ACTRIS WP5 - NA5 Clouds and aerosol quality controlled-observations
Deliverable 5.6: Establish common set of definitions for instrument errors

1. Introduction

The core instrumentation for clouds and aerosols quality controlled-observations at a CloudNet station comprises:

i) Lidar/ceilometer providing profiles of
   a. attenuated backscatter coefficient from aerosol and cloud
   b. linear depolarisation ratio

ii) Doppler cloud radar operating at 35 or 94GHz, providing profiles of
   a. reflectivity, Z,
   b. mean Doppler velocity, v,
   c. Doppler spectral width, σ_v,
   d. standard deviation of the mean Doppler width, σ_{vbar}
   e. linear depolarisation ratio, LDR.

iii) Microwave radiometer providing
   a. brightness temperatures at two or more wavelengths in the range 20-30 GHz
   b. derived water vapour and liquid water path

iv) Additional observations
   a. surface rain rate from raingauge
   b. radiosonde profiles, or NWP model output (temperature, pressure, humidity, winds)

Measurements in blue are not required, but are utilised within the Cloudnet processing scheme, if available.

The profile of attenuated backscatter coefficient, from a lidar/ceilometer, exhibits returns from aerosol, ice and liquid. The molecular return may also be present at visible lidar wavelengths. Attenuation by liquid is severe, and the lidar signal does not penetrate liquid layers that are deeper than about 300 m, thus only reliably detecting the cloud base. Penetration through ice clouds can reach 3 km or more.

The cloud radar is much less affected by attenuation and provides profiles of the first three moments of the Doppler spectra; reflectivity, Z; Doppler velocity; and the spread of Doppler velocities. Additionally, the variation of the mean Doppler velocity can also be calculated; this can be used for estimating the turbulent properties of the atmospheric particulate. The linear depolarisation ratio, if available, is useful for distinguishing insects from clouds and precipitation within the boundary layer, and for identifying the location of melting ice particles.

In ice clouds, the ice water content can be empirically derived from Z and temperature (from radiosonde or NWP model), with an uncertainty that accounts for the scatter in the empirical relationship, the precision in the Z estimate, and by assigning an appropriate error in the temperature profile.

In liquid water clouds, the value of Z is dominated by occasional drizzle drops and is not directly related to liquid water content, LWC. LWC is derived by assuming a linear increase in LWC from cloud base (from lidar/ceilometer) to cloud top (from radar), with the integral scaled to match the column liquid water path obtained from the microwave radiometer.

2. Data specification

All data to be ingested within the Cloudnet scheme is expected to contain the appropriate error variables for each parameter from every instrument. Since each product is required to report uncertainties, all product algorithms will utilise these values to generate uncertainty estimates in the ensuing product; this then allows uncertainty in the measurements to be faithfully propagated through every higher level product generated from the instrument data. In general, the handling of the various error sources by product algorithms is as follows:

- random errors – full treatment, for each output parameter, an error field is provided with the same dimensions as the input parameters,
- systematic errors – treatment depends on the impact of the specific systematic error; this may require an additional error field with the same dimensions as the input parameters, or merely a scalar value.

To facilitate this, provision is made within the Cloudnet processing scheme for each parameter, [parameter name], from each instrument to contain the following attributes:

- `error_variable = '[parameter name]_error'`,
- `bias_variable = '[parameter name]_bias'`,

which refer to the corresponding error variables for each parameter;

- `[parameter name]_error` refers to the random error in the parameter,
- `[parameter name]_bias` refers to the possible systematic error in the parameter.

These error variables should contain a full set of relevant attributes, including appropriate units. Many of these variables are calculated within the Cloudnet processing scheme, as the final determination can depend on other inputs. Note that there may be certain cases where a different approach is required due to the nature of the measurement. The units and composition of the error variables are now described for each instrument. Required inputs for Cloudnet are described in the section entitled 'Cloudnet ingest', and the standard output for the Cloudnet categorization file given in the section 'Processed Cloudnet data.

3. Cloudnet ingest

3.1. Doppler cloud radar

Radar reflectivity factor, denoted Z (or Zh)

Requirements	*Random*	None	calculated within Cloudnet processing
	Systematic	Value or calibration method	derived from method

The precision of the Z estimates can be expressed, in linear space, as

$\Delta Z = 1/\sqrt{M_I}$,

where M_I is the number of equivalent independent samples, given by Doviak and Zrnic (1993):

$M_I = 4\, \sigma_v\, \tau_d\, \pi^{1/2} / \lambda$,

where σ_v is the spectral width, τ_d the dwell time and λ the radar wavelength. For Cloudnet, the radar data are typically averaged over 30 seconds (to match the temporal resolution of other instruments). With a typical spectral width of 0.5 m s^{-1}, the random error in *Z* is about 0.02 dB, or 0.5%, at 94 GHz, and close to 0.04 dB, or 1% at 35 GHz.

Note: Within Cloudnet, this random error, arising from the precision of the estimate, is then combined with the uncertainty in the attenuation correction. All profiles are subject to gaseous attenuation, and profiles with liquid layers present suffer an additional attenuation. It is not currently possible to correct for the serious attenuation due to rain, radome wetting, and the melting level, with confidence.

A larger systematic error is present due to the difficulty in accurately calibrating a radar at millimetre wavelengths. For most of the current calibration methods, the accuracy of the calibration is estimated to be 1.5 dB.

Radar Doppler velocity, denoted v

Requirements	*Random*	velocity resolution nyquist velocity number of bins in FFT	Minimum two out of three; calculated within Cloudnet processing
	Systematic	None	assumed to be negligible

The mean Doppler velocity is measured directly by the radar and the uncertainty is much less than the bin width of the Doppler spectrum produced by the FFT as part of the coherent processing algorithm. Therefore, the relevant value is the velocity resolution given by the FFT. This can also be calculated from the nyquist velocity and the number of bins within the FFT, e.g., a 256-point FFT, together with a nyquist velocity of 5 m s^{-1} results in a velocity resolution of 4 cm s^{-1}. The nyquist velocity (or folding velocity) is also required to determine whether folding of the velocity occurs in precipitation.

Radar Doppler spectral width, denoted width

Requirements	*Random*	Same as for v	calculated within Cloudnet processing
	Systematic	None	assumed to be negligible

The calculation of uncertainty in the Doppler spectral width is considered within the Cloudnet processing scheme, and utilises the same parameters as for the mean Doppler velocity. The precision is better than the bin width of the Doppler spectrum produced by the FFT as part of the coherent processing algorithm as it is calculated from a number of points within the spectrum. Additionally, this value is derived from averaging many values derived from a contiguous series of Doppler spectra. In practice, turbulent, beam broadening, and atmospheric components dominate any artefacts from the FFT windowing technique used.

Note: the spectral width is defined as the standard deviation of the main peak within the Doppler spectrum – the approximation given by the width at half-height (3 dB) must not be used as the peaks cannot be assumed to be of Gaussian form.

Radar standard deviation of the mean Doppler velocity, denoted sigma_v

Requirements	*Random*	Same as for v Number of samples	calculated within Cloudnet processing
	Systematic	None	assumed to be negligible

The calculation of uncertainty in the standard deviation of the mean Doppler velocity, sigma_v, is considered within the Cloudnet processing scheme. The uncertainty is derived from sampling statistics and the velocity resolution; hence, a minimum of 10 samples is required for reasonable estimates. For most systems, 20-30 samples are available if this is calculated internally over 30 seconds from velocity estimates produced at typical raw temporal resolutions of 1- 1.5 seconds; the uncertainty in the individual 1-s velocity estimates is still on the order of, or better than, the velocity resolution given by the bin width of the FFT.

Linear depolarisation ratio, denoted ldr

Requirements	*Random*	SNR for both channels	calculated within Cloudnet processing
	Systematic	None	assumed to be negligible

The full calculation of uncertainty in LDR, is not yet considered in the Cloudnet processing scheme. This parameter is very sensitive to the design of the instrument, such as isolation between the transmitter, and the receivers at the two polarized channels. A filtering of values with low SNR is performed.

3.2. Lidar or ceilometer

Attenuated backscatter, denoted beta

Requirements	*Random*	Value or SNR	
	Systematic	Value or calibration method	derived from method
	laser beam divergence telescope FOV	Values	provide direct to product algorithms

The precision of the backscatter estimates can be derived directly from the SNR for photon counting systems, and similar methods are available for some ceilometers. In Cloudnet we refer to the techniques derived within the EARLINET programme, which also take into account other uncertainties including overlap, beam alignment, filter degradation, etc.

For systems with visible wavelengths, calibration is achieved using the known molecular return. Longer wavelengths, especially for low-power systems, require the use of other atmospheric targets such as liquid cloud layers, or the full aerosol column in combination with sun photometers, to perform calibration. Hence the systematic error due to uncertainty in the calibration may be greater than the random error.

Note: Multiple scattering can also have an impact on the use of attenuated backscatter profiles, especially for liquid layers, and optically thick ice. The instrument specific parameters, laser beam divergence and telescope field-of-view, must be provided so that product algorithms can calculate the impact of multiple scattering when necessary.

3.3. Microwave radiometer

Brightness temperatures, denoted brightness_temperature

Requirements	*Random*	Value	
	Systematic	Value or calibration method	derived from method

Liquid water path, denoted lwp

Requirements	*Random*	Value or None	calculated within Cloudnet processing
	Systematic	Value or calibration method	derived from method

This variable is the vertically integrated liquid water directly over the site. The temporal correlation of errors in liquid water path means that it is not really meaningful to distinguish bias from random error, so only an error variable is provided. The lwp is assumed to be proportional to microwave optical depth, and the coefficients used to derive it are obtained as follows. For the liquid water coefficients, the lidar is used to locate the cloud and the model to diagnose cloud base temperature. The water vapour coefficients are derived from model temperature and vertical humidity distribution. Note that humidity is not used in an absolute sense but only in the sense of determining the effective emission temperature of a given water vapour path. Finally, periods of clear sky identified by lidar are used to estimate calibration errors in the radiometers using the fact that lwp retrieved in these regions should be zero.

3.4. Ancillary measurements

Raingauge, radiosonde and/or NWP model data

Requirements	*Random*	None	assumed negligible
	Systematic	None	assumed negligible

A sanity check is performed to test the performance of these ancillary measurements. In certain cases, especially for tipping bucket rain gauges, it is more appropriate to determine the instantaneous presence of precipitation from the radar measurements, although the long-term accumulation of precipitation from the rain gauge is reliable.

4. Processed Cloudnet data

4.1. Doppler cloud radar

Up to five parameters are available from this instrument. All instrument types provide at least the first two parameters: Z and v.

Radar reflectivity factor, Z,

- Variable containing the random error in Z: Z_error
- Variable containing the bias in Z: Z_bias
- Variable containing the minimum detectable Z: Z_sensitivity

- Z_bias
  - Calibration error in Z, one standard deviation
  - This variable is an estimate of the one-standard-deviation calibration error (i.e. the likely systematic error) in radar reflectivity factor.
  - Units: dB
  - Type: single-precision floating-point scalar
- Z_error(time, height)
  - Random error in Z, one standard deviation
  - This variable is an estimate of the one-standard-deviation random error in radar reflectivity factor. It originates from the following independent sources of error: 1) Precision in reflectivity estimate due to finite signal to noise and finite number of pulses 2) 10% uncertainty in gaseous attenuation correction (mainly due to error in model humidity field) 3) Error in liquid water path (given by the variable lwp_error) and its partitioning with height).
  - Units: dB
  - Type: single-precision floating-point array
- Z_sensitivity(height)
  - Minimum detectable radar reflectivity
  - This variable is an estimate of the radar sensitivity, i.e. the minimum detectable radar reflectivity as a function of height. It includes the effect of ground clutter and gas attenuation but not liquid attenuation.
  - Units: dBZ
  - Type: single-precision floating-point vector

Doppler velocity, v,

- attribute containing the nyquist velocity: folding_velocity
- attribute containing the number of FFT bins (assuming coherent processing): nbinsfft
- folding_velocity
  - nyquist velocity
  - Units: m s-1
  - Type: single-precision floating-point scalar
- nbinsfft
  - number of FFT bins
  - This attribute, together with the folding_velocity, gives the resolution of the velocity measurement. This value is always much greater than the intrinsic error in velocity.
  - Units: None
  - Type: single-precision floating-point scalar (an array is possible)

Doppler spectral width, width,

- No error variables; these can be calculated from the Doppler velocity attributes

Standard deviation of the mean Doppler velocity, sigma_v,

- attribute containing the number of samples: nsamples
- No error variables; these can be calculated from the Doppler velocity attributes and the nsamples attribute
- nsamples
  - Number of samples
  - This attribute can be used to determine the statistical uncertainty in sigma_v
  - Units: None
  - Type: single-precision floating-point scalar (or vector depending on averaging)

Linear Depolarisation Ratio, ldr,

- No error variables as uncertainty not yet considered.

4.2. Lidar and/or ceilometer

A***ttenuated lidar backscatter coefficient, beta,***

- Variable containing the random error in beta: beta_error
- Variable containing the bias in beta: beta_bias
- beta_bias
  - Calibration error in beta, one standard deviation
  - This variable is an estimate of the one-standard-deviation calibration error (i.e. the likely systematic error) in attenuated lidar backscatter coefficient.
  - Units: dB
  - Type: single-precision floating-point scalar
- beta_error
  - Random error in beta, one standard deviation
  - For ceilometers, this variable is a very approximate estimate of the one-standard-deviation random error in attenuated lidar backscatter coefficient. When possible this should take account of signal-to-noise ratio, number of pulses averaged. This is not always possible when the exact algorithm used to calculate the reported backscatter values is proprietary.
  - Units: dB
  - Type: single-precision floating-point scalar or array

4.3. Microwave radiometer

Liquid water path, lwp

- Variable containing the random error in lwp: lwp_error
  - Error in liquid water path, one standard deviation
  - This variable is a rough estimate of the one-standard-deviation error in liquid water path, calculated as a combination of a 20 g m-2 linear error and a 25% fractional error.
  - Units: g m-2
  - Type: single-precision floating-point vector

4.4. Ancillary instrumentation

- No error variables as uncertainty not yet considered for these.