Response to Reviewer

Thank you for your careful and detailed review of our manuscript. We have addressed your comments concerning the literature review, methodological description, uncertainty analysis, and practical application of the proposed method. Changes in the revised manuscript are shown in blue.

We also added a new Fig. 4 to illustrate the U-normalized velocity–direction display (UN-VDD) beam-pointing retrieval. In addition, we expanded the Discussion and Conclusions to address operational monitoring and correction of Doppler-velocity contamination caused by off-vertical pointing.

1 Introduction

Reviewer comment (lines 120–123): "Existing approaches have primarily relied on engineering alignment procedures, statistical characteristics of Doppler velocity, or comparison with independent wind measurements." Please briefly describe these existing approaches and provide appropriate references. This would help place the proposed method in the context of previous work.

Response: We thank the reviewer for this suggestion. Published observation-based studies of pointing errors in vertically or nadir-pointing cloud radars are limited, particularly for ARM ground-based cloud radars. We revised the Introduction to describe mechanical alignment surveys, Doppler-based diagnostics, and comparisons with independent wind measurements. We also clarified that the proposed method quantitatively estimates both the elevation and azimuth pointing offsets of nominally vertically pointing cloud radars.

The revised text reads:

"For vertically or nadir-pointing Doppler radars, beam alignment has traditionally been assessed through mechanical leveling and installation surveys. Observation-based methods have inferred mispointing from residual surface Doppler velocity or systematic features of cloud Doppler-velocity distributions (Haimov and Rodi, 2013; Battaglia and Kollias, 2015). Independent wind profiles from radiosondes or wind profilers can reveal horizontal-wind contamination in nominally vertical Doppler velocities, although their use to retrieve both pointing angles quantitatively has remained limited."

Reviewer comment (line 137): “The method exploits the cosine dependence of Doppler velocity on wind direction to retrieve off-zenith pointing angle and to quantify their impact on Doppler velocity observations.” Please clarify whether previous studies have already used the cosine dependence of Doppler velocity on wind direction.

Response: We thank the reviewer for requesting this clarification. The cosine relationship is similar to the basis of the velocity–azimuth display (VAD) method. We now distinguish the proposed UN-VDD method from conventional VAD. VAD analyzes Doppler velocity as a function of the azimuth of a scanning radar beam, whereas UN-VDD analyzes wind-speed-normalized Doppler velocity from a fixed, nominally vertical beam as a function of independently measured wind direction.

The revised text reads:

“The cosine dependence is the established basis of velocity–azimuth display wind retrievals for scanning Doppler radars (Browning and Wexler, 1968; Doviak and Zrnić, 1993). Here, we introduce a U-normalized velocity–direction display (UN-VDD) for fixed, nominally vertical cloud radars. Unlike VAD, which relates Doppler velocity to scanning-beam azimuth, UN-VDD relates wind-speed-normalized Doppler velocity (Vd/U) to radiosonde wind direction. The amplitude and phase of this relationship provide estimates of the off-vertical pointing angle and pointing azimuth, respectively.”

2 Data description

2.1 Cloud radar observations

Reviewer comment (line 152): It would be helpful to include the range and Doppler velocity resolutions of both radar systems used during CAPE-k.

Response: We thank the reviewer for this helpful suggestion. We added the range resolution, Nyquist velocity, number of fast Fourier transform (FFT) bins, and corresponding Doppler-bin resolution for the KAZR and MWACR configurations used during CAPE-k.

The revised text reads:

“Both KAZR and MWACR were operated with a range resolution of 30 m during CAPE-k. KAZR had a Nyquist velocity of 7.954 m s^{-1} and 256 FFT bins, corresponding to a Doppler-bin resolution of 0.062 m s^{-1}. MWACR had a Nyquist velocity of 5.589 m s^{-1} and 128 FFT bins, corresponding to a Doppler-bin resolution of 0.087 m s^{-1}."

Reviewer comment (lines 166–170): Some of the points made in this paragraph have already been introduced earlier. Consider shortening or consolidating these statements to avoid repetition.

Response: We agree and have shortened this paragraph. Repeated descriptions of the campaign and radar capabilities were removed, while information needed to define the observations used in the analysis was retained. We also removed several other locations with repeated statement.

2.3 Case study of the Vd contribution from horizontal wind

Reviewer comment (line 201): Please explain why this particular date was selected for the analysis. What makes this case especially suitable compared with other days during the campaign?

Response: We thank the reviewer for requesting this clarification. The 6 September 2024 case was not selected because it was unique or produced the largest pointing signature. It was selected as a representative example because both radars provided continuous, high-quality observations of an extensive ice-cloud layer, a collocated radiosonde profile was available, and the Ka- and W-band Doppler velocities differed by approximately 1 m s^{-1} within the cloud. Similar Doppler-velocity differences occurred in many other CAPE-k cases. This case is used only to illustrate the physical basis and processing procedure; the beam-pointing retrieval uses observations collected throughout the campaign. We added these selection criteria to the revised manuscript.

Reviewer comment (line 212): "Consistent with expected fall speeds of small ice particles in stratiform cloud conditions." Remind the reader what typical fall velocities of ice particles are.

Response: We thank the reviewer for this helpful suggestion. We revised the case-study description to state that small ice crystals near cloud top commonly have fall velocities of approximately 0.1–0.5 m s^{-1}, whereas larger particles and aggregates can have fall velocities exceeding 1 m s^{-1} (Protat and Williams, 2011). We also explain later that the fitted mean offsets of approximately 0.68–0.80 m s^{-1} fall within the expected range of ice-particle sedimentation velocities.

Reviewer comment (Fig. 1): Please improve the figure by labeling the individual panels (e.g., a–e) and indicating the radiosonde launch time.

Response: We revised Fig. 1 to include clear panel labels, the radiosonde launch time, and the radar averaging window.

Reviewer comment (lines 219–237): The discussion of Fig. 2 and Eqs. (1)–(2) is somewhat intertwined, making this section difficult to follow. Consider separating the description of the figure from the explanation of the equations and referring more explicitly to either Fig. 2 or the corresponding equations in the text.

Response: We agree that the original discussion combined the geometric interpretation of Fig. 2 with the explanation of Eqs. (1)–(2). We reorganized the section so that the coordinate system, velocity vectors, angle definitions, and sign conventions are first described with reference to Fig. 2. We then introduce Eqs. (1)–(2) and explain each physical term separately. We also clarify that θ_0 is the radar elevation angle measured upward from the horizontal, consistent with the trigonometric factors in the equations. The revised text explicitly describes the vertically pointing limit and the contributions from horizontal wind, vertical air motion, particle fall velocity, and residual instrumental velocity offsets.

Reviewer comment (Eqs. 1–2): Please provide a more detailed explanation of the equations. Clarify which terms represent the projected horizontal wind component, particle fall velocity, and vertical air motion.

Response: We expanded the explanation as follows:

"In Eqs. (1)–(2), the first term represents the projection of the horizontal wind onto the radar beam. The second term represents the projection of vertical air motion, and the third term represents the projection of downward particle fall velocity. Cka and Cw represent residual Doppler-velocity offsets for KAZR and MWACR, respectively, and are expected to be close to zero after velocity calibration."

Reviewer comment (Fig. 2 and line 230): In Fig. 2, θ_0 appears to represent the elevation angle, whereas in the text it is described as the "zenith angle θ_0." Please clarify this discrepancy and revise either the figure or the text as needed. It may also be worth checking the manuscript for consistency in the use of this angle elsewhere.

Response: We thank the reviewer for identifying this inconsistency. We now define θ_0 consistently throughout the manuscript as the elevation angle measured upward from the horizontal. Therefore, θ_0 = 90° represents perfect vertical pointing.

3 Beam-pointing estimation method

3.1 Sensitivity of Doppler velocity to horizontal wind and beam-pointing angle

Reviewer comment (line 248): "When the radar beam is perfectly vertical (θ_0 = 90°)." Please make sure that the definition of θ_0 is consistent with Sect. 2.3.

Response: We now define θ_0 consistently as the elevation angle; therefore, a perfectly vertical beam corresponds to θ_0 = 90°.

Reviewer comment (lines 255–257): "For example, when horizontal wind speed is 10 m s^{-1}, the resulting Doppler velocity magnitude is approximately 0.05 m s^{-1}." The values stated here do not appear to be fully consistent with Fig. 3. From the figure, the 10 m s^{-1} curve appears closer to 0.1 m s^{-1} than to 0.05 m s^{-1}. Please verify this in the figure.

Response: The reviewer is correct. We revised the sentence as follows:

"For example, when the horizontal wind speed is 10 m s^{-1}, the maximum magnitude of the horizontal-wind contribution to Doppler velocity is approximately 0.1 m s^{-1}."

Reviewer comment (Fig. 3): Please label the individual panels (e.g., a–c).

Response: We replotted Fig. 3 and added panel labels.

3.3 Wind dependence of Vd using radiosonde observations

Reviewer comment (lines 307–308): "Typically from ±30 to ±150 minutes." Please clarify the criteria used to determine the integration period. Under what conditions is a window of ±30 minutes used instead of ±150 minutes?

Response: We thank the reviewer for identifying this ambiguity. The original wording incorrectly suggested that different windows were selected for different cases. The primary analysis uses a fixed half-window of ±150 min centered on each radiosonde launch, corresponding to a total averaging period of 300 min. This window provides sufficient cloudy radar samples for a stable UN-VDD fit while limiting the temporal mismatch between the radar observations and radiosonde profile. A shorter window improves temporal collocation but can provide too few cloudy samples, whereas a longer window increases sensitivity to cloud evolution and changes in the wind field.

To evaluate sensitivity to this choice, we repeated the retrieval using half-window lengths of ±30, ±50, ±90, ±120, and ±150 min. The retrieved elevation angle varied by less than 0.3° across these tests. We clarified the window definition in Sect. 3.3 and added the sensitivity results in Sect. 4.4.

Reviewer comment (lines 308–310): A radiosonde typically requires approximately 30 minutes to reach 8 km altitude after launch. Combined with an integration period of up to ±150 minutes, this could result in a temporal separation of roughly 3 hours between the radiosonde and radar observations. How is the representativeness of the environment assessed under these conditions? Wind direction can change substantially over such timescales. Please clarify whether the stability of the wind field during this period is evaluated.

Response: We thank the reviewer for raising this important representativeness issue. We evaluated the sensitivity of the retrieved pointing angle using half-window lengths of ±30, ±50, ±90, ±120, and ±150 min. Variations in wind direction, cloud occurrence, and Doppler velocity within these windows affect the averaged radar profiles and consequently the UN-VDD fit. Nevertheless, the retrieved campaign-level elevation angle varied by less than 0.3° across the tested windows, indicating limited sensitivity to the averaging period in this dataset.

This test does not demonstrate that the wind field is stationary within every individual window. Rapid changes associated with frontal passages, convection, or strong temporal shear can increase scatter and representativeness uncertainty. The campaign-level fit, however, does not rely on a single sounding. It uses approximately 10 000 height-resolved radar–radiosonde matches obtained from multiple launches and altitudes across the campaign, spanning a broad range of wind directions. These matches should not be interpreted as 10 000 statistically independent observations, because adjacent radar gates and profiles are correlated. Case-specific wind variations are therefore expected primarily to increase scatter, whereas persistent or directionally systematic radar–radiosonde mismatches could bias the fitted pointing vector.

We added this limitation to the revised manuscript. For operational applications, we recommend evaluating wind-field stability with collocated wind-profiler, Doppler-lidar, or model data when available.

Reviewer comment (lines 311–315): Earlier (lines 188–190), strong horizontal wind shear is identified as a potential source of uncertainty. Are cases with strong horizontal wind shear filtered out from the analysis? Please explain how these cases are identified.

Response: No explicit wind-shear filter was applied; all ice-cloud observations meeting the radar quality-control and cloud-selection criteria were retained. Vertical wind shear is represented in the height-by-height matching because each averaged radar gate is paired with the radiosonde wind at the corresponding altitude. Strong temporal variability or spatially heterogeneous shear, however, can produce radar–radiosonde representativeness differences and increase scatter in the UN-VDD relationship. We now state explicitly that these cases were not removed and identify unresolved spatial and temporal wind variability as a source of uncertainty. For future operational processing, a shear or wind-stability quality flag based on a collocated profiler, lidar, successive soundings, or model analysis could be used to exclude poorly represented periods.

Reviewer comment (Figs. 1 and 4): Figure 4 shows the sounding used for this case study. When compared with Fig. 1, the ±30 min window appears to contain relatively few cloud observations, whereas substantially more observations may be available within a ±150 min window. What integration window is used for this specific case? Is there a minimum number of observations required to obtain a robust Doppler velocity estimate?

Response: For the case shown in Figs. 1 and 4, radar Doppler velocities were averaged over a ±150 min window centered on the 11:30 UTC radiosonde launch, corresponding to 09:00–14:00 UTC. This window was used to increase the number of valid observations in the 5–8 km ice-cloud layer. The ±30 min window contains fewer cloudy observations, particularly after the launch time.

The pointing retrieval was repeated using half-window lengths of ±30, ±50, ±90, ±120, and ±150 min. Despite differences in cloud sampling, the retrieved elevation angle varied by less than 0.3°. This finding indicates that the campaign-level pointing estimate is not strongly controlled by the selected window or this individual case.

We did not define a universal minimum number of raw radar profiles because KAZR and MWACR have different sampling frequencies and consecutive profiles are not statistically independent. Retrieval reliability is better characterized by temporal cloud coverage, wind-direction diversity, the number of independent soundings, fit uncertainty, and stability across sensitivity tests than by raw profile count alone.

The fitting results in this study are from annual estimations out of hundreds of collocated radar and sonde measurements and 100,000 of data samples to cover full wind direction.

Reviewer comment (lines 332–334): "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." Please provide a few more details on how radar and radiosonde observations are matched in height and over what range the data are combined. For example, is each radar range gate paired with the nearest radiosonde observation, or is some form of averaging or interpolation applied?

Response: We added details of the temporal averaging, vertical matching, and cloud selection. For each radiosonde launch, radar Doppler-velocity profiles are averaged over the selected time window. The temporally averaged radar profile is then matched to the radiosonde altitude grid using nearest-neighbor interpolation in height. Only levels identified as ice cloud and lying within the overlapping vertical coverage of the radar and radiosonde are retained; the illustrative case uses the 5–8 km layer. Thus, wind speed and direction are allowed to vary with altitude rather than being represented by a single layer-mean value.

The revised text reads:

"For each radiosonde launch, radar Doppler-velocity profiles are averaged within a ±150 min window centered on the launch time. The temporal averaging reduces variability associated with turbulence and short-term cloud evolution while preserving comparison with the radiosonde wind profile. The averaged radar profile is then matched to the radiosonde altitude grid by nearest-neighbor interpolation. At each retained ice-cloud level, Doppler velocity is paired with radiosonde wind speed and wind direction at the corresponding altitude. Matched levels from multiple ice-cloud heights and soundings are subsequently combined for the campaign-level UN-VDD fit."

Reviewer comment (Fig. 4): Please label the individual panels (e.g., a–d).

Response: We added panel labels to Fig. 4.

4 Results

4.1 KAZR observations from CAPE-k

Reviewer comment (lines 346–347): "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." This appears inconsistent with the definition in line 233, in which direction is measured clockwise from north toward the direction of flow. Based on this convention, 50–150° corresponds to winds directed toward the northeast-to-southeast sector. Please clarify and use a single convention throughout the manuscript.

Response: We thank the reviewer for identifying this ambiguity. The original text mixed our "toward" convention with conventional meteorological wind names, which describe the direction from which wind originates. We removed the conventional southwesterly, westerly, and northwesterly terminology and now use the "toward" convention consistently throughout the manuscript.

The revised text reads:

"The radiosonde measurements in Fig. 5a show that the dominant in-cloud winds were directed toward azimuths of approximately 50–150°, measured clockwise from north, corresponding to flow toward the northeastern through eastern to south-southeastern sector."

We also clarified the figure caption and other wind-direction descriptions to state that all azimuths indicate the direction toward which the wind flows.

Reviewer comment (line 349): "Baseline Vd at approximately −0.8 m s^{-1}." How is this baseline determined from Fig. 5b, given that the cosine dependence is also present in the observations? Was the baseline estimated from wind directions perpendicular to the beam-pointing offset? Please provide additional explanation.

Response: The fitted baseline is approximately −0.8 m s^{-1}. In the dimensional form used to interpret Fig. 5b, it is the intercept B in

$$Vd = A\,U \cos(\phi - \phi_0) + B.$$

The amplitude A, pointing azimuth ϕ_0, and intercept B are estimated simultaneously using observations spanning the available range of wind directions. The baseline is therefore not determined only from observations for which the wind is perpendicular to the pointing-offset direction. When the wind is perpendicular to the pointing direction, however, the horizontal-wind projection vanishes and the fitted Doppler velocity equals B.

The intercept contains contributions from the reflectivity-weighted particle fall velocity, mean vertical air motion, and any residual instrumental velocity offset. For the large ice-cloud sample considered here, positive and negative air motions are expected to average toward a smaller mean contribution; therefore, the negative intercept is interpreted primarily as particle sedimentation. Its magnitude is consistent with previously reported radar-retrieved and aircraft-derived ice-particle fall velocities (Deng and Mace, 2008a, b; Mitchell et al., 2011; Kalesse and Kollias, 2013).

4.4 Application to recent campaigns and fixed sites

Reviewer comment (lines 482–483): “Considering these factors together, the overall uncertainty in the estimated beam-pointing angle is on the order of 0.5°.” How do the uncertainties discussed in lines 465–473 relate to those quantified in lines 476–483? Is the reported overall uncertainty of 0.5° meant to include both sources of uncertainty, or only the latter?

Response: We thank the reviewer for identifying this ambiguity. The approximately 0.5° value is an empirical sensitivity estimate based on the spread among retrievals using different radar averaging windows and reflectivity thresholds. The averaging-window tests changed the retrieved elevation angle by less than 0.3°, while the reflectivity-threshold tests characterized sensitivity to the sampled particle population and associated sedimentation contribution. The 0.5° value is not a formal propagated uncertainty, because the sensitivity tests are not statistically independent and do not fully represent radiosonde measurement error or radar–radiosonde spatial mismatch.

We revised the manuscript to refer to approximately 0.5° as an “empirical retrieval sensitivity” rather than an “overall uncertainty.”

Reviewer comment (lines 178–181): "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 discussion of these uncertainties later in the manuscript is missing. How are radiosonde wind-speed and wind-direction uncertainties propagated into the beam-pointing uncertainty estimate?

Response: We agree that the original manuscript did not explain this point adequately. Radiosonde measurement uncertainties were not explicitly propagated into the reported 0.5° empirical sensitivity estimate. We now state this limitation and distinguish instrumental wind uncertainty from the larger representativeness uncertainty caused by temporal separation, balloon drift, and differences between the radar sampling volume and radiosonde trajectory.

For the projected horizontal-wind contribution,

$Vh = U \cos(\phi - \phi_0) \cos \theta_0$,

first-order wind measurement errors contribute approximately

$\sigma^2(Vh) \approx [\cos(\phi - \phi_0) \cos \theta_0\, \sigma U]^2 + [U \sin(\phi - \phi_0) \cos \theta_0\, \sigma\phi]^2$,

where $\sigma\phi$ is expressed in radians. Random radiosonde errors should primarily increase scatter when many wind directions and launches are combined, whereas systematic directional errors or persistent radar–radiosonde mismatch could bias the retrieved pointing vector. A complete uncertainty estimate would require Monte Carlo perturbation or another errors-in-variables analysis that includes correlated radar and radiosonde errors. We now identify this as a limitation and no longer describe 0.5° as a complete propagated uncertainty.

Reviewer comment: Please provide practical guidance on when a beam-pointing correction becomes necessary. Given the estimated uncertainty of approximately 0.5°, should a correction be applied only above this threshold, or is another criterion more appropriate?

Response: We added practical guidance based on the expected Doppler-velocity bias rather than a universal angle threshold. For a small off-vertical angle δ in radians, the maximum horizontal-wind contribution is approximately $U\delta$. A 0.5° offset can therefore 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 deterministic correction is most appropriate when (1) the pointing offset is statistically distinguishable from zero, (2) its azimuth is adequately constrained by wind-direction sampling, and (3) the expected projected velocity bias exceeds the acceptable uncertainty for the intended radar product. Estimates comparable to their uncertainty should generally be monitored or flagged rather than corrected deterministically.

Reviewer comment: What are the likely causes of beam-pointing misalignment at fixed sites over longer periods, and how frequently should beam offsets be checked?

Response: We added a new subsection on operational monitoring. Pointing can change because of foundation settling, frost heave, thermal or wind loading, maintenance, scanner or pedestal wear, radome or antenna work, and instrument relocation. We recommend establishing a reference estimate after installation and reassessing pointing after relocation, major maintenance, or severe environmental events. At sites with routine radiosonde launches, rolling UN-VDD estimates could be used to identify gradual or seasonal changes. The appropriate update interval should depend on wind-direction coverage and fit uncertainty rather than a fixed calendar period.

Reviewer comment: It would be interesting to see the corrected Doppler-velocity results for the case study. How do the W-band and Ka-band Doppler velocities compare after the beam-pointing correction is applied?

Response: We agree that this comparison provides a useful physical evaluation of the retrieved pointing offsets. Using the elevation and azimuth convention adopted in this study, the equivalent vertically corrected Doppler velocity is

$$V_{d,corr} = [V_{d,meas} - U \cos(\phi - \phi_0) \cos \theta_0] / \sin \theta_0.$$

This correction removes the projected horizontal-wind contribution and accounts for the projection of the remaining vertical component along the slightly tilted beam. The corrected velocity still contains vertical air motion, particle sedimentation, and any residual instrumental offset. We perfomed one case correction with radiosonde and the resulted Doppler velocity is around -0.5 to 0 m/s, which is consistent with the ice particle velocity. However, for more accurate correction, uncertainty estimation of this correction is needed, which is beyond of this study.

Reviewer comment: How does the method perform when only a limited number of radiosonde observations are available? For example, is a robust fit possible when only a few soundings sample opposing wind directions?

Response: The required sampling period is determined by wind-direction coverage, atmospheric variability, and retrieval uncertainty rather than a fixed number of soundings. A small number of profiles may be sufficient when vertical shear provides broad directional sampling. In contrast, observations confined to two opposing directions constrain only the component of the pointing vector parallel to those directions and do not robustly determine the full two-dimensional tilt vector. Operational retrievals should therefore report directional coverage, confidence intervals, the number of independent soundings, and fit-stability metrics. Poorly constrained estimates should be flagged rather than interpreted as physical pointing changes.

Reviewer comment: Is there a difference between horizontal wind speed and direction measured inside and outside cloud? If differences are expected, please discuss their potential effect on the beam-pointing retrieval.

Response: A radiosonde measures the local wind continuously along its trajectory, regardless of whether it is inside or outside cloud, whereas the cloud radar contributes Doppler samples only where hydrometeors are detected. Wind can change across cloud boundaries because clouds may coincide with vertical shear, convective circulations, or mesoscale gradients. More importantly, the balloon can drift away from the radar column, so the radiosonde and radar may not sample the same cloud volume even at the same altitude. Height-by-height matching represents the observed vertical wind structure but cannot eliminate this spatial mismatch. Random differences increase scatter in the UN-VDD relationship; persistent differences associated with particular wind directions or weather regimes could bias the retrieved pointing vector. We added this limitation and recommend comparison with collocated wind-profiler, Doppler-lidar, or model winds when available.

New discussion text: Operational beam-pointing monitoring

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

The required sampling period should be determined by wind-direction coverage, atmospheric conditions, and retrieval uncertainty rather than 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, the number of independent soundings, confidence intervals, and fit-stability metrics, with poorly constrained retrievals flagged rather than interpreted as physical pointing changes."

New discussion text: Doppler-velocity correction

"The retrieved pointing angles can be used to remove horizontal-wind contamination from measured Doppler velocity. Whether correction is necessary should be determined from the expected velocity bias and the accuracy requirements of the intended radar product rather than a universal pointing-angle threshold. For a small off-vertical angle δ, the maximum horizontal-wind contribution is approximately Uδ, 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. 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 a collocated horizontal-wind profile, the equivalent vertically corrected Doppler velocity is calculated as

$$V_{d,corr} = [V_{d,meas} - U \cos(\phi - \phi_0) \cos \theta_0] / \sin \theta_0. \quad (8)$$

After correction, Doppler velocity contains the vertical contributions from particle sedimentation and air motion, together with any residual instrumental velocity offset. Wind-field uncertainty propagates directly into the corrected velocity, while spatial and temporal separation between the radar and wind measurements can introduce additional bias. Evaluation using independent wind and velocity constraints remains an important topic for future work."

5 References

Reviewer comment: Some references cited in the text appear to be missing from the reference list. Please check consistency between in-text citations and the bibliography. In addition, reference formatting should be standardized throughout.

Response: We thank the reviewer for identifying these inconsistencies. We checked all in-text citations against the bibliography, added the missing references, and standardized the reference list according to the AMT formatting guidelines. We also assigned year suffixes where needed, including Deng and Mace (2008a, b) and Kollias et al. (2007a, b), and updated the corresponding in-text citations.