User's Guide

McGill Radar Doppler Spectra Simulator Software v 1.0

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1 Introduction

The McGill Radar Doppler Spectra Simulator (**MRDSS**) uses input from high resolution Large Eddy Simulations (LES) and Cloud Resolving Models (CRMs) and computes forward modeled radar Doppler spectra from profiling radars (Figure 1). The code is written in MATLAB and uses as input the explicit (bin) microphysics. Bulk microphysical variables can be easily used as input if the user provides a small routine to convert its bulk variables (water content, number concentration) to size distributions.

The output produced by the MRDSS is a netcdf file. The list of output variables is given in Table 5 (Section 4).

Please note that this version MRDSS v1.0 is provided exclusively for liquid phase input from the LES model. For ice/snow cases, the code has to be adapted. In this case, user has to introduce the proper particle backscatter and extinction coefficients. This issue will be addressed on in the next version.

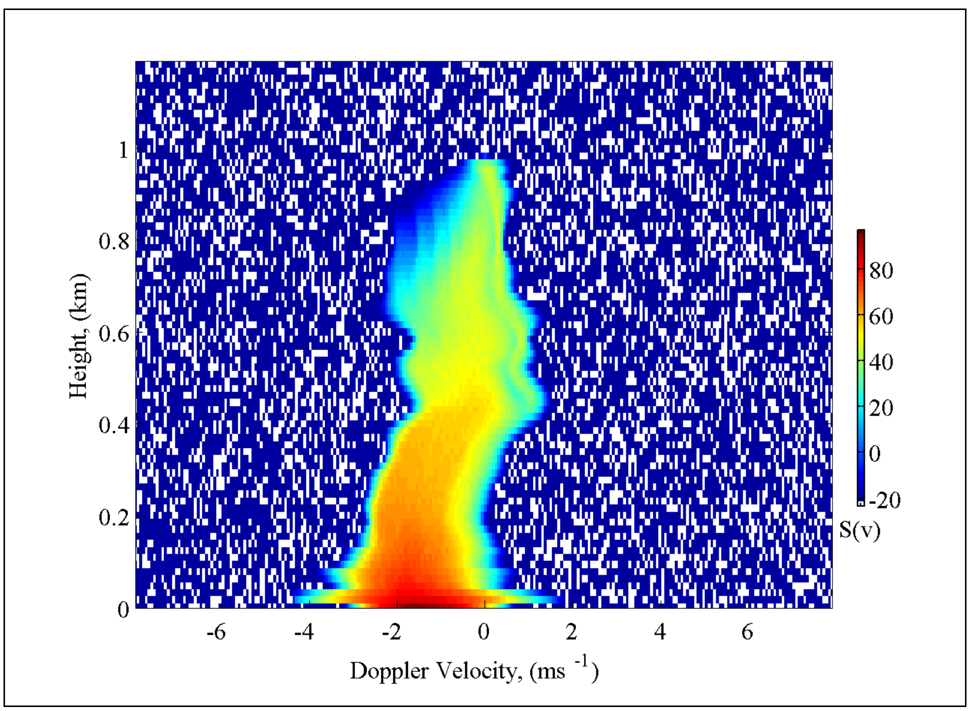

Figure 1: Example of synthetic radar Doppler spectrum from MRDSS

The main features of the MRDSS are the following:

- Accounts for gaseous attenuation calculated using Rosenkranz (1998)
- Account for liquid scattering and attenuation using Mie (1908)
- Provides output at two vertical resolutions: model and radar (specified)
- The model resolution output assumes uniform beam filling conditions
- The radar resolution output accounts for non-uniform beam filling conditions
- Range of input radar frequencies from 0.1-300 GHz
- Offers a complete radar instrument model (Kollias et al., 2014)
- Calculates the kinematic broadening of the Doppler spectrum using model output
- Includes range-dependent radar receiver noise and signal integration
- Post-processing of the radar Doppler spectrum and moment estimation

A test LES scene (drizzling stratus) has been kindly provided by Dr. Andrew Ackerman (NASA/GISS) to help us demonstrate the features of the simulator. The test scene dharma_008884.cdf is included in the MRDSS package and should be used only to test the simulator and not to extract conclusions about the numerical model. Jasmine Remillard (NASA/GISS) provided valuable comments to improve the functionality and speed of the MRDSS.

 If you use the MRDSS software package or its subroutines to simulate LES/CRM model output used in publication, an acknowledgment or reference to Kollias et al., 2014 would be appreciated. If you have any comments, suggestions for improvements, bug fixes or you need help to interface MRDSS with your model output, please contact us (pavlos.kollias@mcgill.ca).

References:

1. Mie, G., 1908: Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen. Ann. Physik, 25, 377–445.

2. Rosenkranz, P. W. (1998), Water vapor microwave continuum absorption: A comparison of measurements and models, Radio Sci., 33(4), 919–928, doi:10.1029/98RS01182.

3. Kollias, Pavlos, Simone Tanelli, Alessandro Battaglia, Aleksandra Tatarevic, 2014: Evaluation of EarthCARE Cloud Profiling Radar Doppler Velocity Measurements in Particle Sedimentation Regimes. *J. Atmos. Oceanic Technol.*, 31, 366–386.

2 Installation

Download the latest version of the MRDSS release. The source code is named MRDSS_[release version].tar.gz. Unpack the software by typing the following:

tar –zxvf MRDSS_[release version].tar.gz

Main distribution of *.m files in the directory **MRDSS** is shown in Table 1.

Table 1: The list if the matlab source files

Name	Description
MRDSS_main.m	Main function that calls all other functions and performs the forward simulation of the LES to radar Doppler spectra at both model (LES) resolution and radar instrument resolution
les_explicit_liquid_scattering.m	This function computes particle backscatter cross section and extinction
scatt.m	Function called by les_explicit_liquid_scattering.m. It computes the scattering coefficients for particles with fixed size x and refractive index relative to medium using the Riccati-Bessel functions of the first and second kind.
ml_dielect.m	Function called by les_explicit_liquid_scattering.m. It computes the complex index of refraction.
gas_attenuation_rose98.m	This function calculates attenuation by various gasses using the method of Rosenkranz (1998)
Turbulence_Convolution.m	This function performs turbulence convolution
spectra_generator.m	This function computes the radar Doppler spectra with Noise and broadening
hsmethod.m	This function computes the noise floor of the radar Doppler spectrum
spectra_unfolding.m	This function performs unfolding of the radar Doppler spectra
spec_to_mom_les_spectra.m	Radar Doppler spectra moment computation
LES_to_DS_netcdf.m	This function writes the MRDSS output variables in the output netcdf file
plot_diagnostic_1.m	This function plots the PSD moments
plot_diagnostic_2.m	This function plots some key input parameters to the MRDSS, the complete spectrogram for a particular (x,y) point of the LES output and the profiles of some key parameters
plot_diagnostic_3.m	This function plots the spectrograms for the LES and Radar vertical resolution
plot_diagnostic_4.m	This function plots z-y plots with 1) dBZ and Skewness and 2) velocity and width
plot_diagnostic_5.m	This function plots liquid water content, and liquid and gaseous 2-way attenuation

3 MRDSS structure

The MRDSS algorithm flow chart is shown in Figure 2. The model processes as depicted.

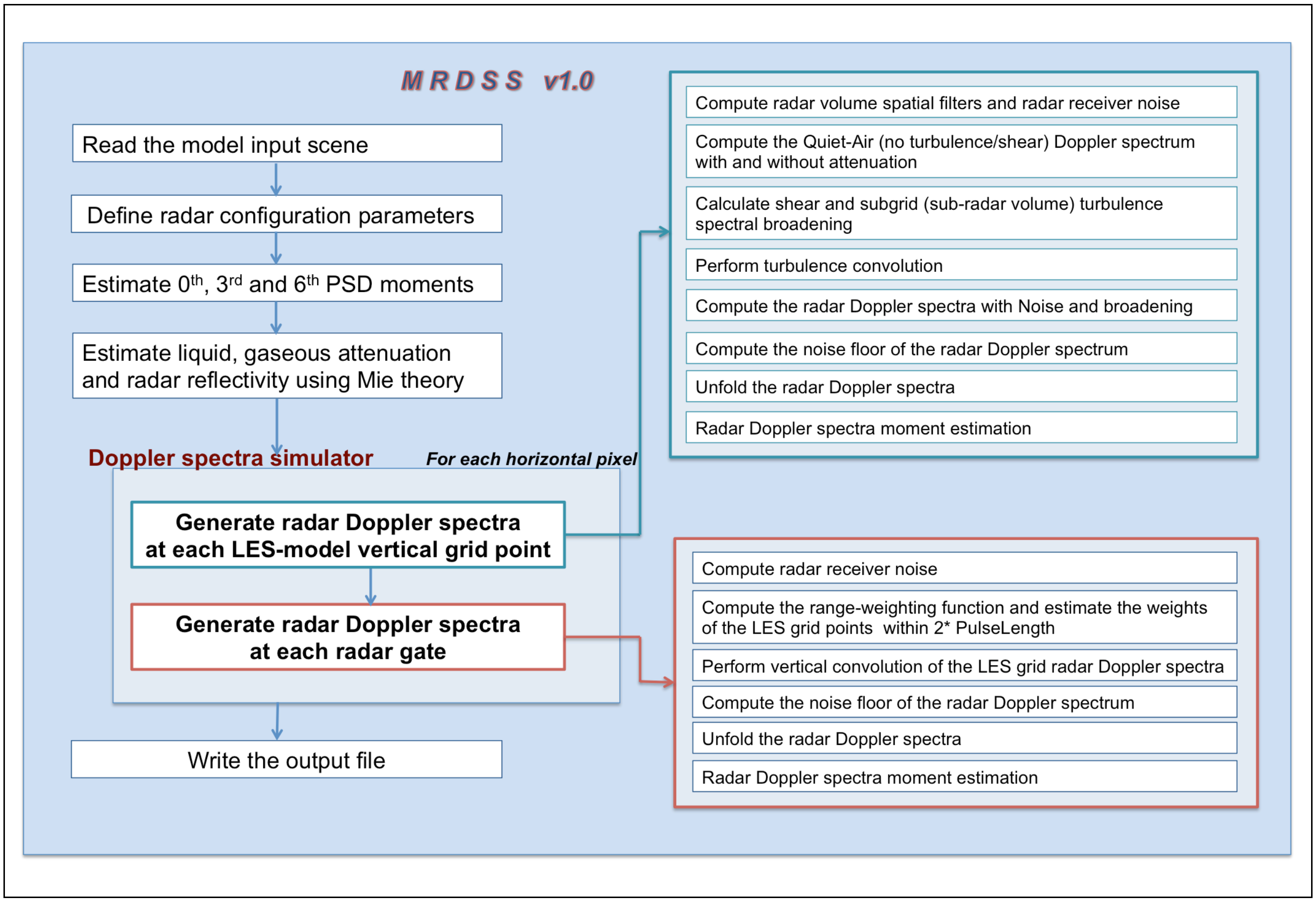

Figure 2: MRDSS algorithm flow chart

The main code is called MRDSS_main.m and calls all the functions needed to run the simulator. The code structure is documented in the following Sections.

3.1 Section 1, MRDSS_main: Input the model scene

Section 1 reads the test scene. Configuration paths that should be modified here in order to correspond to your system configuration are listed bellow:

HomeDir -> MRDSS home directory

InpFileName = 'dharma_008884.cdf' -> the name of the LES test input scene

OutFileName -> the path and the name of the output file

tabulated_data_path -> where the tabulated data are stored

For testing purposes, an LES test scene is provided and all necessary variables are read. The minimum input values are:

Table 2: The list of input dimensions and variable names as provided in the test LES scene (drizzling stratus)

Dimensions				
Symbol	**Meaning**			
nx	Number of grid boxes along the horizontal E-W axis			
nxp1	Number of grid box boundaries along the horizontal E-W axis equal to nx+1			
ny	Number of grid boxes along the horizontal N-S axis			
nyp1	Number of grid box boundaries along the horizontal N-S axis equal to ny+1			
nz	Number of grid boxes along the vertical axis			
nzp1	Number of grid box boundaries along the vertical axis equal to nz+1			
nbin	Number of droplet size bins			
nbinp1	Number of droplet size bin boundaries			
Variables				
Symbol	**Description**	**Units**	**Dim**	**Type**
x	E location of grid box center	m	nx	FLOAT
y	N location of grid box center	m	ny	FLOAT
z	Altitude of grid box center	m	nz	FLOAT
P	Air pressure	mb	nz	FLOAT
T	Air temperature	K	nx,ny,nz	FLOAT
qv	Water vapor mixing ratio	$g\ kg^{-1}$	nx,ny,nz	FLOAT
u	Westerly wind	$m\ s^{-1}$	nxp1,ny,nz	FLOAT
v	Southerly wind	$m\ s^{-1}$	nx,nyp1,nz	FLOAT
w	Vertical wind	$m\ s^{-1}$	nx,ny,nzp1	FLOAT
sgs_diss	Subgrid-scale dissipation	$m^2\ s^{-3}$	nx,ny,nz	FLOAT
r_drops	Radius of mass-weighted droplet bin center	μm	nbin	FLOAT

rbound_drops	Radius at boundary between droplet bins	μm	nbinp1	FLOAT
rhop_drops	Droplet mass density	g cm^{-3}	nbin	FLOAT
vfall_drops	Droplet fall speed	m s^{-1}	nz,nbin	FLOAT
dN_drops	Number concentration of droplets in size bin	cm^{-3}	nx,ny,nz,nbin	FLOAT

The MRDSS code is tailored to read the output format (netcdf) and variables names produced by the NASA GISS **D**istributed **H**ydrodynamic **A**erosol and **R**adiative **M**odeling **A**pplication (**DHARMA**) model. Users with different model output will have to modify the reading routine and ensure that the variable name is consistent with the rest of the code.

3.2 Section 2, MRDSS_main: Setup the radar configuration parameters

In the part Section 2 of MRDSS_main.m, the user can configure the radar parameters given in Table 3. Default setting of radar configuration parameters is close to Ka-band ARM Zenith Radar (KAZR).

Table 3: Radar configuration parameters

Radar configuration parameters			
Parameter name	**Units**	**Value**	**Description**
PulseLength*	m	45	Length of radar pulse
VerticalSampling	m	20	Vertical sampling A/D (digitization) length interval
TimeSampling	s	2	Integration time
Frequency	GHz	94	Radar Frequency
Diameter	m	1.8	Antenna diameter
PRF**	Hz	1.e+4	Pulse Repetition Frequency
c	m s^{-1}	2.9979e+8	Speed of light
NOISE_1km	mm^6 m^{-3}	1.e-5	Noise power in dBZ at 1 km expressed in linear units
NFFT***	-	256	Number of FFT points
zr_min	m	150	First range gate of the radar (should be ≥ 2*PulseLength)
zr_max	m	1200	Last range gate of the radar
zr_dr	m	VerticalSampling	Length of discrete element along a single radial of radar data at which the received signals are sampled (range resolution-it is usually higher than true pulselength)
Radar Parameters derived from given configuration parameters			
Symbol	**Units**	**Definition**	**Description**
PW	s	2*PulseLength/c	Pulse duration
Lambda	m	c/(Frequency*10^9)	Radar wavelength

VNyquist	m s^{-1}	Lambda*PRF/4	Nyquist velocity
Theta	degrees	70*Lambda/Diameter	Antenna beamwidth (3-dB one way)
Theta_rad	radians	Theta*pi/180	Antenna beamwidth (3-dB one way) in radian
Nave	-	round(TimeSampling*PRF/NFFT)	Number of spectral averages
sigma_theta	radians	Theta_rad/(4*sqrt(log(2)))	Multiplication factor needed to determine the physical diameter of the V6 volume
sigma_r	m	0.35*PW*c/2	The width of the range resolution weighting function
zr	m	zr_min : zr_dr : zr_max	Radar range gates

*The PulseLength should be the true radar resolution determined by the pulse length and not the radar resolution of the radar data (VerticalSampling) that is often higher than the PulseLength.
**The PRF is typically 10 kHz for a W-band radar and around 3-5 kHz for a Ka-band radar.
***A nominal number of spectral points (NFFT) is 256.

The following set of 5 configuration parameters should be set to "1" if you wish to produce the figures similar to those in this document. Note that created figures are not automatically saved.

- **plot_diagnostic_1_flag** - plot the N(D) moments
- **plot_diagnostic_2_flag** -plot some of the key input parameters to the radar Doppler spectra simulator, the complete spectrogram for a particular (x,y) point of the LES output, and the profiles of some key parameters some of the key input parameters to the radar
- **plot_diagnostic_3_flag** - plot the two spectrograms for the LES and Radar Vertical Resolution
- **plot_diagnostic_4_flag** - plot some z-y plots to see the simulations :one plot with dBZ and Skewness ant the another one with velocity and width
- **plot_diagnostic_5_flag** - plot LWC, A_liquid and A_gases

3.3 Section 3, MRDSS_main: Compute particle size distribution moments

In this step, the 0^{th}, 3^{rd} and 6^{th} moment of the N(D) are computed. You can plot them if you set the "plot_diagnostic_1_flag" to 1. An example of the plotting output from the plot_diagnostic_1.m subroutine is shown in Figure 3.

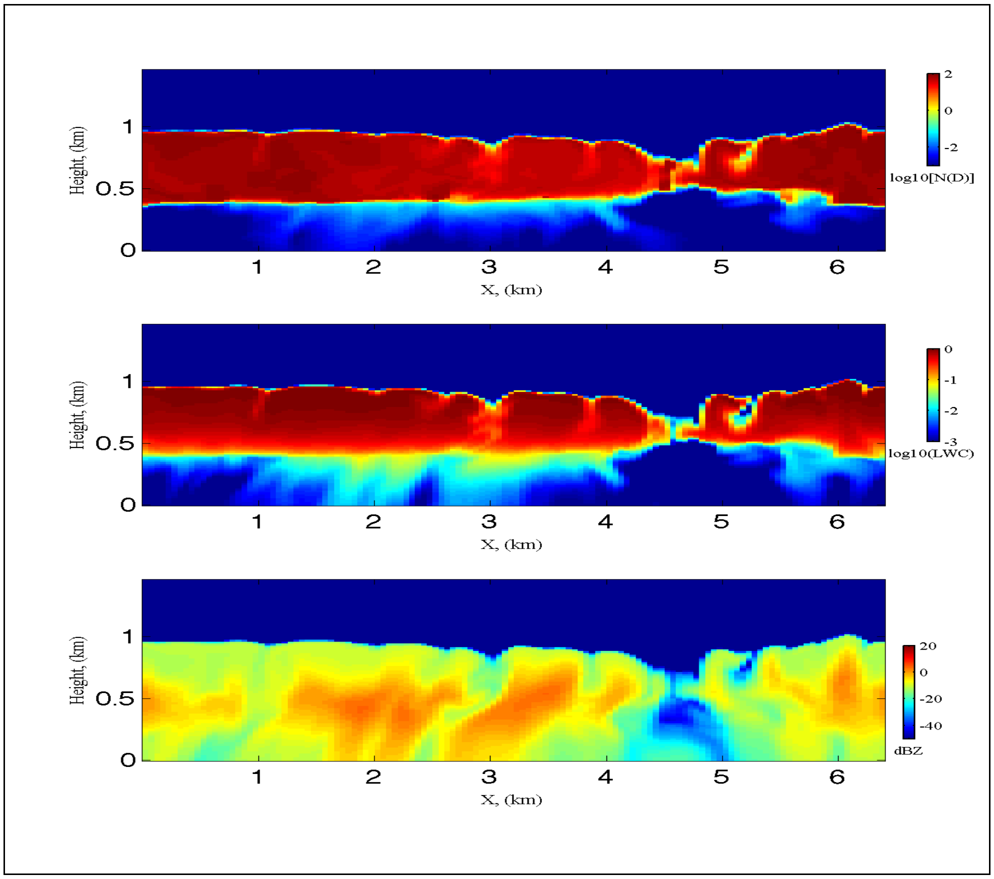

Figure 3: Example of the total number concentration (0^{th} moment, top panel), liquid water content (3^{rd} moment, middle panel) and radar reflectivity factor (6^{th} moment, bottom panel) computed from the microphysical model output for a specific vertical cross section.

3.4 Section 4, MRDSS_main: Compute liquid, gaseous attenuation and radar reflectivity using Mie theory

The "les_explicit_liquid_scattering" function accepts as input the particle diameter in micrometers, the particle density in g/cm^3, the radar wavelength in cm and the temperature in K. The output are Ze_Dl in mm^6 which is use to compute the radar reflectivity (Ze_Mie) and A_Dl in dB/km that is used to compute the liquid attenuation (A_liquid) at each grid point and the accumulated (A_liquid_accum). The "gas_attenuation_rose98" function accepts as input the profiles of: atmospheric pressure (mbar), temperature (Celsius), relative humidity (%), radar frequency (GHz) and vertical grid spacing and computes the gaseous attenuation due to water vapor and oxygen. You can plot them if you set the "plot_diagnostic_5_flag" to 1. An example of the plotting output from the plot_diagnostic_5.m subroutine is shown in Figure 4.

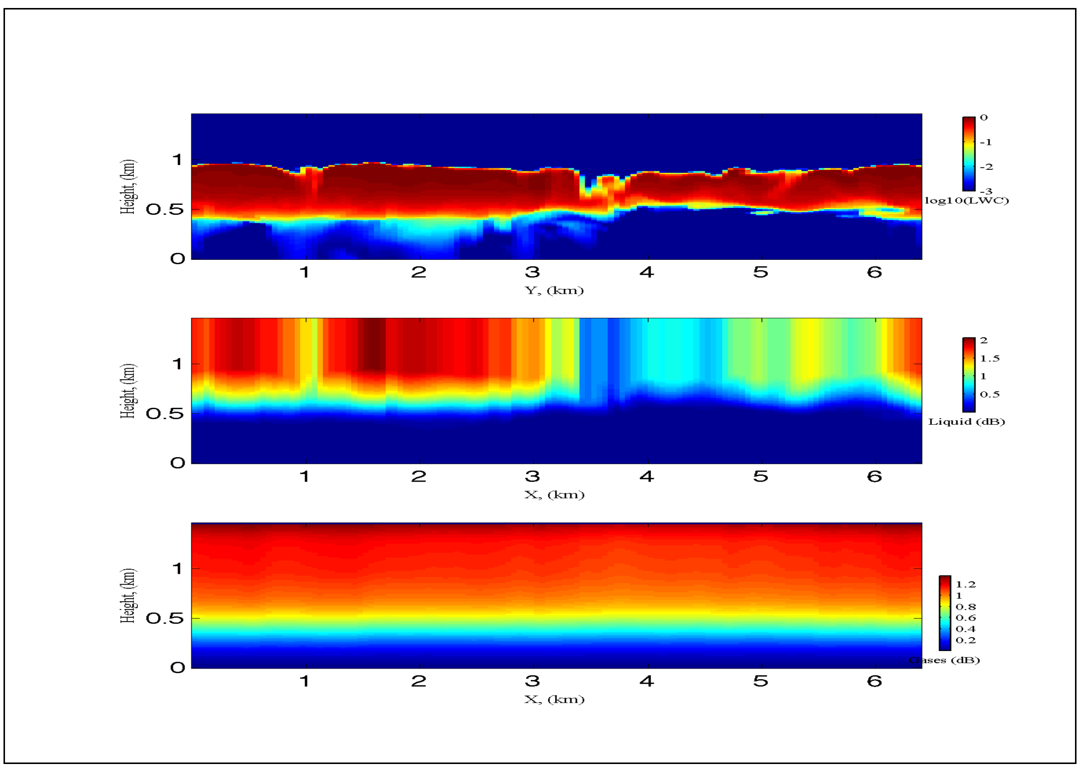

Figure 4: Example of the liquid water content (top panel), two-way liquid attenuation (middle panel) and two-way gaseous attenuation (bottom panel) from the microphysical and the propagation models for a specific vertical cross section.

3.5 Section 5, MRDSS_main: Radar Doppler Spectra Simulator

This is the most important part of the MRDSS. Section 5 contains all the function needed to compute the radar Doppler spectrum using the model output at each grid point and is sub-divided in ten subsections.

3.5.1 Subsection 5.1: Memory Allocation

This Subsection deals with declaration and definition of turbulence variables, spectra variables at LES vertical resolution and spectra variables at radar vertical resolution.

3.5.2 Subsection 5.2: Define the radar volume spatial dimensions and radar noise

The radar receiver noise is provided as a function of range, increasing with the square of the radar range and thus emulating this way the reduction in radar sensitivity with range. The parameter NOISE_1km can be set in Section 2. The noise is expressed in mm^6m^{-3} units, so when combined with the simulated Z can provide an estimate of the Signal-to-Noise Ratio (SNR). The parameter sx and sz are required in order to compute the kinematical broadening (Subsection 5.4).

3.5.3 Subsection 5.3: Compute the non-turbulent radar Doppler spectrum

The radar Doppler spectrum S(v) in units of $mm^6/m^3/ms^{-1}$ is defined using the following formula:

$$S(V) = N(D) \cdot \sigma(D) \cdot \frac{dD}{dV} \tag{1}$$

An interpolation is used to ensure proper computation of the non-turbulent radar Doppler spectrum with attenuation Sv_att and without attenuation Sv. The final step is to compute the vertical air motion W_air in the LES grid box and to determine the total Doppler velocity Vd combining the hydrometeor fall velocity Vb_all and vertical air motion W_air.

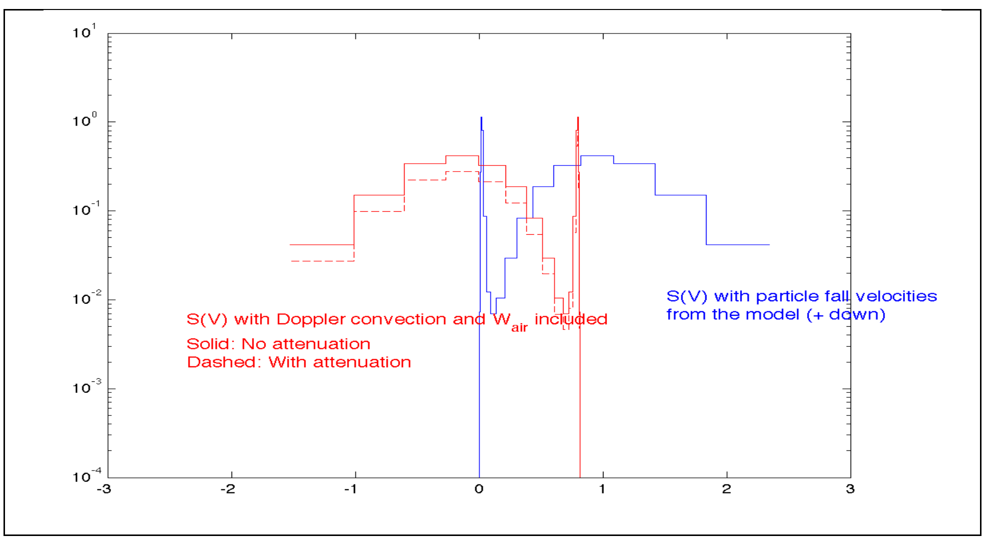

Figure 5: The initial S(v) computed using formula above (blue), the S(v) with radar convection for Doppler velocities without (red solid) and with (red dashed) attenuation. The x-axis units are ms^{-1} and the y-axis units are $mm^6/m^3/ms^{-1}$.

3.5.4 Subsection 5.4: Compute shear and sub-grid (sub-radar volume) turbulence spectral broadening

Three contributions to the kinematic broadening of the radar Doppler spectrum are considered. The first spectral broadening term is due to the antenna motion (or advection of the field across the antenna field of view) SH_magnitude_UV contribution. This term is computed using the following formula (Sloss and Atlas, 1968):

$$\sigma_{ant} \approx 0.3 \cdot U_{hor} \cdot \theta_{3dB}$$

where U_{hor} is the horizontal wind speed. This term is usually very small and matters only if you simulate a radar with very broad beamwidth. The second broadening term is the vertical (W) wind shear across (SH_horizontal_x_W [sh_xW] and SH_horizontal_y_W [sh_yW]) and along (SH_vertical_W [sh_zW]) the forward direction of E/M propagation. Here, the W field is assumed to vary linearly across the LES grid point and can be calculated using the W velocity values in the LES grid boxes surrounding the LES grid point of interest. Once the three terms are determined, the total spectral broadening due to wind shear is given by (Doviak and Zrnic, 1993):

$$\sigma_{shear} = [(z \cdot sx \cdot sh\_xW)^2 + (z \cdot sx \cdot sh\_yW)^2 + (sz \cdot sh\_zW)^2]^{1/2}$$

where z is the range (height).

The final term is the spectral broadening due to the LES sub-grid (sub-radar resolution volume) turbulence. This term requires information on the eddy dissipation rate e_diss within the LES grid volume. If this is provided (as is the case in the LES model output from DHARMA) or is calculated using other resolved parameters then the following formula is used to compute the turbulence induced broadening (Doviak and Zrnic, 1993):

$$if\ sz \leq z \cdot sx$$

$$\sigma_{turb} = \left(\frac{z \cdot sx \cdot 1.6^{1.5} \cdot e\_diss}{0.72}\right)^{1/3}$$

else

$$\sigma_{turb} = \left(e\_diss \cdot sz \cdot (1.35 \cdot 1.6)^{1.5} \cdot \left(\frac{11}{15} + \frac{4}{15} \cdot \left(\frac{z \cdot sx}{sz} \right)^2 \right)^{1.5} \right)^{1/3}$$

The total kinematical broadening of the radar Doppler spectrum is computed as follows:

$$\sigma_t = \left(\sigma_{ant}^2 + \sigma_{shear}^2 + \sigma_{turb}^2 \right)^{1/2}$$

3.5.5 Subsection 5.5: Turbulence convolution (spectral broadening)

The non-turbulent radar Doppler spectrum S(v) (variable Sv_att in the code) is convoluted with a Gaussian function with standard deviation equal to the total kinematical broadening of the radar Doppler spectrum σ_t (variable st in the code) according to Gossard, 1994. The output spectrum (turb_spectra) has a corresponding velocity array velo. An example of the radar Doppler spectrum before and after the turbulence convolution is shown in Figure 6.

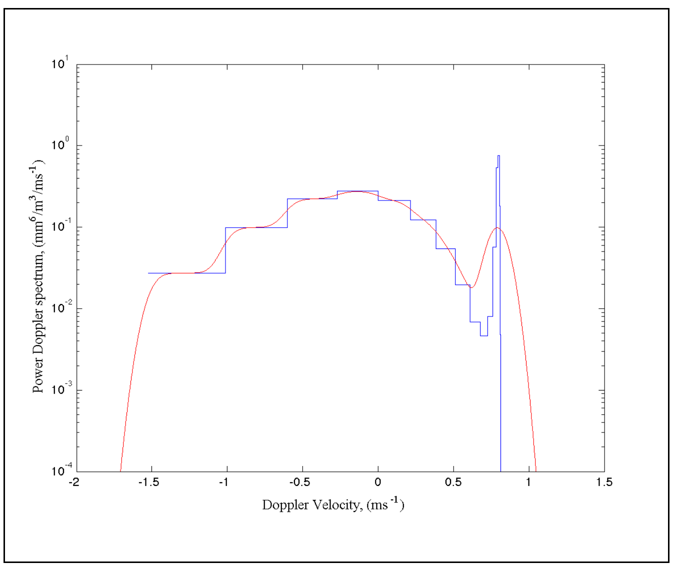

Figure 6: Example of quite-air radar Doppler spectrum (blue, input to the function Turbulence_Convolution) and turbulent radar Doppler spectrum (red, output of the Turbulence_Convolution function).

3.5.6 Subsection 5.6: Compute the radar Doppler spectra with Noise

Here noise is added to the radar Doppler spectrum using the methodology described in Zrnic, 1975. The inputs to the function spectra_generator are the number of FFT-points in the radar Doppler spectrum (NFFT), the radar receiver noise (Noise(k)), the number of spectral averages (Nave, calculated by the radar instrument model in Section 2), the Nyquist velocity (VNyquist), and the output of the function Turbulence_Convolution: velo, turb_spectra. An example of the output of the spectra_generator function is shown in Figure 7.

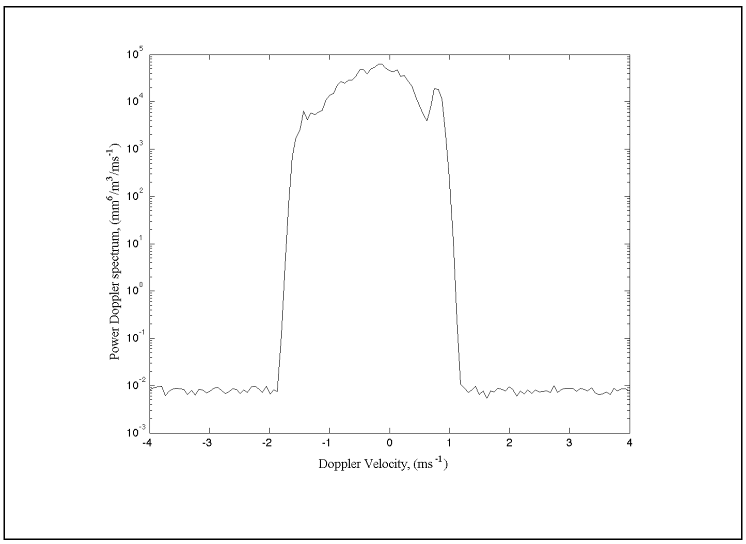

Figure 7: Radar Doppler spectra with noise. Looks smooth since we are using a very large number of I/Q samples and spectral averages.

3.5.7 Subsection 5.7: Compute the noise floor of the radar Doppler spectrum

The noise floor of the radar Doppler spectrum is determined using the methodology proposed by Hildebrand and Sekhon, 1974. The main output of the hsmethod function is the variable Nmean that is the value of the noise floor used in the rest of the code.

3.5.8 Subsection 5.8: Unfold the radar Doppler spectra before moment estimation

The function spectra_unfolding unfolds the radar Doppler spectra *only if* the fall velocity of the hydrometeors is large enough in order to produce partial or complete aliasing of the all the velocities (frequencies) of the hydrometeors. The main output of the spectral_unfolding function is the spectral velocity array (spectra_velo_unfold), and the unfolded radar Doppler spectrum (noise_turb_spectra_unfold).

3.5.9 Subsection 5.9: Radar Doppler spectra moment computation

The spec_to_mom_les_spectra function computes several parameters of interest from the radar Doppler spectra. The output variables are: i) the normalized signal power m0. The signal power is normalized by the radar receiver noise (in the spectra_generator function) and this is the reason the radar receiver noise is needed to recover the true radar reflectivity, ii) the mean Doppler velocity Velo, iii) the radar Doppler spectrum width Width, iv) the radar Doppler spectra skewness Skew, v) the radar Doppler spectrum kurtosis Kurt, vi) the left slope of the radar Doppler spectrum LS, and vii) the right slope of the radar Doppler spectrum RS. The estimation of these moments and parameters is based on Kollias et al., 2007.

Using the function plot_diagnostic_2 you can produce the following plot that shows some of the key input parameters to the radar Doppler spectra simulator, the complete spectrogram for a particular (x,y) point of the LES output and the profiles of some key parameters. An example is shown in Figure 8.

Starting from the top row from left to right plotted are the profiles of the particle size distribution N(D), the liquid water content (LWC) and the number concentration N_T. These three parameters are provided directly by the LES model output or the numerical model of the user. In the middle row plotted from left to right are left: the vertical air motion (W_air) and the total kinematic broadening of the radar Doppler spectrum (st); middle: the profiles of the three shear terms, the vertical

(W) wind shear across (SH_horizontal_x_W [sh_xW] and SH_horizontal_y_W [sh_yW]) and along (SH_vertical_W [sh_zW]); and right: the profiles of the sub-grid volume turbulence broadening term (Std_turb) and the antenna motion SH_magnitude_UV term. Finally, in the bottom row are plotted from left to right, the radar Doppler spectra spectrograph (waterfall plot of all the simulated radar Doppler spectra for this profile), the profiles of mean Doppler velocity (note the random values that the moment estimator provides when there is no signal) and spectrum width and the right panel shows the profile of the radar Doppler spectra skewness.

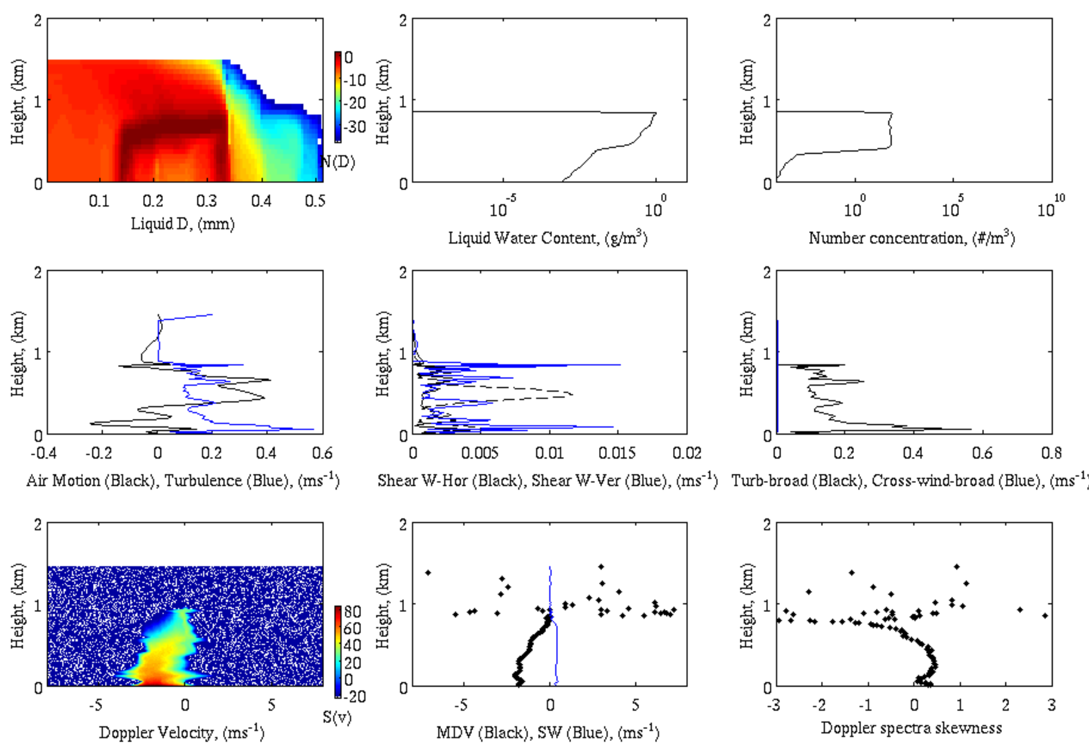

Figure 8: The plot produced by plot_diagnostic_2 showing some of the key input parameters to the radar Doppler spectra simulator, the complete spectrogram for a particular (x,y) point of the LES output and the profiles of selected parameters.

3.5.10 Subsection 5.10: Generate the radar Doppler spectra at the radar resolution

LES models have typically fixed horizontal resolution (50-100 m) but have often very high vertical resolution (e.g., 5-10 m) that also varies with height. On the contrary, profiling radars have typically lower vertical resolution (30-45 m) and fixed with height. The MRDSS produces synthetic radar Doppler spectra at two vertical resolutions: the model resolution (LES or CRM) and the radar range resolution dictated by the radar digital receiver sampling rate (VerticalSampling). However, the true vertical resolution of the radar is determined by the pulse length (PulseLength). These parameters can be set in Section 2 that describes the radar instrument model. The important parameters are given in Table 4.

Table 4: Configuration parameters relevant for the definition of radar range resolution

Radar configuration parameters			
Parameter name	**Units**	**Value**	**Description**
PulseLength*	m	45	Length of radar pulse
VerticalSampling		20	Vertical sampling A/D (digitization)
zr_min	m	150	First range gate of the radar (should be ≥ 2*PulseLength)
zr_max	m	1200	Last range gate of the radar
zr_dr	m	VerticalSampling	Radar range resolution: Length of discrete element along a single radial of radar data at which the received signals are sampled (resolution usually higher than true pulselength)
Radar Parameters derived from given configuration parameters			
Symbol	**Units**	**Definition**	**Description**
zr	m	zr_min : zr_dr : zr_max	Radar range gates

The PulseLength defines the true vertical (range) resolution of the radar (ask the radar engineers/operators to provide you with this number). The VerticalSampling variable is the radar data vertical (range) resolution reported in the data files. Use the variables zr_min, zr_max to define the minimum and maximum height that you would like reported radar Doppler spectra. At the end of subsection 5.9 we have estimated the LES-resolution radar Doppler spectra. That means that there is one synthetic radar Doppler spectra for each LES grid point. In subsection 5.10 we estimate the synthetic radar Doppler spectra in the vertical dimension using the resolution determined by the VerticalSampling parameter. Since the radar vertical resolution is often lower than the LES vertical resolution, each synthetic radar Doppler spectra at the radar-determined resolution will be the composite of a number of LES-resolution radar Doppler spectra. The contribution of each LES-resolution radar Doppler spectra is done using the radar range weighting (W2). This is illustrated in detail in the code below.

The code loops over all (b-variable) the user specified height (zr), and performs the following steps:

i) calculate the radar receiver noise at the specified height

```
Noise_rad(b) = NOISE_1km*(zr(b)/1000).^2; %%% radar receiver noise at each range gate
```

ii) find all the LES grid points that are within 2 PulseLength from the radar-defined height

```
ko = find(z>=zr(b)-2*PulseLength & z <zr(b)+2*PulseLength);  %%%%
```

iii) if there are LES grid points, calulate their "weight" based on the radar range-weighting function

```
if isempty(ko)==0
W2 = exp(-pi^2*(z(ko)-zr(b)).^2/(2*log(2)*PulseLength^2));
```

iv) normalize the coefficients

```
Wr = W2/sum(W2); %%% normalize weights
```

v) perform vertical convolution of the LES grid radar Doppler spectra

```
radar_res_spectra(b,1:NFFT) = nansum(spectra_example(ko,1:NFFT).*repmat(Wr,[1 NFFT])); %%% this takes care partial beam filling
```

The variable radar_res_spectra is the radar Doppler spectra at the radar-specified range resolution.

Using the function plot_diagnostic_3 you can produce the following plot (Figure 9) that shows the spectrograms with the LES and radar vertical resolution and a comparison of their mean Doppler velocity and spectrum width.

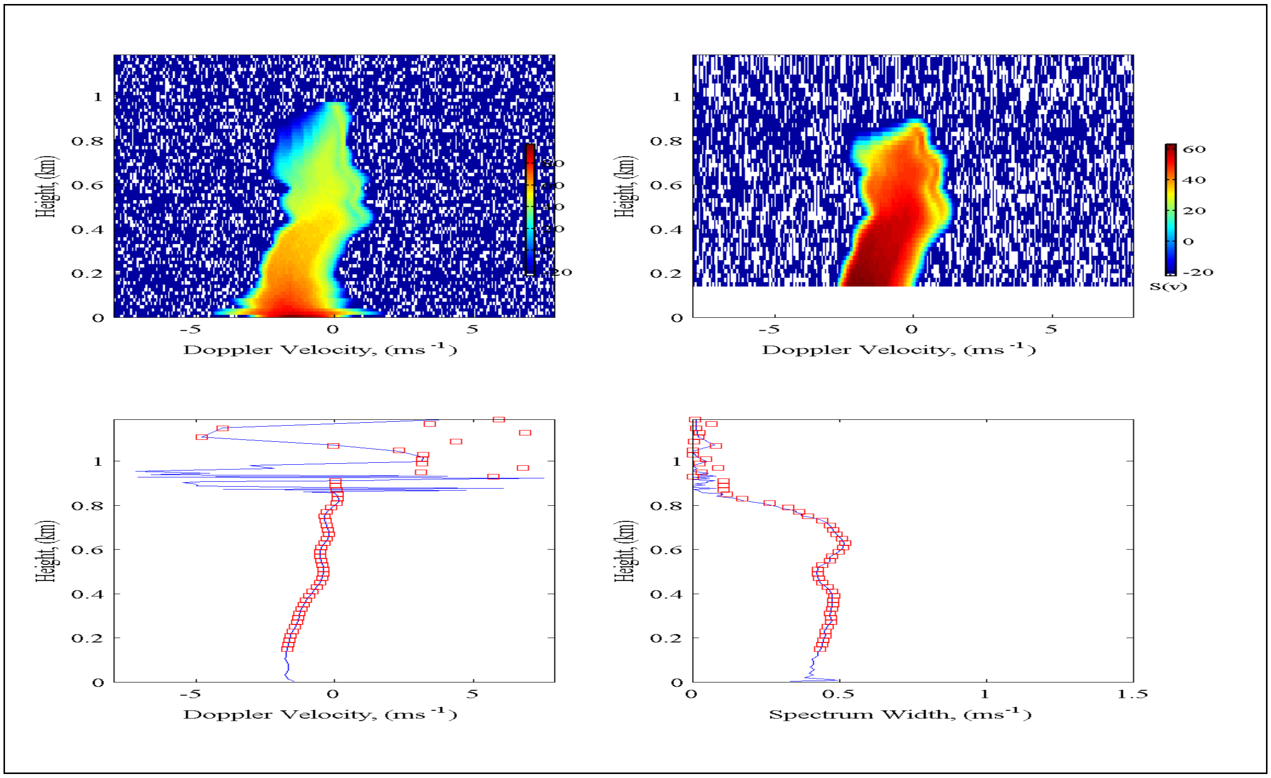

Figure 9: Example of radar Doppler spectrogram at the LES vertical resolution (top left) and radar vertical resolution (top right) and example profiles of mean Doppler velocity and spectrum width at the LES vertical resolution (blue lines) and radar vertical resolution (red squares).

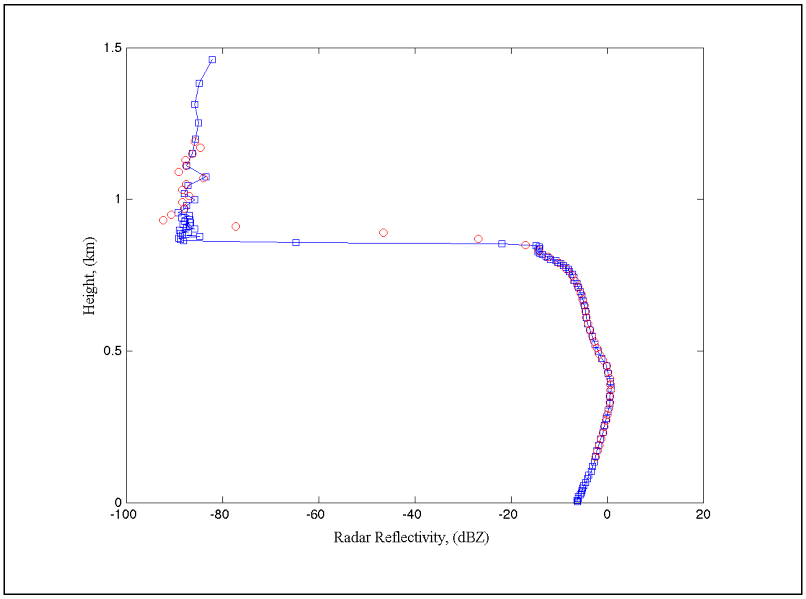

Figure 10: Comparison of radar reflectivity profiles calculated from the simulated radar Doppler spectra at the LES vertical resolution (blue line) and radar vertical resolution (red squares). Note the enhanced (stretched vertically) cloud top boundary due to finite pulse length.

4 Model Output

The structure of created output netcdf file is shown in Table 5.

Table 5: The list of dimensions and variable names in MRDSS output file

Dimensions				
Symbol	**Meaning**			
nx	Number of grid boxes along the horizontal E-W axis			
ny	Number of grid boxes along the horizontal N-S axis			
nz	Number of grid boxes along the vertical axis at LES resolution			
nzr	Number of grid boxes along the vertical axis at radar-specified resolution			
one	1			
Variables				
Symbol	**Description**	**Units**	**Dim**	**Type**
x	E location of grid box center	m	nx	DOUBLE
y	N location of grid box center	m	ny	DOUBLE
z	Altitude of grid box center at LES model resolution	m	nz	DOUBLE
zr	Altitude of grid box center at radar-specified	m	nzr	DOUBLE

	resolution			
Nt_l	Total particle number concentration	cm^{-3}	nx ny nz	DOUBLE
LWC	Liquid Water Content	$g\ m^{-3}$	nx ny nz	DOUBLE
W_air	Vertical air motion within the LES grid	$m\ s^{-1}$	nx ny nz	DOUBLE
dBZ_mie	Radar reflectivity factor computed using Mie theory	dB	nx ny nz	DOUBLE
A_gases	Accumulated Gaseous Attenuation	dB	nx ny nz	DOUBLE
A_liquid_accum	Accumulated Liquid Attenuation	dB	nx ny nz	DOUBLE
dBZ_obs	Observed reflectivity after propagation effects	dBZ	nx ny nz	DOUBLE
VNyquist	Nyquist velocity	$m\ s^{-1}$	one	DOUBLE
NFFT	Number of spectral FFT points	-	one	INTEGER
Nave	Number of spectral averages	-	one	INTEGER
Noise	Radar receiver noise floor at each range gate of the radar Doppler spectrum at LES vertical resolution	$mm^6\ m^{-3}$	nz	DOUBLE
N_max	Maximal value of noise level in Doppler spectra obtained using Hildebrand and Sekhon (1984) method at LES vertical resolution	$(mm^6\ m^{-3})\ /\ ms^{-1}$	nx ny nz	DOUBLE
N_mean	Mean value of noise level in Doppler spectra obtained using Hildebrand and Sekhon (1984) method at LES vertical resolution	$(mm^6\ m^{-3})\ /\ ms^{-1}$	nx ny nz	DOUBLE
Velo	Mean Doppler velocity computed from radar Doppler spectra at LES vertical resolution	$m\ s^{-1}$	nx ny nz	DOUBLE
Width	Radar Doppler spectrum width from radar Doppler spectra at LES vertical resolution	$m\ s^{-1}$	nx ny nz	DOUBLE
Skew	Radar Doppler spectra skewness computed from radar Doppler spectra at LES vertical resolution	-	nx ny nz	DOUBLE
Kurt	Radar Doppler spectrum kurtosis computed from radar Doppler spectra at LES vertical resolution	-	nx ny nz	DOUBLE
LS	Left slope of the radar Doppler spectrum at LES vertical resolution	$(mm^6 m^{-3}\ /\ ms^{-1})\ /\ ms^{-1}$	nx ny nz	DOUBLE
RS	Right slope of the radar Doppler spectrum at LES vertical resolution	$(mm^6 m^{-3}\ /\ ms^{-1})\ /\ ms^{-1}$	nx ny nz	DOUBLE
dBZ_sim	Radar reflectivity of the radar Doppler spectrum at LES vertical resolution	dBZ	nx ny nz	DOUBLE
Std_turb	Doppler spectra broadening due to sub-radar volume TKE-dissipation rate	$m\ s^{-1}$	nx ny nz	DOUBLE
SH_total	Doppler spectra broadening due to wind shear	$m\ s^{-1}$	nx ny nz	DOUBLE
st	Total Doppler spectra broadening due to wind shear and turbulence	$m\ s^{-1}$	nx ny nz	DOUBLE
Noise_rad	Radar receiver noise floor at each range gate of the radar Doppler spectrum at radar-specified range resolution	$mm^6\ m^{-3}$	nzr	DOUBLE
N_max_rad	Maximal value of noise level in Doppler spectra obtained using Hildebrand and Sekhon (1984) method at radar-specified range resolution	$(mm^6\ m^{-3})\ /\ ms^{-1}$	nx ny nzr	DOUBLE
N_mean_rad	Mean value of noise level in Doppler spectra obtained using Hildebrand and Sekhon (1984) method at radar-specified range resolution	$(mm^6\ m^{-3})\ /\ ms^{-1}$	nx ny nzr	DOUBLE
Velo_rad	Mean Doppler velocity computed from radar Doppler spectra at radar-specified range resolution	$m\ s^{-1}$	nx ny nzr	DOUBLE
Width_rad	Radar Doppler spectrum width from radar Doppler	$m\ s^{-1}$	nx ny nzr	DOUBLE

	spectra at radar-specified range resolution			
Skew_rad	Radar Doppler spectra skewness computed from radar Doppler spectra at radar-specified range resolution	-	nx ny nzr	DOUBLE
Kurt_rad	Radar Doppler spectrum kurtosis computed from radar Doppler spectra at radar-specified range resolution	-	nx ny nzr	DOUBLE
LS_rad	Left slope of the radar Doppler spectrum at radar-specified range resolution	$(mm^6 m^{-3} / ms^{-1}) / ms^{-1}$	nx ny nzr	DOUBLE
RS_rad	Right slope of the radar Doppler spectrum at radar-specified range resolution	$(mm^6 m^{-3} / ms^{-1}) / ms^{-1}$	nx ny nzr	DOUBLE
dBZ_sim_rad	Radar reflectivity of the radar Doppler spectrum at radar-specified range resolution	dBZ	nx ny nzr	DOUBLE

5 References

Doviak, R. J., and D. S. Zrnic, 1993: Doppler Radar and Weather Observations. Second Edition. Academic Press, San Diego, California.

Gossard E. E., 1994: Measurements of cloud droplet size spectra by Doppler radar. J. Atmos. Oceanic Technol., 11, 712-726.

Hildebrand P. H., and R. S. Sekhon, 1974: Objective Determination of the Noise Level in Doppler Spectra, Journal of Applied Meteorology, 13, 808-811

Kollias, P., E. E. Clothiaux, M. A. Miller, E. P. Luke, K. L. Johnson, K. P. Moran, K. B. Widener, and B. A. Albrecht (2007), The atmospheric radiation measurement program cloud profiling radars: Second-generation sampling strategies, processing and cloud data products,J. Atmos. Sci., 24, doi:10.1175/JTECH2033.1.

Kollias, P., S. Tanelli, A. Battaglia, A. Tatarevic, 2014: Evaluation of EarthCARE Cloud Profiling Radar Doppler Velocity Measurements in Particle Sedimentation Regimes. *J. Atmos. Oceanic Technol.*, 31, 366–386.

Rosenkranz, P. W. (1998), Water vapor microwave continuum absorption: A comparison of measurements and models, Radio Sci., 33(4), 919–928, doi:10.1029/98RS01182

Sloss, P. W., and D. Atlas, Wind shear and reflectivity gradient effects on Doppler radar spectra, J. Atmos. Sci., 25, 1080±1089, 1968

Zrnić D.S., 1975: Simulation of weather like Doppler spectra and signals, J. Appl. Meteorol., 619-620.