

Supplemental Material for: Helms, *et al.*, “A Nonuniform Beam Filling (NUBF) Doppler Velocity Bias Estimate for Airborne Radars with Arbitrary Pointing Angles” *IEEE Geoscience and Remote Sensing Letters*

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

Abstract—This document is a supplement to “A Nonuniform Beam Filling (NUBF) Doppler Velocity Bias Estimate for Airborne Radars with Arbitrary Pointing Angles” in *IEEE Geoscience and Remote Sensing Letters*. The supplement provides a demonstration of computing the NUBF Doppler velocity bias due to platform motion using a downward-pointing conically-scanning airborne Doppler radar.

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

I. NUBF BIAS CORRECTION OF SCANNING DATA

COMPUTING the non-uniform beamfilling (NUBF) Doppler bias due to platform motion for a scanning Doppler radar differs from the calculations for a fixed-antenna radar only in the steps needed to compute the reflectivity gradients. This supplement will demonstrate the application of the NUBF bias equation to data collected by the ER-2 X-band Radar (EXRAD)[1] scanning antenna. EXRAD is a conically-scanning airborne Doppler radar where the antenna scans about nadir at a 30° off-nadir tilt. The NASA ER-2 high altitude aircraft, on which EXRAD is typically mounted, flies at ~20 km altitude with an airspeed of ~200 m s⁻¹. Because the antenna completes a single scan every ~2.48 seconds, there is approximately 500 m of along-track distance between subsequent antenna boresight views at the same azimuth angle. For reference, the EXRAD data depicted here is thresholded at a signal-to-noise ratio equivalent to one standard deviation of the thermal noise (SNR≈0.1 for this configuration), following standard practice[2].

For this demonstration, we selected an isolated feature observed by the EXRAD scanning antenna at ~1613 UTC 15 January 2023 during the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS)[3] field campaign (Fig. 1a). Due to the interaction between radar viewing geometry and the antenna sidelobes, sidelobe surface returns show up in the reflectivity and Doppler velocity between ~20-km range and the surface (~23-km range) wherever the weather signal is not sufficiently strong to obscure it. Because the aircraft motion is removed from the Doppler velocity based on the antenna boresight viewing angle, these sidelobe surface returns will appear to have very

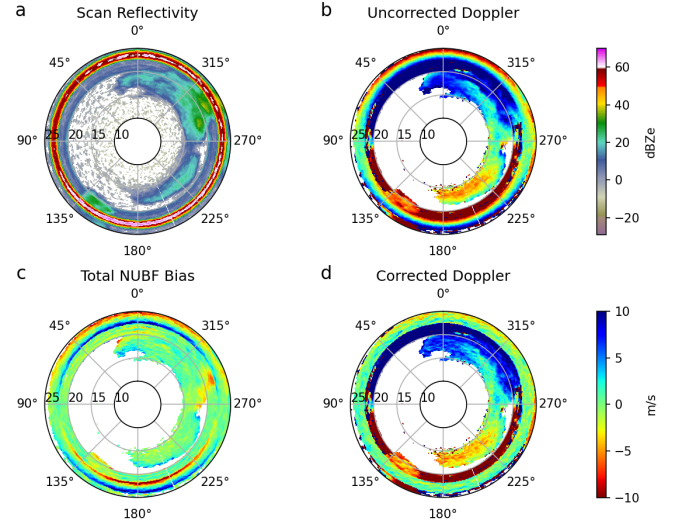


Fig. 1. Polar plots (azimuth [°] and range [km]) demonstrating the application of the NUBF bias correction to conically scanning EXRAD data collected at ~1613 UTC 15 January 2023 during the NASA IMPACTS field campaign[3], including (a) reflectivity [dBZ_e], (b) Doppler velocity [m s⁻¹] without the (c) NUBF correction [m s⁻¹], and (d) Doppler velocity [m s⁻¹] with the NUBF correction. Recall, EXRAD scans at an off-nadir angle of 30°.

strong Doppler velocity after the aircraft motion is removed (Fig. 1b).

Since EXRAD is not designed to ensure that profiles are produced at specific azimuths, we interpolate the scan data in time to a fixed set of azimuths. Specifically, we interpolate the data to 1° azimuth intervals (prior to interpolation, the azimuthal interval is typically near 1.1°). For each azimuth at each range gate, we estimate the along-track (i.e., parallel) reflectivity gradient as though it were a fixed antenna at that pointing angle using a three-point centered finite difference (Fig. 2a). For the purposes of this demonstration, we have made the simplifying assumption that the change in aircraft altitude is negligible over the ~7.5 seconds required for the antenna to complete three rotations, allowing us to treat the range gates as having a constant altitude within a given gradient calculation. The estimate for the co-planar perpendicular reflectivity gradient, $\nabla_{\perp}(\text{dBZ}_e)$, is computed from the parallel reflectivity gradient and the along-beam reflectivity gradient, which is also computed using a three-point centered finite difference, as per Eq. 14 in the main text. Using these

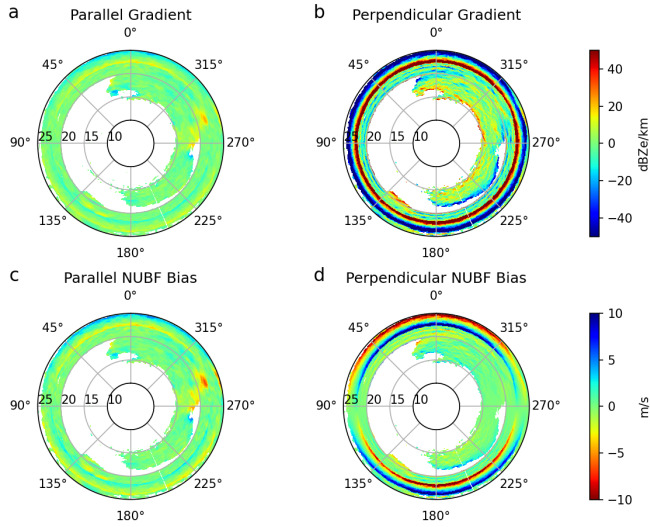


Fig. 2. As in Fig. 1, except plots are depicting (a) the parallel (i.e., along-track) and (b) co-planar perpendicular reflectivity gradients [dBZe km^{-1}] and (c) the parallel and (d) co-planar perpendicular components of the NUBF Doppler bias [m s^{-1}].

reflectivity gradients, we apply Eqs. 12 and 13 from the main text to estimate the NUBF Doppler bias (Fig. 1c), which is then removed from the uncorrected Doppler to produce a corrected Doppler (Fig. 1d).

The largest NUBF corrections (Fig. 1c) are associated with the strong co-planar perpendicular gradients produced by the surface return (all azimuths, $\sim 23\text{-km}$ range) and the parallel (i.e., along-track) reflectivity gradient present at the edges of the reflectivity feature ($\sim 260\text{--}290^\circ$ azimuth, $\sim 17\text{--}22\text{-km}$ range). The effectiveness of the correction can best be seen in the surface return. Under ideal conditions with ideal targets and perfectly accurate knowledge of viewing geometries, the entire surface return should have a Doppler velocity close to 0 m s^{-1} . Given that the actual observations will not have such an ideal set up, the NUBF correction is remarkably successful at achieving a near 0 m s^{-1} Doppler velocity within the surface return.

Evaluating the effectiveness of the NUBF correction for the non-surface reflectivity feature is more complicated. For this, we must understand how the viewing geometry, boresight aircraft motion correction, and radar-relative particle motions combine to produce a Doppler velocity measurement, schematic representations of which are depicted in Fig. 3. For a positive parallel reflectivity gradient (i.e., increasing reflectivity in the along-track direction) with stationary particles (in an Earth-relative sense), radar-relative motion in the forward half of the beam will be weighted more heavily in the resulting Doppler velocity than the rearward half of the beam. Because the boresight aircraft motion removal will always result in the forward half of the beam having an apparent Doppler motion towards the radar, the NUBF bias in the presence of a positive parallel reflectivity gradient will be towards the radar regardless of whether the tilt of the antenna is forward or rearward (Fig. 3a,b). In contrast to this, the sign of the co-planar perpendicular component of the NUBF

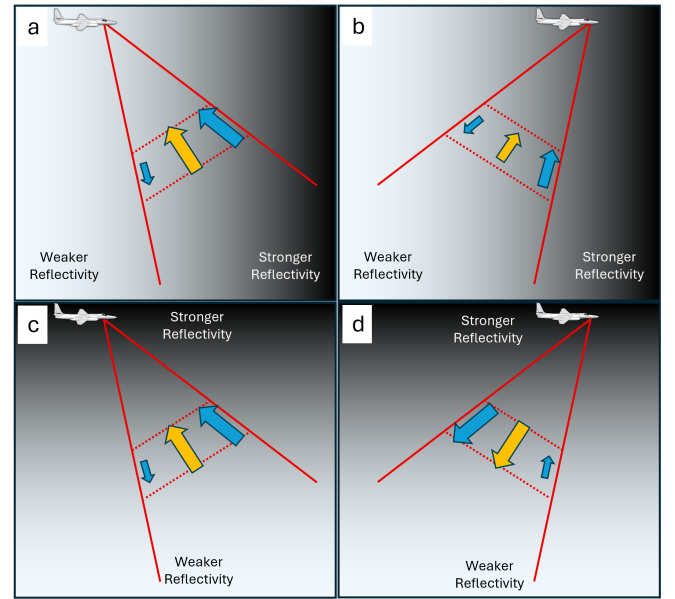


Fig. 3. Schematic representation of interaction between reflectivity gradient (shading), scanning beam geometry (red, exaggerated), reflectivity-weighted radar-relative particle motion after boresight aircraft motion correction (blue arrows), and resulting NUBF bias (orange arrows) for (a, b) positive parallel gradients and (c, d) negative perpendicular gradients with (a, c) positive and (b, d) negative co-planar tilt angles. Motion away from the radar indicates positive values. Particles are stationary in an Earth-relative framework.

bias will change depending on if the antenna co-planar tilt is positive or negative (Fig. 3c,d). Close examination of the signs of the reflectivity gradients and NUBF components (Fig. 2) reveals that the signs of the NUBF components and the related gradients match the expectations, as conceptualized in the schematic representations (Fig. 3).

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