# Up in the air

**The ash cloud from the eruption of Icelandic volcano Eyjafjallajökull stranded many across Europe as flights were cancelled. Lidar remote sensing, used in various aspects of atmospheric research, provided crucial data for monitoring the ash cloud, as Greg Blackman finds out**

Those stranded by the ash cloud from Eyjafjallajökull, the Icelandic volcano that grounded flights across Europe, will recall very well the disruptions that that caused to their travel plans. The eruption on 14 April 2010 threw thousands of tonnes of mineral ash into the air, with particles rising 6 to 10km into the atmosphere. As the ash cloud drifted south, European airspace was gradually closed due to fears over safety. The danger was that the fine volcanic ash would melt inside jet engines, which operate at around 1,400°C, and fuse onto and erode the turbine blades – causing the engine to stall. The ash could also potentially blind the pilot by sandblasting the windscreen, meaning the plane would have to rely solely on instruments upon landing.

During the event, national meteorological services under the coordination of Volcanic Ash Advisory Centres (VAACs) and the World Meteorological Organisation (WMO) issued information on the spread of the ash cloud to civil aviation authorities. Ash cloud models developed by the VAACs were used to calculate the movement of the ash in the prevailing winds as well as to predict the dispersion of the ash particles to concentrations where it would be safe to fly. The models incorporate various atmospheric data, along with information from satellites, volcanic observatories and other weather radar data. The VAACs and the WMO were also in daily contact with lidar research networks, including EARLINET, the European Aerosol Research Lidar Network, which was established in 2000 for tropospheric aerosol studies and currently operates 27 advanced lidar stations distributed across Europe.

'Lidar data was used in combination with the satellite and other data to achieve an accurate picture of the ash cloud,' states Dr Gelsomina

**The Karlsruhe Institute of Technology research station, located on Mount Zugspitze, Germany, operates a lidar system for atmospheric measurements with an excimer laser from Coherent.** Image courtesy of Coherent

Pappalardo, coordinator of EARLINET and a researcher at the Institute of Methodologies for Environmental Analysis (IMAA) at the Italian National Research Council (CNR). Pappalardo and colleagues at EARLINET presented lidar data collected over the course of the eruption at the SPIE Remote Sensing conference, which took place in Toulouse, France in September 2010.

EARLINET performed almost continuous measurements of the volcanic plume over Europe for the duration of the event, initially as part of its standard atmospheric monitoring. 'Lidar is the only technique for providing information on the altitude of the ash cloud in the atmosphere,' explains Pappalardo. 'Satellite data can be used, but assumptions have to be made on the altitude. This is a critical point for air traffic, because you need to know where the plume is.'

Using advanced lidar systems, the ash plume could be distinguished from other particles in the atmosphere that aren't dangerous for air traffic. Lidar also provides valuable information for research aircraft that were deployed by the VAACs and the WMO to gather in situ evidence, which in turn was used to corroborate and calibrate the lidar and model data and provide an assessment of absolute ash density values.

Lidar operates through shining a laser into the atmosphere and collecting the photons scattered by the particles and molecules present. The main scattering process used for atmospheric investigations is Rayleigh scattering from molecules or Mie scattering from particles. Raman scattering can also be used to identify specific atmospheric compounds. Using Mie and Raman techniques, information on extinction and backscatter can be collected independently. By generating this information at different wavelengths, different aerosol types can be distinguished through their spectral behaviour. In addition, the shape of the particle can be derived by using lidar depolarisation observations. In the volcanic eruption, a lot of large and non-spherical particles were observed, which were characteristic of the ash cloud, allowing researchers to identify and track the plume.

'An advanced lidar system [multi-wavelength Raman lidar, for instance] can provide quantitative information with error bars, which is very important when providing data that will be used by the authorities, as in the case of the Icelandic volcano,' Pappalardo notes.

'It's important to work with satellite data, because there cannot be lidar systems positioned everywhere,' continues Pappalardo. 'It's a wonderful technique, especially the multi-wavelength Raman lidar technique. On the other hand, if it's raining: no measurements.'

Pappalardo states that when the volcano erupted EARLINET was unprepared for the scale of the monitoring task. EARLINET is not an operational lidar network providing continuous measurements, but a research network recording advanced observations for long-term monitoring of aerosol distributions over Europe. She says that there is a strong need for such an operational network and that there is also still a lot of research needed in order to improve the characterisation of aerosol microphysics.

## Ozone monitoring

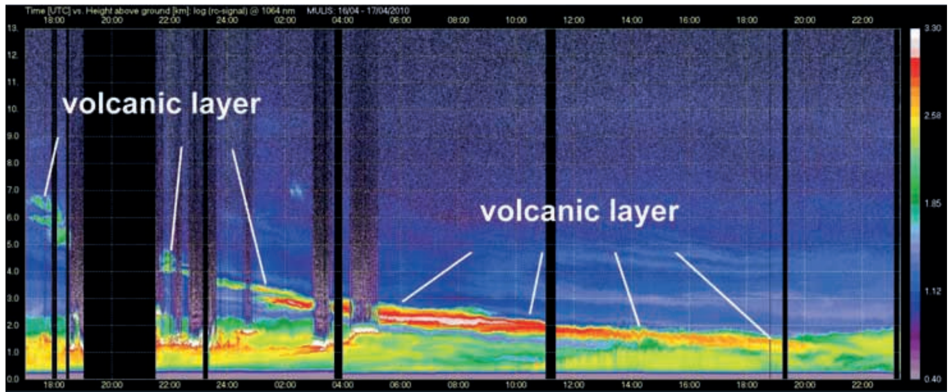
In the majority of cases, lidar stations are connected in networks and are positioned strategically across the globe. The data is woven together to provide a global picture of atmospheric phenomena, such as stratospheric ozone depletion. The international Network ➤

for the Detection of Atmospheric Composition Change (NDACC), for instance, was established in 1991 and composed of 70 remote-sensing research stations. It monitors changes in the stratosphere, including long-term studies of ozone levels.

The Institute for Meteorology and Climate Research – Atmospheric Environmental Research at the Karlsruhe Institute of Technology has installed an excimer laser system from Coherent as part of its lidar system for atmospheric monitoring, which includes water vapour measurements. The research station is located on Mount Zugspitze, the highest point in Germany, to avoid disturbance from ground fog or low-lying local pollution.

Ozone absorbs in the UV, and excimer lasers operating at 308nm provide high enough output power (up to 300W is typically used) to make high-altitude, stratospheric ozone measurements. Dr Ralph Delmdahl, product marketing manager, excimer business unit at Coherent, comments: 'For ozone mapping, lasers need to have a high pulse energy and high repetition rate to increase the signal-to-noise ratio of the measurements.'

Delmdahl adds that excimer lasers are also now much more reliable, with long gas and optics lifetimes. 'The lasers are now industrial pieces of equipment and the same excimer lasers at 308nm for lidar systems are also used in mass production of flat panel displays, for example. A 500W excimer laser in industrial production, for instance, can today be in constant operation for one year without replacement of spare parts. Many lidar systems are still using older laser technology; modern excimer lasers offer the incentive of significantly higher power and significantly higher uptime for these systems.'




**Lidar data taken from the EARLINET station in Munich between 16 and 17 April 2010, showing altitude changes of the volcanic ash layer over time.** Image courtesy of Matthias Wiegner, University of Munich

Lidar covers various different techniques based on the same remote sensing principle of detecting and analysing the scattered radiation. DIAL (Differential Absorption Lidar) is one method for measuring ozone. Two wavelengths are transmitted: 308nm directly from the eximer laser, which is strongly absorbed by ozone, and 353nm light generated through stimulated Raman processes in a Raman cell, which is less strongly absorbed. Both wavelengths are emitted collinearly. By comparing the signals from the two wavelengths, the concentration of ozone can be determined and a vertical ozone profile generated, i.e. the ozone concentration against altitude.

Raman lidar is often used to monitor spatial and temporal water vapour fluctuations. This involves emitting 308nm light into the atmosphere and collecting the backscattered photons, some of which will be Raman-shifted light from water vapour at 347nm and from nitrogen at 332nm. The ratio between the hydrogen signal at 347nm (from the water vapour) and the nitrogen signal provides the fraction of water vapour present, known as the water vapour mixing ratio. The wavelengths denote the molecule and from the time delay of the backscattered radiation the altitude can be calculated.

Along with the laser light source, the detector is an important component in a lidar system. Stuart Nunn, technical sales engineer at Laser Components, notes: 'Over long distances the returning signal from the media or surface is generally very weak, so the detector requires a high signal-to-noise ratio SNR.'

Laser Components supply pulsed laser diodes (PLDs) and avalanche photodiodes (APDs) that are used in various lidar systems. 'The rise and fall time of the detector, which is the time taken for incident light to produce an electrical signal, needs to be short,' Nunn says, adding that a narrow bandpass filter can also improve the SNR by optically filtering out background radiation.

## Wind speed measurements

Lidar systems can also be used to measure wind speed, in wind farm development surveys for instance. Researchers at the National Center for Atmospheric Research (NCAR) in the US have developed a novel lidar system for conducting wind speed measurements onboard a jet aircraft at high altitude. 'We're trying to measure very accurately, on the order of a few tenths of a metre per second, vertical and horizontal wind speeds for meteorological and atmospheric science research, from an in-flight aircraft,' explains Dr Scott Spuler, research engineer at NCAR. Typically, pressure ports on the aircraft would be used to measure wind speed. However, as the sensors are positioned on the skin of the aircraft, they're susceptible to accuracy errors due to the

## 3D MAPPING

Lidar mapping is now a valuable tool for surveyors to generate high-definition 3D images of an environment. Mandli Communications, a US company specialising in roadway infrastructure data collection and analysis, is using lidar systems from Velodyne onboard its surveying vehicles to take accurate measurements of highway structures for various departments of transport.

Velodyne's lidar sensor has a rotating head with 64 lasers, each firing up to 20,000 pulses per second. More than 1.3 million data points are generated per second providing a dense point cloud in which objects like overhead wires can be identified at distances of 100m.

The resolution of the Velodyne's HDL-64E lidar system allowed Mandli vehicles to scan the environment at motorway speeds, a big benefit to highway departments surveying bridges, for instance, as previous methods would require a motorway lane to be closed. The system generates a virtual 3D map of the area, which the user can navigate through. Height clearance data for multiple lanes of traffic passing through bridges can be determined from a single pass of the surveying vehicle, something that would, in the past, have had to be obtained manually and involved closing lanes of traffic. Other features, such as signs and road markings, can be identified.

Velodyne's lidar technology was originally developed as part of the US Defense Advanced Research Project Agency's (DARPA) Grand Challenge, in which contestants were tasked with developing autonomous vehicles to navigate different terrain. High-definition lidar was one of the sensors employed by some teams, along with other sensor data, to produce a digital view of the vehicle's surroundings.

flow distortion created by the plane – levels of accuracy of around 1m/s can be achieved. 'This might be good enough for some studies, but it's not accurate for quite a lot of the things we'd like to do in terms of atmospheric science,' states Spuler.

Vertical winds are used for eddy flux measurements. The research teams are typically trying to find out about the exchange of different trace gases, such as $CO_2$ and water vapour, in the atmosphere. Horizontal wind velocities measured to a few tenths of a metre per second with the lidar system, are useful for understanding mesoscale phenomena, including understanding flow patterns in pre-storm environments, land-breeze circulations, and how the atmosphere flows over mountains.

The NCAR system is not a traditional lidar ranging device, but has a single range-gate using a CW fibre laser from NKT Photonics as a seed. Most lidar systems use a pulsed laser to record the time delay of the backscattered radiation. In this case, the system provides a single range-gate measurement by focusing the beam at around 30m distance, beyond the flow distortion of the plane.

Using a focused CW laser system has the benefit of faster averaging. 'One of the real challenges is getting accurate lidar measurements at high altitudes, which is something the technology is only just allowing us to do,' comments Spuler.

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The system relies on the Doppler Effect from light scattered from aerosols – the wind speed can be calculated from the Doppler frequency. 'This is relatively easy to do on the ground where aerosol concentrations are high, but aerosol concentrations at 40,000ft are up to two orders of magnitude lower,' Spuler says. Therefore, the system has to carry out a significant amount of averaging – typically around 200,000 spectra are averaged for a one second measurement.

'Five Watts of CW laser power is really what enables us to make the measurements from the plane [at high altitudes],' explains Spuler. For this Doppler system, Spuler says a single frequency laser was required that had very low noise with no other sidebands. NKT Photonics supplied the seed laser operating at around 20mW, which was amplified to 5W. 'You really need to start with a very pure laser frequency,' continues Spuler. 'Otherwise, there is contamination and if you're trying to look at these other frequencies you'd see broad noise signatures just from the laser itself and you'd never be able to pick up the wind speeds. NKT's lasers are often used for Doppler lidar systems, because they are so low noise and single frequency. They're very useful for that.'

To date, the research team has conducted around 13 test flights with the laser pointing straight in front of the aircraft in order to measure true air speed. 'The system worked well and we were able to get some signal return at 41,000ft in clear air,' states Spuler. In the next stage of development, still currently ongoing, there will be lasers emitting at different angles allowing vertical and horizontal wind velocities to be identified.