EarthCARE Cloud Profiling Radar (CPR) Doppler measurements in deep convection: challenges, post-processing and science applications

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ABSTRACT

The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) satellite is a joint European Space Agency and Japanese Aerospace Exploration Agency mission scheduled to launch in 2021. EarthCARE (EC) will host the first Doppler cloud profiling radar (CPR) in space which, in addition to constraining microphysical retrievals in particle sedimentation regimes, is expected to provide the first ever global observations of convective vertical air motion and associated mass fluxes. Here, the potential of the EC-CPR velocity measurements in convection is evaluated using forward-simulations performed using a state-of-the-art EC-CPR Doppler simulator and output from high-resolution, bulk microphysics numerical models. Results indicate that the EC-CPR has the potential to measure Doppler velocities in the top 40% of convective cores, the rest being not observed/contaminated by attenuation and multiple scattering. In these observable regions, non-uniform beam filling (NUBF) and velocity aliasing could affect the quality of the velocity measurements. We show how observed reflectivity gradient can be used to correct for NUBF effects on Doppler velocity to achieve an accuracy higher than 0.3-0.5 ms\textsuperscript{-1}. Velocity aliasing remains an important challenge. Our results suggest that the current Nyquist velocity of the EC-CPR will enable it to document, with minimal need for de-aliasing correction, convective events with vertical velocity below 7-8 ms\textsuperscript{-1} while the information collected about more vigorous events is expected to be more challenging to recover. Overall, despite it being affected by several limiting factors, the EC-CPR has the potential to collect valuable velocity observations in deep convection thus complementing the current sparse ground-based record.

Keywords: EarthCARE, Cloud Profiling Radar (CPR), Doppler velocity, convection, vertical air motion, multiple scattering, non-uniform beam filling, velocity aliasing

1. INTRODUCTION

The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission aims to better understand the cloud, radiative and aerosol processes that play a role in regulating the climate system\textsuperscript{[1]}. The EarthCARE-cloud profiling radar (CPR; hereafter EC-CPR) performance is expected to exceed that of currently deployed satellites. Owing to its lower orbit and larger antenna, it is expected to be 6 dB more sensitive than NASA’s CloudSat CPR\textsuperscript{[3]}. This enhanced sensitivity combined with the EC-CPR ability to perform considerable oversampling in range (every 100 m for a 500 m pulse) and its possibly improved receiver filter are expected to contribute to an improved detection of cloud systems\textsuperscript{[3]}. However, it is expected that the EC-CPR will face the same challenges as the CloudSat-CPR when it comes to observing strongly attenuating cloud systems and the lowest 1 km of the atmosphere unless shorter pulse length or pulse compression techniques are introduced\textsuperscript{[4, 5]}.

Another significant improvement of the EC-CPR includes recording, for the first time, Doppler velocity information from space. Several factors are expected to impact the quality of the EC-CPR Doppler velocity measurements\textsuperscript{[6, 7]}; 1) the pulse-transmitting configuration; The EC-CPR uses single pulse repetition frequency (PRF) with no polarization diversity\textsuperscript{[3]}.

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Figure 1. ECCC light-to-moderate convective scene in terms of radar reflectivity as would be detected by an unattenuated unbiased 94-GHz radar. The dotted lines indicate the location of the convective core.

and thus has narrow Nyquist velocity boundaries (5.2 – 6.0 ms\(^{-1}\)), 2) the satellite’s relatively high speed; The EC-CPR moves at approximately 7.6 km s\(^{-1}\), which introduces significant broadening of the Doppler velocity spectrum\[^{[9, 10]}\]', 3) the pointing of the CPR antenna, which can introduce a Doppler velocity biases (up to several meters per second) if the CPR is pointing off-nadir in the along track direction\[^{[11-14]}\]. Other factors such as attenuation, multiple scattering\[^{[15-17]}\], non-uniform beam filling\[^{[18]}\], and aliasing\[^{[19]}\] have also been identified but their effect has yet to be quantified.

Here, we will evaluate the impact of these factors in the context of the ability of the EC-CPR to probe deep convective clouds. Deep convective clouds are a very challenging target for 94-GHz radar due to the significant hydrometeor attenuation and the complicate interpretation of mean Doppler velocity measurements since the fall speed of their hydrometeors may be non-negligible fall velocity (\(V_f\)) such that observed mean Doppler velocity (\(V_D = V_f + V_A\)) cannot be assumed representative of vertical air motion (\(V_A\)). Evaluation will be performed in the context of a forward-simulator to compensate for the fact that the EC-CPR has yet to launch.

2. MODEL SCENES

The potential of the EC-CPR to provide measurements of up- and downdrafts velocity in deep convective clouds is evaluated using forward simulations of two high-resolution model output scenes.

The first scene is one of the three baseline test scenes used for EC L1/L2 data product development and validation efforts. It was created by the Environment and Climate Change Canada (ECCC) Global Environment Multiscale numerical weather prediction model which operates with a 0.25 km horizontal resolution, 100 m vertical resolution and a double-moment bulk microphysics scheme\[^{[20]}\]. The ECCC model scene is 6,200 km long but we focus here on the tropical convective cloud system with an over 600 km ice cloud producing a 400 km of widespread precipitation shaft and generating light-to-moderate convective motions (\(|V_A| < 6-7 \text{ m s}^{-1}\)). Using scattering calculation alone, we create a benchmark of how this cloud scene would appear, in terms of radar reflectivity (Fig. 1; colors) and mean Doppler velocity (Fig. 2; colors), to an unbiased, unattenuated, motion-less nadir-pointing radar.

The second case was generated by the System for Atmospheric Modeling (SAM) model\[^{[21]}\] at a 50 m horizontal and vertical resolution and using the single-moment bulk microphysics scheme described in (21). The SAM model simulation was initialized using the Idealized Global Atmospheric Research Program's Atlantic Tropical Experiment (GATE) Simulations of Convection over the Tropical Atlantic set-up\[^{[22]}\]. The SAM model scene has a horizontal domain of 150
Figure 2. ECCC light-to-moderate convective scene in terms of mean Doppler velocity as would be detected by an unattenuated unbiased 94-GHz radar. Upward velocities are negative and downward velocities are positive. The black contour indicates vertical air motion.

Figure 3. SAM vigorous convective scene in terms of (a) radar reflectivity and, (b) mean Doppler velocity as would be detected by an unattenuated unbiased 94-GHz radar. Upward velocities are negative and downward velocities are positive. The black contour indicates the region where the vertical air motion exceeds 15 m s\(^{-1}\).

km x150 km but we focus here on the 20-30 km wide deep convective cloud system presented in Fig. 3 which presented vigorous convective motions (\(|V_A| > 12-15 \text{ ms}^{-1}\)). For evaluation purposes, we present how this cloud scene would appear to an unbiased, unattenuated, motion-less nadir-pointing radar in terms of radar reflectivity (Fig. 3a) and mean Doppler velocity (Fig. 3b).

The contours in both Fig. 2 and Fig. 3b indicate the magnitude of the simulated air motion while the colors represent the magnitude of the observed mean Doppler velocity (with negative indicating upward motion). In both instances, in the convective regions where air motion exceeds a critical updraft velocity value, notice how the mean Doppler velocity always takes on a negative value (updraft) indicating that it is mostly affected by air motion rather than hydrometeor fall velocity. This suggests that in deep convection, observed mean Doppler velocity has potential to retrieve air motion if we can account for the non-negligible hydrometeor sedimentation.
3. THE EC-CPR FORWARD-SIMULATIONS

The model scenes radar reflectivity factor and mean Doppler velocity fields are used as input to the EC-CPR forward-simulator that estimates radar reflectivity and Doppler velocity accounting for several additional factors including 1) introducing a realistic Earth’s surface echo[3], 2) considering the EC-CPR sampling geometry (i.e. antenna beamwidth, pulse length and pulse repetition frequency)[9], 3) considering the EC-CPR signal sampling strategy (i.e. receiver noise, pulse-pair Doppler moment estimator)[9] and 4) accounting for the variations in the EC-CPR’s location; including changes in orbital altitude and pointing[9] as well as antenna vibration which are corrected using the Earth’s surface reference Doppler velocity[11, 12].

The EC-CPR forward-simulator also accounts for the Doppler spectra broadening due to the platform motion, non-uniform beam filling and for Doppler velocity aliasing[9]. Regrettably, the EC-CPR forward-simulator doesn’t not account for the effect of multiple scattering on signal propagation. However, the EC-CPR forward-simulator includes a multiple scattering (MS) flag to identify the maximum height within cloud where MS has no effect on Doppler velocity measurements[23]. Table 1 presents a list of the EC-CPR parameters used in the forward simulations.

3.1 Non-uniform beam filling correction

Besides evaluating the impact of these various effects, we propose to evaluate the performance of a non-uniform beam filling (NUBF) correction in the context of this forward-simulator. NUBF accounts for the general case of a radar sampling volume contains an inhomogeneous 3D distribution of hydrometeors that results in bias radar reflectivity and Doppler velocities. In spaceborne Doppler radars, inhomogeneities in the radar reflectivity field (Z_e) especially in the along track direction (x) can introduce significant Doppler velocity biases[18]. Biases introduced by NUBF correlate well with the gradient of the along-track radar reflectivity within the CPR sampling volume:

\[ V_{NUBF, bias} = \alpha \cdot \frac{\Delta Z_e(x)}{\Delta x} \]  

(1)

where \( \alpha \) is the correlation coefficient in (m s\(^{-1}\) (dB km\(^{-1}\))\(^{-1}\) between the NUBF velocity error and the along-track derivative of the measured reflectivity (Z_e) expressed in dBZ. The parameter \( \alpha \) can take values from 0.165 in the cases where the radar reflectivity field is linear radar to 0.22 when radar reflectivity changes in a step function[9]. A linearly evolving along track radar reflectivity field will be assumed here and a parameter \( \alpha \) of 0.17 used. Reflectivity gradient will be computed via a central finite-difference formula between consecutive samples which implies that, given our 500 m sampling resolution, reflectivity gradients will be estimated over 1 km. Note that the NUBF corrections are applied in the complex voltage space which is equivalent to correcting for NUBF in the pulse-pair correlation function. The performance of this algorithm will be evaluated in the two model scenes presented in Sec. 2.

Table 1. EC-CPR radar characteristics using in the forward simulations

<table>
<thead>
<tr>
<th>EC-CPR Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>94 GHz</td>
</tr>
<tr>
<td>Antenna size</td>
<td>2.5 m</td>
</tr>
<tr>
<td>PRF</td>
<td>7000 Hz</td>
</tr>
<tr>
<td>3-dB beamwidth</td>
<td>0.09°</td>
</tr>
<tr>
<td>Pulse length</td>
<td>3.3 µs</td>
</tr>
<tr>
<td>Altitude</td>
<td>400 km</td>
</tr>
<tr>
<td>Speed</td>
<td>7.6 kms(^{-1})</td>
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<tr>
<td>Sensitivity (single pulse)</td>
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</tr>
<tr>
<td>Along track integration</td>
<td>500 m</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>100 m</td>
</tr>
</tbody>
</table>
3.2 EC-CPR performance in the ECCC’s light-to-moderate convective scene

Using the EC-CPR described above we performed a forward simulation of the ECCC light-to-moderate convective scene presented in Sec. 2 Fig. 1-2. The forward simulated radar reflectivity field presented has a resolution of 500 m along-track and 100 m in the vertical. The strongest echo observed is the Earth’s surface (40-50 dBZ) which vertical extent is limited to approximately 1 km consistent with our experience with the CloudSat CPR\(^2\). Because of its 500-m along track integration of approximately 500 pulses, the EC-CPR is capable of detecting signals as low as -35 dBZ. However, signal attenuation by hydrometeors (which is important at 94 GHz) becomes important in the convective region between 2,700 km and 2,800 km along track where the radar signal is completely lost. Note how MS effects become significant only a few 100 meters above the level of complete extinction (around 8-12 km; as indicated by the black circles in Fig. 4).

Figure 5a shows the Doppler velocity bias for this scene due to NUBF as estimated by the EC-CPR simulator given that we know the detail along track radar reflectivity field within each CPR sampling volume. The highest Doppler velocity biases due to NUBF are observed near cloud edges. The majority of the severe (over 1 m s\(^{-1}\)) NUBF Doppler velocity biases occur at low radar reflectivity values (signal to noise ratio (SNR) < 3 dB, or dBZ < -18.5; Fig. 5a contours). Owing to the platform motion, the EC-CPR is anyways not expected to produce reliable Doppler velocity measurements at such low SNR conditions\(^3\). Figure 5b shows the residual NUBF Doppler velocity bias after applying the NUBF correction presented in Eq. 1. Overall, the NUBF Doppler velocity correction appears to perform well. The performance of the NUBF correction will be further illustrated in Fig. 6.

Figure 6 shows the reduction in the NUBF-induced Doppler velocity bias using Eq. 1 in the stratiform (\(|V_A| < 2\) m s\(^{-1}\), Fig. 6a) and convective (\(|V_A| > 2\) m s\(^{-1}\), Fig. 6b) regions of this scene. In the stratiform region (Fig. 6a, blue line), the NUBF-induced bias does not exceed 1.0 m s\(^{-1}\) suggesting that in general the along track radar reflectivity gradient is lower than 5 dB km\(^{-1}\). The correction (Fig. 6a, black line) removes the large NUBF-induced Doppler velocity biases. Overall, the NUBF correction does not complete remove the bias and an uncertainty of 0.2 m s\(^{-1}\) remains. This is attributed to the lack of knowledge from the EC-CPR observations of the exact along track variability of the radar reflectivity field. In the convective region (Fig. 6b, blue line), the NUBF-induced bias reaches values up to 2.0 m s\(^{-1}\) suggesting that in general the along track radar reflectivity gradient can reach 10 dB km\(^{-1}\). In this case, the NUBF correction has a larger impact and reduces the large NUBF-induced Doppler velocity biases. The remaining uncertainty (Fig. 6b, black line) is close to 0.3 m s\(^{-1}\).

Figure 7 shows the forward simulated EC-CPR Doppler velocity field of echoes with SNR > 3 dB or dBZ > -18.5, after all discussed corrections have been applied. The comparison between Fig. 7 and Fig. 2 suggests that the EC-CPR is able to detect the presence of updrafts in this particular convective cloud system. MS effects will probably limit our ability to use the full observed column of EC-CPR Doppler velocities, however, the location of the updraft cores is clearly detectable.

![Figure 4. ECCC light-to-moderate convective scene in terms of radar reflectivity as would be detected by the EC-CPR.](image-url)
In addition to the NUBF-induced Doppler velocity bias, another concern with the EC-CPR Doppler velocities is aliasing. The correction of aliased velocities—the so-called dealiasing or unfolding—is a challenging technical task and becomes increasingly difficult with a decreasing Nyquist velocity or increasing noise in the data. In Fig. 7, most of the Doppler velocity aliasing occurs in the stratiform part of the precipitation (negative (upward) velocities in the lowest 5 km). In these regions, the vertical air motion is weak ($|V_A| < 2 \text{ m s}^{-1}$), thus, the observed negative Doppler velocities cannot be the result of strong upward motions. The observed negative velocities are the result of large raindrops falling with Doppler velocity higher than the Nyquist velocity ($V_N = 5.6 \text{ ms}^{-1}$ for a PRF of 7,000 Hz) and thus alias to negative Doppler velocities. In this case, the correction is straightforward (not shown). On the other hand, the observed negative Doppler velocities above 8 km are the result of updrafts and the observed EC-CPR Doppler velocities are very close to those estimated directly by the ECCC model (with no platform motion).
Figure 7. ECCC light-to-moderate convective scene in terms of mean Doppler velocity retrieved by the EC-CPR after the spacecraft motion, antenna mis-pointing and NUBF Doppler velocity bias corrections have been applied. The circles indicate the maximum penetration depth before MS effects become significant and the contours indicate the location of the 2, 4 and 6 m s$^{-1}$ updrafts.

3.3 EC-CPR performance in the SAM’s vigorous convective scene

Using the EC-CPR described above we also performed a forward simulation of the SAM vigorous convective scene presented in Sec. 2 Fig. 3. Once again the forward simulated radar reflectivity field presented has a resolution of 500 m along-track and 100 m in the vertical (Fig. 8a). Strong hydrometeor attenuation at 94-GHz result in complete signal extinction below 8 km for a significant part of the convective cloud system. The corresponding EC-CPR mean Doppler velocity field is shown in Fig. 8b. The Doppler velocity field shown in Fig. 8b is very noisy and shows very little resemblance to the SAM model mean Doppler velocity field (Fig. 3b). To a large extend this is expected given the magnitude of the Doppler velocities in SAM (± 20 m s$^{-1}$) and the limited Nyquist velocity ($V_N = ± 5.6$ m s$^{-1}$) of the EC-CPR which causes Doppler velocity aliasing.

Fig. 9a shows the Doppler velocity bias due to NUBF as estimated by the EC-CPR simulator given that we know the detail along track radar reflectivity field within each CPR sampling volume. Note the difference in the color scale limits between Fig. 9a and Fig. 5a. Near the cloud edge, significant Doppler velocity biases due to NUBF are observed (over 5-8 m s$^{-1}$).

Figure 8. SAM vigorous convective scene in terms of radar reflectivity, and mean Doppler velocity as would be detected by the EC-CPR.
Figure 9. (a) The Doppler velocity bias induced by the NUBF, (b) the residual Doppler velocity bias due to NUBF bias after the NUBF correction that assumes linear radar reflectivity field is applied.

Once again, the majority of the severe NUBF Doppler velocity biases occurs at low radar reflectivity values (SNR < 3 dB, or dBZ < -18.5). The high NUBF Doppler velocity biases observed in the interior of the convective cloud system (6-8 km height, 245-255 km along track) are induced by differences in the path integrated attenuation. Fig. 5b show the residual NUBF Doppler velocity bias after the NUBF correction shown in Eq. 1 is applied to the simulated EC-CPR Doppler velocities. Despite the vigorous convective nature of the SAM scene, the Doppler velocity correction due to NUBF biases appears to work well.

Fig. 10 show the reduction in the NUBF-induced Doppler velocity bias using Eq. 1 in the stratiform ($|V_A| < 2$ m s$^{-1}$, Fig 10a) and convective ($|V_A| > 2$ m s$^{-1}$, Fig 10b) regions in this scene. In the stratiform region (Fig. 10a, blue line), the NUBF-induced bias reaches 2.5 m s$^{-1}$ suggesting that despite the weak dynamics, there is considerable variability in the radar reflectivity field. The NUBF correction (Fig. 10a, black line) has little impact mainly due to the fact that most of the weak dynamic regions are near cloud edges where the estimation of the along track radar reflectivity gradient is challenging. In

Figure 10. (a) the distribution of the NUBF-induced Doppler velocity bias before (blue) and after (black) the NUBF bias correction is applied in the particle sedimentation regime ($|V_A| < 2$ m s$^{-1}$) and (b) the distribution of the NUBF-induced Doppler velocity bias before (blue) and after (black) the NUBF bias correction is applied in the convective regime ($|V_A| > 2$ m s$^{-1}$).
the convective regions more instance of high NUBF-biases are observed (Fig. 10b, blue line). So proper NUBF correction in this region has a larger impact than in stratiform regions. The remaining uncertainty in the convective regions (Fig 6b, black line) is found to be close to 0.5 m s\(^{-1}\).

The SAM convective cloud scene has stronger along track radar reflectivity gradients and thus experiences higher NUBF-induced Doppler velocity biases. However, the EC-CPR simulations indicate that the NUBF correction can account for most of the velocity bias and mitigate it. Fig. 11 shows the difference between SAM’s original model scene in terms of Doppler velocity (our benchmark) and the EC-CPR forward simulated Doppler velocity. A difference of \(2V_N\) is estimated suggesting that aliasing can explain most of the observed differences especially regions of strong updrafts (Fig. 11). In ground-based and airborne-based radar systems, aliasing is easily identifiable as abrupt changes in the velocity field, which is why most de-aliasing techniques are based on spatial (along a radial) and temporal continuity rules\(^{[24]}\). However, in the case of EarthCARE, the application of this approach is not straightforward. The CPR Doppler velocities are characterized by large uncertainty that can lead to aliasing in the absence of microphysical and/or dynamical effects. Furthermore, NUBF conditions can also lead to velocity aliasing in the absence of microphysical and/or dynamical effects.

4. SUMMARY AND DISCUSSION

Convective motions affect microphysical processes and control the transport of moisture, momentum, heat, trace gases and aerosols from the boundary layer to the upper troposphere. Collecting holistic observations of convective motion from the ground remains challenging owing to a shortage of profiling sensors (especially in marine settings) and to the complexity of retrieving vertical velocity using scanning sensors (e.g., multi-Doppler approach) with an accuracy better than 1-2 m s\(^{-1}\).

With its global coverage and Doppler capability, there is an expectation for the EC-CPR to fill this gap. However, when it comes to estimating mean Doppler velocity in deep convective clouds, the EC-CPR is challenged by several factors.

Hydrometeor-induced 94-GHz signal attenuation is expected to limit the penetration of the EC-CPR signal thus restricting measurements to the upper cloud of convective clouds. In addition, the presence of multiple scattering (MS) effects are expected to contaminate the EC-CPR measurements even at heights where the EC-CPR signal is able to penetrate. Fortunately, forward simulations and analysis of CloudSat observations suggest that the EC-CPR will experience less MS effects than the CloudSat CPR due to its smaller field of view and that MS typically onsets below 8-10 km; Given this, the
EC-CPR is expected to collect reliable Doppler measurements in 40% of convective cores. Attenuation and MS effect do pose a serious limitation regarding the penetration depth of the EC-CPR observations.

Another factor affecting the quality of the EC-CPR Doppler measurements is the Doppler velocity bias due to non-uniform beam filling (NUBF). As expected and confirmed by forward-simulations, convective regions are particularly prone to NUBF-induced Doppler velocity bias owing to their highly inhomogeneous nature. It was shown here that, using observed radar reflectivity gradients, it is possible to limits the uncertainty in the resulting Doppler velocities to below 0.3-0.5 m s^{-1} in convective regions (compare to 0.2 m s^{-1} in stratiform regions). NUBF is enhanced in convection, however, it appears that its impact of the EC-CPR Doppler velocities can be addressed adequately.

Lastly, the EC-CPR Doppler velocity estimates are expected to experience considerable aliasing when observing strong convective updrafts and downdrafts if those have of velocity well beyond its Nyquist velocity of 5.2 - 6.0 m s^{-1}. Two model scenes were examined here to investigate the occurrence and importance of Doppler aliasing in future EC-CPR measurement. In the first scene (ECCC scene) a combination of the gentle updrafts (\(|V_a| < 6-7\) m s^{-1}) and particle sedimentation velocity resulted in Doppler velocities that lied comfortably with the EC-CPR Nyquist velocity limits leading to only a few isolated aliased Doppler velocity observation which were relatively easy to identify and to correct for. In a second scene (SAM scene) dominated by very strong updrafts (\(|V_a| > 10-12\) m s^{-1}) Doppler velocity aliasing occurred in many instances. Furthermore, the enhanced noise in the EC-CPR Doppler velocity estimates due to the platform motion make difficult the identification of sharp Doppler velocity discontinuities often found at the boundaries between aliased and non-aliased Doppler velocity observations in ground-based systems. This is expected to make the Doppler velocity unfolding very challenging. Doppler velocity aliasing is more complex challenge and clearly depends on the strength of the convection. A sensitivity study on the range of PRF values that provide adequate EC-CPR Doppler velocity measurements in convection suggests that the EC-CPR should strive to operate with a PRF above 7000 Hz.

As mentioned in the introduction, another critical factor that will come forward in the utilization of spaceborne Doppler velocity measurements is their interpretation. In a profiling pointing mode (nadir or zenith pointing), observed Doppler velocities are the sum of the hydrometeor fall velocity (weighted by the backscattering cross section and the number concentration; \(V_f\)) and vertical air motion (\(V_a\)). The relative contribution of the two terms to the observed Doppler velocity (\(V_D\)) depends strongly on the strength of the cloud dynamics and on the size of the hydrometeors (i.e., on their radar reflectivity). Thus, it is important that we identify the hydrometeor type and the dynamical state of the cloud/precipitation scheme before we interpret the observed Doppler velocities from space. At low radar reflectivity values (< -25 dBZ), \(V_f\) can be considered negligible\(^{25}\) and the observed Doppler velocity can be considered an estimate of the vertical air motion (i.e., \(V_D \approx V_a\)). The EC-CPR is expected to detect clouds with radar reflectivity as low as -35 dBZ, however, the radar samples decorrelation induce by the platform motion will result to noisy Doppler velocity estimates when the radar reflectivity is lower than -20 or even -15 dBZ.

In situations with weak or no cloud dynamics (particle sedimentation regimes), the contribution of \(V_a\) to the observed \(V_D\) is either small\(^{26, 27}\) (such as in stratiform clouds where \(V_f \sim 3-5\) m s^{-1} and \(V_a \sim 0.2\) m s^{-1}) or when averaged over large temporal/spatial interval is negligible compared to the contributions from hydrometeors (such as in ice clouds). However, in situations with strong cloud dynamics (convective clouds), the vertical air motion \(V_a\) contribution to the observed \(V_D\) is significant, while the contribution of the \(V_f\) cannot be neglected and needs to be remove from the observed \(V_D\) before the vertical air motion can be estimated. One approach to remove the reflectivity-weighted hydrometeor fall velocity is to parameterize \(V_f\) as a function of radar reflectivity\(^{28}\) (\(Z\)). Assuming a particle size distribution (PSD) and a given terminal fall velocity-diameter relationship, the reflectivity-weighted mean velocity of the assumed PSD \(V_f = aZ^b\). The difference between the estimated Doppler velocity (\(V_f\)) and the observed mean Doppler velocity (\(V_D\)) is indicative of the vertical air motion (\(V_a\)). This method has demonstrated some success in estimating the air motion\(^{29}\) (uncertainty \(\sigma_f\) near 1.2-1.5 m s^{-1}). If \(\sigma_f\) is combined with the uncertainty in estimating \(V_D\) with the EC-CPR (no along-track integration) \(\sigma_D \sim 0.5-1.0\) m s^{-1}, this results to an uncertainty \(\sigma_a < 2\) m s^{-1} in estimating the vertical air motion \(V_a\). An uncertainty of 2 m s^{-1} in estimating the vertical air motion in deep convective clouds using the EC-CPR is comparable to that we can achieve from the ground using vertically pointing radars\(^{30, 31}\) and lower than the uncertainty of multi-Doppler radar techniques\(^{32, 33}\) especially in the upper part (above 6 km height) of convective clouds.
Concluding, for deep convective clouds with \( V_t \) lower than 7-8 m s\(^{-1}\), the EC-CPR is expected to perform relatively well in estimating the vertical air motion. In more vigorous convective conditions (\( V_t > 10 \) m s\(^{-1}\)), sophisticated de-aliasing algorithms need to be developed before the potential of the EC-CPR to observed vertical air motion can be realized.

**REFERENCES**


