

An initial assessment of the Robust And Compact Hybrid Environmental Lidar (RACHEL)

A.C. Povey¹, D.M. Peters¹, R.G. Grainger¹, D. Rees², and J.L. Agnew³

¹ University of Oxford, Atmospheric, Oceanic, and Planetary Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom, povey@atm.ox.ac.uk

² Hovemere Ltd., Tonbridge, TN9 1RF, United Kingdom

³ STFC Rutherford Appleton Laboratory, HSIC, Didcot, OX11 0QX, United Kingdom

ABSTRACT

The Robust And Compact Hybrid Environmental Lidar (RACHEL) is a 355nm, 4-channel Raman lidar system that has been developed for unattended, continuous measurement of the distributions of particulates, water vapour, and other pollutants in the boundary layer and troposphere, including the capacity for scanning the full hemisphere. The system has been designed to be portable and low-cost, providing the potential to investigate a wide range of environments with a single instrument.

Deployment at the beginning of 2010 at the STFC Chilbolton Observatory has provided a unique opportunity to cross-compare the instrument against the numerous lidar and radar systems stationed at the observatory and to evaluate the implementation of various measurements into the data evaluation, such as radiosondes, radiometers, and aircraft observations. The system was deployed during the Eyjafjallajökull eruption of April 2010, observing the appearance and evolution of the ash plume over southern England.

1. INTRODUCTION

Aerosols present the greatest source of uncertainty in global climate models [1]. Their rapid variability in both time and space present a measurement challenge that lidar is almost uniquely placed to fulfil. Through the use of Raman lidar techniques, the extinction and backscatter coefficients of an aerosol can be measured simultaneously, providing the capacity to characterise the aerosols [2].

The EARLINET collaboration has demonstrated the advantages of networking lidars to produce wide spatial coverage and allow tracking of features across Europe [3]. However, the cost of an individual lidar system is sufficient that currently the assembly of a high-density, automated lidar network is impractical, despite the significant science gains such a network could provide.

2. LIDAR APPARATUS

The Robust And Compact Hybrid Environmental Lidar (RACHEL), developed by Hovemere Ltd. under a NERC-funded Small Business Research Initiative grant, is a four-channel, coaxial Raman lidar system designed to be portable and automated with the capacity to scan the entire sky. The prototype system utilises a frequency-tripled Continuum Inlite-II Nd:YAG laser (355 nm) operating at 20 Hz with an average pulse energy of 65 mJ and pulse widths of 5 to 7 ns. The



Figure 1. RACHEL deployed at the Chilbolton Observatory in southern England. Reflective insulation has been applied to the surfaces exposed to direct sunlight to improve temperature stability.

beam is expanded by a factor five to a diameter of 35 mm with divergence < 0.3 mrad and is transmitted through a scanning system, which consists of two mirrors mounted at 45° on steerable axes.

The returned signal is collected parallel to the beam line through the scanning system by a commercial Schmidt-Cassegrain telescope with 203 mm diameter primary mirror. The focus of the telescope is coupled directly into an optical fibre, producing a field-of-view of 0.2 mrad. As this is smaller than the divergence of the laser, there is an incomplete overlap between the beam and field, but measurement of the overlap function reveals that it tends to a constant value above 600 m and varies slowly above 200 m, providing excellent low-level coverage.

An optical fibre transmits the returned signal into a sealed unit, where it is separated into four channels by a series of dichroic filters, with an edge filter providing at least 10^{-6} blocking of the elastic signal. These can be easily replaced to investigate different species and are currently assembled to observe the elastic backscatter and the Raman backscattering from nitrogen and water vapour (354.7, 386.7, and 407.5 nm, respectively), with the fourth channel currently unused. Each channel is further refined through an interference filter with 1 nm full-width at half-maximum and blocking in excess of 10^{-6} outside of this range. Beam pipes

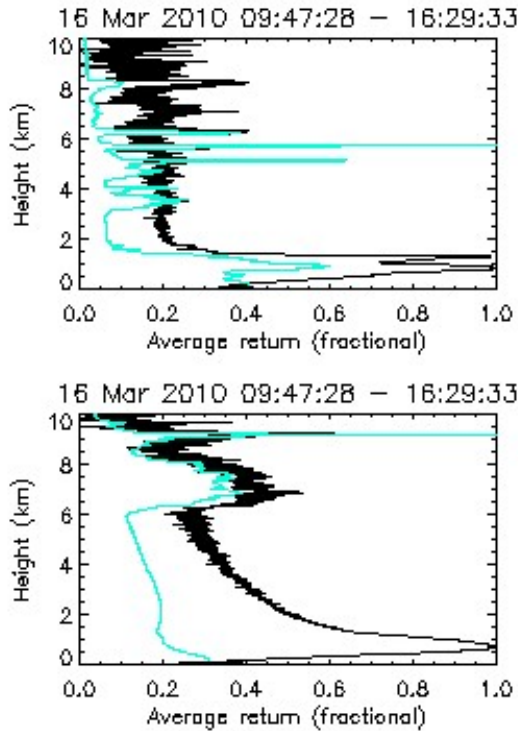


Figure 2. Peak-normalised ABC profiles observed by RACHEL (black) and the Chilbolton UV lidar (blue) for a selection of days. Each profile is averaged across the time period given in the plot title. February 26th was a partly cloudy day with a variety of clouds at all levels throughout the morning observed. March 16th was a clearer day, with tenuous cirrus dissipating over the afternoon. The Chilbolton profiles have been vertically smoothed, but are significantly correlated with the RACHEL profiles in the region above 2 km where the respective overlap functions are not relevant.

are used to restrict cross-talk between the channels.

Photon-counting Hamamatsu photomultiplier tubes measure each channel at a sampling rate determined by the user, with this study using 9 m bin widths, and are generally stored as 10 s averages, giving the freedom to select *a posteriori* an appropriate averaging time to account for conditions. A neutral density filter is installed in the elastic channel to reduce the signal by a factor of four to prevent saturation of the detector at low range. This can be removed to observe the free troposphere, but as the Raman channels are not sensitive beyond 6 km, this mode of operation has not been utilised.

For this study, the RACHEL system has been deployed at the Chilbolton Observatory in southern England (51.1445° N, 1.4370° W, 84 m) [4]. This rural site hosts a variety of instruments operating continuously, including a 905 nm Vaisala lidar ceilometer, the 35 GHz Copernicus cloud radar, a 355 nm Leosphere Raman lidar, a 1.5 micron Doppler lidar, radiometers, and surface meteorology. A higher powered 355 nm Raman lidar system is also operated on a case-study basis. These instruments provide a unique opportunity for calibration and validation of the RACHEL system and for the inter-comparison of different methods of atmospheric characterisation.

3. PERFORMANCE

The performance of RACHEL is assessed by its correlation against the other instruments stationed at the Chilbolton Observatory. These investigations are still underway, but initial results are very promising, with consistent observations through the entire observable range (fig. 2).

The Chilbolton data are presented as attenuated backscatter coefficients (ABC), defined by,

$$\beta_a(r) = \frac{[P(r) - P_B]r^2}{P_0 O(r) \tau_R^2(r)}, \quad (1)$$

where $P(r)$ is the number of photons observed from range r ; P_B is the background photon count due to skylight and dark current; P_0 is the number of photons emitted by the laser; $O(r)$ is the instrument's overlap function; and, $\tau_R(r)$ is the transmission of the atmosphere assuming only Rayleigh scattering, calculated assuming a standard atmosphere [4] from surface measurements (or STP when not available).

The ABC has the advantage of being easy to calculate and being a monotonic function of the input functions, unlike more commonly used measurements of the extinction or backscatter coefficients [2, 6] which also depend on the experimenter-chosen parameters of the algorithm.

We are in the process of assessing various calibration methods and so present data on an arbitrary scale. The Chilbolton group apply the calibration methods outlined in [7]. However, as this is constant in time, it does not present any problems to intercomparison.

Though the dynamic range of the system is limited by the photomultiplier tubes, excellent coverage of the planetary boundary layer (PBL) and lower troposphere is achieved continuously, with measurements significantly greater than noise up to a range of 4 km during the day (7 km at night) for the elastic channel and 2 km by day (6 km at night) for the nitrogen Raman channel over five minute averages. Water vapour measurements are currently under assessment, but reliable signals have been observed up to a range of 2 km at night, though using longer averages. These figures indicate that the RACHEL system is well placed to observe the evolution of the PBL continuously, especially urban pollution.

4. THE EYJAFJALLAJÖJULL ERUPTION

The RACHEL system was deployed during the Eyjafjallajökull volcanic eruption of April 2010 and was used to monitor the appearance and evolution of the ash plume over southern England. A cloud-like feature is first observed at about 1230 UT on April 16th, indicated in region 1 of figure 3, and is seen to descend towards the PBL. These observations are confirmed by other instruments on the site and by *in situ* aircraft observations, with a dark layer about 300 m thick recorded around 6500 ft clearly distinct from the PBL. Measurements of a strong depolarization ratio suggest that the cloud is comprised of volcanic ash opposed to the aerosols normally observed at the site.

Over time, the ash mixes into the PBL, forming a com-

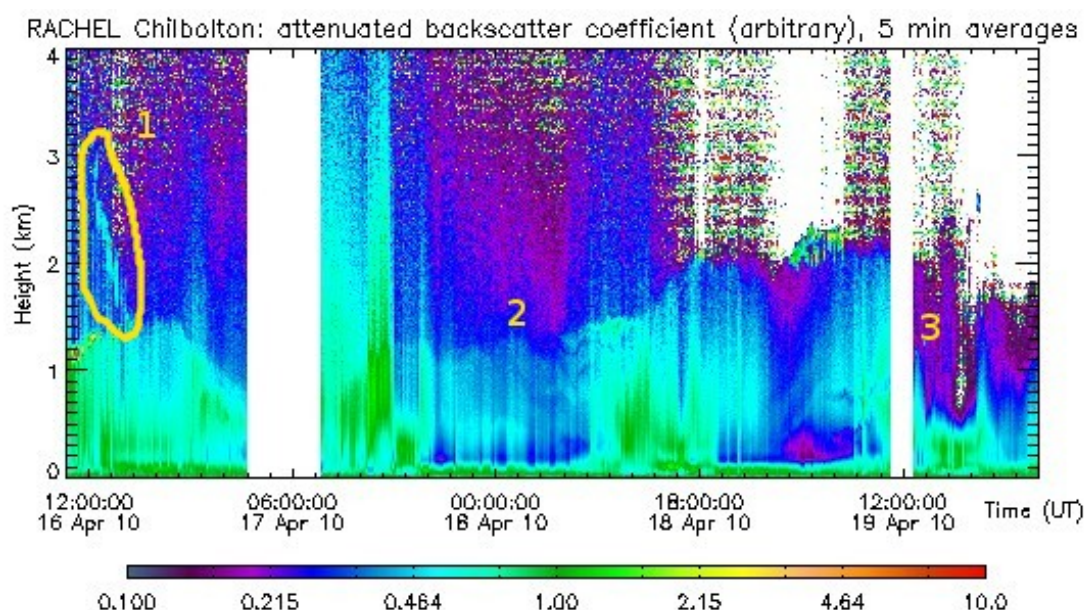


Figure 3. The attenuated backscatter coefficient observed by RACHEL from April 16th to 19th, 2010. Region 1 highlights what is believed to be the initial appearance of the ash plume. A layered structure appears to have formed within the PBL in region 2. The passing of a weak frontal system around midday on April 19th significantly reduces the concentration of ash, evident in region 3.

plex layered structure (region 2). The high density of aerosol present reveals motions within the PBL with a previously unseen clarity, such as the turbulent motions on the morning of April 19th. The density is sufficient that during the ash event, the top of the PBL is difficult to clearly identify.

The ash is observed to be significantly depleted with the passing of a weak frontal system at midday on the 19th (region 3), with conditions returning to the usually observed daily cycle.

5. CONCLUSIONS

The RACHEL system provides a new opportunity for continuous, unattended operation of a Raman lidar system in a range of urban and rural environments with the capacity to monitor aerosols and, potentially, water vapour in the planetary boundary layer and lower troposphere. Simultaneous measurement with a similar lidar system at the Chilbolton Observatory show an impressive degree of correlation between the instruments over most of their range, revealing RACHEL to be a robust and accurate measurement device.

A unique opportunity was presented by the Eyjafjallajökull eruption of April 2010, with extensive measurements from the RACHEL system showing the initial appearance of the ash plume over southern England and its subsequent mixing with the PBL. Over the coming months we aim to develop optimal estimation retrieval algorithms to retrieve high quality measurements of the ash plume with rigorous error analysis, assisted through the assimilation of the multitude of lidar and radiometer measurements available at the STFC Chilbolton Observatory.

ACKNOWLEDGEMENTS

This work is supported by a NERC CASE studentship with Hovemere Ltd. Thanks to J. Lass and S. Harrington for administration, J. Storey for his invaluable instruction, C. Wrench for guidance and support, D. McKay for assistance with data collection, C. Leonard for assistance with the measurements at the end of April, and to everyone else at the Chilbolton Observatory for their patience and conversations.

REFERENCES

- [1] Solomon S., *et. al.*, 2007: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
- [2] Ansmann A., U. Wandinger, M. Riebesell, C. Waitkamp, W. Michaelis, 1992: Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined raman elastic-backscatter lidar, *Applied Optics*, **31(33)**, pp. 7113-7131.
- [3] Amodeo, A., *et. al.*, 2007: Optimization of lidar data processing: a goal of the EARILINET-ASOS project, *Proceedings of SPIE*, **6750**, pp. F7500.
- [4] Science and Technology Facilities Council (STFC), Chilbolton Facility for Atmospheric and Radio Research, [Wrench, C.L.] 2003-2010: Chilbolton Facility for Atmospheric and Radio Research (CFARR) data, [Internet]. British Atmospheric Data Centre. Available from <http://badc.nerc.ac.uk/data/chilbolton/>.

- [5] U.S. Government Printing Office, 1976: U.S. Standard Atmosphere, NOAA-S/T 76-1562.
 - [6] Klett, J.D., 1985: Lidar inversion with variable backscatter extinction ratios, *Applied Optics*, **24(11)**, pp. 1638-1643.
 - [7] O'Connor, E. J., A. J. Illingworth, R. J. Hogan, 2004: A technique for autocalibration of cloud lidar, *Journal of Atmospheric and Oceanic Technology*, **21(5)**, pp. 777-786.
-