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Improved Estimates of Moments and Winds from Radar Wind Profiler

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ARM
CLIMATE RESEARCH FACILITY

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

ACRF	ARM Climate Research Facility
ARM	Atmospheric Radiation Measurement Climate Research Facility
DOE	U.S. Department of Energy
ENA	Eastern North Atlantic
LCL	Lifting Condensation Level
MHz	megahertz
RWP	radar wind profiler
SGP	Southern Great Plains
SNR	signal-to-noise ratio

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1.0 Introduction

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) operates nine radar wind profilers (RWP) across its sites. These RWPs operate at 915 MHz or 1290 MHz frequency and report the first three moments of the Doppler spectrum. The operational settings of the RWP were modified in summer, 2015 to have single pulse length setting for the wind mode and two pulse length settings for the precipitation mode. The moments data collected during the wind mode are used to retrieve horizontal winds. The vendor-reported winds are available at variable time resolution (10 mins, 60 mins, etc.) and contain a significant amount of contamination due to noise and clutter. In this data product we have recalculated the moments and the winds from the raw radar Doppler spectrum and have made efforts to mitigate the contamination due to instrument noise in the wind estimates. Additionally, the moments and wind data has been reported in a harmonized layout identical for all locations and sites.

2.0 Input Data

The raw radar Doppler spectrum collected during the wind mode forms the basis of this data product. The algorithm has been tested for the RWP present at the ARM Southern Great Plains (SGP) and Eastern North Atlantic (ENA) sites.

3.0 Algorithm and Methodology

The general algorithm framework is shown in Figure 1. The algorithm is divided in two parts, calculation of improved estimates of moments, and calculation of winds fields.

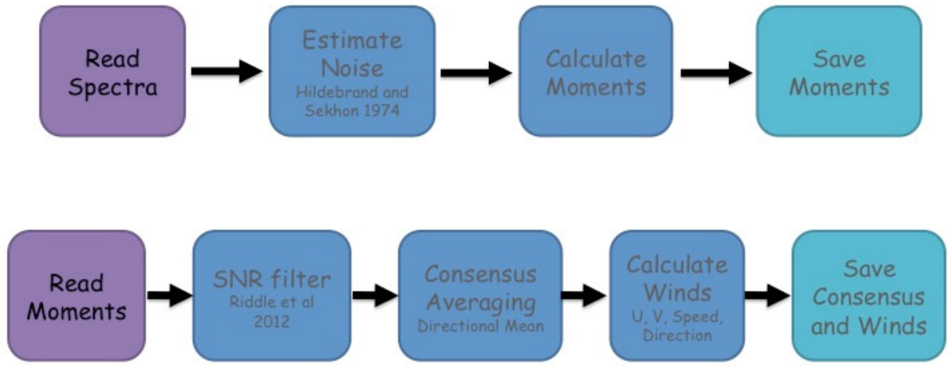

Figure 1. Flowchart describing the algorithm used to calculate the improved estimates of moments and winds.

3.1 Calculation of Moments

After reading the vendor reported spectral data from the wind mode, the noise floor for each Doppler spectrum is calculated using the Hildbrand and Sekhon (1974) technique. Estimates of the first three moments of the Doppler spectra—signal-to-noise ratio (SNR), spectral width, and velocity—are made by finding the peak in the spectrum that is above the noise floor and contains the velocity bin with the largest amplitude. The noise floor and calculated moments are saved in the moments datastream.

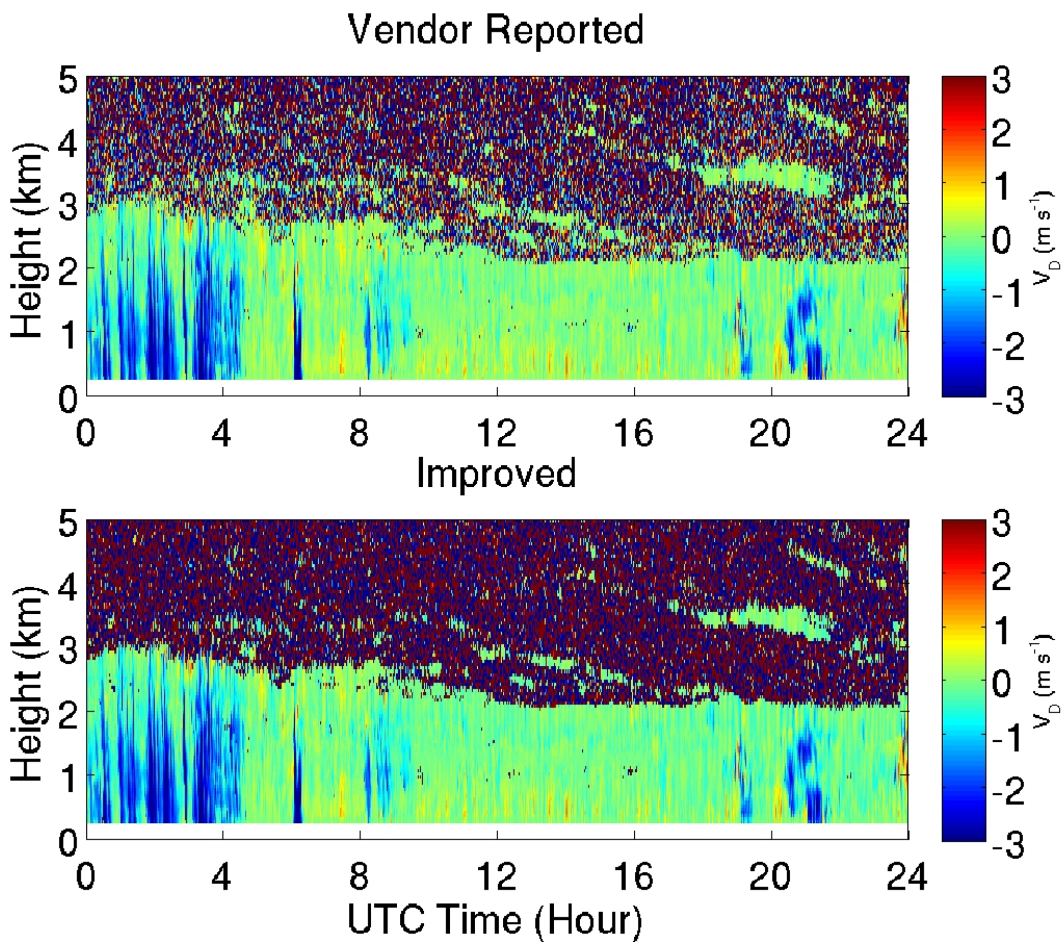

Figure 2. Time-height cross-section of the mean Doppler velocity recorded by the RWP at the ENA site in zenith pointing mode on 6 August, 2016. The vendor-reported values are shown in the top panel, while the improved estimates are shown in the bottom panel. Due to better noise estimates, echo boundaries are sharper.

3.2 Calculation of Consensus Velocities

To calculate a consensus velocity, all velocities within the consensus period are collected. A directional mean is used to average these velocities after removing samples for which the corresponding SNR is below an empirical threshold derived from the sampling parameters. This threshold is recorded in the output wind datastream's global attributes and follows the work by Riddle et al (2012). Consensus velocities are calculated at each range gate bin and beam, at the chosen consensus interval (10 minutes in this data product) and are stored in the output wind datastream. A sentinel missing value is used when no velocities within the consensus period are above the SNR threshold.

3.3 Calculation of Wind Fields

Using the consensus velocities for the three beams, the components of the horizontal wind (*u* and *v*) are calculated using the following equations:

$$A = \frac{V_{o1}\text{-} - cos\phi \cdot V_z}{sin\phi}$$

$$B = \frac{V_{o2}\text{-} - cos\phi \cdot V_z}{sin\phi}$$

$$v = \frac{A \cdot sin\theta_2 - B \cdot sin\theta_1}{cos\theta_1 \cdot \sin\theta_2 - \sin\theta_1 \cdot cos\theta_2}$$

$$u = \frac{B \cdot cos\theta_1 - A \cdot cos\theta_2}{cos\theta_1 \cdot \sin\theta_2 - \sin\theta_1 \cdot cos\theta_2}$$

Where V_{o1} and V_{o2} are the consensus radial velocities of the two oblique beams collected at azimuth angles of θ_1 and θ_2 and an off-zenith tilt angle of ϕ. V_z is the consensus radial velocity of the zenith beam.

In addition, the horizontal wind can be expressed in a speed and direction according to:

$$speed = \sqrt{A^2 + B^2}$$

$$direction = \arctan\frac{u}{v}$$

Both representations are calculated and included in the wind datastream.

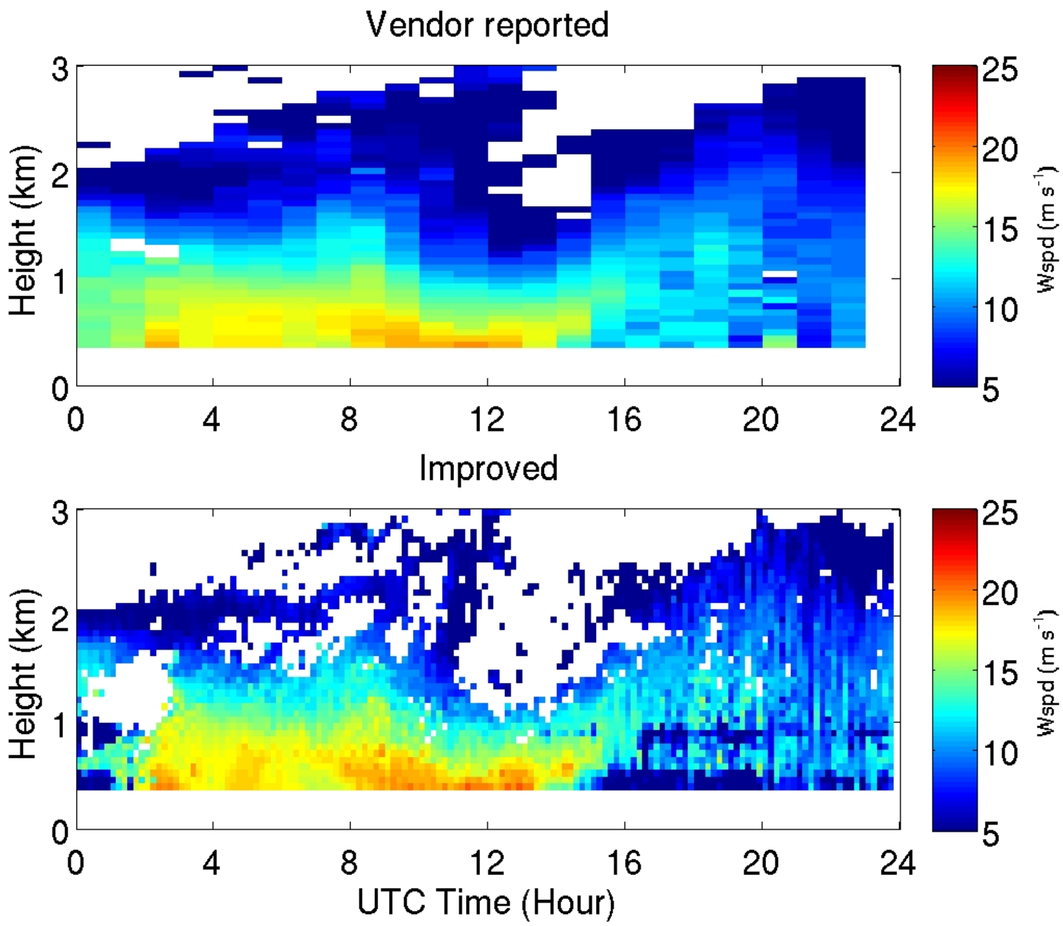

Figure 3. Time-height mapping of the horizontal wind speed reported by the RWP at the SGP I10 site on 10 June, 2016. The vendor-reported hourly values are shown in the top panel, while the improved 10-minute values are shown in the bottom panel.

4.0 Output

Below is the header of a moments file.

```
netcdf ena1290rwpwindmomentsC1.c1.20160610.000008 {
dimensions:
        time = UNLIMITED ; // (4813 currently)
        range_gate = 95 ;
        modes = 1 ;
        beams = 3 ;
        string_length = 64 ;
variables:
        int base_time ;
                base_time:string = "2016-06-10 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 2016-06-10 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 2016-06-10 00:00:00 0:00" ;
                time:standard_name = "time" ;
        float mean_radial_velocity(time, range_gate) ;
                mean_radial_velocity:long_name = "Mean radial beam velocity" ;
                mean_radial_velocity:units = "m/s" ;
                mean_radial_velocity:missing_value = -9999.f ;
                mean_radial_velocity:comment = "negative values indicate a downward motion towards
the instrument" ;
        float spectral_width(time, range_gate) ;
                spectral_width:long_name = "Spectral width" ;
                spectral_width:units = "m/s" ;
                spectral_width:missing_value = -9999.f ;
        float snr(time, range_gate) ;
                snr:long_name = "Signal to noise ratio" ;
                snr:units = "dB" ;
                snr:missing_value = -9999.f ;
        float noise(time, range_gate) ;
                noise:long_name = "Noise signal level" ;
                noise:units = "1" ;
                noise:missing_value = -9999.f ;
        int valid_height(modes, beams) ;
                valid_height:long_name = "Number of valid heights for each mode and beam" ;
                valid_height:units = "counts" ;
                valid_height:missing_value = -9999 ;
        int mode_flag(time) ;
                mode_flag:long_name = "Mode flag" ;
                mode_flag:units = "1" ;
                mode_flag:missing_value = -9999 ;
        int beam_flag(time) ;
                beam_flag:long_name = "Beam flag" ;
                beam_flag:units = "1" ;
                beam_flag:missing_value = -9999 ;
        char mode_description(modes, string_length) ;
                mode_description:long_name = "Description of the RWP operational modes" ;
                mode_description:units = "1" ;
        char beam_description(beams, string_length) ;
                beam_description:long_name = "Description of the RWP pointing beams" ;
                beam_description:units = "1" ;
        float elevation(modes, beams) ;
                elevation:long_name = "Elevation angle of beam" ;
                elevation:units = "degree" ;
                elevation:comment = "Angle between beam and horizon" ;
                elevation:missing_value = -9999.f ;
        float azimuth(modes, beams) ;
                azimuth:long_name = "Azimuth angle of beam" ;
```

```
                azimuth:units = "degree" ;
                azimuth:missing_value = -9999.f ;
        float nyquist_velocity(modes, beams) ;
                nyquist_velocity:long_name = "Nyquist velocity for a given mode and beam" ;
                nyquist_velocity:units = "m/s" ;
                nyquist_velocity:comment = "Doppler velocities measured by the instrument range from plus or minus the values reported in this variable" ;
                nyquist_velocity:missing_value = -9999.f ;
        float height(modes, beams, range_gate) ;
                height:long_name = "Array of heights for each mode and beam" ;
                height:units = "km" ;
                height:missing_value = -9999.f ;
        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:
                :Conventions = "ARM-1.2" ;
                :command_line = "./rwp_spectra_to_moments.py ../DATA/ena_2016/ena1290rwpwindspeclowC1.a0/ena1290rwpwindspeclowC1.a0.20160610.000008.nc" ;
                :process_version = "rwp_spectra_to_moments-1.0-0" ;
                :dod_version = "1290rwpwindmoments-c1-1.0" ;
                :input_datastreams = "ena1290rwpwindspeclowC1.a0 : 9.9 : 20160610.000008" ;
                :site_id = "ena" ;
                :platform_id = "1290rwpwindmoments" ;
                :facility_id = "C1" ;
                :data_level = "c1" ;
                :location_description = "Eastern North Atlantic (ENA), Graciosa Island, Azores" ;
                :datastream = "ena1290rwpwindmomentsC1.c1" ;
                :title = "Atmospheric Radiation Measurement (ARM) Facility Radar Wind Profiler Wind Moments" ;
                :institution = "U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Facility" ;
                :description = "Radar Wind Profilers Moments calculated from Doppler spectra" ;
                :doi = "10.5439/1327840" ;
                :doi_url = "http://dx.doi.org/10.5439/1327840" ;
```

```
		:frequency = "1290 MHz" ;
		:history = "created by user jhelmus on machine EVS353921L at 2016-12-09T10:31:53.154618" ;
}
```

Below is the header of a winds file.

```
netcdf ena1290rwpwindwindsC1.c1.20160610.000008 {
dimensions:
	time = UNLIMITED ; // (144 currently)
	range_gate = 95 ;
	modes = 1 ;
	beams = 3 ;
	bound = 2 ;
	string_length = 64 ;
variables:
	int base_time ;
		base_time:string = "2016-06-10 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 2016-06-10 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 2016-06-10 00:00:00 0:00" ;
		time:bounds = "time_bounds" ;
		time:standard_name = "time" ;
	double time_bounds(time, bound) ;
		time_bounds:long_name = "Time cell bounds" ;
		time_bounds:bound_offsets = 0., 600. ;
	float height(modes, range_gate) ;
		height:long_name = "Array of heights for each mode" ;
		height:units = "km" ;
		height:missing_value = -9999.f ;
	char mode_description(modes, string_length) ;
		mode_description:long_name = "Description of the RWP operational modes" ;
		mode_description:units = "1" ;
	float wind_speed(time, range_gate, modes) ;
		wind_speed:long_name = "Horizontal wind speed" ;
		wind_speed:units = "m/s" ;
		wind_speed:missing_value = -9999.f ;
	float wind_direction(time, range_gate, modes) ;
		wind_direction:long_name = "Horizontal wind direction" ;
		wind_direction:units = "degree" ;
		wind_direction:missing_value = -9999.f ;
```

```
        float u_wind(time, range_gate, modes) ;
                u_wind:long_name = "Easterly wind component" ;
                u_wind:units = "m/s" ;
                u_wind:missing_value = -9999.f ;
        float v_wind(time, range_gate, modes) ;
                v_wind:long_name = "Northerly wind component" ;
                v_wind:units = "m/s" ;
                v_wind:missing_value = -9999.f ;
        float radial_velocity(time, range_gate, modes, beams) ;
                radial_velocity:long_name = "Radial velocity of specific beam for each mode" ;
                radial_velocity:units = "m/s" ;
                radial_velocity:missing_value = -9999.f ;
        int samples_in_consensus(time, range_gate, modes, beams) ;
                samples_in_consensus:long_name = "Number of samples that met consensus criteria" ;
                samples_in_consensus:units = "1" ;
                samples_in_consensus:missing_value = -9999 ;
        int valid_height(modes) ;
                valid_height:long_name = "Number of valid heights for each mode and beam" ;
                valid_height:units = "1" ;
                valid_height:missing_value = -9999 ;
        float nyquist_velocity(modes, beams) ;
                nyquist_velocity:long_name = "Nyquist velocity for a given mode and beam" ;
                nyquist_velocity:units = "m/s" ;
                nyquist_velocity:missing_value = -9999.f ;
        float azimuth(modes, beams) ;
                azimuth:long_name = "Azimuth angle of beam" ;
                azimuth:units = "degree" ;
                azimuth:missing_value = -9999.f ;
        float elevation(modes, beams) ;
                elevation:long_name = "Elevation angle of beam" ;
                elevation:units = "degree" ;
                elevation:missing_value = -9999.f ;
        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:
```

```
		:Conventions = "ARM-1.2" ;
		:command_line = "./rwp_moments_to_winds.py -c 10 --lower_thresh -7.5 ena1290rwpwindmomentsC1.c1.20160610.000008.nc" ;
		:process_version = "rwp_moments_to_winds-1.0-0" ;
		:dod_version = "1290rwpwindwinds-c1-1.0" ;
		:input_datastreams = "ena1290rwpwindmomentsC1.c1 : 1.0 : 20160610000008" ;
		:site_id = "ena" ;
		:platform_id = "1290rwpwindwinds" ;
		:facility_id = "C1" ;
		:data_level = "c1" ;
		:location_description = "Eastern North Atlantic (ENA), Graciosa Island, Azores" ;
		:datastream = "ena1290rwpwindwindsC1.c1" ;
		:title = "Atmospheric Radiation Measurement (ARM) Facility Radar Wind Profiler Winds" ;
		:institution = "U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Facility" ;
		:description = "Radar Wind Profilers Winds." ;
		:doi = "10.5439/1327837" ;
		:doi_url = "http://dx.doi.org/10.5439/1327837" ;
		:frequency = "1290 MHz" ;
		:snr_threshold = -7.5 ;
		:consensus_period = 10. ;
		:history = "created by user jhelmus on machine EVS353921L at 2016-12-09T10:52:25.343440" ;
}
```

5.0 Uncertainty Estimates and Interpreting Output Data

Assuming the uncertainty of the calculated winds is caused solely by the uncertainty of the consensus velocities, these uncertainties were propagated to derived analytical expressions for the uncertainty of the horizontal components, *δ(v)* and *δ(u)*:

$$\delta(v) = \left|\frac{1}{\gamma \cdot sin\phi}\right| \cdot \sqrt{(\delta(v_1) \cdot sin\theta_2)^2 + (\delta(v_2) \cdot sin\theta_1)^2 + (\delta(v_z) \cdot \cos\phi \cdot (sin\theta_1 - sin\theta_2))^2}$$

$$\delta(u) = \left|\frac{1}{\gamma \cdot sin\phi}\right| \cdot \sqrt{(\delta(v_1) \cdot cos\theta_2)^2 + (\delta(v_2) \cdot cos\theta_1)^2 + (\delta(v_z) \cdot \cos\phi \cdot (cos\theta_2 - cos\theta_1))^2}$$

where

$$\gamma = cos\theta_1 \cdot sin\theta_2 - sin\theta_1 \cdot \cos\theta_2$$

Here $\delta(v_1)$ and $\delta(v_2)$ are the uncertainties of the oblique beam consensus velocities and $\delta(v_z)$ the uncertainty of the zenith beam consensus velocity. Other variables are identical to those defined above.

An estimate of the uncertainties of the consensus velocities for the three beams, $\delta(v_1)$, $\delta(v_2)$, and $\delta(v_z)$ was made by examining the standard deviation of the sampled velocities over each consensus period. Typical standard deviations for these populations were: 0.13 m/s for all beams at the ENA C1 site. 0.40 m/s for the zenith beam and 0.18 m/s for the oblique beams at the SGP C1 site. 0.34 m/s for the zenith beam and 0.14 m/s for the oblique beams at the SGP I8, I9, and I10 sites. The differences in the standard deviations between the RWPs and different beams are primarily due to the differences in sensitivity and dwell times. The standard error of the mean provides a good estimate of the consensus velocity uncertainties from the standard deviation:

$$\delta(v) = \frac{\sigma}{\sqrt{N}}$$

Where N is the number of samples that go into the calculation of the mean. These values are recorded in the wind datastream for each beam. Figure 2 provides plots of uncertainties for the wind components for the ENA and SGP sites for various numbers of samples using the standard deviations mentioned above for estimates of the uncertainty of the beam consensus velocities.

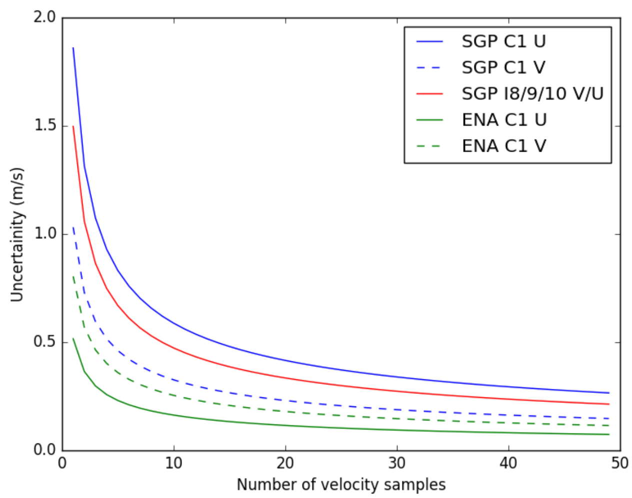

Figure 4. Plots of the dependencies of the uncertainties for the wind components for the ENA and SGP sites on the number samples using used to compute the mean.

The winds fields are calculated for every 10 minutes regardless of the number of samples that fit the consensus criteria. However, the number of samples used to calculate the consensus averages are reported in the wind datastream. Below we have summarized the maximum number of consensus samples that go for each RWP. We have also reported the recommended threshold for the number of samples going to the consensus averaging that we deem suitable for using wind fields. The differences in the maximum number of samples and the threshold between the sites us primarily due to differences in the operational settings of the RWP. The table below is applicable for data collected after summer, 2015.

Table 1. Consensus samples for each RWP.

Location	Maximum number of samples of vertical beam within 10-minute period	Recommended threshold for number of samples in the vertical beam consensus for wind fields
SGP C1	15	6
SGP I8, I9, and I10	6	4
ENA	12	10

6.0 Example Plots and Known Issues

The SNR recorded by the RWPs present at the ARM SGP site on 10 June, 2016 is shown in Figure 5.

- A static clutter signal can be seen ~1100m at the SGP-C1 RWP. Although the number of samples going into the consensus averages and hence in the wind calculations will be high at this level, we discourage use of winds from these heights. A sophisticated technique is needed to objectively identify clutter signals during various weather phenomenon.
- Clouds were present during this day as shown by the ceilometer-detected cloud base height estimates. The fall velocity of the hydrometeor affects the mean Doppler velocity reported by the radar and hence influences the wind estimates. This issue is severe during precipitation events. Caution must be taken to avoid using data during precipitating conditions because the reported wind estimates do not correspond to background winds at those times.

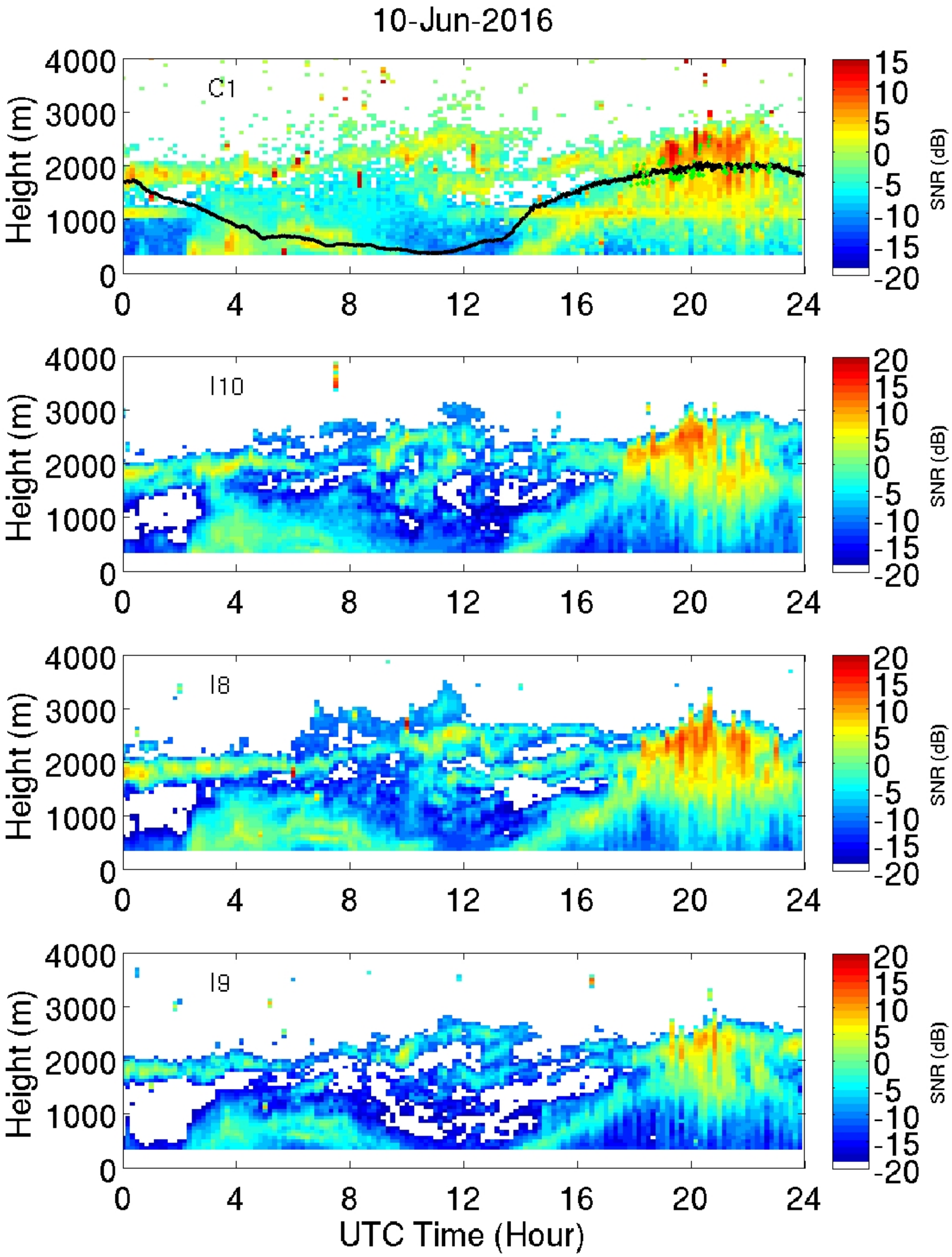

Figure 5. Time-height cross-section of the SNR reported by the RWP at the SGP sites on 10 June, 2016. The facility locations are reported in each panel. The Lifting Condensation Level (LCL)

calculated from the surface met station (black), and the ceilometer-recorded cloud base height (green dots) are shown in the top panel.

7.0 References

Hildebrand, PH, and RS Sekhon. 1974. "Objective Determination of the Noise Level in Doppler Spectra." *Journal of Applied Meteorology* 13: 808-811, doi:10.1175/1520-0450(1974)013<0808:ODOTNL>2.0.CO;2.

Riddle, AC, LM Hartten, DA Carter, PE Johnston, and CR Williams. 2012. "A Minimum Threshold for Wind Profiler Signal-to-Noise Ratios." *Journal of Atmospheric and Oceanic Technology* 29: 889-895, doi:10.1175/JTECH-D-11-00173.1.

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