Volcanic Ash Observation Flights and Ash Detection

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ABSTRACT

Military and civil aviation in Europe and over the Atlantic was severely affected in 2010 and 2011 by eruptions of the Eyafjallajökull and Grimsvötn volcanoes. Calculated ash concentrations were above threshold levels defined by aviation authorities for safe operations and aircraft were grounded. An immediate need for information about actual ash concentrations in the atmosphere emerged. One of the sources used to gather information was (next to space- and ground-based measurements) airborne measurements of volcanic ash concentrations. NLR performed such measurement flights in 2010 and 2011 using visual observations and a very basic sensor suite that was assembled in the hours just before the flights. Valuable information was gathered on these flights that aided national decision making. The preparation and execution of the NLR volcanic ash observation flights after the Eyafjallajökull and Grimsvötn eruptions are described in this paper.

Since then the civil regulation with respect to operations in volcanic ash has been rationalised with other threshold levels for volcanic ash levels. Facilities to deal with the situations with volcanic ash in the atmosphere have been improved. On a European and even global scale initiatives have resulted in, amongst others, recommendations for standardized in-situ measurement flights, including a recommended measurement sensor suite and addressing operational issues. Improvements have been made for a new volcanic eruption, but are we well prepared now? The current situation is described.

1.0 INTRODUCTION

In 2010 and 2011 aviation in Europe and over the Atlantic was severely affected by eruptions of the Eyafjallajökull and Grimsvötn volcanoes. As an initial response Transport Ministers in European countries responded in accordance with [1] by closing national airspace in preparation of ash clouds being predicted to drift over their country. Soon thereafter a more flexible approach was chosen where National Service Providers adapted the Level of Service in certain parts of airspace according to information provided by Volcanic Ash Advisory Centres (VAACs) and/or the national Met Offices. This flexible approach required updated information from several sources to be integrated and interpreted into decisions about the Level of Service. One of the sources used to gather information was (next to space- and ground-based measurements), and will be, airborne in-situ measurements of volcanic ash concentrations. In the days following the eruption of Eyafjallajökull in April 2010, a number of research aircraft flew through the ash plume, carrying different sensors in an attempt to measure the extent, composition and density of the ash over Europe. Operators involved were DLR (flying over Germany, The Netherlands, UK and Denmark), FAAM (flying over the UK), Metair (flying over Switzerland), NERC (over UK), SAFIRE (over France), INTA (over Spain) and NLR (over The Netherlands). Although co-ordination schemes existed, for example through the European Facility for Airborne Research (EUFAR), the research aircraft were basically considered part of the national infrastructure, were typically commissioned by the respective national Met Offices and, with the exception of the DLR Falcon, were flown mainly inside their national airspace. Initial focus of the in-situ data gathering activities was to attempt to validate the calculated ash concentrations through observations.

DLR Falcon-20 | FAAM BAe-146 | NLR Citation II

NERC Do-228 | SAFIRE ATR-42 | INTA CASA212

Figure 1-1: Some of the European research aircraft that were involved in volcanic ash observation flights.

Research aircraft typically have limited availability and development and installation of a specific sensor suite will normally take considerable time. This time was not available following the initial eruption. It was by chance that the mentioned aircraft, listed in Figure 1-1, were available and it was possible to instrument the aircraft for aerosol measurements in a short time.

Complementary to these flights three research flights were performed with a Lufthansa Airbus A340-600 passenger aeroplane. Data on ash and several gases was recorded in a special mission carrying the CARIBIC observatory (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container) in the Eyafjallajökull plume, mostly over the North Atlantic Ocean [2], [3].

In response to the volcanic eruption of 2010 the UK Met Office commissioned a Met Office Civil Contingency Aircraft (MOCCA) tasked to monitor the atmosphere for future volcanic ash incidents. It will also respond to a wider range of civil contingency events. The aircraft, a Cessna 421, is equipped with instrumentation to measure gases and aerosols in the atmosphere, both remotely and in-situ.

This paper presents the current status with respect to any future ash observation flights and ash detection in view of the experiences of the 2010 and 2011 flight campaigns. The approach of supporting predictions and nowcasting of volcanic ash in the Dutch airspace with airborne observation as it has been presented before [4] is summarised in this paper. Next, various options for instrumenting aircraft are described, ranging from a wide variety of advanced measurement techniques, towards a minimum necessary number of techniques. Finally the situation for any future volcanic ash incident is elaborated with a focus on Dutch airspace.

2.0 NLR OBSERVATION FLIGHTS IN 2010 AND 2011

The NLR/TU Delft aircraft, a modified Cessna Citation II with call sign PH-LAB, was involved in the 2010 and 2011 campaigns. The first flight was performed without a measurement sensor, simply carrying a KNMI (the Dutch Meteorological Office) Meteorologist to the “crime scene” to perform visual observations. Subsequent flights were performed with one or more sensors installed, including two different Particle Counters, a Liquid Water Content sensor and a humidity sensor. Valuable information was gathered on these flights that aided national decision making. An example is given in Figure 2-1, where visual observations from a KNMI Observer, combined with on-board measurements, lead to the conclusion that a trace of volcanic ash was present, but restricted to an altitude band between FL150 and FL210. Subsequently, low-level operations were cleared within the airspace concerned.

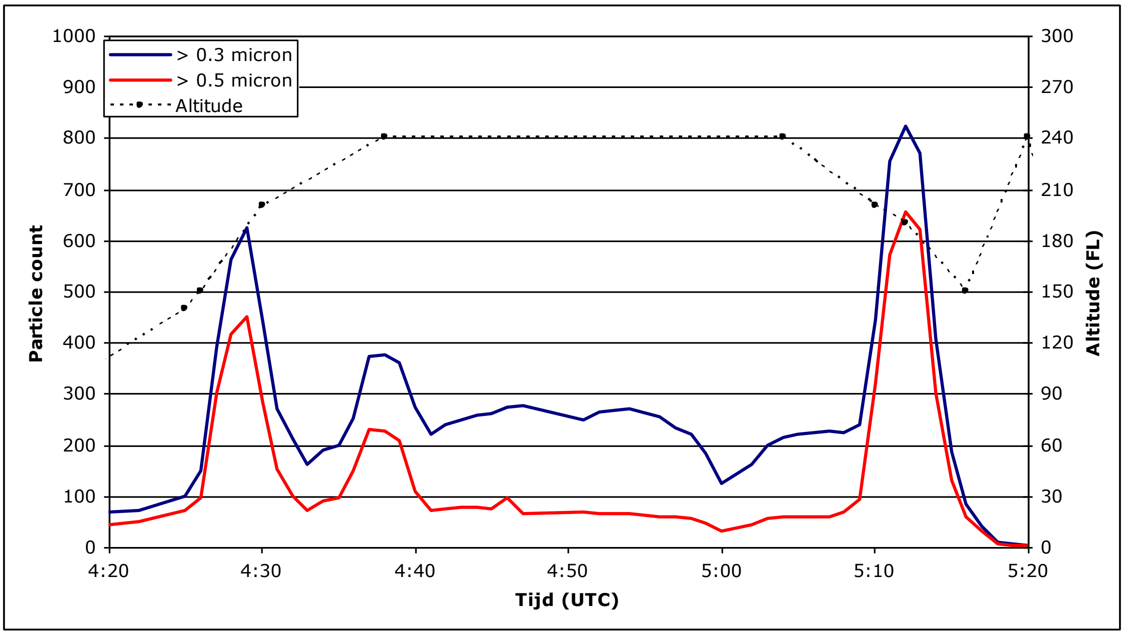

Figure 2-1: LPC measurements of particle densities in [x1000 particles per cubic feet] with sizes larger than 0.3 micrometer (blue line, left scale) and larger than 0.5 micrometer (red line, left scale) and the flight altitude of the aircraft (black dotted line, right scale) from May 18, 2010

2.1 Strategy during the NLR volcanic ash observation flights

The objective of the NLR observation flights was to verify presence of ash as predicted by the VAAC London model output or KNMI forecasts. The chosen strategy was to primarily use visual observations; an observer of KNMI was in the aircraft during all flights in the campaigns. To support these visual observations instrumentation, and in particular a particle counter, was installed in the aircraft. Together with a humidity sensor and a Liquid Water Content sensor this combination of sensors was able to distinguish between volcanic ash and liquid water particles in the air for most of the flights.

The measurements support the visual observation objectively, but since the installed instrumentation was not calibrated, it did not give absolute quantified information related to the established limit of ash in the atmosphere such as the 2 and 4 [mg/m^3] limits that were introduced as a response on the 2010 event.

In the end the NLR aircraft flew in air without significant volcanic ash concentrations, confirmed both visually and with measurements. The aircraft and engines were inspected after each flight (by use of a video endoscope and OEM prescribed measures) and no anomalies were found. As such there was confidence that the aircraft had, as planned, not encountered any significant volcanic ash concentrations.

In general the model output and predictions were of high quality, the NLR flights have been able to confirm these.

Research aircraft may be granted operational benefits through waivers or permits that are normally not available to commercial traffic. As such it may be possible to extend the research flight into airspace considered contaminated with predicted, modelled, measured or reported increased concentrations of volcanic ash. For NLR the Flight Operations made a thorough Safety Assessment for the volcanic ash monitoring flights which were presented in [4]. This was a precondition for national authorities allowing NLR to perform the monitoring flights during the airspace closure.

3.0 ASH DETECTION

The airborne detection methods applied in the 2010 and 2011 volcanic eruptions were the detection methods that were available on the research aircraft available at that time. Actions have been deployed to define optimized instrumentation systems, amongst others in an ICAO International Volcanic Ash Task Force (IVATF) [5], resulting in recommendations in an ICAO manual [1]. The number of aircraft equipped with the recommended instrumentation is, however, very small and certainly not always available for volcanic ash cloud investigations on short notice. UK Met Office nowadays has the availability of a Cessna 421 Met Office Civil Contingency Aircraft (MOCCA) [6] with sufficient instrumentation to monitor volcanic ash clouds. This aircraft is specifically commissioned to cope with volcanic ash cloud events and other disruptive atmospheric events. As such the fleet for airborne observations is still small and in the event of a new volcanic eruption deployment of aircraft with limited instrumentation may be valuable again.

Ash cloud monitoring should comprise both remote detection and because remote detection is not accurate enough additional in-situ, on-board measurement of ash appears necessary. The remote capability is important in flight operations. To avoid high concentrations of ash or gases during the measurement flights the clouds have to be remotely monitored first. Different techniques are employed:

- Lidar
- IR
- Visual detection

Remote detection has a limited accuracy. Therefore on-board measurements are supplementing the remote measurements. Techniques employed are:

- Particle collector
- Particle counter
- Optical particle spectrometer
- Gas detector
- Basic atmospheric instrumentation

Some relevant characteristics of these techniques are summarized below. Also, a more complete description of the measurement principle is given in [4].

3.1 LiDAR

Light Detection and Ranging (LiDAR) is an optical remote sensing technology that can measure the distance to [7], [8], or other properties of a target with, typically, pulses of laser light. The basic operating principle is similar to radar: a (high energy) laser beam is transmitted and reflects off particles, in this case volcanic ash particles. Part of this light returns to the receiver (a receiving telescope and photo detector). The measured signal can give the following information:

- Range: As a function of signal runtime, is used to determine the distance of the target from the laser
- Velocity: The relative velocity between the aircraft and the particles through the Doppler effect. The returned frequency of the signal is a direct measure of the particles’ relative motion by measuring its

Doppler shift.

- Gas concentrations: Gases introduce wavelength dependent, differential absorption on the light path. By using the absorption property of molecular gases, suitable combinations of LiDAR wavelengths can allow for remote mapping of atmospheric contents by looking for wavelength-dependent changes in the intensity of the returned signal. For example, it is possible to identify areas with increased SO_2 content.

- Particle shape: When the laser transmits a polarized signal, the polarization of the received (backscattered) signal contains information of the reflecting particles. For pure spherical particles, such as cloud droplets, the backscattered light is fully polarized in the same direction as the transmitted beam. However, for a cloud composed of non-spherical particles, such as ice crystals or volcanic ash particles, the backscattered light can be partially depolarized; i.e., it can have a "cross-polarized" component. The ratio of the cross-polarized to the co-polarized components of the backscattered light is called the depolarization ratio. In principle a correlation exists between the number of particles and thus the density of the ash and the depolarization ratio, but a lot of effort is required to adequately interpret the data.

- Particle density: The amplitude of the received signal depends on the reflectivity of the reflecting particle. Ash particles will have a different reflectivity than common aerosols or ice crystals.

LiDARs have been applied in atmospheric research as an instrument to detect and analyze aerosols and have gained considerable reputation in several flight test applications [7], [8], but they can also be used to remotely detect the presence of layers of volcanic dust. Using different wavelengths and measuring the amplitude and depolarization ratio of the backscattered signal can, in theory, also provide information on properties such as particle size distribution, mass distribution (density), chemical composition and air mass velocity, but obtaining these derived measures requires determining a set of assumptions and a careful calibration of the measurement technique. Currently, there is still a relatively large uncertainty in the derived measures when using LiDAR measurements for volcanic ash or dust. Furthermore, LiDARs can not detect through layers of clouds which hence limits its application.

In the 2010 and 2011 eruptions LiDARs were used extensively in different ways:

- Ground based – EARLINET, a European network of 27 (presently 28) ground-based LiDARs was able to detect the presence of volcanic ash at different altitudes over the ground stations.

- Space based – Because high energy LiDARs are relatively heavy and have a high power requirement, operating a LiDAR in space is not trivial. The first aerosol measuring LiDAR (LITE) was carried as a Shuttle payload on STS-64 in 1994. At the time of the Icelandic eruptions NASA's CALIPSO satellite was the only satellite capable of capturing the plume using a two-wavelength polarization-sensitive LiDAR.

- Airborne – DLR operates a Falcon-20 equipped with a downward-looking LiDAR originally developed to map wind profiles, but capable of detecting volcanic ash or dust. During the 2010 eruptions this aircraft was able to provide valuable measurements of the ash plume, contributing to ground- and space-based LiDAR observations. UK Met Office today deploys in MOCCA a LiDAR that can look either up or down.

3.2 Infrared imaging

Infrared (IR) detection is also a remote sensing technology that is based on the premise that an air mass containing sulphur dioxide and volcanic ash has a different brightness temperature, visible at specific IR wavelengths around 10 µm using a passive receiver. Many weather satellites, for example the European Meteosat satellites, have imaging sensors that operate in this wavelength, capable of identifying cloud height and type and surface temperatures. This technique is also the basis of the Airborne Volcanic Object Infrared Detector (AVOID) and declares it can determine density remotely [9]. Different trials have been performed with the AVOID system near Etna, Stromboli and releasing ash over the ocean from an aircraft. Although the passive IR sensor promises it can be used in an airborne sensor similar to weather radar in theory, this claim still remains to be substantiated. Similar to LiDAR, IR-detection is unable to look through clouds, limiting the availability of measurements. The AVOID system therefore includes uplinked data from ground stations or other aircraft in its concept.

LiDAR and IR are remote sensing techniques as opposed to in-situ, on-board measurements. On-board detection methods require the sensor to be taken to the place of interest. This is a complicating factor as it requires an aircraft or other vehicle, but on-board, in-situ measurements do not suffer from clouds, day/night variations and do not require a cumbersome calibration based on a number of assumptions: on-board measurements are more accurate.

3.3 Visual detection

Although not perfect, visual ash detection works for a pilot in daylight conditions if there is no other moisture in the atmosphere [10]. Volcanic ash with concentrations of 2 mg/m^3 and more will be visible in these conditions, but no information will be available to determine whether the contamination is at any specific level. Volcanic ash traces are visible as “dirty” air, not very different from a smog layer but with a slight brownish colour and not necessarily bounded by an inversion, which is often the case for low-level smog. A lower sun position over the horizon aids in visual detection of ash traces.

3.4 Particle collector

Using filter cups is the simplest way of collecting particles. Weighing the filters before and after the sampling gives the amount of particulate mass collected, and by knowing the amount of air drawn through the filter the mass concentration can be calculated. This method is not very accurate and requires post-flight analysis of the filter samples in a laboratory environment. An improved method is applying a (multi-stage) cascade impactor. Cascade impactors (frequently used for pollution control) consist of a number of impactor stages connected in series with smaller and smaller cut-off diameter. The cut-off diameter in each stage depends on the air velocity and geometry of the stage (i.e. the distance from the nozzle to the impaction plate).

This method of measuring is able to differentiate between heavier and lighter particles in an air sample. Although particle collectors have been carried on board research aircraft during the 2010 and 2011 eruptions, hardly any data was collected from these sensors. An addition to the method is conceivable where the impaction plate is replaced by a resonating membrane mass: the oscillating frequency is a direct measurement of particle mass, enabling an accurate measurement of volcanic ash density. This enhancement may prove valuable in the future.

3.5 Particle counter

A Particle Counter is a stand-alone optical sensor capable of counting individual ash particles and capable of determining a size distribution of these particles based on the intensity of the scattered light for a given refractive index. Depending on brand name, these instruments are referred to as a Laser Particle Counter (LPC) or an Optical Particle Counter (OPC). The airflow is directed through a light beam in the sensor. The light beam scatters light on a detector every time a particle comes in the light beam. An LPC/OPC sensor cannot by itself discriminate between different types of particles, for example a small enough water droplet will appear in the particle count in the same way as an ash particle.

3.6 Optical particle spectrometer

The principle of the LPC/OPC is the basis for the operation of aerosol spectrometers. Different multi-channel standardized pods exist, including the EUFAR Airborne Aerosol Reference Pod (AARP), and the Droplet Measurement Technologies (DMT) Passive Cavity Aerosol Spectrometer Probe (PCASP) and Cloud Droplet Probe (CDP).

Using optical particle spectrometers, mass concentration of ash cannot be measured directly but is determined from the particle size distribution measured for a given refractive index and density of the particles. Therefore, it is important to cover the entire size range of ash particles in the plume. From the results of the 2010 and 2011 campaigns, where several airborne platforms used, typically, wing-mounted spectrometers it is estimated that resultant uncertainty in ash mass concentration is about a factor of two [5].

3.7 Gas detector

Although SO_2 diffuses differently from volcanic ash, there is a strong correlation between the presence of volcanic ash particles and the SO_2 ratio in the air, especially in the first couple of days following an eruption. Another method of tracing volcanic ash is therefore by not trying to find ash particles, but by chemically analyzing the air and looking for SO_2 as an indication for air mass from a volcano. SO_2 also constitutes a danger for the aircraft because of its corroding effects on materials. Previously it was shown that this can effectively be done with IR detection at specific wavelengths, on-board measurement can be done at a higher accuracy using a mass spectrometer or a fluorescent analyser. Although the name (“spectrometer”) is similar, a mass spectrometer should not be confused with an optical particle spectrometer. A mass spectrometer works by ionizing particles in an air sample and then exposing the ions to a magnetic field. A mass spectrometer will yield the relative abundance of trace gases in the air sample with a high accuracy.

3.8 Basic atmospheric measurements

In addition to the specific instruments described above, in the earlier volcanic ash observation flights a multitude of additional basic atmospheric measurements were taken, such as position and altitude, Total Air Temperature (TAT) or Static Air Temperature (SAT), humidity and air density. Especially to complement the LPC/OPC measurements and to be able to identify presence of liquid water particles in lieu of volcanic ash particles, a Liquid Water Content Sensor (LWCS) was carried on the NLR flights in 2011. The sensor uses a heated wire; droplets hitting the wire will evaporate and reduce the temperature of the wire. The power needed to heat the wire is therefore a measure of liquid water content.

3.9 Overview of detection methods

The pros and cons of the different sensors are summarized in the following Table 1-1.

It can be concluded that remote (LiDAR, IR) measurements are best augmented with on-board, in-situ measurements using particle collectors or counters, combined with humidity sensors or LWC sensors to help the analysis of on-board detectors. Rather than applying one specific sensor, a sensor suite seems to be the best option [5], [1]. Also it can be concluded that no sensor directly measures in real-time the output of the model predictions and the basis for decision making i.e. the concentration of volcanic ash in a given volume of air [mg/m^3].

Table 1-1: Pros and cons of the different detection methods

Sensor	Range	Measurement	Derived	Cons
LiDAR	Remote	Location of ash particles		Cannot see through clouds Calibration
IR detector	Remote	Location of air mass with ash particles		Cannot see through clouds Calibration
Visual detection	Remote	Location of ash particles		Cannot see through clouds Subjective and not quantitative
Particle collector	In-situ	Particle size distribution	Mass distribution	Post-flight analysis
Particle counter	In-situ	Particle size distribution	Mass distribution	Cannot determine particle source
Optical particle spectrometer	In-situ	Particle size distribution	Mass distribution	Cannot determine particle source
Gas detector	In-situ	Air chemical composition		Local measurement

4.0 AIRBORNE VERIFICATION OF ABSENCE OF VOLCANIC ASH IN FUTURE EVENTS

The capabilities of forecasting and nowcasting volcanic ash concentrations in the atmosphere have been improved, notably for satellite detection on clouds. ESA and WMO enhanced capabilities substantially with studies and workshops. Contingency plans are updated and in place [11]. Capabilities have limitations, such as in air masses with water clouds and a need for future airborne verification of the absence of ash in air masses may exist. The number of aircraft specifically available for ash cloud monitoring, including research aircraft specially equipped for cloud physics investigations, is very low and in an event like the 2010 Eyafjallajökull and 2011 Grimsvötn eruptions an urgent need for airborne verification of the airspace may arise. Flights with limited instrumentation or only visual observations may provide the verification of the location or absence of volcanic ash clouds again. The observations will also have limitations for having daylight and not too much water clouds in the atmosphere, but flights will be useful in case these prerequisites are fulfilled. Volcanic ash from Icelandic origin will likely be embedded in polar air masses which have low water content. The flights will only indicate absence of ash, also small concentrations of ash, well below thresholds, will result in observations [10]. Observation flights will therefore provide a conservative measure for releasing airspace.

5.0 CONCLUSIONS

The preparation and execution of the NLR research aircraft volcanic ash observation flights after the 2010 Eyafjallajökull and 2011 Grimsvötn eruptions are described. These flights were performed with no or limited instrumentation for measuring the ash content of air. This is not as effective as it can be, but even retrospectively, a useful exercise that may be repeated if the absence of ash clouds has to be confirmed in the future. The possibility for such a need is however small with the revised regulation for ash in the atmosphere and the improved satellite and ground observations.

Sensor technology exists to measure volcanic ash; both remote sensing from space-, ground- and airborne platforms as well as in-situ, on-board airborne measurement technology can be applied. Recommendations for a sensor suite best suited for future airborne campaigns have been generated. The availability of aircraft with such a sensor suite is currently limited, which may lead to deployment of also less ideally instrumented aircraft.

It can be concluded that we are better prepared than during the large scale disruption of air travel in 2010 and 2011. However, the situation is not ideal with sufficient satellite, ground and in-flight detection capabilities for any event, which makes awareness of experiences such as enhanced in this symposium a useful effort.

REFERENCES

[1] ICAO, “Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds”, ICAO Doc. 9691 AN/954, 3rd Edition, 2015

[2] Angela K. Baker, Armin Rauthe-Schöch, Tanja J. Schuck, Carl A. M. Brenninkmeijer, Peter F. J. van Velthoven, Adam Wisher, and David E. Oram, “Investigation of chlorine radical chemistry in the Eyjafjallajökull volcanic plume using observed depletions in non-methane hydrocarbons”, Geophys. Res. Lett., 38, L13801, doi:10.1029/2011GL047571 (2011)

[3] K.-P. Heue, C. A. M. Brenninkmeijer, A. K. Baker, A. Rauthe-Schöch, D. Walter, T. Wagner, C. Hörmann, H. Sihler, B. Dix, U. Frieß, U. Platt, B. G. Martinsson, P. F. J. van Velthoven, A. Zahn, and R. Ebinghaus, “SO2 and BrO observation in the plume of the Eyjafjallajökull volcano 2010: CARIBIC and GOME-2 retrievals”, Atmos. Chem. Phys., 11, 2973–2989, doi:10.5194/acp-11-2973-2011 (2011)

[4] A.K. Karwal and H.W. Jentink, “Volcanic Ash Observation Flights, 2010, 2011 and Beyond”, presented at the 23rd SFTE (EC) Symposium, Amsterdam, The Netherlands, 11-13 June 2012

[5] ICAO International Volcanic Ash Task Force (IVATF), Task TF-SCI01.3 Report, “Recommendations for Conducting Airborne Sampling of Volcanic Ash Clouds”, presented at IVATF 4th meeting, Montréal, 13-15 June 2012

[6] Met Office Civil Contingency Aircraft (MOCCA), http://www.metoffice.gov.uk/services/public-sector/emergencies/civil_contingency_aircraft

[7] Henk W. Jentink and Rodney K. Bogue, “Optical Air Flow Measurements for Flight Tests and Flight Testing Optical Air Flow Meters”, SFTE (EC) symposium 2005 proceedings, Warsaw, Poland, / Meeting Proceedings RTO-MP-SCI-162, Paper 11 (2005).

[8] Rodney K. Bogue and Henk W. Jentink, “Optical Air Flow Measurements in Flight”, RTO AGARDograph 160, Flight Test Instrumentation Series, Vol. 20 / SCI-033 (2002).

[9] Prata, A.J. et al., “Artificial cloud test confirms volcanic ash detection using infrared spectral

imaging.”, Sci. Rep. 6, 25620; doi: 10.1038/srep25620 (2016)

[10] Bernadett Weinzierl, Daniel Sauer, Andreas Minikin, Oliver Reitebuch, Florian Dahlkötter, Bernhard Mayer, Claudia Emde, Ina Tegen, Josef Gasteiger, Andreas Petzold, Andreas Veira, Ulrich Kueppers, Ulrich Schumann, “On the visibility of airborne volcanic ash and mineral dust from the pilot’s perspective in flight“, Physics and Chemistry of the Earth 45-46, p 87–102 (2012)

[11] ICAO, Volcanic Ash Contingency Plan – European and North Atlantic Regions (EUR/NAT VACP, EUR Doc 019, NAT Doc 006, Part II) –Edition 2.0.0, July 2016