NUMERICAL SOLVER FOR VERTICAL AIR MOTION ESTIMATION

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ABSTRACT

We present preliminary research on a method to estimate Vertical Air Motion (VAM) at a particular height by comparing the measured rain-rate (RR) by a vertically-pointing S-band Frequency-Modulated Continuous-Wave (FMCW) radar with that of a ground-based disdrometer. The method is based on a constrained parametric solver, assuming high correlation between 5-min averaged rain rates measured by the radar and disdrometer. The method is tested over disdrometer and radar observations during the Verification of the ORigins Tornado EXperiment in South East US (VORTEX-SE) project. Finally, the results are partially validated by means of fitting a gamma distribution to the VAM-corrected DSD profiles and studying its parameters.

***Index Terms*—** Vertical Air Motion, S-Band radar, Rain Rate, Drop Size Distribution

1. INTRODUCTION

Several different ground-based remote sensing instruments are able to assess temperature and/or humidity profiles in the boundary layer including infrared spectrometers and microwave radiometers [1]. However, these instruments have a common drawback, which is their poor performance under precipitation scenarios. Alternatively, lower microwave frequency radar observations are mostly unaffected during precipitation, and hence, they emerge as an alternative in order to reveal details regarding precipitation microphysical processes [2]. Among the distinct radar technologies available, the S-band ($\sim$ 10 cm) Frequency-Modulated Continuous Wave (FMCW) radar has been used to monitor boundary layer features since the 1960s [3].

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During the VORTEX-SE project, two intensive field campaigns were carried out in 2016 and 2017 [2], in which the University of Massachusetts (UMass) S-Band radar and the Collaborative Lower Atmospheric Profiling System (CLAMPS) [4] yielded a wealth of observations. The key objectives encompassed the assessment of the atmospheric-boundary-layer evolution and the characterization of precipitation microphysical processes in northern Alabama in the context of tornado warning and monitoring [2].

The rainfall rate (RR) and the drop-size distribution (DSD) are key parameters that can be retrieved from vertically pointed radar observations. RR estimation is influenced by the assumed DSD. In turn, the DSD can be computed from the vertically pointed radar Doppler spectrum with the assumption that the drops are Rayleigh scatterers falling at their terminal velocities [5]. However, in practice, the Doppler spectrum is affected by the ambient vertical air motion (VAM). Thus, given the Doppler spectrum as a function of height, RR and DSD retrievals require height-dependent VAM correction. While raw velocity bins in the radar observations represent a shifted, and possibly aliased, version of the mean Doppler radial velocity, velocity bins after VAM correction are expected to represent the true terminal fall velocity of the raindrops.

Different approaches to estimate VAM have been carried out in the literature: Kim et al. [6] obtained VAM estimations using Doppler spectra derived from a 1290-MHz wind profiler, which showed good agreement in comparison with the VAM derived at 300 m in height from a K-band micro-rain radar and at surface from a disdrometer. They used the Sans Air Motion (SAM) gamma-size hydrometeor distribution model introduced by Williams [7], who proposed a method to estimate VAM based on iterative fitting the DSD retrieved from the velocity-shifted observed spectrum and the SAM-DSD model. In contrast, this paper tackles VAM estimation relying on RR measurements by a ground-based disdrometer, assuming high RR correlation between different measurement heights considering 5-min average ensembles. Although collision and coallescence processes limit radar- and disdrometer-DSD coincidence, correlation coefficients of $\rho \simeq 0.75$ are found for the RR between disdrometer and radar at 500 m in [5]. This paper is organised as follows: Sect. 2 presents the instrumentation including the OTT Parsivel2 disdrometer and the UMASS S-band radar, and the retrieval methods for the RR and DSD products and the VAM estimation. Sect. 3 shows a case study on the proposed VAM estimation method, and Sect. 4 gives conclusion remarks.

2. INSTRUMENTS AND METHODS

2.1. The UMASS S-Band radar

The S-Band FMCW radar employed during VORTEX-SE was developed by the Microwave Remote Sensing Laboratory from the University of Massachusetts. This radar is deployed on a truck for mobility and uses two parabolic dish antennas, both with diameter of 2.4 m and gain of 34 dB, and a 250 W transmitter [3]. This system measures the volume reflectivity spectral density (with respect to velocity), $\eta(v)$, with averaged spatial and temporal resolutions of 5 m and 16 s, respectively. From these it is possible to obtain profiles of the spectral reflectivity factor, $Z(v)$, vertical velocity, v, and spectrum width, w. This radar enables to study the atmospheric boundary layer behaviour as well as precipitation events, because it is able to detect both clear-air echo and precipitation [5].

2.2. The OTT Parsivel2 disdrometer

The OTT Parsivel2 disdrometer used for VORTEX-SE measurement campaign is deployed as a part of the Portable *In situ* Precipitation Station (PIPS), designed and developed by Purdue University and the U.S. National Severe Storms Laboratory. This is a ground-based instrument that measures optically at 1 dimension the precipitation size particle-by-particle. The disdrometer has an approximate temporal resolution of $\simeq$10 s and measures different rain-related parameters such as the DSD and the RR, among others [8].

2.3. Data products and Vertical Air Motion correction

Data products.- The steps to estimate the RR and DSD from radar measurements begin with the measured radar volume reflectivity $\eta(v)$ as a function of velocity (see details in Appendix of [5] and physical basis in [9]). The DSD is defined as

$$N(D) = \frac{\eta(D)}{\sigma(D)}, \tag{1}$$

where $\sigma(D)$ is the single-particle backscattering cross section of a drop of diameter D, and $\eta(D)$ is the radar reflectivity density as a function of diameter. The rain rate is computed as

$$RR = \pi/6 \int_0^\infty N(D) D^3 v(D) dD, \tag{2}$$

which is essentially the third order moment of the DSD and fall velocity as a function of drop diameter, $v(D)$.

VAM correction.- The fundamental raindrop terminal-velocity-to-diameter relationship, denoted $v(D)$ in Eq. 2, assumes that there is no vertical air motion [9],

$$v(D_n) = (9.65 - 10.3e^{-0.6 \cdot D_n})\delta v(h), \tag{3}$$

where D_n is the raindrop diameter, $\delta v(h)$ is an air density correction for the terminal velocity as a function of height, and velocities are positive down. In the presence of VAM, the Doppler velocity measured by the vertically-pointing radar is given by

$$v_{Doppler} = v + v_{VAM}, \tag{4}$$

where $v = v(D)$ is the terminal fall velocity for raindrops of diameter D, $v_{Doppler}$ is the corresponding Doppler velocity measured by the radar, and v_{VAM} is the VAM velocity. In what follows, dependency with diameter D will be skipped because VAM is a property related to atmospheric dynamics and turbulence and therefore, it is equally affecting all particle sizes. Size retrieval from Doppler velocity measurements must include the correction, $v = v_{Doppler} - v_{VAM}$ when computing Eq. 3 inverse function, $D(v)$, and subsequent retrieval of the DSD and RR via Eq. 1 and Eq. 2, respectively. Therefore, in practice, the RR product can be defined as a function of the VAM velocity correction as $RR(VAM)$.

VAM estimation.- The VAM estimation method consists on an optimisation problem by solving Eq. 2 as a function of the VAM velocity correction. The optimization problem can be formulated as

$$VAM = \underset{VAM}{arg\ min}\ ||RR_{disdro} - RR(VAM)||^2, \quad (5)$$

where $RR(VAM)$ is the RR radar product obtained as a function of the VAM velocity correction solving Eq. 2. Eq. 5 above is posed assuming that RR_{disdro} and $RR(VAM)$ are correlated in height (at altitudes considerably lower than the melting layer) when considering 5-min averages. The VAM optimization is carried out by means of a constrained non-linear Least-Squares algorithm, minimizing the squared error between RR_{disdro} and $RR(VAM)$.

3. RESULTS AND DISCUSSION

The algorithm presented in subsection 2.3 has been applied to radar and disdrometer measurements (5-min averaged) taken during April 30, 2016 00:00-01:00 UTC in the context of VORTEX-SE measurement campaign. The algorithm estimated VAM values that, when used to correct the radar reflectivity measurements at 500 m height, provided RR values virtually identical to RR_{disdro} ($||RR_{disdro} - RR(VAM)||^2 < 0.002 mm \cdot h^{-1}$). Fig. 1 compares the radar-measured RR at 500 m, with and without VAM correction (solid black and gray traces, respectively), to RR_{disdro} (dashed blue). It can be observed that without correction, radar-derived RR shows considerably lower values ($\simeq$ 0.1 $mm \cdot h^{-1}$) compared to RR_{disdro} ($\simeq$ 0.4 - 0.8 $mm \cdot h^{-1}$) mainly due to VAM-velocity-induced error [10]. With VAM correction, the radar-derived RR trace overlaps RR_{disdro} time series, and the estimated VAM time series is obtained (dashed brown trace), showing a nearly constant value of $\simeq$ 4 $m \cdot s^{-1}$. The background color map depicts the 5-min averaged DSD measured by the FMCW radar after VAM correction.

In order to validate the VAM-corrected DSDs obtained for each 5-min average, and thus, the estimated RRs and VAM velocities, the gamma distribution parameterization of DSD was derived by means of the method of moments [11]. The gamma distribution representation of N(D) is formulated as

$$N(D) = N_0 D^{\mu} e^{-\Lambda D}, \quad (6)$$

being characterized by N_0, μ, and Λ parameters. Fig. 2 shows a DSD parameterization example in which the average DSD measured by the radar between 00:00 UTC and 00:05 UTC, with and without VAM correction (solid trace, b) and a) panels, respectively), is plotted along its gamma parameterization (dashed trace). It can be observed that without VAM correction (Fig. 2 a)) the measured DSD is poorly fitted to a gamma distribution, showing a great bias between the modelled and measured

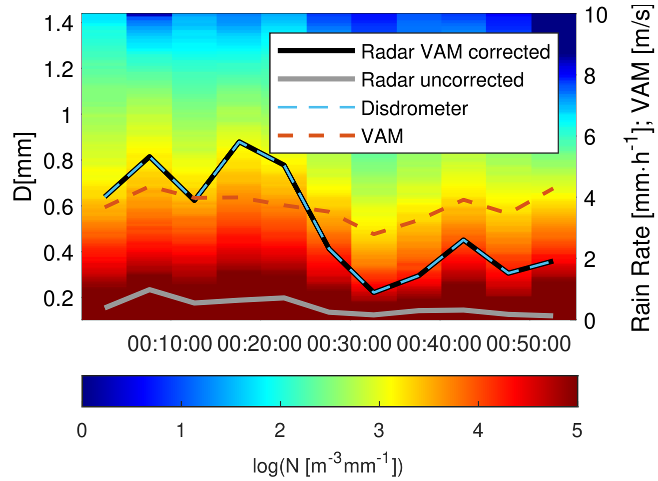

Fig. 1. Time series representing the radar-measured RR, with and without VAM correction, the disdrometer-measured RR and the VAM estimation results. The DSD is represented on the background.

DSDs. This is further evidenced by the gamma distribution parameters obtained, with $\mu = -3.574$ which is out of the accepted range in the literature for μ values ($\mu \in [-3, 8]$) [9]. On the other hand, after VAM correction (Fig. 2 b)), the obtained DSD can be nicely fitted to a gamma distribution. This result is quantitatively validated as well by the gamma distribution parameters obtained, now with $\mu = -2.185$ within the expected ranges.

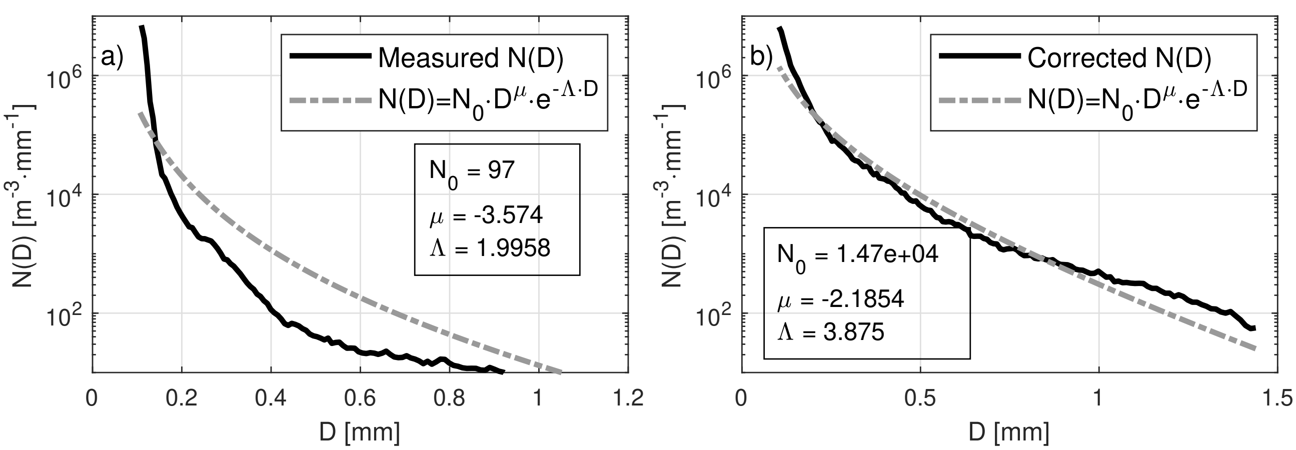

Fig. 2. Case example showing the gamma distribution fitting to a radar-measured DSD without (panel a)) and with (panel b)) VAM correction.

Table 1 depicts the gamma distribution parameters obtained for each of the 5-min averaged DSD measurements after VAM correction. N_0 values range from a minimum of $5.94{\cdot}10^3$ at 00:35 UTC, corresponding to the lowest RR within the measurement period under study, to a maximum of $6.66 \cdot 10^4$. μ values remain approximately constant around $\mu = -2$, and finally, Λ ranges from a minimum of 3.87 at 00:05 UTC to a maximum of 7.44 at 00:55 UTC. The obtained values are in accordance with the ranges found in the literature [9] and their temporal correlation seem to validate the VAM estimations obtained. However, all we have shown is that the radar-derived RR can be made to match the disdrometer-derived RR, and that the resulting radar-derived

Time (UTC+2)	N_0	μ	Λ
00:05:00	$1.47 \cdot 10^4$	-2.19	3.87
00:10:00	$3.15 \cdot 10^4$	-2.19	4.50
00:15:00	$2.33 \cdot 10^4$	-2.12	4.49
00:20:00	$5.76 \cdot 10^4$	-1.91	5.07
00:25:00	$3.95 \cdot 10^4$	-1.97	4.78
00:30:00	$1.43 \cdot 10^4$	-2.19	4.58
00:35:00	$5.94 \cdot 10^3$	-1.99	4.58
00:40:00	$8.85 \cdot 10^3$	-2.01	4.5
00:45:00	$1.45 \cdot 10^4$	-2.33	4.53
00:50:00	$2.35 \cdot 10^4$	-1.53	5.45
00:55:00	$6.66 \cdot 10^4$	-1.99	7.44

Table 1. Gamma distribution N_0, μ, and Λ fit parameters found for the VAM-corrected radar-measured DSDs for the measurement period under study (April 30, 2016 00:00-01:00 UTC) in the context of VORTEX-SE campaign. Each row corresponds to a DSD 5-minute average.

DSD seems realistic. The Gamma distribution parameters obtained still need to be validated according to the rain type present in the scenario under study, and the DSDs from the two instruments should be compared in light of their respective sensitivities. The rather substantial apparent VAM over the course of 1 hour also deserves further investigation.

4. CONCLUSIONS

A methodology to estimate VAM velocity from radar and disdrometer RR measurements has been presented. The method consists on fitting the radar-retrieved RR, as a function of VAM velocity correction, to the disdrometer-measured RR using constrained non-linear Least-Squares optimization.

The methodology was tested over experimental data captured during a 1-hour period by an S-band FMCW radar and an OTT Parsivel2 disdrometer in the context of VORTEX-SE measurement campaign. The estimation results found a nearly constant VAM velocity of $\simeq$4 m/s during the observation period. After VAM correction, the radar-measured RR was found to match almost ideally the disdrometer-measured RR. In order to validate these results, the gamma distribution parameterization was derived for each of the estimated DSD. It was found that without VAM correction, the gamma distribution parameters showed unrealistic values, outside of the accepted bounds for a precipitation process. On the other hand, after VAM-correction, realistic values for all parameters were found with a coherent temporal continuity, showing the methodology improvement of the radar measurements.

Although good performance of the algorithm has been observed, it needs to be tested over different experimental data, validating the VAM estimations by means of radar wind profilers. Moreover, the effect of reflectivity density aliasing needs to be studied as well.

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