TARA data processing

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Date: 3/10/2003

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Introduction

This document is intended to give a description of the data processing done for the TARA system. For a better understanding of the processing a short description of the radar and its hardware is given. A separate chapter is included describing the calibration of the system. Next the different processing steps are described in detail. In the Appendix, a derivation of the radar equation used for the calibration is given.

System description

TARA is an FMCW radar system. It uses a linear frequency sweep of maximally 50 MHz. Isolation between the transmitter and the receiver is realized by the use of two separate antennas. Each antenna has three feeds. The on-focus feed is dual polarized. The off-focus feeds are single polarized and generate beams at an angle of 15° off axis. These beams are used in conjunction with the central beam to calculate three dimensional wind fields. The antennas have a symmetrical pattern in the E- and H-plane with a beam width of 2.2° and an antenna gain of 38.5 dBi. The cross polar isolation of the antennas is -29 dB for distributed targets. The sidelobes of the antennas are -20 dB for the near lobs and around -70 dB for the lobes in the 90° direction. This last value is an averaged value in presence of the large shields around the antennas. A picture of the antenna patterns is shown in figure 1.

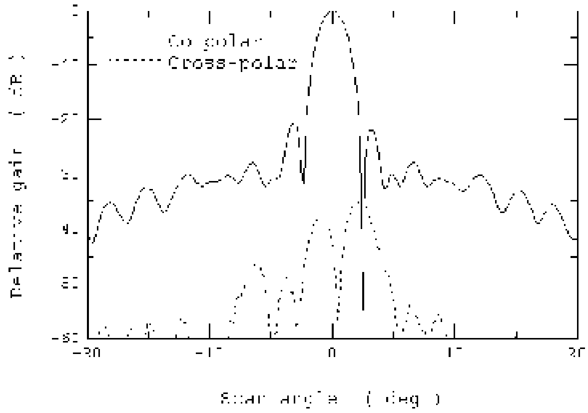

Figure 1: Antenna patterns of the TARA antenna.

Each antenna is controlled independently. As the central feed is multi-polarized, this means that the full polarization scattering matrix can be measured. Due to processing limitations in the standard mode of operations, the full Doppler spectrum in each polarization state has to be measured before the next polarization state can be measured.

The maximum transmit power of TARA is around 140 W. Therefore, it can be a solid state transmitter. The power out of the antenna is 36 W due to losses in cables and the beam forming network. A sensitivity analysis of the system is given in the calibration chapter.

After reflection, the received frequency sweep is mixed with the instantaneous transmitted signal generating a frequency difference signal. For multiple targets, a Fourier transform (FFT) is needed to analyze this signal. This transform gives range I and Q terms. A number of successive sweeps is collected such that for each range cell a Doppler FFT can be calculated. Of each Doppler spectrum, the first three moments are calculated being the reflectivity, the averaged velocity and the Doppler spectral width. The specifications of the system are listed in table 1.

Table 1: Specifications of the TARA system.

Type	FM-CW	
Central frequency	3.315 *GHz*	
Max. transmitted power	≥ 140 *W*	Out of amplifier (36W out of antenna)
Receiver		
Dynamic range	80 - 90 *dB*	
Noise figure	1 *dB*	
Signal generation		
Sweep frequency F	2 ≤ F ≤ 50 *MHz*	computer control
sweep shape	saw tooth	
sweep time T_s	$1 \le T_s \le 1000$ *ms*	
Sampling	≤ 1 *MHz*	16 bits ADC
#samples per sweep	1024	
#sweeps per spectrum	512	2 Mbyte per spectrum
Power settings	10 *dB* steps	computer control
Polarimetry		
Polarisation	XX YY XY	Central beam only
Doppler		
Max. speed	±22.7 *m/s*	If $T_s = 1$ *ms* with saw-tooth sweep
Resolution	0.089 *m/s*	512 cells
Stability		
Power	≤ 0.1 *dB/s*	≤1 *dB/day*
Phase	≤ 1°/*s*	
Internal calibration	delay line 5 *µs*	Saw
Antennae		
Beam width	2.2°	
Gain	38.5 *dBi*	
cross polarisation	≤ -30 *dB*	averaged over beam
1st side lob	≤ -25 *dB*	
far side lob	≤ -70 *dB*	90°
Near field	≤ 200 *m*	
Sensitivity[1]	@5 *km*	@1 *km*
Reflectivity	$\le 2.3\ 10^{-14}\ m^{-1}$	$\le 0.9 \times 10^{-15}\ m^{-1}$
Reflectivity factor	≤ -21 *dBz*	≤ -35 *dBz*
Structure constant	$\le 2.7 \times 10^{-14}\ m^{-2/3}$	$\le 1.1 \times 10^{-15}\ m^{-2/3}$
RCS	$\le 1.8 \times 10^{-8}\ m^2$	$\le 2.8 \times 10^{-11}\ m^2$
Cutter suppression		
Hardware	Antennas	low side lobs
Processing	Doppler spectrum	

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[1] *SNR = 0 dB, resolution = 40 m,*
After Doppler filter: noise bandwidth = 1 kHz, signal bandwidth = 80 Hz.

Table 1: Cloudnet settings for TARA.

Transmitted power	≥ 140 *W*	Out of amplifier (36 W out of antenna)
Sweep frequency	5 *MHz*	30 *m* resolution
sweep shape	saw tooth	
sweep time T_s	1 *ms*	
#samples per sweep	1024	
#sweeps per spectrum	512	
Polarisation	HH	
Doppler		
Max. speed	±22.7 *m/s*	
Resolution	0.089 *m/s*	
Sensitivity[2]	@5 *km*	@1 *km*
Reflectivity	$\leq 2.3\ 10^{-14}\ m^{-1}$	$\leq 0.9\times10^{-15}\ m^{-1}$
Reflectivity factor	≤ -21 *dBz*	≤ -35 *dBz*
Structure constant	$\leq 2.7\times10^{-14}\ m^{-2/3}$	$\leq 1.1\times10^{-15}\ m^{-2/3}$
RCS	$\leq 1.8\times10^{-8}\ m^{2}$	$\leq 2.8\times10^{-11}\ m^{2}$

The radar is computer controlled. Settings that can be changed include transmit power, bandwidth, sweep time, and polarization state. During changes of the polarization state, the transmit power is switched off and no data samples are taken. Delayed sampling is used to allow the system to relax to steady state. This means that during each sweep, the first 1/8th of the sweep time is used for setting up the system while the last 7/8th of the sweep time is used to sample the signal.

For volume scattering range spreading and, therefore, the drop in reflected signal strength has a squared dependency on range. To compensate for this, a squared low amplifier is used. This means that the gain of the amplifier is increased with the square of the frequency. The advantage of this is that a target of a certain reflectivity factor will lead to a signal strength at the ADC input independent of the position of that target. The gain of the amplifier can be deduced from the noise characteristic as shown in Fig.2. As can be seen, the frequency dependent gain is not exactly quadratic and needs to be corrected for in the calibration. For range cells higher than cell 450, a drop in the noise level is observed. This originates from the low-pass filters in the receiver chain. At low range cells a peak in the noise floor is detected. Other peaks on the noise curve originate from switched mode power supplies in the system that can not be removed in hardware. For completeness, a photograph of the TARA system is shown in figure 3.

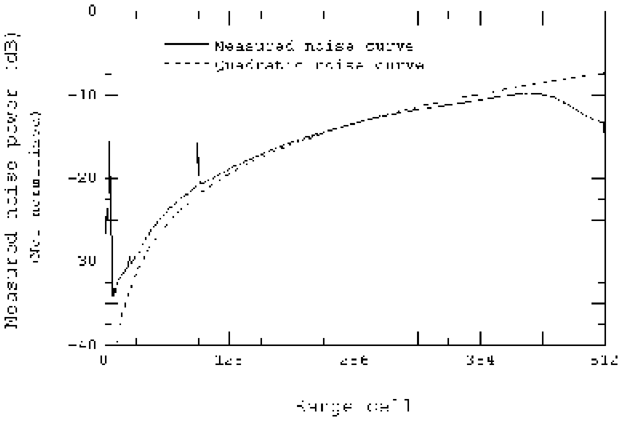

Figure 2: Measured noise for different range cells.

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[2] *SNR = 0 dB, resolution = 40 m,*
After Doppler filter: noise bandwidth = 1 kHz, signal bandwidth = 80 Hz.

Figure 3: Photograph of the TARA system.

Calibration

The TARA system is calibrated using the receiver noise power. To do this, it is of eminent importance to know exactly the transmitted power and the noise figure of the receiver. Also exact knowledge of the antenna pattern is needed.

For this calibration, use is made of an inverted radar equation for volume scattering that relates the reflectivity to the radar parameters (derivation is given in appendix):

$$Z = \cdot \frac{P_r}{P_t} \frac{512\left(2\ln 2\right)\lambda^2}{2\pi^3\theta G^2 \;\, {}^2 \left|K\right|^2 \Delta r} r^2 \;\; 10^{18} . \qquad (1)$$

For the TARA system the different variables are given by:

$P_r = k_b T F_n B \quad k_b\left(T_{sys} \quad T_{ant}\right)B \quad \left[W\right]$

$k_b = \cdot 1.3807 \;\; 10^{-23} \quad \left[\,\right] W / K\ Hz$

$\Delta r = \dfrac{C}{2F_{sweep}} \quad \left[m\right]$

$P_t = 36 \quad \left[W\right]$

$G = 38.5 \quad \left[dBi\right]$

$\theta = 2.2^\circ \quad 0.0384 \quad \left[rad\right]$

$\left|K\right|^2 = 0.93$

$\lambda = 0.0909 \quad \left[m\right]$

$F_n = 1 \quad \left[db\right]$

The bandwidth B is related to the sweep time according to $B = {}^{8}\!/_{7T_{sweep}}$. The factor 8/7 comes from the part of the sweep where no samples are taken. When using Eq. 1, linear values for G and F_n should be used and θ should be in radians. To calculate the noise power in the receiver, the noise figure is interpreted as an added noise temperature. This temperature is added to the antenna temperature. A 1 *dB* noise figure is equivalent to a noise temperature of 75 *K*, which should be added to the antenna temperature of 50 *K*. Therefore the total noise power per unit of bandwidth equates to $P_n = \cdot 1.73 \;\; 10^{-21} W / Hz$.

An effective Z_{noise} can be calculated using the above given equations and values. This Z_{noise} corresponds to a reflectivity factor having the same power as the system noise. In the following figures Z_{noise} is calculated for different frequency excursions and for different sweep times.

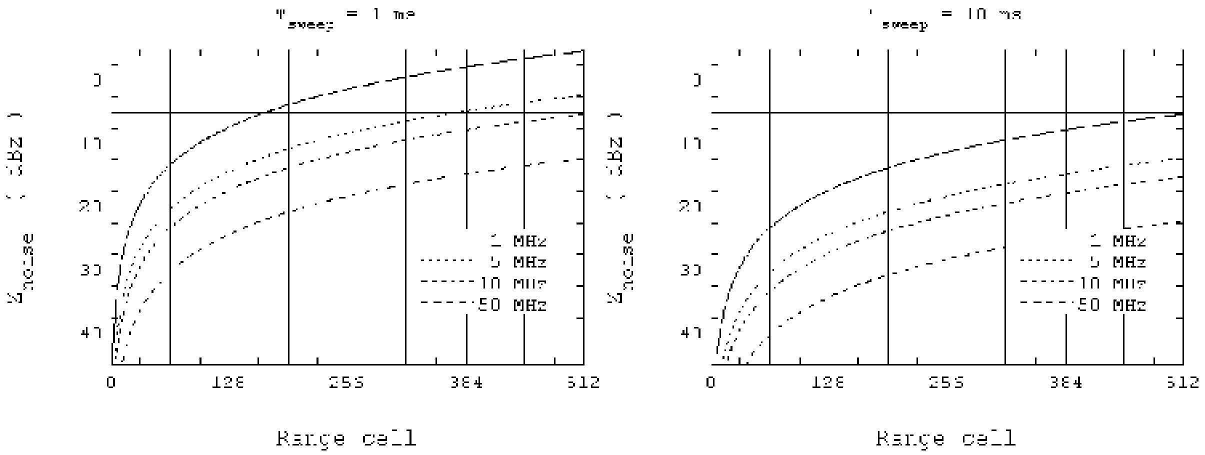

Figure 4: Calculated effective noise reflectivity factors for different sweep times.

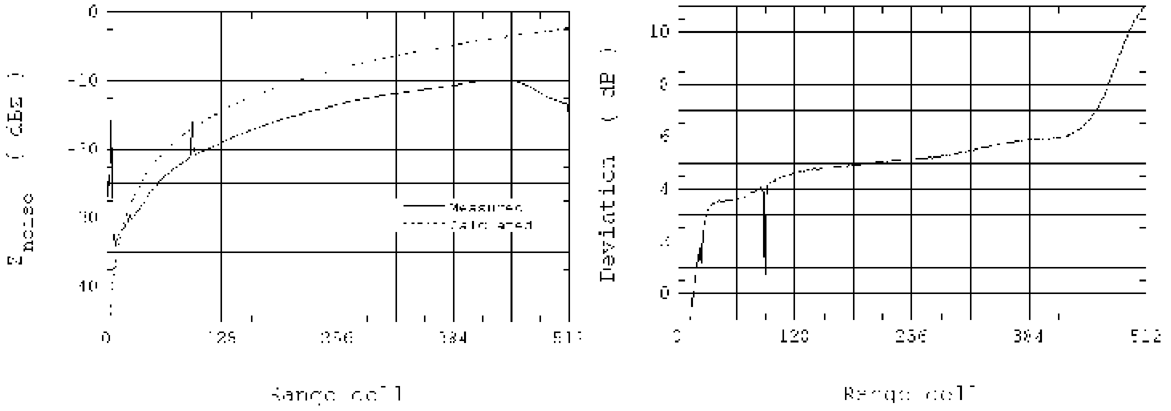

Figure 5: Comparison of measured noise power with calculated noise powers.

From Fig.5 it can be seen that a calibration correction is needed for TARA. This correction is 5.1 *dB* at half range but varies with range.

Processing steps

The raw data stream coming out of the receiver is sampled with a 16bit ADC. A FFT over 1024 samples is calculated to give the range dependent amplitudes and phases. For this FFT a rectangular window is used. Next, 512 sweeps are collected and for each range cell, a Doppler FFT is calculated. Again a rectangular window is used for calculating the FFT. On each Doppler spectrum several processing steps are applied. For these calculations, the phase information is dropped and only the amplitude is maintained. First, clutter is suppressed by suppressing the zero velocity Doppler bin. An interpolation from the neighboring cells is applied for correcting the atmospheric target contribution. Second, the maximum of the Doppler spectrum is calculated and the spectrum is centered around this value. This will ensure an accurate velocity and spectral width calculation. Third, a moving average is calculated. Finally clipping is applied to reduce the thermal noise contribution to the calculated moments of the spectra. After these processing steps the moments are calculated according to:

$$m_0 = \sum_{i=1}^{512} m_i$$

for the zeroth moment being the reflectivity:

$$m_1 = \langle v \rangle = \frac{\sum_{i=1}^{512} m_i v_i}{\sum_{i=1}^{512} m_i} = \frac{\sum_{i=1}^{512} m_i v_i}{m_0}$$

for the first moment being the Doppler velocity:

$$m_2 = \sqrt{\frac{\sum_{i=1}^{512} m_i \left(v_i - \langle v \rangle\right)^2}{m_0}}$$

for the second moment being the Doppler spectral width. The different processing steps are depicted in Fig. 6 while Fig 7 shows the final result of a time-height plot of a rainfall event.

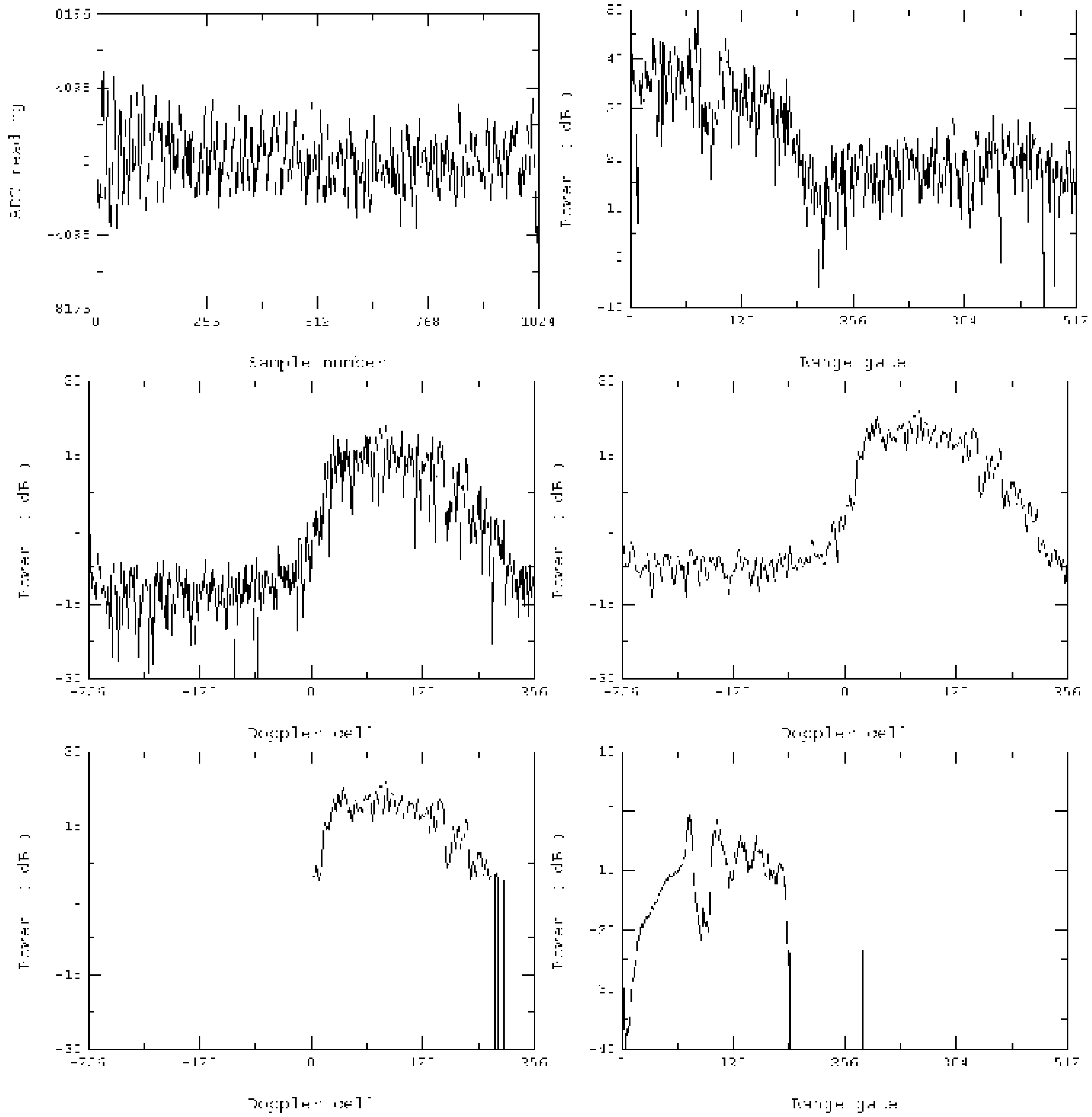

Figure 6: Different steps in signal processing: a)Raw data stream, b) Range spectrum after a single FFT, c) Doppler spectrum at range cell 60, d) Doppler spectrum after clutter suppression and moving average, e) Doppler spectrum after clipping, f) Reflectivity profile after processing

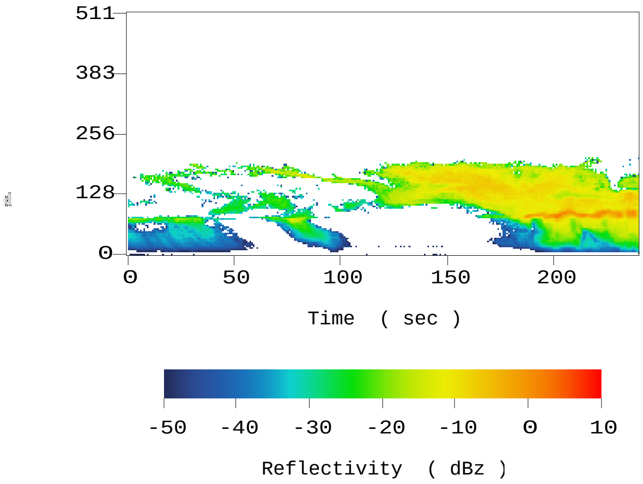

Figure 7: Reflectivity as a function of range and time for a rainfall event.

These three moments are calculated with a temporal resolution of maximally 0.512 *s*. These high temporal resolution moments are averaged to a time resolution of 5.12 sec and stored in a NETCDF file. For this, the reflectivity is calculated to a linear scale and subsequently averaged over 10 samples. The velocity and spectral width are calculated by a weighted average of the moments against the reflectivity. In formula form:

$$\langle m_0\rangle = \sum_{i=1}^{10} m_{0,i};\ \langle v\rangle = \frac{\sum_{i=1}^{10} m_{0,i}m_{1,i}}{\sum_{i=1}^{10} m_{0,i}};\ \langle w\rangle = \frac{\sum_{i=1}^{10} m_{0,i}m_{2,i}}{\sum_{i=1}^{10} m_{0,i}}.$$

As a latest step in the processing a correction is made for the spatial separation of the transmit and the receive antennas. This leads to a range dependent correction given by:

$$Pcor = -20\log 10\left(\exp\left(\frac{6.122}{\theta r}\right)\right),$$

with θ the -3 *dB* beam width and *r* the range. The correction curve is shown in Fig. 8. It shows that for ranges outside of 1 *km* this correction is negligible. For ranges shorter than this, the correction becomes increasingly important. At a range of 100 *m* this correction is 2.84 *dB*.

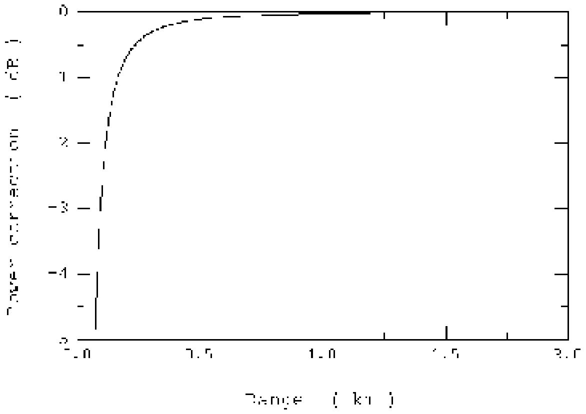

Figure 8: Beam overlap correction for the TARA system.

NETCDF files

For cloudnet, the TARA data is submitted as daily NETCDF files. The standard file size is 50 *MByte*. The name convention of the file is: yyyymmdd_tara.nc e.g. a measurement on December 5th, 2002 would be called: 20021205_tara.nc

The NETCDF files have two dimensions:

`Range`

512 range cells with a size of 30 m. (Some files can have different resolution)

`Time`

16875 time cells of each 5.12 sec. are used

The following variables are in the files

`Frequency`

Radar frequency in GHz (3.3)

`Latitude`

Latitude of TARA in Cabauw in deg (51.9678)

`Longitude`

Longitude of TARA in Cabauw in deg (4.9295)

`Altitude`

The altitude of the radar antenna above sea level in meters

`Elevation`

Antenna elevation in deg from horizon (90)

`Time`

A vector containing the timestamp in decimal hours UTC

`Range`

A vector containing the cell centered range in m

`Reflectivity`

An array containing the effective radar reflectivity in dBz * 100. This array is stored as integer values to save space. It should be multiplied with the reflectivity scaling of 0.01 to get the correct values.

`Velocity`

An array containing the radial velocity in m/s *1000. This array is stored as integer values to save space. It should be multiplied with the velocity scaling of 0.001 to get the correct values. Negative velocity means towards the radar.

`Width`

An array containing the Doppler spectral width in m/s *1000. This array is stored as integer values to save space. It should be multiplied with the width scaling of 0.001 to get the correct values.

Optional variable

Ldr

Linear depolarization ratio in dB * 100. This array is stored as integer values to save space. It should be multiplied with the Ldr scaling of 0.01 to get the correct values.

Appendix A: Derivation of the Radar equation

The radar equation for reflections from a single target is given by:

$$\mathrm{P_r} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 r^4},$$

where P_t and P_r are the transmitted and received power respectively, G is the antenna gain, λ the wavelength, r the range of the target and σ the radar cross section of the target.

For reflection from a volume filled isotropic with scatterers, the received power is the sum of the power received from all individual scatterers leading to:

$$\mathrm{P_r} = \frac{P_t G^2 \lambda^2 \theta \phi h}{512 \pi^2 r^2} \eta$$

with $V_m = \pi \left(r \frac{\theta}{2} \right) \left(r \frac{\phi}{2} \right) \frac{h}{2}$ the scattering volume, θ and ϕ the beam width in the elevation and azimuth direction, *h* the pulse length and $\eta = \sum_{vol} \sigma_i$ the scattering cross section per unit volume. It is assumed that the antenna has identical gain in all directions. Taking into account the Probert-Jones correction for a Gaussian shaped antenna gain pattern and assuming identical beam width in the θ and ϕ directions gives:

$$\mathrm{P_r} = \frac{P_t G^2 \lambda^2 \theta^2 h}{512 (2 \ln 2) \pi^2 r^2} \eta$$

Using the following definition of the reflectivity

$$Z = \frac{\lambda^4}{|K|^2 \pi^5} \eta \; 10^{18}$$

and inverting the radar equation leads to

$$Z = \frac{P_r}{P_t} \frac{512 (2 \ln 2) \lambda^2}{2 \pi^3 \theta^2 G^2 |K|^2 \Delta r} r^2 \; 10^{18},$$

where $h = 2 \Delta r$ is used implicitly