#)
 1077 [B.: An unattended cloud-profiling radar for use in climate research, Bull. Amer. Meteor.](#)
 1078 [Soc., 79, 443–455, \[https://doi.org/10.1175/1520-\]\(https://doi.org/10.1175/1520-0477\(1998\)079%3C0443:AUCPRF%3E2.0.CO;2\)](#)
 1079 [0477\(1998\)079%3C0443:AUCPRF%3E2.0.CO;2, 1998.](#)

Formatted: Font: 12 pt

Formatted: Font: 12 pt

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

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: and Coauthors, 2026:

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: Establishes

Deleted: New Site

Deleted: Studies

Deleted: Land–Aerosol–Cloud Interactions

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: Southeastern

Deleted: .

Deleted:

Deleted: <https://doi.org/10.1175/BAMS-D-25-0072.1>, Luke, E. P. and Kollias, P.: Separating cloud and drizzle radar moments during precipitation onset using Doppler spectra, J.

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: Ocean. Technol., 30, 1656–1671, <https://doi.org/10.1175/JTECH-D-11-00195.1>, 2013

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Deleted: <https://doi.org/10.1175/BAMS-D-11-00218.1>,

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Heading 1, Indent: Left: 0", First line: 0", Space After: 0 pt

Deleted: <0443

Deleted: >2

Formatted: Font: 12 pt

Formatted: Font: 12 pt

1104 Nash, J., Oakley, T., Vömel, H., and Wei, L.: WMO [Intercomparison of High Quality](#)
1105 [Radiosonde Systems, Yangjiang, China, 12 July–3 August 2010](#), Instruments and
1106 Observing Methods Report No. 107, [WMO/TD-No. 1580](#), World Meteorological
1107 Organization, Geneva, Switzerland, [249 pp.](#), <https://library.wmo.int/idurl/4/50499> (last
1108 [access: 14 August 2026](#)), 2011.

1109 [Protat, A., and Williams, C. R.: The accuracy of radar estimates of ice terminal fall](#)
1110 [speed from vertically pointing Doppler radar measurements, J. Appl. Meteor. Climatol.,](#)
1111 [50, 2120–2138, https://doi.org/10.1175/JAMC-D-10-05031.1, 2011.](#)

1112 [Seidel, D. J., Sun, B., Petey, M., and Reale, A.: Global radiosonde balloon drift](#)
1113 [statistics, J. Geophys. Res.-Atmos., 116, D07102,](#)
1114 [https://doi.org/10.1029/2010JD014891, 2011.](#)

1115 [Shupe, M. D., Kollias, P., Poellot, M., and Eloranta, E.: On deriving vertical air motions](#)
1116 [from cloud radar Doppler spectra, J. Atmos. Oceanic Technol., 25, 547–557,](#)
1117 [https://doi.org/10.1175/2007JTECHA1007.1, 2008.](#)

1118 [Shupe, M. D., Comstock, J. M., Turner, D. D., and Mace, G. G.: Cloud property](#)
1119 [retrievals in the ARM Program, Meteor. Monogr., 57, 19.1–19.20,](#)
1120 [https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0030.1, 2016.](#)

1121

1122 [Zhu, Z., Kollias, P., Yang, F., and Luke, E.: On the estimation of in-cloud vertical air](#)
1123 [motion using radar Doppler spectra, Geophys. Res. Lett., 48, e2020GL090682,](#)
1124 [https://doi.org/10.1029/2020GL090682, 2021.](#)

- Deleted: intercomparison
- Formatted: Font: 12 pt
- Deleted: high quality radiosonde systems, WMO
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Deleted: Kollias, P., Matrosov, S. Y.,
- Formatted: Font: 12 pt
- Deleted: Schneider, T. L.: Deriving mixed-phase cloud properties from
- Deleted: spectra, J.
- Formatted: Font: 12 pt
- Deleted: Ocean. Technol., 21, 660–670
- Deleted: 1520-0426(2004)021<0660:DMCPFD>2.0.CO;2, 2004
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Deleted: Shupe, M. D., J. M. Comstock, D. D. Turner (... [9])
- Moved down [16]: Monogr.,
- Deleted: 57, 19.1– (... [10])
- Formatted: Font: 12 pt
- Deleted: A focus on mixed-phase clouds: The (... [11])
- Deleted: Soc., 89, 1549–1562, (... [12])
- Deleted: & Eloranta, E. (2008).⁴
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Formatted: Font: 12 pt
- Formatted: Indent: Left: 0", First line: 0"
- Deleted: &
- Deleted: . (2021).⁴
- Deleted: .⁴ (... [14])
- Deleted: .⁴ (... [15])
- Moved up [13]: Kollias, P.,
- Deleted: & Yang, F. (2023).⁴ (... [16])

Page 10: [1] Deleted	Deng, Min	8/14/26 4:09:00 PM
Page 13: [2] Deleted	Deng, Min	8/14/26 4:09:00 PM
Page 22: [3] Deleted	Deng, Min	8/14/26 4:09:00 PM
Page 24: [4] Deleted	Deng, Min	8/14/26 4:09:00 PM
Page 31: [5] Deleted	Deng, Min	8/14/26 4:09:00 PM

▼

Page 31: [6] Deleted	Deng, Min	8/14/26 4:09:00 PM
----------------------	-----------	--------------------

▼

Page 31: [7] Deleted	Deng, Min	8/14/26 4:09:00 PM
----------------------	-----------	--------------------

▼

Page 31: [8] Deleted	Deng, Min	8/14/26 4:09:00 PM
----------------------	-----------	--------------------

▼

Page 33: [9] Deleted	Deng, Min	8/14/26 4:09:00 PM
----------------------	-----------	--------------------

▼

Page 33: [10] Deleted	Deng, Min	8/14/26 4:09:00 PM
-----------------------	-----------	--------------------

▼

Page 33: [11] Deleted	Deng, Min	8/14/26 4:09:00 PM
-----------------------	-----------	--------------------

▼

Page 33: [12] Deleted	Deng, Min	8/14/26 4:09:00 PM
-----------------------	-----------	--------------------



Page 33: [13] Deleted

Deng, Min

8/14/26 4:09:00 PM



Page 33: [14] Deleted

Deng, Min

8/14/26 4:09:00 PM



Page 33: [15] Deleted

Deng, Min

8/14/26 4:09:00 PM



Page 33: [16] Deleted

Deng, Min

8/14/26 4:09:00 PM

