Virtual Mobility- Complete Report

Seasonal variation in the Rayleigh calibration factor of Automatic Lidar-Ceilometers: amplitude across Europe and possible explanations

M. Van Hove, H. Diémoz

1. Abstract

Comparability among measurements from Automatic Lidar-Ceilometers (ALCs) in heterogeneous measurement networks (such as EUMETNET E-PROFILE) strongly depends on the accuracy of the adopted calibration procedures. Furthermore, the retrieval of higher-level products such as aerosol extinction and mass concentration is based on attenuated backscatter; hence, large uncertainties in the calibration constant strongly hamper the use of ALC products from an end-user perspective. Several calibration techniques have been developed in the last decades, notably the one based on molecular/Rayleigh scattering in an aerosol-free layer of the atmosphere. One severe uncertainty is associated with a seasonal cycle found in the calibration values. This systematic variation is still of unknown origin but needs to be carefully addressed during the application of the calibration procedures. In this VMG, a statistical approach to the data is adopted to investigate the origin of the cycle by analyzing a large number of calibration datasets across Europe provided by the E-PROFILE network, covering a strong diversity of instrument models and ages, and environmental conditions. For the first time, the amplitudes of the cycle over such a large scale (involving 70 stations) are homogeneously compared using a single method. As a first step, the E-PROFILE calibration dataset is compared for a selection of sites to the results of the calibration methods adopted in the frame of other European initiatives, such as the DWD (Germany) and the Alicenet (Italy) ALC networks. No relevant systematic differences are found in the comparison of the calibration methods, with discrepancies mainly arising from single outliers attributed to the presence of elevated aerosol layers. The variations of the magnitude of the cycle found during the analysis among the European sites do not reveal any clear geographical pattern, e.g., as a function of latitude or other environmental characteristics of the sites. In the second part of the study, the temporal variations of the ALC calibration factor are correlated with some instrumental parameters in several sites. Significant similarities are found between the variation of the calibration factor and the following parameters: the laser pulse numbers, the detector sensitivity and the background noise. Finally, an on-going assessment to find a way to express the lidar constants only with housekeeping data showed first encouraging results. Progress on this topic will help networks develop operational calibration procedures.

2. Introduction

With the rising number of Automatic Lidar-Ceilometers (ALCs) deployed across the world, it is essential to ensure the quality and the homogeneity of the retrieved information. Calibration is therefore a key step, upon which all subsequent processing steps and products depend.

A widely deployed method relies on identifying an aerosol-free layer in the atmosphere for performing the inversion of the lidar signal. Clear-sky nights are chosen for the purpose and altitudes higher than 2km are considered; those conditions simulate a clean atmosphere and help prevent aerosols contamination. After determining the calibration factor using this backward method, subsequent profiles can be easily retrieved using more direct (forward) methods (e.g., Wiegner and Geiss, 2012).

The definition of the Lidar constant (CL) in the algorithms considered in this study is based on the equation:

$$C_{\mathrm{L}} = P\,z^{2}\,\beta(z)^{-1}\exp\left\{2\int_{z_{\mathrm{ovl}}}^{z}\alpha(z')\mathrm{d}z'\right\}$$

Pz^2 being the range corrected signal, β the volume aerosol backscatter coefficient, and α the volume aerosol extinction coefficient. While P is measured by the ceilometer, α and β are retrieved from the backward procedure assuming that $\alpha = \beta \cdot LR$, LR being the lidar ratio (LR).

Several studies brought to light a seasonal variability of the CL such as the Virtual Mobility lead by Maxim Hervo (TOPROF, 2015). Two main theories about its origins were considered: in this same study, a first assessment of the sensitivity of the ALCs' instrumental components to the temperature was done for the CHM15k of Leipzig, Germany. In fact, multiple studies showed an effect of the instrument internal temperature on the laser diode (Prokeš A., 2007). Then, as another possible cause of the CL variability in the framework of the Virtual Mobility lead by Joelle Buxmann (PROBE Cost Action 2022), the focus was made on the presence of undetected backscattered signal in summer. As a result, in J. Buxmann's study, the aerosol contamination seems responsible of outliers but not of the seasonal cycle; however, M. Hervo found a seasonal cycle of the laser power, suggesting a possible influence of the instrumental components on the signal. Moreover, the backscattered signal in summer was found to cause outliers in the CL. Depending on the main cause of the seasonal variability of the CL, the consideration of this cycle is questioned. If it appears to be purely instrumental related, or if we don't find a significant atmospheric cause, we would need to take it into account and apply a time dependent calibration on the signal. Otherwise, we might consider using the minimum of the CL and improve the CL retrieval.

The research is organized as follows:

1. The lidar constants calculated by different groups are compared for a selection of instruments belonging to both E-PROFILE and another national network.
2. Then, we use a selection of ALCs of the E-Profile network in an attempt of finding evidences of a geographical parameters influence.
3. Finally, we focus on a smaller selection of instruments to study the housekeeping data and their potential effect on the CL.

3. Data

The initial dataset used for the statistical analysis and investigation is provided by the E-Profile network which contains 143 Lufft CHM-15k ALCs across Europe and one in Canada. To avoid possible impacts of firmware and hardware (LOM) changes, and to ensure a sufficient length of the resulting dataset for the seasonal analysis (Sect 5.3), the initial dataset was reduced to include only sites with more than 1 year of data, and not impacted by changes of firmware and laser. This first selection contains 70 sites, spread across Europe. Finally, for a detailed analysis of the influence of instrumental properties on the CL (Sect. 5.4), we select ten sites between Italy, Germany, the UK and the Netherlands, with diversity in stability (no change of LOM/firmware VS one or several changes) and relative amplitude.

To compare the values retrieved within E-PROFILE with the DWD lidar constants (Sect. 5.2), we chose the following German sites:

- List (wigos: 0-20000-0-10020)
- Potsdam (wigos: 0-20000-0-10379)
- Bonn (wigos: 0-20000-0-10519)
- Freiburg (wigos: 0-20000-0-10803)

Indeed, those sites show different relative amplitudes by the algorithm at MeteoSwiss and climatologic types.

Alicenet provided calibration values from the following sites:

- Messina (wigos: 0-20000-0-00203)
- Aosta (wigos: 0-380-5-1)

4. Methods

4.1 Algorithm comparisons

The 3 algorithms compared are provided by MeteoSwiss (used for the network E-Profile), the DWD (Germany) and Alicenet (Italy). As mentioned in section 1, the CL definition is the same for the three algorithms. They all share the same origin, a code written by M. Hervo in Matlab. However, the DWD always used it ever since, while in MeteoSwiss the operational code is a translation of the Matlab code in Python (M. Hervo). At Alicenet, a translated version in R was developed by H. Diémoz and A. Bellini, and improved in order to avoid to generate outliers.

4.2 Calculation of the relative amplitude of the cycle

A definition of the “relative amplitude” of the seasonal cycle is needed to consistently compare the datasets from different sites and the results from the three algorithms. We use the following method:

1. First, the outliers are removed using a threshold of 2.5 times the interquartile range of the signal, as a first filter.

2. Then, a long-term trend is calculated to take into account possible drifts. This trend is defined with the Prophet library in python (v.1.1.5, Facebook’s Core Data Science Team, retrieved from https://github.com/facebook/prophet); it takes into account a possible yearly

variability with a multiplicative model, as the seasonal variability might not be constant through time.

3. Finally, the long-term fit is removed from the dataset resulting from step 1 to highlight the seasonal cycle and the data are divided by the long-term trend to calculate the relative amplitude of the seasonal cycle. This is formally defined as half of the difference between quartile 95 and quartile 2 - most of the outliers being in summer and high extremes, using quartile 98 didn't seem accurate enough.

Figure 1 shows an example of this method application; however, most of the sites show drifts of a significantly lower amplitude than the one in Fuerstenzell, Germany, so usually the first and second rows are very similar. This method is used for the rest of the analysis.

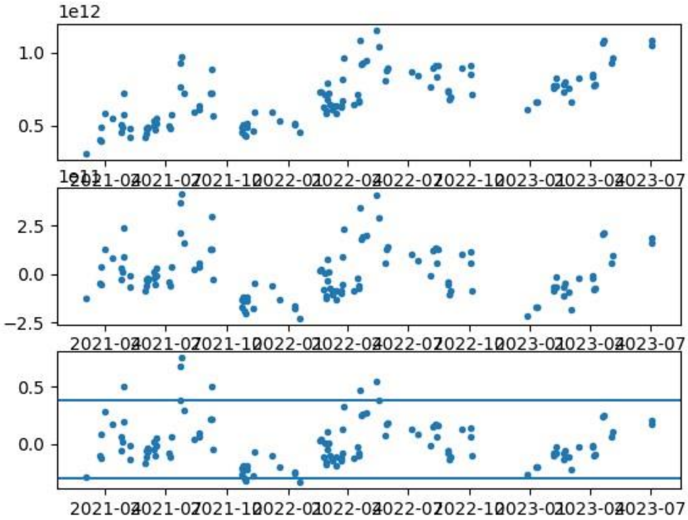
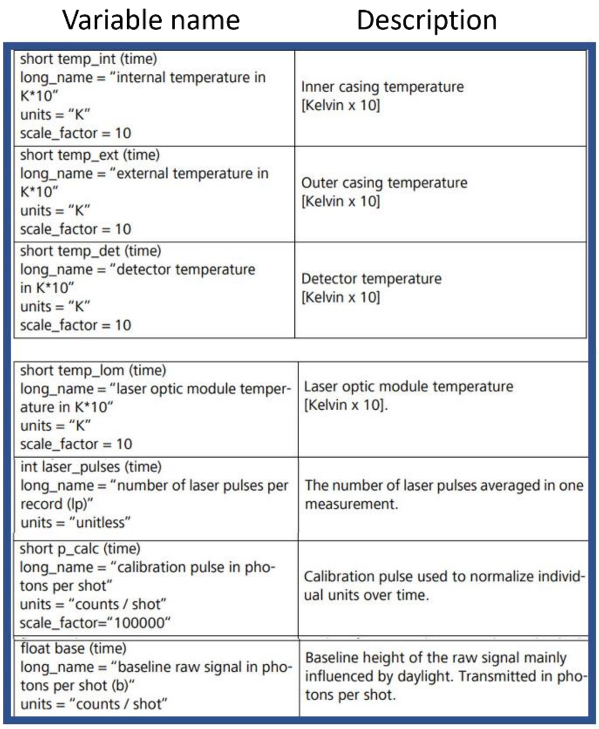


Figure 1 : Estimation of the relative amplitude at Fuerstenzell, Germany. Upper: original CL, middle: detrended signal, lower: relative amplitude

4.3 Influence of instrumental factors

The instrumental parameters studied are listed in the Table 1. As mentioned in the introduction, some of them have been already studied in the frame of a previous COST Action (TOPROF).



Variable name	Description
short temp_int (time) long_name = "internal temperature in K*10" units = "K" scale_factor = 10	Inner casing temperature [Kelvin x 10]
short temp_ext (time) long_name = "external temperature in K*10" units = "K" scale_factor = 10	Outer casing temperature [Kelvin x 10]
short temp_det (time) long_name = "detector temperature in K*10" units = "K" scale_factor = 10	Detector temperature [Kelvin x 10]
short temp_lom (time) long_name = "laser optic module temperature in K*10" units = "K" scale_factor = 10	Laser optic module temperature [Kelvin x 10].
int laser_pulses (time) long_name = "number of laser pulses per record (lp)" units = "unitless"	The number of laser pulses averaged in one measurement.
short p_calc (time) long_name = "calibration pulse in photons per shot" units = "counts / shot" scale_factor="100000"	Calibration pulse used to normalize individual units over time.
float base (time) long_name = "baseline raw signal in photons per shot (b)" units = "counts / shot"	Baseline height of the raw signal mainly influenced by daylight. Transmitted in photons per shot.

Table 1: Device variables studied, source: Manual Ceilometer CHM15k "Nimbus" by Lufft

According to the CHM15k user guide:

-*calibration_pulse* is the calibration pulse intensity, and is used to normalize individual units over time: in other terms, it shows the detector sensitivity. It is expressed in photons per shot.

-*laser_pulse* is the laser pulse number per record, which shows the laser power.

-*temp_ext*, *temp_int, temperature_detector* and *temperature_optical _module* are respectively the external and internal temperatures, the temperature measured at the sensor, and the temperature of the laser optical module, all of them in Kelvin.

These factors are included in the pre-processing of the ALC signal by the firmware, according to the definition of the "corrected signal" (CHM15k Manual):

$$P(r) = \frac{\left(\frac{P_{raw}}{lp} - b\right)}{cs * O(r)} \cdot \frac{1}{p_{calc}} \tag{1}$$

Praw is defined as the raw signal detected by the sensor. It is not archived in the raw files coming out of the instruments, hence nor in the L1-level files, from the raw2l1 code (SIRTA). However, the parameters b, the background noise, p_calc, the detector sensitivity and lp, the laser pulses, i.e., the laser power, were available in our internal database of L1-level files. Therefore, we were able to recreate the raw signal Praw for a study case. The parameters cs, i.e., the scaling factor used to normalize individual devices against a reference system, and O(r), the overlap function provided by the manufacturer, are constant over time (unless a change of LOM occurs), therefore they are not considered here.

5. Results and discussion

5.1 Initial assessment of the impact of hardware/firmware changes

A first assessment confirmed that a change of the laser impacts the lidar constants (average, absolute amplitude and sometimes drift), almost systematically. A change of firmware may impact them, especially depending on how the operator sets the mode “AFD” of the instrument. The most noticeable impact on LC due to firmware changes occurred between version 0.559 and 0.743 in the UK for 11 sites in 2019. Most of the firmware changes do not seem to impact the LC since then and at the other sites. However, at Fuerstenzell, we noticed a strong change in the CL after a LOM replacement (Figure 2), and an increase of the relative amplitude.

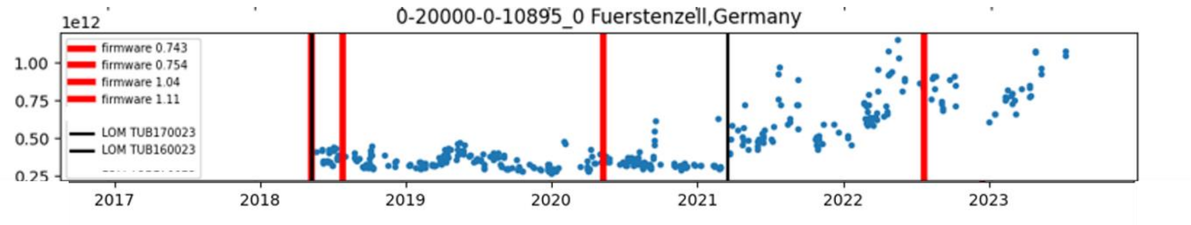


Figure 2 : Lidar constants at Fuerstenzell, Germany

5.2 Algorithm comparisons

No significant differences were found between the three algorithms (E-PROFILE, Alicenet and DWD). The presence of a seasonal cycle can be found for all the datasets compared, with similar amplitude, with an example at Freiburg in Figure 3. Therefore, it becomes less probable that the seasonal cycle is generated and influenced by an algorithmic cause.

Site	**List, Germany**	**Potsdam, Germany**	**Bonn, Germany**	**Freiburg, Germany**	**Messina, Italy**	**Aosta, Italy**
Wigos	0-20000-0-10020	0-20000-0-10379	0-20000-0-10519	0-20000-0-10803	0-20000-0-00203	0-380-5-1
E-Profile	28%	35%	43%	27%	26%	30%
DWD	33%	37%	39%	28%		
ALICENET					26%	28%

Table 2 : Comparison between the relative amplitudes retrieved from the three algorithms

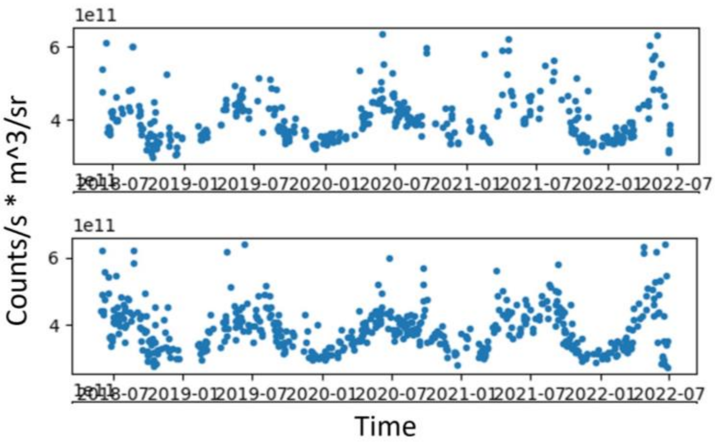


Figure 3: Comparison between algorithm of MeteoSwiss (upper) and DWD (lower) at Freiburg, Germany

5.3 Geographical dependence

A total of 70 instruments were analyzed; some of the highest relative amplitudes are reached at Milano, Italy and Payerne, Switzerland with respectively 48% (maximum value) and 43%, while lower values are reached at Bern, Switzerland and Andoya, Norway with respectively 25% and 23% (minimum value). The city of Bern being 7 times denser than Payerne, it is unlikely that the pollution is a main leader of this variability. The statistical analysis of the relative amplitude of the seasonal cycle did not bring to light any obvious pattern related to geographical parameters or climate conditions. It is likely that either atmospheric conditions are not the main factor of the seasonal variability of the lidar constants or, if such influence exists, an instrumental effect might cover their impact. Nevertheless, the amplitudes obtained across Europe in this analysis can be useful to assess the overall range of magnitudes for this seasonal effect, in particular for uncertainty purposes.

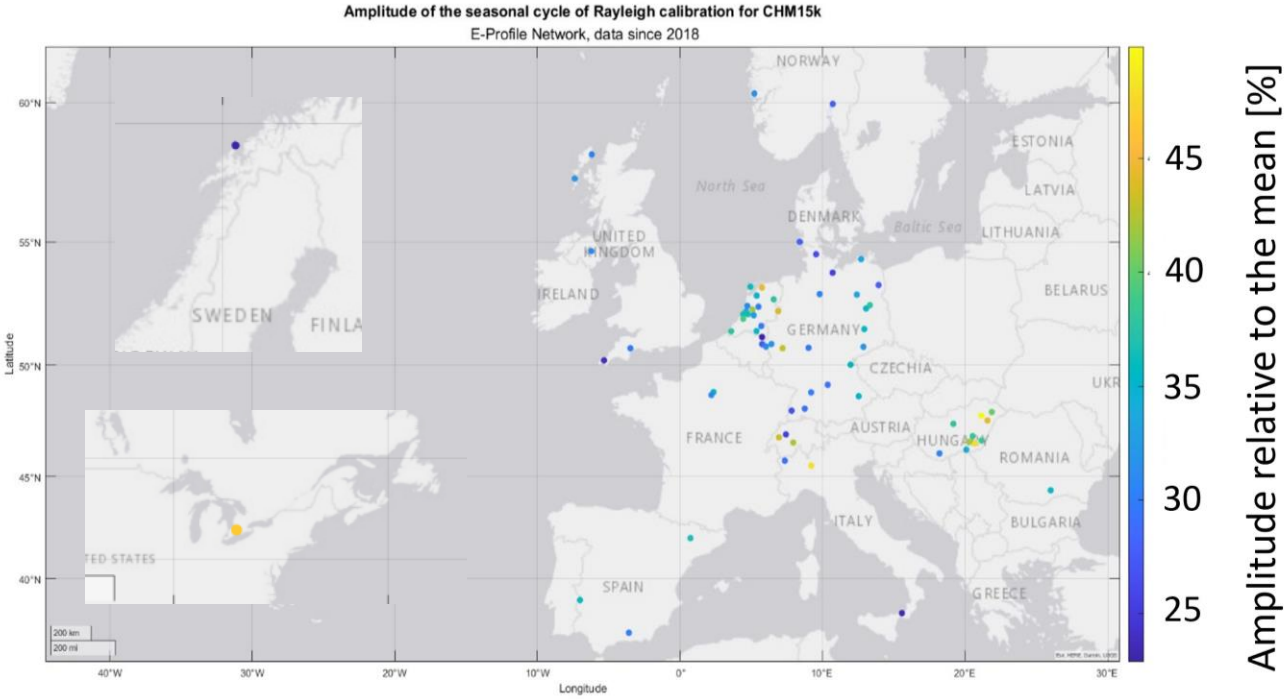


Figure 4 : Relative amplitude of the seasonal cycle in Europe

However, as we saw in the first assessment, the calibration values can highly differ between two different LOM. Moreover, in Fuerstenzell, the relative amplitude goes from 20% to more than 30% after the LOM TUB170023 is replaced with TUB160023. If the LOM didn't impact the calibration values relative amplitude between two different sites, it would be easier to extract a geographical influence. Hence, the relative amplitude can depend on the LOM and multiple instruments might not be easily comparable to highlight a purely atmospheric influence.

5.4 Analysis of instrumental factors

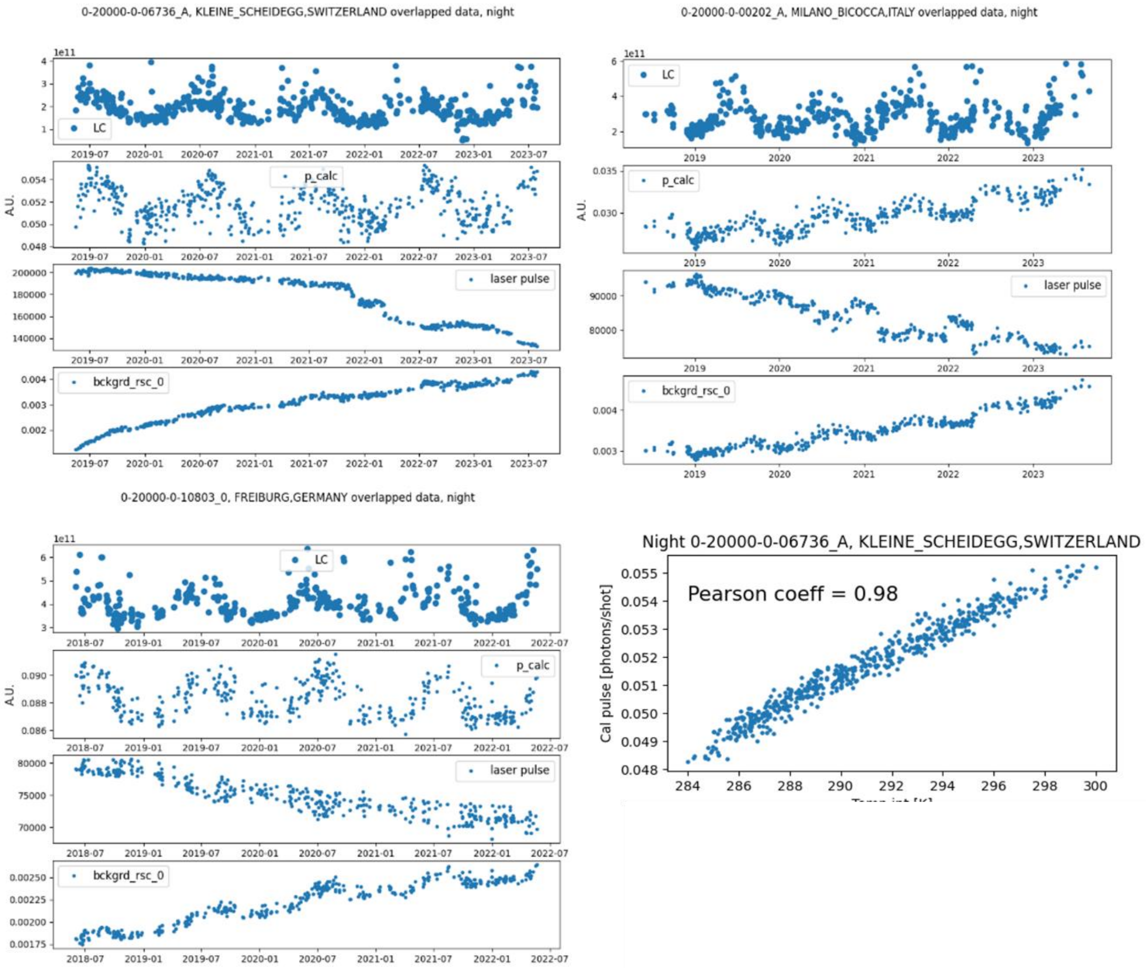


Figure 5 : Comparison between CL and instrumental parameters (average over the interval of the Rayleigh calibration period, during the night) at the Kleine Scheidegg Switzerland, Milano (Italy) and Freiburg (Germany), from upper to lower: C_L; calibration pulses; laser pulses; background

As we see in figure 5, all time-dependent parameters show a seasonal cycle. We highly suspect an effect of the internal temperature; as expected, at the Kleine Scheidegg, the correlation between the calibration pulse and the internal temperature shows an index of correlation of 0.98.

In figure 6, we compared the raw signal and the corrected signal. The raw signal was built from the equation (1). The relative amplitudes between them are similar as they differ of around 6 %.

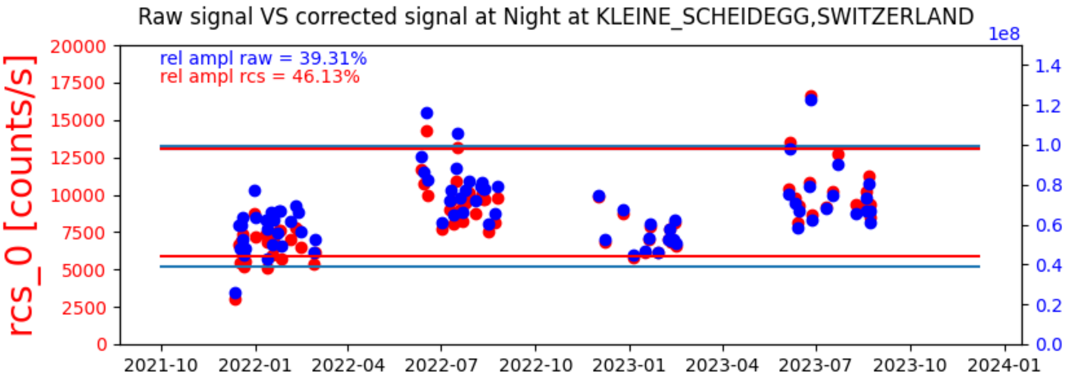


Figure 6 : Comparison between the raw signal and the corrected signal at the Kleine Scheidegg, Switzerland

The instrument parameters variability is usually between 1% and 8%, while the calibration constants, the “corrected” signal and the raw signal variability reach more than 25% of relative amplitude. Assuming the raw signal variability is instrumental related, the variability of the housekeeping data is therefore not sufficient to correct it. Multiple theories can explain this, such as an undetected heterogeneity of the internal temperature or a default in the sensitivity of the housekeeping data which would not be representative of the amplitude required to correct the signal.

Moreover, with the contribution of M. Hervo, a multiple linear regression model has shown very promising results to express the lidar constants only based on the housekeeping variables (Figure 7).

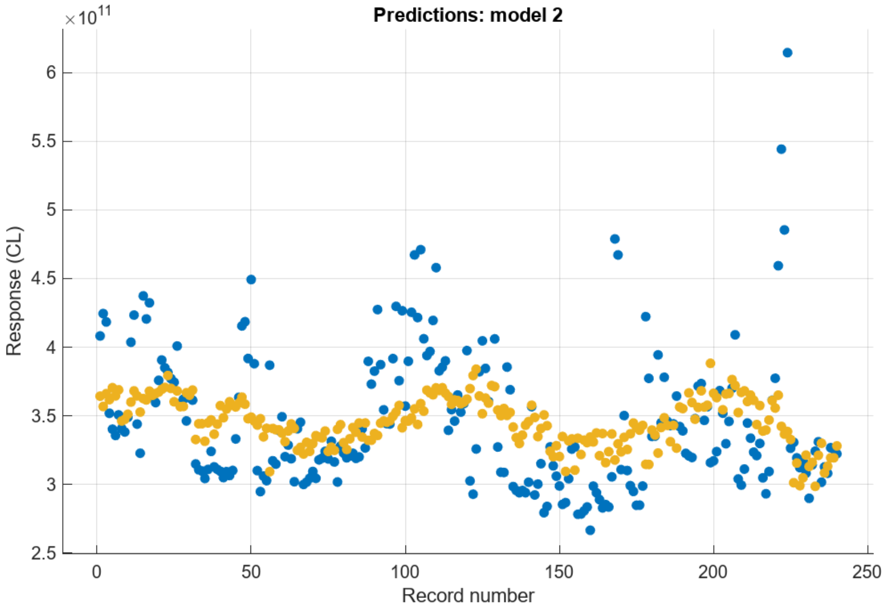


Figure 7 : Prediction model of the CL from instrumental parameters at Fuerstenzell, Germany

This analysis has been done on the datasets of Payerne, Switzerland and the Kleine Scheidegg, Switzerland, with similar results.

Conclusion

This study was an attempt of highlight a main factor leading the seasonal cycle of the lidar constants of the Rayleigh calibration applied on Lufft CHM15k ALCs. At European scale, no evidence of an atmospheric related factor was found.

Nevertheless, we showed clear seasonal variabilities in most of the instrumental parameters for the sites studied. As we know the internal temperature has a confirmed effect on the laser power, it is very likely to find it as well on other housekeeping parameters. A difference of the relative amplitudes between the CL and the instrumental variables suggests that the correction provided by the firmware is not sufficient. In fact, as a first proof that this correction is possible, for three sites an equation has been found to define the total CL relative amplitude by taking into account the housekeeping data only. Those results provide additional arguments in favor of the theory of the instrument related variability. As a future assessment, it would be interesting to find if one single equation can define the CL from several sites and for several LOM, and by testing different types of models (e.g., non-parametrical).