

# PROBE WG2 “Advanced ABL profiling” - Deliverable 2.1

**D2.1: Reports, white and review papers on key ABL parameters, their applications, and the end-user requirements.**

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<b>Project end date</b>	<b>04/2021</b>

<b>Project title (acronym)</b>	Deliverable 2.1
<b>Authors</b>	Document preparation conducted by P. Martinet and E. O'Connor  Authors (by alphabetical order): J-A. Bravo Aranda, J. Buxmann, D. Cimini, M. José Granados Munoz, M. Haeffelin, S. Kotthaus, E. O'Connor, P. Martinet, H. Ricketts, T. Rieutord, R. Ruefenacht with additional contribution from PROBE WG2 members



## 1 INTRODUCTION

This report aims at providing a synthesis of key ABL parameters for several applications and end-users with the corresponding existing algorithms. The information on end-users requirements will be filled later during the action after the finalization of the deliverable 1.2 that will be provided by working group 1 (knowledge exchange). For each group of products several references are provided so that the reader can get more details on specific products or accuracy evaluation.

Through all the documents the following acronyms are used:

- ALC: Automatic Lidar Ceilometer
- DL: Doppler Lidar
- MWR: MicroWave Radiometer
- DIAL: Differential Absorption Lidar
- CR, DCR: Cloud Radar, Doppler Cloud Radar
- RL: Raman Lidar
- DeL: Depolarization Lidar
- BL: Backscatter lidar
- RWP: Radar Wind Profilers
- ABL: Atmospheric Boundary Layer

## 2 CLOUDS AND PRECIPITATION (TASK LEADER: M. JOSÉ GRANADOS MUNOZ)

### Instrument description for ABL profiling of clouds

One of the main instruments for cloud profiling within the ABL is the Cloud Radar (CR), operating either at 35 or 94 GHz. The use of ceilometers (ALC) is also extended within the cloud profiling community. The synergy of CL with ALC and MWRs is a powerful tool for the study of cloud properties vertical distribution and combined databases of the three instruments are usually used in the existing retrieval algorithms. Many stations within Europe are already continuously reporting within the CLOUDNET network (<https://cloudnet.fmi.fi/>) as part of ACTRIS, which combines CR, ALC and MWR for the detection, classification and retrieval of cloud properties.

For this section, these specific acronyms are used:

- DSD: Droplet Size Distribution
- CDNC: Cloud Droplet Number Concentration
- ACI: Aerosol-Cloud Interaction <sup>5</sup>
- Reff: Effective Radius
- CF: Cloud Fraction
- LWC/IWC: Liquid/Ice Water Content
- OEM: Optimal Estimation Method

Available networks: ACTRIS/CLOUDNET, ARM

Products	Cloud detection / classification / CF	Liquid/Ice water content	Cloud optical depth	Microphysical properties	ACI <sup>5</sup>
<b>Instruments</b>	- ALC - DL - CR - CR + ALC/DL	- ALC (with depolarisation) - CR+ALC+ MWR -RL	- CR - RL - ALC+CR -ALC+ sunphotometer	- CR - ALC+CR - ALC + CR + MWR	- ALC+CR - RL+CR
<b>Accuracy requirements (from WG1)</b>					
<b>Temporal resolution Requirements (from WG1)</b>	Optimal temporal resolution for CLADS to be effective is < 2s.				
<b>Assumptions needed</b>	Drizzle:  Liquid clouds without ice phase, cloud base, cloud top  CF:  CF over time assumed to be projected area CF	- CR+MWR synergy: a DSD should be prescribed for LWC retrieval	Monomodal DSD for LWC	Monomodal DSD for LWC	Liquid water clouds only. Well-mixed conditions, CDNC and monomodal gamma DSD constant with height
<b>Existing algorithms</b>	CLOUDNET <sup>1</sup> (CR + ALC/DL, also provides target classification)  Drizzle classification:  CLADS <sup>3</sup> (CR)	For LWC:  - CLOUDNET <sup>1</sup> -SYRSOC <sup>2</sup> -IPT <sup>8</sup> for MWR + CR -MWR+ CR: OEM with model combination:  in	Liquid:  SYRSOC <sup>2</sup>  Ice:  DARDAR <sup>10</sup>	Liquid:  SYRSOC <sup>2</sup>  IPT <sup>8</sup> for MWR + CR  MWR+ CR: OEM with model combination:  in	Sarna, 2015 <sup>6,7</sup>

		development  For IWC:  CLOUDNET <sup>1</sup>  DARDAR <sup>10</sup>  For drizzle water content:  O'Connor <sup>9</sup>		development  Ice:  DARDAR <sup>10</sup>  Drizzle:  O'Connor <sup>9</sup> (operates within CLOUDNET)	
<b>Applications</b>	1) Data Assimilation 2) Evaluation and verification in Numerical Weather Prediction 3) Climate and hydrological models 4) Satellite evaluation and Cal/Val.				
<b>End users</b>	- Scientific community - NWP and other modelling communities - Space agencies				
<b>Readiness for operation</b>	CLOUDNET: Yes SYRSOC: No CLADS: In preparation IPT: Yes DARDAR: Yes OEM with model combination: No				
<b>Accuracy of existing products</b>	Evaluation is difficult as these are the reference instruments. Drizzle classification requires evaluation	~20%	30-70%	~50% for CDNC 5-15% for $r_{eff}$ <sup>4</sup>  O'Connor provides LWF (drizzle liquid water flux) to within a factor of two	Further evaluation required

<b>Uncertainty estimates existing?</b>	N	Y	Y	Y	N
<b>Temporal resolution</b>	< 30 seconds				
<b>Timeliness</b>	< 1 day (< 1 hour being testing)				
<b>Data availability</b>	24//7  For CLOUDNET, near-real-time (<1day)				
<b>Data format</b>	NetCDF for CLOUDNET products				

Note that there are many more algorithms for deriving cloud properties, some of which include additional instrumentation.

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### 3. AEROSOLS (INCLUDING VOLCANIC ASH, POLLEN, FOREST FIRES AND AIR QUALITY ALERTS TASK LEADER: J. BUXMANN AND R.RUEFENACHT SUBSTITUTE :H. RICKETTS)

#### INSTRUMENT DESCRIPTION FOR ABL PROFILING OF AEROSOLS

The most common way of gaining ABL aerosol profiling observation is using the lidar (light detection and ranging) technique. Within this report we concentrate on ground-based lidar systems, which include e.g. Ceilometers (low-power backscatter lidar (BL), operating continuously), Raman lidar (RL), and depolarization lidar (DeL). These methods can be applied either at one or at multiple wavelengths (MBL, MRL). Automatic lidars and state-of-the-art ceilometers (short ALC) are already reporting within networks to measure continuously cloud base height and aerosol profiles (e.g. <https://ceilometer.e-profile.eu/>).

Since the estimation of microphysical aerosol properties is ill-posed additional measurements can be highly beneficial. Therefore, column integrated photometer observations are included in the table below. Photometer measurements are available from various networks such as AERONET (<https://aeronet.gsfc.nasa.gov/> ) and SKYnet (<https://www.skynet-isdc.org/> ) and can be collocated with lidar sites. Other instruments with aerosol profiling capabilities, such as Doppler radars and lidars, Multi Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) instruments, differential absorption lidars (DIAL) or high spectral resolution lidar, do exist. They are not included in the summary table due to their limited availability or technical readiness. They may, however, prove to be beneficial with new technical developments in the future or as additional sources of information.

Aerosol vertical profiling from space, like the Cloud and Aerosol Lidar Pathfinder for Spaceborne Observations (CALIPSO) is not considered within the following table due to limitations, such as e.g. lower sensitivity especially in the BL as compared to ground-based lidar systems, bias of satellites due to limitations in time resolution and limited possibility of satellite observations under elevated cloud layers. Nevertheless, satellite information could well be used for tracking of long-distance transport.

Available networks by area: AERONET (global), E-PROFILE (Europe), ACTRIS/EARLINET, Pollynet

Other networks outside Europe: GALION (global), ADnet, MPLNet, LALINET,

For this section, these specific acronyms are used:

- Ceilo: Ceilometer,
- BL: backscatter lidar,
- RL: Raman lidar,
- DeL: depolarisation lidar,
- ALC: automatic lidars and ceilometers,
- LR: lidar ratio,
- AOD: Aerosol Optical Depth

Products	Extinction	Intensive properties (depolarization, LR, AOD..)	Mass concentration	Aerosol typing
<b>Instruments</b>	- Ceilo, ALC - BL - RL - DeL +photometers	- RL - DeL - photometer	- Ceilo, ALC - BL - RL + photometers	- RL - DeL, + photometer + Ceilo, ALC
<b>Additional instruments</b>	MAX-DOAS	No	Doppler radar	No
<b>Existing algorithms</b>	Yes for all lidars <small>1,2,3,4,5,6,7</small> - Backward Klett for reliable in-place calibration (high power lidars), - Forward Klett for stable instruments with archived calibration constant (ALC) - Synergetic approaches: GRASP <sup>11</sup> , GARRLIC <sup>10</sup>	Yes <sup>8,9 10,11</sup> RL: LR  DeL: volume and particle depol. ratio  Photometer: LR(column)	Yes: Algorithms based on extinction/backscatter profiles with simple multiplication of an appropriate extinction/backscatter-to-mass-ratio	- Ceilo: only in combination with other instruments  -RL/DL/photometer:yes: GARRLIC <sup>10</sup> , GRASP <sup>11</sup>
<b>Assumptions needed</b>	- Ceilo, BL, DL: prescribed LR  - Ceilo, BL, DL + photometer: no assumption needed  - RL: no assumption needed	- RL, DeL: no assumption needed  - Photometer: yes, based on particle model	extinction/backscatter-to-mass-ratio <sup>11,12</sup>	Depends on algorithm
<b>End-Users</b>	- Scientific community  - National Weather Services  - Space Agency	- Scientific community  - Aviation  - Air quality agency  - National Weather Services	- Volcanic Ash Advisory Center  - National Weather Services  - Air quality agencies	- Scientific community  - Volcanic Ash Advisory Center  - National Weather Services
<b>Application</b>	<ul style="list-style-type: none"> <li>- Data assimilation</li> <li>- Airport safety procedure</li> <li>- Satellite Cal/Val</li> <li>- Process studies</li> </ul>			
<b>Readiness for</b>	Yes partly, e.g. internal use within			In development

<b>operation</b>	National Weather services			
<b>Expected accuracy</b>	For Ceilo <sup>14</sup> : 30-35 % (for known aerosol type), 40-50 % (aerosol type unknown)  For lidar <sup>14</sup> : 10-50% can be calculated based on Monte Carlo simulations or intercomparisons	No information	Depends on extinction accuracy + uncertainty for extinction-to-mass conversion (e.g. uncertainty of $K_{ext}$ could be up to 100% <sup>12,13</sup> )	Not applicable
	Accuracy depends on the technical settings and specification of each retrieval/instrument			
<b>Temporal resolution</b>	Minutes to hours (flexible)			
<b>Timeliness</b>	For automatic networks: few minutes to hours, For research instruments: variable			
<b>Data availability</b>	ALC: continuous EARLINET and other lidars: based on specific schedule No product above or within clouds for all products			
<b>Data format</b>	NetCDF, ASCII, (BUFR upcoming)	NetCDF, ASCII	NetCDF, ASCII, (BUFR upcoming)	NetCDF, ASCII

<b>Products</b>	<b>Air quality alerts</b>	<b>Layer tracking</b>
<b>Instruments</b>	- Synergy	- ALC network (automatic instruments and spatial distribution needed)
<b>Additional instruments</b>	Currently done by model and ground based instruments (not profiling)	Satellite
<b>Existing algorithms</b>	Based on different aerosol types depending on properties such as Mass or AOD	Currently done by hand, future developments for automated solution
<b>Assumptions needed</b>	Depends on product required	Requires cloud-screening
<b>End-Users</b>	- Aviation  - Health authorities (air quality)	- National Weather services  - Aviation
<b>Applications</b>	<ul style="list-style-type: none"> <li>- Air quality alerts</li> <li>- Airport safety procedure</li> <li>- Satellite Cal/Val</li> <li>- Process studies</li> </ul>	
<b>Readiness for operation</b>	In development	In development
<b>Expected accuracy</b>	Depends on product, e.g. if based on mass concentration, accuracy depends on that	Not applicable
<b>Temporal resolution</b>	- Minutes to hours (flexible)	
<b>Timeliness</b>	For automatic networks: few minutes to hours, For research instruments: variable	
<b>Data availability</b>	ALC: continuous EARLINET and other lidars: based on specific schedule No product above or within clouds for all products	
<b>Data format</b>	ASCII	Typically images

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## 4. WIND, TURBULENCE, GUST (TASK LEADER: E. O'CONNOR) INCLUDES GUST/WIND-SHEAR ALERTS

### Instrument description for ABL profiling of winds

Doppler lidar measures the radial Doppler velocity of the backscattered signal. Commercial systems typically operate at infra-red wavelengths close to 1.5 or 2  $\mu\text{m}$  and use heterodyne (coherent) detection to determine the Doppler velocity. Ground-based 'long-range' Doppler lidars are capable of deriving radial velocities and higher moments for turbulent properties with high spatial and temporal resolution. Vertical winds are obtained directly using operation at vertical, whereas the vertical profile of horizontal winds must be derived from a set of scans. Possible scan patterns are Doppler beam swinging (DBS), which comprise a set of 3-5 scans in at least 3 orthogonal directions, and for instruments with hemispherical scanning capability, Velocity Azimuth Display (VAD), which is a conical scan in azimuth at a constant elevation. This scan may contain any number of beams, and is also referred to as a Plan-Position-Indicator (PPI) scan if performed at elevation angles close to horizontal. Turbulent properties can be derived from both vertical and scanning operation.

Other instruments capable of providing profiles of horizontal winds in the ABL include sodars, radar wind profilers (RWP), typically operating at lower frequencies than weather radar, and weather radar. Most RWP use a 4 or 5-beam DBS approach and can obtain winds both in clear air and in cloud/precipitation. Weather radars use VAD or VVP (volume velocity processing<sup>1</sup>), with winds being retrieved in the presence of sufficient cloud or precipitation throughout the extent of the scan. The operational weather radar scan schedule may only contain a few low-elevation angle scans.

Scintillometers can also provide information on turbulent parameters such as structure functions and fluxes in the ABL.

Available networks: EPROFILE, ARM, ACTRIS-CLOUDNET (future)

Products	Radial winds	Mean horizontal winds	Vertical winds	Turbulent properties
<b>Instruments</b>	- DL - DCR	- DL - scanning DCR	- DL - DCR	- DL - DCR
<b>Accuracy requirements (from WG1)</b>		OSCAR-database breakthrough/goal req		
<b>Temporal resolution Requirements (from WG1)</b>		OSCAR-database breakthrough/goal req.: 10-30 min		
<b>Assumptions needed</b>	None for radial winds. Pointing accuracy	Assumption of homogeneity	None, if direct measurement (vertical stare)  Reconstruct from VAD.	Stationarity assumption and measurement of inertial scales (Kolmogorov)
<b>Existing algorithms</b>	Uncertainty calculation and background correction <sup>2,3,4</sup>	DBS <sup>5</sup>  VAD <sup>6,7,8</sup>  DVAD <sup>9</sup> (Distance Velocity–Azimuth Display)  virtual tower <sup>10,11,12</sup>	Direct measurement (screening of precipitation required)	Vertical <sup>13</sup>  Scanning <sup>14,15</sup>  6-beam <sup>16</sup>  RHI + vertical <sup>17</sup>

<b>Applications</b>	<ul style="list-style-type: none"> <li>- Data Assimilation</li> <li>- Evaluation and verification in Numerical Weather Prediction, climate and air quality models.</li> <li>- Wind energy</li> <li>- Process studies</li> </ul>			
<b>End users</b>	<ul style="list-style-type: none"> <li>- Scientific community,</li> <li>- Atmospheric modelling (NWP, Climate, Air Quality)</li> <li>- E-PROFILE</li> <li>- National Weather Services</li> <li>- Aviation</li> <li>- Wind energy</li> </ul>			
<b>Readiness for operation</b>	Y	Y	Y	Y
<b>Expected accuracy</b>	Depends on SNR			
<b>Uncertainty estimates existing?</b>	Y	Y	Y	Y
<b>Temporal resolution</b>	< 30 s (usually < 2 s)	< 15 mins (depends on scan schedule - individual scan takes < 2 min)	Usually < 30 s	30 s (3 min for some properties)
<b>Timeliness</b>	Real-time (< 5 min)	Real-time (< 5 min)	Immediately	Currently 1 day (requires extensive processing)
<b>Data availability</b>	24/7 although data availability also depends on SNR			
<b>Data format</b>	netCDF			

<b>Products</b>	<b>Wind gusts</b>	<b>Alerts</b>
<b>Instruments</b>	- DL	- DL - DCR
<b>Accuracy requirements (from WG1)</b>		
<b>Temporal resolution Requirements (from WG1)</b>		
<b>Assumptions needed</b>	Ability to upscale observed frequency to 'standard' meteorological definition	None
<b>Existing algorithms</b>	Suomi et al. <sup>18</sup>	In development

<b>Applications</b>	Nowcasting and forecasting	
<b>End users</b>	<ul style="list-style-type: none"> <li>- National Weather Services</li> <li>- Aviation</li> <li>- Wind energy</li> </ul>	
<b>Readiness for operation</b>	N	N
<b>Expected accuracy</b>	Depends on SNR	
<b>Uncertainty estimates existing?</b>	N	N
<b>Temporal resolution</b>	10 min	Same as horizontal winds
<b>Timeliness</b>	10 min	< 5 min
<b>Data availability</b>	24/7 although data availability also depends on SNR	
<b>Data format</b>	netCDF	

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**Note that there are many more algorithms for deriving winds and turbulent properties, some of which include additional instrumentation.**

## 5. TEMPERATURE AND HUMIDITY PROFILING, INVERSION STRENGTH AND POSITION (TASK LEADER: P. MARTINET)

Continuous Temperature and humidity profiling from ground is commonly based on passive microwave and infrared instruments and active lidar systems. Each type of instrument has its own advantages and limitations.

Active sensors provide vertical profiles with a better vertical resolution but cannot provide information within and above clouds due to the attenuation of the lidar signal. They also suffer from a “blind zone” which is in general between the surface and 50 m or as high as a few hundreds of meters.

Passive instruments do not suffer from any blind zone which makes them sensitive to the very lowest layers of the atmosphere but have a coarser vertical resolution compared to active instruments. Hyperspectral infrared spectrometers provide more information on the vertical structure compared to microwave radiometers but their signal is totally attenuated within optically thick clouds similarly to lidars. Microwave radiometers have the possibility to provide vertical profiles in all-sky conditions well resolved for temperature in the boundary layer but with a poor description of the vertical structure for water vapor.

In this section the following acronyms are used:

- MWR: microwave radiometer ( 20 to 60 GHz spectral bands)
- DIAL: Differential Absorption Lidar (wavelength depending on the DIAL system)
- Raman lidar (typical laser wavelength of 355 nm)
- IRS: Infrared Spectrometer (~ 3 to 20  $\mu\text{m}$ )

For MWR and IRS, two types of retrieval algorithms exist: statistical retrievals (neural network, statistical regularization method<sup>17</sup>, linear and quadratic regressions) based on a training dataset dependent on the site and physically-based algorithms (called OEM for optimal estimation methods) that do not need a training but combine the observations with an a priori information of the atmospheric state (either from a short-term-forecast or from a climatology of profiles).

<b>Products</b>	<b>Temperature profile</b>	<b>Humidity Profile</b>
<b>Instruments</b>	- Below cloud: MWR, IRS, Raman lidars  - Within and above cloud: MWR	- Below cloud: Raman lidars, DIAL, IRS, MWR  - Within and above cloud: MWR
<b>Accuracy requirements (from WG1)</b>		
<b>Temporal resolution Requirements (from WG1)</b>		
<b>Applications</b>	- Data assimilation - Process studies - Validation of satellite products - Weather nowcasting	
<b>End-Users</b>	- National Weather services - University (Academy)	- National Weather services - University (Academy)

	<ul style="list-style-type: none"> <li>- Space agency</li> <li>- Private companies (wind energy sector)</li> </ul>	<ul style="list-style-type: none"> <li>- Space agency</li> </ul>
<b>Existing algorithms</b>	<ul style="list-style-type: none"> <li>- <u>For MWRs alone:</u> <ul style="list-style-type: none"> <li>- IPT (Cologne University): OEM retrieval using a climatology as the “a-priori”<sup>5</sup></li> <li>- Net1D (Météo-France/IMAA)<sup>3</sup>: OEM retrieval using a NWP model short-term forecast as the “a priori”</li> <li>- Statistical regularization method<sup>17</sup> (Single channel MWR): physically-based retrieval using temperature autocorrelation matrix calculated from a climatology of radio soundings as the “a-priori”</li> <li>- TROPoe (NOAA)<sup>1</sup>: OEM retrieval using a climatology as the “a-priori”</li> <li>- Neural network: provided by manufacturers for each MWR unit trained from either a climatology of radiosoundings or model re-analyses</li> <li>- Linear / quadratic regressions trained either from a climatology of radiosoundings or model re-analyses: can be provided by manufacturer or the MWRpro chain provided by the university of Cologne: <a href="ftp://gop.meteo.uni-koeln.de/pub/loehnert/mwr_data_flow/">ftp://gop.meteo.uni-koeln.de/pub/loehnert/mwr_data_flow/</a></li> </ul> </li> <li>- <u>For IRS alone:</u> TROPoe<sup>1</sup>: OEM retrieval using a climatology as the “a-priori”</li> <li>- <u>For Raman lidar:</u> no need of advanced algorithms, the temperature profile is derived directly from the ratio of the pure rotational Raman channels.</li> <li>- <u>For synergistic retrievals:</u> TROPoe<sup>2</sup> allows combination from IRS/ MWR and Raman lidars</li> </ul>	<ul style="list-style-type: none"> <li>- <u>For MWRs alone:</u> <ul style="list-style-type: none"> <li>- IPT (Cologne University): OEM retrieval using a climatology as the “a-priori”<sup>5</sup></li> <li>- Net1D (Météo-France/IMAA)<sup>3</sup>: OEM retrieval use a NWP model short-term forecast as the “a priori”</li> <li>- TROPoe (NOAA)<sup>1</sup>: OEM retrieval using a climatology as the “a-priori”</li> <li>- Neural network: provided by manufacturers for each MWR unit trained from either a climatology of radiosoundings or model re-analyses</li> <li>- Linear / quadratic regressions trained either from a climatology of radiosoundings or model re-analyses: can be provided by manufacturer, MWRpro chain provided by the university of Cologne: <a href="ftp://gop.meteo.uni-koeln.de/pub/loehnert/mwr_data_flow/">ftp://gop.meteo.uni-koeln.de/pub/loehnert/mwr_data_flow/</a></li> </ul> </li> <li>- <u>For IRS alone:</u> TROPoe<sup>1</sup>: OEM retrieval using a climatology as the “a-priori”</li> <li>- <u>For DIAL and Raman Lidar</u><sup>23</sup>: no need of advanced algorithm, the water vapor mixing ratio is directly derived from the ratio of the power received by the instrument at two wavelengths</li> <li>-Relative Humidity from Raman lidar: <ul style="list-style-type: none"> <li>□ Using OEM approach (MeteoSwiss)<sup>12</sup></li> </ul> </li> <li>- <u>For synergistic retrievals:</u> <ul style="list-style-type: none"> <li>- TROPoe<sup>2</sup> :allows combination from IRS/MWR/Raman lidars and DIAL</li> <li>- OEM for Raman lidar and MWR (MeteoSwiss)<sup>24</sup></li> </ul> </li> </ul>
<b>Assumptions needed</b>	<ul style="list-style-type: none"> <li>- For Raman lidar calibration: calibration is done against an external reference, typically a radiosonde or a MWR profile. Assumptions include proximity of reference</li> </ul>	<ul style="list-style-type: none"> <li>- For Raman lidar calibration: absolute calibration is done against external reference, typically a radiosonde profile or a total column measurement from MWR or GPS. Assumptions</li> </ul>

	<p>measurement in space and time and/or homogeneous atmosphere.</p> <p>- For MWR: horizontal homogeneity in area around ~2 km from the instrument when using measurements at low elevation angles</p>	<p>include proximity in space and time and/or a homogeneous atmosphere. Alternatively, the displacement can be accounted for <sup>13</sup>.</p> <p>Once an absolute calibration is established, a relative calibration with the background signals can be performed<sub>15, 11</sub></p>
<b>Accuracy of existing products</b>	<p>- MWRs alone:</p> <ul style="list-style-type: none"> <li>- Statistical retrievals: 0.2 to 2 K within 4 km <sup>22</sup></li> <li>- Regularization method (single-channel MWR): 0.2 to 1.5 K <sup>19,21</sup> up to 1 km</li> <li>- Up to 6 km altitude with Net1D, IPT: 0.5 to 1.5 K <sup>3,4,5</sup></li> </ul> <p>- IRS alone: 0.2 to 1.0 K within 2 km</p> <p>- Raman Lidar: 0.5 K for 0-5 km and 1.5 K for 5-10 km with 30 min integration / 10 W @ 355 nm <sup>16, 9</sup></p>	<p>- for Raman Lidar (30 min integration / 10W@355 nm): Accuracy: 5-10% for entire troposphere; Precision: &lt;5% below 5 km; &lt;20% for 5-10 km <sup>14, 16</sup></p> <p>- for DIAL: 0.1 to 0.8 g/kg up to 1km<sup>6,7</sup></p> <p>- MWR alone: 0.2 to 1.5 g/m<sup>3</sup> <sup>3</sup></p> <p>- IRS alone: 0.1 to 1.0 g/kg within 2 km</p>
<b>Uncertainty estimates existing?</b>	<p>- <u>For MWRs alone:</u></p> <ul style="list-style-type: none"> <li><input type="checkbox"/> Net1D chain: provides full error covariance matrix</li> <li><input type="checkbox"/> IPT chain: provides full error covariance matrix</li> <li><input type="checkbox"/> TROPoe chain: provides full error covariance matrix</li> </ul> <p>- <u>IRS alone:</u> TROPoe provides full error covariance matrix</p> <p>- <u>For synergistic retrievals:</u> TROPoe <sup>1</sup> provides full error-covariance matrix</p>	<p>- <u>for DIAL:</u> yes</p> <p>- <u>for IRS alone:</u> TROPoe provides full error covariance matrix</p> <p>- <u>For MWRs alone:</u></p> <ul style="list-style-type: none"> <li><input type="checkbox"/> Net1D chain: provides full error covariance matrix</li> <li><input type="checkbox"/> IPT chain: provides full error covariance matrix</li> <li><input type="checkbox"/> TROPoe chain: provides full error covariance matrix</li> </ul>
<b>Readiness for operation</b>	<p>For MWRs: yes</p> <p>For IRS: yes</p> <p>Raman lidar: no (deployed units are still most of the time “home-made instruments”, homogenization in the calibration techniques are probably needed, first commercial instruments appear on the market, but validation of performance is still missing <sup>16</sup>).</p>	<p>- for DIAL: close to operational maturity as few prototypes close to full commercial production have already been evaluated <sup>6</sup></p> <p>- for IRS: yes</p> <p>- for MWR: yes</p> <p>Raman lidar: no (deployed units are still most of the time “home-made instruments”, homogenization in the calibration techniques are probably needed. First commercial instruments are available, but validation of performance is missing <sup>16</sup>.)</p>
<b>Temporal</b>	<p>- MWR (depends on scanning strategy): 2 to</p>	<p>- DIAL: averaging time ~20 min</p>

<b>resolution</b>	5 min averaging time typically every 20 minutes  - IRS: 1-min, but 5-min is typical  - Raman lidar: 5 min	- IRS: 1-min, but 5-min is typical  - MWR: 1 second  - Raman lidar: 5 min
<b>Timeliness</b>	- MWR (depends on scanning strategy): - < 20 min for statistical retrievals or OEM method - < 1 hour for OEM based on model forecast  - IRS: < 5 min  - Raman lidar: <10 min	- MWR and IRS < 5 min  - DIAL: < 30 minutes  - Raman lidar: <10 min
<b>Data availability</b>	- IRS: 24/7 in non-precipitating conditions and below optically thick clouds  - MWR: 24/7 in non-heavy precipitation conditions  Raman Lidar: 24/7 in non-precipitating conditions	- for DIAL: 24/7  - IRS: 24/7 in non-precipitating conditions and below optically thick clouds  - MWR: 24/7 in non-precipitating conditions  Raman Lidar: 24/7 in non-precipitating conditions
<b>Data format</b>	- MWR: netcdf, ASCII  - IRS: netcdf  - Raman lidar: custom	- for DIAL: ASCII and netcdf  - IRS: netCDF  - Raman lidar : custom

<b>Products</b>	<b>Inversion strength and position</b>
<b>Instruments</b>	- MWR - IRS
<b>Accuracy requirements (from WG1)</b>	
<b>Temporal resolution Requirements (from WG1)</b>	
<b>Applications</b>	- Good indicator of ABL stability and potential pollutants accumulation - Weather application (alerts): heavy convection / fog
<b>End-Users</b>	- Air quality agency - National Weather Services - Wind energy sector - Airports - Nuclear power plants

<b>Existing algorithms</b>	<ul style="list-style-type: none"> <li>- Directly derived from the brightness temperature measurements: in development</li> <li>- Derived from the retrieved temperature profile: available (manufacturer software for single-channel MWR, and TROPOe<sup>1</sup> for other instruments)</li> </ul>
<b>Assumptions needed</b>	<ul style="list-style-type: none"> <li>- For MWR: horizontal homogeneity in area around ~2 km from the instrument when using measurements at low elevation angles</li> </ul>
<b>Accuracy of existing products</b>	<ul style="list-style-type: none"> <li>- in development</li> </ul>
<b>Uncertainty estimates existing?</b>	<ul style="list-style-type: none"> <li>- no</li> </ul>
<b>Readiness for operation</b>	<ul style="list-style-type: none"> <li>- Further evaluation of the products are necessary but used instrumentation is operational (MWR and IRS)</li> </ul>
<b>Temporal resolution</b>	<ul style="list-style-type: none"> <li>- MWR (depends on scanning strategy): 2 to 5 min averaging time typically every 20 minutes</li> <li>- IRS: 1-min, but 5-min is typical</li> </ul>
<b>Timeliness</b>	<ul style="list-style-type: none"> <li>- MWR (depends on scanning strategy): <ul style="list-style-type: none"> <li>- &lt; 20 min for statistical retrievals or OEM method</li> <li>- &lt; 1 hour for OEM based on model forecast</li> </ul> </li> <li>- IRS: &lt; 5 min</li> </ul>
<b>Data availability</b>	<ul style="list-style-type: none"> <li>- IRS: 24/7 in non-precipitating conditions and below optically thick clouds</li> <li>- MWR: 24/7 in non-heavy precipitation conditions</li> </ul>
<b>Data format</b>	<ul style="list-style-type: none"> <li>- IRS: netcdf</li> <li>- MWR: graphics possible or custom format</li> </ul>

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## 6. FORECAST INDICES (TASK LEADER: D. CIMINI)

	Forecast indices
<b>Instruments</b>	<ul style="list-style-type: none"> <li>- MWR</li> <li>- MWR + DIAL + satellite synergy</li> <li>- IRS</li> <li>- IRS + DIAL</li> </ul>
<b>Accuracy requirements (from WG1)</b>	<ul style="list-style-type: none"> <li>- TBD</li> </ul>
<b>Temporal resolution Requirements (from WG1)</b>	<ul style="list-style-type: none"> <li>- Order of minutes to an hour</li> </ul>
<b>Applications</b>	<ul style="list-style-type: none"> <li>- Weather alerts</li> <li>- Air quality alerts</li> </ul>
<b>End-Users</b>	<ul style="list-style-type: none"> <li>- National Weather Services</li> <li>- Air quality agency</li> </ul>
<b>Existing algorithms</b>	<ul style="list-style-type: none"> <li>- For MWR and MWR + satellite synergy: Neural network or statistical regressions applied to the raw measurements <sup>4</sup></li> <li>- Forecast indices can be derived from Temperature and humidity profiles previously retrieved <sup>3</sup></li> <li>- For MWR, IRS and DIAL: TROPoe and SHARPy <sup>1,2</sup> (physically-based retrievals)</li> </ul>
<b>Assumptions needed</b>	<p>For MWR: Clear and cloudy (non-precipitating) conditions            For IRS: Clear conditions. In cloudy conditions, retrievals possible up to cloud base only.</p>
<b>Accuracy of existing products</b>	<ul style="list-style-type: none"> <li>- Evaluation of derived forecast indices can be found here: from MWR<sup>3</sup>, from MWR + satellite + DIAL<sup>4</sup> or from IRS<sup>2</sup></li> <li>- The accuracy depends on the forecast index but correlations above 0.7 with reference measurements have been demonstrated</li> </ul>
<b>Uncertainty estimates existing ?</b>	No
<b>Readiness for operation</b>	<ul style="list-style-type: none"> <li>- For MWR, IRS and DIAL: TROPoe+SHARPy: yes</li> <li>- For satellite synergy: a larger evaluation is needed</li> </ul>
<b>Temporal resolution</b>	<ul style="list-style-type: none"> <li>- MWR (depends on scanning strategy): 2 to 5 min averaging time typically every 20 minutes</li> </ul>

	- IRS: 1-min, but 5-min is typical
<b>Timeliness</b>	< 5 minutes
<b>Data availability</b>	<ul style="list-style-type: none"> <li>- IRS: 24/7 in non-precipitating conditions and below optically thick clouds</li> <li>- MWR: 24/7 in non-precipitation conditions</li> </ul>
<b>Data format</b>	- For MWR, IRS and DIAL: TROPoe+SHARPPy: netCDF

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## 7. ABL CHARACTERISATION (TASK LEADER: J-A BRAVO ARANDA AND S. KOTTHAUS)

To characterise the ABL, various advanced algorithms are now available, with two main objectives. While most methods provide an estimation of the **height of the ABL** and/or its sublayers, first studies offer additional information on ABL characteristics such as cloud type, atmospheric stability, or the origin of turbulence.

- a) All types of ground-based remote sensing profilers have been used as input to automatic algorithms for **boundary layer height** detection, with most work done on ALC, DL and MWR observations. However, results from different methods can vary substantially<sup>1</sup>, simply because they are assessing the ABL sublayer heights based on different atmospheric quantities. Especially during morning growth and evening decay of the mixed layer, the height retrievals may disagree. Comparison studies<sup>2</sup> indicate that layer heights derived from thermodynamic methods (e.g. analysing MWR profiles) tend to rise ahead of turbulence-based methods (e.g. analysing DL) which again show an earlier growth onset than aerosol-based approaches (e.g. using ALC). Ground-based remote sensing profilers have different capabilities and algorithm uncertainties depend on a variety of atmospheric characteristics which again means the performance of the various retrieval methods can change throughout the diurnal evolution of the ABL<sup>3</sup>.
- b) Algorithms providing additional information about the state of the ABL are starting to emerge. Given the importance of cloud dynamics for ABL exchange processes, the **cloud type** (convective, stratiform) is assessed in addition to **cloud base height** products (link to cloud and precipitation subgroup). Where temperature (and even humidity) profiles are available from e.g. MWR, the atmospheric stability of the ABL can be determined. DL turbulence observations are now being exploited to characterise the origin of turbulence in the ABL (e.g. surface-driven, shear-driven, clouds-driven)

Given the multitude of available algorithms, fact sheets on recent advanced methods have been collected and will be continuously updated throughout the action. You can find the reference for all the known algorithms available on March 2021 in Appendix A.

Products	Mixed layer height (MLH), height of stable layer, ABLH	ABL type (e.g. cloud type, source of turbulence)
<b>Instruments</b>	- ALC (usually applicable to aerosol lidars), - MWR - IRS - Raman lidar - DL	- ALC - MWR - IRS - Raman lidar - DL
<b>Accuracy requirements (from WG1)</b>		
<b>Temporal resolution Requirements (from WG1)</b>		

<b>Assumptions needed</b>	<ul style="list-style-type: none"> <li>- Sufficient signal-to-noise ratio</li> <li>- Suitable optical overlap at heights where layers of interest are located</li> <li>- Substantial differences within ABL sublayers must exist when multiple layers have to be detected *</li> </ul>	<ul style="list-style-type: none"> <li>- Convective vs stratiform cloud-topped ABL determination: observed vertical column is assumed to be representative of a larger area, and lidars do not see through to cloud top.</li> <li>- Turbulent source attribution assumes that buoyancy-production (cloud or surface-driven) dominates shear production.</li> </ul>
<b>Existing algorithms</b>	<p>As a wide range of algorithms exist, further details are provided in Appendix A:</p> <p>CABAM<sup>4,5,6</sup>, STRATfinder<sup>6,7,8</sup>, KABL<sup>9</sup>, ADABL<sup>9</sup>, ACME<sup>10</sup>, ABLMAX, BLUSC, ABL characteristics from DL<sup>11,12,13</sup></p>	
<b>Application</b>	<ul style="list-style-type: none"> <li>- Air quality research and forecast</li> <li>- Numerical Weather Prediction</li> <li>- Greenhouse gas assessment</li> <li>- Air traffic security</li> </ul>	
<b>End users</b>	<ul style="list-style-type: none"> <li>- Air quality agency</li> <li>- National Weather Services</li> <li>- University (Academy)</li> <li>- Airports</li> </ul>	
<b>Readiness for operation</b>	<p>ALC algorithms being tested for operational applications,</p> <p>MWR and DL algorithms close to operational but used instrumentation is operational</p> <p>Raman lidar: not enough maturity for instrument and algorithm</p>	<ul style="list-style-type: none"> <li>- DL: In development, algorithms have been tested on multi-year datasets at multiple sites across Europe and ARM</li> </ul>
<b>Expected accuracy</b>	<p>Aerosol-based ABLH algorithms have been reported to agree well with thermodynamic layer heights from 12UTC radiosonde ascends, e.g. found within <math>\pm 150</math> m of each other for 94% of the time<sup>14</sup> or with an RMSE of <math>\sim 160</math> m<sup>8</sup>. Comparison statistics can be slightly worse when the whole diurnal cycle is considered<sup>6</sup>. Thermodynamic methods applied to MWR profile data show similar or slightly better accuracy than aerosol-based methods (e.g. RMSE <math>\sim 200</math> m for both<sup>15</sup>). Comparison statistics depend highly on timing of radiosondes, methods applied, cloud conditions, and quality control filtering (e.g. screening of rainy periods).</p>	<ul style="list-style-type: none"> <li>- Compared to SYNOP reports, the automatic cloud classification method of CABAM shows good agreement (<math>&gt; 80\%</math>), with improved performance during daytime.</li> <li>- ABL classification schemes from MWR and DL data show physically reasonable results, however, given the lack of reference information, evaluation and quantification of accuracy remains challenging</li> </ul>

	Please note that progress needs to be done on the assessment of boundary layer height detection accuracy. This is very challenging due to two major reasons: a) there is no “objective reference” available for comparison and b) results from methods based on different atmospheric quantities can differ due to their physical representation of the atmosphere.	and is subject to ongoing research
<b>Temporal resolution</b>	On the order of seconds to minutes (can depend on scanning schedule for MWR and DL)	
<b>Timeliness</b>	On the order of seconds to hours	
<b>Data availability</b>	24/7	
<b>Data format</b>	Mostly netCDF	Instrument .hpl (text) files, or netCDF

\* To detect the heights of ABL sublayers, atmospheric quantities within the sublayers must be substantially different so that a layer boundary can be detected. For example, aerosol characteristics in the mixed layer and residual layer above need to be sufficiently different so that a contrast in attenuated backscatter can be observed. Same holds true for turbulence or temperature profile observations.

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## 8. FOG ALERT (TASK LEADER: MARTIAL HAEFFELIN)

Products	Fog alerts
<b>Instruments</b>	<ul style="list-style-type: none"> <li>- ALC</li> <li>- CR</li> <li>- MWR</li> </ul> <p>Additional instruments: Weather stations (T°C, RH,...), Scatterometer sensor</p>
<b>Accuracy requirements (from WG1)</b>	
<b>Temporal resolution Requirements (from WG1)</b>	
<b>Applications</b>	Support nowcasting fog formation/dissipation
<b>End-Users</b>	<ul style="list-style-type: none"> <li>- National weather services</li> <li>- Airports</li> <li>- Highway road services</li> </ul>
<b>Existing algorithms</b>	<ul style="list-style-type: none"> <li>- PARAFOG (IPSL-LMD/SIRTA): <ul style="list-style-type: none"> <li>- Formation: ALC + weather station (RH) + scatterometer sensor <sup>1</sup></li> <li>- Dissipation: scatterometer sensor, MWR, CR</li> </ul> </li> <li>- Low Visibility Procedures - LVP (University of Innsbruck): weather station + scatterometer sensor <sup>2</sup></li> </ul>
<b>Assumptions needed</b>	None
<b>Accuracy of existing products</b>	<ol style="list-style-type: none"> <li>1) PARAFOG: <ol style="list-style-type: none"> <li>a. radiation fog formation: hit rate ~100% and False alarm ratio ~10% for lead times of 45min.</li> <li>b. Stratus lowering formation: hit rate ~100% and False alarm ratio ~30% for lead times of 45min.</li> <li>c. Dissipation time: on-going evaluation</li> </ol> </li> <li>2) LVP: Lead times from 10 to 120 min using OLR (ordered logistic regression). Verification using RPS (Ranked Probability Score): 0.0075 at 30 min, 0.0155 by 120 min (lower score is better).</li> </ol>
<b>Uncertainty estimates existing?</b>	Binary forecasts, so uncertainty is only available

	in terms of Skill Scores
<b>Readiness for operation</b>	<ul style="list-style-type: none"> <li>- PARAFOG:               <ul style="list-style-type: none"> <li>- Fog formation: yes</li> <li>- Fog dissipation: ongoing</li> </ul> </li> <li>- LVP: yes</li> </ul>
<b>timeliness</b>	<ul style="list-style-type: none"> <li>- PARAFOG: near real-time. 1 min resolution updated every ~5 min</li> <li>- LVP: near real-time. 10min resolution.</li> </ul>
<b>Data availability</b>	<ul style="list-style-type: none"> <li>- PARAFOG: 24/7</li> <li>- LVP: 24/7</li> </ul>
<b>Data format</b>	<ul style="list-style-type: none"> <li>- PARAFOG: netCDF</li> <li>- LVP: Unknown</li> </ul>

References:

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## 9. ICING ALERT (TASK LEADER: E. O'CONNOR)

	Icing and alerts	Icing and alerts
<b>Instruments</b>	ALC + NWP	ALC with depolarisation + NWP
<b>Accuracy requirements (from WG1)</b>		
<b>Temporal resolution Requirements (from WG1)</b>		
<b>Assumptions needed</b>	Requires identification of supercooled liquid from attenuated backscatter profiles, and assumes that the temperature profile from NWP is accurate close to the ground.	Inclusion of depolarisation will increase confidence in supercooled liquid layer identification.
<b>Existing algorithms</b>	ALC icing detection <sup>1</sup>	In development, using <sup>1</sup>
<b>Applications</b>	Nowcasting of icing conditions	
<b>End users</b>	<ul style="list-style-type: none"> <li>- Numerical Weather Prediction</li> <li>- National Weather Services</li> <li>- Aviation</li> <li>- electricity grid</li> <li>- wind energy</li> </ul>	
<b>Readiness for operation</b>	Y	N
<b>Expected accuracy</b>	Under evaluation (comparison against icing detectors on masts)	
<b>Temporal resolution</b>	Nominal instrument resolution	
<b>Timeliness</b>	Real-time (< 5 minutes)	
<b>Data availability</b>	24/7 from any ALC. Observation altitude extent is liquid cloud base dependent as the ceilometer will not see beyond the first optically-thick cloud layer.	

<b>Data format</b>	netCDF
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References:

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# Appendix A: Algorithms for the automatic detection of ABL heights and ABL characteristics (status report March 2021)

Contributions from (alphabetical order): Alexander Hieden (ZAMG, Austria), Simone Kotthaus (IPSL, France), Quentin Laffineur (RMI, Belgium), Ewan O'Connor (FMI, Finland), and Thomas Rieutord (Météo-France, France)

## Outline

### **ABLH algorithms**

- CABAM
- STRATfinder
- KABL
- ADABL
- ACME
- ABLMAX

### **ABL characterisation**

- CABAM
- BLUSC
- Boundary layer classification from Doppler lidar

### **References**

# 1. ABLH ALGORITHMS

## 1.1. CABAM

### Name of algorithm

CABAM

### Key publications

Kotthaus and Grimmond (2018a,b), Kotthaus et al. (2020)

### Contact person/ institution(s)

Simone Kotthaus, IPSL (France) and University of Reading (UK)

### Output variable/ output information

Mixed layer height (MLH), ABLH (first estimate)

### Atmospheric variable analysed

Attenuated backscatter, cloud base height from low-SNR ALC

### Algorithm approach

Layer detection based on vertical gradients, layer attribution based on decision tree

### Assumptions / corrections

Instrument-related background and near-range artefacts corrected (Kotthaus et al. 2016)

### Ancillary data required

no

### Evaluation (number of sensors/stations, time periods, reference data)

Applied to multi-year data (CL31, CL51) at multiple sites (10 sites, Paris, London, Beijing, Payerne)

Compared to MLH from DWL; MLH and ABLH from AMDAR temperature profiles; STRATfinder results

### Is it already applied in 'operational mode', i.e. in near real-time? Results visible online?

Near real-time implementation at multiple sites: <https://www.lmd.polytechnique.fr/sirta/ml/>

### Input data (instrument raw files, ncdf formatted according to some network standard)

E-PROFILE L1

### Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)

ncdf, CF compliant

### How does the algorithm handle precipitation, clouds/fog?

Internal and external quality control is implemented to remove false layer detection during precipitation. ABLH and MLH can not significantly exceed cloud base height.

### Site-specific settings?

Maximum ABLH than may occur, morning growth rate of MLH

**Are quality flags provided? If so, how are they determined?**

Quality control flags MLH considered physically unreasonable; no flag to indicate uncertainty

**Output temporal resolution**

Detection performed at native raw resolution (e.g. 30 sec), output averaged to 15 minutes

**Algorithm code language**

R

**License and code availability to others**

GNU General Public License v3.0, on Github; implementation not yet very user friendly

**Readiness for operation (known remaining weaknesses?)**

Algorithm ready for operation. Now being tested in E-PROFILE ABLH testbed.

Remaining issues include:

- Performance clearly depends on quality of input data (e.g. better for CL51 than CL31 input).
- Situations of deep convection (> 2.4km) are not always captured accurately due to noise.
- A specific module is needed to improve detection of residual layer height.
- Interpretation of clouds needs further work: i.e. how to interpret the strong gradient in attenuated backscatter at cloud base of stratiform clouds/fog? Could broken Cumulus clouds form 'within' the ABL?

## 1.2. STRATFINDER

**Name of algorithm**

STRATfinder

**Key publications**

Kotthaus et al. (2020), Haeffelin et al (2012), Poltera et al. (2017)

**Contact person/ institution(s)**

Simone Kotthaus and Martial Haeffelin, IPSL (France)

**Output variable/ output information**

Mixed layer height (MLH), ABLH

**Atmospheric variable analysed**

Attenuated backscatter, cloud base height from high-SNR ALC

**Algorithm approach**

Graph-theory pathfinding algorithm using field of vertical gradient and variance

**Assumptions / corrections**

Dynamic overlap model (Hervo et al. 2016)

**Ancillary data required**

no

#### **Evaluation (number of sensors/stations, time periods, reference data)**

Applied to multi-year data (CHM15k) at 2 sites (Paris, Payerne), applied to selected case studies from CHM8k (Munich)

Compared to MLH and ABLH from AMDAR temperature profiles; CABAM results

#### **Is it already applied in 'operational mode', i.e. in near real-time? Results visible online?**

Near real-time implementation at 2 sites: <https://www.lmd.polytechnique.fr/sirta/ml/>

#### **Input data (instrument raw files, ncdf formatted according to some network standard)**

E-PROFILE L1

#### **Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)**

ncdf, CF compliant

#### **How does the algorithm handle precipitation, clouds/fog?**

Internal and external quality control is implemented to remove false layer detection during precipitation. ABLH and MLH can not significantly exceed cloud base height.

#### **Site-specific settings?**

Maximum ABLH than may occur, maximum nocturnal MLH, morning growth rate of MLH

#### **Are quality flags provided? If so, how are they determined?**

Quality control flags MLH considered physically unreasonable; no flag to indicate uncertainty

#### **Output temporal resolution**

Native raw resolution (e.g. 30 sec)

#### **Algorithm code language**

Matlab. Mcc compiled version now available

#### **License and code availability to others**

GNU General Public License v3.0, on Github; also mcc compiled version now available

#### **Readiness for operation (known remaining weaknesses?)**

Algorithm ready for operation. Now being tested in E-PROFILE ABLH testbed.

Remaining issues include:

- Weakest point is detection of shallow layers (< 250 m) due to overlap uncertainty.
- Interpretation of clouds needs further work: i.e. how to interpret the strong gradient in attenuated backscatter at cloud base of stratiform clouds/fog? Could broken Cumulus clouds form 'within' the ABL?

## **1.3. KABL**

### **Name of algorithm**

K-means for Atmospheric Boundary Layer (KABL)

### **Key publications**

Rieutord et al., AMT-D (2021)

### **Contact person/ institution(s)**

Thomas Rieutord and Sylvain Aubert, Météo-France

### **Output variable/ output information**

Mixed layer height (MLH)

### **Atmospheric variable analysed**

Range-corrected backscatter

### **Algorithm approach**

Unsupervised classification of measurement points into a “boundary layer” class with K-means

### **Assumptions / corrections**

The mixing layer is in contact with the ground, it has backscatter values significantly different than other layers

### **Ancillary data required**

None

### **Evaluation (number of sensors/stations, time periods, reference data)**

Applied on MiniMPL lidar (SigmaSpace) on two sites (Brest and Trappes, France) over 2 years (2017-2018). Compared to ADABL and the manufacturer’s algorithm.

### **Is it already applied in ‘operational mode’, i.e. in near real-time? Results visible online?**

No

### **Input data (instrument raw files, ncdf formatted according to some network standard)**

NetCDF issued from raw2l1 (E-PROFILE L1) one file per day

### **Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)**

Add a field “blh” in the NetCDF input file. Probably not CF-compliant but easy to change

### **How does the algorithm handle precipitation, clouds/fog?**

Precipitations and fog discarded from the evaluation. For cloud, an additional class is created in the profile. When no other layer is present between the ground and the cloud, the MLH is the cloud base height.

### **Site-specific settings?**

No

### **Are quality flags provided? If so, how are they determined?**

No. Some quality scores are calculated on the classification, but their use as quality flag is still to be tested.

### **Output temporal resolution**

Same as the input (one estimation per profile)

### **Algorithm code language**

Python 3

#### License and code availability to others

CeCILL (French equivalent of GNU/GPL), available on Github : <https://github.com/ThomasRieutord/kabl>

#### Readiness for operation (known remaining weaknesses?)

- Continuity of the estimation in time is not very good (e.g. oscillations between surface layer and cloud). It can be corrected thanks to a post-processing, for example, with a moving average or by imposing a maximum BLH growth rate (Poltera et al., 2017).
- Operation on various device was not tested

## 1.4. ADABL

#### Name of algorithm

AdaBoost for Atmospheric Boundary Layer (ADABL)

#### Key publications

Rieutord et al., AMT-D (2021)

#### Contact person/ institution(s)

Thomas Rieutord and Sylvain Aubert, Météo-France

#### Output variable/ output information

Mixed layer height (MLH)

#### Atmospheric variable analysed

Range-corrected backscatter in co-polarised and cross-polarised channel

#### Algorithm approach

Supervised classification of measurement points into a “boundary layer” class with boosting

#### Assumptions / corrections

The mixing layer is characterized by values similar to those used to train the boosting algorithm

#### Ancillary data required

None

#### Evaluation (number of sensors/stations, time periods, reference data)

Applied on MiniMPL lidar (SigmaSpace) on two sites (Brest and Trappes, France) over 2 years (2017-2018). Compared to ADABL and the manufacturer’s algorithm.

#### Is it already applied in ‘operational mode’, i.e. in near real-time? Results visible online?

No

#### Input data (instrument raw files, ncdf formatted according to some network standard)

NetCDF issued from raw2l1 (E-PROFILE L1) one file per day

#### Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)

Add a field “blh” in the NetCDF input file. Probably not CF-compliant but easy to change

### **How does the algorithm handle precipitation, clouds/fog?**

It recognize it from the training set and identify the MLH accordingly

### **Site-specific settings?**

Will work better when trained on data from the same site

### **Are quality flags provided? If so, how are they determined?**

No. Some quality scores are calculated on the classification, but their use as quality flag is still to be tested.

### **Output temporal resolution**

Same as the input (one estimation per profile)

### **Algorithm code language**

Python 3

### **License and code availability to others**

CeCILL (French equivalent of GNU/GPL), available on Github :  
<https://github.com/ThomasRieutord/kabl>

### **Readiness for operation (known remaining weaknesses?)**

- The training is the main limitation : it is done with human-expertised MLH time series, it must be a large set (several days), with various conditions
- Operations on various device was not tested and it is expected to be highly device-dependent

## **1.5. ACME**

### **Name of algorithm**

ACME (Austrian CeiloMeter Evaluation)

### **Key publications**

Lotteraner and Piringer (2016)

### **Contact person/ institution(s)**

Hieden Alexander, ZAMG (Austria)

### **Output variable/ output information**

Aerosol Layer Heights (ALH), Mixing Height (MH)

### **Atmospheric variable analysed**

ALH: Attenuated backscatter, cloud base height

MH: lowest ALH, lowest cloud base height, wind speed

### **Algorithm approach**

ALH: Derivative analyses of the backscatter intensity

MH: Using the lowest ALH; using the lowest cloud base height, if the lowest cloud is stratiform;  
outlier filtering; filling gaps by linear interpolation; height limitation of nocturnal values depending  
on wind speed; smoothing by moving average

#### **Assumptions / corrections**

ALH: outlier filtering, cluster merging

MH: Aerosols and polluted air emitted near the ground disperse vertically primarily up to the lowest aerosol-layer height. Limitation of nocturnal values depending on wind speed

#### **Ancillary data required**

ALH: no

MH: wind speed, site-specific parameters

#### **Evaluation (number of sensors/stations, time periods, reference data)**

Multi-year evaluations of ALH for 30 sites, selected case studies (ALH and MH)

#### **Is it already applied in 'operational mode', i.e. in near real-time? Results visible online?**

ALH: Near real time operation of ALH for 27 sites. Online results – internal access only.

MH: not yet

#### **Input data (instrument raw files, ncdf formatted according to some network standard)**

ALH: Raw device output

MH: lowest ALH, lowest cloud layer height, wind speed, site-specific parameters

#### **Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)**

ALH: Text & ncdf

MH: Text

#### **How does the algorithm handle precipitation, clouds/fog?**

ALH: Precipitation and clouds are filtered out by a functional match of the backscattering amplitude against a sigmoid function of the height.

#### **Site-specific settings?**

ALH: No

MH: Yes (real horizon heightening and geographical coordinates for day-night separation)

#### **Are quality flags provided? If so, how are they determined?**

No

#### **Output temporal resolution**

ALH: Selectable

MH: 5 minutes

#### **Algorithm code language**

ALH: Python 3+

MH: Fortran90

#### License and code availability to others

No

#### Readiness for operation (known remaining weaknesses?)

- Cloud and precipitation filtering needs further improvement
- Uncertainty rises with higher spatial and temporal resolutions
- Mixing Height not yet operational, but foreseen in 2021

## 1.6. ABLOMAX

#### Name of algorithm

ABLOMAX

#### Key publications

Not yet

#### Contact person/ institution(s)

Quentin Laffineur, RMI (Belgium)

#### Output variable/ output information

Mixed layer height (MLH), quality flag

#### Atmospheric variable analysed

Attenuated backscatter, cloud base height (CBH)

#### Algorithm approach

Calculation of the occurrence for each level where there is a local extremum in the domain of the vertical gradient and the variance in a given time interval.

#### Assumptions / corrections

The level where the occurrence is highest near the ground is considered as the mixing layer height (MLH)

#### Ancillary data required

no

#### Evaluation (number of sensors/stations, time periods, reference data)

Applied on 4 CL51 in Belgium from September 2020 up to now. Evaluation on CL51 data of June 2019. A long-term study is still needed.

#### Is it already applied in 'operational mode', i.e. in near real-time? Results visible online?

Near real-time on 4 sites (CL51)

Visible on this link: <https://cloud.meteo.be/s/xMGGbjeD2Qz3bwN> (PWD: ABLOMAX2021)

#### Input data (instrument raw files, ncdf formatted according to some network standard)

Vaisala data file format

**Output data format? (text or netcdf? Compliant with [CF-conventions](#)?)**

text

**How does the algorithm handle precipitation, clouds/fog?**

ABLMAX continuously outputs a MLH value except under fog or heavy precipitation conditions. MLH can not exceed CBH.

**Site-specific settings?**

No

**Are quality flags provided? If so, how are they determined?**

Quality control flags based on the backscatter values at the top and bottom of the mixing layer level.

**Output temporal resolution**

10 min

**Algorithm code language**

Python 2.7

**License and code availability to others**

No

**Readiness for operation (known remaining weaknesses?)**

Algorithm ready for operation.

Remaining issues include:

· Situations of deep convection and low backscatter signal are not always captured accurately.

## 2. ABL CHARACTERISATION

### 2.1. CABAM

**Name of algorithm**

CABAM

**Key publications**

Kotthaus and Grimmond (2018a,b), Kotthaus et al. (2020)

**Contact person/ institution(s)**

Simone Kotthaus, IPSL (France) and University of Reading (UK)

**Output variable/ output information**

Dominant ABL cloud type (cloud free, cumulus, stratiform, MLH remaining below stratiform cloud base) for nocturnal (between sunset and sunrise) and daytime periods

**Atmospheric variable analysed**

Attenuated backscatter, cloud base height from low-SNR ALC

### **Algorithm approach**

Combining cloud base height temporal variability with MLH products

### **Assumptions / corrections**

Instrument-related background and near-range artefacts corrected (Kotthaus et al. 2016)

### **Ancillary data required**

no

### **Evaluation (number of sensors/stations, time periods, reference data)**

Applied to multi-year data (CL31) at multiple sites (10 sites, Paris, London, Beijing, Payerne)

Compared to SYNOP reports for London

### **Is it already applied in 'operational mode', i.e. in near real-time? Results visible online?**

Not yet implemented operationally

### **Input data (instrument raw files, ncdf formatted according to some network standard)**

E-PROFILE L1

### **Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)**

Not yet standardised

### **How does the algorithm handle precipitation, clouds/fog?**

Precipitation flags from MLH detection algorithm

### **Site-specific settings?**

Maximum ABLH than may occur, morning growth rate of MLH

### **Are quality flags provided? If so, how are they determined?**

no flag to indicate uncertainty

### **Output temporal resolution**

Detection performed on 15 minute data, output aggregates nocturnal and daily conditions

### **Algorithm code language**

R

### **License and code availability to others**

To be included into CABAM GNU General Public License v3.0 on Github

### **Readiness for operation (known remaining weaknesses?)**

- Further testing and evaluation required

## **2.2. BLUSC**

### **Name of algorithm**

Boundary Layer Unsupervised and Supervised Classification

### **Key publications**

In preparation: Rieutord et al. (2021)

### **Contact person/ institution(s)**

Thomas Rieutord, Météo-France

### **Output variable/ output information**

Pixel-based boundary layer classification

### **Atmospheric variable analysed**

Absolute temperature from MWR

Range-corrected backscatter from ceilometer

### **Algorithm approach**

Two approaches are proposed:

- unsupervised classification with hierarchical clustering --classes are unidentified, and
- supervised classification (several algorithms) --classes are identified but these algorithms need training.

### **Assumptions / corrections**

There exist several types of boundary layer and they are marked by significantly different values in the temperature and backscatter measurements.

### **Ancillary data required**

None

### **Evaluation (number of sensors/stations, time periods, reference data)**

Constructed on a set of 10 days during Passy-2015 campaign

### **Is it already applied in 'operational mode', i.e. in near real-time? Results visible online?**

No, current status is only the proof of concept

### **Input data (instrument raw files, ncdf formatted according to some network standard)**

NetCDF CF-compliant files

### **Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)**

Add three fields in the input netCDF :

- rawlabels (integer identifying the BL type for each pixel),
- label\_identification (dict associating label to BL type short name), and
- label\_long\_names (dict associating BL type short and long name).

### **How does the algorithm handle precipitation, clouds/fog?**

They are identified as a such with a dedicated class

### **Site-specific settings?**

No for unsupervised classification, probably yes for supervised

**Are quality flags provided? If so, how are they determined?**

No

**Output temporal resolution**

Chosen by the user. Recommendations are to use the resolution of the coarsest instrument

**Algorithm code language**

Python 3

**License and code availability to others**

CeCILL (French equivalent of GNU/GPL), available on Github : <https://github.com/ThomasRieutord/bl-classification>

**Readiness for operation (known remaining weaknesses?)**

- Preliminary work
- Run on a broader data set, with various conditions, geography and instruments
- Define a relevant evaluation metric and compare to existing BL classification

## 2.3. BOUNDARY LAYER CLASSIFICATION FROM DOPPLER LIDAR

**Name of algorithm**

Boundary layer classification from Doppler lidar (Halo lidar toolbox)

**Key publications**

Manninen et al. (2018), Vakkari et al. (2019), Pentikäinen et al. (2020)

**Contact person/ institution(s)**

Ewan O'Connor, FMI (Finland)

**Output variable/ output information**

Presence of turbulence, source of turbulence, and whether the region is in contact with the surface.

**Atmospheric variable analysed**

Vertical Doppler velocity moments, attenuated backscatter, vertical profile of horizontal winds

**Algorithm approach**

Combines turbulent parameters (epsilon and skewness) with winds (horizontal and shear), cloud and precipitation identification, to determine presence of turbulence, source of turbulence, and whether the region is in contact with the surface.

**Assumptions / corrections**

Requires reliable background, telescope focus corrections, calibration.

**Ancillary data required**

None, but inclusion of atmospheric stability or surface heat flux aids interpretation

**Evaluation (number of sensors/stations, time periods, reference data)**

Applied to about 10 sites in Europe, and at 5 ARM sites

**Is it already applied in ‘operational mode’, i.e. in near real-time? Results visible online?**

Being tested in NRT for a few sites, these results are not yet visible online. Previous datasets are available online

**Input data (instrument raw files, ncdf formatted according to some network standard)**

Instrument .hpl (text) files, or netCDF

**Output data format? (text or ncdf? Compliant with [CF-conventions](#)?)**

netCDF compliant with CF conventions where possible

**How does the algorithm handle precipitation, clouds/fog?**

Precipitation and cloud are handled as part of the classification process

**Site-specific settings?**

In principle no, but SNR at some sites/instruments is very low hampering calculation of turbulent properties. Correction for background and telescope focus function key to algorithm performance

**Are quality flags provided? If so, how are they determined?**

Uncertainties of interim products are calculated. Plan is to combine all uncertainties into probability classes.

**Output temporal resolution**

Usual temporal resolution is 3 minutes, but can be averaged over longer periods at sites with low SNR.

**Algorithm code language**

Currently Matlab, but due to be ported to Python.

**License and code availability to others**

Available on github

**Readiness for operation (known remaining weaknesses?)**

Better diagnosis of convective vs shear driven turbulence. Dealing with site variability in SNR. Improving setup for new stations/instruments. Better diagnosis of light precipitation, and gravity-wave contribution.

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