WMO/IAGOS Technical Experts Workshop on Requirements for In-Service Aircraft Aerosol Measurement Systems

Rapporteur: Andreas Petzold (DLR): andreas.petzold@dlr.de; Date of Issue: 20 July 2011

Workshop Report

1. Scope of the Workshop

The eruption of the Icelandic volcano Eyjafjallajökull in April/May 2010 and the resulting shutdown of the European airspace highlighted the sensitivity of civil aviation to airborne particles from natural hazards. In the aftermath of the airspace closure, an intense discussion ensued on the potential impacts on the airframes and engines of civil aircraft. It turned out that a quantitative knowledge of the exposure of aircraft encountering fine or coarse volcanogenic particles and gases in the atmosphere is very limited. This information, however, is critical to optimal operation and maintenance of aviation fleets. Furthermore, there are strong analogies between the issues and hazards associated with aircraft passage through volcanic ash and mineral (desert) dust clouds. The hazardous potential of these two different types of coarse mode aerosol with particle diameters in the super-µm range is, however, different because of their different patterns of atmospheric occurrence. Volcanic ash clouds threaten aviation mainly at cruise altitude, or at least in the free troposphere, i.e., above approx. 2-3 km above ground level. On the other hand dense mineral dust layers are mostly confined to the planetary boundary layer, which, however, can extent up to 4 km above ground level over desert regions. While exposure of aircraft/engine to mineral dust aerosol is less hazardous from its expected impacts, this situation is persistently and more frequently encountered by aircraft over many regions of the globe, and especially during take off and landing, which carries higher risk compared to cruise.

The European infrastructure project IAGOS (In-service Aircraft for a Global Observing System; http://www.iagos.org/) aims to enhance global observations of climate gases and aerosol using in-service civil aircraft. The project takes advantage of a unique commercial aircraft to collect this data on a day-to-day basis. In addition, airborne instrumented in-service aircraft may also serve as measurement platforms to make in-situ measurements of volcanic aerosol. The IAGOS community is currently preparing an instrumentation package for aerosol particles to address these needs of the aviation industry. This will provide a measure of volcanic aerosol dose to evaluate the potential for damage to aircraft engines and airframes, and will help to improve enhanced maintenance scheduling. Those improved instrumentation, however, will not overrule current procedures which permit flying into visible ash clouds.

The WMO/IAGOS Technical Experts Workshop on Requirements of In-Service Aircraft Aerosol Measurement Systems workshop will communicate the unique features of the IAGOS research infrastructure to the global aviation industry and seek their feedback on the planned observation system. The workshop will bring together stakeholders from the aviation industry (airline operators, airframe manufacturers and aircraft engine manufacturers), meteorological services, airlines, and experts on volcanic ash and mineral dust.

2. Workshop Details

2.1. Workshop Programme

Venue: WMO Headquarters, Geneva, CH

22 March 2011: Introduction and statements of aviation industry

- Welcome and purpose of the workshop (A. Petzold, DLR)
- Recap of the volcanic ash crisis 2010 (J. Taylor, UK Met Office)
- Key statements from OEM Engines (RR, P&W, Snecma)
- Key statement from OEM Airframes (Airbus, Boeing)
- Introduction to IAGOS (A. Volz-Thomas)

Introductory statements by invited experts

- Andreas Minikin (DLR, Germany): Particle and gas phase volcanic ash plume properties, key requirements for in-situ instrumentation with the focus on volcanic ash and mineral dust.
- Konrad Kandler (TU Darmstadt, Germany): Overview over chemical composition of volcanic ash and mineral dust particles incl. melting points of compounds.
- Adam Durant (NILU, Univ. Cambridge): Instrumentation for volcanic ash plumes based on remote sensing approaches.
- Costanza Bonadonna (Univ. Geneva, CH): Properties of volcanic eruption plumes incl. gas phase and particulates.
- Michael Herzog (Univ. Cambridge, UK): Microphysical processes, particle transformation and the role of water in plume evolution.
- Arnau Folch (BSC, ES): Predictions of far field ash concentrations and particle aggregation in aged volcanic ash plumes.

Identification of key issues for the working groups of Day 2

- 23 March 2011, 09:00 – 12:00: Break-out working groups
- 23 March 2011, 13:00 – 17:00: Reports of working group rapporteurs
- 24 March 2011, 09:00 – 13:00: Workshop synthesis

2.2. Key objectives to be addressed by the workshop

- Establish a link between aerosol dose on aircraft/engine and maintenance requirements.
- Improve the forecasting of aviation hazard areas.
- Improve the unambiguous detection of volcanic ash and mineral dust particles by simple and robust instruments suitable for on-board instrumentation of civil aircraft.

2.3. Key stakeholder issues from today’s knowledge

- How to use available information to avoid hazardous airspace.
- How to monitor the impact on airframes and engines.
- How to better manage maintenance schedules.

3. Key Issues of Experts' Statements

3.1. VA impact on aircraft

- Avoiding operations in visible ash has demonstrated the highest level of flight safety based on historical events.
- Ash plume visibility is no a sufficient criteria for potential hazards; 2 mg/m^3 limit incorporates current uncertainty from modelling and measurement; industry requires probability distribution of VA plumes > 2 mg/m^3.
- For operation purposes, industry wants to focus on the critical composition at the limiting VA concentration.
- For understanding the threats detailed knowledge of the chemical composition and related properties is beneficial.
- No certification standard is set for engine VA impact; currently, aviation industry does not share a common view on future certification standards for volcanic ash.
- Based on current legislation, key recommendation to date remains: avoid visual ash.

3.2. VA transport modelling

- Source term is complex and highly unsteady and uncertain.
- Correlation between particle mass flux and SO_2 mass flux varies over five orders of magnitude for different volcanoes; SO_2 is not a reliable proxy for VA mass concentration. Enhanced SO_2 may also be associated to other sources like anthropogenic emissions.
- Wide range of particle sizes in volcanic plumes (bombs > 1 m in diameter to ultrafine particles with d_p < 1 µm), but only particles of d_p <20 mm (strong plumes) and d_p <1 mm (weak plumes) reach the horizontally spreading current of the volcanic eruption plume.
- Airborne fine ash (d_p < 63 µm) represents only a minor fraction of the emitted volcanic ash particle size spectrum, but is dominant in aged volcanic ash plumes several days after the eruption/emission.
- Residence time of small ash particles (d_p < 63 µm) in the horizontally spreading current is controlled by particle aggregation. Processes of particle aggregation are not well understood and require further research in order to better understand and predict potential threats of volcanic ash to cruising aircraft in aged volcanic ash plumes.
- Ash, ice particles and sulphate aerosol coexist in an elevated ash plume; this coexistence makes passive remote sensing of volcanic ash in clouds which contain ice, water drops and water vapour a difficult task.
- Aggregation is a key process influencing particle lifetime and particle size distribution in the spreading cloud, generating large uncertainties in atmospheric modelling and VA mass concentration forecast.

3.3. VA particle properties

- Under conditions valid for engines (high pressure, high flow speed, high temperature), maximum particle sizes of d_p = 6 µm are expected to survive inside the engine, aggregates and larger particles fragment when entering the engine.
- Melting properties of mixed particles are hard to predict because a combination of minerals with high melting points can result in significantly lower melting points of the mixture; melting of mixed volcanic ash particles may start at temperatures as low as 700°C. So far, melting properties are known for bulk material under laboratory conditions.
- Desert mineral dust is assumed to have a higher melting point than volcanic ash, though it is known that at least a fraction can melt in jet engines.
- Transferability from a bulk sample melting point to melting points of single particles is highly questionable.

- Transferability of melting point data from laboratory conditions to conditions valid inside an engine compressor or combustor is not yet known. Detailed research is needed.
- Impact of high pressures inside the engine and high water content on melting behaviour of VA particles is not clear. Particularly high pressure may influence the melting behaviour; further research is needed.
- Models are required for assessing the impact of large particles on aircraft engines, including the conditions inside a gas turbine combustor. Concerns include the combustor as well as the effects of the melted particles on the turbine.

4. Working Group Reports

4.1. Management of enhanced maintenance due to aircraft-ash cloud exposure

1. What is the ash particle size fraction that is of importance to: (a) jet turbine engines; and (b) airframes?
2. What are the chemical species of relevance for enhanced maintenance?
3. What data would be required to monitor ash exposure with respect to: (a) jet turbine engines; and (b) airframes?

Rapporteur: Costanza Bonadonna

Participants Herbert Pümpel, Andreas Waibel, Konrad Kandler, Fabien Dezitter, Rory Clarkson; Karl Beswick

Conclusions:

1. Size has implications on the type of damage, e.g., large particles that behave ballistic (1 mm < d_p < 100 µm) are a problem for abrasion and airframes. There is no real upper and lower limit, but 100 µm – 100 nm can be considered as a plausible range that can cause different types of damage (e.g., abrasion, clogging). Particles that get inside the hot part of engine are assumed to be of about 6 µm in diameter, so particles that get melted are < 6 µm. The 100 µm upper limit is used in dispersal modelling as it is believed to travel large distances, but in fact there is not an upper limit. An open question is the differential breaking of different types of particles, e.g., glassy particles or ice crystals.
2. Various sulphur compounds and chlorine attack silver which is used to lubricate fast-rotating turbomachinery. They may also attack the turbine blades. Any potential impact of these chemical species on the airframe is not clear.
3. Detect (in order of importance): i) mass concentration of ash, ii) size distribution, iii) potentially corrosive gaseous species, which are mainly sulphur species, water, chlorine, fluorine, and carbon dioxide for the cabin interior. Most water will be in the form of ice at these altitudes. It is important to know the composition because typically ash composition does not significantly change during a same eruption from the same event, but no need to have in-situ detection.

Issues to be addressed:

1. Need to better understand ice-rich ash clouds: Ash acts as nuclei for ice crystal formation. Ice and liquid water play an important role in aggregation and may promote the formation of larger ash clusters which will sediment out quicker and may thus reduce the atmospheric lifetime of ash.
2. Maintenance problems caused by various sulphur compounds, chlorine, etc.

3. Overall impact from ice crystals is higher because it is more frequent, i.e. chronic problem (long term but less severe) whereas ash is an acute problem (short duration but severe).

Main message:

1. Engine and airframe manufacturers recommend the in-situ measurements of i) mass concentration of ash, ii) size distribution, iii) gaseous species (S species the most important) and low concentration levels accessible by civil aircraft. Measurements in dense clouds remain in the core research work. It is not yet clear whether SO_2 may be used as a surrogate for S-species, or if we need an integrated measurement of all sulphur species (SO_2, H_2SO_4, and sulphates).
2. Need of a database for understanding maintenance, e.g. exposure time to ash.

4.2. Safety considerations during a volcanic ash cloud crisis

1. What are the strengths, weaknesses and potential applications of aircraft mounted volcanic ash measurement and volcanic ash detection instrumentation?
2. To what extent are airlines interested in complete avoidance versus calculated risks of flying through low concentrations?
3. In order to effectively manage a volcanic ash crisis, exactly what information do airlines require?
4. Which parameters are required for on-board real-time information in order to keep the aircrew informed about potential hazardous areas?

Rapporteur, Adam Durant

Participants: Jean Cammas, Steven Baughcum, Jonathan Goulds, Andreas Minikin, Jonathan Taylor, Karl Beswick

4.2.1 Aircraft mounted volcanic ash measurement

In summary: Aircraft-mounted instrumentation has potential to aid navigation of contingency/ research aircraft, and would have potential to enhance the safety of operational aircraft.

During flight in an ash cloud environment, the following conditions may apply to the operation of an aircraft-mounted ash detection system:

Operational

- Based on current legislation, the policy remains to avoid visible ash.
- Commercial aircraft collecting *in situ* data could provide a test of model-predicted low ash particle concentrations and verification of concentrations within any zone designated < 2 mgm^3.
- Detection of ash particle concentrations could identify a previously unknown region impacted by volcanic ash.
- Commercial aircraft instrumented with volcanic ash detection devices need the flexibility to be assigned to the ash-cloud region of interest and to act as a pathfinder aircraft searching for possible routes of low ash concentration; alternatively the ash-cloud measurement strategy would require a large proportion of the fleet to be instrumented to ensure all regions are covered in the case of an ash-cloud event. Furthermore, such instrumented aircraft could provide much needed validation of model predictions.

- The system should have the ability to: (1) transmit raw data online, (2) send information (ash detection product) to the pilot in real-time, and provide a warning to the crew if contaminated airspace is ahead (remote sensing) or entered (in-situ).
- Remote sensing – has advantage of providing advance warning of ash clouds and therefore has potential to improve aircraft safety during operation.
- *In situ* – provides a measurement of exposure that has the potential to inform maintenance decisions.
- All measurements require some a priori assumptions (e.g., refractive index uncertainty) and so the limitations should be understood during interpretation of the information
- The ash detection system must have a high degree of reliability and stability. The data generated must aim to remove false positives and particularly false negatives (this would require a test procedure on the instrument).
- The system needs to be sufficiently robust to operate reliably in a commercial environment (e.g., some periodic maintenance).
- Potential to add additional capability to detect other aviation hazards e.g., high ice crystal concentrations and CAT in parallel

Research

- There needs to be a logistics management strategy for aircraft and instrumentation.
- IAGOS package data has the potential to motivate advances in modelling and forecast.

4.2.2 Airline/manufacturer perceptions

- Engine and airframe manufacturers, and airline operators – policy remains to avoid visible ash.
- Airline operators – primary interest to avoid incidents.
- Engine manufacturers – *in situ* data needed to improve understanding of engine damage from ash ingestion and potentially manage maintenance (research mode).
- Engine manufacturers are not supportive of ash tolerability certification.
- There are multiple situations where it may not be possible to identify ash visually so it is important to utilise all other available mitigation tools (VAAC reports, PIREPs, etc).

4.2.3 Flight operations information for safety management

- Given a known eruption, pilots need boundaries of ash cloud, thickness (and layering), horizontal/vertical extent, and spatial variability in concentrations
- Spatial extent of ash particle concentration
- Ash product (data or map) with 1000 ft vertical resolution (although current computing capability does not provide this).
- Rapid updates (e.g., hourly).
- Airlines need multi day forecasts to allow best planning of use of assets particularly with tasking of instrumented aircraft.
- Also need shorter term 24h forecasting for specific route planning.

4.2.4 Flight deck real-time information

- In the case of an unexpected ash cloud located in the flight path and detected using onboard instrumentation, a simple instruction needs to be sent to the pilot.
- Displays that show the spatial distribution of ash may be useful.
- The downlink capability may need to be increased to handle more data on existing aircraft.

Table 1. Assessment of methods available for on-board detection of hazardous particles.

Approach	Strengths	Weaknesses	Potential applications
In situ	Provides knowledge of passage into regions of low ash particle concentrations Provides size spectrum of particle mass distribution	1. Inlet sampling bias 2. Requires interpretation by experts 3. Complicated retrievals for optical systems 4. Uncertainty in mass concentration determination of at least a factor of two 5. For optical-based systems: Uncertainty in refractive index	1. Maintenance scheduling 2. Initiate immediate change in course 3. Distributed measurements from an integrated measurement system in real-time would assist flight planning
Remote sensing	Advance warning of airborne volcanic ash in the atmosphere	1. Water clouds and optically thick clouds complicate retrieval 2. Uncertainty in particle size distribution and refractive index adds uncertainty to measurements 3. Maintenance to keep forward facing windows clean (dirt, deicing fluid, etc.) 4. Sensitivity, detection limit, and background noise may depend on solar zenith angle and direction of flight	1. Time to adjust course and avoid ash encounter 2. Distributed measurements from an integrated measurement system in real-time would assist flight planning

4.3. Improvement of ash cloud forecasts and dissemination of information

1. What existing and/or developing volcanic ash measuring and detection capabilities could be made available for integration into near real-time operational systems?
2. How could information from in-flight aircraft enhance volcanic ash crisis management? And how could this information be rapidly disseminated in real time to other players in the industry?
3. To what extend have particle transformation processes being considered in the cloud forecast with respect to the modification of size distribution etc. which may change the hazardous potential of the particles?

Rapporteur: Timothy Gill

Participants: Arnau Folch, Andreas Volz-Thomas, Geir Braathen, Michael Herzog, Greg Kok, Andreas Petzold

4.3.1 Improvement of ash cloud forecasting

Burden of safety is shifting to the operators; therefore operators can take two broad approaches:

1. avoid ash completely wherever possible or,
2. airline operators may encounter ash during operations and take a safety assessment approach (Airlines carry out an on-going safety assessment before and throughout a flight to assess the probability of encountering ash in unsafe amounts).

Point number two puts even more emphasis on the need for accurate, reliable and robust modelling available through established routes available on a worldwide basis through VAACs.

4.3.2 End users requirements

- Accurate forecasts for dealing with ash events.
- Support for the transmission and capture of data through VAACs in a consistent and uniform format.
- More far-field information should be made available, i.e. 2 mg/m^3 isolines and mass concentration gradients in order to gain a better understanding of where plumes are and where they are likely to travel over time.
- Sulphur compounds and other corrosive substance forecasting would be highly desirable for engine maintenance considerations. Forecasting these compounds is fundamentally different from the ash product forecast because gas phase and coarse mode plume phase may separate in the atmosphere. More detail on the vertical resolution of VAAC products.

4.3.3 Thoughts for improving the forecasting of ash

- SO_2 is not a good proxy for ash.
- Aggregation either in the transport model or the source term should be included and is an open research question.
- Accurate forecasting requires fine-tuning of models, because the aggregation of particles could result in non-linear effects, which complicate the accuracy of model outputs. This can result in patches of differing accuracy in forecasts.
- There is a need for more validation points to improve modelling which combine measurements from in-situ environments with other formats such as remote sensing to achieve maximum results in accuracy.
- In this respect, on-board aircraft measurements are extremely useful, as even a zero measurement from these instruments will provide significant data points for modellers.
- If airline operators use a safety based approach, what are the acceptable margins of error in forecasting?

4.3.4 Options for improving forecasting

- Radiosonde coupled with an aerosol sonde should be deployed at locations at less than 100 km from source with near real time data transmission.
- Aircraft based in-situ measurements provide vertical profiles. The number of aircraft carrying equipment is important to provide sufficient reference points for models.
- The order of input data needs – large numbers of vertical profiles from landings/takeoffs over land or as many data as possible enroute at cruise altitude - might influence the choice of aircraft to instrument.

- It is important that all available data be centralised through a single mechanism, e.g. GTS[1].
- Modelling techniques require further development in order to improve the vertical structure and horizontal position of the plume.
- Model input requires improvement because if the information (real time observations) going into even a perfect model is insufficient (or inaccurate) to initialise the model correctly then the model output will inevitably suffer from inaccuracies. Vertical resolution accuracy of VA layers will improve but expectations need to be managed in terms of what the science and indeed the current integrated VA observation networks can produce.
- LIDAR and sun-photometer networks are useful, if data are provided in near real time.

4.3.5 Benefits of in-situ and further ground based observations

- IAGOS instrument package can provide the missing in-situ observations element.
- Provide validation of satellites retrieval algorithms.
- Improve initial inputs to modelling of ash and subsequent movements of the plume from separate sets of measurements (radiosondes, sun-photometers, lidar, etc.) and from IAGOS instruments for low-concentration ash plumes.
- Improve interpretation of satellite level 2 data outputs.

4.3.6 Costs/Coordination

- GMES – How volcanic ash data gathering and distribution would data fit into GMES. Be aware of other spaceborne observing systems such as A-TRAIN, MODIS, METEOSAT.

[1] The GTS is the WMO-based system for the exchange of all essential meteorological, hydrological and marine information between all 189 National Met and Hydrological Services. The GTS will morph into the WIS (WMO Information System) over the next 4 years, a much more interoperable and SWIM orientated system although the following should be borne in mind - GTS and WIS are not ICAO approved means for the dissemination of aviation meteorological information nor is there any sort of essential or indeed additional requirement for VA observations of whatever type at this stage.

5. Stakeholder Statements

5.1. Engine Manufacturers

Engine Manufacturers strongly support the IAGOS approach of routine on-board PM measurement.
Data from routine on-board measurements are clearly needed for building up a data base on particle load and engine maintenance.

Required parameters in the order of priority:
- mass concentration (direct)
- size distribution and inferred mass concentration (indirect)
- techniques for distinguishing ash from ice crystals
- S-containing species (particulate + gas phase) and other corrosive species
- data are needed on routine basis from normal operation

5.2. Airframe Manufacturers

Data from routine on-board measurements research projects are useful for improving forecast models.
Information on encounters of ash and ice crystals requires better in-situ data.
Airframe Manufacturers support IAGOS approach and further research on this subject.

5.3. Airlines

Threshold for PM impact on engines is still not sufficiently constrained.
More accurate prediction of ash clouds is required.
Airlines support IAGOS approach for improving the data base for modelling and NWP.

5.4. Modelling Community

The source term is still a significant source of uncertainty; in-situ observations on board of routine aircraft can help constrain some aspects of the source. This is a field of fundamental research.
In-situ data from routine aircraft will improve the knowledge on PM concentration in the far field of volcanic eruptions considerably; data are needed to constrain the input.
In-situ data from routine aircraft are required for the validation of models and of satellite products. NWP supports IAGOS approach.

6. Identification of operational and research priorities for ash cloud hazard reduction

1. What are the research priorities for the physical, chemical and radiometric properties of volcanic ash and volcanic gases and their effects on aircraft?

Required parameters in the order of priority:
- mass concentration (direct)
- size distribution and inferred mass concentration (indirect)
- techniques for distinguishing ash from ice crystals
- S-containing species (particulate + gas phase) and other corrosive species
- data are needed on routine basis from normal operation

2. How can data collected through the IAGOS project feed into operational and/or research priorities?

VAAC are first institution for data collection.

GMES may offer a potential pathway for feeding operational data into the environmental monitoring process.

3. Identify programmes that are already available today or become available in the near future for coordinating the required research in instrumentation development

- EC WEZARD Coordinating Support Activity (CSA), actually in the negotiation phase; contains programmatic elements for instrument development.
- IAGOS – Volcanic Ash project (to be decided); requires support from the European Commission.
- SAVAA – Support to Aviation for Volcanic Ash Avoidance now in 3rd year of project funded by the European Space Agency. There is likely to be a second 36 month phase of this project starting at the end of 2011.

7. Workshop Participants

Name		Company	Expertise	Contact
Experts				
Minikin	Andreas	DLR	Measurement	andreas.minikin@dlr.de
Kandler	Konrad	TU Darmstadt	Measurement	kzk@gmx.de
Durant	Adam	NILU, UNiv. CAM	Measurement	ajd90@cam.ac.uk
Folch	Arnau	BSC	Plume Modelling	arnau.folch@bsc.es
Bonadonna	Costanza	Univ Geneva	Volcanology	costanza.bonadonna@unige.ch
Herzog	Micahel	Univ Cambridge	Plume Modelling	michael.herzog@geog.cam.ac.uk
External				
Clarkson	Rory	RR-D	Engine	Rory.Clarkson@Rolls-Royce.com
Goulds	Jonathan	P&W	Engine	jonathan.gould@pw.utc.com
Dezitter	Fabien	Airbus	Airframe	fabien.dezitter@airbus.com
Cammas	Jean	Airbus	Airframe	Jean.CAMMAS@airbus.com
Kok	Greg	DMT	Instruments	gkok@dropletmeasurement.com
Kraan	Adrie	Boeing	Airframe	adrie.kraan@boeing.com
Baughcum	Steven L	Boeing	Airframe	Steven.L.Baughcum@boeing.com
Weber	Konradin	FH Düsseldorf	Instruments	konradin.weber@fh-duesseldorf.de
Hugues	Michel	Snecma	Engine	michel.hugues@snecma.fr
Weiss	Brigitte	European Commission		Brigitte.WEISS@ec.europa.eu
Baltensperger	Urs	PSI	Aerosol expert	urs.baltensperger@psi.ch
IAGOS Internal				
Taylor	Jonathan P.	UK MetOffice		jonathan.p.taylor@metoffice.gov.uk
Waibel	Andreas	LH		andreas.waibel@dlh.de
Gill	Timothy	BA		timothy.gill@ba.com
Braathen	Geir	WMO		GBraathen@wmo.int
Pümpel	Herbert	WMO		HPuempel@wmo.int
Nikovic	Slobodan	WMO		SNickovic@wmo.int
Ickes	Luisa	WMO		LIckes@wmo.int
Petzold	Andreas	DLR		andreas.petzold@dlr.de
Volz-Thomas	Andreas	FZJ		a.volz-thomas@fz-juelich.de
Beswick	Karl	Univ. of Manchester		karl.beswick@manchester.ac.uk

8. Workshop Organising Committee

Chair: Andreas Petzold (DLR; IAGOS PI for Aerosols and member of GAW Aerosol SAG)

Geir Braathen (WMO; IAGOS PI)

Herbert Puempel (WMO; AVIATION Commission and Volcanic Ash Lead)

Urs Baltensperger (PSI; acknowledged aerosol expert)

Markus Hermann (IfT; CARIBIC)

Slobodan Nickovic (WMO; Sand and Dust Storm Warning Advisory and Assessment System)

Ian Lisk (British Met Office; Volcanic Ash Advisory Centre London)

Adam Durant (University of Cambridge/NILU; volcanic ash remote sensing expert)

Andreas Waibel (Lufthansa ; IAGOS PI)

Timothy Gill (British Airways; IAGOS PI)