SCIENTIFIC REPORT

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MEETING: ALC WG1, special working group meeting
TITLE: Errors and uncertainties of aerosol profiling with ALCs
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Introduction

The objective of this meeting was to come up with a summary of all uncertainties and systematic effects which influence the accuracy of aerosol profiles which are retrieved in an automated way from automated lidars and ceilometers (ALC) in the framework of E-PROFILE and TOPROF.

Aerosol profiles are profiles of attenuated backscatter (calibrated, range-corrected signals), particle backscatter coefficients, particle extinction coefficients, and estimates of mass concentrations.

Each participant was requested to prepare a table with a formalized description of the nature, strength, and methods for correction of the corresponding error source.

Results or Achievements

Below we provide tables with the formalized descriptions of sources of errors and uncertainties. Further, all errors which are relevant for the operational retrieval of profiles of attenuated backscatter, backscatter coefficient, and extinction coefficient in the framework of EPROFILE were combined in summary tables for the different instrument types.

1. Water vapor absorption (Matthias Wiegner)

Matthias Wiegner reported about the influence of absorption of the emitted and received laser light by water vapor (wv) molecules in the atmosphere. Ceilometers operating in the spectral range around 910 nm are affected by this effect. For the correction of this effect, it is essential to know the emitted laser spectrum (central wavelength and spectral width) and its temperature dependence. Representatives of Vaisala announced to check for the possibility to measure and provide the wavelength of individual lasers in future firmware versions.

Usually, profiles of attenuated backscatter (ß*) are not corrected for WV absorption. Therefore, ß*-profiles at 905-910nm are not directly comparable to those at 1064 nm.

Uncertainties of particle backscatter coefficients due to wv absorption	
Affected instrument types	All ALC emitting in the range of 905-910 nm (i.e. Vaisala, Campbell)
Affected altitude range	Complete range
Systematic error	Only if no water vapor correction is done: particle backscatter coefficients are overestimated /underestimated when they were retrieved by backward / forward inversion (Klett/Fernald solution).
Statistical error	5-10% , increasing with height and humidity
Can be corrected	Yes, if laser spectrum and water vapor concentration is known.
Uncertainty of correction[1]	Negligible to low (1-5%)
Methods for quantification	compare actual of water vapor profile at site with profile assumed profile for correction, make sensitivity study on effects of emission spectrum
references	Wiegner et al., 2014 Wiegner and Gasteiger, 2015

[1] Remaining uncertainty of the derived product after the correction was applied.

2. Near-range effects (Simone Kotthaus)

Simone Kotthaus reported about systematic effects in case of CL31 instruments that occur in the very near-range. Those effects are due to the correction of sudden increase of signals (e.g. if a bird is sitting on the instrument's window). CL51 instruments might be affected as well, but systematic investigations are not yet available.

Uncertainties of all products due to near-range effects	
Affected instrument types	Vaisala CL31 and CL51
Affected altitude range	CL31: 0-90 m CL51: 0-150 m (?)
Systematic error	CL31: Instrument specific, ± 50 % Semi-correction in FWV 1.72, 1.73, 2.03, 2.04 Switch-on semi-correction in FVW ≥ 1.75 & ≥ 2.05 via algorithm option (0, 3) CL51: unknown
Statistical error	
Can be corrected	CL31: partly, Kotthaus et al. (2016) & Kotthaus and Grimmond (2017) CL51: more investigation needed
Uncertainty of correction[1]	CL31: Range and instrument dependent. Up to 50 % < 50 m
Methods for quantification	climatology analysis
references	CL31: Kotthaus et al. (2016) & Kotthaus and Grimmond (2017)

3. Overlap issues (Yann Poltera and Simone Kotthaus)

For all instruments in E-PROFILE and TOPROF, the reported attenuated backscatter is already corrected for the incomplete overlap between laser and telescope field-of-view. Yann Poltera and Simone Kotthaus reported about systematic artefacts of these corrections and how to quantify and correct these artefacts for CHM15k and CL31 instruments. Systematic investigations of overlap issues of CL51 are not yet available.

Uncertainties of all products due to overlap issues		
Affected instrument types	Lufft CHM15k	Vaisala CL31 and CL51
Affected altitude range	CHM15k: 0-1200 m	CL31: 0-70 m CL51: 0-520 m
Systematic error	Instrument , range specific 50%-0%, peaks usually around 350m Without correction, attn. bsc. can be either too small or too large	There are systematic differences between algorithm version 0 and version 1
Statistical error	temperature specific, 0-50%	No temperature dependence
Can be corrected	CHM15k: yes (Hervo, Poltera et Haefele, 2016) Need the overlap function used by the manufacturer, ~1 year of data Implementation assumes negligible ratio of molecular to particle scattering in the PBL.	
Uncertainty of correction[1]	CHM15k: Range, instrument and temperature dependent. Not quantified.	CL31: Range and instrument dependent. Up to 50 % < 50 m
Methods for quantification	Measurement in well-mixed PBL, climatology reveals dependence of overlap on temperature or high voltage settings	climatology analysis
references	Hervo et al. (2016) Wiegner and Geiß (2017)	CL31: Kotthaus et al. (2016) & Kotthaus and Grimmond (2017)

4. Signal artifacts in free troposphere (Margit Pattantyús-Ábrahám and Simone Kotthaus)

Margit Pattantyús-Ábrahám reported on signal artefacts in the free troposphere (ft) which were measured with a covered telescope (termination hood) during the CeiLinEx2015 campaign. The observed signal artifacts do not only depend on instrument type and firmware version, but are different for each individual instrument. Thus, the results of the CeiLinEx2015 campaign can provide a good estimate of the magnitude of artifacts of different instrument types, but the campaign data cannot provide data for the correction of individual measurements.

Uncertainties of all products due to signal artifacts in ft					
Affected instrument types	Lufft CHM15k	Lufft CHX	Vaisala CL51	Vaisala CL31	CS 135
Affected altitude range	> 6000 m	> 2000 m	500-9000 m	500 - 8000 m	500 - 8000 m
Systematic error [m^{-1}sr^{-1}]	0	0	1 E-7	1 E-07	1-7 E-07
Statistical error	0.2 E-8	Up to 2.5 E-7 increasing with the height		noisy	
Can be corrected	For each instrument separately. Only one covered telescope measurement		More measurement needed. Check on background light	More measurement needed	
Uncertainty of correction[1] [m^{-1}sr^{-1}]	0.1 E-8	1 E-7	1 E-7	1-2.5 E-07	2.5 E-07
Methods for quantification	Covered telescope vs Rayleigh				
references	CeiLinEx 2015				

Simone Kotthaus used climatology analysis of CL31 data for the characterization of signal artefacts of CL31 instruments.

Uncertainties of all products due to signal artifacts in ft	
Affected instrument types	Vaisala CL31
Affected altitude range	0-7700 m
Systematic error	1 E-7 Depends on instrument hardware and firmware and range. ± 2 E-6 $m^{-1}sr^{-1}$, generally -6 E-6 $m^{-1}sr^{-1}$ for instruments with cosmetic shift (e.g. firmware 1.71)
Statistical error	Some sensors show slight temperature dependence (~ 2 E-8 $m^{-1}sr^{-1}$ K^{-1}); Regions of increased noise around 5000 m and 7000m due to internal storage Procedure; discontinueity at 2400m due to internal storage procedure for FWV <2.03
Can be corrected	Subtract background profile from climatology analysis or termination hood measurements
Uncertainty of correction[1]	Range dependent. ~ 3 x 10-7 $m^{-1}sr^{-1}$ (FMV 2.xx), ~ 5 x 10-7 $m^{-1}sr^{-1}$ (FMV 1.xx)
Methods for quantification	climatology analysis or termination hood measurements
references	Kotthaus et al. (2016)

5. Cloud calibration (Emma Hopkin, Frank Wagner)

The cloud calibration method can be affected by the following effects:

- Multiple scattering
- Water vapor absorption
- Signal saturation
- Contributions from aerosols below cloud / signal artifacts in free troposphere

Uncertainties of lidar constants due to multiple scattering	
Affected instrument types	All
Affected altitude range	All: the multiple scattering correction is relevant for any optically thick medium (particularly liquid water cloud) but if the correction is not done then this leads to a bias of retrieved backscatter for all ranges (due to bias in calibration coefficient). The size of the bias in the calibration increases with height of the clouds used.
Systematic error	Without correction, lidar constant is too small and resulting attenuated backscatter / backscatter coefficients are too large Size of correction increasing with height
Statistical error	<5%
Can be corrected	Multiple scattering corrections as a function of wavelength (nm), divergence of beam (mrad), telescope field of view (mrad) and lidar altitude above sea level (m) are available for IR wavelengths, see http://www.met.reading.ac.uk/~swr99ejo/lidar_calibration/
Uncertainty of correction[1]	<5% (Must exclude profiles with drizzle)
Methods for quantification	Calculation of multiple scattering for various droplet radii (4-10 μm) and extinctions (15-20 km^{-1})
references	O'Connor, E., et al., 2004 Hogan, R.J., 2006; Hogan, R.J., 2008

Uncertainties of lidar constants due to the selection of region of Integration in Cloud Calibration	
Affected instrument types	All
Affected altitude range	Instrument dependent CL31 – 0.1-4.0 km (H2-ON instruments, max height 2.4 km) CL51 – 0.5-4.0 km CHM15k – 0.5-4.0 km
Systematic error	Above cloud inclusion – if beam is fully attenuated, there is no signal just noise so should average to zero. Therefore important to have relevant firmware corrections and dark current/instrument noise correction. Below cloud – Inclusion of aerosol below cloud leads to systematically larger bsc integral (B). Increasing with cloud altitude (higher cloud = more aerosol included in integral). Magnitude is negligible compared to size of cloud signal. REJECT PROFILES WHEN $B_{aer} > 0.05\ B_{Cloud}$ - Offset by attenuation by aerosol. Backscatter is systematically smaller.
Statistical error	<5%
Can be corrected	Could do a transmission correction but this introduces its own error as must assume a lidar ratio of the aerosol below cloud. Instead, reject profiles when $B_{aer} > 0.05\ B_{Cloud}$
Uncertainty of correction[1]	The influence of aerosol particles below 100 m (CL31) / 500m (CL51 and CHM15k) is unknown
Methods for quantification	If the value of S(aer) were the same as that of the cloud, then including the B(aer) in the total value of B would give the correct calibration, but if S(aer) were twice the value of the cloud, then including profiles with B(aer) < 0.05 Bcloud, would lead to up to 5% underestimate of the calibration factor.
references	Kotthaus et al., 2016 (for dark current info); Hopkin et al (2017), in prep

Uncertainties of lidar constants due to saturation of ceilometer receiver	
Affected instrument types	Photon Counting Ceilometers – CHM15k
Affected altitude range	Primarily below 2 km but can be higher
Systematic error	Large signals – ie clouds, cause receiver to saturate → bsc is too small Likelihood of saturation decreases with distance
Statistical error	…
Can be corrected	No – saturated profiles should be flagged/removed above point of saturation
Uncertainty of correction[1]	Negligible – saturated profiles are removed so problem is avoided
Methods for quantification	• Overshoot (negative attenuated backscatter values) gives indication of magnitude of saturation but is not a linear relationship • Signals which are larger than the signal of the internal test pulse are probably affected by saturation [1]
references	[1] Holger Wille, Lufft – personal communication

6. Rayleigh calibration (Maxime Hervo)

The Rayleigh calibration method is usually applied to ceilometers with negligible signal distortions in the free troposphere (e.g. CHM15k). Calibration results can be influenced by the following effects:

- Correction of atmospheric transmission due to aerosols (with lidar ratio assumption)
- Temperature
- Noise

Uncertainties of lidar constants due to atmospheric transmission and lidar ratio assumption	
Affected instrument types	Instruments Calibrated with Rayleigh Calibration (CHM15k, MPL)
Affected altitude range	All (bias in calibration coefficient causes bias in all other products)
Systematic error	Up to 25% without correction of the transmission
Statistical error	
Can be corrected	Correction requires lr assumption
Uncertainty of correction	2.5 to 11.4%
Methods for quantification	Reference lidar
references	Wiegner and Geiß, 2012

Uncertainties of lidar constants due to measurements noise	
Affected instrument types	Ceilometers suitable for Rayleigh calibration– CHM15k
Affected altitude range	all
Systematic error	<0.5% (for integration time > 120min)
Statistical error	<2.5% (for integration time > 120min)
Can be corrected	No
Uncertainty of correction	
Methods for quantification	Noise quantification between 12 and 15km (Assumption that the noise is constant on the whole profile). Applied on a simulated profile.
references	

7. Annual cycle and temperature dependence of calibration values (Davide Dionisi, Henri Diémoz, Ina Mattis, Maxime Hervo)

Calibration values (from Rayleigh and from cloud calibration) of CHM15k instruments show an annual cycle. Calibration coefficients (lidar constants) are up to a factor of two larger in summer than in winter. A significant correlation between calibration and internal temperature could be found in case of

1. 1 individual instrument (CHM110115 at San Pietro Capofiume) with firmware version 0.556
2. In case of very high external temperatures, when temperature stabilization of the lom does not work and lom temperatures increase.

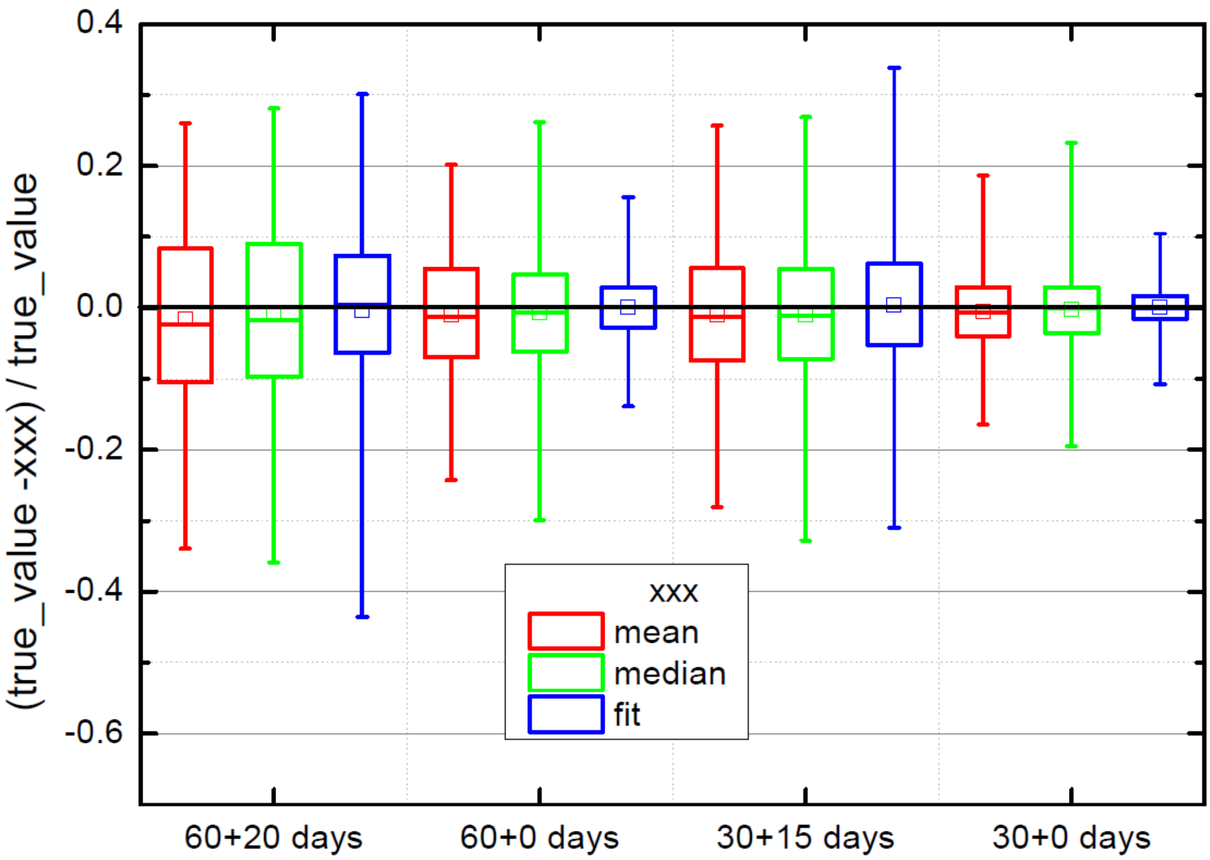
In both cases, the temperature dependence of the calibration needs to be parametrized and corrected. Otherwise it is not possible to apply the Rayleigh calibrations (derived during cooler nights) to daytime measurements with high temperatures.

In case of measurements at Leipzig, no correlation between calibration parameter and temperature (internal, external, lom, difference between internal and external) could be found. There is also no correlation with the optical depth of the profile nor with humidity, extinction, or visible range at ground level.

AERONET observations indicate an annual cycle of lidar ratio values over Leipzig. Indeed, the lidar ratio assumption has an influence on the retrieved calibration, but not more than 15%. The number of lidar ratio observations is limited and the range of variations in lidar ratio cannot explain the annual cycle of calibrations.

8. Extrapolation (Ina Mattis)

Ina Mattis presented results of a small study concerning the uncertainty of calibration values which are derived by extrapolation from a time series of previous calibration measurements. This uncertainty is caused by an annual cycle of calibration values or by trends, e.g. due to accumulation of dust on the instrument window or due to decreasing laser power.



The analysis of an example data set (about 60 ceilometers in Germany in 2016) shows that the uncertainty is smallest (typically ± 3%) if the extrapolation is done by means of a linear fit of the calibration values of the last 30 days. Analysis time series which are shorter than 30 days cannot be recommended because there needs to be a certain minimum number (e.g. 10) of successful calibrations within this period.

A not yet finally solved point of discussion is the **handling of window transmission**. The transmission decreases with time when dirt is collected at the windows until the window is cleaned by heavy rain or maintenance. There are two different approaches:

1. Calculation of calibration parameters only from measurements with clean windows. In this case, the calibration parameter is constant with time

(neglecting other sources of instrument degradation). But, if the calibration values shall be applied to measurements which were obtained with dirty windows, we need to know the relation between the 'state optics' parameter (which qualitatively corresponds to window transmission) and the calibration parameter.

2. Calibration parameters are obtained in all conditions, as long as the window is not too dirty (not enough signal). If measurements are calibrated with values which were derived close in time, both –the calibration measurement and the calibrated measurement - are performed with comparable window transmission and no correction of the calibration needs to be applied. This approach will not work properly in case of sudden changes of window transmission.

9. Uncertainties of profiles of particle backscatter coefficient caused by lidar ratio assumption (Davide Dionisi, Henri Diémoz, Mariana Adam)

If the aerosol type is not known, the lidar ratio may have values between 20 and 80 sr. The resulting uncertainty of particle backscatter coefficients is smaller at larger wavelengths.

	With known aerosol type	Aerosol type unknown
Affected instrument types	all	
Affected altitude range	All. The uncertainty decreases / increases with altitude in case of backward / forward inversion for particle backscatter coefficients (Klett/Fernald solution).	
Systematic error	The results depend on the aerosol type => site-dependent	
Statistical error[2]	2-5%	5-10%
Can be corrected	Any previous a-priori characterization of the aerosol can be used to constrain the aerosol type simulated in the model to improve the accuracy of the method	
Uncertainty of correction		
Methods for quantification	Combined forward +backward inversion	
references	Barnaba and Gobbi, 2001 and 2004 (532 nm) Dionisi et al., 2015 (1064 nm, continental) Dionisi et al., 2017 (in preparation) Davide's STSM report Diémoz et al., 2017 (in preparation)	

[2] At 900-1064 nm

10. Uncertainties of profiles of particle extinction coefficients and volume concentration caused by lidar ratio assumption (Davide Dionisi, Henri Diémoz)

The uncertainties of extinction coefficients and volume concentrations are comparable. If mass concentrations shall be derived, the unknown density of the aerosol particles (1-1.5 to 2-2.5 g cm^{-3}) causes additional uncertainties.

	With known aerosol type	Aerosol type unknown
Affected instrument types	all	
Affected altitude range	all	
Systematic error	The results depend on the aerosol type => site-dependent	
Statistical error	30-35%	40%-50%
Can be corrected	Any previous a-priori characterization of the aerosol can be used to constrain the aerosol type simulated in the model to improve the accuracy of the method	
Uncertainty of correction		
Methods for quantification	Comparison to OPCs, better NOT at ground (e.g., Jungfraujoch) or tilted installation, tethered balloon	
references	Barnaba and Gobbi, 2001 and 2004 (532 nm) Dionisi et al., 2015 (1064 nm, continental) Dionisi et al., 2017 (in preparation) Davide's STSM report Diémoz et al., 2017 (in preparation)	

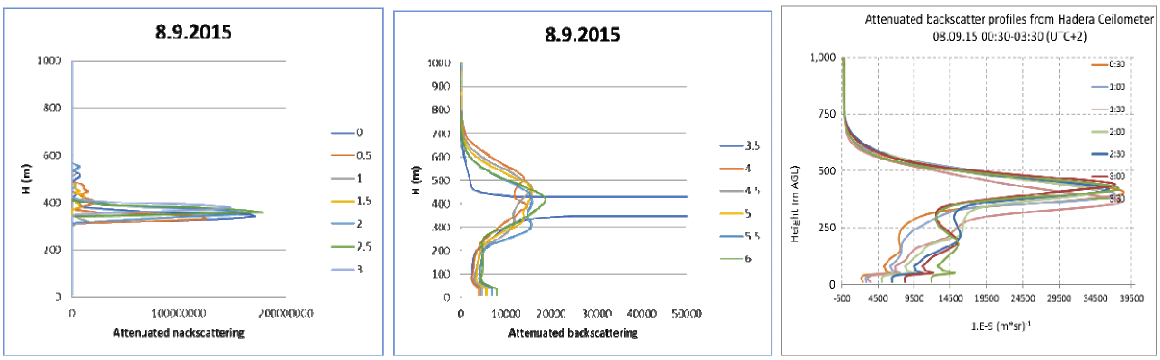
11. 2015 dust storm (Smadar Egert)

Israeli ceilometers are used to study the 3d (spatial and vertical) distribution of aerosols. 8-10 instruments are deployed covering most of Israel. Save one, all instruments are Vaisala Cl31 owned by several authorities that store the data usually in BLVIEW format.

The focus of this study is the dust event in September 2015 that originated in north east to Israel. Various sub bursts of dust starting as a thermal low in the north of Israel were followed by several fronts. It was unprecedented and the 3 models developed so far to explain it, still do not follow completely the LIDAR measurement in Cyprus and several ground PM10 monitors in Israel.

The ceilometers provided the entire event development over Israel. We wish to focus on its entry. From 18:00 GMT on September 7th till 3:30 on the 8th all stations measured a lofted layer. Its depth was ~150m, its height changed with time, following the lowering MLH. Radiometers and satellite identified it as dust having medium OD (~1) and huge non saturated attenuated backscattering. Within 0.5 hour- 3:30 to 4:00am the signals decreased by 4 orders of magnitude and the OD raised to ~3. Estimating the extinction coefficient using Coshmider formula and using typical dust LIDAR ratio 40, the attenuated backscattering gives the order of magnitude of the signals measured after 4:00am but does not offer any explanation for the elevated plume (fig. left &center).

High backscattering with high OD are usually associated with clouds. However, according to the satellites and observations near sunrise, there were no clouds and the OD was ~1. Such measurements are usually associated with oriented non spherical particles like ice cirrus clouds. Due to the high temperature and low elevation (00:00 radiosonde) the presence of ice crystals embedded in the dust seems unlikely. It looks as though the dust particles were oriented. The Ceilometer in Hadera that was tilted 12° to the north measured similar signals from 18:00 to 07:00 am next day (fig. right). We are trying to verify the reason for such orientation never reported in previous LIDAR dust measurements.



Summary tables (all)

The following tables summarize typical errors and uncertainties that will occur in the EPROFILE data analysis chain for different instrument types in several altitude ranges.

CHM15k version > 0.7*													
Altitude [km]	Attenuated bsc									Bsc coef	Ext coef	Mass concentr.	
	overlap			Rayleigh calibration[3]					noise	lr[4 5]	lr[5]	Bsc-vol-ratio[5]	density[5]
	No corr[6]	corr[7]	Corr with T[8]	lr	noise	T[9]	Interpo-lation						
							temp[10]	all					
0-0.2[11]	Do not use data for aerosol profiling												
0.2-0.5[12]	±50%	±25%	±5%	±12%	±2.5%	±12%	±30%	±5%	Calc from std dev	±10%	±45%	±45%	±40%
0.5-1.2[13]	±10%	0%	0%	±12%	±2.5%	±12%	±30%	±5%		±10%	±45%	±45%	±40%
1.2-15	0%	0%	0%	±12%	±2.5%	±12%	±30%	±5%		±5%	±45%	± 45%	±40%

[3] with correction of aerosol transmission

[4] in case of backward integration at 1064 nm

[5] In case of unknown aerosol type

[6] use overlap function as provided from manufacturer

[7] Use correction of overlap function as described by Hervo and Poltera

[8] Use temperature dependent correction of overlap function as described by Hervo and Poltera

[9] after correction of the temperature dependency, relevant only for version 0.5* with not fixed Temperature option

[10] for measurements where Tlom is not constant

[11] where ovl function is smaller than 0.05

[12] where ovl function is smaller than 0.8

[13] where ovl function is larger than 0.8, but not equal 1

CL51[14]											
Altitude [km]	Attenuated bsc[15]										
	ovl[16]	NR effect[17]	WV absorption		Background profile[18]		Cloud calibration				noise
			no corr	With corr	no corr	With corr	Mult scat[19]	Aerosol below cloud[20]	WV[21]	Extr apol.	
0-0.12	>±20%	±20%	≥5%	±1%	0	0	±5%	-5 ..0%	±2%	±5%	Calc from std dev
0.12-0.5	0..20%	0%	≥5%	±2%	0	0	±5%	-5 ..0%	±2%	±5%	
0.5-14.8	0%	0%	≥50%	±5%	2E-7 $m^{-1}sr^{-1}$	5E-8 $m^{-1}sr^{-1}$	±5%	-5 ..0%	±2%	±5%	

CL31[14]											
Altitude [km]	Attenuated bsc[15]										
	ovl[16]	NR effect[17]	WV absorption		Background profile[18]		Cloud calibration				noise
			no corr	With corr	no corr	With corr	Mult scat[19]	Aerosol below cloud[20]	WV[21]	Extr apol.	
0-0.09	>±20%	±20%	≥5%	±1%	0	0	±5%	-5 ..0%	±2%	±5%	Calc from std dev
0.09-0.5	0..20%	0%	≥5%	±2%	0	0	±5%	-5 ..0%	±2%	±5%	
0.5-7	0%	0%	≥50%	±5%	2E-7 $m^{-1}sr^{-1}$	5E-8 $m^{-1}sr^{-1}$	±5%	-5 ..0%	±2%	±5%	

[14] Uncertainties of bsc coef, ext coef, and mass concentration are the same as in case of CHM15k plus the additional uncertainty due to the wv correction which is ±5% at all altitudes.
[15] Attenuated by aerosols and water vapor
[16] Due to different overlap correction functions in different algorithm options
[17] Due to correction of 'bird' effect
[18] Strongly depends on firmware version and H2 mode. Example for v1.034, H2on
[19] if corrected, if geometry of the instrument is known
[20] if bsc below cloud > 5% rejected
[21] If water vapor absorption is corrected

Conclusions

The SWG elaborated a comprehensive review of a large set of sources of uncertainties and summarized the magnitude of the different effects based on the current state of knowledge. Several individual studies of the participants helped to quantify the effects. Nonetheless there are still many problems unsolved and requires further joint studies of academia, operators and manufacturers.

The scientific report will be posted on the TOPROF website: www.toprof.eu.