# SCIENTIFIC REPORT

**ACTION:** ES1303 TOPROF

**STSM:** COST-STSM-ES1303-TOPROF

**TOPIC:** Testing recommendations for processing of Vaisala CL31 profile observations

**VENUE:** Palaiseau, France

**PERIOD:** 11 – 15 April 2016


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## Introduction

Ceilometers are manufactured by several companies and even between model of one manufacturere the sensor optics, hardware components and software algorithms may differ significantly. Discussions in the TOPROF community have revealed the importance of a detailed understanding of instrument specifics to identify the necessary processing steps that enable appropriate interpretation and harmonisation of the final data products. For example, the extensive CeiLinEx2015 campaign (www.ceilinex2015.de) was conducted by TOPROF members in 2015 to evaluate attenuated backscatter and cloud base height products from a range of ceilometer models from several manufacturers (including Lufft/Jenoptik, Campbell Sci., and Vaisala). This study addresses the commonly deployed Vaisala CL31 ceilometers. Earlier Vaisala ceilometer models are the LD40 and CT25K; its successor is the CL51.

Comparing a Vaisala LD40 and two CL31 ceilometers, Emeis et al. (2009) show that attenuated backscatter may vary distinctly between those sensors with clear implications for their representation of ABL structures. As these differences are manifested in vertical structures rather than a simple offset related they can not be explained by a lack of absolute calibration. Emeis et al. (2009) state 'internally generated artefacts from the instrument's software' could play a role, however refraining from providing further details. While software-related artefacts might contribute, the discrepancy between the attenuated backscatter profiles observed by the two CL31 sensors tested (Emeis et al., 2009) might also be explained by the hardware-related (electronic or optical) background profile. Recent work on a Halo Doppler lidar suggests such impacts of the background profile could be corrected for during post-processing (Manninen et al., 2016).

Due to the co-axial beam design, the full optical overlap for the CL31 is reached already at low ranges (Münkel et al., 2009). Although Vaisala suggests that the attenuated backscatter profile is reliable down to the first range gate, Sokół et al. (2014) document a distinct local minimum in CL31 attenuated backscatter observations at the 5$^{th}$ range gate persisting throughout their whole observational campaign. As others have found artefacts in CL31 profiles below 70 m (e.g. Martucci et al. 2010; Tsaknakis et al. 2011) these lowest ranges are often excluded during processing. Sundström et al. (2009) evaluate the applicability of CL31 observations for quantitative aerosol measurements and conclude the artefacts in the range gates near the instrument to be a major source of uncertainty. Van der Kamp (2008) smooth out systematic features by strong vertical averaging, which, however, condones reduction of real physical signals.

Kotthaus et al. (2016) present a quality control procedure for CL31 profile observations developed based on observations from the LUMO and Met Office networks in the UK. Corrections account for effects of signal background and near-range artefacts. The aim of this work is to evaluate their methodologies using an independent dataset from the SIRTA site at Palaiseau, France (Haeffelin et al., 2005). The correction of near-range artefacts is critical to support future research on low-visibility events using attenuated backscatter observations from CL31 ceilometers.

## Objectives

The initial objectives of this STSM were twofold:



1) To evaluate recommendations by Kotthaus et al. (2016) for CL31 observations from the SIRTA site
2) To evaluate low visibility events based on the urban ceilometer network LUMO

As reliable profiles of attenuated backscatter are required to study low-visibility events, the STSM was focused mainly on the first objective. This included the evaluation of

- Background correction based on night-time climatology
- Near-range correction
- Effectiveness of signal-to-noise ratio (SNR) filter

## Data

Long-term measurements of the Vaisala CL31 ceilometer are available at the SIRTA site (Haeffelin et al., 2005), however, the recommended setting (*Message profile noise_h2 on*, see Kotthaus et al. (2016) for details) was only applied in May 2015. Hence the current analysis focuses on the period 20 May 2015 – 10 April 2016. The SIRTA CL31 has an engine board CLE321 and receiver CLR321 and is operating firmware version 2.01 for the whole period analysed. Data were captured at a frequency of 2 s, but 30 s averages of the original data are analysed here. The range resolution is 15 m.

Data from the SIRTA ceilometer (sensor ID 'S') are compared to observations form the LUMO network which operates two sensors of older hardware generation (sensors A and B) and two of the same generation as the SIRTA ceilometer (sensors C and D).

## Methodology

CL31 observations from SIRTA were used to evaluate methodologies proposed for the background correction, correction of near-range artefacts and filtering based on SNR (Kotthaus et al., 2016).

The backscattered signal detected by ALC generally consists of actual signal contributions from atmospheric attenuation, the atmospheric background associated with scattered solar radiation and the instrument-related background (Cao et al., 2013). The CL31 measurement design accounts for temporal variations in solar radiation by introducing a variable zero-level (Kotthaus et al., 2016). The atmospheric background still contributes to the noise in the profile. On average, the range-corrected signal reported (labelled 'range-corrected attenuated backscatter' in CL31 output, but called 'signal' here due to the lack of absolute calibration) is

inherently corrected for the impact of atmospheric background and only the instrument-related background needs to be accounted for to derive the background-corrected signal. For sensors running firmware version 2.01, the background correction may be estimated based on a climatology of night-time observations under the absence of clouds.
Given the primary function of cloud base height detection, Vaisala designed CL31 firmware to identify and address effects causing extremely high backscatter values outside of clouds. Under severe window obstruction (e.g. leaf on the window), values for the first range gates would be unrealistically high. A correction is applied to restrict the backscatter profile in the ranges closest to the instrument. At times, this correction introduces extremely small values at ranges < 50 m that are clearly offset from the observations above this height. In addition to this artefact from the obstruction correction, for some sensors, backscatter values in the range of 50-80 m are slightly offset by a hardware-related perturbation. Both the artefacts from the obstruction correction and the hardware-related perturbation do not impact the detection of clouds, vertical visibility or boundary layer structures (above 80 m). Only if attenuated backscatter is to be analysed below 80 m, the impact of these artefacts needs to be accounted for.

To evaluate the effect of the obstruction-correction and hardware-related perturbation, profiles of the range corrected reported signal in the lowest 90 m are normalised by the value at 100 m (Kotthaus et al., 2016). Characteristic profiles reveal a consistent peak at a given range gate below 100 m ($5^{th}$ range gate for LUMO sensors operating with 10 m resolution). The near-range correction proposed initially, used the strength of this peak value to scale the correction factor based on a linear regression. All profiles were corrected.

To evaluate the quality of background-corrected attenuated backscatter it can be compared to the *noise floor*. The latter represents variations associated with electric and optical noise and noise introduced by the solar background light. When no high cirrus clouds are present, it is assumed the signal observed at the very highest range gates contains only noise (i.e. the atmospheric signal contribution is negligible). In this case, the noise floor $F$ can be defined as the mean plus standard deviation of the background-corrected attenuated backscatter (i.e. before range correction) across a certain set of gates from the top of the profile. Statistics are applied across these gates at the top of the profile and moving temporal windows (Kotthaus et al., 2016). The SNR is defined at the ratio of the average non-range corrected backscatter across a set of moving time- and range windows to the noise floor determined from the top range gates. To evaluate where the signal contribution is clearly distinguishable from the noise, Welch's t-test (Welch, 1947) was performed. Based on a p-value < 0.01 acceptance levels of 50% - 90% correspond to SNR values of 0.05 – 0.20 for the LUMO sensors. An SNR threshold of 0.18 was hence chosen to filter data with significant information content.

## Results

Night-time profiles (hourly average data, 22-02h) of the SIRTA observations were selected for times without significant cloud (< 10% of the hour; Figure 1e) and compared to similar observations from the LUMO sensors (Figure 1a-d). Discussion on the specifics of LUMO observations are provided in Kotthaus et al. (2016).

The time series (Figure 1, left) revealed a sudden change in observations from the SIRTA site on the week of 7 September 2015. As seen for some LUMO sensors, this coincided with a maintenance event later confirmed by Meteo France, i.e. a change in transmitter CLT. Grouping the selected nocturnal profiles, by transmitter (i.e. data collected before and after 7 September 2015, respectively) median background profile are determined (Figure 1e, right). Profiles of the SIRTA sensor show lower variability (smaller inter-quartile range illustrated by shading in Figure 1, right) compared to the LUMO sensors, presumably because 30 s averages of the data recorded at 2 s resolution are analysed here (LUMO data have 15 s resolution).

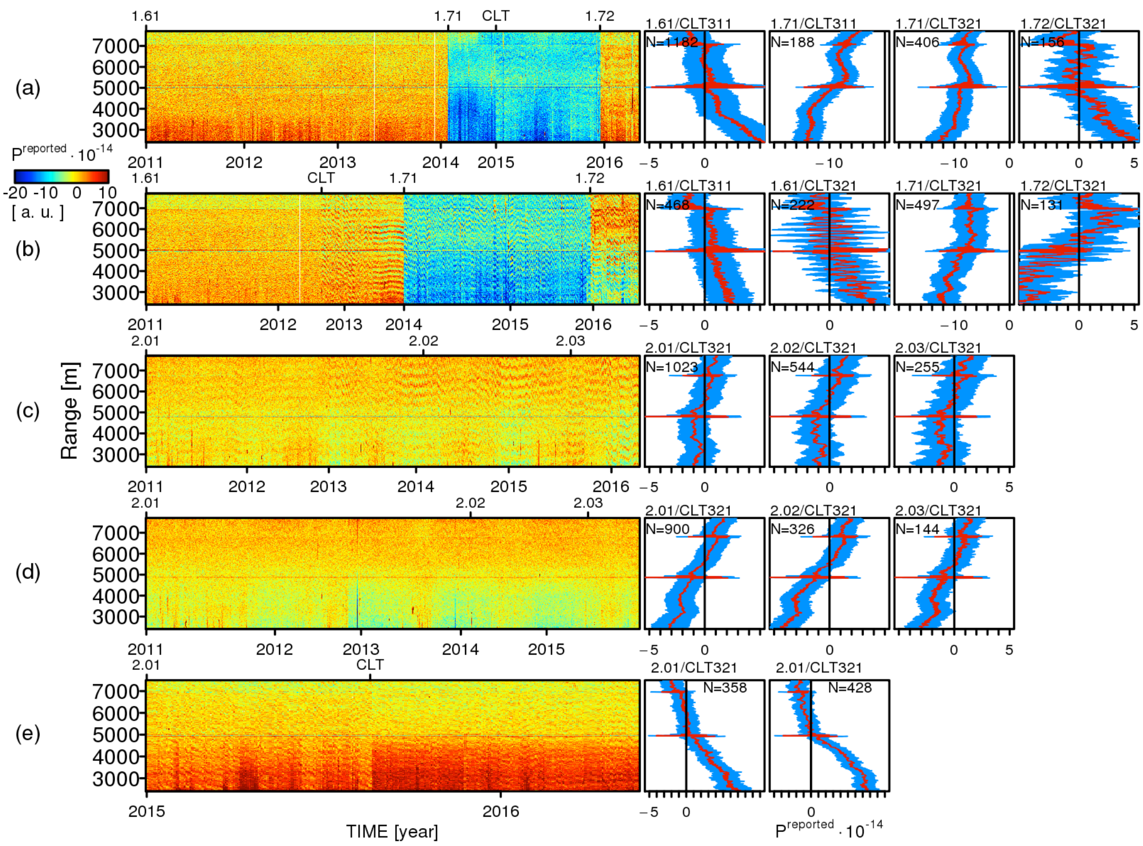


*Figure 1: Reported signal $P^{reported}$ (after reverting range-correction) observed with Vaisala CL31 sensors operating with (a, b) engine board CLE311 + receiver CLR311 (A, B) and (c, d, e) CLE321 + CLR321 (C, D, S), respectively, from (a-d) January 2011 through April 2016 and (e) May 2015 – April 2016 for range > 2400 m. Observations (four hours around midnight, 22-02 UTC) are hourly means of profiles when: clouds detected for < 10% of the hour, no fog, average window transmission > 80%, laser pulse energy > 98% and data availability > 90%. (left) Top axis shows firmware updates (version 1.71, then 1.72 for sensors A & B; versions 2.02, then 2.03 for C & D; version 2.01 for S) and hardware changes/upgrades (transmitter CLT311 replaced by CLT321 for sensors A and B; CLT321 replaced by a new CLT321 for sensor S). (right) median profiles (with IQR shading) of all selected observations grouped by firmware version and transmitter, with N indicating the number of profiles. Figure published in Kotthaus et al. (2016).*

While background profiles of the LUMO sensors of the new generation (sensors C and D) generally between each other (no clear differences associated with firmware versions) the background profile of the SIRTA sensor S is significantly different. Sensors C and D exhibit a slightly negative background below about 5000 m while sensor S is influenced by a strong, positive background profile (Figure 2a). Before testing the SIRTA sensor, it was assumed that CL31 ceilometers of the new generation have a small, negative background (as seen for sensors C and D). Including the SIRTA data into the analysis hence revealed great insights into the nature of background profiles, i.e. that each sensor has to be evaluated individually even for the new generation hardware.

To evaluate whether the night-time climatology is a suitable basis on which to determine the background profile, test-measurements for four LUMO sensors with recent firmware and hardware configurations (see Kotthaus et al. (2016) for details). As there are no data available from the climatology approach for ranges below 2400 m (Figure 2b), profiles are assumed to be constant up to this range (Figure 2a, c). This results in an obvious discrepancy between the climatology-derived background and the termination hood profiles (Figure 2**Error! Reference source not found.**c). During the STSM, implications of this assumption were tested after range correction is performed (Figure 2d-e), which revealed the uncertainty is greatly reduced. Although uncertainties remain regarding the background profiles below a range of 2400 m, termination hood reference measurements give confidence that the night-time climatology measurements are not significantly influenced by backscatter from atmospheric particles and hence provide reasonable estimates of the background profiles.

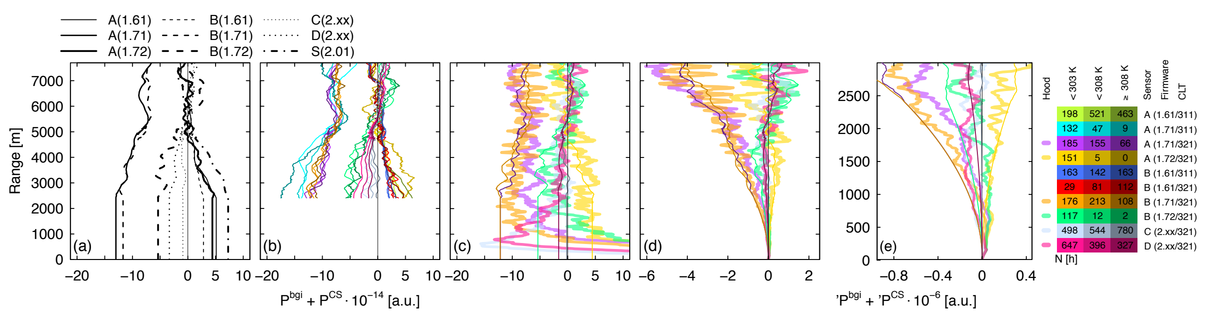


*Figure 2: Long-term median vertical profiles of range-dependent background $P^{bgi}$ for Vaisala CL31 sensors (A, B, C, D, S). Statistics are based on hourly mean profiles (> 2410 m) of reported signal with after reverting the range-correction $P^{reported}$ observed around midnight (same data as Figure 1). Ceilometers A & B operated with firmware 1.61, 1.71 or 1.72 and transmitter type CLT311 or CLT321, respectively; ceilometers C & D operated with CLT321 and firmware 2.01, 2.02, and 2.03; ceilometer S operated with firmware 2.01 and CLT321. (a) Median profiles for each sensor calculated separately by firmware version for sensors C & D, all are combined for C & D (2.xx) due to their similarity; (b) as in (a) for sensors A, C, B, D but also separating by ceilometer transmitter CLT and laser heat sink temperature combinations (see legend); laser heat sink temperature (as reported by the ceilometer) is used to subdivide profiles into three classes ($T_{laser}$ < 303, 303 ≤ $T_{laser}$ < 308 K, and $T_{laser}$ ≥ 308 K), (c) as in (b) but for selected profiles (solid lines, A & B with 1.71 and 1.72; C & D with 2.03) and their respective background profiles as determined by a 30-min termination hood measurement at the same setting and laser heat sink temperature class (thick lines); (d) as in (c) but range-corrected; and (e) as in (d) but zoomed into the range < 3000 m. Number of hourly mean profiles N [h] available for each combination of sensor, firmware, transmitter type CLT and laser temperature is listed in the legend. Profiles are smoothed vertically with a moving average over a window of 210 m, only for profiles from sensor B a smoothing window of 310 m is used. Figure published in Kotthaus et al. (2016).*

Low-range artefacts of the SIRTA CL31 (Figure 3) are of similar nature as detected for the four LUMO sensors (see Figure 6 in Kotthaus et al. (2016), with a pronounced peak at 60 m, i.e. the 4th range gate. Discussions about the initially proposed near-range correction revealed issues during pre-fog conditions when hygroscopic growth of aerosols may introduce significant gradients along the profile of attenuated backscatter below 100 m. Under these conditions, the initially proposed correction was not suitable. In response to this discussion, the near-range correction was slightly updated during the STSM. The near-range correction is based on the median climatological profiles (e.g. Figure 3), with the aim to reduce the impact of the obstruction correction and hardware-related perturbation. Only profiles that roughly match the general shape of the climatology are corrected, i.e. if strong vertical gradients in the reported signal are observed (such as those associated with descending fog) the profile approach is not applicable. Still, in such conditions, the disturbances are usually small compared to the physical processes influencing the attenuated backscatter across the profile.



Given all sensors tested (from LUMO and SIRTA network) are characterised by a distinct peak at a certain range gate, this peak is used to indicate if a correction should be applied. The aim is to apply the near-range correction only to profiles with a pronounced peak value that appears physically unreasonable. Firstly, it is determined at which range gate the peak is located based on the climatology (5th range gate for LUMO sensors, 4th for SIRTA). The peak strength is then defined as the ratio of the range-corrected signal reported at this range gate to that observed at the adjacent gates (i.e. 4th and 6th for LUMO sensors). If both these peak-strength indicators of a given profile are at least 25% as strong as the peak-strength indicators of the climatology profile, the values of this profile in the near-range (< 100 m) are divided by the median climatology profile. Profiles affected by the obstruction correction, i.e. with clearly offset values in the first four range gates, are treated separately. If the first peak-strength

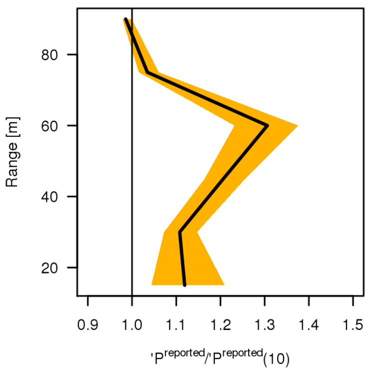


*Figure 3: Median range-corrected signal '$P^{reported}$ of the lowest 6 range gates (15 – 90 m) normalised by the value at the 105 m for SIRTA sensor S. Statistics calculated for all profiles observed between 11-16 UTC with '$P^{reported}$ < 400 × $10^{-8}$ a.u. in the lowest 400 m: median (solid line) and inter-quartile rage (shading).*

indicator (i.e. the one below the peak) is at least 50% as strong as the respective indicator of the climatology of this regime and the value at the range gate of the peak is greater than the values in the two range gates above, the respective median climatology profile is used for the correction. See Kotthaus et al. (2016) for more details.



For selected case studies, the background correction according to Kotthaus et al. (2016) was applied to observations from the SIRTA sensor (e.g. Figure 4). The range corrected attenuated backscatter at 30 s resolution (Figure 4a) is quite noisy so that the evolution of the ABL is hardly apparent. When the moving average is applied (Figure 4b), the signal contribution clearly increases so that aerosol layers can be identified visually. However the contrast between ABL and the clear air above is less sharp than might be expected because the positive background of sensor S (Figure 3a) leads to an overestimation of the signal below about 5000 m. Similar effects were detected for LUMO sensors with positive background (Kotthaus et al., 2016).

The described artefacts can be mostly corrected by the proposed background correction (Figure 4c) as it improves the contrast at the boundary layer top. As demonstrated for LUMO sensors, applying the *SNR* filter to the SIRTA observations (Figure 4d) further helps to distinguish data with significant information content, such as found in the ABL or clouds. The same statistical threshold (*SNR* = 0.18) was used to ensure data quality for later applications (e.g. mixing height detection). Still, some significant noise may remain near the ABL top for sensors of old hardware generation running with firmware 1.xx (Kotthaus et al., 2016). Comparing to the SIRTA data allows the conclusion to be drawn that data quality of sensors of

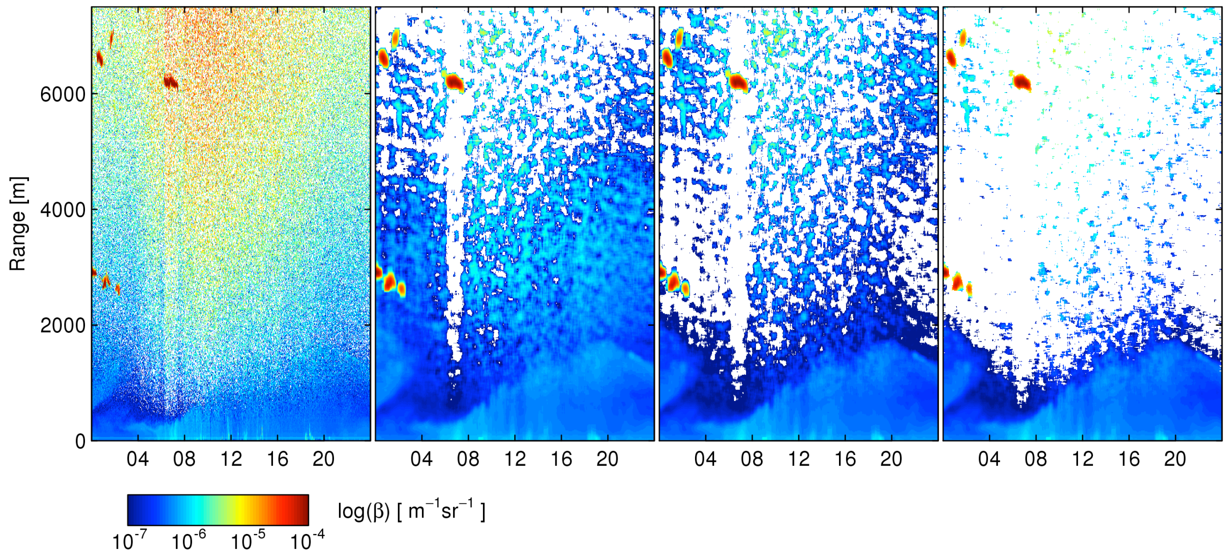


*Figure 4: Observations of the CL31 ceilometer at SIRTA on 29 June 2016: (a) Range corrected attenuated backscatter, 30 s block averages of 2 s data recorded, (b) as in (a) with running average (~ 25 min, ~ 100 m) applied, (c) as in (b) but including correction of instrument-related background, and (d) as in (c) but filtered for* SNR *> 0.18. Extracted from Figure 10, Kotthaus et al. (2016).*

the recent hardware generation, i.e. those operating firmware versions 2.xx are clearly superior to older generations.

## Conclusions



Following achievements of this STSM, CL31 observations from SIRTA are now incorporated into the analysis of Kotthaus et al. (2016) and Martial Haeffelin joined the list of authors. In response to discussion and data analysis during this STSM, the near-range correction was improved, the justification of the assumption of a constant background correction below 2400 m was strengthened and conclusions regarding consistency of background profiles were updated. Generally, the STSM contributed significant improvements to the work of Kotthaus et al. (2016).

This STSM demonstrated that the CL31 corrections developed based on LUMO and Met Office data can be transferred to work on other sensors quite easily. Taking into account instrument specific characteristics (related to both hardware and firmware) can clearly improve attenuated backscatter observations of Vaisala CL31 ceilometers. We suggest, a QAQC tool could be developed that would make the proposed corrections easily applicable for other ALC networks.

The results of this STSM and Kotthaus et al. (2016) were presented at the CEILINEX SWG (April 2016) where great interest to test this QAQC tool on a larger scale was recognised. This should be done in the framework of TOPROF (within next 12 months). If we demonstrate the usefulness for an ALC network, there is a potential to apply it to all E-PROFILE.

Sue Grimmond at University of Reading agrees that IPSL could do the work to adapt the QAQC code of Kotthaus so that it can be applied to any CL31/CL51 dataset (in NetCDF produced by RAW2L1). This requires developing configuration files that include input information to execute the code and adapt the output. Then we would test this on the E-PROFILE testbed (about 10 ALCs in Europe).

Further collaboration between IPSL and UoR on the topic of low-visibility events is planned for the future.

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## Confirmation by the host institution of the successful execution

The host institution (IPSL) confirms the successful execution of the STSM by Simone Kotthaus 11-15 April 2016.