# INSTRUMENT REQUIREMENTS

Clouds form a major component of the Earth's radiation budget. They vary rapidly in space and time, with associated rapid variation in the radiation and precipitation impinging on the Earth's surface. To obtain quantitative information on how clouds evolve in space and time requires instruments that can capture both the vertical profile and the temporal variation with sufficient resolution.

Within ACTRIS, the primary objective is to obtain the **vertical cloud structure** within an atmospheric column, utilising the temporal dimension to yield the equivalent of a two-dimensional slice through the three-dimensional atmosphere. The resolution required to capture such highly variable entities necessitates the use of active remote sensing in the form of cloud radar and lidar or ceilometer. Both instruments, each sensing a different portion of the electromagnetic spectrum, are required to disentangle ambiguities in the **atmospheric targets** that are detected.

In the following, a comprehensive description of the technical concepts and requirements for ACTRIS Observational Platforms is provided.

## I.     Required CRS instruments

The objective to provide continuous long-term vertical profiles of **cloud fraction** and **water** and **ice cloud properties** requires the synergistic use of several instruments: Doppler cloud radar, lidar/ceilometer, multi-channel microwave radiometer and a disdrometer. To qualify as an ACTRIS compatible cloud-profiling station, the instrument setup must be capable of continuously providing vertical profiles of clouds at the nominal Cloudnet resolution of 30 seconds and 60 metres.

### 1)  Doppler Cloud Radar

#### ❖  Instrument description

Cloud radars are active systems similar to weather radar, but operating at higher frequencies, typically 35 and 94 GHz. These higher frequencies permit much smaller antennae and power consumption than weather radar frequencies but suffer more from gaseous and liquid attenuation, which must be corrected for. Higher frequencies also have an advantage with clutter suppression, due to the more focused radar beam, and a reduction in the amount of scattering by insects ubiquitous in the lower atmosphere; insect sizes relative to the radar wavelength mean they are scattering in the Mie regime. The radar must be Dopplerized, as Doppler velocity measurements are required for hydrometeor diagnosis (e.g., liquid cloud droplets versus drizzle drops, identification of the melting layer as slowly falling snowflakes melt to become rain drops with significant terminal fall speeds), and for discriminating between insects and other hydrometeors. The second moment of the Doppler

spectrum, Doppler spectral width, is a useful but not strictly necessary additional parameter. Both pulsed and frequency-modulated continuous-wave (FMCW) Doppler radars are suitable, provided there is no saturation. Cloud radars capable of measuring Linear Depolarisation Ratio (LDR) provide significant advantages in insect discrimination, melting layer determination and ice crystal classification.

The preferred measurement mode is vertical pointing, since this permits the direct use of Doppler velocities (after correction for the motion of the air) in microphysical retrieval and reduces the severity of attenuation due to gases and liquid. Scanning is permitted but is not directly applicable for ACTRIS measurements. Note that without measurements of liquid water path, it is not possible to determine how strongly the profile of radar reflectivity is attenuated by an intervening liquid layer. Sensitivity to ice clouds above a liquid layer is then reduced by an unknown amount, potentially causing issues in determining cloud fraction, and there is an unknown bias in the reflectivity profile harming measurements in ice above the liquid layer.

The amount of radar reflectivity attenuation due to liquid is frequency dependent. The two-way attenuation due to a cloud with a liquid water path of 500 g m$^{-2}$ is around 4.5 dB at 94 GHz, but only 1.2 dB at 35 GHz, and less at lower frequencies. Hence, it is possible to sidestep the issue of liquid attenuation in particular locations under certain conditions through the use of a lower-frequency radar – such as the Arctic in winter when there are no warm liquid layers present, only thin supercooled liquid layers with very low liquid water path.

The cloud radar must be capable of detecting the vast majority of optically relevant clouds, which can be directly expressed in terms of radar reflectivity. Comparing radar returns with the optical depth derived from lidar, for ice clouds up to a height of 9 km, Protat et al. (2006) show that a radar with a sensitivity of –55 dBZ at 1 km should detect 80% of the ice clouds with an optical depth above 0.05 and 97% of clouds with an optical depth greater than 0.1. For a radar with –60 dBZ sensitivity at 1 km the percentages are 98% and 100%, respectively. Hence, a minimum requirement is −50 dBZ at 1 km with a temporal resolution of 30 seconds and 60 m resolution in the vertical. Calibration of the reflectivity is vital for removing bias in both calculating cloud fraction amounts and in deriving ice water contents; a systematic 1 dB radar calibration error results in a 15% error in mean ice water content when using the radar reflectivity-temperature method of Hogan et al. (2006). Hence, radar reflectivity calibration should take place at least twice a year (see calibration methods described in the concept paper of the Centre for Cloud Remote Sensing in D4.1). Doppler velocity calibration is usually not necessary but can be checked by pointing at a hard target. Ensuring that the instrument is indeed pointing vertically is very important; off-vertical Doppler velocity measurements will contain a component from the horizontal wind which may be significant at altitudes close to the tropopause where horizontal wind speeds can easily exceed 50 m s$^{-1}$.

Precipitation can cause wetting of the radome or antenna, causing significant attenuation which is difficult to ascertain. Reflectivity data is not reliable in these conditions and should be flagged. Atmospheric attenuation, including gaseous, liquid rain, and the melting layer, is diagnosed and corrected for, if appropriate, in the data processing stage.

❖ Observational capabilities

| Doppler cloud radar | | |
|---|---|---|
| **Criteria** | **Minimum requirements** | **Optimum set up** |
| Minimum sensitivity | −40 dBZ at 1 km in the absence of attenuation. | −50 dBZ at 1 km in the absence of attenuation. |
| Temporal resolution | 30 seconds and 60 m resolution in the vertical | 1 second and 10 m resolution (or better) in the vertical |
| Velocity resolution | 10 cm s-1 or better | 5 cm s-1 or better |
| Doppler spectrum | No | Yes |
| Polarisation diversity | No | Yes (LDR preferred but SLDR also suitable) |
| Type of instruments that fulfill the Minimum requirement or the optimum setup | 35 or 95 GHz cloud radar in vertical pointing mode | Polarisation and Doppler spectrum capabilities. Elevation scanning capabilities with angular resolution better than 2° |

**Minimum requirements: Cloud radar** with Doppler capability providing profiles of radar reflectivity factor and Doppler velocity: Minimum sensitivity should be about −50 dBZ at 1 km in the absence of attenuation.

**Optimal set up: Cloud radar** providing the full Doppler spectrum, together with the first 3 moments of the Doppler spectrum (reflectivity, Doppler velocity, and spectral width) and linear depolarisation ratio is the basic instrument. The minimum sensitivity should be at least −60 dBZ at 1 km for 10 second integration time enabling the detection of almost all radiatively significant **ice clouds** in non-precipitating conditions. This sensitivity can be achieved with both pulsed and frequency-modulated continuous-wave (FMCW) Doppler radars operating at 35 or 94 GHz (and potentially at higher frequencies).

At these frequencies, correction for attenuation by atmospheric gases and, more importantly, liquid water clouds is necessary; attenuation is less at 35 GHz, so this frequency is preferable to 94 GHz. In addition, radome wetting during periods of rainfall leads to large signal losses and unreliable data.

Lower frequency radar (e.g., 10 GHz more typical of weather radar) can also achieve the desired sensitivity in vertically-pointing mode and be able to provide reliable data during periods of rainfall. However, lower frequencies pose additional constraints such as enhanced sensitivity to insects and clutter issues at near range (larger sidelobes due to antenna size constraints limiting how focused the transmit beam is), and a minimum range that may preclude measurements of liquid layers in the boundary layer.

Higher temporal resolution (especially 1 second integration time) permits the generation of products based on the velocity variation (e.g. **turbulence**, **drizzle products** based on skewness) in addition to the standard products. The full Doppler spectrum permits the analysis of situations where more than

one distinct hydrometeor population is occupying the same volume (e.g., **mixed-phase clouds** with both supercooled liquid and ice particles, stratocumulus containing liquid droplets and drizzle drops). The velocity resolution, usually determined from the Nyquist velocity and the number of points in the FFT used to obtain the Doppler spectrum, should be 10 cm s$^{-1}$ or better to make maximum use of these capabilities.

Inclusion of additional radar frequencies also expands the range and accuracy of products that can be derived. Dual-frequency (e.g. 35 and 94 GHz) permits the vertical **profile of liquid water content** to be derived without restrictive assumptions, and triple-frequency (e.g. 10, 35, 94 GHz) permits **ice microphysical properties** to be deduced without certain density and habit assumptions through accounting for Mie scattering at higher frequencies. Multiple frequencies also assist in accounting for atmospheric attenuation, especially if one of the selected frequencies is around 10 GHz or less.

**[Also see the Doppler cloud radar Standard Operating Procedures (SOPs)](#)**

### 2) Microwave radiometer

#### ❖ Instrument description

Microwave radiometers are passive receivers that measure the downwelling thermal emission from the atmosphere and its components (mainly oxygen, water vapour and cloud liquid water). From these observations, some atmospheric thermodynamic properties can be deduced. The quantity measured is atmospheric radiance (W m$^{-2}$ sr$^{-1}$ Hz$^{-1}$), typically converted into brightness temperature (Tb, in Kelvin). Thermal emission is usually measured in the 20−60 GHz range. The 22−35 GHz band provides information on water vapour and cloud liquid water, with at least two channels (usually 23.8 and 30−31 GHz) required to retrieve the column-integrated water vapour path and liquid water path. Additional channels in this region can provide information on the vertical distribution of water vapour content. Many instruments make observations at 50−60 GHz to derive temperature information, with a vertical profile usually obtained through scanning at multiple elevation angles. Current systems have a temporal resolution better than 1 minute.

Microwave radiometers need to be calibrated before making use of their data. There are several automatic procedures that are carried out regularly, such as an internal black-body target at ambient temperature and noise power injected by diode sources. These calibrations are relative calibration, assuming some constant calibration parameters. Therefore, absolute calibration has to be performed using two blackbodies at different temperatures (internal target at ambient temperature as well as an external target cooled with liquid nitrogen). In addition, a tipping curve method can be applied for scanning systems, but this method is limited for the K-Band and under homogeneous low humidity conditions. Calibrated microwave radiometers are then expected to be capable of providing brightness temperatures with an absolute accuracy of 0.3−0.5 K. This results in measurements of LWP with an accuracy of about 15 g m$^{-2}$. External calibration with a liquid nitrogen target is recommended at least twice a year (see calibration methods described in the concept paper of the Centre for Cloud Remote Sensing in D4.1).

Precipitation causes wetting of the radome, with similar attenuation issues as experienced by the cloud radars. The data is not reliable in these conditions and must be flagged. Most microwave radiometers are equipped with a standard weather station (temperature, humidity, pressure) and a precipitation sensor. Another instrument that is often operated along is an infrared pyrometer which is mainly used to estimate cloud base height in combination with the derived temperature profile.

❖ Observational capabilities

| Microwave radiometer | | |
|---|---|---|
| **Criteria** | **Minimum requirements** | **Optimum set up** |
| Parameters observed | Cloud liquid water path (LWP)<br>Integrated water vapor (IWV) | Cloud liquid water path (LWP)<br>Integrated water vapor (IWV)<br>Temperature profile<br>Humidity profile |
| Temporal resolution | 1 minute (LWP, IWV) | 1 second (LWP, IWV)<br>15 minutes (T-profile) |
| Accuracy | 30 g/m² (LWP), 1 kg/m² (IWV) | 15 g/m² (LWP), 0.5 kg/m² (IWV) |
| Type of instruments that fulfill the Min. requirement or the optimum setup | Dual-frequency radiometers in K-Band (e.g. 23.8/31.4 GHz) | Multi-frequency radiometers with elevation scanning capabilities.. Measurements at 5-10 frequencies in both K- (22-32 GHz) and V-Band (51-59 GHz), potentially additional channels in higher bands (89 GHz) |

**Minimum requirements: Dual-frequency vertical pointing microwave radiometers**, where the cloud liquid water path and water vapour path are derived from two brightness temperatures ideally measured at frequencies close to 23.8 and 31.4 GHz. The approach by Gaussiat et al. (2007) is then used to derive an accurate liquid water path by correcting for instrumental drifts in calibration and unknown absorption coefficients by adding a calibration offset to the derived optical depths. The offset is determined in clear-sky periods as indicated by the ceilometer, when it is expected that the liquid water path be zero.

The temporal resolution of the standard vertical observations should be 1 minute or better to capture the variability of clouds.

**Optimum setup: Multi-channel scanning microwave radiometer** permits the retrieval of **temperature** and **humidity profiles**, in addition to the standard column-integrated measurements.

The Elevation scanning capability increases the quality and accuracy of temperature profiles in the lowest 2000 m.

The addition of an extra-high frequency channel (such as 89 or 150 GHz) provides extra sensitivity to thin clouds with very low liquid water path (LWP) that are still radiatively important (such as supercooled layers found in the Arctic). Channels around 183 GHz can improve the water vapor observations in areas with low humidity (high mountains, polar regions).

The optimum temporal resolution of standard vertical observations is 1 second, in order to capture short-term LWP variability in clouds.

**Also see the Microwave radiometer  Standard Operating Procedures (SOPs)**

### 3) Automatic lidars and ceilometers

❖ Instrument description

Automatic lidars and ceilometers (ALC) are single-wavelength, low-power, automatic lidars typically operating at wavelengths ranging from 850 to 1064 nm, originally designed to provide the cloud base altitude. Since clouds are very strong scatterers at near-infrared wavelengths, these systems do not require the high power expected for aerosol lidar systems. However, the sensitivity of current ceilometers is sufficient to detect aerosol within the boundary layer, and thicker ice cloud. High-power aerosol lidar systems can also be used.

The key cloud parameter for the ALC is detection of liquid layers, including supercooled liquid layers. To improve sensitivity, averaging of data to 15−30 m in the vertical and 15−30 seconds in time is therefore appropriate.  The minimum range should be ~200 m or less to enable detection of fog layers, which might be missed by the cloud radar causing unaccounted-for attenuation. Maximum range should exceed 7.5 km to enable detection of supercooled liquid layers down to almost −40 °C. Instrument design may mean that full overlap between receiver and transmitter is not reached until 1 km or so, with correction of the signal possible in part of the overlap region; this is permissible as long as detection of liquid layers at 200 m is still possible. Possible saturation of the lidar signal in clouds at low altitudes must be flagged and mitigation procedures adopted to prevent this occurring.

Instrument sensitivity is dependent on the signal-to-noise ratio (SNR) which is a function of the emitted power, telescope design, averaging time, background light, and the strength of the backscattered return from atmospheric targets. Thus, stray background light (solar radiation) entering the detector chain leads to a drop in sensitivity during the day.

The required sensitivity for liquid-layer detection can be expressed in terms of extinction, with typical values exceeding 10 $km^{-1}$. Since the lidar ratio for cloud droplets is about 20 sr at almost all lidar wavelengths, this translates to a backscatter coefficient of about 0.5 $km^{-1}$ $sr^{-1}$ which is achieved by all current ALC systems up to 7 km even during daytime as long as the instrument is operating at designed performance levels. Note that this sensitivity is not sufficient to detect high ice clouds, which can have lower extinction than 0.05 $km^{-1}$.

ALCare calibrated by the manufacturer, and the calibration is regarded as stable over time. However, absolute calibration is required periodically over time using a standard naturally occurring atmospheric target with a known backscatter, such as molecular backscatter or liquid clouds that fully extinguish the signal (see calibration methods described in the concept paper of the Centre for Cloud Remote Sensing in D4.1). These calibration methods yield a calibration accurate to about 10% (O'Connor et al. 2004, Wiegner and Geiß 2012), suitable for cloud detection and target categorization.

High-power aerosol lidar systems can also be used instead of ALC. These should utilise a near-range channel to reduce overlap issues, and include neutral-density filters to mitigate saturation in liquid layers. Full calibration should follow the specifications given in the concept paper of the Centre for Aerosol Remote Sensing in D4.1.

Further use of the lidar signal in specific algorithms may require much more stringent tests on calibration, stability, and the calculation of the influence of multiple scattering.

❖ Observational capabilities

| Automatic lidars and ceilometers | | |
|---|---|---|
| Criteria | Minimum requirements | Optimum set up |
| Minimum sensitivity | Sufficient SNR for detection of liquid water layers in the near range (< 200 m) | Far range detection > 7.5 km |
| Advanced capabilities | … | Depolarization channel |
| Advanced capabilities | … | Ability to retrieve extinction directly through high-spectral-resolution or Raman methods |
| … | | |
| Type of instruments that fulfill the Min. requirement or the optimum setup | | |

**Minimum requirements: ALC** (low-power lidar) capable of detecting liquid water layers, including supercooled liquid layers, up to 7.5 km in altitude: In this mode, the primary function of the ALC is purely the detection of liquid water in the lower troposphere.

**Optimum setup: High-power aerosol lidar (**capable of detecting **thin ice clouds**, **elevated aerosol layers** and the molecular backscatter signal) provides **additional** retrieval capabilities and improves high-altitude cloud statistics. A depolarization channel is desirable for unambiguous **particle phase discrimination**. Note: depolarisation capabilities start to be available for new ALC models. The ability to retrieve extinction directly through high-spectral-resolution or Raman methods also greatly improves retrieval uncertainties and provides a consistency check. Aerosol properties at high resolution permit synergy between EARLINET and Cloudnet retrievals allowing investigation of **aerosol-cloud interactions** in the same profile.

[Also see the automatic lidars and ceilometers Standard Operating Procedures (SOPs)](#)

**4) Disdrometers**

❖ Instrument description

Disdrometers measure the size distribution and falling velocity of precipitation at the surface. The measured drop size distribution is then used to derive other moments of the size distribution, such as reflectivity. For warm precipitation (rainfall), the radar reflectivity for any radar frequency can be

derived reliably, using the appropriate dielectric factor and Mie scattering calculations for the specific radar frequency. The derived radar reflectivity during rain periods is then used to track the calibration of the cloud radar through comparison with the cloud radar reflectivity measured at the lowest reliable altitude range that the radar provides.

The disdrometer is calibrated by dropping spheres of known sizes and density (known fall speed) through the measurement beam. During operation, reliable rainfall measurements are ensured by checking that the size and fall speed in each class match the expected theoretical size-fall-speed relationship for water drops (e.g. Beard, 1976). Some variation from the theoretical size-fall-speed relationship is expected, due to both variations in the vertical air motion, and whether the drops are falling in equilibrium, but measurements outside this envelope are then disregarded when calculating the reflectivity for calibration.

The situation is more challenging for solid precipitation (snow and hail) as there are more assumptions to be made when deriving radar reflectivity from the size distribution (dielectric factor, particle density, etc.). Periods with solid precipitation are therefore not used for calibration, but assuming that the cloud radar has been calibrated (e.g. during warm precipitation or solid reflector), the combination of cloud radar reflectivity and the disdrometer measured size-fall-speed relationship enable the retrieval of particle density and other parameters.

❖ Observational capabilities

| Disdrometer | | |
|---|---|---|
| **Criteria** | **Minimum requirements** | **Optimum set up** |
| Observed parameter | Speed class histogram<br>Size class histogram | Particle velocity for each hydrometeor by a single particle counter.<br>Particle size for each hydrometeor by a single particle counter. |
| Temporal resolution | 1min | 1min |
| Particle size range | 0.2 to 8 mm | 0.05 to 8 mm |
| Velocity range | 0.2 to 20 m/s | 0.1 to 20m/s |
| Type of instruments that fulfill the Min. requirement or the optimum setup | Laser disdrometer.<br>Clear space on a radius of 30m around the sensor. | Laser disdrometer with single particles capabilities |

**Also see the disdrometers Standard Operating Procedures (SOPs)**

5) **Weather station**

**A tipping bucket rain-gauge**

Precipitation has several potential sources of impact, arising from radome wetting (both cloud radar and radiometer), scattering assumptions no longer applicable (microwave radiometer), and attenuation in the atmospheric column (cloud radar). Periods when the measurements are potentially affected by precipitation can usually be determined from the measurements themselves. However, the addition of a rain-gauge provides the surface rain-rate which will aid identifying those periods where only radome wetting is an issue (weak precipitation), and periods where the precipitation is strong enough to cause serious attenuation of the radar reflectivity profile. For identifying radome wetting conditions, a fast response instrument sensitive to weak precipitation must be employed, such as optical sensors and disdrometers; a standard tipping bucket rain-gauge has very slow response times to weak precipitation (has to wait for the internal bucket to fill before tipping) and is not suited for this application. A tipping bucket rain-gauge may be more accurate in strong precipitation conditions and when calculating accumulations, which can then be used to check the performance of the disdrometer.

**Temperature and relative humidity sensor**

Temperature is an important parameter to identify the solid precipitation that can reach the ground. A temperature threshold will be applied to focus our study and comparison between disdrometers and cloud-radar only for liquid precipitations.

Relative humidity will be used to identify periods without fog events in applying a threshold and to consider only precipitation events.

**Wind speed sensor**

Wind speed can have a significant impact on the quality of disdrometer measurement during precipitation events: fall drop velocity can be modified by strong surface dynamics. Representative wind speed near the ground level is also necessary to optimise the monitoring of the cloud radar calibration constant with the disdrometer.

❖ Observational capabilities

| Weather Station | | |
|---|---|---|
| **Criteria** | **Minimum requirements** | **Optimum set up** |
| Observed parameter | Precipitation rate<br>Air temperature<br>Wind speed | Precipitation rate<br>Air temperature<br>Relative humidity<br>Wind speed<br>Wind direction |
| Temporal resolution | 1min | 1min |
| Accuracy | Precipitation rate resolution of 0.2mm | Precipitation rate resolution of 0.1mm |
| Type of instruments that fulfill the | A tipping bucket rain-gauge with a 6-month calibration | A tipping bucket rain-gauge validated by WMO with a 6-month calibration period. |

| Minimum requirement or the optimum setup | period. | |
|---|---|---|

## II.    Recommended CRS instruments

### 1)  Doppler lidar

❖  Instrument description

Doppler lidars are single-wavelength lidar systems that provide profiles of SNR and radial Doppler velocity. These instruments are typically low-power, eye-safe, automatic lidar systems operating at wavelengths close to 1500 nm, and Doppler velocity is usually obtained using the heterodyne technique. The scattering targets are aerosol particles and cloud droplets, which act as tracers from which winds and turbulent properties can be derived, and larger hydrometeors such as ice and rain drops. Vertical profiles of the horizontal wind are obtained by pointing off-zenith, whether by combining three or four orthogonal beams (Doppler Beam Swinging – DBS) or by conical scanning (Velocity Azimuth Display - VAD), hence one key requirement is that the Doppler lidar instrument is configured with multi-beam or scanning capability.

The other key requirement for the Doppler lidar is that it must have sufficient sensitivity to obtain velocity information throughout the extent of the boundary layer. The majority of the scattering targets in the boundary layer are aerosol particles and the required sensitivity is therefore similar to ceilometer systems. The minimum measurement height should be 100 m or less, but this can be mitigated through the use of scanning at low elevation angles (minimum range may exceed 100 m), and the maximum range should extend beyond the boundary layer (i.e. maximum range should be at least 2 km in most cases).

Quantitative measurements of winds and turbulent mixing in the atmosphere require accurate characterization of the uncertainties in the radial SNR and Doppler velocities. Since radial Doppler velocity uncertainty estimates are derived from SNR, full characterization of the background noise behaviour of the instrument, and possible subsequent post-processing, is necessary (Manninen et al., 2016). This improvement in the radial Doppler velocity uncertainty estimate propagates directly through to wind retrievals **and is vital for deriving reliable higher order velocity statistics** such as variance, skewness and dissipation rates; for example, the observed variance contains contributions from both the true variance and the error variance (e.g. O'Connor et al., 2010).

Doppler velocity calibration is performed by the manufacturer and the calibration is regarded as stable over time. However, the velocity calibration should be checked periodically using stationary targets in the far field of the instrument, such as towers, masts, buildings, or hills. Such targets, especially towers, masts and buildings, also enable the azimuthal and elevation pointing accuracy to be assessed.

If the telescope function is known accurately, the attenuated backscatter profile can be obtained from the SNR profile (Hirsikko et al., 2014), and the Doppler lidar can act as a surrogate ceilometer.

Calibration should be checked periodically over time using a standard naturally occurring atmospheric target with a known backscatter, such as liquid clouds that fully extinguish the signal (see calibration methods described in the concept paper of the Centre for Cloud Remote Sensing in D4.1). This method yields a calibration accurate to about 15% (O'Connor et al. 2004; Westbrook et al., 2012), suitable for cloud detection and target categorization. Note that the molecular backscatter return is too low to detect at typical Doppler lidar operating wavelengths.

Further use of the Doppler lidar signal in specific algorithms may require much more stringent tests on calibration, stability and the post-processing corrections applied.

❖ Observational capabilities

| Doppler lidar | |
|---|---|
| **Criteria** | **Optimum set up** |
| Sensitivity | Able to capture the full depth of the boundary layer (in most conditions) |
| Scanning capability | Ability to scan required for deriving profiles of the horizontal wind. VAD is preferred over DBS, with full hemispheric scanning enabling optimisation for specific location (elevation angle(s), maximum expected wind speeds). <br><br> Vertical operation provides turbulent properties, although can be obtained from scanning. |
| Temporal resolution | < 10 s (for turbulent properties) |
| Velocity resolution | < 10 cm s-1 |
| Nyquist range | > -15 to +15  ms-1 for scanning operation (elevation angle dependent) |
| Range resolution | < 50 m (for turbulent properties), < 50 m in vertical extent (for wind), range resolution can be greater (elevation angle dependent) |
| Type of instruments that fulfill the optimum setup | |

**Doppler lidar** provides the **dynamical features** of the atmospheric boundary layer, including winds, turbulent properties, shear, mixing-level-height, low-level jets, and classification of the turbulent sources. In combination with EARLINET and Cloudnet retrievals, such properties permit the identification of aerosol layers and clouds that are directly coupled to the surface, extends the in-situ measurements at the surface vertically through the atmospheric column, and provides the **timescales for turbulent transport**.

III.    Complementary added value observations

Complementary added-value observations may help in the scientific use and interpretation of data from an ACTRIS observational component. Added-value observations are not necessarily part of

ACTRIS and thus do not always follow ACTRIS QA/QC procedures. They may however be subject to integration into ACTRIS in the future or follow the standards of other research infrastructures or international bodies.

**Water vapour** and **temperature** profiles measured with **Raman lidar** can provide useful information on the atmospheric conditions under which clouds develop. The profiling capabilities for water vapor content and relative humidity can be further improved when Raman lidar and **microwave radiometer** measurements are combined in synergistic retrievals. For this purpose, the high-power lidar used in the optimum setup can be equipped with additional measurement channels.

**Radar wind profilers** provide the vertical profile of **horizontal and vertical winds**. The horizontal wind profile can be used to determine appropriate advection-based averaging for cloud variables, provide suitable length scales for deriving turbulent parameters and statistical-based algorithms and determine the beam-broadening component for radar vertical velocity uncertainties. The profile of the vertical wind (determined from clear-air returns) can be used to provide the 'true' vertical wind. The cloud radar measures the hydrometeor velocity, which is the sum of the hydrometeor fall velocity and vertical air motion. The hydrometeor fall velocity provides excellent information on the hydrometeor size, density and shape; after correction for the vertical air motion, algorithms can use the cloud radar Doppler velocity as an additional component to constrain microphysical properties. Winds throughout the full tropospheric profile are of interest.

Combination of a **sonic anemometer** and a **Licor gas analyser** permits the calculation of the **sensible and latent heat flux** (and $CO_2$ flux) at the surface. Together with radiation measurements, the full surface energy balance can be obtained using micrometeorological methods by including a **soil heat plate** to determine the **heat flux into the ground**.

The **atmospheric emitted radiance interferometer** (AERI) is a ground-based instrument that measures the **downwelling infrared radiance** with sufficient spectral resolution to discriminate among gaseous emitters (e.g., carbon dioxide and water vapour) and suspended matter (e.g., aerosols, water droplets, and ice crystals). These upward-looking surface observations can be used to obtain vertical profiles of tropospheric **temperature and water vapour**, as well as measurements of **trace gases** (e.g., ozone, carbon monoxide, and methane) and **downwelling infrared spectral signatures** of clouds and aerosols.

The **micro rain radar** (MRR) is a very low-power vertically-pointing FMCW Doppler radar operating at 24 GHz providing the full Doppler spectrum, from which vertical profiles of the **drop size distribution of precipitation** are derived. This instrument complements the cloud radar in the nearest 2 km by providing the precipitation profile to the surface, enabling correction for any saturation in the cloud radar near field, and aiding calibration activities.

**Drop-counting raingauges** and **snowgauges** provide closure methods for microphysical profiles of precipitation derived from the active remote sensing vertical profiles. Various types of **disdrometers** and cameras can provide information on the **hydrometeor size distribution, phase, shape and density**.

**Broad-band shortwave** and **longwave radiation** measurements at the surface (e.g., BSRN station) are an obvious complement to cloud profiling, and also provide an opportunity to implement closure studies on the vertical profile of microphysical properties derived from the cloud-profiling measurements. For full closure, it is recommended that all radiation components are measured (shortwave down, net, direct and diffuse, and longwave down and net).

## IV.    Auxiliary measurements and data sources

### 1)  Auxiliary measurements

Auxiliary measurements cover fundamental parameters (e.g., meteorological data) needed to process or evaluate ACTRIS data and follow established international standards. If adequate, added-value observations and auxiliary measurements are shared among the observational components at the same NF.

Vertical profiles of **meteorological parameters** (temperature, pressure, specific humidity and winds) are required for quantifying instrument, atmospheric attenuation and retrieval uncertainties. They may be taken from the output of a high-resolution weather forecast model or radiosoundings. **Radiosondes** measure high-resolution vertical profiles of **temperature, humidity and winds**, thus providing the parameters necessary for specific instrument corrections within the cloud profile processing scheme, independent from any model that might be evaluated. However, only radiosonde launches at sites where the frequency is twice per day or higher are suitable for inclusion within the processing.

**Standard meteorological measurements** (e.g., **automatic weather station**) provide useful information on surface conditions, especially those that may impact the core measurements, such as precipitation, strong winds, extreme heat or cold, and can be used within the QA system. The measurement system should include a precipitation detection system with fast response times (i.e. optical rain gauge or present weather detector).

### 2)  Auxiliary data sources: temperature and humidity profile

The target categorization includes profiles of temperature, humidity and horizontal winds for assisting in quantifying uncertainties in particular retrievals, initialising a background state, estimating temporal or spatial scales, and for determining constants or variables that are temperature or humidity dependent where appropriate. Certain instrument uncertainties also require these parameters as an input. The profiles of temperature, humidity and horizontal winds are normally taken from the output of a high-resolution weather forecast model. Radiosoundings can also be used if available, and the ingest code will provide them in a format that emulates the weather forecast model input file. In addition, horizontal winds from a wind profiler can also be incorporated if preferred.