

Relationship between Horizontal Wind Velocity and Normalized Surface Cross Section Using Data from the HIWRAP Dual-Frequency Airborne Radar

R. MENE GHINI,^a L. LIAO,^b AND G. M. HEYMSFIELD^a

^a NASA Goddard Space Flight Center, Greenbelt, Maryland

^b Goddard Earth Science Technology and Research, Morgan State University, Baltimore, Maryland

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ABSTRACT: The High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) dual-frequency conically scanning airborne radar provides estimates of the range-profiled mean Doppler and backscattered power from the precipitation and surface. A velocity–azimuth display analysis yields near-surface estimates of the mean horizontal wind vector v_h in cases in which precipitation is present throughout the scan. From the surface return, the normalized radar cross section (NRCS) is obtained, which, by a method previously described, can be corrected for path attenuation. Comparisons between v_h and the attenuation-corrected NRCS are used to derive transfer functions that provide estimates of the wind vector from the NRCS data under both rain and rain-free conditions. A reasonably robust transfer function is found by using the mean NRCS ($\langle \text{NRCS} \rangle$) over the scan along with a filtering of the data based on a Fourier series analysis of v_h and the NRCS. The approach gives good correlation coefficients between v_h and $\langle \text{NRCS} \rangle$ at Ku band at incidence angles of 30° and 40°. The correlation degrades if the Ka-band data are used rather than the Ku band.

KEYWORDS: Algorithms; Radars/Radar observations; Remote sensing; Weather radar signal processing

1. Introduction

A number of airborne and satellite-based instruments and techniques have been used to estimate winds over ocean. Instruments include lidar as well as passive and active microwave and millimeter-wave sensors (e.g., Hu et al. 2008; Bentamy et al. 2019; Horstmann et al. 2003; Ricciardulli and Wentz 2015). For frequencies at X band (10 GHz) and above, attenuation by precipitation can limit the accuracy of the wind estimate (Weissman et al. 2012). Even at lower frequencies, the effects of downdrafts and modifications to the surface scattering properties caused by raindrop impacts can affect the retrieval (Balasubramaniam and Ruf 2020; Contreras and Plant 2006). The study presented here is focused on data from a dual-frequency, airborne Doppler radar where attenuation by precipitation can be a significant source of error.

The intent of the study is to investigate the relationship in rain between the mean Doppler radial velocity measured just above the surface and the normalized surface cross section just below. Obtaining a robust relationship in rain between the mean horizontal wind vector and some characteristic of the surface scatter allows an extension of this relationship to rain-free areas so that wind vector estimates can be retrieved under all-weather conditions from the surface scattering characteristics alone. While this is the ultimate goal of the work, the focus of this paper is to investigate relationship between the horizontal wind speed v_h and normalized radar cross section

(NRCS) as a function of frequency (Ku and Ka band) and incidence angle (30° and 40°) in the presence of rain.

Since it is the intrinsic value of the NRCS that is of interest and not the measured value, it is necessary to first correct the NRCS for path attenuation. Several methods have been investigated (Draper and Long 2004a,b; Stiles et al. 2010; Meneghini et al. 2019). Because we use the dual-frequency approach described in Meneghini et al. (2019), this method will only briefly be described.

Characteristics of the conically scanning dual-frequency High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) radar are given in Table 1 (Helms et al. 2020; Li et al. 2016; Tian et al. 2015; Guimond et al. 2014, 2020). Because the instrument provides backscattered power measurements and Doppler radial velocity at two frequencies (Ku and Ka band) and two incidence angles simultaneously, it permits an examination of the Doppler velocity and NRCS data in close proximity. To simplify the analysis, we use a velocity–azimuth display (VAD) approach for the Doppler data to retrieve horizontal and vertical wind speeds averaged over a conical scan. A similar Fourier analysis is applied to the NRCS data. Results from the Fourier analysis allow a filtering of the data that amounts to choosing scans in which the Doppler velocity over the scan is well represented by a one-period sinusoid, with offset, and in which the NRCS data are accurately represented by terms up to and including a two-period sinusoid. With this filtering, we examine the correspondence between the horizontal wind vector, derived from the Doppler data, on one hand and the mean (scan-averaged), attenuation-corrected NRCS, $\langle \text{NRCS} \rangle$, on the other. With two incidence angles and two frequencies, four sets of results are derived that link v_h and $\langle \text{NRCS} \rangle$. Correlation between the two is higher at Ku band than at Ka band. Despite this, test cases show that the Ka-band estimates obtained from the NRCS

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Corresponding author: Robert Meneghini, robert.meneghini-1@nasa.gov

TABLE 1. HIWRAP system parameters/specifications.

	Inner beam		Outer beam	
Frequency (GHz)	13.91	35.56	13.47	33.72
Transmit peak power (W)	80	40	80	40
Antenna gain (dBi)	35.4	42.2	35.2	42.6
Azimuth 3-dB beamwidth (°)	2.9	1.2	3.1	1.3
Elevation 3-dB beamwidth (°)	3.0	1.2	2.9	1.2
Incidence angle from nadir (°)	30.0		39.6	
Polarization	H		V	
Antenna sidelobe (dB)	<−26.4	−27.2	<−23.2	−26.6
PRF (Hz)	4464/3571 dual PRF			
Pulse width (μs)	20 (chirp), 2 (pulse)			
Receive bandwidth (MHz)	2			
Chirp bandwidth (MHz)	2			
Dynamic range (dB)	> 65			
Min detectable reflectivity (dBZe; 150-m range resolution; 10-km range; 20-μs/1-MHz chirp; 16-RPM scanning rate)	7.8	1.5	7.8	1.5
Doppler velocity (m s ^{−1})	~47 (Ka) or ~98 (Ku); accuracy ~1.0 m s ^{−1}			
Scanning	Conical; ~16 RPM			

often give reasonable estimates of wind speed as compared with those derived from the Doppler data.

Section 2 provides a description of the attenuation correction procedure. Section 3 describes Fourier series analyses of the Doppler and NRCS data that are used to estimate the Doppler-derived wind speed and to filter the data. Section 4 presents sample Doppler and NRCS waveforms and the resultant v_h –NRCS transfer functions. The results are summarized by estimates of v_h as determined from the Doppler and the NRCS for several flight segments. A discussion and summary are given in section 5.

2. Path attenuation corrections

The path attenuation corrections to the measured NRCS at Ku and Ka band— $\sigma^0(\text{Ku})$ and $\sigma^0(\text{Ka})$ —rely on the fact that, over ocean and under rain-free conditions, these quantities are highly correlated (Meneghini et al. 2019). Scatterplots in the $\sigma^0(\text{Ku})$ – $\sigma^0(\text{Ka})$ plane under rain-free conditions show that the data tend to be concentrated along a line, with a slope close to unity, with excursions along this line determined primarily by the wind vector. In the presence of rain, the NRCS values migrate downward from the line toward lower NRCS values. Since the attenuation at Ka band tends to be about 6 times larger than that at Ku band, the trajectories tend to be displaced from the rain-free regression line along lines with approximately this slope.

Given a set of data that contains a large number of fields of view within and outside of the precipitation, separate linear regression fits are made to the rain and rain-free data in the $\sigma^0(\text{Ku})$ – $\sigma^0(\text{Ka})$ plane. Labeling the regression slopes through the rain-free and raining data as s_{NR} and s_R , respectively, then the correction algorithm consists simply of translating each data point [$\sigma_m^0(\text{Ku})$, $\sigma_m^0(\text{Ka})$], measured in rain, along the slope s_R until it intersects the rain-free regression line. This gives the attenuation-corrected values where the magnitude of the changes along the y axis [$\sigma^0(\text{Ka})$] and x axis [$\sigma^0(\text{Ku})$] are equal to the path attenuations at Ka and Ku band, respectively.

Letting α and s_{NR} be the intercept and slope, respectively, of the regression line for the rain-free data (NR) and p and s_R be the intercept and slope of the regression line for the NRCS data in the presence of rain, then the attenuation-corrected values are given by

$$\sigma^0(\text{Ka}) = \frac{s_R \alpha - s_{\text{NR}} \gamma}{s_R - s_{\text{NR}}} \quad \text{and} \quad (1)$$

$$\sigma^0(\text{Ku}) = \frac{\alpha - \gamma}{s_R - s_{\text{NR}}}, \quad (2)$$

where $\gamma = \sigma_m^0(\text{Ka}) - s_R \sigma_m^0(\text{Ku})$.

In the expression for γ , the subscript “ m ” denotes the measured value of the NRCS, before attenuation correction. Note that all of the NRCS quantities in the above equations are in decibels. Estimates of the path attenuations A (in decibels) are obtained by subtracting σ_m^0 from the expressions above so that $A(\text{Ka}) = \sigma^0(\text{Ka}) - \sigma_m^0(\text{Ka})$ and $A(\text{Ku}) = \sigma^0(\text{Ku}) - \sigma_m^0(\text{Ku})$.

Shown in Fig. 1 are two-dimensional probability density functions (pdf) of $\sigma^0(\text{Ka})$ and $\sigma^0(\text{Ku})$ in the absence (left) and presence of rain (center) for an incidence angle of 30°. These data were acquired by the HIWRAP airborne radar off the east coast of Florida on 1 September 2016 during the NOAA Sensing Hazards with Operational Unmanned Technology field campaign (SHOUT-2016; <https://uas.noaa.gov/Program/projects/shout>). The attenuation-corrected σ^0 are shown in the right-hand panel. The attenuation correction algorithm translates the measured data point along the rain regression line of slope s_R , in this case $s_R = 6.42$, until the point intersects the rain-free regression line.

Errors in the method include the fact that the $A(\text{Ka})/A(\text{Ku})$ ratio is not constant but a function of the precipitation particle size distributions along the path (Meneghini et al. 2012). Raindrop impacts on the surface, creating stalks and ring waves, modify the NRCS and degrade its dependence on wind speed (Bliven and Giovanangeli 1993; Bliven et al. 1997; Contreras et al. 2003; Contreras and Plant 2006). Positive biases are caused by contributions to the backscattered power

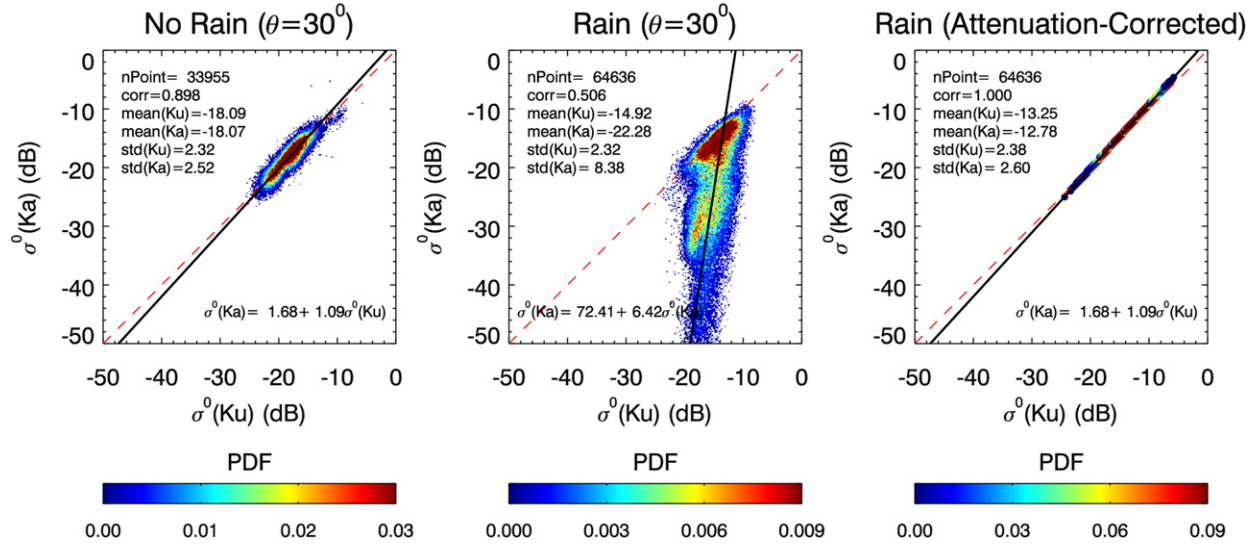


FIG. 1. (left) The 2D pdf of $\sigma^0(\text{Ka})$ and $\sigma^0(\text{Ku})$ under rain-free conditions for a flight conducted on 1 Sep 2016. (center) A similar 2D pdf but in the presence of rain, where rain is considered present if dBZ > 10 dB over 20 range gates. (right) The results of the 2D pdf after attenuation correction where the data are aligned along the rain-free regression line.

from precipitation near the surface (Stiles and Yueh 2002; Tournadre and Quilfen 2003; Weissman and Bourassa 2008; Draper and Long 2004a,b); for HIWRAP, this effect is generally small but can be significant at the higher incidence angle and higher frequency when the rain rates and attenuations are large. An error more specific to this particular method is the dependence of the slope on the judgement as to what constitutes a rain or rain-free measurement, which, in turn, depends on the minimum detectable signal. For flights for which the number of light rain rates is large, the slope is affected by changes in the wind vector [along which the variation in the $\sigma^0(\text{Ku})$ – $\sigma^0(\text{Ka})$ plane follows a slope of ~ 1], which decreases the slope s_R and increases the attenuation-corrected σ^0 values. Determining the slope through the rain data after filtering out the light rain rates can mitigate this error.

3. Relevant equations for the Doppler

A simple picture of the measurement geometry is shown in Fig. 2. The aircraft is assumed to fly along the positive x axis. We assume a right-handed coordinate system with z pointing up; θ is the polar angle measured with respect to nadir, and ϕ is the azimuthal angle measured relative to the x axis. Positive radial Doppler velocity V_D is assumed to be away from the radar so that

$$V_D = \bar{v} \cdot \hat{\mathbf{r}} = v_x \cos\phi \sin\theta + v_y \sin\phi \sin\theta - v_z \cos\theta, \quad (3)$$

where $\bar{v}$ is the reflectivity-weighted mean velocity of the hydrometeors in the radar resolution volume and $\hat{\mathbf{r}}$ is a unit vector directed along the center of the main lobe of the radar antenna. Assuming that the horizontal wind vector v_h makes an angle β with respect to the x axis, then $v_x = v_h \cos\beta$ and $v_y = v_h \sin\beta$. Substituting these expressions into (3) and using the fact that $\cos(\phi - \beta) = \cos\phi \cos\beta + \sin\phi \sin\beta$, then

$$V_D = \bar{v} \cdot \hat{\mathbf{r}} = v_h \cos(\phi - \beta) \sin\theta - v_z \cos\theta. \quad (4)$$

Equation (4) suggests a simple way to estimate v_h if v_h and v_z are constant over the scan (~ 18.5 km at 30° and ~ 25 km at 40° at the surface). Integrating each term of (4) over a full scan ($-\pi, \pi$) and noting that the integral of the first term on the right side of (4) is zero, since v_h is assumed constant, then

$$v_z \cos\theta = -(2\pi)^{-1} \left[\int_{-\pi}^{\pi} V_D(\phi) d\phi \right]. \quad (5)$$

Substituting this back into (4) and evaluating the expression at $\phi = \beta$ gives an estimate of v_h :

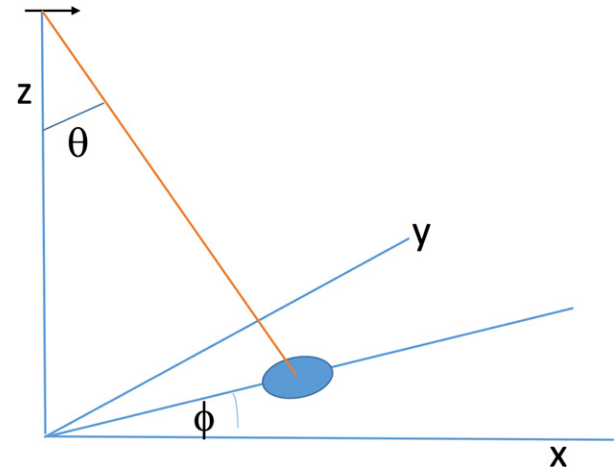


FIG. 2. Simplified depiction of the measurement geometry in which a right-handed coordinate system is used. The aircraft is assumed to travel along the x axis.

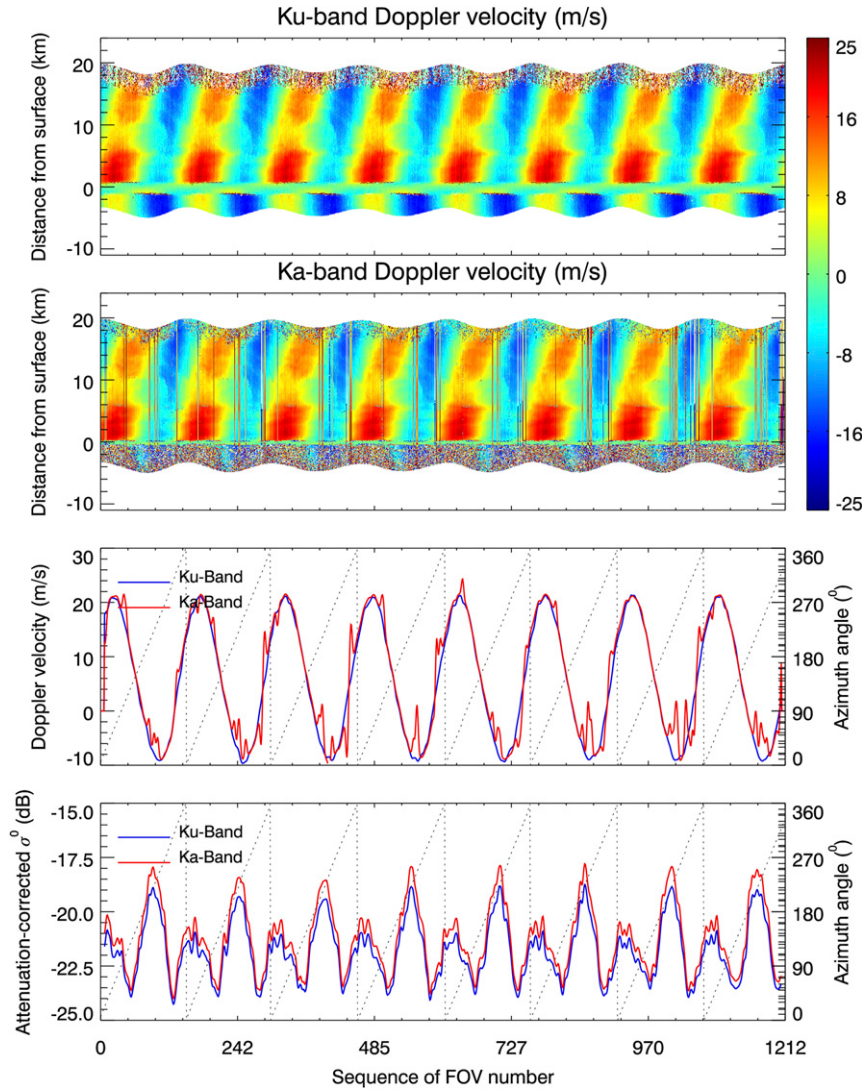


FIG. 3. The Doppler data at (top) Ku and (top middle) Ka band over approximately eight scans of data at an incidence angle of 40° . Also shown are the Ku- and Ka-band (bottom middle) Doppler velocity (m s^{-1}) measured just above the surface and (bottom) the attenuation-corrected NRCS derived from the surface returns just below. The sawtooth waveform (dashed lines) in the two lower panels represents the azimuthal angle (given on the right-hand ordinate) measured with respect to the flight direction (x axis).

$$v_h = \frac{V_D(\phi = \beta) - (2\pi)^{-1} \int_{-\pi}^{\pi} V_D(\phi) d\phi}{\sin\theta}. \quad (6)$$

A second estimate of v_h is given below [in (12)]. The two estimates have been found to be in good agreement.

When the wind field is not strictly linear and uniform over the swath, we follow [Browning and Wexler \(1968\)](#) and [Tian et al. \(2015\)](#) with a slight modification. These authors use a Taylor expansion of v_x and v_y relative to the center of the swath but do not expand v_z in a similar way. However, for the HIWRAP radar geometry, it seems that an expansion in v_z should be included as well. This has the effect of modifying the coefficients of the $\sin\phi$ and $\cos\phi$ terms. Under the

approximations that are used, the results are unaffected. It does show, however, the approximations that are needed in making the simplification.

Expanding v_x , v_y and v_z in a Taylor's series about the center of the swath $(x_0, y_0, 0)$, we have

$$\begin{aligned} v_x &= v_{x0} + \left(\frac{\partial v_x}{\partial x}\right)(x - x_0) + \left(\frac{\partial v_x}{\partial y}\right)(y - y_0) \\ v_y &= v_{y0} + \left(\frac{\partial v_y}{\partial x}\right)(x - x_0) + \left(\frac{\partial v_y}{\partial y}\right)(y - y_0) \\ v_z &= v_{z0} + \left(\frac{\partial v_z}{\partial x}\right)(x - x_0) + \left(\frac{\partial v_z}{\partial y}\right)(y - y_0). \end{aligned} \quad (7)$$

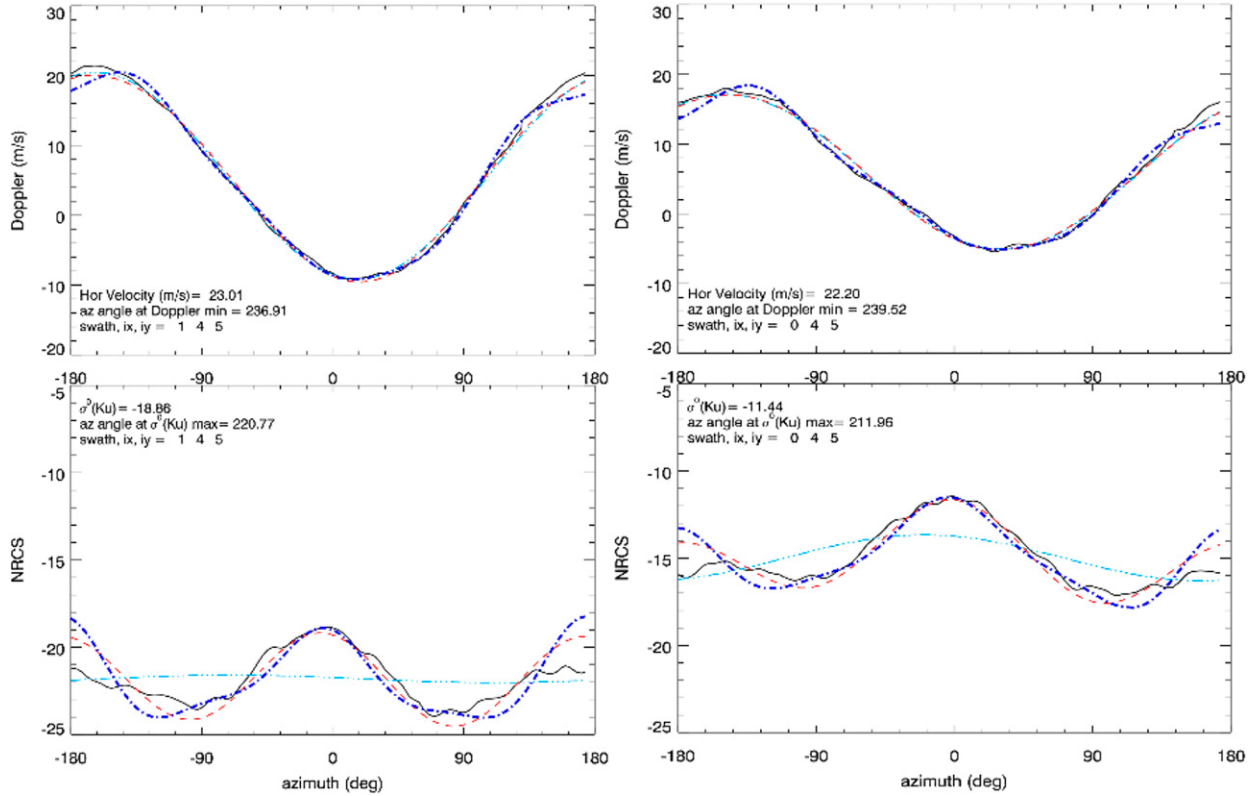


FIG. 4. (top) Ku-band Doppler and (bottom) corresponding $\sigma^0(\text{Ku})$ at (left) 40° and (right) 30° for one of the scans shown in Fig. 3. The measured Doppler and the attenuation-corrected $\sigma^0(\text{Ku})$ are given by the black lines; light-blue lines are FS(1), red lines are FS(2), and dark-blue lines are FS(4) (see the text).

Note that $(x - x_0) = r \cos \phi \sin \theta$ and $(y - y_0) = r \sin \phi \sin \theta$, where r is the distance from the radar to the center of a field of view just above the surface. Using the identities $\cos^2 \phi = 0.5[1 + \cos 2\phi]$, $\sin^2 \phi = 0.5[1 - \cos 2\phi]$, and $\cos \phi \sin \phi = 0.5 \sin 2\phi$ and substituting the relations given by (7) into (3), we find that V_D can be written in the form of a Fourier series up to order 2ϕ :

$$V_D = \frac{a_0}{2} + a_1 \cos \phi + b_1 \sin \phi + a_2 \cos 2\phi + b_2 \sin 2\phi, \quad (8)$$

where

$$\begin{aligned} \frac{a_0}{2} &= -v_{z0} \cos \theta + 0.5r \sin^2 \theta \operatorname{div}(\mathbf{v}_h) \\ a_1 &= -v_{x0} \sin \theta - \left(\frac{\partial v_z}{\partial x} \right) r \sin \theta \cos \theta \\ b_1 &= -v_{y0} \sin \theta - \left(\frac{\partial v_z}{\partial y} \right) r \sin \theta \cos \theta \\ a_2 &= 0.5r \sin^2 \theta \left(\frac{\partial v_x}{\partial x} - \frac{\partial v_y}{\partial y} \right) \\ b_2 &= 0.5r \sin^2 \theta \left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right), \end{aligned} \quad (9)$$

and

$$\operatorname{div}(\mathbf{v}_h) = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y}. \quad (10)$$

The coefficients are given by

$$\begin{aligned} a_n &= \frac{1}{\pi} \int_{-\pi}^{\pi} V_D \cos(n\phi) d\phi \quad \text{and} \\ b_n &= \frac{1}{\pi} \int_{-\pi}^{\pi} V_D \sin(n\phi) d\phi \end{aligned} \quad (11)$$

for $n = 1$ and $n = 2$. Note that a_0 is given by the above formula with $n = 0$, which reduces to an integral of V_D over the full scan divided by π so that the mean value of V_D is given by $a_0/2$.

From (9) it can be seen that if we ignore terms that depend on the partial derivatives of v_z with respect to x or y then

$$v_h = \frac{(a_1^2 + b_1^2)^{0.5}}{\sin \theta}. \quad (12)$$

This provides an alternative estimate to (6) for the horizontal wind speed. It is also the formula used for the results throughout the paper.

Before showing results, it is worth mentioning several features of the above equations. Tian et al. (2015) include an additional term that accounts for the antenna scanning that affects the Doppler along the direction of aircraft motion. They argue that

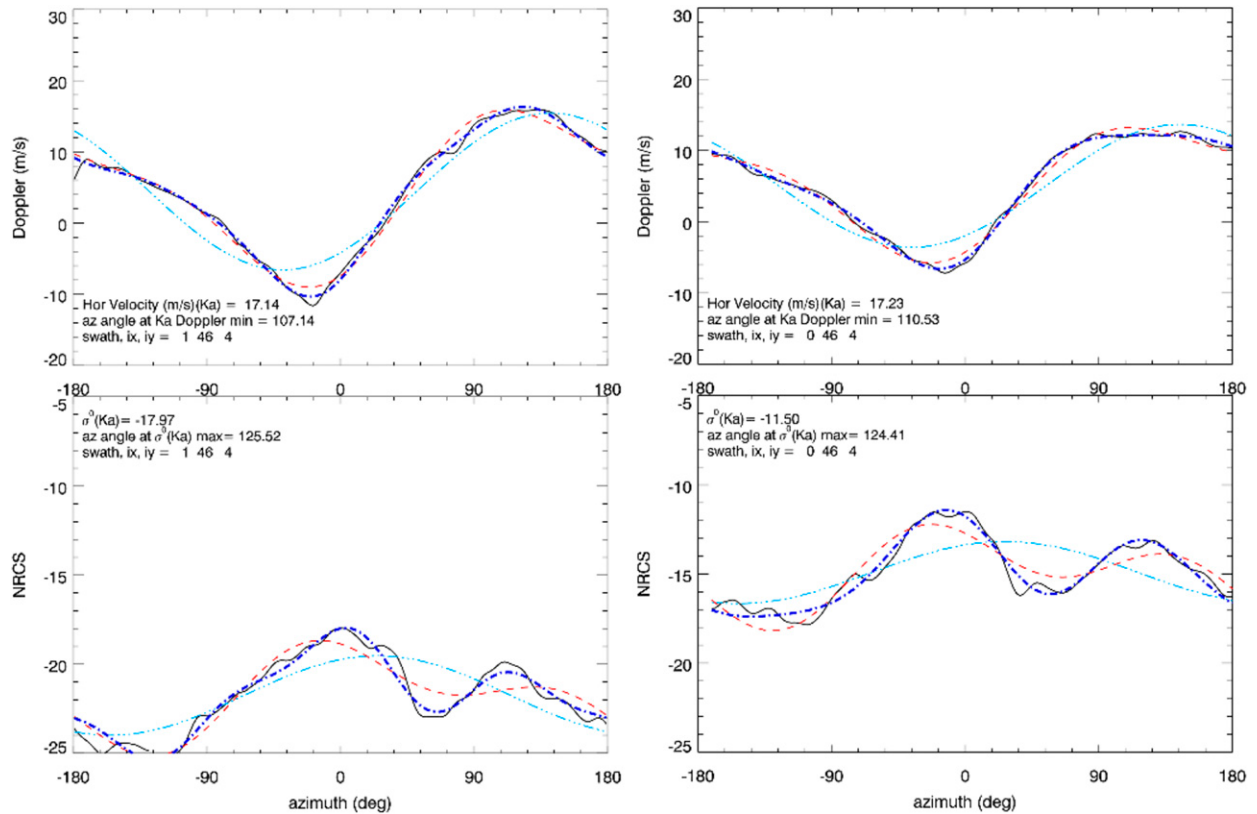


FIG. 5. (top) Doppler and (bottom) NRCS at Ka band over one antenna scan for incidence angles of (left) 40° and (right) 30°. Light-blue, red, and dark-blue curves are the Fourier series representations of the waveforms for FS(1), FS(2) and FS(4). Measured Ka-band Doppler and attenuation-corrected σ^0 are given by the black lines.

the deviation from circular to helical scan is small relative to the scan diameter and that terms involving the antenna angular motion can be neglected. We have followed this assumption. Also, since the Doppler data have been corrected for the aircraft motion, this is not included in the equations.

Apart from the horizontal wind divergence term shown above, Browning and Wexler (1968) identify the partial derivatives that appear in the expression for a_2 as the stretching deformation and the partials that appear in b_2 as the shearing deformation.

The HIWRAP instrument was designed so that the 30° incidence channel is horizontally polarized (transmit and receive) while the 40° incidence channel is vertically polarized so that, to prevent ambiguity, the designations (hh or vv) should be used whenever estimates from both channels are used. Inspection of (9) shows that v_z and $\text{div}(\mathbf{v}_h)$ can be evaluated in terms of the Fourier coefficients obtained from data taken at the two incidence angles. For example, if we write a_0 of (9) explicitly as a function of the polar angle θ , then equations for $a_{0,hh}(\theta_1)$ and $a_{0,vv}(\theta_2)$, where $\theta_1 = 30^\circ$ and $\theta_2 = 40^\circ$, allow us to solve for v_{z0} and $\text{div}(\mathbf{v}_h)$. Evaluating the various trigonometric functions that enter into the equations, we find

$$v_{z0} = 1.17 \left[\frac{a_{0,vv}(\theta_2)}{2} \right] - 2.19 \left[\frac{a_{0,hh}(\theta_1)}{2} \right] \quad \text{and} \quad (13)$$

$$\nabla \cdot \mathbf{v}_h = H^{-1} \left\{ 7.04 \left[\frac{a_{0,vv}(\theta_2)}{2} \right] - 6.23 \left[\frac{a_{0,hh}(\theta_1)}{2} \right] \right\}. \quad (14)$$

Examination of the other Fourier coefficients in (9)—that is, a_1 , b_1 , a_2 , and b_2 —shows that it is not possible to solve for the unknowns on the right-hand side using data at 30° and 40°. For example, we cannot obtain v_{x0} and $\partial v_z / \partial x$ by solving the equations for $a_{1,hh}(30)$ and $a_{1,vv}(40)$ because the equations are linearly dependent with a determinant equal to zero.

The VAD approach just described uses Doppler radial velocities in cases where precipitation is present just above the surface for all or most of the conical scan. In the results shown in the next sections, (12)–(14) along with a Fourier series analysis of the NRCS are used to relate the attenuation-corrected NRCS to the horizontal velocity obtained from the VAD analysis.

4. Results

a. Analysis of individual waveforms

Doppler data at 40° over a sequence of about eight antenna scans (an approximately 5 km flight segment) during the 1 September 2016 flight are shown in Fig. 3 where the top panel and the panel second from the top show the Doppler data at Ku and Ka band, respectively. The third panel from the top shows

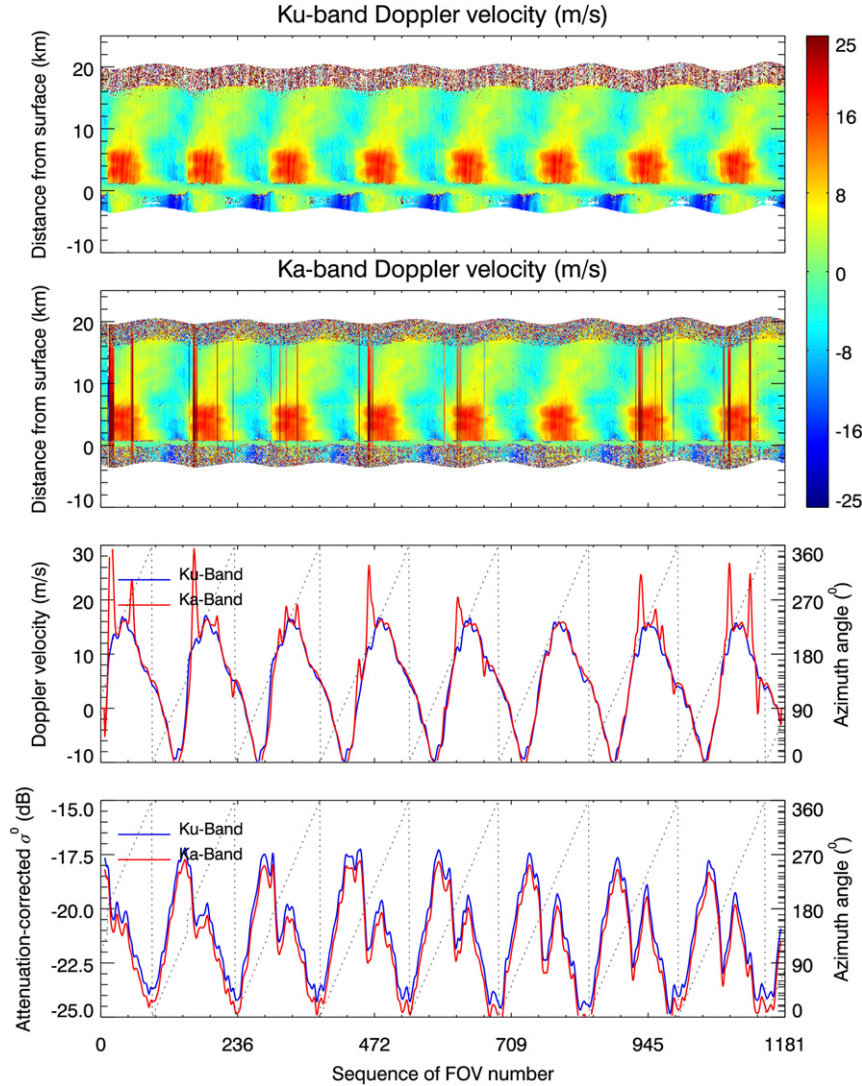


FIG. 6. As in Fig. 3, at an incidence angle of 40° for data taken on 1 Sep 2016 for a different eight-scan sequence. Note that Ka-band data from the sixth scan are shown on the left in Fig. 5.

the Doppler at Ku and Ka band just above the surface; note that the sawtooth waveform represents the scan angle in degrees where 0° represents the position where the antenna beam is directed along the flight line (positive x axis). Displayed in the bottom panel are the attenuation-corrected σ^0 at the two frequencies.

The Doppler and NRCS for one of the scans shown in Fig. 3 are represented by the black lines in Fig. 4 for both the 40° (left) and 30° (right) cases. The light-blue, red, and dark-blue lines are derived from the Fourier series representations using different numbers of terms. We use the following notation

$$\text{FS}(n) = \frac{a_0}{2} + \sum_{j=1}^n (a_j \cos j\phi + b_j \sin j\phi) \quad (15)$$

so that, for example, FS(2) represents the Fourier series representation of a function up to and including the $\cos(2\phi)$ and

$\sin(2\phi)$ terms. This two-period azimuthal dependence is a well-known feature of the NRCS over the ocean (Jones et al. 1977, 1982). In Fig. 4, the light blue line represents the FS(1) (sinusoid of period 1 with offset) approximation for the Doppler(Ku) (top) and σ^0 (Ku) (bottom). It can be seen in these examples that the FS(1) approximation provides an accurate representation of the measured Doppler data (black curve) whereas FS(2) (red line) is needed to give a good approximation to the measured σ^0 (Ku). We can quantify the goodness of the representation by computing a residual error, defined by

$$\text{RS}(n) = \left\{ \frac{\sum_{i=1}^N [y_i - \text{FS}_i(n)]^2}{\sum_{i=1}^N y_i^2} \right\}^{1/2}, \quad (16)$$

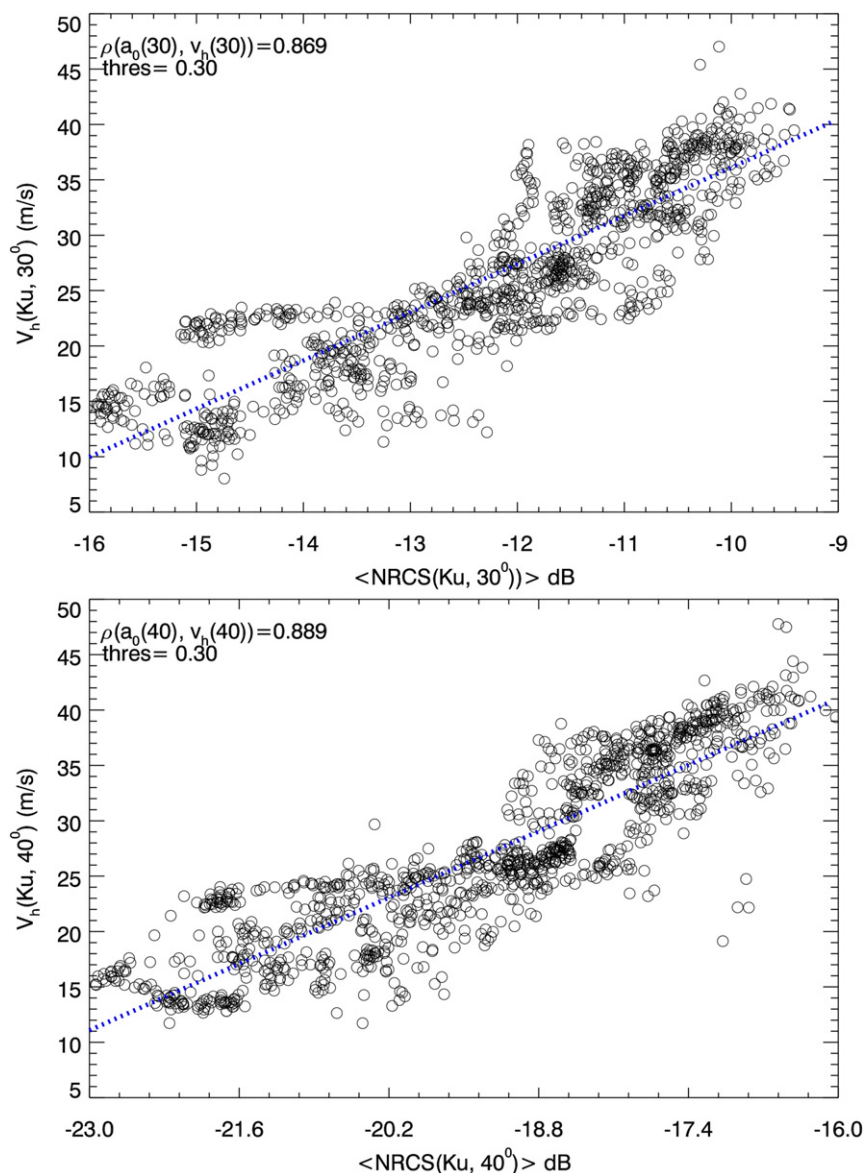


FIG. 7. Horizontal wind speed v_h derived from the Doppler Ku-band data vs the mean NRCS(Ku) for incidence angles of (top) 30° and (bottom) 40° . Each point is derived from the Doppler and NRCS data over a single scan.

where the summation from $i = 1$ to N is taken over the data within the scan and where N is the number of fields of view that compose the scan. The function y in (16) can be either $V_D(\text{Ku})$ or $\sigma^0(\text{Ku})$. For the data that will be shown later, we require $\text{RS}(1) < \tau$ for the Doppler radial velocity and $\text{RS}(2) < \tau$ for $\sigma^0(\text{Ku})$, where the threshold value τ is typically taken to be 0.3. These criteria are used to filter the data so that the Doppler is close to a single-period sinusoid and the NRCS is close to a two-period sinusoid.

For the 40° case shown on the left in Fig. 4 we find that, expressed in percentages and using either “D” (Doppler) or “ σ ” (NRCS) subscript to indicate the type of data, then $\text{RS}_D(1) = 6.3\%$ and $\text{RS}_\sigma(2) = 3.9\%$; for the 30° incidence case on the right,

$\text{RS}_D(1) = 7.8\%$ and $\text{RS}_\sigma(2) = 4.4\%$. Note that for the statistics presented later, we take the threshold to be 30% so that these examples are well within this threshold requirement.

For estimates of horizontal wind speed, the Doppler estimates at 30° and 40° are in good agreement in this case: $v_h(30^\circ) = 22.2 \text{ m s}^{-1}$ and $v_h(40^\circ) = 23 \text{ m s}^{-1}$. Several estimates of the vertical velocity are available. Neglecting the divergence term, then from (9) we have $v_z = -a_0(\theta)/(2 \cos \theta)$; substituting the values of a_0 for 30° and 40° incidence angles gives $v_z(30^\circ) = -6.97 \text{ m s}^{-1}$ and $v_z(40^\circ) = -7.40 \text{ m s}^{-1}$. In principle, (13) provides a better approximation for v_z since the divergence term does not need to be assumed negligible and uses information from both incidence angles. For this case, use of

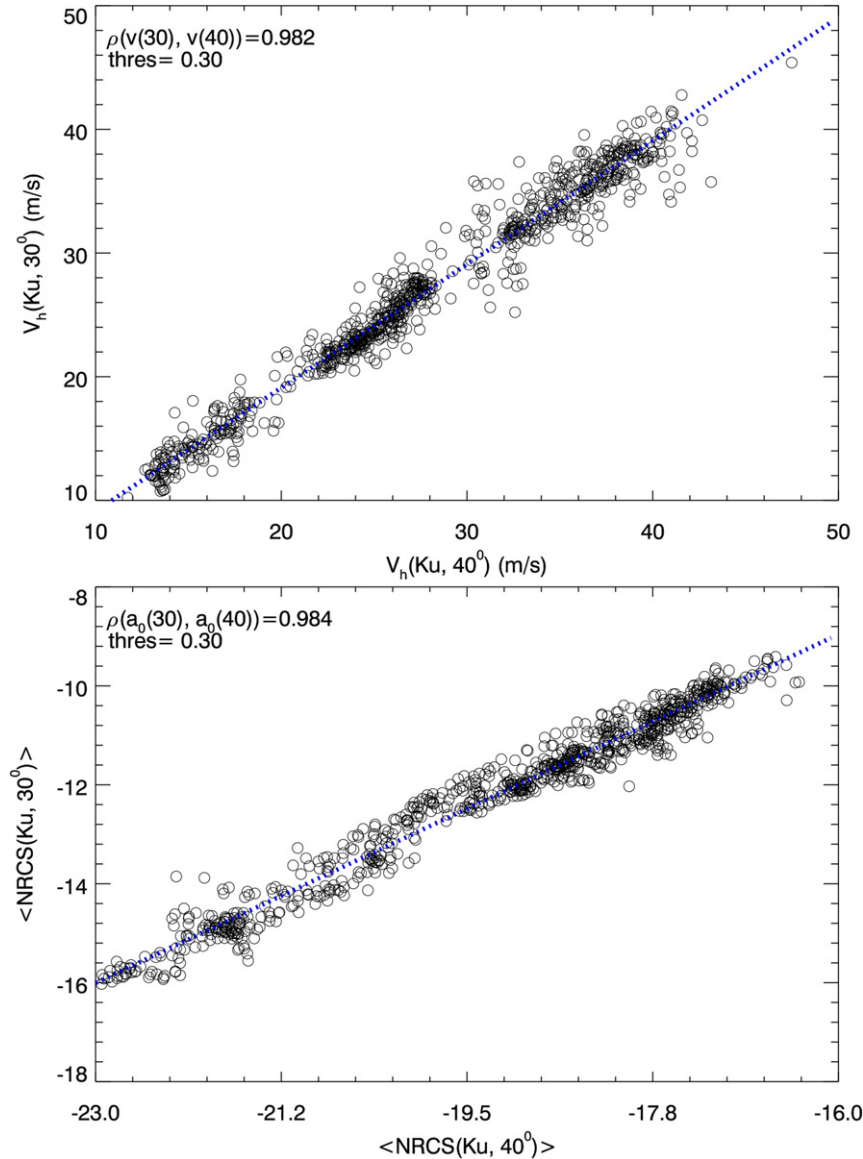


FIG. 8. (top) Ku-band Doppler-derived v_h from data at 30° incidence vs Ku-band Doppler-derived v_h from data at 40° incidence. (bottom) Mean NRCS(Ku) at 30° vs mean NRCS(Ku) at 40° .

(13) gives $v_z = -6.59 \text{ m s}^{-1}$ so that the three estimates are comparable and consistent with typical raindrop fall speeds.

With respect to the wind direction, note that negative Doppler corresponds to motion toward the radar (upwind or headwind direction) so that the peak negative Doppler should correspond to the maximum NRCS. The results in Fig. 4 show differences: for example, for the 40° incidence case on the left, the maximum NRCS occurs at about 221° whereas the minimum Doppler occurs at 237° for a difference of about 16° . For the 30° incidence case on the right, the maximum NRCS occurs at 212° while $V_{D\min}$ occurs at about 240° . Note that in this case the Doppler estimates of wind direction from data taken at 30° and 40° are in good agreement: 237° at 40° versus 240° at 30° .

Occasionally the “secondary” maximum, corresponding to the downwind or tailwind direction, is the actual maximum and the differences in wind direction derived from the Doppler and the NRCS are much larger. This is a fairly typical ambiguity in scatterometer measurements (Wentz and Smith 1999; Ricciardulli and Wentz 2015) where other information is needed to distinguish the upwind and downwind directions.

In many cases, the residual errors are larger than those seen in Fig. 4. Some of this is simply caused by the fact that rain is missing over portions of the scan so that the Doppler is not measurable over the full scan. Other cases occur where the Doppler data are noisy or partially missing over the scan. A more interesting kind of

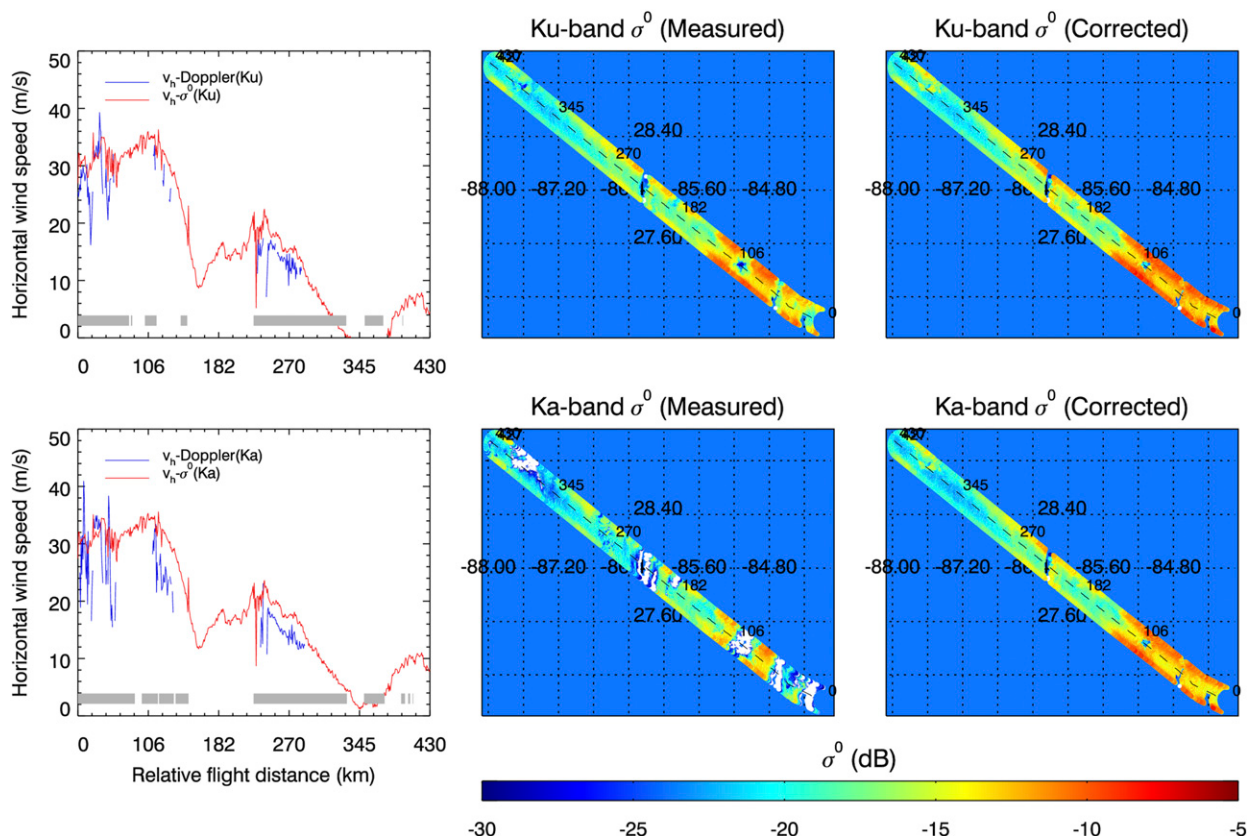


FIG. 9. The (top left) Ku-band and (bottom left) Ka-band $v_h(D)$ (blue) and $v_h(\sigma^0)$ (red); the incidence angle is 30° . The Doppler-derived wind speed, in blue, is shown only when $RS_D(1) < 0.5$, whereas $v_h(\sigma^0)$ is unrestricted. Gray bars at the bottom of the panels indicate the presence of rain as detected by the Ku- and Ka-band radars; The time period is 1652:00–1730:52 UT 1 Sep 2016. Also shown is the NRCS (center) before (i.e., measured data) and (right) after attenuation correction for the (top) Ku and (bottom) Ka bands.

case occurs when the data are generally good but where the Doppler deviates from the FS(1) representation and/or the NRCS deviates from the FS(2) representation.

Figure 5 shows examples of single scans of the Ka-band Doppler and NRCS data for incidence angles at 40° (left) and 30° (right) incidence where the measured data are given by the black lines, and the FS(1), FS(2), and FS(4) Fourier series approximations are given by the light-blue, red, and dark-blue lines. (Figure 6 shows the Doppler and NRCS at 40° for an 8-scan sequence, where the Ka-band portion of the sixth scan is shown on the left-hand panel in Fig. 5.) In these cases, the Doppler waveforms are not particularly well represented by the FS(1) estimates, given by the light-blue curves, and we need to look at FS(2) and higher to get better representations of the waveform. The NRCS data, moreover, are not particularly well represented by FS(2) whereas the FS(4) gives an accurate approximation.

Despite these deficiencies in FS(1) for the Doppler(Ka) and FS(2) for the σ^0 (Ka), we find that $RS_D(1) = 15.3\%$ and $RS_\sigma(2) = 5\%$ for the 30° incidence case (right, Fig. 5) and $RS_D(1) = 10.7\%$ and $RS_\sigma(2) = 3.5\%$ for the 40° incidence case (left, Fig. 5) and within the threshold used for the statistics shown in the next section. It might be noted, however, that of the eight scans shown in Fig. 6, it is only the sixth scan (the one shown in Fig. 5) where the

Ka-band Doppler is relatively noise free. Analysis of the other waveforms, without further filtering, shows that the residual errors are larger than in the case shown.

With respect to the horizontal velocity estimates, we obtain for this case: $v_h(30^\circ) = 17.23 \text{ m s}^{-1}$ and $v_h(40^\circ) = 17.14 \text{ m s}^{-1}$. For estimates of the upwind direction we obtain the four estimates: 107° (Doppler; 30°), 111° (Doppler; 40°), 126° [$\sigma^0(30^\circ)$] and 124° [$\sigma^0(40^\circ)$] where all estimates are based on the Ka-band data.

Estimates of the vertical velocity and divergence for this case give $a_0(30^\circ)/2 = 5.08$ and $a_0(40^\circ)/2 = 4.56$, which from (13) yields $v_{z0} = -5.79 \text{ m s}^{-1}$ and $\text{div}(\mathbf{v}_h) = 2.67 \times 10^{-5} \text{ s}^{-1}$ (using $H = 18000 \text{ m}$). Equation (9), on the other hand, under the assumption that the divergence is zero, gives $v_z = -5.08/\cos(30^\circ) = -5.86 \text{ m s}^{-1}$ and $v_z = -4.56/\cos(40^\circ) = -5.95 \text{ m s}^{-1}$, so that the three estimates for v_z in this case are similar.

As a final comment on this example, it is worth remarking on the differences between the σ^0 data shown in the bottom panels of Figs. 3 and 6. The data in Fig. 3 are consistent with the classic pattern of primary and secondary maxima with an angular separation between them of about 180° , coinciding with the upwind and downwind directions. The pattern in Fig. 6 is quite different, with primary and secondary maxima spaced more closely together in angle. Examination of the sequence of eight

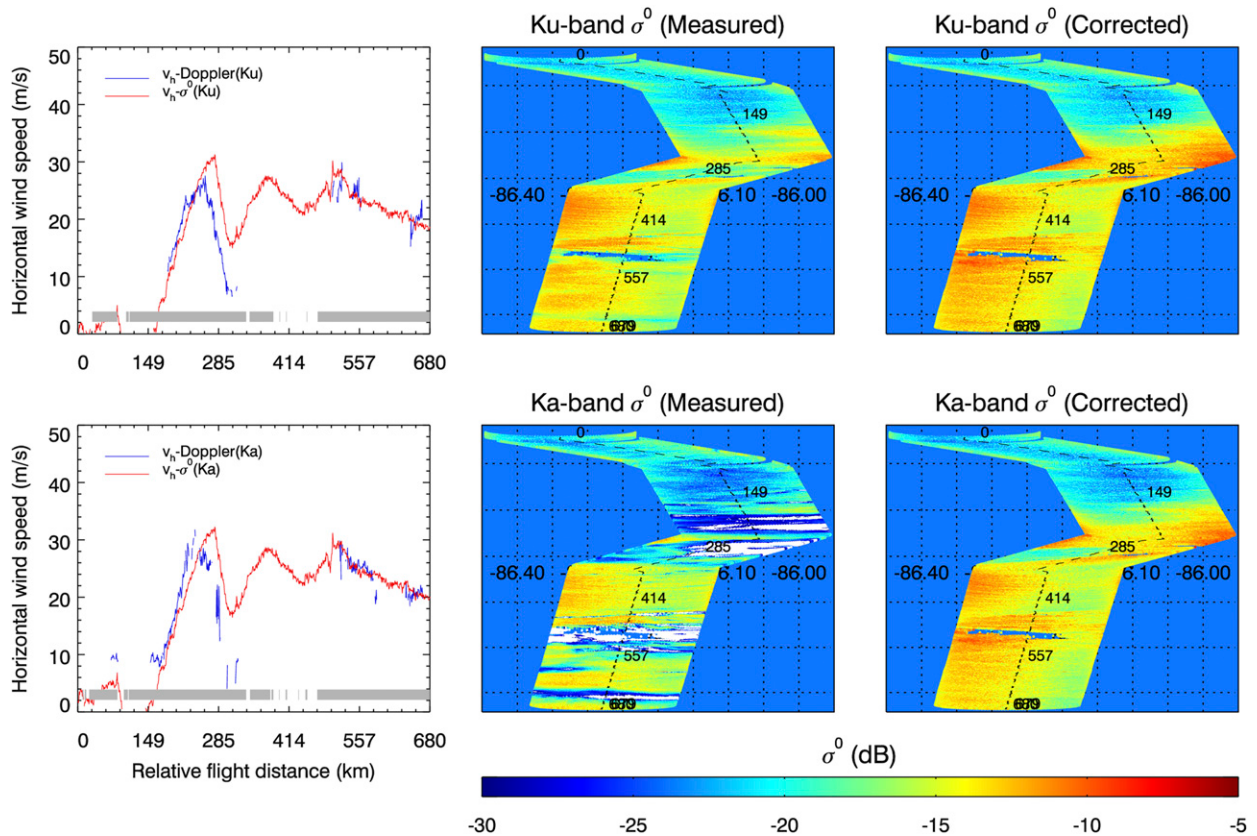


FIG. 10. As in Fig. 9, but for 1103:00–1206:39 UT 1 Sep 2016.

scans (approximately 5 km along the flight path) in Fig. 6 shows that for the waveforms on the left, the primary and secondary maxima are barely distinguishable as their angular separation is small and the secondary maximum is significantly smaller than the primary maximum. However, in going to the right, the separation becomes larger with a more clearly defined minimum between the two maxima, along with an increase in the magnitude of the secondary maximum. It is probably no coincidence that the deviations in the Doppler from a one-period sinusoid and deviations in σ^0 from a two-period sinusoid in these cases reflect the more complicated, nonlinear behavior of the wind field over the scans.

b. Statistical results

The primary goal of this study is to examine the correspondence between the horizontal wind speed derived from the Doppler and either the maximum NRCS or the mean value of the NRCS over the scan. Because the correlations are generally higher between the Doppler-derived wind speed and the mean NRCS, we focus on this relationship. These values are derived for each scan and the data are filtered by how well they are represented by a Fourier series. As noted above, we generally require less than 30% residual error, as given by RS(1), for the Doppler and less than 30% residual error, as given by RS(2), for the NRCS. Many cases fail this test either because of partial rain coverage over the swath, which gives a noisy

Doppler over part of the scan, or because of the occurrence of discontinuities in the azimuthal angle, representing data gaps in Doppler and NRCS over the scan. In other cases, the Doppler is simply too noisy over the full scan to satisfy the imposed condition. It is generally the case that the NRCS data are better behaved than the Doppler, which is not surprising as a surface return is almost always present regardless of whether it is raining.

The data shown in Figs. 7 and 8 have been combined from the processing of twelve files, corresponding to twelve ~40-min flight segments. Figure 7, top, shows a scatterplot of the horizontal wind speed v_h , derived from the Doppler Ku-band data, using (12), versus the mean attenuation-corrected NRCS(Ku) (equal to the $a_0/2$ term of the Fourier series), for an incidence angle of 30° . Each point is derived from the Doppler and NRCS data over a single scan. The bottom plot of Fig. 7 shows a similar result but using data from the 40° incidence data. The data plotted in Fig. 7 satisfy the requirement that $RS_D(1) < 30\%$ and $RS_\sigma(2) < 30\%$ and yield correlation coefficients of $\rho[v_h(\text{Ku}; 30^\circ), \langle \sigma^0(\text{Ku}; 30^\circ) \rangle] = 0.87$ and $\rho[v_h(\text{Ku}; 40^\circ), \langle \sigma^0(\text{Ku}; 40^\circ) \rangle] = 0.89$. Linear regression fits to the data, where $v_h(\sigma^0) = \alpha_0 + \alpha_1 \langle \sigma^0 \rangle$, yield for 30° incidence $[\alpha_0, \alpha_1] = [75.27, 3.98]$ and for 40° incidence $[\alpha_0, \alpha_1] = [105.8, 4.09]$. The change in these coefficients with change in threshold is relatively small so that even though the scatter increases as the threshold is increased, the regression line remains relatively constant.

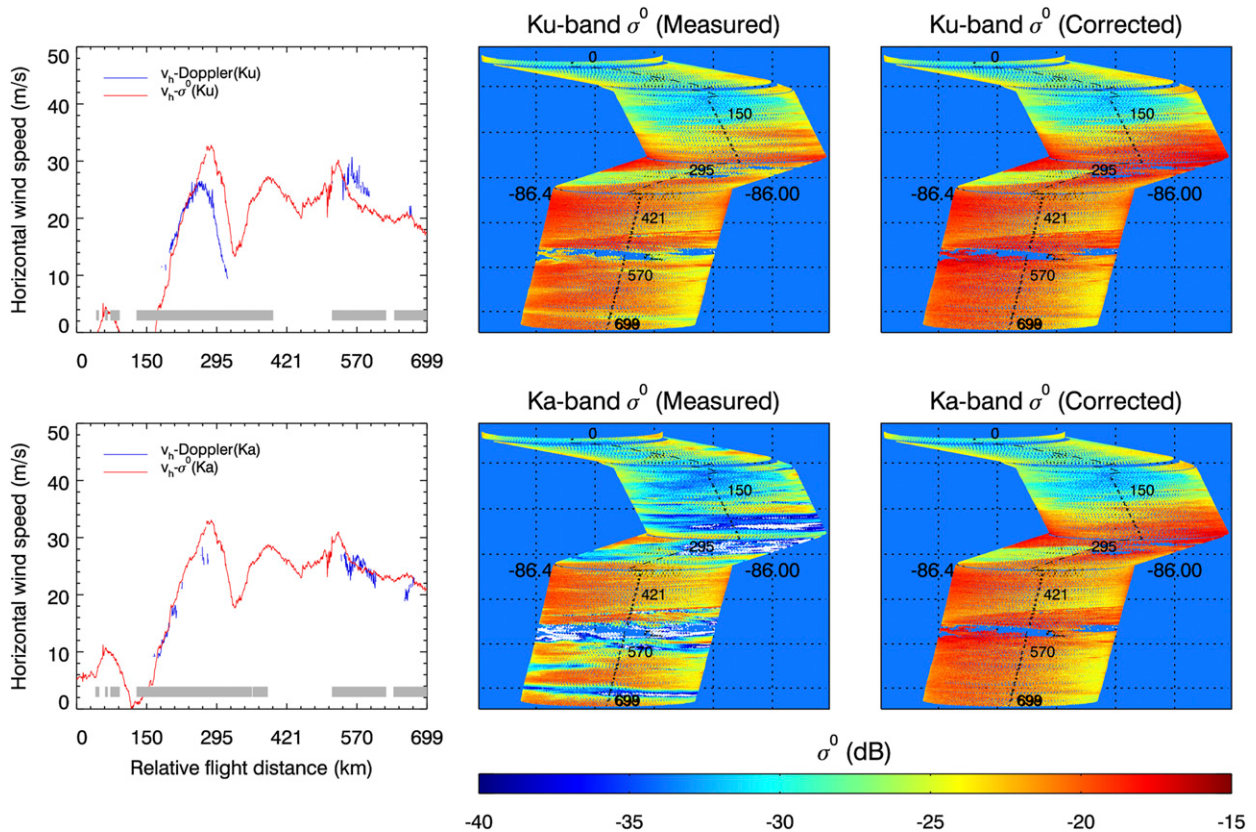


FIG. 11. As in Fig. 10, but for an incidence angle of 40° .

For the Ka-band results, the correlations degrade to $\rho[v_h(\text{Ka}; 30^\circ), \langle \sigma^0(\text{Ka}; 30^\circ) \rangle] = 0.75$ and $\rho[v_h(\text{Ku}; 40^\circ), \langle \sigma^0(\text{Ku}; 40^\circ) \rangle] = 0.60$. A slight improvement occurs if the thresholds are lowered from 0.3 to 0.2 where the correlation coefficient at 30° increases to 0.79 and that at 40° to 0.64. Linear regression fits to the Ka-band data, where $v_h(\sigma^0) = \alpha_0 + \alpha_1 \langle \sigma^0 \rangle$, yield for 30° incidence $[\alpha_0, \alpha_1] = [75.37, 3.75]$ and for 40° incidence $[\alpha_0, \alpha_1] = [94.4, 3.33]$. These relationships at Ku and Ka band are used in Figs. 9–14 to convert $\langle \sigma^0 \rangle$ to an estimate of horizontal wind speed $v_h(\sigma^0)$.

Figure 8, top, shows a comparison between $v_h(\text{Ku})$ as derived from the Doppler data at 30° incidence angle with the Doppler data at 40° incidence, where we have matched the scan numbers and “angle” bins between the two. The correlation is high even though the fields of view do not exactly coincide. Note that the threshold for inclusion of the data is taken to be 30% for both the Doppler and σ^0 ; that is, $\text{RS}_D(1) < 0.3$ and $\text{RS}_\sigma(2) < 0.3$. The bottom plot shows a scatterplot between $\langle \sigma^0(\text{Ku}; 30^\circ) \rangle$ and $\langle \sigma^0(\text{Ku}; 40^\circ) \rangle$ for the same set of matching pairs. For these cases and this threshold, the correlation coefficients for the Doppler and the $\langle \text{NRCS} \rangle$ are approximately the same at 0.98. At Ka band the correlations between $v_h(30^\circ)$ and $v_h(40^\circ)$ decrease to 0.93 while the correlation between $\langle \sigma^0(\text{Ku}; 30^\circ) \rangle$ and $\langle \sigma^0(\text{Ku}; 40^\circ) \rangle$ decreases to 0.89.

Although linear relationships between v_h and $\sigma^0(\text{dB})$ are given above, it should be noted that a power law between σ^0 , in linear units, and v_h has been shown to give excellent agreement

to measured data (e.g., Jones et al. 1977). This power-law relationship implies that an alternative model function of the form $\sigma^0 = \alpha + \beta \log(v_h)$, where σ^0 is in decibels and where β depends on incidence angle and polarization, could be employed. For the results below, only the linear model is used.

c. Summary results

We summarize in the figures below the attenuation correction procedure, estimation of horizontal wind speed, v_h , from σ^0 and its comparison with the Doppler v_h estimates using data from four flight segments. Each of Figs. 9–13 consists of six panels. The two panels on the left show the horizontal wind speed as determined by the Doppler VAD, $v_h(D)$ given by (12) and shown in blue, and as derived from σ^0 using the v_h – σ^0 linear relationships given above and shown in red. The Ku-band results are given in the top plots and Ka band in the bottom. The four panels on the right show the NRCS before (i.e., the measured data) and after attenuation correction with the attenuation-corrected NRCS given on the far right. Similar plots for the Ka-band data are given in the bottom two panels. It is worth noting that the data on the far-right panels, averaged over the scan, yield v_h as obtained from the v_h – σ^0 transfer function. Note that in the NRCS plots, only the forward portion of the scan is plotted.

The $v_h(D)$ data are plotted only when the Doppler data for that scan satisfies the threshold criterion $\text{RS}_D(1) < 0.5$ so that the residual error between the Fourier series, including terms

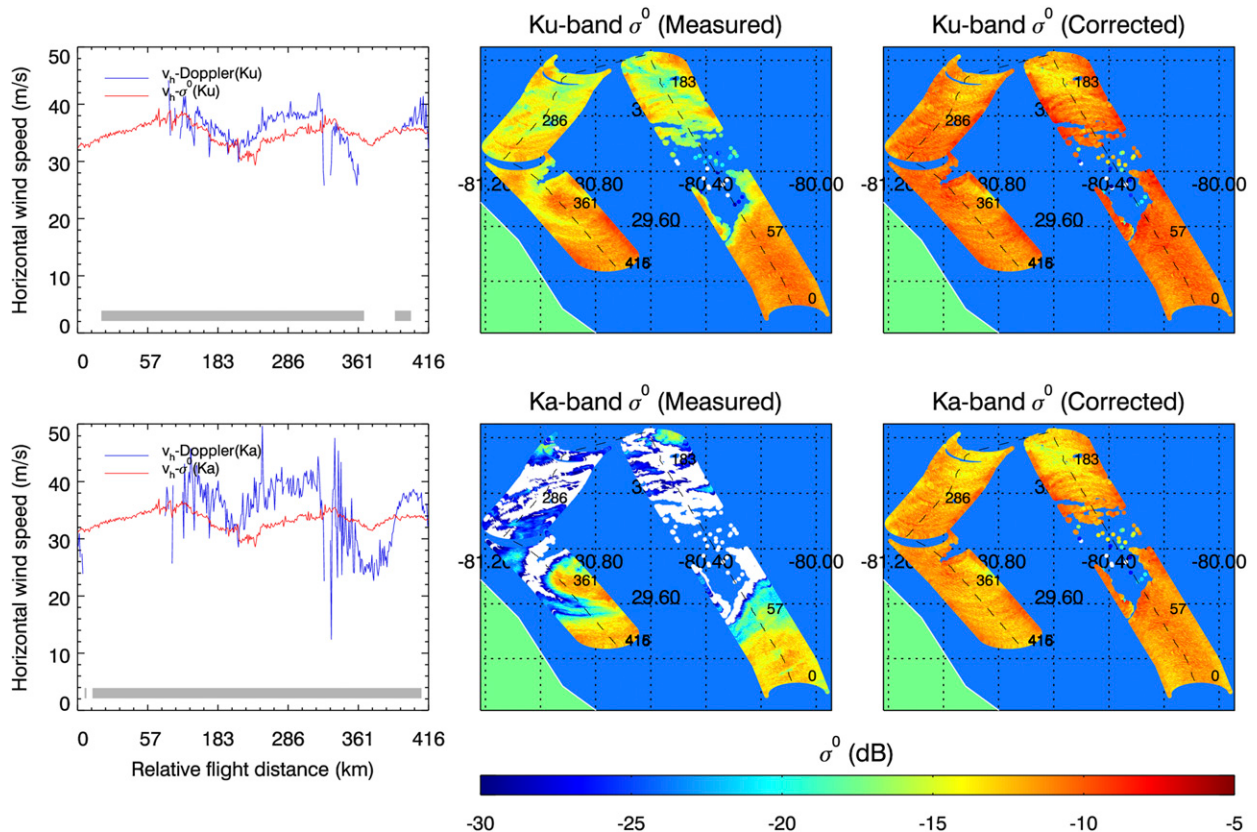


FIG. 12. As in Fig. 9, but for 1806:00–1845:00 UT 7 Oct 2016.

of up to period one, and the measured data is less than 50%. (The reasons for increasing this from the nominal 0.3 value is to show a greater fraction of the Doppler estimates.) A gray bar at the bottom of each panel on the left is used to indicate those scans over which the fraction of rain is greater than 70% (i.e., rain is detected in over 70% of the fields of view that compose the scan). Since the rain detection capability is somewhat different at Ku and Ka band, the gray bars in the top (Ku) and bottom (Ka) plots are not identical. In contrast to the intermittent nature of the $v_h(D)$ results, a $v_h(\sigma^0)$ estimate is obtained at each scan as σ^0 exists almost everywhere, as shown by plots of σ^0 on the far-right panels. Filtering of the NRCS data will be discussed in connection with Fig. 13.

Note that if the axis of the conical scan is greater than 2° off nadir then the data are not processed; consequently, data taken during aircraft banking are discarded. Correlating the line plots on the left with the NRCS images on the right is somewhat difficult because of breaks in the data typically caused by banking. For each flight, we first divide the data into 5 data segments with equal number of data points along the flight direction, and accumulate displacements between consecutive points based on their geolocation (longitude and latitude). Labeling the beginning of the flight $x = 0$ km, then the flight distance is summed to the end of the first segment (106 km as labeled in Fig. 9). This process continues to the end of the second segment (182 km). There are equal number of data

points (at nadir) between 0 and 106 km as there are between 106 and 182 km. This applies to all the data segments. Note that the forward scan data are used in the computation of the relative flight distance. All data in the plots below were measured on 1 September 2016, with the exception of the data shown in Fig. 12, which were taken during Hurricane Matthew on 7 October 2016 and described in Guimond et al. (2020). The duration of each flight segment is typically about 40 min.

For the results shown in Fig. 9, only data from the inner conical scan of 30° are used. In this case the $v_h(\sigma^0)$ results at Ku and Ka band, as shown by the red lines in the top- and bottom-left-hand panels, are in good agreement and, in turn, in fairly good agreement with Doppler VAD estimates given by the blue lines. Also encouraging is the fact that the $v_h(\sigma^0)$ results are continuous across rain/no-rain boundaries; this follows from the fact that the σ^0 images shown on the right-hand plots are continuous across these boundaries and the fact that the $v_h-\sigma^0$ relationships are well represented by a simple linear model.

Errors in the Ku-band $v_h(\sigma^0)$ estimates can be seen over the segment of data along the x axis centered at about 355 km where $v_h(\sigma^0; \text{Ku})$ estimates are less than zero. The reason for this error can be traced to the regression plots shown in Fig. 7 where valid $v_h(D)$ data are available at Ku band only when $-16 < E(\sigma^0) < -9$ dB at 30° and $-23 < E(\sigma^0) < -18$ dB at 40° , where $E(\sigma^0)$ represents the scan-averaged value. (In both cases, this represents a range of v_h from about 10 to 40 m s^{-1}).

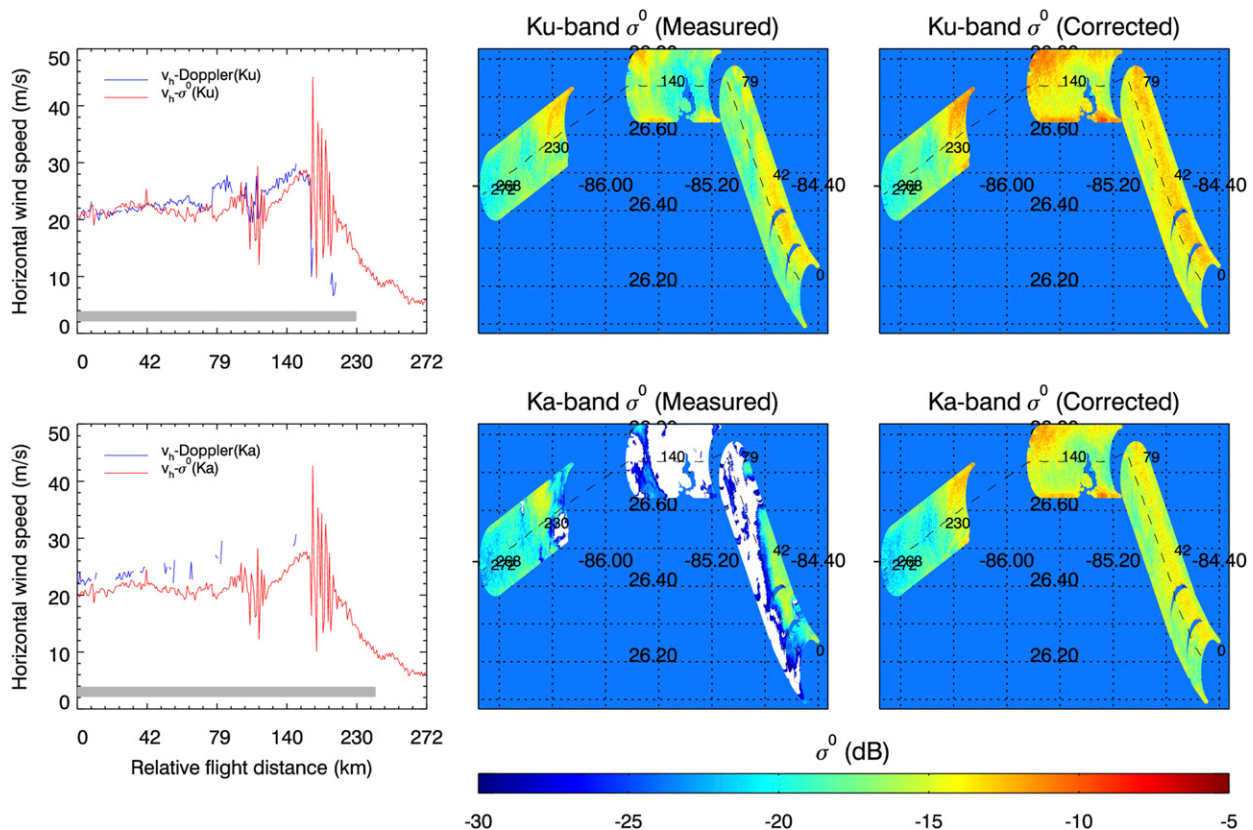


FIG. 13. As in Fig. 9, but for 0830:55–0856:06 UT 1 Sep 2016 and the Doppler-derived wind speed is shown for $RS_D(1) < 0.3$ while $v_h(\sigma^0)$ is unrestricted.

As the transfer function is used even when $\langle \sigma^0 \rangle$ falls outside these bounds, $v_h(\sigma^0)$ will become negative at sufficiently low values of $\langle \sigma^0 \rangle$. This kind of error suggests that the $v_h(\sigma^0)$ transfer functions at both frequencies and incidence angles are unreliable in light winds (below $\sim 10 \text{ m s}^{-1}$) and low values of the NRCS because of insufficient Doppler data. Conversely, at medium to high wind speeds, from about 10 to 40 m s^{-1} , where the Doppler derived wind speeds are extensive, the $v_h(\sigma^0)$ transfer functions are more robust.

A second example, also using data from the inner cone (30°), is shown in Fig. 10. As in the previous example, some missing $v_h(\sigma^0)$ values are seen in the first segment of the flight up to about 150 km. Using $v_h(D)$ as a reference, it appears that $v_h(\sigma^0)$ captures fairly well the first peak at about 210 km. On the other hand, $v_h(\sigma^0)$ is significantly larger than the first wind speed minimum, occurring at $x \sim 270 \text{ km}$, where $v_h(D)$ is well below 10 m s^{-1} whereas $v_h(\sigma^0) \sim 18 \text{ m s}^{-1}$. For the latter portion of the flight, beyond about 450 km, the Doppler and σ^0 estimates of wind speed are well aligned at both frequencies.

Data at 40° from the same flight are shown in Fig. 11. For this case, apart from the low wind speed/low NRCS along the first segment of the flight, there is generally good agreement in wind speed as derived from the Doppler and from σ^0 as estimated from data at the two incidence angles and two frequencies.

In the cases shown above, the filtered Doppler data yield estimates of v_h over only a relatively small fraction of the

flight data. In Fig. 12, $\theta = 30^\circ$, the valid Doppler data are more prevalent. The top-left panel (Ku band) shows relatively good agreement between $v_h(D; \text{Ku})$ and $v_h(\sigma^0; \text{Ku})$. The Ka-band comparisons, shown in the bottom-left panel, exhibit poorer agreement. Comparisons between $v_h(D; \text{Ka})$ and $v_h(D; \text{Ku})$ show the former to be higher in magnitude and noisier. Comparison between $v_h(\sigma^0; \text{Ka})$ and $v_h(\sigma^0; \text{Ku})$ show the former to be about $1\text{--}2 \text{ m s}^{-1}$ smaller but with a similar shape. The results at 40° (not shown) give similar results: fairly good agreement between $v_h(D; \text{Ku})$ and $v_h(\sigma^0; \text{Ku})$ but relatively poor agreement between $v_h(D; \text{Ka})$ and $v_h(\sigma^0; \text{Ka})$, with the former being larger than the latter.

Note that this result is fairly typical of the data analyzed where agreement between $v_h(D)$ and $v_h(\sigma^0)$ using Ku-band data is better than the comparisons using the Ka-band data. This holds at both incidence angles and is not surprisingly in light of the higher correlations between $v_h(D)$ and σ^0 that are obtained at Ku band.

Another flight segment with a fairly high proportion of valid Doppler data is shown in Fig. 13 using data from the inner conical scan. In this case, we have required $RS_D(1) < 0.3$; different choices of threshold are shown in Fig. 14. Good agreement between $v_h(D; \text{Ku})$ and $v_h(\sigma^0; \text{Ku})$ can be seen in the top-left panel up to about $x \sim 180 \text{ km}$. At Ka band, as shown in the bottom-left panel, $v_h(\sigma^0; \text{Ka})$ is seen to be in good agreement with both $v_h(D; \text{Ku})$ and

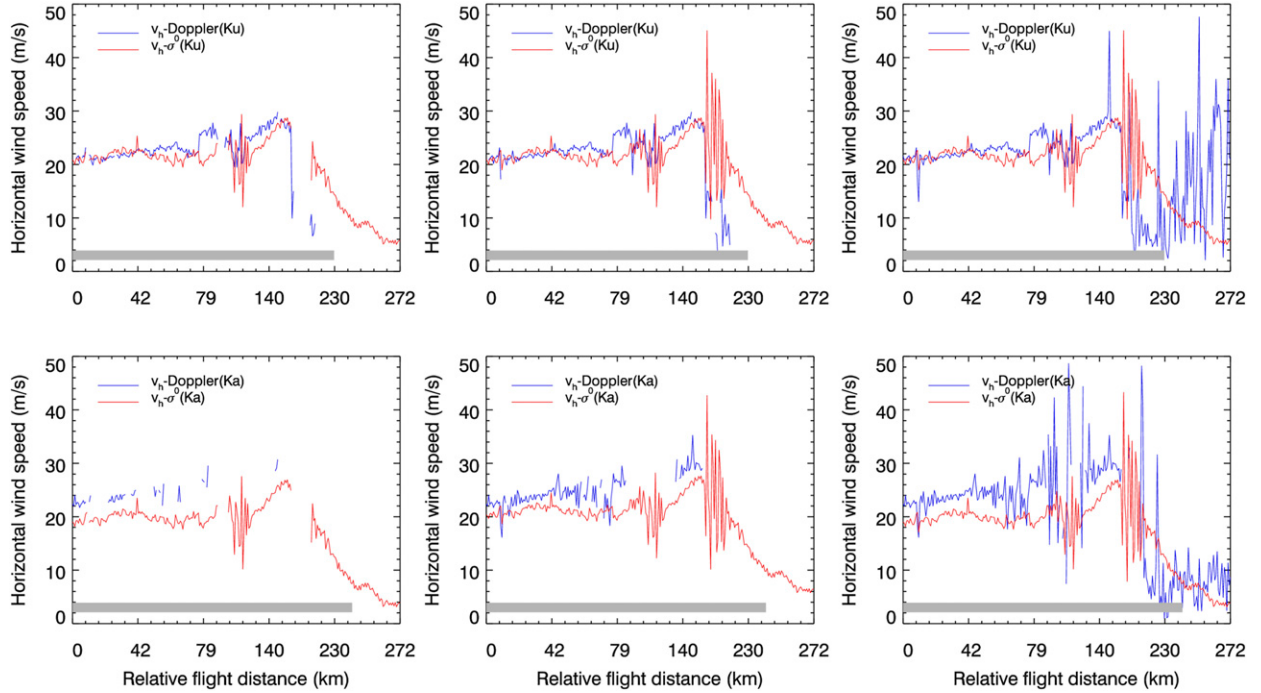


FIG. 14. The (top) Ku-band and (bottom) Ka-band data, where $v_h(D)$ is shown in blue and $v_h(\sigma^0)$ is shown in red: (left) $v_h(\sigma^0)$ is plotted for $RS_D(1) < 0.3$, and $v_h(D)$ is plotted for $RS_D(1) < 0.3$; (center) $v_h(D)$ is plotted for $RS_D(1) < 0.5$, whereas $v_h(\sigma^0)$ is unrestricted; (right) $v_h(D)$ and $v_h(\sigma^0)$ are unrestricted.

$v_h(\sigma^0; \text{Ku})$ but not in good agreement with $v_h(D; \text{Ka})$, which tends to be noisy and only intermittently reliable; that is, $RS_D(1) < 0.3$.

For x between about 180 to 210 km, the $v_h(\sigma^0)$ at both frequencies exhibit an oscillatory behavior. Valid Doppler $v_h(D)$ data during this period are largely missing, although the small amount of Doppler data at Ku band suggests that the $v_h(\sigma^0)$ estimates are positively biased. To better understand the situation, it is useful to replot the results with changes in the thresholds. As noted earlier, for the results in Figs. 9–12, we have chosen the threshold $RS_D(1) < 0.5$ for the Doppler data but have not imposed any restriction on the NRCS data. In other words, irrespective of the residual error in the NRCS, we have used the $v_h(\sigma^0)$ to obtain a wind speed estimate. If, however, we impose the condition that $RS_D(2) < 0.2$ then we obtain the results shown on the left-hand plots in Fig. 14. (Recall that $RS_D(2)$ denotes the residual error between the attenuation-corrected NRCS over the scan and the Fourier series representation using terms up to $\sin 2\phi$ and $\cos 2\phi$.) By imposing this filtering on the NRCS, most of the large oscillations in $v_h(\sigma^0)$ are removed.

We can also modify the $RS_D(1)$ threshold. In the middle panels of Fig. 14, we have chosen the threshold $RS_D(1) < 0.5$ so that a greater fraction of the Doppler estimates (blue lines) are plotted. In the right-hand panels, we have removed the restriction on the Doppler error entirely so that $v_h(D)$ estimates are given at all scans. Note that for the middle and right-hand plots, the residual error on σ^0 is not

considered so that $v_h(\sigma^0)$, given by the red lines, are the same as in Fig. 13.

5. Discussion and summary

Data from the HIWRAP dual-frequency Doppler radar afford an opportunity to examine the Doppler-derived horizontal wind field v_h near the surface in close proximity to the attenuation-corrected estimates of σ^0 . Although the data show a substantial amount of scatter in the $v_h-\sigma^0$ plane, a Fourier series analysis permits the choice of Doppler and σ^0 waveforms from individual scans that are well represented by 1-period and 2-period sinusoids, respectively. These filtered data, with residual errors less than 30%, show good correlations in $v_h-\sigma^0$ space, particularly at Ku band at incidence angles of 30° and 40° .

At Ka band, the results are less robust with correlations, at a threshold of 30%, of 0.75 at 30° and 0.6 at 40° . These results raise the issue of the accuracy of the attenuation correction, particularly since the Ka-band attenuation tends to be larger by about a factor of 6 than that at Ku band and clearly affects the Ka-band data more strongly.

Some comparisons of the $v_h-\sigma^0$ transfer function obtained here with the QuikScat/NASA Scatterometer (NSCAT) geophysical model function (GMF) (Jones et al. 1982; Wentz and Smith, 1999; Ricciardulli and Wentz 2015) have been conducted by inserting the HIWRAP σ^0 (either average or peak value) data into the NSCAT GMF. The values of v_h obtained in this way, however, are smaller than the v_h obtained from the

HIWRAP Doppler. On the other hand, the slope in the v_h - σ^0 plane is similar to that given by the HIWRAP results. The offset in v_h between the two results may indicate an error in the HIWRAP σ^0 estimates, an error in the attenuation correction or, less likely, an error in the HIWRAP Doppler. It is important to note that the Doppler-derived wind speed estimates given here are obtained from measurements several hundred meters above the surface whereas the NSCAT transfer function is derived from estimates of the vector wind at 10-m height in a neutrally stable atmosphere.

It worth mentioning again the presence of other error sources. Because of the strong attenuation that sometimes occurs at Ka band, the backscatter from rain near the surface will positively bias the estimate of the NRCS. This bias becomes stronger at higher incidence angles because the surface return decreases as the incidence angle increases so that there will be a certain fraction of cases at 40° in which the rain and surface returns will be of comparable magnitude. In the data processing done here, we have not attempted to correct for this bias. Another error source is caused by the effects of raindrops on the NRCS. In particular, Contreras and Plant (2006) have shown at Ku band that perturbations on the NRCS caused by the impact of raindrops on the surface increase as the angle of incidence increases so that the 40° incidence data are expected to be more strongly affected than measurements at 30° incidence; it is reasonable to assume that the Ka-band data are affected in a similar way. Although the effects of surface perturbations should reduce as the wind speed increases, increasing rain rate will counter this effect.

Despite discrepancies between the transfer functions derived here and for NSCAT, as long as the HIWRAP Doppler wind speed estimates are valid, then the v_h - σ^0 should be applicable to estimates of v_h under both raining and rain-free conditions using the σ^0 estimates from HIWRAP. However, as the transfer function applies only to the mean value of σ^0 over the swath, the resolution of the estimates is limited to the swath widths of approximately 18.5 km for the inner swath and 25 km for the outer swath. As noted earlier, the v_h - σ^0 results are probably less accurate at light wind speeds than at moderate and high wind speeds because of a lack of accurate full-scan Doppler data at light wind speeds. This is understandable in view of the fact that the field campaign was focused on mid-latitude severe storms; future missions are expected to obtain data over a wider variety of wind speeds that include those at the lower end.

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REFERENCES

- Balasubramaniam, R., and C. Ruf, 2020: Characterization of rain impact on L-band GNSS-R ocean surface. *Remote Sens. Environ.*, **239**, 111607, <https://doi.org/10.1016/j.rse.2019.111607>.
- Bentamy, A., A. Mouchi, A. Grouazel, A. Moujane, and A. A. Mohamed, 2019: Using Sentinel-1A SAR wind retrievals for enhancing scatterometer and radiometer regional wind analyses. *Int. J. Remote Sens.*, **40**, 1120–1147, <https://doi.org/10.1080/01431161.2018.1524174>.
- Bliven, L. F., and J. P. Giovanangeli, 1993: Experimental study of microwave scattering from rain- and wind-roughened seas. *Int. J. Remote Sens.*, **14**, 855–869, <https://doi.org/10.1080/01431169308904382>.
- , P. W. Sobieski, and C. Craeye, 1997: Rain generated ringwaves: Measurements and modeling for remote sensing. *Int. J. Remote Sens.*, **18**, 221–228, <https://doi.org/10.1080/014311697219385>.
- Browning, K. A., and R. Wexler, 1968: The determination of kinematic properties of a wind field using Doppler radar. *J. Appl. Meteor.*, **7**, 105–113, [https://doi.org/10.1175/1520-0450\(1968\)007<0105:TDOKPO>2.0.CO;2](https://doi.org/10.1175/1520-0450(1968)007<0105:TDOKPO>2.0.CO;2).
- Contreras, R. F., and W. J. Plant, 2006: Surface effect of rain on microwave backscatter from the ocean: Measurements and modeling. *J. Geophys. Res.*, **111**, C08019, <https://doi.org/10.1029/2005JC003356>.
- , W. C. Keller, K. Hayes, and J. Nystuen, 2003: Effects of rain on Ku-band backscatter from the ocean. *J. Geophys. Res.*, **108**, 3165, <https://doi.org/10.1029/2001JC001255>.
- Draper, D. W., and D. G. Long, 2004a: Evaluating the effect of rain on SeaWinds scatterometer measurements. *J. Geophys. Res.*, **109**, C02005, <https://doi.org/10.1029/2002JC001741>.
- , and —, 2004b: Simultaneous wind and rain retrieval using SeaWinds data. *IEEE Trans. Geosci. Remote Sens.*, **42**, 1411–1423, <https://doi.org/10.1109/TGRS.2004.830169>.
- Guimond, S. R., L. Tian, G. M. Heymsfield, and S. J. Frasier, 2014: Wind retrieval algorithms for the IWRAP and HIWRAP airborne Doppler radars with applications to hurricanes. *J. Atmos. Oceanic Technol.*, **31**, 1189–1215, <https://doi.org/10.1175/JTECH-D-13-00140.1>.
- , P. D. Reasor, G. M. Heymsfield, and M. M. McLinden, 2020: The dynamics of vortex Rossby waves and secondary eyewall development in Hurricane Matthew (2016): New insights from radar measurements. *J. Atmos. Sci.*, **77**, 2349–2374, <https://doi.org/10.1175/JAS-D-19-0284.1>.
- Helms, C. N., M. L. McLinden, and G. M. Heymsfield, 2020: Reducing errors in airborne velocity–azimuth display (VAD) wind and deformation retrievals in convective environments. *J. Atmos. Oceanic Technol.*, **37**, 2251–2266, <https://doi.org/10.1175/JTECH-D-20-0034.1>.
- Horstmann, J., H. Schiller, J. Schulz-Stellenfleth, and S. Lehner, 2003: Global wind speed retrieval from SAR. *IEEE Trans. Geosci. Remote Sens.*, **41**, 2277–2286, <https://doi.org/10.1109/TGRS.2003.814658>.
- Hu, and Coauthors, 2008: Sea surface wind speed estimation from space-based lidar measurements. *Atmos. Chem. Phys.*, **8**, 3593–3601, <https://doi.org/10.5194/acp-8-3593-2008>.
- Jones, W. L., L. C. Schroeder, and J. L. Mitchell, 1977: Aircraft measurements of the microwave scattering signature of the ocean. *IEEE J. Oceanic Eng.*, **2**, 52–61, <https://doi.org/10.1109/JOE.1977.1145330>.
- , and Coauthors, 1982: The Seasat-A satellite scatterometer: The geophysical evaluation of remotely sensed winds over the ocean. *J. Geophys. Res.*, **87**, 3297–3317, <https://doi.org/10.1029/JC087iC05p03297>.
- Li, L., and Coauthors, 2016: The NASA High-Altitude Imaging Wind and Rain Airborne Profiler. *IEEE Trans. Geosci. Remote Sens.*, **54**, 298–310, <https://doi.org/10.1109/TGRS.2015.2456501>.
- Meneghini, R., L. Liao, S. Tanelli, and S. L. Durden, 2012: Assessment of the performance of a dual-frequency surface reference technique over ocean. *IEEE Trans. Geosci. Remote Sens.*, **50**, 2968–2977, <https://doi.org/10.1109/TGRS.2011.2180727>.

- , —, and G. M. Heymsfield, 2019: Attenuation correction over ocean for the HIWRAP dual-frequency airborne scatterometer. *J. Atmos. Oceanic Technol.*, **36**, 2015–2030, <https://doi.org/10.1175/JTECH-D-19-0039.1>.
- Ricciardulli, L., and F. J. Wentz, 2015: A scatterometer geophysical model function for climate-quality winds: QuikSCAT Ku-2011. *J. Atmos. Oceanic Technol.*, **32**, 1829–1846, <https://doi.org/10.1175/JTECH-D-15-0008.1>.
- Stiles, B. W., and S. H. Yueh, 2002: Impact of rain on space-borne Ku-band wind scatterometer data. *IEEE Trans. Geosci. Remote Sens.*, **40**, 1973–1983, <https://doi.org/10.1109/TGRS.2002.803846>.
- , and Coauthors, 2010: Obtaining accurate ocean surface winds in hurricane conditions: A dual-frequency scatterometry approach. *IEEE Trans. Geosci. Remote Sens.*, **48**, 3101–3113, <https://doi.org/10.1109/TGRS.2010.2045765>.
- Tian, L., G. M. Heymsfield, A. C. Didlake, S. Guimond, and L. Li, 2015: Velocity–azimuth display analysis of Doppler velocity data for HIWRAP. *J. Appl. Meteor. Climatol.*, **54**, 1792–1808, <https://doi.org/10.1175/JAMC-D-14-0054.1>.
- Tournadre, J., and Y. Quilfen, 2003: Impact of rain cell on scatterometer data: 1. Theory and modeling. *J. Geophys. Res.*, **108**, 3225, <https://doi.org/10.1029/2002JC001428>.
- Weissman, D. E., and M. A. Bourassa, 2008: Measurements of the effect of rain-induced sea surface roughness on the QuikSCAT scatterometer radar cross section. *IEEE Trans. Geosci. Remote Sens.*, **46**, 2882–2894, <https://doi.org/10.1109/TGRS.2008.2001032>.
- , B. W. Stiles, S. M. Hristova-Veleva, D. G. Long, D. K. Smith, K. A. Hilburn, and W. L. Jones, 2012: Challenges to satellite sensors of ocean winds: Addressing precipitation effects. *J. Atmos. Oceanic Technol.*, **29**, 356–374, <https://doi.org/10.1175/JTECH-D-11-00054.1>.
- Wentz, F. J., and D. K. Smith, 1999: A model function for the ocean normalized radar cross section at 14 GHz derived from NSCAT observations. *J. Geophys. Res.*, **104**, 11 499–11 514, <https://doi.org/10.1029/98JC02148>.