Toward an observation of volcanic ash: which kind of observation can be made by different instruments and how to design a network

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Abstract

The 2010 eruptions of the Eyjafjallajökull (Icelandic volcano) resulted in one of the greatest air traffic disruption in Western Europe with 107,000 flights cancellations during an 8-day period, accounting for 48% of total air traffic and roughly 10 million passengers. The estimated cost of this European controlled airspace shutdown is about € 1.3 billion according to the International Air Transport Association (IATA).

London Volcanic Ash Advisory Center (VAAC) was responsible for providing information about the ash plume to the relevant civil aviation authorities in the form of Volcanic Ash Advisories (VAA). On this basis, the authorities made decisions about when and where airspace should be closed due to the safety issues.

It was difficult for the VAAC to provide accurate information about the size and concentration of the volcanic particles. As a result, Toulouse VAAC asked Météo-France to find solutions to detect volcanic ashes from the ground to a 12km altitude and to assess their concentration.

Météo-France conducted an intercomparison campaign between several lidars and ceilometers during summer 2012 in order to assess their ability to detect aerosols dust for lack of volcanic ashes. The observations produced by the instruments are obtained thanks to several algorithms: STRAT from SIRTA and BASIC from the LOA (both French laboratories). It turns out it was difficult to compare the data with one another for several reasons: there is no aerosol measurement reference, instruments have different wavelengths, they can be dual-polarized.
Results show the aerosols lidar technology may be a good mean to meet the VAAC requirements.
Moreover, having the desire to built an efficient network in terms of number and location of sites over metropolitan France, Météo-France has run a model of pollutant dispersion, named MOCAGE, in retro-plume mode with different configurations in order to define the network which provides the best coverage.

This paper describes how the intercomparison was conducted, the processing algorithms used, the difficulties encountered and the method used to design an optimum volcanic ash detection network.

1 Background and motivation

Eyjafjallajökull (Icelandic volcano) erupted from March 20th 2010 to June 23rd 2010 with a most intense phase between April 14th and April 29th. The volcanic ash cloud spread all over Europe and the Northern Atlantic and reached up to a 6 km altitude above mean sea level.

The consequences on air traffic were huge: more than 107,000 flights were canceled during an 8-day period, 10 million passengers were stuck in airports. According to the International Air Transport Association, the loss for airline industry was around € 1.3 billion.

Among the nine Volcanic Ash Advisory Centers (VAAC), London VAAC was responsible for providing information about the ash plume because the Eyjafjallajökull was located in its area of responsibility. Toulouse VAAC was active in the background. It was very difficult to provide accurate information about the ash plume because of a lack of observations.

As a consequence Toulouse VAAC asked Météo-France to find solutions to detect and identify volcanic ashes from the ground to a 12 km altitude above mean sea level and to assess its concentration (VAAC thresholds are 0.2, 2 and 4 $mg.m^{-3}$)

The instrument chosen because it fulfills the VAAC requirements is the LiDAR (Light Detection And Ranging). The operating principle consists in a light emission in the atmosphere from the emission part of the lidar. This light interacts with all atmosphere components such as clouds, aerosols, etc. by being absorbed or scattered. A very small fraction of the initial light is backscattered to the lidar in the detection part of the instrument where it is quantified, digitalized and sent to an acquisition computer (Figure 1)

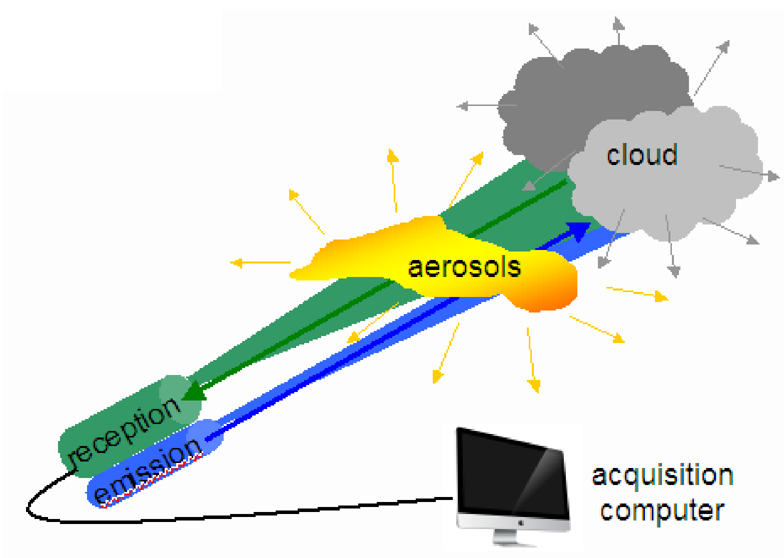


Figure 1 : ***Operating principle of a LiDAR*** *: a light is emitted in the atmosphere from the emission part of the lidar. A very small fraction of the initial light is backscattered by clouds and aerosols to the lidar in the detection part of the instrument where it is quantified, digitalized and sent to an acquisition computer.*

To fulfill the VAAC requirements, it was necessary to assess the lidars existing on the market. Questions were the following:

- Are existing lidars and ceilometers operational? Are they robust, easily deployable and maintainable?

- o What characteristics are needed? Dual polarization? Raman N_2 channel? Which wavelength ?
- o Can ceilometers, used to measure cloud base height, meet the requirements?

As there is no standard to define the range and the quality of a lidar, we decided to assess in situ the various instruments available on the market in order to find the best answers to these questions.

2 Needs to set up an intercomparison campaign

When it was decided to set up an intercomparison campaign, Météo-France faced the following questions and problems :

- o How to choose the site ?
- o How to compare the instruments? Is it possible to find a reference measurement ?

Following the advice of French laboratories and manufacturers, it was decided to compare lidars and ceilometers with a powerful research lidar in reference (to get a similar but more accurate measurement) and with plane and radiosounding in situ measurements.

Regarding the site selection, it is important to note that, usually, a test instrument is accomplished by evaluating its ability to measure the parameter one wants to measure. In the case of lidars, our goal is to detect volcanic ash but this aerosol type is rarely present - fortunately! - in the atmosphere. Thus, a site where regular passing desert dust takes place - a particle with characteristics similar to volcanic ash – was preferred. It was also considered important to choose a site with moderate cloud cover, because a lidar or a ceilometer cannot properly measure beyond a cloud if it is too thick.

Besides, to face expected and unexpected events during the campaign (data dissemination problems, laser or PC crashes, daily monitoring, …) a site with easy access for teams which take care of the instruments was selected.
Last but not least, the site choice was conditioned by the possibility to get the necessary authorizations: laser emission license for the lidar reference (that may be not eye-safe), and flight authorization for plane and balloons.

Before the campaign, and in addition to the technical preparation of the site, the administrative aspect of the provision of the instruments was prepared: loan, rent or purchase. It may be noted that human resources needed during and before the intercomparison were underestimated.

3 Météo-France 2012 intercomparison campaign

The intercomparison campaign was carried out in 2012, from March to August.

The campaign was conducted on two sites:

- Toulouse, which is experiencing episodes of dust and which benefits from the presence of staff (Toulouse is the main center of Météo-France)
- Candillargues, for which licenses could be obtained (licenses to fly and to emit laser light)

In Toulouse, four lidars and three ceilometers were assessed, working in UV, green and IR. A photometer was also assessed, in order, firstly to compare the AOD (Aerosol Optical Depth) measured with the AOD calculated by the lidars, and secondly to assess the value of such an instrument combined with a lidar (Figure 2).

Figure 2 : the photometer assessed in Toulouse, 2012

A large area without building was selected (Figure 3), firstly to allow the photometer to make measurements in good conditions – a photometer has to be able to follow the sun at anytime - , and secondly to install the instruments far enough from people.

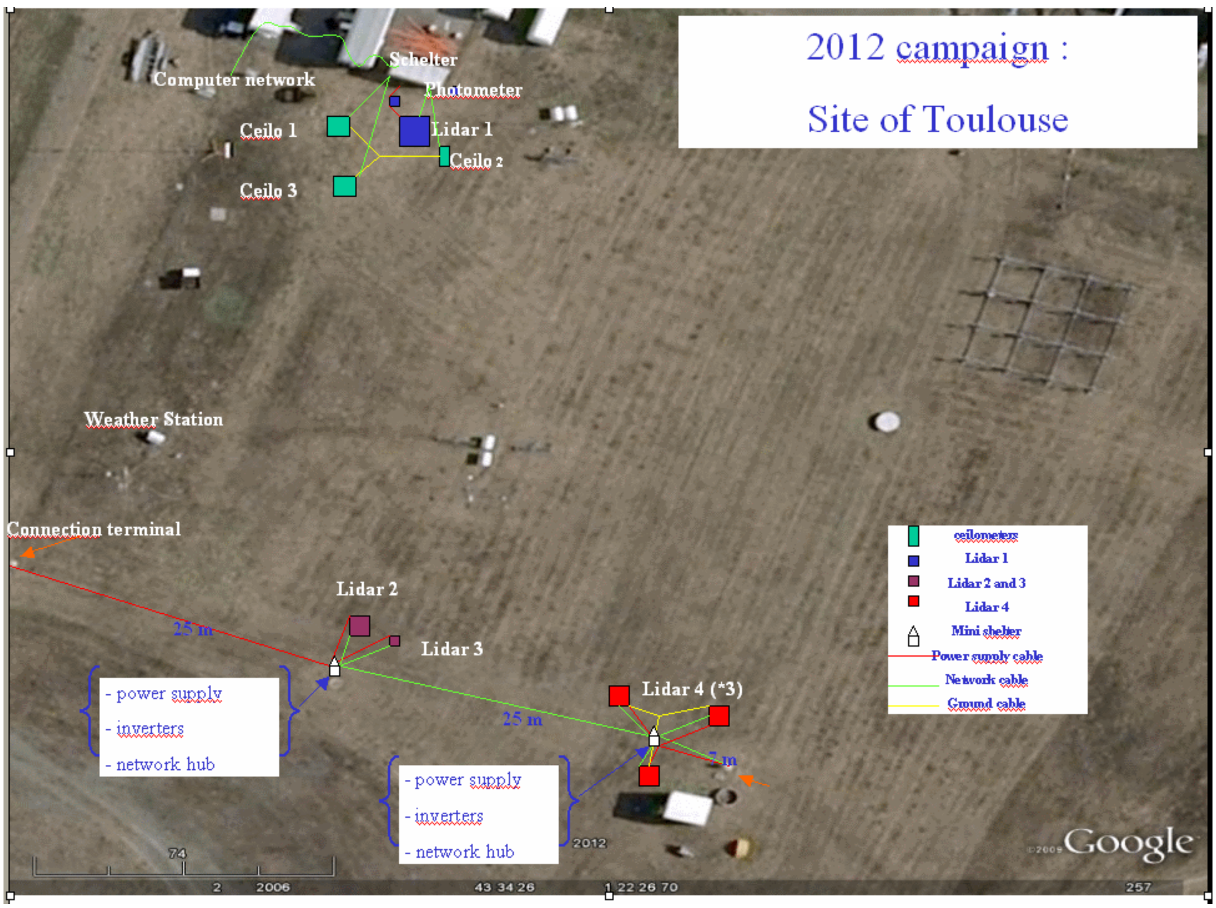


Figure 3 : *site in Toulouse with a large area to allow the photometer to make measurements in good conditions, and to install the instruments far enough from people.*

In Candillargues, a lidar already tested in Toulouse was moved there and compared to a powerful research lidar MOBILIS (Figure 4), from the IPSL (Institut Pierre Simon Laplace, France) institute : a multi-wavelength lidar with a Raman N_2 channel.

Figure 4 : IPSL MOBILIS lidar *(Institut Pierre Simon Laplace, France), multi-wavelength and Raman N_2 channel, used as a reference during the 2012 intercomparison carried out by Météo-France.*

Flight measurements were also conducted, thereby allowing to know the presence and the concentration of particles thanks to a Condensation Particle Counter (CPC).

Figure 5 : Condensation Particle Counter, on the ATR42-SAFIRE plane, *allowing the detection and the counting of particles by enlarging them, using the particles as nucleation centers to create droplets*

The aircraft (ATR42 from SAFIRE, France) probes the atmosphere by making turning flights in the shape of a hippodrome (Figure 5)

The LOAC radiosonde (distributed by French companies Environnement SA and Modem) was also able to make in situ measurements in Candillargues (Figure 6).

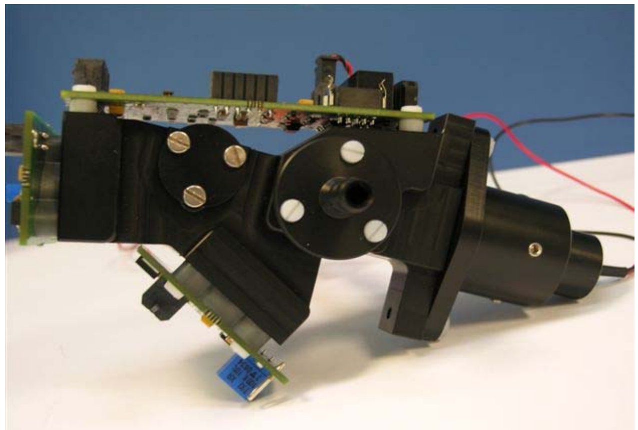


Figure 6 : part of the LOAC radiosonde : *size and nature of the particles estimation*

This sensor emits a laser beam whose scattering on the particle is measured from two angles: 12° (scattering independent of the nature of particles) and 60° (scattering dependent of the nature of particles). The combination of these two measurements allows a precise estimation of the size distribution and the nature of particles.

The significant cost of this radiosonde requires three people, for the launching and the monitoring, and two specific softwares : a first software to program the drop of the radiosonde at a fixed altitude (to avoid the radiosonde going to far) and a second one to predict the path of the radiosonde and to track it in order to get it back before radiosonde hunters.

On both sites, Météo-France used data from Mocage, Météo-France chemistry and transport model, in order to forecast the presence of dust and determine the best time to fly LOAC and aircraft simultaneously. This information was supplemented by the use of satellite images.

4 Data collection

Due to security or practical concerns, some lidars were not connected to Météo-France network. Others were only connected to a local network. Consequently, data were retrieved on a daily basis with a USB key. Moreover, manufacturers, without internet access, were not able to control data in real time, except for one lidar that disseminated data by using an USB 3G internet key.

Data were stored in a PC connected on the local network. A backup copy was made on another PC on a weekly basis. Data were finally stored on Météo-France fileserver.

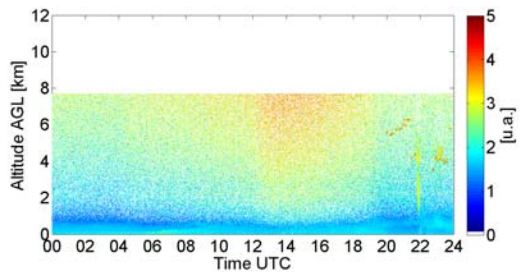
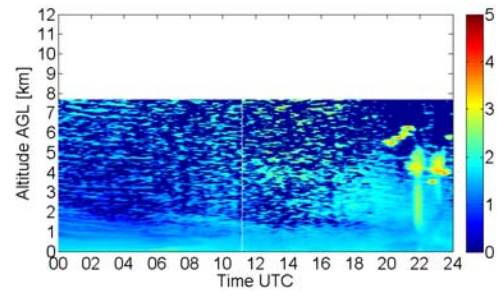
5 Algorithms

Météo-France decided to use its own technical resources in order to analyze objectively the datasets. Météo-France did not want to depend on the manufacturers software because it is often impossible to know exactly how they deal with the data (corrections, algorithms, etc.). Moreover, the file formats are very different from one manufacturer to another: binary, ASCII, NetCDF, etc. As a consequence, we used different algorithms to retrieve and visualize lidar data in the same way They all come from French laboratories.

STRAT (STRucture of the ATmosphere) is one of them (Morille et al., 2010). It has been developed by the SIRTA[1] (Site Instrumental de Recherche par Télédétection Atmosphérique). After converting raw data formats into NetCDF files, STRAT is designed to retrieve the vertical

[1] http://sirta.ipsl.fr/

distribution of cloud and aerosol layers in the boundary layer and the free troposphere, to identify particle-free regions above the instrument and the range at which the lidar signal becomes too attenuated for data exploitation, from either single or multi-wavelength lidar systems. STRAT allows smoothing the lidar signal and making a classification (cloud, aerosol and molecular layers) (Figure 7)

<table>
<tr><th></th><th>Input Data</th><th>Output Data</th></tr>
<tr><td>Smoothing 27/06/2012 - Toulouse, France</td><td>
</td><td>
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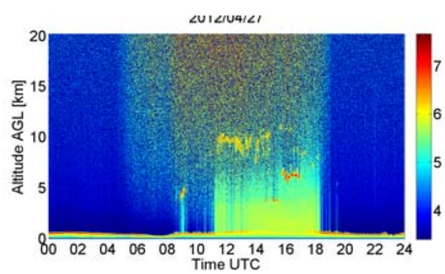
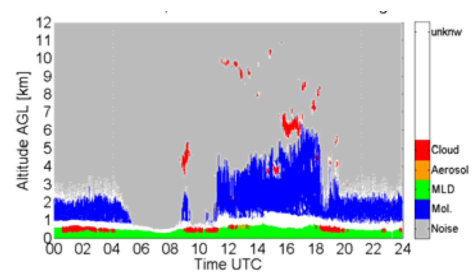
<tr><td>Classification 27/04/2012 -Toulouse, France.</td><td>
</td><td>
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Figure 7 : examples of STRAT algorithm output data. *Example of very noisy data taken from a ceilometer in Toulouse on June 27th 2012 (top left corner). Same data but smoothed with STRAT algorithm (top right corner). Example of lidar raw data above Toulouse on April 27th 2012 (bottom left corner). Classification applied with STRAT algorithm (bottom right corner): cloud, aerosol, molecular, mean layer depth, noise and unknown.*

BASIC (Mortier, 2013), another algorithm developed by the LOA[2] (Laboratoire d'Optique Atmosphérique), is useful to calculate aerosols backscatter and extinction coefficients and massic aerosols concentrations with an uncertainity of 40% (Figure 8).

	Input Data	Output Data

[2] http://www-loa.univ-lille1.fr/

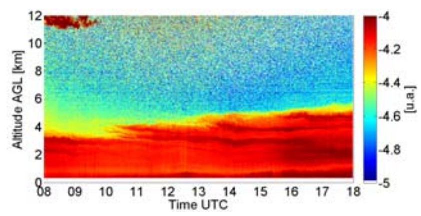
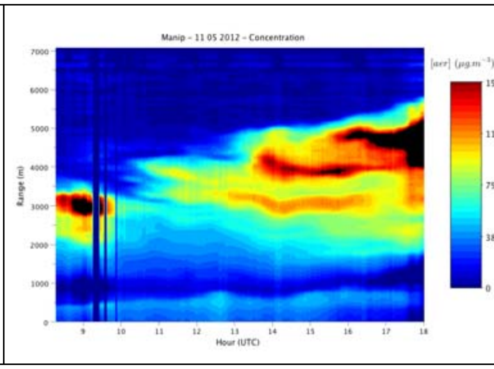
Aerosol massic concentration (05/11/2012 – Toulouse, France)		

Figure 8 : example of BASIC output data. *Example of a range corrected signal from a lidar in Toulouse, France on May 11st 2012 (left) and the corresponding aerosol massic concentration computed by BASIC algorithm (right).*

6 Results

The data analysis is mostly based on the visualization of lidars range corrected signal.

6.1 Example: 06/27/2012 – Toulouse, France

On June 27th 2012, an aerosol event occurred above Toulouse, France. Saharan dust was carried away in mid-troposphere resulting in a yellowish sky from midday in Toulouse with higher AOD values (0.6 at 532 nm) and smaller ångström coefficient (Figure 9) (A thicker AOD means there are more or/and bigger aerosols in the atmosphere; a smaller ångström coefficient means that aerosols are bigger)

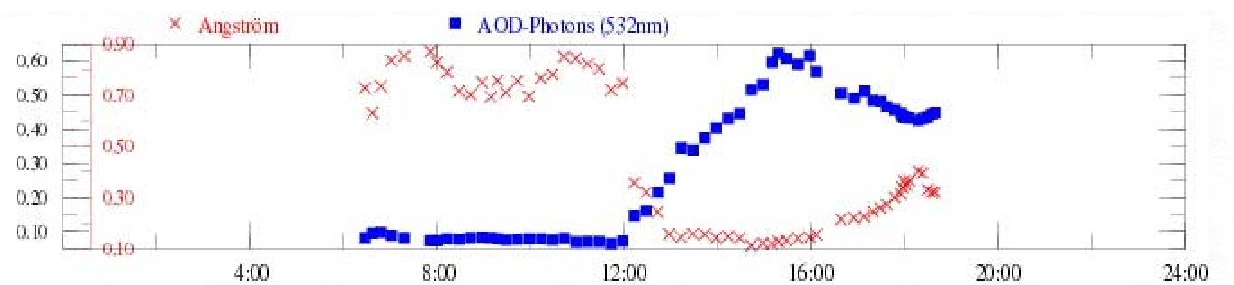


Figure 9 : AOD (532 nm) and ångström coefficient in Toulouse, France - 06/27/2012. *The dust event started around midday with higher AOD values and lower ångström coefficient (bigger particles).*

One can notice the correct MOCAGE[3] aerosol concentration forecast compared to a lidar observation (Figure 10)

Observation	Forecast

[3] Météo-France atmospheric chemistry numerical model

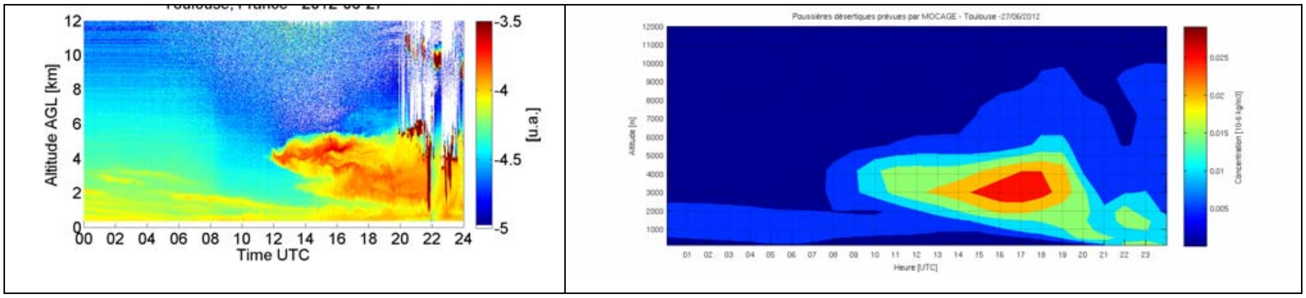


Figure 10 Comparison between observation and MOCAGE forecast of the aerosol plume above Toulouse, France on June 27th 2012. *(left) Lidar data above Toulouse, France on June 26th 2012 and (right) MOCAGE aerosol concentration forecast. Good correlation between observation and forecast*

The French intercomparison of lidars and ceilometer in 2012 showed interesting features, on the 27th of June and the other days when we had chance to observe sand dust :

1. By using the same software, we were able to note great differences between lidars and ceilometers in their ability to detect aerosol layers as it can be seen in Figure 11. Clouds and shower at 22 UTC are clearly visible on both instruments but only the lidar is able to highlight the aerosol layer overnight and the big aerosol layer that overlaid Toulouse at 12 UTC.

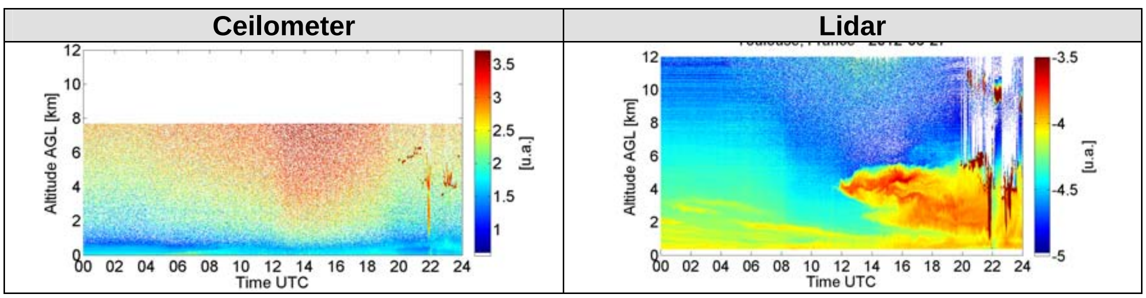


Figure 11 Comparison between ceilometer (left) and lidar (right) in Toulouse, France on June 27th 2012. *One can see that the ceilometer data are very noisy whereas lidar data showed interesting features such as an important aerosol layer at midday in mid-troposphere.*

2. In the infrared, at the power of the tested ceilometers, the molecular signal range is weak. Therefore, it is hard to calibrate the lidar on the molecular signal in an aerosols free layer.
   In the UV, molecules are the main component of the lidar signal (aerosols may be less well seen).
3. It is difficult to compare instruments because of their very different technology (wavelength, laser energy, detection mode, etc.)
4. Double polarization (parallel and perpendicular channels) gives information about the sphericity of the particle.

6.2 Example: 10/12/2012 – Candillargues, France

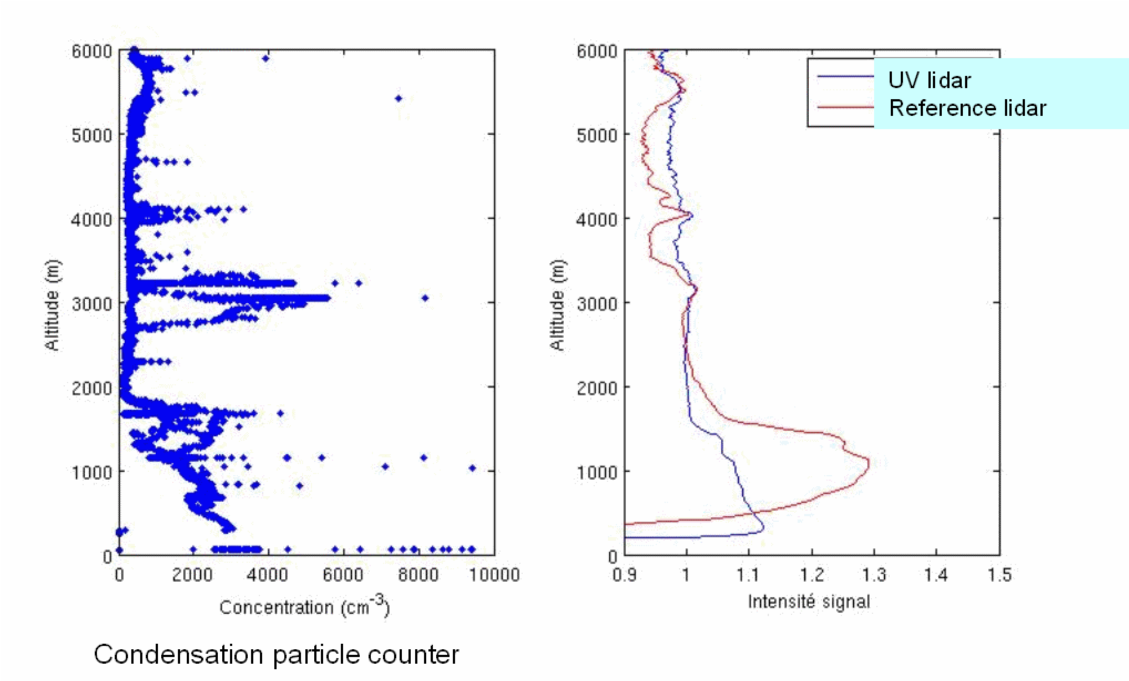


Figure 12 : comparison between a commercial UV lidar, a powerful research lidar and a condensation particle counter (CPC) on October 10th 2012. *One can see peaks in the CPC signal when lidars detect an aerosol layer. The commercial lidar signal is smoothed much more than the signal of the research lidar.*

In this example (Figure 12), and among the different observations made, we see a significant correlation between the measurements made by the CPC, the reference lidar reference and the operational lidar. The measurement of the probe LOAC could not be exploited sufficiently (only one launching could be made).

7 Design of a network

A study has been carried out in order to determine the number of lidars to be deployed in France with the aim of getting an optimal detection with a minimum of instruments. The aim of the study was to optimize the geographical location of the lidar.

The model MOCAGE was used in the accident version in reverse mode.

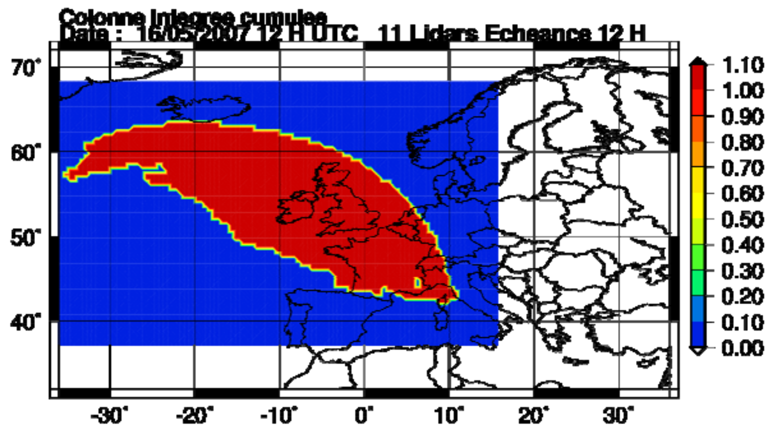


Figure 13 – example of a retroplume from Mocage-Accident : *if the ash cloud is located in the red area, it will be detected by the lidar network within 12 hours.*

MOCAGE aims at forecasting the development, over time, of the chemical composition of the atmosphere. In the 'accident' version, the chemical model is not used, the transportation component only is used. The reverse mode is used to determine where the pollutant comes from. It consists in computing all the points where a pollutant detected by one or more instruments could come from, i.e. the possible origin area (Figure 13).

For this study, MOCAGE was coupled with the French atmospheric model ARPEGE. In so far as the drift of the pollutant (for example ash) is strongly linked to the weather situation, MOCAGE was driven by nineteen typical meteorological situations. The detection coverage of thirty-two pre-defined sites was calculated (Figure 14).

Figure 14 : 32 pre-defined site used

Sites are classified according to their individual coverage. Then, for each meteorological situation, the total coverage of the best network with n lidars is calculated (n evolving from 1 to 32). It is then possible to determine the number N of lidars from which the addition of an extra lidar has little impact on the coverage. This approach was applied from 12 hours to 72 hours back trajectories.

However, the 12 hours back trajectories was privileged since, in case of an ash crisis, the goal is to detect and track the ash cloud as quickly as possible.

Moreover, the coverage was calculated on the global domain and on a smaller area, surrounding France (since it is important to detect an ash cloud being already in France).

Finally, to measure the impact of the failure of one of the lidars, the coverage was calculated when one of the lidar was removed in the network (Figure 15).

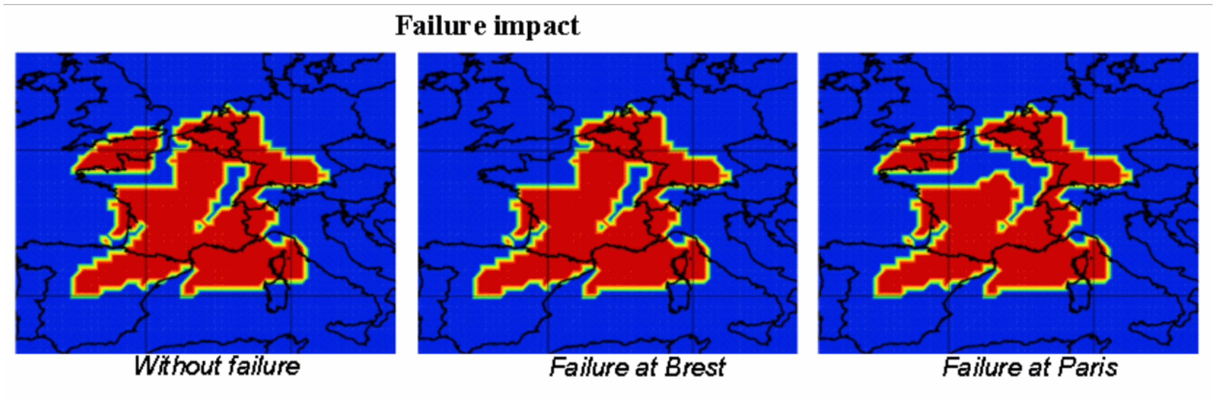


Figure 15 : impact of a failure *: coverage without failure (left), coverage with the failure of the lidar of Brest (middle), coverage with the failure of the lidar of Brest (right)*

Thus, this tool allows to:

- determine the number of lidar to deploy to more effectively detect an ash cloud at a given maturity
- optimize the distribution of the network
- know the consequence of a failure on the network

8 Conclusion

The 2010 Eyjafjallajökull eruption highlighted a lack of aerosol observations especially above France. Météo-France would like to fill this gap by deploying a network of aerosols lidars. In order to establish the instruments characteristics, Météo-France conducted an intercomparison campaign with lidars and ceilometers. The contribution of a sun photometer was also assessed. Those instruments were compared to reference observations: a research lidar, a radiosonde, and flight observations on two different sites. The aim was to realize an inventory of existing instruments and to assess the ability of each type of instrument in the field of volcanic ash detection. Météo-France, with manufacturers and French research laboratories succeeded in overcoming several issues to achieve this campaign, highlighting the difficulties of this kind of exercise that need a very powerful preparation before the campaign takes place.

The numerous sand dust aerosols episodes (sand dust almost have the same characteristics as volcanic ash) and the research laboratories algorithms made possible the assessment of all instruments, but a more complete validation procedure including the manufacturers would be helpful for a next campaign : the meteorological conditions under which the instruments could be assessed, basic definitions of optical parameters and algorithms to retrieve them would be a good start. The difficulties of this kind of intercomparison campaign are the absence of volcanic ash in the atmosphere (whereas this is the parameter we want to study), the different technologies used by lidars (wavelength for instance) and existing algorithms to retrieve parameters that are not defined by a reference yet. Outside a context agreed by everyone, Météo-France has not published any result.

Along with this experiment, a tool based on the use of backtrajectories from Météo-France atmospheric chemistry numerical model MOCAGE was created. Thanks to it, we are able to determine the number and distribution of aerosols lidars to deploy in order to detect in the best way volcanic ash. We are able to assess a breakdown impact on this network as well.

9 Acknowledgements

The authors would like to thank their colleagues from Météo-France : Pierre Chaduteau, Guillaume Poujol, Lionel Cortes, Jean-Luc Jouve, Matthieu Lacan, Quentin Kryszak, Christophe Barrière, Anne Chaumont, Jean-Marie Donier, Thierry Douffet, Rémi Guillot, Alain Dabas, Olivier Garrouste, Jean Coppeaux for helping to conduct the inter-comparison of lidars at Toulouse and Candillargues and preparing the necessary data for analysis.
We would like also to thank Dimitri Edouart et Pierre Flamant from the Laboratoire de Météorologie Dynamique (LMD - France) for the loan and running of the reference lidar.
We thank too the SAFIRE team for the aircraft measurement, Jean-Baptiste Renard from LPC2E-CNRS-Orléans for the LOAC radiosonde, the LOA (CNRS-Lille) team led by P. Goloub, the SIRTA (IPSL-PARIS-Palaiseau) led by M. Haeffelin, and all the manufacturers that helped us during this experiment.

10 References

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