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Doppler Lidar Horizontal Wind Profiles Value-Added Product

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Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
ASCII	American Standard Code for Information Interchange
DLPROF-WIND	Doppler Lidar Horizontal Wind Profiles VAP
DLWIND	Original name of Doppler Lidar Horizontal Wind Profiles VAP
DOE	U.S. Department of Energy
MET	surface meteorological instrumentation
netCDF	Network Common Data Form
PPI	plan-position-indicator
QC	quality control
SNR	signal-to-noise ratio
VAD	velocity-azimuth-display
VAP	value-added product

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1.0 Introduction

Wind speed and direction, together with pressure, temperature and relative humidity, are the most fundamental atmospheric state parameters. Accurate measurement of these parameters is crucial for numerical weather prediction. Vertically resolved wind measurements in the atmospheric boundary layer are particularly important for modeling pollutant and aerosol transport. The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility currently operates several scanning coherent Doppler lidar systems that are capable of providing accurate height-resolved measurements of wind speed and direction.

These instruments operate in the near infrared (IR;1.5 microns) and provide range-resolved measurements of radial velocity, attenuated aerosol backscatter, and signal-to-noise ratio (SNR). The systems are operated using a fixed scan schedule consisting of plan-position-indicator (PPI) scans that are performed several times per hour (PPI scans are performed by scanning the beam in azimuth while maintaining a fixed elevation angle). Radial velocity data from these scans are processed to yield profiles of wind speed direction.

This report describes the algorithm used to generate the wind profiles, its input and output, and data quality control procedures. We refer to the output as the Doppler Lidar Horizontal Wind Profiles (DLPROF-WIND) value-added-product (VAP). The VAP consists of time- and height-resolved estimates of wind speed and direction that are computed from PPI scan data (i.e., *dlppi*.b1.* files) using a method based on the traditional velocity-azimuth-display (VAD) algorithm (Browning and Wexler 1968).

2.0 Input Data

The DLPROF-WIND algorithm reads in data from the <*site*>dlppi<*facility*>.b1 datastream and <site>met<facility>.b1, and parameters from one ASCII configuration file. The configuration file contains parameters used in generating quicklook plots, and a threshold value for the signal-to-noise ratio.

Specific variables required from the input datastreams are listed in Table 1 and Table 2.

Table 1. Variables and global attributes from the <*site*>dlppi<*facility*>.b1 datastream used by the DLPROF-WIND algorithm.

Variable Name	Description	Units
base_time	seconds since 1970-1-1 0:00:00 0:00	sec
time_offset	Time offset from base_time	sec
Range	Distance from Lidar to center of range gate	M
Azimuth	Beam azimuth relative to true north	deg
elevation	Beam elevation	deg
radial_velocity	Radial velocity	ms^{-1}
intensity	Intensity (signal-to-noise ratio + 1)	unitless
Alt	Altitude above mean sea level	m
dlat (global attribute)	Lidar latitude in double precision	deg
dlon (global attribute)	Lidar longitude in double precision	deg

Table 2. Variables and global attributes from the <*site*>met<*facility*>.b1 datastream used by the DLPROF-WIND algorithm.

Variable Name	Description	Units
Atmos_pressure	Atmospheric pressure	kPa
pwd_precip_rate_mean	PWD 1-minute mean precipitation rate	Mm/hr
rh_mean	Relative humidity mean	%
temp_mean	Temperature mean	degC
wdir_vec_mean	Wind direction vector mean	deg
wspd_vec_mean_velocity	Wind speed vector mean	m/s
Lat	North latitude	degree_N
Lon	East longitude	degree_E
Alt	Altitude above mean sea level	m

3.0 Algorithm and Methodology

Estimates of the *u*, *v,* and *w* components of the wind field are computed using the methodology described in Newsom et al. 2017. The algorithm uses PPI scan data, and assumes the flow to be horizontally uniform and steady at a given height above ground level. At a fixed range from the lidar the conical PPI scan traces out a circle centered above the lidar position, as indicated in Figure 1. As the beam is scanned in azimuth, the radial velocity varies sinusoidally. The *u*, *v,* and *w* components are retrieved by fitting a sinusoid to the radial velocity data; the amplitude, phase, and offset of the sinusoid determine the wind speed, wind direction, and vertical velocity, respectively. The derived winds are representative of averages taken over the circumference of the circle and over the time it takes to complete a full PPI scan, which is typically anywhere from about 30 seconds to a couple of minutes, depending on the pulse integration time and number of beams used.

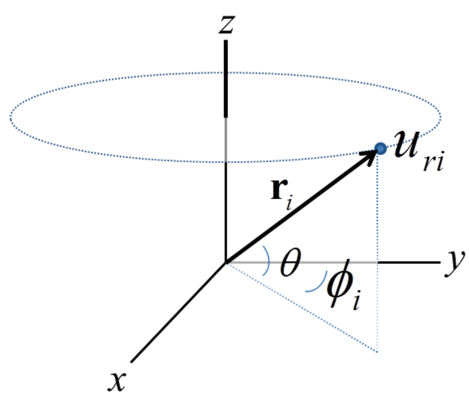

Figure 1. Geometry for computing the winds at a fixed height. The *x*, *y,* and *z* axes define the east, north, and up directions, respectively. The lidar is located at the origin of the coordinate system. The position vector from the lidar to the observation point is $\mathbf{r}_i$, and u_{ri} is the radial velocity at the observation point. The elevation and azimuth angles of the observation point are θ and ϕ_i, respectively.

The fit is performed at each range gate or height by minimizing the following cost function:

$$L = \sum_{i=0}^{N-1} \left(\mathbf{u} \cdot \hat{\mathbf{r}}_i - u_{ri} \right)^2 , \tag{1}$$

where $\mathbf{u}$ is the unknown velocity vector, u_{ri} is a radial velocity measurement, and $\hat{\mathbf{r}}_i$ is the unit vector from the lidar to the observation point, as indicated in Figure 1. The summation in equation (1) is performed over all *N* beams at a fixed range gate.

The unknown velocity in equation (1) is given by

$$\mathbf{u} = u\hat{\mathbf{x}} + v\hat{\mathbf{y}} + w\hat{\mathbf{z}} \tag{2}$$

and the position unit vector is given by

$$\hat{\mathbf{r}}_i = \cos\theta \sin\phi_i \hat{\mathbf{x}} + \cos\theta \cos\phi_i \hat{\mathbf{y}} + \sin\theta \hat{\mathbf{z}} \tag{3}$$

where $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$ are unit vectors along the *x*, *y,* and *z* axes, respectively. The velocity components *u*, *v,* and *w* are assumed to be constant along the circle. Minimizing equation (1) with respect to *u*, *v,* and *w* (i.e., solving $\partial L / \partial u = 0$, $\partial L / \partial v = 0$, and $\partial L / \partial w = 0$) results in a system of three equations, and three unknowns, *u*, *v,* and *w*. The solution is given by

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{pmatrix}^{-1} \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} , \tag{4}$$

where

$$A_{11} = \cos^2\theta \sum_{i=0}^{N-1} \sin^2\phi_i ,$$

$$A_{12} = A_{21} = \cos^2\theta \sum_{i=0}^{N-1} \cos\phi_i \sin\phi_i ,$$

$$A_{13} = A_{31} = \cos\theta \sin\theta \sum_{i=0}^{N-1} \sin\phi_i ,$$

$$A_{22} = \cos^2\theta \sum_{i=0}^{N-1} \cos^2\phi_i ,$$

$$A_{23} = A_{32} = \cos\theta \sin\theta \sum_{i=0}^{N-1} \cos\phi_i ,$$

$$A_{33} = N \sin^2\theta ,$$

and

$$b_1 = \cos\theta \sum_{i=0}^{N-1} u_{ri} \sin\phi_i ,$$

$$b_2 = \cos\theta \sum_{i=0}^{N-1} u_{ri} \cos\phi_i ,$$

$$b_3 = \sin\theta \sum_{i=0}^{N-1} u_{ri} .$$

Uncertainty estimates for u, v, and w are obtained from the diagonal elements of $\mathbf{A}^{-1}$ (Press et al. 1988), i.e.

$$\delta u^2 = \mathbf{A}_{11}^{-1} , \quad (5)$$

$$\delta v^2 = \mathbf{A}_{22}^{-1} \quad (6)$$

and

$$\delta w^2 = \mathbf{A}_{33}^{-1} , \quad (7)$$

where $\mathbf{A}^{-1}$ is obtained using standard numerical matrix inversion methods (Press et al. 1988). The quality of the least squares fit is assessed using the fit residual and the linear correlation coefficient. These quantities are defined as follows:

Residual $$= \sqrt{\overline{\left(\mathbf{u}\cdot\mathbf{r} - u_r\right)^2}} \quad (8)$$

Correlation $$= \frac{\overline{\left(\mathbf{u}\cdot\hat{\mathbf{r}} - \overline{\mathbf{u}\cdot\hat{\mathbf{r}}}\right)\left(u_r - \overline{u_r}\right)}}{\left(\overline{\left(\mathbf{u}\cdot\hat{\mathbf{r}} - \overline{\mathbf{u}\cdot\hat{\mathbf{r}}}\right)^2}\right)^{1/2}\left(\overline{\left(u_r - \overline{u_r}\right)^2}\right)^{1/2}} \quad (9)$$

Equations 4, 5, 6, and 7 determine the velocity components and random uncertainties at a fixed height or range gate. Wind profiles (and uncertainties) are then constructed by repeating the analysis for all range gates.

The configuration file for the DLPROF-WIND algorithm contains an SNR threshold value used in quality control of the data. Radial velocity estimates corresponding to SNR values below this threshold are not used in the computation of the wind profiles. We find that a threshold value of about 0.008 works well in rejecting most of the poor-quality radial velocity data.

4.0 Output Data

The DLPROF-WIND algorithm produces a single netCDF file per day. The output datastream name is <*site*>dlprofwind4news<*facility*>.c1. Fields contained in this datastream include the eastward and northward wind components (*u* and *v*, respectively), vertical velocity, and corresponding uncertainty fields. Also included are several fields useful for quality control, such as the mean signal-to-noise ratio (SNR), fit residuals, and linear correlations. Metadata fields include the elapse time for the PPI scan, the elevation angle of the PPI scan, and the number of azimuth angles.

The number of profiles in a given file is equal to the number of PPI scans that were performed on that day. The height resolution of the wind profiles depends on the range gate size and scan elevation angle. The ARM Doppler lidars are typically operated with 30-m range gates, and PPI scans are typically performed at an elevation angle of 60^o using N=8 evenly spaced beams in azimuth. Thus, a typical height resolution is $30\sin(60^o)$=26m. Additionally, the minimum range for the Doppler lidar is approximately 100 m. This results in a minimum height of about 87m for a 60^o PPI scan.

The ARM Doppler lidars operate in the near infrared and are thus sensitive to scattering from aerosol but insensitive to molecular scattering. The lidar's backscatter signal typically decreases dramatically above the atmospheric boundary layer as the aerosol concentrations fall off. As a result, good-quality radial velocity measurements are primarily constrained to the lowest 2 to 3 km of the atmosphere. Thus, the DLPROF-WIND algorithm is configured to process data up to a maximum height of 3 km.

Primary variables in the output datastream include the three wind components (*u*, *v,* and *w*), wind speed, wind direction, and corresponding uncertainty estimates. Other important variables in the output include the fit residual (equation 8), the linear correlation coefficient (equation 9), and the mean SNR (averaged along the circumference of the circle traced out by the PPI scan at a fixed height). The primary variables will contain missing values in regions where the SNR is below threshold. Users can apply additional QC by filtering out wind estimates corresponding to large fit residuals and/or small linear correlation coefficients. Additionally, users can use the mean SNR field to apply a higher SNR threshold than was used in the original processing.

The DLPROF-WIND VAP also includes several variables from the surface meteorological instrument (MET) station. These have been included to facilitate comparison with independent measurements of wind speed and wind direction (i.e., to provide a sanity check on the lidar measurements), and to provide additional QC of the lidar measurements. The precipitation rate measurement from the MET station is useful for determining when the lidar measurements may be adversely affected by precipitation. A complete listing of all output variables is given in Appendix A.

4.1 Scientific Output Variables

A list of primary variables is given in Table 3.

Table 3. DLPROF-WIND VAP primary variables.

Measurement	Variable Name
easterly wind component	u
easterly wind component uncertainty estimate	u_error
northerly wind component	v
northerly wind component uncertainty estimate	v_error
wind speed	wind_speed
wind speed uncertainty estimate	wind_speed_error
wind direction	wind_direction
wind direction uncertainty estimate	wind_direction_error

5.0 Summary

The DLPROF-WIND algorithm uses PPI scan data from the ARM Doppler lidars to compute vertical profiles of wind speed and direction using a method based on the traditional velocity-azimuth-display algorithm (Browning and Wexler 1968). Primary variables in the output datastream include the three wind components (u, v, and w), wind speed, wind direction, and corresponding uncertainty estimates.

The DLPROF-WIND algorithm produces a single netCDF file per day, and one vertical profile is generated for each PPI scan performed. The ARM Doppler lidars typically perform several PPI scans per hour, and each PPI scan takes anywhere from roughly 30 seconds to a couple of minutes to complete, depending on how the lidar is configured. As an example, a typical configuration is to perform one 8-beam PPI scan every 15 minutes. The elapse time for the 8-beam PPI is roughly 40 seconds. Thus, the output contains nominally 4x24=96 wind profiles, with each profile representing a 40 second average taken every 15 minutes.

The vertical resolution of the output is determined by the PPI elevation angle and the range resolution. The ARM Doppler lidars are typically operated with 30-m range gates, and PPI scans are typically performed at an elevation angle of 60^o. Thus, a typical height resolution is $30\sin(60^o)=26$m. Additionally, the minimum range for the Doppler lidar is approximately 100 m. This results in a minimum height of about 87m for a 60^o PPI scan.

6.0 Example Plots

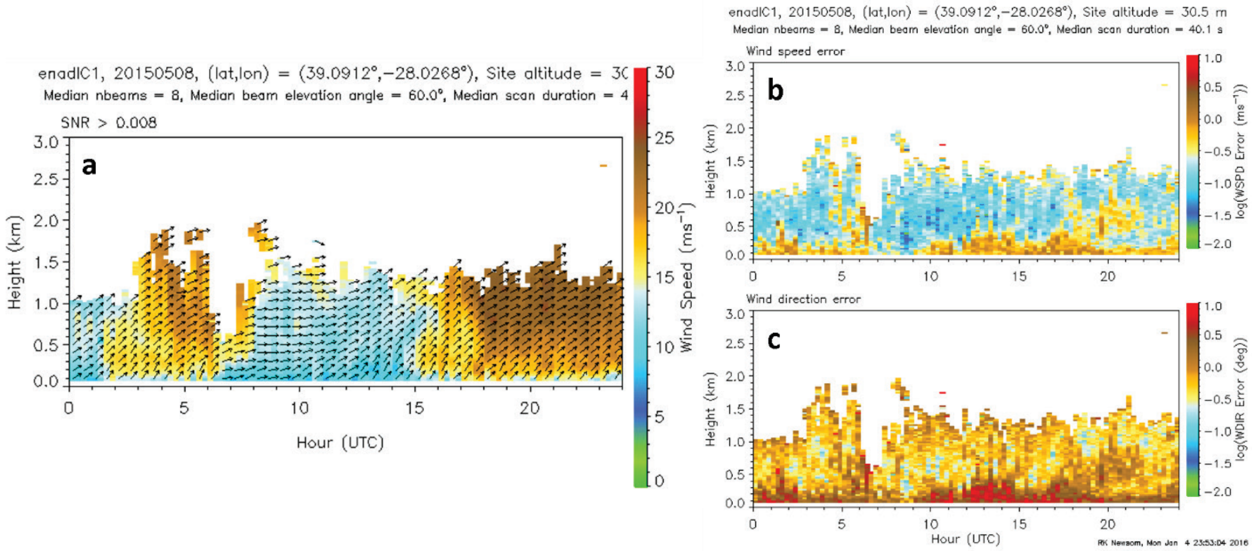

Figure 2. Sample quicklook plots from the Doppler lidar at ARM's Eastern North Atlantic site on 8 May 2015. a) Wind speed (color) and wind vector direction (arrows) for SNR>0.008; b) wind speed error; c) wind direction error.

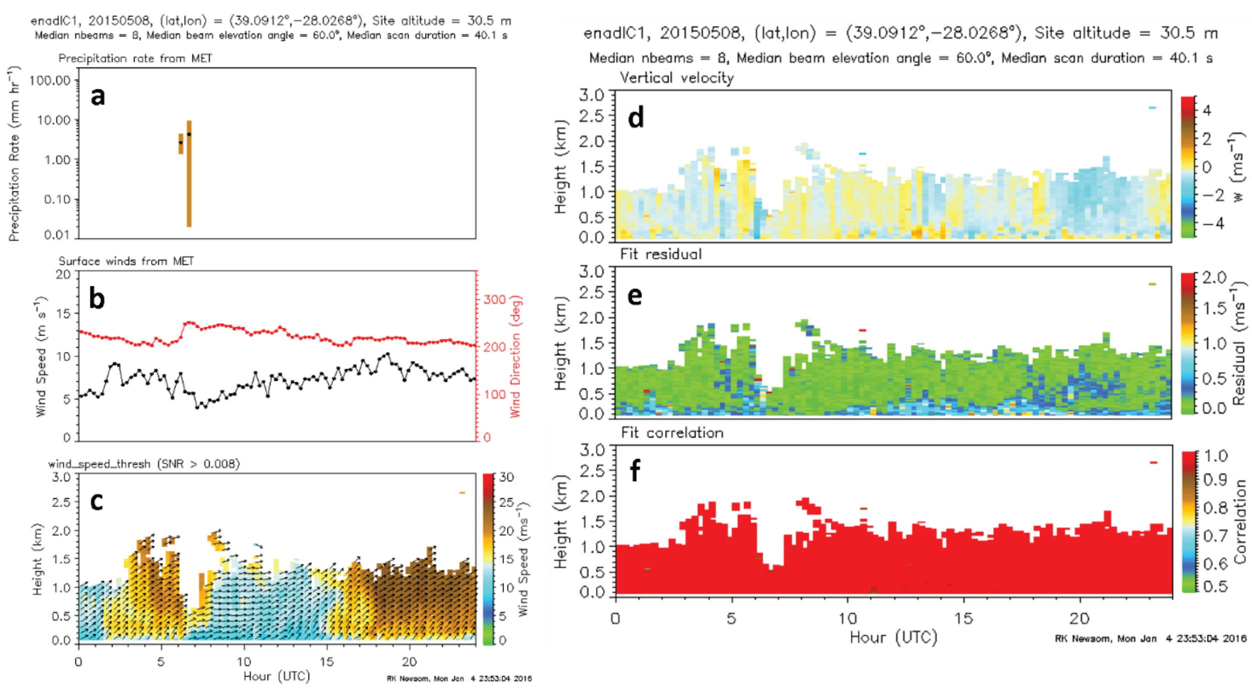

Figure 3. Sample quicklook plots from the Doppler lidar at ARM's Eastern North Atlantic site on 8 May 2015. a) Precipitation rate from the surface MET station; b) Wind speed (black) and wind direction (red) from the surface MET station; c) Wind speed (color) and wind vector direction (arrows) for SNR>0.008; d) vertical velocity; e) fit residual; f) fit correlation.

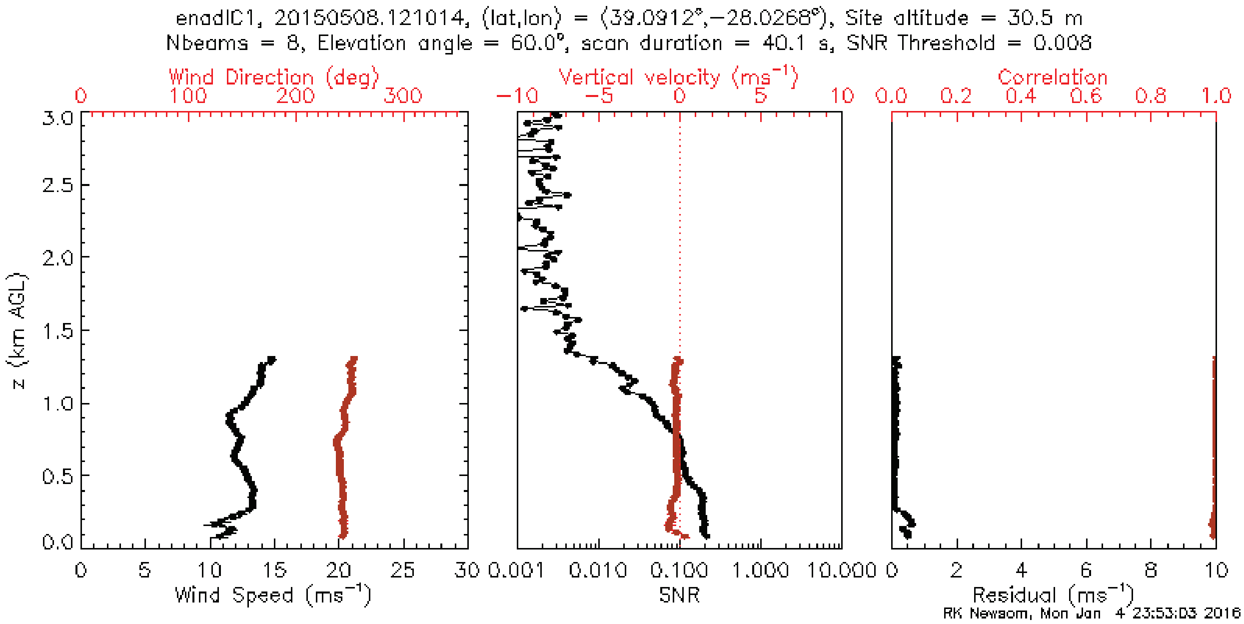

Figure 4. Sample quicklook plots from the Doppler lidar at ARM's Eastern North Atlantic site at 12:10:14 UTC on 8 May 2015. The right panel shows profiles of wind speed (black) and wind direction (red). The middle panel shows profiles of the mean SNR (black) and vertical velocity (red). The right panel shows profiles of the fit residual (black) and the correlation coefficient (red).

7.0 References

Browning, KA, and R Wexler. 1968. "The determination of kinematic properties of a wind field using Doppler radar." *Journal of Applied Meteorology* 7(1): 105-113, https://doi.org/10.1175/1520-0450(1968)007<0105:TDOKPO>2.0.CO;2

Newsom, RK, WA Brewer, JM Wilczak, DE Wolfe, SP Oncley, and JK Lundquist. 2017. "Validating Precision Estimates in Horizontal Wind Measurements from a Doppler Lidar." *Atmospheric Measurement Techniques* 10(3):1229-1240, https://doi.org/10.5194/amt-10-1229-2017

Press, WH, SA Teukolsky, WT Vetterling, and BP Flannery. 1988. *Numerical Recipes in C*. Cambridge University Press, Cambridge, pp. 528-534.

Appendix A

DLPROF-WIND VAP Contents

```
netcdf sgpdlprofwind4newsC1.c1.20150421.000644 {
dimensions:
	time = UNLIMITED ; // (94 currently)
	height = 164 ;
	bound = 2 ;
variables:
	int base_time ;
		base_time:string = "2015-04-21 00:00:00 0:00" ;
		base_time:long_name = "Base time in Epoch" ;
		base_time:units = "seconds since 1970-1-1 0:00:00 0:00" ;
		base_time:ancillary_variables = "time_offset" ;
	double time_offset(time) ;
		time_offset:long_name = "Time offset from base_time" ;
		time_offset:units = "seconds since 2015-04-21 00:00:00 0:00" ;
		time_offset:ancillary_variables = "base_time" ;
	double time(time) ;
		time:long_name = "Time offset from midnight" ;
		time:units = "seconds since 2015-04-21 00:00:00 0:00" ;
		time:bounds = "time_bounds" ;
	double time_bounds(time, bound) ;
	float height(height) ;
		height:long_name = "Height above ground level" ;
		height:units = "m" ;
		height:standard_name = "height" ;
	float scan_duration(time) ;
		scan_duration:long_name = "PPI scan duration" ;
		scan_duration:units = "second" ;
		scan_duration:missing_value = -9999.f ;
	float elevation_angle(time) ;
		elevation_angle:long_name = "Beam elevation angle" ;
		elevation_angle:units = "degree" ;
		elevation_angle:missing_value = -9999.f ;
	short nbeams(time) ;
		nbeams:long_name = "Number of beams (azimuth angles) used in wind vector estimation" ;
		nbeams:units = "unitless" ;
	float u(time, height) ;
		u:long_name = "Eastward component of wind vector" ;
		u:units = "m/s" ;
```

```
        u:missing_value = -9999.f ;
    float u_error(time, height) ;
        u_error:long_name = "Estimated error in eastward component of wind vector" ;
        u_error:units = "m/s" ;
        u_error:missing_value = -9999.f ;
    float v(time, height) ;
        v:long_name = "Northward component of wind vector" ;
        v:units = "m/s" ;
        v:missing_value = -9999.f ;
    float v_error(time, height) ;
        v_error:long_name = "Estimated error in northward component of wind vector" ;
        v_error:units = "m/s" ;
        v_error:missing_value = -9999.f ;
    float w(time, height) ;
        w:long_name = "Vertical component of wind vector" ;
        w:units = "m/s" ;
        w:missing_value = -9999.f ;
    float w_error(time, height) ;
        w_error:long_name = "Estimated error in vertical component of wind vector" ;
        w_error:units = "m/s" ;
        w_error:missing_value = -9999.f ;
    float wind_speed(time, height) ;
        wind_speed:long_name = "Wind speed" ;
        wind_speed:units = "m/s" ;
        wind_speed:missing_value = -9999.f ;
    float wind_speed_error(time, height) ;
        wind_speed_error:long_name = "Wind speed error" ;
        wind_speed_error:units = "m/s" ;
        wind_speed_error:missing_value = -9999.f ;
    float wind_direction(time, height) ;
        wind_direction:long_name = "Wind direction" ;
        wind_direction:units = "degree" ;
        wind_direction:missing_value = -9999.f ;
    float wind_direction_error(time, height) ;
        wind_direction_error:long_name = "Wind direction error" ;
        wind_direction_error:units = "degree" ;
        wind_direction_error:missing_value = -9999.f ;
    float residual(time, height) ;
        residual:long_name = "Fit residual" ;
        residual:units = "m/s" ;
        residual:missing_value = -9999.f ;
    float correlation(time, height) ;
        correlation:long_name = "Fit correlation coefficient" ;
        correlation:units = "unitless" ;
        correlation:missing_value = -9999.f ;
    float mean_snr(time, height) ;
        mean_snr:long_name = "Signal to noise ratio averaged over nbeams" ;
        mean_snr:units = "unitless" ;
        mean_snr:missing_value = -9999.f ;
    float snr_threshold ;
        snr_threshold:long_name = "SNR threshold" ;
```

```
		snr_threshold:units = "unitless" ;
		snr_threshold:missing_value = -9999.f ;
	float met_wspd(time) ;
		met_wspd:long_name = "Vector mean surface wind speed from MET" ;
		met_wspd:units = "m/s" ;
		met_wspd:missing_value = -9999.f ;
		met_wspd:cell_methods = "time: mean" ;
	float met_wdir(time) ;
		met_wdir:long_name = "Vector mean surface wind direction from MET" ;
		met_wdir:units = "degree" ;
		met_wdir:missing_value = -9999.f ;
		met_wdir:cell_methods = "time: mean" ;
	float met_spr(time) ;
		met_spr:long_name = "Mean surface precipitation rate during averaging period from MET" ;
		met_spr:units = "mm/hr" ;
		met_spr:missing_value = -9999.f ;
		met_spr:cell_methods = "time: mean" ;
	float met_spr_min(time) ;
		met_spr_min:long_name = "Minimum surface precipitation rate during averaging period
from MET" ;
		met_spr_min:units = "mm/hr" ;
		met_spr_min:missing_value = -9999.f ;
		met_spr_min:cell_methods = "time: minimum" ;
	float met_spr_max(time) ;
		met_spr_max:long_name = "Maximum surface precipitation rate during averaging period
from MET" ;
		met_spr_max:units = "mm/hr" ;
		met_spr_max:missing_value = -9999.f ;
		met_spr_max:cell_methods = "time: maximum" ;
	float met_dt ;
		met_dt:long_name = "Averaging period length used for MET data" ;
		met_dt:units = "second" ;
		met_dt:missing_value = -9999.f ;
	float met_lat ;
		met_lat:long_name = "MET latitude" ;
		met_lat:units = "degree_N" ;
		met_lat:missing_value = -9999.f ;
		met_lat:standard_name = "latitude" ;
	float met_lon ;
		met_lon:long_name = "MET longitude" ;
		met_lon:units = "degree_E" ;
		met_lon:missing_value = -9999.f ;
		met_lon:standard_name = "longitude" ;
	float met_alt ;
		met_alt:long_name = "MET altitude" ;
		met_alt:units = "m" ;
		met_alt:missing_value = -9999.f ;
		met_alt:standard_name = "altitude" ;
	float lat ;
		lat:long_name = "North latitude" ;
		lat:units = "degree_N" ;
```

```
		lat:valid_min = -90.f ;
		lat:valid_max = 90.f ;
		lat:standard_name = "latitude" ;
	float lon ;
		lon:long_name = "East longitude" ;
		lon:units = "degree_E" ;
		lon:valid_min = -180.f ;
		lon:valid_max = 180.f ;
		lon:standard_name = "longitude" ;
	float alt ;
		alt:long_name = "Altitude above mean sea level" ;
		alt:units = "m" ;
		alt:standard_name = "altitude" ;

// global attributes:
		:process_version = "vap-dlprof_wind-0.4-0.el6" ;
		:command_line = "idl -D 0 -R -n dlprof_wind -s sgp -f C1 -d 20150421" ;
		:dod_version = "dlprofwind4news-c1-1.0" ;
		:Conventions = "ARM-1.1" ;
		:site_id = "sgp" ;
		:platform_id = "dlprofwind4news" ;
		:location_description = "Southern Great Plains (SGP), Lamont, Oklahoma" ;
		:datastream = "sgpdlprofwind4newsC1.c1" ;
		:data_level = "c1" ;
		:facility_id = "C1" ;
		:input_datastreams = "sgpdlppiC1.b1 : 2.10 : 20150421.000624-20150421.234538\n",
			"sgpmetE13.b1 : 4.28 : 20150420.000000-20150422.000000" ;
		:dlat = "36.60530" ;
		:dlon = "-97.48649" ;
		:serial_number = "0710-07" ;
		:doi = "DOI:10.5439/1178582" ;
		:doi_url = "http://dx.doi.org/10.5439/1178582" ;
		:history = "created by user dsmgr on machine ruby at 2015-05-21 20:42:26, using vap-
dlprof_wind-0.4-0.el6" ;
```

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