

# A Nonuniform Beam Filling (NUBF) Doppler Velocity Bias Estimate for Airborne Radars with Arbitrary Pointing Angles

Charles N. Helms, Matthew L. Walker McLinden, and Gerald M. Heymsfield

**Abstract**—Doppler velocity biases introduced by nonuniform beam filling (NUBF) can often resemble legitimate meteorological features, potentially resulting in misinterpretation of radar data. Existing NUBF Doppler velocity bias corrections for airborne radars generally assume the antenna is pointing in the nadir direction. This work generalizes the NUBF bias correction equations to work for any antenna pointing angle, regardless of whether the angle is fixed or changing with time.

**Index Terms**—Doppler velocity, nonuniform beam filling (NUBF), radar reflectivity gradient.

## I. INTRODUCTION

NONUNIFORM beam filling (NUBF) biases in Doppler velocity measurements are introduced when a radar mounted on a moving platform observes a reflectivity gradient and both the gradient and platform motion vectors have a component perpendicular to the radar antenna boresight pointing direction. Equations to estimate this NUBF bias have previously been derived for nadir-pointing radars [1][2][3], where the NUBF bias can be attributed almost entirely to horizontal gradients in equivalent reflectivity factor, hereafter referred to as reflectivity. The present work generalizes the equations presented in Walker McLinden *et al.* [3] to estimate NUBF bias in Doppler velocity measurements made by a radar pointing in any direction, be it fixed angle or scanning.

While NUBF Doppler velocity biases will arise when observing a reflectivity gradient in the presence of wind shear within the pulse volume or target motion relative to the radar, here we will only consider the NUBF biases produced by the radar platform moving relative to the Earth. These platform-motion-induced NUBF biases are an aspect of the projection of the platform motion onto the quasi-conical radar beam. Platform motion is typically removed from airborne Doppler velocity measurements by projecting the platform motion onto the antenna boresight. Because the Doppler velocity is the reflectivity-weighted particle motion, however, the removal of the boresight-projected platform motion will only completely

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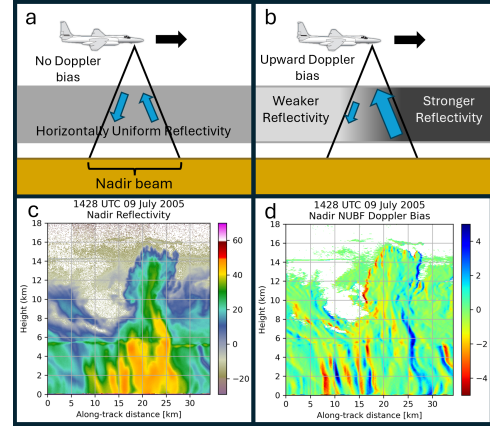


Fig. 1. Demonstration of NUBF effects on Doppler velocity including (a,b) a schematic representation of NUBF bias for a nadir-pointing radar and (c,d) an example with airborne measurements collected by a nadir-pointing radar during the TCSP field campaign [4][5] between 1428 UTC and 1431 UTC 9 July 2005. (c) depicts the reflectivity, in dBZ, while (d) depicts the NUBF Doppler velocity bias, in  $\text{m s}^{-1}$  with positive downward (away from radar).

remove the platform motion if the reflectivity field is uniform (Fig. 1a). When there is a reflectivity gradient across the radar beam, the radar-relative motions in the forward half and rearward half of the radar beam no longer cancel one another, resulting in an NUBF bias (Fig. 1b). The NUBF bias is proportional to the reflectivity gradient (Fig. 1c–d) and can produce features that can easily be interpreted as overturning circulations collocated with reflectivity maxima (Fig. 1d).

## II. NUBF DOPPLER BIAS EQUATION DERIVATION

Correcting NUBF biases in Doppler velocity requires relating the reflectivity gradient to the NUBF bias. For NUBF Doppler corrections of nominally nadir-pointing radars, the relevant reflectivity gradient is assumed to be entirely described by the horizontal reflectivity gradient along the direction of travel, hereafter referred to as the along-track direction. In order to correct NUBF Doppler biases for off-nadir pointing angles, we must account for the three-dimensional reflectivity gradients when deriving the NUBF bias equations.

As demonstrated in Sy *et al.* [2] and Walker McLinden *et al.* [3], the effect of NUBF on Doppler velocity for a moving radar platform manifests as an offset to the antenna boresight angle. To characterize the NUBF Doppler velocity bias for a moving radar with an arbitrary pointing angle, we need to derive an equation that captures this apparent offset to the antenna boresight angle as a function of the relative weighting of the backscattered signal on Doppler velocity in the presence of a linear gradient in log-space reflectivity. We accomplish

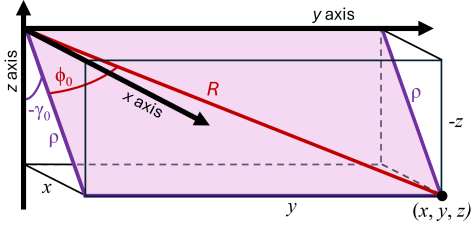


Fig. 2. Schematic of the spherical and cylindrical coordinate systems used here. The pink shaded area represents the  $\gamma$  plane.

this by deriving the NUBF bias equation using a spherical coordinate system (Fig. 2). In this coordinate system,  $\phi_0$  is the co-planar tilt of the antenna boresight within a plane that is co-planar with the platform motion vector and the antenna boresight vector, hereafter referred to as the  $\gamma$  plane,  $\gamma_0$  is the across-track tilt of the antenna boresight relative to nadir, and  $R$  is the range from the antenna.

We approximate the relative weighting of the backscattered signal on Doppler velocity by combining a Gaussian function, representing the antenna pattern, with the log-space reflectivity field, assumed to vary trilinearly in space. The Gaussian function for the two-way antenna illumination pattern is

$$G^2 = G_0^2 \exp\left(-\frac{8 \ln(2)}{\beta^2} \phi^2\right), \quad (1)$$

where  $\beta$  is the co-planar beamwidth in radians,  $G_0^2$  is the peak two-way antenna pattern, and  $\phi$  is the co-planar tilt angle to the target relative to the antenna boresight. Expanding the parametric form of a Gaussian equation and labeling  $\exp(-(\Delta\phi)^2/b)$  as  $c$  enables comparisons with Eq. 1:

$$f(x) = \exp\left(-\frac{(\phi - \Delta\phi)^2}{b}\right) = c \exp\left(-\frac{\phi^2}{b} + \frac{2\Delta\phi}{b}\phi\right), \quad (2)$$

where  $\Delta\phi$  corresponds to the NUBF-induced apparent offset to the co-planar boresight angle and  $b$  and  $c$  are constants with respect to  $\phi$ . Comparing Eqs. 1 and 2, we can conclude that, for a constant reflectivity field where the relative backscatter signal weighting on Doppler velocity is unity everywhere,  $b$  equals  $\frac{\beta^2}{8 \ln(2)}$ ,  $c$  equals  $G_0^2$ , and  $\Delta\phi$  equals zero.  $\Delta\phi=0$  indicates that there is no NUBF-induced apparent offset to boresight angle, matching our expectation that a constant reflectivity field will not produce an NUBF bias.

As previously mentioned, we can approximate the NUBF bias caused by a three-dimensional reflectivity gradient by taking the product of the Gaussian two-way antenna illumination pattern and the reflectivity field. As there is no component of platform motion orthogonal to the  $\gamma$  plane, the NUBF bias will only depend on the reflectivity gradient within the  $\gamma$  plane. As such, we can express the relevant portions of the trilinear reflectivity field with a bilinear decomposition consisting of the gradient parallel to the direction of motion (positive forward),  $\nabla_{\parallel}(dBZ_e)$ , and the co-planar gradient perpendicular to the motion (positive away from radar),  $\nabla_{\perp}(dBZ_e)$ . For a fixed  $\gamma_0$ , reflectivity can be expressed as

$$dBZ_e = dBZ_0 + y\nabla_{\parallel}(dBZ_e) + \rho\nabla_{\perp}(dBZ_e), \quad (3)$$

where  $dBZ_0$  is the value of  $dBZ_e$  at  $y = 0$  and  $\rho = 0$ ,  $y$  is the along-track distance from the antenna and  $\rho$  is the radial distance from the  $y$  axis (Fig. 2).

Recall,  $dBZ_e = 10 \log_{10}(Z_e)$ , where  $Z_e$  is the reflectivity expressed in linear space. Solving for  $Z_e$  and re-expressing using a natural logarithm, gives us  $Z_e = \exp\{0.1 \ln(10) dBZ_e\}$ . Substituting Eq. 3 into this equation we find

$$Z_e = Z_0 \exp\{0.1 \ln(10) [y\nabla_{\parallel}(dBZ_e) + \rho\nabla_{\perp}(dBZ_e)]\}, \quad (4)$$

where  $Z_0$  is the value of  $Z_e$  at  $y = 0$  and  $\rho = 0$ . We next re-express Eq. 4 in polar coordinates to match Eq. 1 by substituting  $y = R \sin(\phi + \phi_0)$  and  $\rho = R \cos(\phi + \phi_0)$ :

$$Z_e = Z_0 \exp\{0.1 R \ln(10) [\sin(\phi + \phi_0) \nabla_{\parallel}(dBZ_e) + \cos(\phi + \phi_0) \nabla_{\perp}(dBZ_e)]\}. \quad (5)$$

We can now produce an equation for the relative weighting of the backscattered signal on Doppler velocity by multiplying Eqs. 1 and 5. The equation for the apparent boresight offset,  $\Delta\phi$ , can then be obtained via comparison with Eq. 2. In order to match the form of Eq. 2, however, we must extract  $\phi$  from within the trigonometric functions in Eq. 5 via a pair of first-order Taylor series approximations centered about  $\phi_0$ :

$$\sin(\phi + \phi_0)|_{(\phi + \phi_0) \approx \phi_0} \approx \sin \phi_0 + \phi \cos \phi_0, \text{ and} \quad (6)$$

$$\cos(\phi + \phi_0)|_{(\phi + \phi_0) \approx \phi_0} \approx \cos \phi_0 - \phi \sin \phi_0. \quad (7)$$

Although this approximation introduces an error source to the correction, the relative magnitude of the error is always less than 0.4% for beamwidths less than  $10^\circ$  (i.e.,  $\phi < 5^\circ$ ).

Substituting Eqs. 6 and 7 into Eq. 5 gives us the expression for  $Z_e$  in polar coordinates,

$$Z_e = Z_0 \exp\{0.1 R \ln(10) [\phi(\cos \phi_0 \nabla_{\parallel}(dBZ) - \sin \phi_0 \nabla_{\perp}(dBZ_e)) + (\sin \phi_0 \nabla_{\parallel}(dBZ_e) + \cos \phi_0 \nabla_{\perp}(dBZ_e))]\}. \quad (8)$$

Multiplying by  $G^2$  (Eq. 1) gives an expression for the relative weighting of the backscatter signal on the Doppler velocity:

$$G^2 Z_e = k \exp\left\{-\frac{8 \ln(2)}{\beta^2} \phi^2 + \phi \cdot 0.1 R \ln(10) [\cos \phi_0 \nabla_{\parallel}(dBZ_e) - \sin \phi_0 \nabla_{\perp}(dBZ_e)]\right\}, \quad (9)$$

where  $k$  is a constant. Comparing Eqs. 1 and 9, we see that the effect of NUBF on Doppler velocity is to apply an offset to the Gaussian function in Eq. 1. Furthermore, comparing Eq. 9 to Eq. 2, we see that

$$b = \frac{\beta^2}{8 \ln(2)} \text{ and} \quad (10)$$

$$\frac{2\Delta\phi}{b} = 0.1 R \ln(10) (\cos \phi_0 \nabla_{\parallel}(dBZ) - \sin \phi_0 \nabla_{\perp}(dBZ_e)). \quad (11)$$

Solving Eq. 11 for  $\Delta\phi$ , the apparent shift in co-planar boresight angle introduced by the NUBF Doppler velocity bias, we find

$$\Delta\phi = \frac{\beta^2 R \ln(10)}{160 \ln(2)} (\cos \phi_0 \nabla_{\parallel}(dBZ_e) - \sin \phi_0 \nabla_{\perp}(dBZ_e)). \quad (12)$$

The apparent Doppler velocity,  $v_{ap}$  due to platform motion, including both NUBF effects and the projection of platform motion onto the antenna boresight vector, can be expressed as  $v_{ap} = -v_p \sin(\phi_0 + \Delta\phi)$ , where  $v_p$  is the horizontal platform motion. We can then isolate the NUBF Doppler bias itself by subtracting the platform motion projected onto the boresight:

$$v_N = -v_p (\sin(\phi_0 + \Delta\phi) - \sin\phi_0). \quad (13)$$

The benefit of using the parallel and co-planar perpendicular reflectivity gradients,  $\nabla_{\parallel}(dBZ_e)$  and  $\nabla_{\perp}(dBZ_e)$ , to estimate the NUBF bias is that these gradients can be computed directly from the parallel (i.e., along-track) and along-beam reflectivity gradients. This is accomplished using an approach that parallels that of a dual-Doppler wind calculation:

$$\nabla_{\perp}(dBZ_e) = \frac{\nabla_{Beam}(dBZ_e) - \nabla_{\parallel}(dBZ_e) \sin\phi_0}{\cos\phi_0}, \quad (14)$$

where  $\nabla_{Beam}(dBZ_e)$  is the along-beam gradient (positive away from radar). The parallel gradient in Eq. 14 can be computed from successive profiles at a given azimuth under the assumption that a given range gate has a locally constant height with respect to time. In this way, Eqs. 12, 13, and 14 can be used to estimate the NUBF Doppler bias correction for an antenna pointing in any direction, thereby enabling NUBF Doppler bias corrections for both fixed angle and scanning radars of any configuration for which the parallel (along-track) and along-beam reflectivity gradients can be computed.

### III. REAL DATA EXAMPLE

As a demonstration of the off-nadir NUBF bias correction and the impacts it can have on an analysis, we applied Eqs. 12, 13, and 14 to data collected by the EDOP (ER-2 Doppler Radar) radar [6] during a NASA Tropical Cloud Systems and Processes (TCSP) field campaign flight over Hurricane Dennis at approximately 1430 UTC 9 July 2005 [4][5]. EDOP is an X-band radar that flew aboard the NASA ER-2 at an altitude of approximately 20 km. EDOP had two antennas: a near nadir antenna and a forward-tilt antenna pointing  $\sim 33^\circ$  forward of nadir. The reflectivity and NUBF bias for data collected by the nadir antenna are shown in Fig. 1c–d while the reflectivity, uncorrected and corrected Doppler velocity, and NUBF bias for the data collected by the forward antenna are depicted in Fig. 3a–f. A dual-Doppler analysis was performed using the nadir and forward-tilt antenna data and the results are shown in Fig. 4, both with and without the NUBF Doppler velocity bias removed. For these calculations, we did not perform any additional smoothing beyond what is inherent in the data processing;  $\nabla_{\parallel}(dBZ_e)$  was computed from successive profiles from the forward antenna data.

This example demonstrates that the NUBF bias in Doppler velocity can produce a sufficient difference in the velocities to result in misleading interpretations of the Doppler radar observations. The magnitudes of the NUBF bias for both the nadir and forward-tilt antenna data frequently exceed  $2 \text{ m s}^{-1}$  and can create the appearance of vertical overturning circulations associated with horizontally-narrow reflectivity maxima. These apparent overturning circulations can easily

be mistaken for a legitimate meteorological feature. Likewise, the uncorrected forward-tilt antenna Doppler velocity (Fig. 3b) and the dual-Doppler horizontal winds (Fig. 4a) incorrectly suggest the presence of a horizontal wind dipole associated with the melting level, located near 6-km altitude. Particularly troubling, however, are the convective dynamics implied by the couplets of strong and weak horizontal winds in the lowest 4 km of the uncorrected observations (black rectangle in Fig. 4a). If interpreted as truth, these couplets imply the existence of shallow towers of convergent air near the surface. Given that these observations were collected in a hurricane, it is not unexpected to find regions of strong convergence at low levels. Contrary to this expectation, however, these towers of apparent convergence are almost entirely a result of the NUBF biases; correcting the horizontal wind observations removes almost all of these horizontal wind couplets (Fig. 4b).

In addition to the fixed antenna EDOP case, we also applied the corrections to data collected by the EXRAD (ER-2 X-band Radar) radar [7], as demonstrated in the supplemental material. Like EDOP, EXRAD is an X-band airborne radar frequently flown aboard the NASA ER-2. EXRAD has both a fixed nadir antenna and an antenna that scans conically about nadir with a  $30^\circ$  tilt. We found that the computed NUBF biases for the scanning antenna data were consistent with theoretical predictions based on the physical relationship between reflectivity gradients, antenna illumination patterns, platform motion, and Doppler velocity measurements.

### IV. NUBF BIAS SUSCEPTIBILITY OF A RADAR

Sy *et al.* [2] and Walker McLinden *et al.* [3] both defined an NUBF coefficient to characterize the typical susceptibility of a radar to NUBF Doppler velocity biases. This NUBF coefficient has units of  $\text{m s}^{-1} (\text{dB km}^{-1})^{-1}$ ; multiplying the NUBF coefficient by the expected reflectivity gradients gives an approximation of the expected NUBF Doppler velocity biases and enables an evaluation of the susceptibility of a radar to NUBF biases. We are able to produce an analogous trio of coefficients that independently describe the susceptibility of a radar to NUBF effects caused by across-track reflectivity gradients ( $\alpha_x$ ), along-track reflectivity gradients ( $\alpha_y$ ), and by vertical reflectivity gradients ( $\alpha_z$ ). To obtain these equations, we must first extract  $\Delta\phi$  from the sine function in Eq. 13 using the Taylor series approximation for  $\sin(\phi_0 + \Delta\phi) |_{(\phi_0 + \Delta\phi) \approx \phi_0}$  (per Eq. 6). Doing so results in  $v_N = -v_p \Delta\phi \cos\phi_0$ . Next, we must transform the parallel and co-planar perpendicular reflectivity gradients in Eq. 12 ( $\nabla_{\parallel}(dBZ_e)$  and  $\nabla_{\perp}(dBZ_e)$ ) into Cartesian aircraft coordinates ( $\nabla_x(dBZ_e)$ ,  $\nabla_y(dBZ_e)$ , and  $\nabla_z(dBZ_e)$ ) via the following transforms:

$$\nabla_{\parallel}(dBZ_e) = \nabla_y(dBZ_e) \text{ and} \quad (15)$$

$$\nabla_{\perp}(dBZ_e) = -\nabla_x(dBZ_e) \sin\gamma_0 - \nabla_z(dBZ_e) \cos\gamma_0, \quad (16)$$

where  $\gamma_0$  is the across-track angle (i.e., between nadir and  $\rho$  in Fig. 2). Because  $\gamma_0$  is referenced to nadir rather than zenith, care must be taken to ensure the correct quadrant is referenced in the calculations (e.g., via an  $\text{atan2}(-x, -z)$  function, common to many programming languages). Applying this

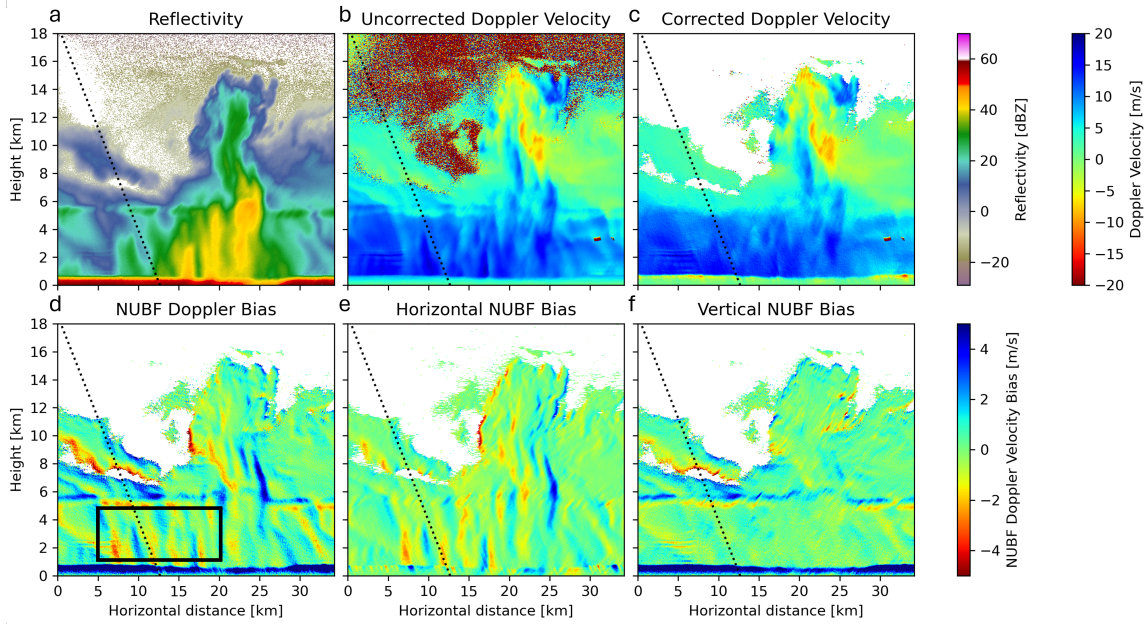


Fig. 3. Example NUBF Doppler velocity bias correction using EDOP forward-tilt antenna data from the TCSP field campaign collected between 1428 UTC and 1431 UTC 9 July 2005, including (a) reflectivity, Doppler velocity (b) without and (c) with the (d) NUBF bias correction. The NUBF bias contributions by the (e) horizontal and (f) vertical reflectivity gradients are also depicted. Positive velocity and bias values correspond to motion away from the radar. The black dotted line indicates the antenna boresight orientation. The mean (maximum) absolute NUBF bias in the black rectangle is  $0.84 \text{ m s}^{-1}$  ( $3.91 \text{ m s}^{-1}$ ).

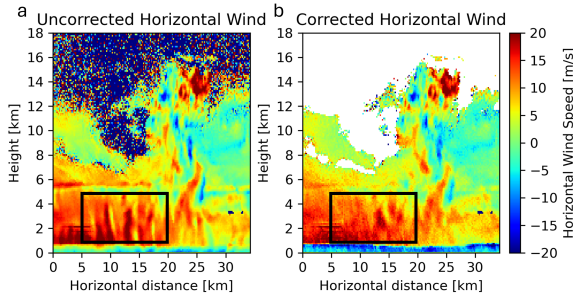


Fig. 4. Horizontal wind speeds determined via a dual Doppler analysis of the nadir and forward-tilt EDOP data (a) before and (b) after the NUBF bias correction. The data was collected between 1428 UTC and 1431 UTC 9 July 2005 as part of a TCSP field campaign flight into Hurricane Dennis (2005). Positive values indicate a wind blowing in the direction of increasing horizontal distance. The mean (maximum) absolute correction to horizontal wind within the black rectangle is  $1.91 \text{ m s}^{-1}$  ( $8.86 \text{ m s}^{-1}$ ).

transformation and substituting the results into the simplified equation for  $v_N$ , we get

$$v_N \approx -v_p \frac{\beta^2 R \ln(10)}{160 \ln(2)} \left( \sin \phi_0 \cos \phi_0 \sin \gamma_0 \nabla_x (dBZ_e) + \cos^2 \phi_0 \nabla_y (dBZ_e) + \sin \phi_0 \cos \phi_0 \cos \gamma_0 \nabla_z (dBZ_e) \right). \quad (17)$$

The NUBF coefficients ( $\alpha_x$ ,  $\alpha_y$ , and  $\alpha_z$ ) are obtained by setting the opposing gradients (e.g.,  $\nabla_x (dBZ_e)$  and  $\nabla_z (dBZ_e)$  for  $\alpha_y$ ) to zero and dividing through by the remaining gradient (e.g.,  $\nabla_y (dBZ_e)$  for  $\alpha_y$ ). Doing so gives

$$\alpha_x = -v_p \frac{\beta^2 R \ln(10)}{160 \ln(2)} \sin \phi_0 \cos \phi_0 \sin \gamma_0, \quad (18)$$

$$\alpha_y = -v_p \frac{\beta^2 R \ln(10)}{160 \ln(2)} \cos^2 \phi_0, \text{ and} \quad (19)$$

$$\alpha_z = -v_p \frac{\beta^2 R \ln(10)}{160 \ln(2)} \sin \phi_0 \cos \phi_0 \cos \gamma_0. \quad (20)$$

Table I provides examples of the NUBF coefficients for several airborne and spaceborne Doppler radars. The  $\alpha$  value ranges indicate the typical susceptibility of each radar to NUBF effects based on a target at 5 km altitude. When sampling tropical deep convection,  $10 \text{ dB km}^{-1}$  horizontal or vertical reflectivity gradients are not uncommon. While the vertical NUBF coefficients ( $\alpha_z$ ) tend to be smaller than the along-track NUBF coefficients ( $\alpha_y$ ), vertical gradients tend to be larger, especially near the melting layer bright band, where vertical gradients in excess of  $20 \text{ dB km}^{-1}$  are not uncommon.

## V. CONCLUSION

Nonuniform beam filling (NUBF) occurs when there is a gradient in reflectivity within a radar sample volume. For a radar mounted on a moving platform, NUBF will introduce a bias in Doppler velocity that is a function of the reflectivity gradient and platform velocity as well as the beamwidth, range, and boresight pointing angle. This paper provides an equation to estimate the NUBF Doppler velocity bias due to platform motion, ideally by combining Eqs. 12, 13, and 14, under the assumption of a trilinear reflectivity gradient for an arbitrary antenna pointing direction. In the special case of a nadir-pointing radar, the equation derived here simplifies to those derived in the literature (e.g., [2][3]). By allowing off-nadir boresight pointing angles, the equation, derived herein, enables the correction of any airborne (or spaceborne) radar for which along-track and along-beam reflectivity gradients

TABLE I

NUBF COEFFICIENTS FOR SEVERAL AIRBORNE AND SPACEBORNE DOPPLER RADARS USING APPROXIMATE VALUES OF PLATFORM SPEED, BEAMWIDTH, ALONG-TRACK TILT, AND TYPICAL RANGE TO A TARGET AT 5-KM ALTITUDE. RADAR DESCRIPTIONS CAN BE FOUND WITHIN THE CITED PAPERS.

| Comparable Radar<br>(Nominal Orientation) | Paper<br>Ref. | Speed<br>$v_p$ [m s <sup>-1</sup> ] | Beamwidth<br>$\beta$ [°] | Tilt Angles<br>$\phi_0, \gamma_0$ [°] | Range<br>$R$ [km] | $\alpha_x$<br>[m s <sup>-1</sup> ] | $\alpha_y$<br>(dB km <sup>-1</sup> ) <sup>-1</sup> | $\alpha_z$   |
|-------------------------------------------|---------------|-------------------------------------|--------------------------|---------------------------------------|-------------------|------------------------------------|----------------------------------------------------|--------------|
| CRS (nadir fixed)                         | [8]           | 200                                 | 0.45                     | 1*, 1*                                | 15                | 1E-6                               | 0.004                                              | 7E-5         |
| EDOP (nadir fixed)                        | [6]           | 200                                 | 3                        | 0.4*, 0.3*                            | 15                | 6E-6                               | 0.17                                               | 0.001        |
| EDOP (forward-tilt fixed)                 | [6]           | 200                                 | 3                        | 33*, 1*                               | 17.9              | 0.002                              | 0.14                                               | 0.09         |
| EXRAD (nadir fixed)                       | [7]           | 200                                 | 3.3                      | 1*, 0.5*                              | 15                | 3E-5                               | 0.21                                               | 0.004        |
| EXRAD (conical about nadir)               | [7]           | 200                                 | 3.3                      | 0 – 30, 0 – 30                        | 17.3              | 0 – 0.03                           | 0.18 – 0.24                                        | 0 – 0.10     |
| HIWRAP Ku (conical about nadir)           | [9]           | 200                                 | 2.9                      | 0 – 40, 0 – 40                        | 19.6              | 0 – 0.04                           | 0.12 – 0.21                                        | 0 – 0.10     |
| HIWRAP Ka (conical about nadir)           | [9]           | 200                                 | 1.2                      | 0 – 40, 0 – 40                        | 19.6              | 0 – 0.007                          | 0.02 – 0.04                                        | 0 – 0.02     |
| NOAA P-3 TDR (conical about track)        | [10]          | 170                                 | 2                        | 20, 95.7 – 180**                      | 3 – 30            | 0 – 0.09                           | 0.003 – 0.03                                       | 0.009 – 0.01 |
| EarthCARE CPR (nadir fixed)               | [2][11]       | 7600                                | 0.095                    | 0.09*, 0.003*                         | 395               | 1E-8                               | 0.17                                               | 0.0003       |
| WIVERN (conical about nadir)              | [12]          | 7600                                | 0.069                    | 0 – 38, 0 – 38                        | 644               | 0 – 0.03                           | 0.09 – 0.15                                        | 0 – 0.07     |

\*The typical tilts for fixed-angle radars were determined as the median absolute angle observed in a representative data file during level flight.

\*\*The TDR across-track tilts correspond to those required to produce the listed spread of range values.

can be estimated, regardless of whether the radar has a fixed angle or has scanning capabilities.

While the Taylor series approximation and assumption of a Gaussian antenna pattern are both sources of error in the NUBF bias calculations, we expect the largest source of error will be the reflectivity gradient estimate, particularly that of the parallel (i.e., along-track) component. Consideration must be given to the effects of sampling frequency, beamwidth, platform speed, and signal-to-noise ratio (SNR) when estimating the gradient. Larger beamwidths or smaller measurement SNR will require a larger gradient calculation window to ensure a sufficiently high SNR in the gradient estimate. Additionally, low sampling frequency with large platform motion can inhibit the ability to fully resolve reflectivity features, thereby negatively impacting any reflectivity gradient estimates.

This paper demonstrates the NUBF bias correction equation using real-world data collected in Hurricane Dennis during the TCSP field campaign. The NUBF biases produce a number of structures that could be conflated with actual meteorological signals. Of particular concern are the appearance of convergence structures in the lower troposphere that, were they real, would be a very interesting feature, but are, in fact, almost entirely an artifact of the NUBF Doppler velocity bias.

Finally, we define three NUBF coefficients that convey the susceptibility of a radar system to NUBF effects, similar to Walker McLinden *et al.* [3]. When multiplied by an expected horizontal or vertical reflectivity gradient in dBZ km<sup>-1</sup>, the typical magnitude of the NUBF Doppler velocity biases is obtained. While the NUBF biases can be estimated with the coefficients rather than using the NUBF bias equations (i.e., Eqs. 12, 13, and 14), the real strength of these coefficients lies in their ability to inform whether an NUBF bias correction is needed to meet specific application requirements in the presence of expected reflectivity gradients.

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