SCIENTIFIC REPORT

ACTION: ES1303 TOPROF
MEETING: SWG WG 4
TITLE: Forward models for ceilometer/lidar backscatter
VENUE: Reading, UK
DATE: 27-28 July 2015

Produced by: Cristina Charlton-Perez (Met Office, UK), Sue Ballard (Met Office, UK) and Roland Potthast (DWD, Germany)

Submission date: 30.09.2015

Contribution by: Andreas Behrendt (U. Hohenheim, Germany), Angela Benedetti (ECMWF), Armin Geisinger (U. Hohenheim, Germany), Sue Grimmond (U. Reading, UK), Emma Hopkin (U. Reading), James Hocking (Met Office, UK), Marta Janiskova (ECMWF), Simone Kotthaus (U. Reading, UK), Elliott Warren (U. Reading, UK), Chris Westbrook (U. Reading, UK), Volker Wulfmeyer (U. Hohenheim, Germany).

Introduction

This Special Working Group (SWG) meeting of Working Group (WG) 4 on Data Assimilation (DA) was organised to exchange information between various groups currently working on the design and implementation of forward operators for atmospheric backscatter observed using ceilometers or lidars. This was the first SWG organized by WG 4 with the aim of information gathering on the state-of-the-art for forward models of atmospheric backscatter. The intent was to learn the motivation behind the creation of each forward model and the status of the forward models from each active research group involved in TOPROF. The goal of the meeting was to explore collaboration or cooperation options for future development. Below is a summary of the meeting organised as a summary of the talks and then a set of questions with answers given by the participants.

Summary of Talks

- *Roland Potthast* gave a brief talk that emphasized the importance of improving observation networks that specifically measure variables in the boundary layer. He talked about the difficulties in planning future observation networks from a scientific, technical and organizational point of view and discussed a study at DWD where they performed an OSSE using winds observed at 100 m from wind energy parks.
- *Volker Wulfmeyer* gave a talk called "Towards Seamless Mesoscale Prediction of the Land System for Europe." He talked about multiple observation types and how using sensors synergistically can inform work on turbulence transport theories and turbulence parameterizations (Wulfmeyer et. al., 2015). Volker talked about seamless modeling of the land-atmosphere system and interdisciplinary (meteorology-hydrology) efforts currently underway in Germany (www.caos-project.de). He discussed several data assimilation projects and emphasized the need for direct observations of thermodynamic state of the atmosphere. Finally, Volker brought up the need for research scientists to try harder to drive the demand on instrument manufacturers to meet atmospheric research needs.
- *Andreas Behrendt* gave a talk on the development of two types of lidar at the University of Hohenheim: DIfferential Absorption Lidar (DIAL) and Rotational Raman Lidar (RRL). DIAL operates a laser at two wavelengths 532 nm and 820 nm while the RRL is a UV laser operating at 354 nm. Andreas discussed profiling aerosols with various scanning strategies. The last part of his talk was about using RRL technology to measure temperature fluctuations in the boundary layer (Behrendt et. al. 2015).

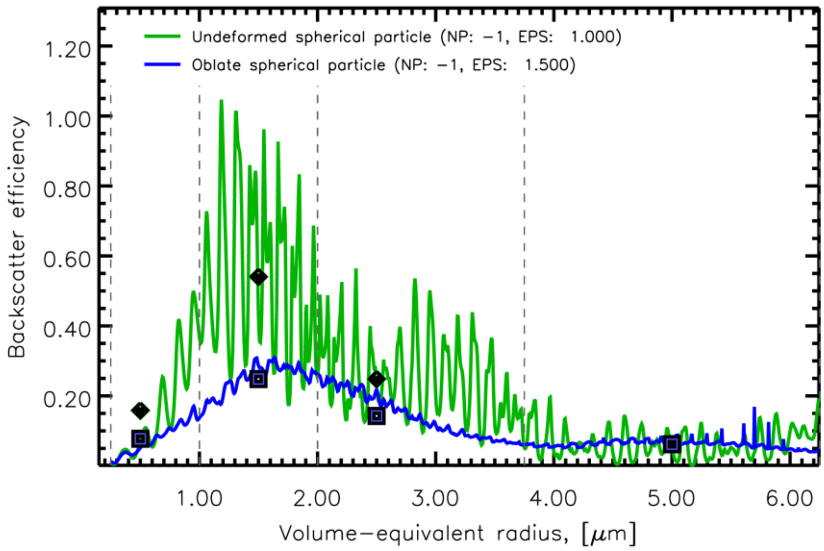
- *Armin Geisinger* talked about the forward model (BaLiFOp) that he is developing to compute model equivalent lidar backscatter. His focus is on aerosols as the scattering particles. Armin presented a case study of the backscatter produced by the ash resulting from the Eyjafjallajökull eruption, in Iceland during April/May 2010. He discussed the studies that he was undertaking to understand the sensitivity of the forward model to the uncertainty of the wavelength of the laser in the instrument and the index of refraction. See Figures 1 and 2. Armin has carried out many tests taking into account the variation of particle shapes and the orientation of the particles.

- *Angela Benedetti* gave a talk about the lidar forward operator in use at ECMWF to compute backscatter due to aerosols. She has developed the operator using the work of J-J. Morcrette and O. Stiller. Angela gave numerous case study examples of difference between observations (both satellite and ground-based) and the forward modeled backscatter.

- *Cristina Charlton-Perez* presented work from the Met Office in collaboration with Ewan O'Connor (FMI) on a forward model for ceilometer backscatter. This forward model considers rain, liquid cloud and aerosol and there are plans to include ice cloud in the future. Cristina explained how the high-resolution UK model inputs were used to create a synthetic backscatter profile and showed examples from the Met Office network of observations for comparison.

- *Emma Hopkin* presented a method for calibrating the ceilometers in a unified way across an observation network, in this case the UK network of the Met Office. Emma's method is based on the O'Connor et al (2004) liquid cloud (stratocumulus) calibration method. She explained how the method filters out unsuitable profiles, such as high aerosol events and drizzle and rain, to ensure only statocumulus cloud, where the lidar ratio is 18.8 +/- 0.8 sr, is used in the automated calibration. For a year of data, results show that the instruments are stable. An example for the Vaisala CL31 at Middle Wallop, UK is shown in Figure 3.

a)



b)

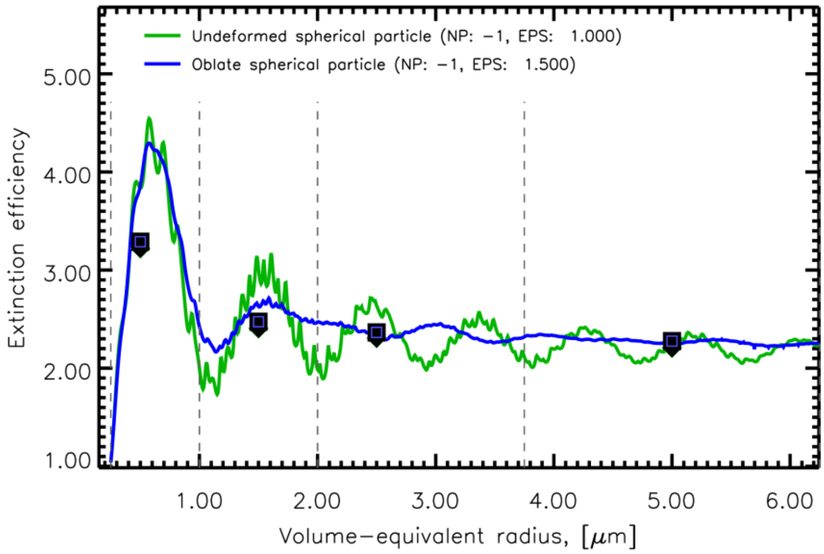


Figure1 Panel a) shows the Mie backscatter efficiency and panel b) shows the Mie extinction efficiency against the volume-equal radius of a scattering particle. The calculation was done with T-Matrix scattering routines from Mishchenko (1996) in double precision arithmetic (See http://www.giss.nasa.gov/staff/mmishchenko/t_matrix.html). The variables NP and EPS are used in the T-Matrix code of Mishchenko to describe the particle. NP=-1 stands for spherical, NP=-2 would be cylindrical and positive values of NP are for Chebyshev particles. EPS is the asymmetry factor

calculated from the ratio of minor and major axes of the particle. A spherical particle with EPS=1 would be a perfect sphere, EPS > 1 is a flat (oblate) ellipsoid and EPS < 1 is a thin ellipsoid (prolate). The refractive index we use here is 1.59-0.004i. The green line is the reference, which is based on a spherical scatterer with an aspect ratio of 1:1 and without edges. The blue line is a sample particle which is in this case an ellipsoid with an aspect ratio of 1.5:1 (a flat ellipsoid). The diamonds and squares represent the respective mean value of each size class where the size class margins are indicated as vertical dashed lines. Interpreting this plot, it seems that especially the backscatter efficiency of a sphere is much higher than that of an ellipsoid if the particle radius is equal to the laser wavelength (1064 nm). This can lead to an over-estimation of the signal within forward operators if spherical particles are assumed for non-spherical aerosols. (Armin Geisinger) a)

b)

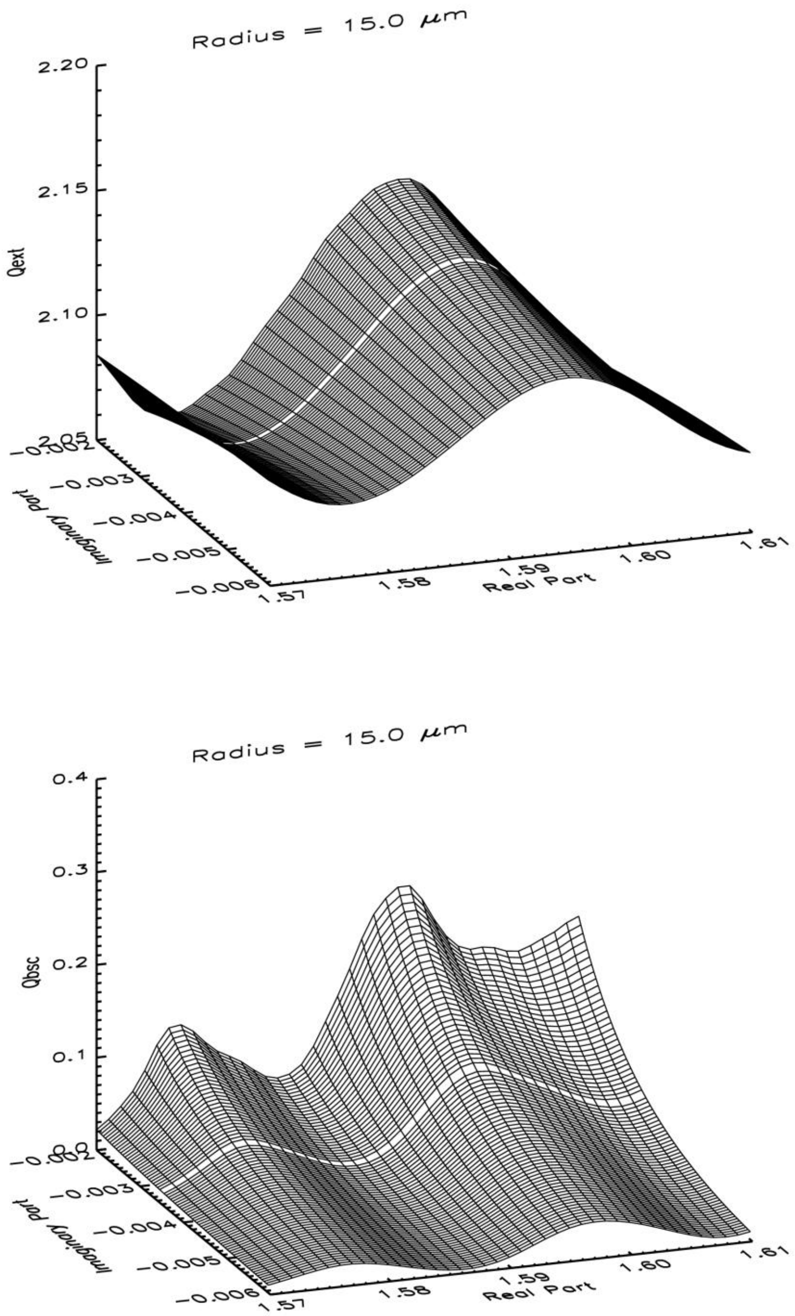


Figure 2 The variability of the a) Mie extinction and b) backscatter efficiency

is plotted on the z axis for a fixed particle radius (15 microns), a fixed laser wavelength(1064 nm), but for a given range of refractive indices where the real part of the refractive index is given on the x axis and the complex part is on the y axis. While the extinction efficiency is relatively insensitive to the refractive index (only some percent difference to the mean), the backscatter efficiency varies between 0.01 and 0.3. (Armin Geisinger)

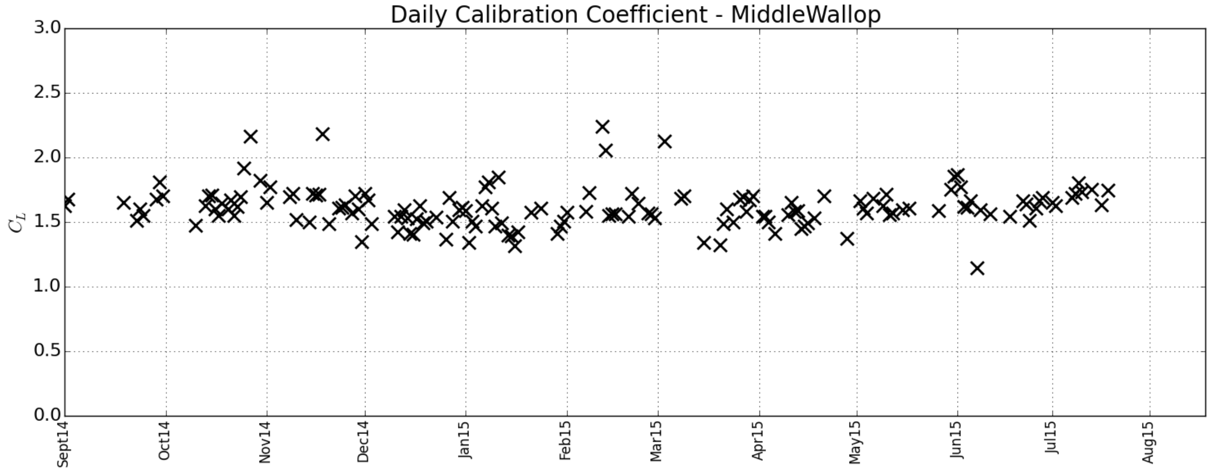


Figure 3. Calibration coefficient (C_L) for Middle Wallop, UK (51.08N, 01.34W), calculated using the liquid water cloud method for the period 01 September 2014 to 31 August 2015. Mean C_L is 1.56 +/- 0.26.(Emma Hopkin)

Outcomes

This section is organised as a list of questions that were posed to the group and the answers or comments gathered during discussions are listed below each question.

1. What is the state-of-the-art in forward models of ceilometer/lidar backscatter?

- First the participants worked to put together a list (in no particular order) of all of the forward models for ceilometer (or lidar) backscatter known to the group at the present time. The forward models listed here are not necessarily operational at the Met Services, but may be research models.
- ECMWF (Cloud and aerosol forward operators are separate. Tangent linear model (TLM) and Adjoint models have been created.) Angela Benedetti and Marta Janiskova.
- Institut für Physik und Meteorologie (IPM), University of Hohenheim in cooperation with DWD (lidar forward operator Aerosol, including volcanic

ash, called "BaLiFOp".) Armin Geisinger, Andreas Behrendt and Volker Wulfmeyer, DWD contact point Roland Potthast

- University of Cologne (lidar forward operator for aerosol, may have TLM and Adjoint models) Hendrick Elbern and Caroline Lang
- Met Office (Ceilometer forward operator. Cloud, aerosol and rain.) Cristina Charlton-Perez, Ewan O'Connor and Sue Ballard
- Météo-France (lidar forward operator is based on ECMWF lidar operator) Bojan Sič and Laaziz El Amraoui
- Institut Pierre-Simon Laplace (ISPL) (lidar forward operator, aerosol, cloud)
- University of Paris-East and Laboratoire des Sciences du Climat et de l'Environnement (LSCE) part of ISPL. (lidar forward operator for aerosol) Wang, Y., Sartelet, K. N., Bocquet, M., and Chazette, P.: Assimilation of ground versus lidar observations for PM10 forecasting, Atmos. Chem. Phys., 13, 269-283, doi:10.5194/acp-13-269-2013, 2013 (http://www.atmos-chem-phys.net/13/269/2013/acp-13-269-2013.html).
- Japan Meteorological Agency (JMA) Aerosol lidar forward model. They have assimilated lidar observations with Ensemble KF in an offline Chemical Transport model (CTM), but have not assimilated lidar observations in their operational NWP. The meteorology for the CTM comes from their NWP model.
- Naval Research Laboratory (NRL) lidar operator for aerosol. Possibly their aim is for assimilation of lidar profiles (CALIPSO) with EnsKF system.
- NASA – Goddard Space Flight Center Lidar operator for aerosol

It was suggested to examine the differences in approach by each research group. Many groups have focused on backscatter due to aerosols; however, only a few groups have considered the backscatter due to clouds and/or precipitation (eg. Met Office and ECMWF). It was discussed that often forward operators are tailored to fit the modelling systems used at the institutes or operational centres; therefore it could be difficult to draw general conclusions from studying the various aerosol backscatter forward models. Are there some obvious commonalities, for example, treatment of the shape of particles, etc.?

Modelling the aerosol and cloud interactions was brought up as an exciting upcoming development. The comments on this topic were that this sort of modeling is still in its infancy and some currently see this interaction as a second-order effect. If you have a good aerosol climatology, then you don't get much of a gain from including these interactive processes. You need to beat the positive effect of the good climatology. However, in limited area models, for example, linking aerosol to the microphysics can improve the simulation of drizzle.

Backscatter due to cloud and aerosol are treated differently by different groups even within the same organisation (eg. ECMWF). Different groups tend to focus on different aerosol types and/or clouds. This will affect choices made on how to forward model the backscatter.

Large numerical fluctuations exist in the extinction efficiencies across particle sizes and there is a dependence of the aerosol backscatter on the complex index of refraction.

Backscatter due to liquid cloud and rain are being forward modeled at the Met Office in addition to backscatter due to aerosol. The motivation for the Met Office work is to improve forecasts of cloud in the high-resolution NWP model by improving the initial conditions for that model. The Met Office high-resolution NWP model only crudely approximates the aerosol content of the atmosphere and does not differentiate between aerosol species during the forecast. Therefore, the forward model for backscatter due to aerosol is a basic one, consistent with the assumptions made in the NWP model.

Attenuated backscatter profiles are needed for use in DA and in other quantitative studies. It is vital to communicate to manufacturers that the best possible measurement of this variable is required.

If High Spectral Resolution Lidar (HSRL) and/or RRL are used, then the extinction and backscatter profiles are delivered separately, so that both are available to be compared to versions simulated by forward operators. We see the need for further investigation in this area.

2. What are the critical issues and which areas need more research and understanding?

- **Calibrated attenuated backscatter** coefficients are needed for use in research and DA. The DA community needs to understand these observations and their associated errors Thus, WG 4 should take note of the results from the Ceilometer Performance Experiment at Lindenberg or CeiLinEx2015 (http://ceilinex2015.de/) and use outcomes from E-Profile. Changes in window transmission and laser power of the ceilometers can affect the magnitude of the backscatter profiles and, therefore, these quantities should be monitored alongside calibration coefficients.

- One issue that was mentioned is that the lidar community has a central calibration facility. "Most lidar calibration standards apply to lidars operating at visible or UV wavelengths (i.e. EARLINET European Aerosol Research Lidar Network http://www.earlinet.org/) and may be partly based on molecular scattering. There will be an ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure Network) (http://www.actris.net/) central calibration facility, but this will be for much more powerful systems operating predominantly in UV/visible wavelengths (they often have a channel at 1064 nm as well)." (Ewan O'Connor, personal communication). Should the same type of central calibration facility be developed for ceilometers?

- **Certification** for the lidar at a given site needs to be updated periodically. This is done by EARLINET for Raman lidar systems. There was a proposal for similar periodic certification for ceilometers. The CeiLinEx2015 intercomparison might be a start for understanding how this might be done. We should listen to what is said at the next E-Profile meeting (21 October 2015, following on from TOPROF meeting).

- There is, potentially, the issue of the **signal saturating in cloud.** The actual peak values of attenuated backscatter are needed for research and DA and not a threshold value that is a maximum value that is essentially determined by the instrument's design. Another issue that is a result of instrument design is the need for overlap correction. Any correction done on ceilometer data due to the overlap must also be made transparent. Could we suggest to Lufft that a 355 nm channel (with rotation Raman channel) be added to the current 1064 nm channel? Such a ceilometer could be set up as a reference system. What are the uncertainties in the system, for example laser power variations and any other changes in gain changes? This may help to supply accuracy and precision for the profiles from a given instrument type. [Request for help from WG1 with this.]

- Ideally, researchers would define the meteorological variables that are products of the instruments firmware/software in **collaboration with the manufacturers**. What is meant by PBL height? Or Cloud base height? We need standardization across manufacturers and transparency of the algorithms and definitions used. [Request help from WG1 with this.] E-

Profile has produced a glossary for lidar and ceilometer terminology that could be a good starting point.

- **A critical issue is standardization**. Different instrument designs demand the signal be processed in a specific way so that the exact same algorithm cannot be applied across all instruments.

- Can a simple lidar be designed with an inelastic channel to measure the **extinction** profile?

3. What are the outstanding issues or problems with models or observations?

Observation-Operator:

- Water vapour absorption at near-IR wavelengths is one issue. The effects of water vapour absorption can be simulated with a forward model using laser diode spectra and expected frequency stability. Alternatively, this effect of water vapour could be treated as an error and not forward modeled.
- For forward models, there is still an open question as to how best to simulate the effects of humidity on the aerosol properties.

Observation Errors

- Need to have better estimates on error or noise from the observations:
  - Detecting weak cloud signal or other weak signal. If the background noise is well-characterised then it may be possible to detect a weaker signal from either aerosol or ice cloud by time or space averaging. Ask manufacturers to produce a well-behaved noise time series alongside the vertical profile of a ceilometer.
  - Assume that noise is uncorrelated between profiles; then estimate errors by computing the autocovariance of timeseries, lag-0 minus lag-1 (Lenschow et. al., 2000)..
  - There should be a standard way to compute the errors.

ART-Model[1]:

- Many assumptions are used in the models regarding particle size distribution, complex refractive indices and particle shape. These

[1] ART=Aerosols and Reactive Trace Gases

assumptions pose challenges for designing forward models of aerosol backscatter. Can we estimate the uncertainties on these assumptions? What range of values that describe the aerosol properties are acceptable or reasonable?

NWP-Model:

- What is the impact of the vertical resolution of our driving (NWP) model (the model providing the inputs to the forward model)? It may be that the higher resolution gives more benefit than a new parametrization. Angela Benedetti's example of the test of a new parametrization to simulate the injection of a smoke plume. Higher vertical resolution of the model appeared to give better performance than a parameterization, reducing the immediate need for the parametrization (Figure 4). However, computing cost is an issue when vertical levels are increased from 60 to 137 vertical model levels, but if the benefits are very positive, it may be worth the move to higher vertical resolution.
- There is a need for water vapour and temperature profiles with better resolution and accuracy. Thermodynamic observations network needed for weather and climate.
- Global model improvements tend to be measured with an emphasis on synoptic scales for example measuring at 500 hPa. Convective scale modeling is more focused on precipitation fields and clouds. We expect to see the benefit of ground-based instruments when measurements and predictions near the surface are taken into account.[2]
- It is considered important that the lidar data are assimilated in a full NWP-aerosol model system in order to take advantage of the information on dynamics in the backscatter data.

[2] See for example Wulfmeyer et al. Rev. Geophys. 2015 (http://onlinelibrary.wiley.com/doi/10.1002/2014RG000476/full) or the OSSE carried out by Declair, Stephan, Reich, Schraff and Potthast (currently in draft mode).

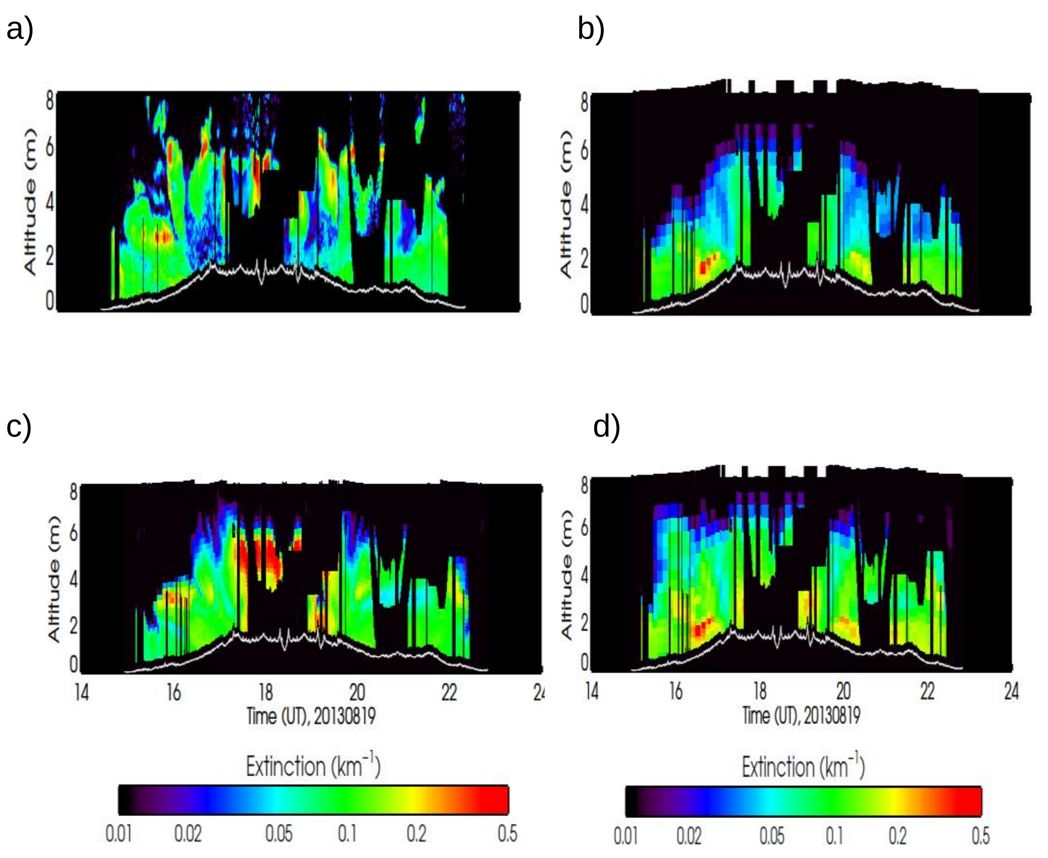


Figure 4. Height-time profiles of ten hours of extinction (km^{-1}) data from DIAL/HSRL observations (panel a). These images were acquired with the DIAL/HSRL airborne lidar that was deployed on the NASA DC-8 aircraft (https://espo.nasa.gov/home/seac4rs/content/SEAC4RS_DC-8_Instrument_Payload) during the NASA SEAC4RS mission (https://espo.nasa.gov/home/seac4rs/content/SEAC4RS) in August-September, 2013. Smoke was observed throughout much of the flight between the altitudes of about 3-8 km and was often mixed with other aerosol (e.g. pollution). The red values of high aerosol extinction were typically associated with smoke. Also shown are three model simulations

b) MACCIII T255 (60 levels), c) MACC-III T1279 (137 levels) and d) MACC-III with plume rise model. Model resolution was increased from T255 (80 km) with 60 vertical levels to T1279 (16 km) with 137 vertical levels. The white line at the bottom of all of the images represents the ground. The higher resolution simulation (c) represents smoke altitude better than a simulation assimilating MODIS (NASA's Moderate-resolution Imaging Spectroradiometer) Aerosol Optical Thickness (AOT) or a simulation using a plume rise model (panel d). (Angela Benedetti, ECMWF; Rich Ferrare and Sharon Burton, NASA Langley.)

Network Design including Politics

- The question was raised how important is it for the meteorological services to develop new observation networks? What about the development of new instruments? How does the network design fit into research agendas, the political agendas, our responsibility to tax payers etc. **Drivers** for network design can also be commercial, for example aviation forecasting.
- The point was raised[3] that there is no **balance** between different networks such as radar and lidar networks. The European Radar network goes forward with dual polarization, but if these data are assimilated then a strong model imbalance could be introduced at initial time due to the lack of knowledge of the thermodynamic environment. This reduces strongly the impact of radar data. How much proof is needed to convince people of the benefits of a European network of ceilometers and other ground-based profiling instruments?
- There has been no organizational or **political pressure** for active and passive ground-based remote sensing to be further developed[4]. Focus has been on satellites. For global models this is understandable, but for limited area models the ground-based networks are important. Even radiosonde launches are being curtailed. Aircraft data is being pushed forward.
- It is important to consider what ground-based observation networks (including which instruments are used and which meteorological variables observed) are necessary to improve convective-scale DA and NWP. For background, the World Meteorological Organisation has published a vision for 2025: EGOS-IP/2025: The Implementation Plan for Evolution of Global Observing Systems, that discusses ground-based networks in Section 5 of the report. (https://www.wmo.int/pages/prog/www/OSY/gos-vision.html). In May 2016, there will be a WMO workshop held in Shanghai, China on the Impact of Various Observing Systems on NWP. This meeting could be of interest to WG4 and the wider TOPROF group. Certainly, the outcomes of that workshop should be considered by WG4 in the future.

---

[3] Several points brought up by Volker Wulfmeyer.

[4] Roland Potthast reports about activities going on at the German Met Service in this direction currently by a steering group on the further development of the DWD measurement network 2015-2025 which includes himself and Volker Lehmann from Lindenberg Observatory, also participant of TOPROF.

Ceilometer Manufacturers and Market

- We discussed the question "how much could we be driving the market for instruments from meteorological point of view?" An example suggested during the discussion was : "Ceilometers have suboptimal performance. Why are the instruments using 910nm, pulsed laser diodes? This is causing the water vapour issue. Lufft is using 1064 nm because the laser transmitter (monolithic Nd:YAG laser) is also commercially available but from another market. Raymetric flash lamps (355 nm) are also sub-optimal because they require strong maintenance efforts and are very inefficient. First Doppler lidar was available due to drive from military. Next came the fiber-based lasers, which were driven by the telecommunication market."
- We did agree that the meteorological community is NOT driving the market currently and that we need to be more active in making our needs and requirements known.
- We agree that the reliability of networks is critical.

4. What are the next steps for each group?

- **Should we be collaborating?** We agreed that we should continue coordinating work at this stage. There are several independent lines of development which reflect the breadth of the topic (clouds, dust, Saharan sand, ash etc). Sharing a summary of techniques and forward models is very beneficial to all of us, as is sharing insight into the literature and current work. We do need to communicate more and will propose another SWG via TOPROF to accomplish this.

- **Is there a specific piece of work that would benefit from a Short Term Scientific Mission (STSM)?** ECMWF (Angela) invites a TOPROF participant to work with her on the ECMWF lidar forward operator, its evaluation, and ideas related to use of profiling with ceilometer and lidars. On task would be to expand the lidar forward operator to the ceilometer frequency from the current CALIOP (**Cloud-Aerosol Lidar with Orthogonal Polarization**) instrument frequency (532 nm) (http://www-calipso.larc.nasa.gov/about/payload.php#CALIOP). This will pave the road for possible applications of ceilometer data in the Copernicus Atmosphere Monitoring Service (CAMS) system.

- **Should we propose another SWG?** Yes, the groups' work would benefit from more frequent communication. Volker, Andreas and Armin have offered to host another SWG at the University of Hohenheim. Suggestions for discussion by the Hohenheim group:

- Discuss the optimization of lidar backscatter forward operators, e.g., with respect to the optical properties of aerosol particles and the representation of different aerosol types.
- Use existing data sets for comparisons with the forward operator outputs in order to test model aerosol microphysics, dynamics, and thermodynamics (model-obs. statistics).
- Propose improvements of existing instrumentation (calibration, simplify data processing, added value of Raman channels, multi-wavelength, etc.).
- Work strongly towards the assimilation of the data of ceilometer backscatter and more complex aerosol lidar systems (eg. add aerosol control variables in DA systems, determination of background error covariance matrices, etc.).

- **Should we make any recommendations to TOPROF?** We suggest that a group from TOPROF (WG1?) visit a manufacturer (Lufft) for a fact-finding mission, carrying out a STSM style visit, with the goal to establish a communication channel between users, network designers and manufacturers.

Conclusions

The meeting was an important step for the groups working on forward operators for ceilometer and lidar backscatter. The area is very diverse and immature. There is much work to be done to perfect the forward modeling as well as to explore observation characteristics and to develop measurement networks. It is important to continue the promising work being done by the TOPROF action. The aim of this meeting was to establish where all the different groups are at present and this aim was achieved.

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

References

Behrendt A., Wulfmeyer V., Hammann E., Muppa S. K., and Pal, S.(2015) Profiles of second- to fourth-order moments of turbulent temperature fluctuations in the convective boundary layer: first measurements with rotational Raman lidar. Atmos. Chem. Phys. 15:5485-5500. DOI: 10.5194/acp-15-5485-2015

Lenschow D. H., Wulfmeyer V. and Senff, C. (2000) Measuring Second- through Fourth-Order Moments in Noisy Data. J. Atmos. Oceanic Technol., 17: 1330-1347.

O'Connor E., Illingworth A. and Hogan R. (2004) A Technique for Autocalibration of Cloud Lidar. *J. Atmos. Oceanic Technol.*, **21**, 777–786.
doi: http://dx.doi.org/10.1175/1520-0426(2004)021<0777:ATFAOC>2.0.CO;2

Mishchenko M. I., Travis L. D., and Mackowski D. W.(1996) T-matrix computations of light scattering by nonspherical particles: A review, J. Quant. Spectrosc. Radiat. Transfer, 55: 535-575.

Wulfmeyer V., Pal S., Turner D. D. and Wagner E. (2010) Can Water Vapour Raman Lidar Resolve Profiles of Turbulent Variables in the Convective Boundary Layer? Bound-Lay Meteorol. 136: 253–284. DOI 10.1007/s10546-010-9494-z

Wulfmeyer V., Hardesty R. M., Turner D. D., Behrendt A., Cadeddu M. P., Di Girolamo P., Schlüssel P., Van Baelen J. , and Zus F. (2015), A review of the remote sensing of lower tropospheric thermodynamic profiles and its indispensable role for the understanding and the simulation of water and energy cycles, Rev. Geophys., 53:1-77, doi:10.1002/2014RG000476.