Flying into Volcanic Ash Clouds: An Evaluation of Hazard Potential

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ABSTRACT

Within the German Aerospace Center's (DLR) internal project VolcATS (Volcanic ash impact on the Air Transport System), the DLR Institute of Flight Systems investigated the impact of volcanic ash on aircraft systems, especially on navigation and communication systems. In order to get a general overview of recent encounters of aircraft with volcanic ash clouds and possible damage to the aircraft, a compilation of known incidents from 2010 through 2016 was created in collaboration with the U.S. Geological Survey (USGS). Together with the DLR Institute of Flight Guidance, a more detailed analysis for selected incidents was performed by combining both flight trajectories and modeled volcanic ash concentration data. Finally, the database of known incidents from 1953-2009 published by USGS [1] was merged with the new compilation in order to get a unique database of worldwide encounters of aircraft with volcanic ash clouds from 1953-2016.

1. INTRODUCTION

The disruptions to air transport during the volcanic eruptions in Iceland in 2010 and 2011 are still widely remembered. Eruptions since then – such as Merapi (Indonesia, 2010), Cordón Caulle (Chile, 2011) and Kelut (Indonesia, 2014) – have reminded the world that the risk of volcanic ash clouds is still present and may at any time become a threat for flight safety and also for air traffic management. Improvements have been made since 2010, e.g. in the area of air traffic management and detection and dispersion modeling of volcanic ash clouds. Nevertheless, the extent to which various aircraft systems tolerate exposure to different volcanic ash-cloud concentration levels is not yet fully understood.

In this paper we give an overview of the incidents since 1953, showing for example the distribution over the severity index classes, aircraft type, and typical reported system failures or other effects impacting flight safety. Selected incidents of this decade are analyzed and effects on avionics systems are discussed. In order to better understand risks for aircraft imposed by volcanic ash, data of worldwide aircraft encounters with volcanic ash or gas clouds have been collected. Encounters that occurred before 2010 have been compiled and published by the USGS [1]. In collaboration between DLR and USGS, that dataset has been updated mainly with cases related to the Eyjafjallajökull eruption in 2010 and since then through 2016. The main source of new data was a compilation of known incidents from EUROCONTROL Voluntary ATM Incident Reporting (EVAIR) [2], provided to the authors by the European Aviation Safety Agency (EASA) and subsequently amended by news reports, internet databases, and oral or written communication within the volcanic ash community. Missing information on some encounters was located; other cases were judged inconclusive and rejected. Over one hundred new volcanic ash or gas encounters have been found and added to the existing database. The full database will soon be published as an amendment to the USGS report [1].

Every encounter is assigned to a severity class according to an index (described in Section 2) which has been endorsed by the International Civil Aviation Organization (ICAO). However, some reported impacts on aircraft are not represented by the current severity index. Therefore, we propose an amended severity index at Section 4 to this paper that includes the judgment of pilots and other experts about the system impacts.

2. UPDATE PROCESS OF COMPILATION OF KNOWN INCIDENTS

The updated compilation of known incidents builds on [1]. In order to avoid repeating explanations, only the most important and new aspects will be discussed here.

Plausibility checks were made on each new encounter report to determine whether it could have been a volcanic ash or gas encounter, and attempts were made to gather information not included in the original reports, such as flight identification and engine assignment. The flight identification was often done by using the EUROCONTROL Demand Data Repository (DDR) service [3]. A traffic sample from the DDR contains the flights departing on a specific day. The 4D flight trajectory consists of all waypoints necessary to reliably characterize the flight path.

Encounters are reported with varying ambiguity, and may contain incomplete information on encounter location, time, and duration. Where possible, exact coordinates and the encounter country were retrospectively added to each entry. In addition, the source volcano for the volcanic ash or gas clouds was identified. Because the volcanoes in question typically had multiple or continuous eruptions rather than a single discrete explosive eruption, it was not possible to determine delta time, i.e. the time elapsed between the start of volcanic ash production at the source volcano and the subsequent encounter (defined as delta time in the original database).

Each incident was classified according to an existing severity index which was formulated in 1994 by Tom Casadevall and Karin Budding in consultation with engine and airframe manufacturers and the Air Line Pilots Association (ALPA) and endorsed by ICAO. Table 1 is a slightly modified version [1] from ICAO [4] as follows: (1) to class 0, adding criteria that includes observation of anomalous haze and ash reported or suspected by flight crew; and (2) to class 1, adding a criterion that considers volcanic ash deposits on exterior of aircraft. The index has six classes defined by the types of damage or conditions reported during actual encounters. Class 0 incidents (lowest severity) are characterized by sulfurous smells in the cockpit with no resulting damage to the aircraft; severity class 1 comprises non-damaging incidents but “dust” (ash) particles were observed in the cabin or were deposited on the exterior of the aircraft. Severity classes 2–5 constitute damaging encounters; fortunately, no encounters of severity class 5 (loss of aircraft) have occurred to date.

Severity class 0 warrants further explanation. Volcanic activity is the only source of large amounts of sulfur gases (primarily sulfur dioxide) at cruise altitudes of jet aircraft [5], and the smell of sulfur gases in the cockpit may indicate an encounter with a volcanic ash cloud. However, the smell of sulfur gases by itself is not necessarily an indicator of the presence of hazardous amounts of volcanic ash [1]. Many incidents in the updated report are based only on the smell of sulfur and therefore should be correctly described as suspected aircraft encounters with volcanic ash clouds. The process of updating the database is shown in Figure 1.

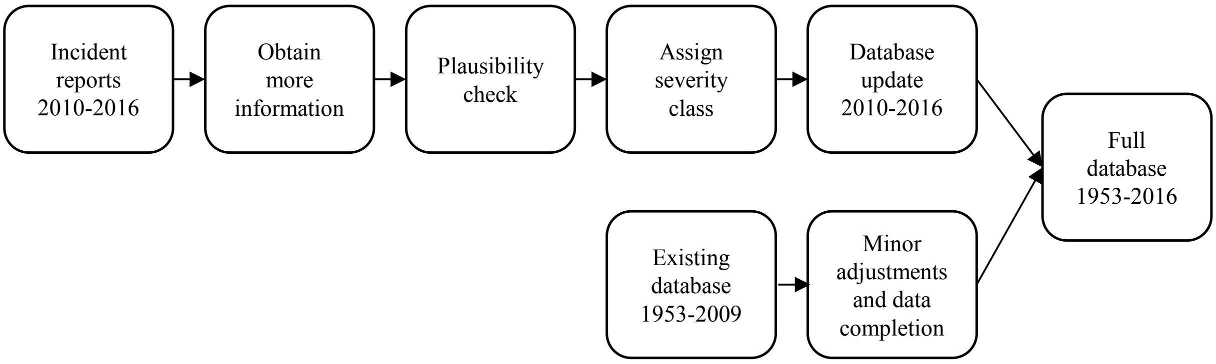

Figure 1: Data processing in the course of database update

Minor adjustments and data completion include, for example, the additional data field “aircraft type” according to ICAO [6] or eliminating duplicate entries.

Table 1: Severity index table for encounters of aircraft with volcanic ash or gas clouds, from [1]

Class	Criteria
0	• Sulfur odor noted in cabin. • Anomalous atmospheric haze observed. • Electrostatic discharge (St. Elmo’s fire) on windshield, nose, or engine cowls. • Ash reported or suspected by flight crew but no other effects or damage noted.
1	• Light dust observed in cabin. • Ash deposits on exterior of aircraft. • Fluctuations in exhaust gas temperature with return to normal values.
2	• Heavy cabin dust. • Contamination of air handling and air conditioning systems requiring use of oxygen. • Abrasion damage to exterior surfaces, engine inlet, and compressor fan blades. • Pitting, frosting, or breaking of windscreen or windows. • Minor plugging of pitot-static system, insufficient to affect instrument readings. • Deposition of ash in engine.
3	• Vibration or surging of engine(s). • Plugging of pitot-static system to give erroneous instrument readings. • Contamination of engine oil or hydraulic system fluids. • Damage to electrical or computer systems. • Engine damage.
4	• Temporary engine failure requiring in-flight restart of engine.
5	• Engine failure or other damage leading to crash.

3. ANALYSIS OF INCIDENTS

3.1. General Analysis

After the plausibility analysis mentioned in Section 2, a total of 253 encounters with volcanic ash or gas clouds between 1953 and 2016 were identified, of which 122 occurred in the period 2010-2016. Significant effects worth mentioning include:

- blocked pitot tubes
- replacement of damaged engines
- multiple engine failure
- electrical and computer failure
- physical restrictions (breathing, speech, nausea, eye irritation)

Table 2 presents the number of aircraft encounters with volcanic ash or gas clouds according to severity class. (An entry of >0 indicates that available data are sufficient to determine that the severity is not 0 but are insufficient to provide a more precise classification.)

Table 2: Number of aircraft encounters with volcanic ash or gas according to severity class, for 1953-2016 (full database period) and 2010-2016 (update period)

	1953-2016		2010-2016	
Severity class	Number	Subtotal	Number	Subtotal
Class 5	0		0	
Class 4	9		0	
Class 3	24		8	
Class 2	67		14	
Subtotal of damaging encounters with volcanic ash		100		22
Class 1	53		40	
Class >0	3		0	
Subtotal of encounters with volcanic ash		56		40
Class 0	82		60	
Incidents with insufficient data to assign severity	15		0	
Total number of incidents reported	253		122	

Approximately half of the incidents are severity class 0, mainly through sulfur smell noted in the cockpit. Severity class 1 incidents were mostly concerning reports of volcanic ash deposits on exterior of aircraft without further damage. For the 2010-2016 data, 82% of the incidents were severity class 0 and 1. Abrasion damage to exterior surfaces, engine inlet or compressor fan blades are the primary reasons for a severity 2 classification. The reported damages were often detected after the flight during post-flight or regular inspections, i.e. they did not have an impact on the mission of the aircraft. Engine bleed failure or engine fluctuations, ingested volcanic ash or melted volcanic ash on the interior of the engines were some of the reasons for a severity class 3 encounter. Incidents with severity class 4 had engine failure with engine restart during flight, mostly in combination with other significant disturbances on aircraft systems. Table 3 shows an overview of severity class occurrences per aircraft type according to the ICAO [6].

Table 3: Overview of severity class occurrences per aircraft type (ISD means insufficient data with respect to aircraft type)

	Severity class							
Aircraft type	**ISD**	**0**	**>0**	**1**	**2**	**3**	**4**	**∑**
Unknown aircraft type	11	11	1	5	1			29
Helicopter (H)								16
Turboprop/-shaft (H_T)		1		7	1			
Unknown (H--)				6		1		
Landplane (L)								208
Piston (L-P)		5		3	2			
Turboprop/-shaft (L-T)		13		5	2		1	
Jet (L-J)	4	44	2	25	60	23	8	
Unknown (L--)		8		2	1			
∑	15	82	3	53	67	24	9	253

Landplane aircraft represent by far the largest group in which mostly jet engines have been affected. Helicopters, which fly mainly at low altitudes, also have some reported occurrences. Most of the world-wide operating aircraft are jet-driven landplanes which may explain the low number of encounters with turboprop/-shaft engines or helicopters.

The effect on the aircraft relating to the distance from the source volcano was also investigated. Although the distance could only be determined for just over half of the events (usually because the location of the encounter is inexact), the distances shown in Figure 2 indicate that even at distances greater than a few thousand kilometers there were encounters in volcanic ash clouds that had notable effects on aircraft. This occurred primarily for large eruptions.

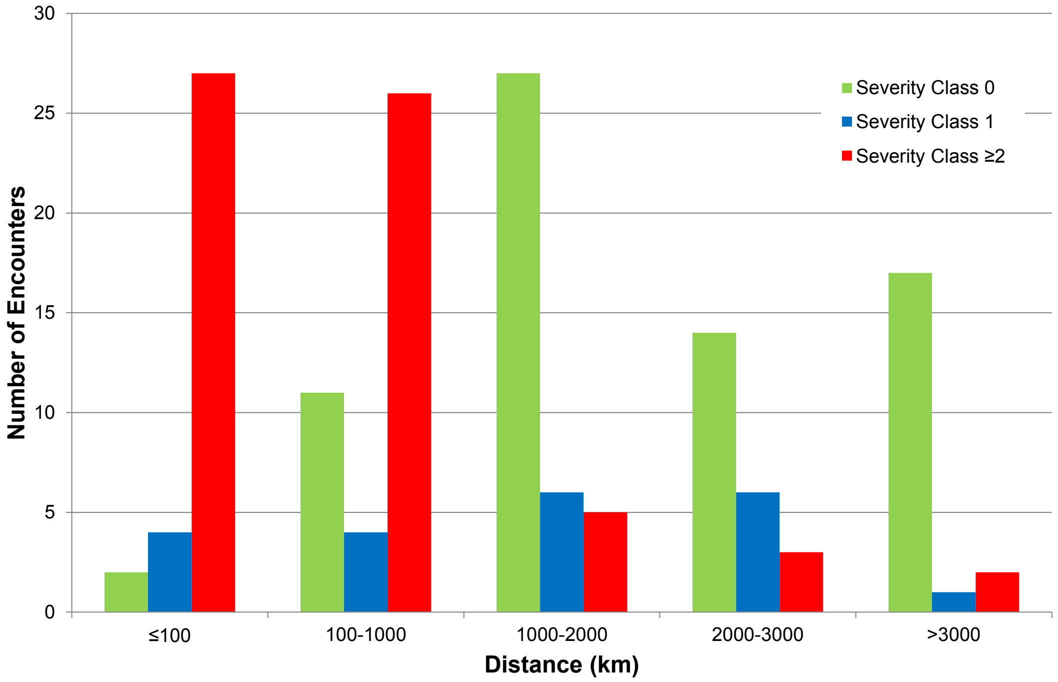

Figure 2: Number of encounters according to severity class and distance (estimated distance between the encounter and the source volcano)

More than half of the encounters were related to only seven volcanoes worldwide as presented in Table 4. In total, at least 48 different source volcanoes are included in the database.

Table 4: List of most common source volcanoes and associated encounters

Volcano and country	Number of encounters	Number of encounters ≥ severity class 2
Eyjafjallajökull, Iceland	91	16
Pinatubo, Philippines	17	8
Sakura-jima, Japan	14	13
Mount St. Helens, United States	9	9
Augustine, United States	8	6
Redoubt, United States	7	6
Chaitén, Chile	6	4

Figure 3 shows the annual frequency of aircraft encounters with volcanic ash clouds since 1953, but excludes severity class 0 incidents. The large spike seen in 2010 is related to the Eyjafjallajökull eruption, which affected a large area of airspace. The number of higher severity encounters (severity classes 3 and 4) in various years is indicated by red squares. The 33 high-severity encounters (severity classes 3 and 4) occurred sporadically between 1980 and 2016.

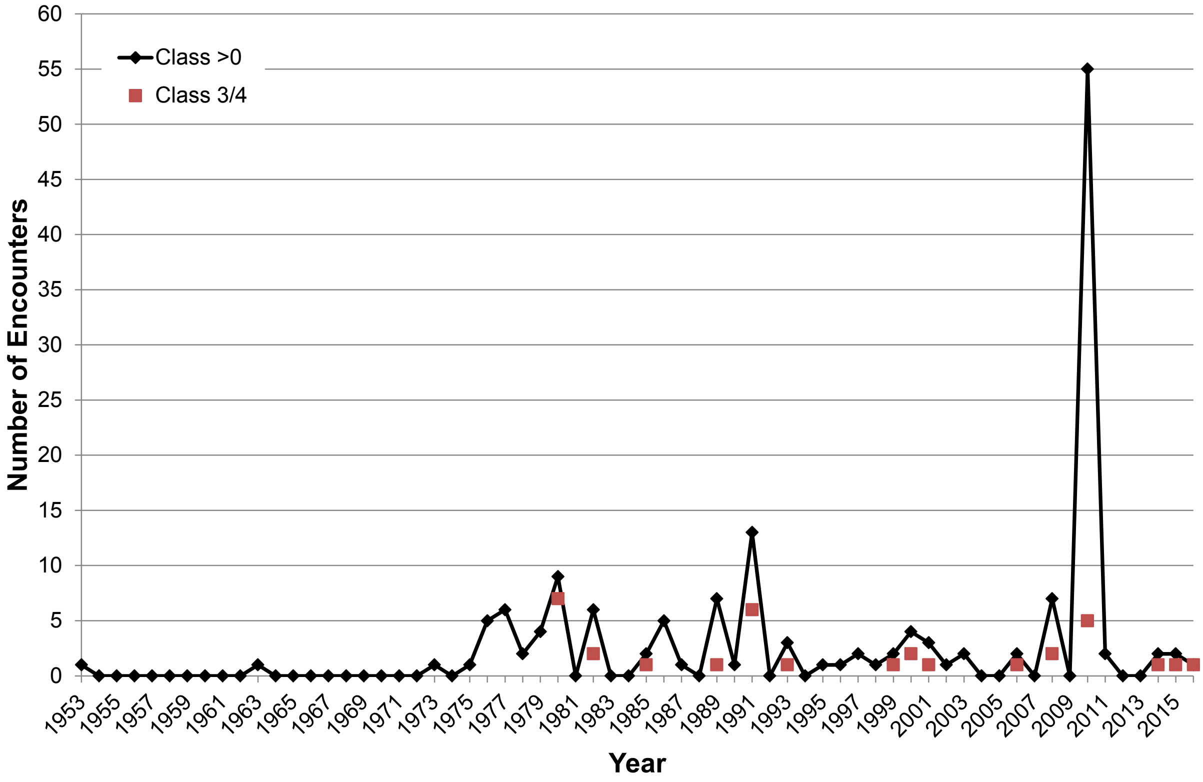

Figure 3: Annual frequency of aircraft encounters with volcanic ash clouds, 1953-2016

3.2. Detailed Analysis of Selected Incidents since 2010

This section describes the analysis of selected recent encounters. For a discussion of incidents prior to 2010 see [1].

3.2.1. Analysis Methodology and Tools

We analyzed selected incidents in terms of exposure to modeled volcanic ash concentrations. The Met Office UK provided modeled volcanic ash concentration data for selected days during the Eyjafjallajökull eruption in 2010 with three different concentration levels, based on a zoning system that depicts areas of low, medium and high concentrations in three altitude bands. The model data are derived from a 6-hour mean model output showing the potential location of the volcanic ash cloud over the time period, rather than just being a snap-shot. It is important to know that the modeled volcanic ash concentration data are generated from a rerun using a newer version of the NAME model with a revised height and emission profile [7], so plots may appear slightly different to plots issued at the time. The terminology is defined by ICAO [8] as follows in Table 5:

Table 5: Definition of volcanic ash contamination areas [8]

Area of … contamination	Definition
Low (displayed cyan)	An airspace of defined dimensions where volcanic ash may be encountered at concentrations equal to or less than 2 mg/m^3.
Medium (displayed grey)	An airspace of defined dimensions where volcanic ash may be encountered at concentrations greater than 2 mg/m^3, but less than 4 mg/m^3.
High (displayed red)	An airspace of defined dimensions where volcanic ash may be encountered at concentrations equal to or greater than 4 mg/m^3, or areas of contaminated airspace where no ash concentration guidance is available.

However, in the model data the lower threshold is 0.2 mg/m^3 for the low contamination area.

It should be noted that “defined dimensions” refers to horizontal and vertical limits. The three altitude bands in terms of flight levels (FL) are:

- FL000 – FL200
- FL200 – FL350
- FL350 – FL550

For example, assuming there is a thin layer of volcanic ash in FL220, the entire altitude band FL200-FL350 is marked as volcanic ash contaminated (with the corresponding concentration). Therefore, the real volcanic ash concentration or volcanic ash dosage (cloud concentration times exposure duration) cannot be determined with this kind of modeled data. Accordingly, the data were used, inter alia, to check whether the reporting aircraft was in or in the vicinity of modeled volcanic ash areas. As future work, encounter cases of high interest (e.g. severe damage) could be investigated more profoundly, e.g. with model data at a higher vertical resolution which would need to be generated specifically.

For the more detailed analysis, FATS (Future Air Traffic Simulator) of the DLR Institute of Flight Guidance was used. FATS detects conflicts of flight trajectories with defined airspaces like volcanic ash-contaminated areas, calculates start and end time of conflicts and has a three dimensional representation for visualization purposes. The software tool can handle data from the EUROCONTROL DDR service as well as the volcanic ash concentration, using CSV files (comma-separated values) issued by Met Office UK for aviation purposes without changing the software. A more detailed description of the flight path conflict detection can be found in [9].

In cases where the affected flight was not already identified in the original report, the flight trajectories of the potential flights (flights with similar characteristics as given in the report, e.g. time, region, aircraft model) were loaded together with the associated modeled volcanic ash data. It was then checked whether one (or more) of the potential flights were routed through modeled volcanic ash-contaminated airspace.

3.2.2. Flight in Modeled Low Concentration Volcanic Ash Zone (ID2010-82)

This incident is derived from the 2011 EVAIR database. A twin-engine jet (L2J) wide-body aircraft was inbound to London Heathrow airport (EGLL) on 16 May 2010 when the aircrew reported an acrid smell on the flight deck at 6,000 ft. On taxi-in after landing, the aircrew noticed number 2 engine pressure ratio (EPR) gauge fluctuations from 1.01 to 1.10, subsequently thought to be a volcanic ash encounter. The engine was shut down during taxi-in. Since the fluctuations did not return to normal values, this incident is rated as severity class 3. Overlay of flight information with modeled volcanic ash concentrations shows potential hazards. Between noon and 1800 UTC, the greater vicinity south of London Heathrow airport was free of volcanic ash clouds according to the dispersion model data (left panel of Figure 4). After 1800 UTC, it can be seen in the right panel of Figure 4 that the volcanic ash cloud in the modeled data covers London and enters the coast of France. Both panels show low ash concentrations (between 0.2 mg/m^3 and 2 mg/m^3).

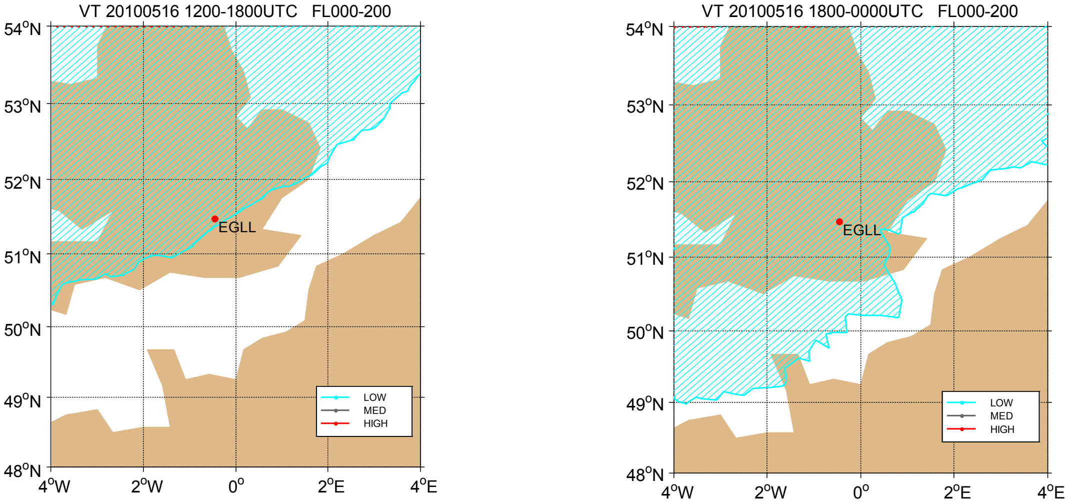

Figure 4: Modeled volcanic ash clouds (cyan pattern) between 1200-0000 UTC on 16 May 2010.

Figure 5: Screenshot of FATS with the flight trajectories inbound London

Whilst an approach to London Heathrow without a significant conflict with a modeled volcanic ash area was possible from Central Europe between 1200 and 1800 UTC, every approach to London Heathrow after 1800 UTC was performed through modeled low contaminated airspace. In total it was found that the DDR data showed 14 flights with the affected type of aircraft landed at London Heathrow in the time period in question. For these flights, the flight time within the volcanic ash contaminated airspace was calculated, varying from about 3 minutes up to 24 minutes. Seven aircraft in total operated more than 15 minutes in low volcanic ash contaminated airspace, with two of these operating more than 20 minutes. With the data available, the duration of this encounter cannot be determined because the identity of the flight was not known. Figure 5 shows the trajectories (yellow) of the 14 flights which arrived at London Heathrow displayed in FATS (some of the flights have the same arrival route). The yellow marked flight trajectories change the color to red if there is an overlap with a modeled volcanic ash zone. This severity class 3 encounter shows that even flights through volcanic ash clouds with modeled low concentration could be hazardous.

3.2.3. Flight outside Modeled Low Concentration Volcanic Ash Zone (ID2010-85)

In this incident, during a descent into Paris on 17 May 2010, the flight crew of a four-engine wide-body aircraft (L4J) reported at about 0400 UTC engine fluctuations and therefore the incident is classified with severity class 3. Unfortunately, no further information on the engine damage is available, but the flight trajectory of the flight can be determined and combined with the modeled volcanic ash dispersion data.

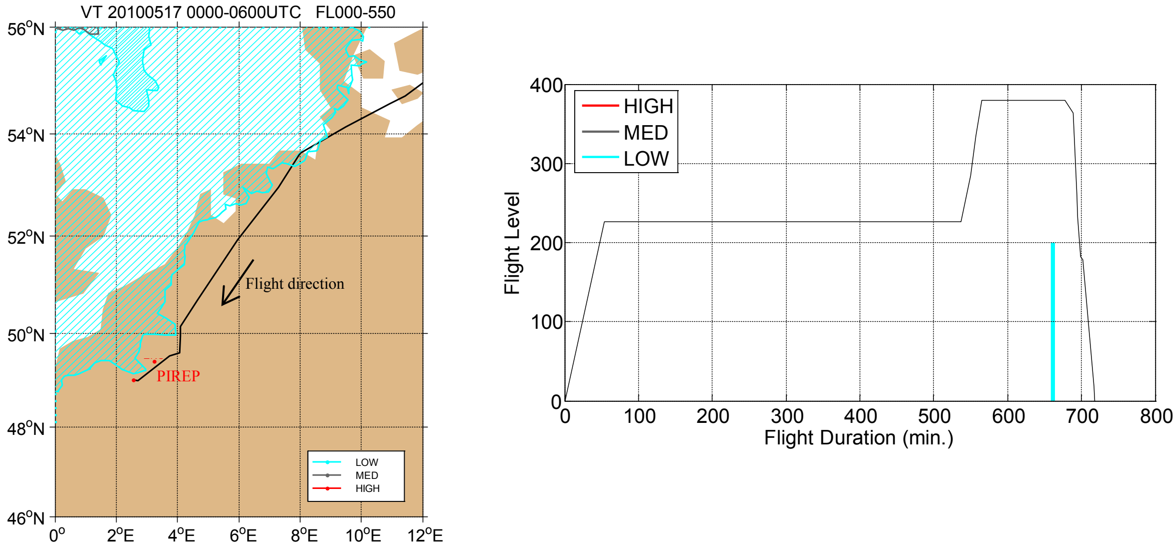

Figure 6: Flight trajectory (left, only last part of the flight) and cross section (right, whole flight) with modeled volcanic ash dispersion for encounter 2010-85

Figure 6 shows that the flight trajectory is at altitudes well above the modeled volcanic ash-contaminated zones. One possible explanation for the reported impact on the aircraft is the uncertainty of the dispersion model, i.e. the actual volcanic ash contaminated zone might have been larger and/or higher than shown in Figure 6. However, it must be recalled that in the model data the lower threshold is 0.2 mg/m^3 for the low contamination area. This means that the aircraft could possibly have flown (a longer time) in a concentration less than the lower threshold. Another explanation for the engine fluctuations could be the presence of volcanic gases which are not part of the volcanic ash advisories. The shown example case is representative of many more cases in which the reporting aircraft has been outside modeled volcanic ash-contaminated airspace. It should therefore be considered that even flying near to modeled low contaminated volcanic ash zones may have effects on aircraft systems, in this case the engines.

3.2.4. Impact on Aircraft Occupants (ID2010-69)

The flight crew of a single aisle two-engine jet aircraft (L2J) reported at about 0900 UTC on 9th May 2010 a smell of sulfur and decided to descend to FL240, where the situation seemed to improve. But the first officer appeared to be sick due to the smell. Based on the severity index shown above in Table 1, the report was assigned to severity class 0, although a member of the flight deck crew was affected. The flight trajectory of the aircraft including the modeled volcanic ash dispersion is shown in Figure 7.

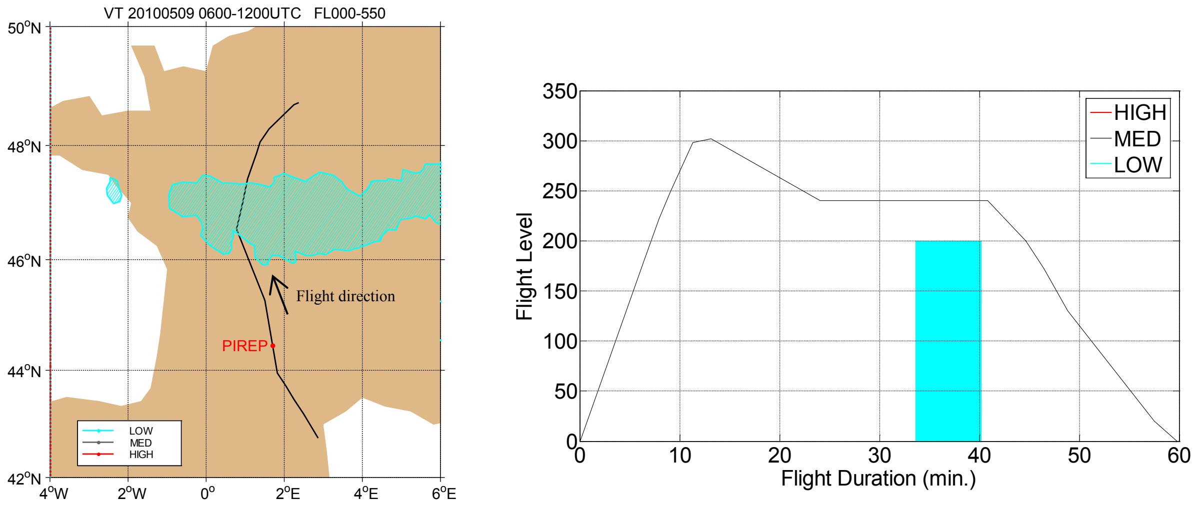

Figure 7: Flight trajectory (left) and cross section (right) with modeled volcanic ash dispersion for encounter 2010-69

Similar to a previously discussed encounter (cf. 3.2.3), a flight not only within volcanic ash clouds can be negatively affected but also a flight close to and not necessarily within a modeled volcanic ash-contaminated zone may result in on-board effects. In this case the effect was sickness of a flight crew member, caused by volcanic gas associated with the volcanic ash cloud.

3.2.5. Situational Awareness of Flight Crew (ID2016-01)

The last known encounter entered in our database happened in 2016 in Mexico. A single aisle two-engine jet aircraft (L2J) was heading towards Colima. The aircraft had to enter a holding pattern before performing a landing attempt. The landing was aborted for unknown reasons and the aircraft diverted to an alternate airport. En-route to the alternate airport, the aircraft entered the upper limit of a forecasted volcanic ash-contaminated zone with unknown concentration emitted from the Colima volcano in close proximity. After successful landing at the alternate airport, both engines were removed due to volcanic ash ingestion and the aircraft was out of service for approximately two months. Unfortunately, detailed information on engine damage is not available. Figure 8 shows the flight trajectory and the forecasted volcanic ash-contaminated zone (red marked part of the flight trajectory). The flight intersects the top of the modeled cloud.

During the flight preparation very early in the morning, the latest Volcanic Ash Advisory (VAA) indicated no volcanic ash cloud from Colima volcano was observable from satellite data or seen in webcam. However, the volcano had been repeatedly active in the previous days and months; with this information, the flight crew departed to Colima. About 20 minutes before top of descent, a new VAA was issued by the responsible Volcanic Ash Advisory Center (VAAC) with an observed volcanic ash cloud up to FL 170 in the area shown in Figure 8. It is not known when the flight crew became aware of the new situation. But the flight crew had then to deal with a volcanic ash cloud in the close proximity of their destination which might have been the reason for the subsequent holding pattern. It must be mentioned that the area information is provided during flight time to the flight crew by means of a row of coordinates and not with a graphic, a fact which complicates the situation for the flight crew.

This case is a very good example of situational awareness of the flight crew being very important for flight safety. This applies in particular for flight crews flying to an airport with an active volcano in the vicinity. A graphical presentation of the volcanic ash-contaminated airspace (instead of solely coordinates) or even a volcanic ash or volcanic gas detection sensor on board of the aircraft might have prevented the encounter or reduced its severity and accordingly the subsequent non-availability of the aircraft.

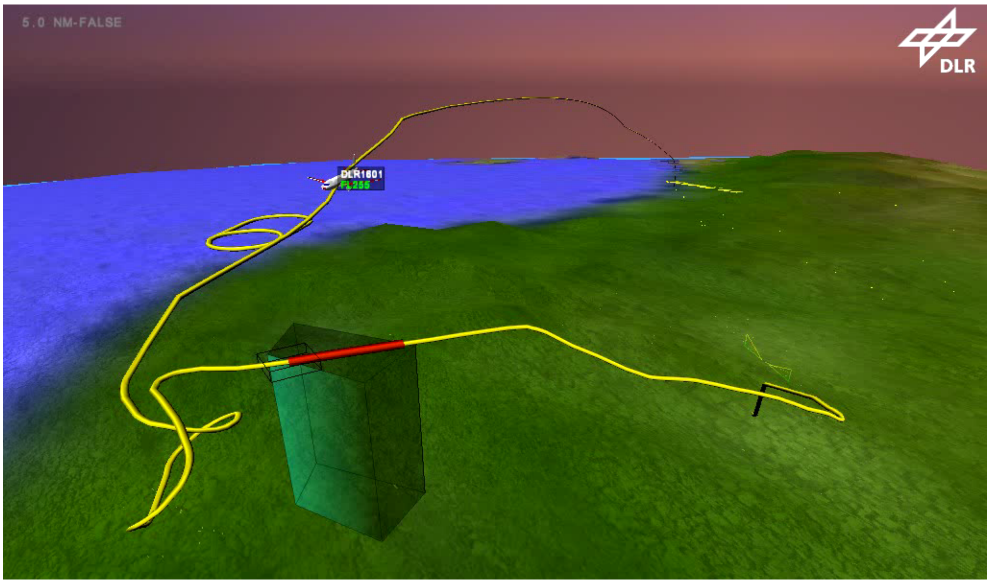

Figure 8: Flight path and the forecasted volcanic ash-contaminated zone for encounter 2016-01 in FATS (flight trajectory with permission from Flightradar24)

4. REVISION OF THE SEVERITY INDEX

During the compilation of the reported recent encounters we found that some relevant criteria were not yet included in the severity index. Accordingly, some pilots, aerospace engineers and other persons associated with the volcanic ash topic were asked to review and propose amendments to the severity index. The participants returned some general comments. For example, some questioned whether the severity classification should be based on potential hazard to the aircraft, mission fulfillment, repair costs or economic impact. The authors then clarified that "potential hazard to the aircraft" is the driving criterion for the severity index. As the entire aircraft is within the volcanic ash-contaminated air, several aircraft systems are exposed to volcanic ash and simultaneous failures are likely, but not considered in the severity index. This raises the question whether a matrix should be used rather than a table. Some revised wording was suggested by aviation experts; e.g. "Leading to crash" should be changed to "Loss of aircraft" or "Loss of control" which are both commonly used in aircraft accident investigations.

In terms of "additional criteria not considered" in the current severity index table, feedback was received from five experienced pilots with at least a commercial pilot license. They fly aircraft such as Bombardier Challenger 604, Airbus A320/A330/A340 or Boeing B747 as captain and/or first officer. Some of them have additional licenses such as (experimental) test pilot or type rating examiner. Table 6 shows the proposed additional criteria and an averaged class assignment over the five pilots (A-E). Their opinions are quite unambiguous with very low spread. Health problems of flight crew include for example sickness, restrictions on breathing and speech, dryness of throat.

Table 6: Proposed additional criteria with severity class assignment

Criterion	A	B	C	D	E	Avg.
Interference of navigation or communication systems	3-4	2	3	3	3	2.9
Engine failure requiring in-flight permanent shutdown of engine	4-5	5	4	4	4-5	4.4
Reduced engine thrust due to contaminated engine(s)	4	4	3	4	4	3.8
Health problems of flight crew (e.g. due to sulfur odor/dust)	4	3	4	5	4-5	4.1
Complete loss of VHF communication	2-3	2	3	3	3	2.7

One pilot has commented that existing criteria should be moved into a more critical severity class, e.g. a criterion in severity class 3 should be moved into severity class 4, to take into account the potential hazard to the aircraft. Other experts have also expressed the view that the current severity class is too low for some criteria. Considering the reviewed documents, the pilot survey, and numerous discussions with international experts, a revised severity index was proposed (Table 7) for consideration by the broader volcanic ash community, including aircraft and engine manufacturers. The revised index keeps the general structure of the original. However, for the first time effects on the aircraft occupants are listed. The classification is based on the FAA Advisory Circular 23.1309-1E [10]. Changes to Table 1 are marked in red italics.

Table 7: Proposed revisions to the severity index

Class	Criteria
0	Sulfur odor *or volcanic gas* noted in cabin. Anomalous atmospheric haze observed. Electrostatic discharge (St. Elmo's fire) on windshield, nose, or engine cowls. Volcanic ash reported or suspected by flight crew but no other effects or damage noted.
1	Light dust observed in cabin *and/or cockpit with inconvenience for passengers and/or flight crew*. Volcanic ash deposits on exterior of aircraft. Fluctuations in exhaust gas temperature with return to normal values.
2	*Volcanic ash deposited in cabin and/or cockpit*. *Physical discomfort for passengers (e.g. due to sulfur odor/dust)*. *Volcanic ash deposited in* pitot-static system, insufficient to affect instrument readings. Pitting, frosting, or breaking of windscreen or windows. Contamination of air *systems*. Deposition of volcanic ash in engine. Abrasion damage to exterior surfaces, engine inlet, and compressor fan blades. *Engine damage without removal or replacement of engine(s)*.
3	*Interference of navigation or communication systems*. Damage to electrical or computer systems. Plugging of pitot-static system to give erroneous instrument readings. Vibration or surging of engine(s). Contamination of engine oil or hydraulic system fluids. Engine damage *with removal or replacement of engine(s)*. *Physical discomfort for flight crew (e.g. due to sulfur odor/dust)*.
4	Temporary engine failure requiring in-flight restart of engine. *Engine failure requiring in-flight permanent shutdown of engine(s)*. *Reduced engine thrust due to contaminated engine(s)*. *Physical distress to flight crew (e.g. due to sulfur odor/dust) impairing ability to perform tasks*.
5	Engine failure or other damage *resulting in loss of aircraft*.

Summary descriptions of the six classes are given in Table 8.

Table 8: Summary description of severity classes

Class		Summary description of severity classes
0		Volcanic ash encounter possible but not confirmed.
1		Volcanic ash encountered with no or transient adverse impacts.
2	Minor	failure conditions or damage sustained.
3	Major	
4	Hazardous	
5	Catastrophic	

5. HAZARDS OF VOLCANIC ASH TO AVIONICS SYSTEMS

Engine failure is the most serious (life threatening) risk caused by volcanic ash to aircraft, but other aircraft systems can also be affected, as shown in Table 1 and Table 7. Considering the increasing importance placed on a risk-based approach for the air traffic management during a volcanic crisis [11], understanding the hazards and risks posed on the whole aircraft helps to establish more comprehensive safety risk assessments and derive mitigating procedures.

Available reports show at least 36 cases of incidents involving electrical and avionics systems. These include antenna abrasion, radio interference, electrostatic discharges, volcanic ash deposit on avionics, electrical or computer failure, contamination or clogging of pitot tubes, and problems with speed indication due to clogged pitot tubes. Encounters have been categorized up to class 3 in the severity index (Table 1). Whilst the severity index gauges the generic impact on the aircraft, a more detailed analysis of interference mechanisms and modes of failure can help us to understand the specific hazards to flight operations [12].

Even though they mostly lead to smaller safety effects than engine failures, avionics failures can reduce flight-safety margins or increase crew workload in a situation which is already stressful. Indeed, hazards may arise from combined failures, malfunctions, external events or errors [10]. External factors (e.g. inadvertent encounter following insufficient volcanic ash data provided to the crew) may thus have to be addressed in the detailed safety risk assessment. In addition, volcanic ash may be a common source of multiple failure conditions; thus it is possible that multiple different systems are affected. If volcanic ash disturbs the primary system, it may also affect secondary or tertiary systems and thus weaken system redundancy.

5.1. Electrical or Computer Failure

Existing reports of electrical or computer failures also indicate the presence of volcanic ash inside the aircraft. Different mechanisms are possible for the electrical or computer failure due to volcanic ash. Firstly, reduced equipment cooling may be the result of volcanic ash blocking filters and therefore reducing air flow, or of volcanic ash ingested into air conditioning and cooling systems, reducing the efficiency of heat exchangers [4] [13] [14]. Secondly, volcanic ash particles which penetrate equipment enclosures can directly cause damage or failure, either due to their conductivity causing small arcing and short circuits or due to their static charges causing small electrostatic discharges on sensitive electronic components [4] [13] [15]. Finally, contaminated fire-warning systems can generate false fire warnings by mistaking the volcanic ash in the air for smoke from a fire [4].

A wide variety of failure modes can occur due to electrical or computer failure, ranging from small unnoticed effects at the small component level to degradation or even denial of service of important systems. The resulting failure conditions may even be catastrophic (e.g. total loss of electronic primary flight control systems).

5.2. Interference with Air Data Systems

Some reports indicated blocked pitot systems and problems with airspeed indication. Pitot-static systems use a tube to measure the total air pressure as well as a static port to measure the static pressure of the surrounding air. The indicated airspeed is derived from both measurements. If the total air pressure measurement is influenced by volcanic ash, the indicated airspeed is affected. The static ports are also used to calculate barometric altitude and vertical speed of the aircraft. However, in contrast to the pitot tubes, the static ports are not in parallel to the air flow, so that their clogging with volcanic ash is less probable. In addition to pitot-static systems, angle-of-attack vanes and temperature probes could be affected by volcanic ash, especially by erosion. Because air vents allow the airflow to exit, blocking of temperature probes is less expected.

Contaminated pitot tubes can cause fluctuating or unreliable airspeed indications, erroneous warnings, and loss of airspeed information [4] [13] [14]. For air data systems there is thus the risk of degradation of service, denial of service, and misleading information. One possible effect is on the Auto Flight System. It uses the airspeed and can change engine thrust and/or pitch according to indicated changes. This may bring the aircraft closer to the stall limit or to the structural stability limit due to misreading data points.

5.3. Interference with Navigation and Communication Systems

Navigation and communication systems of aircraft may be affected in different ways, including abrasion of antennas, attenuation and refraction of waves in volcanic ash clouds and electrostatic discharges. Figure 9 depicts the possible processes taking part in the interference with navigation and communication systems.

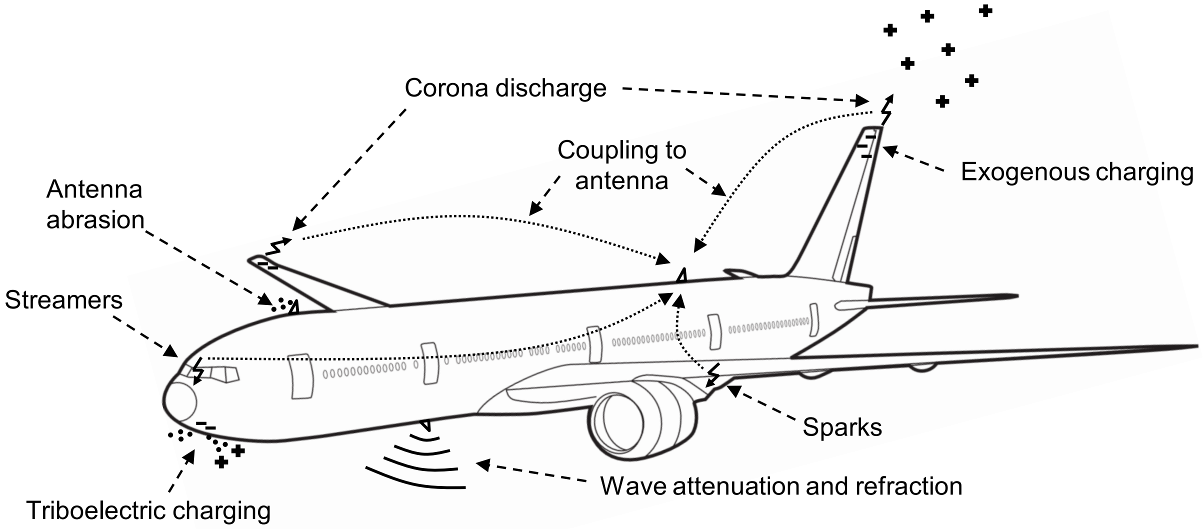

Figure 9: Processes involved in the interference with navigation and communication systems

Electrostatic discharges have been identified as having the most disruptive effect on navigation and communication systems [12]. They are the result of excessive charging of the aircraft structure which cannot be completely discharged in a controlled way by on-board static dischargers. Charging may be induced by an electric field inside the volcanic ash cloud (also responsible for some volcanic lightning [16]); this is called exogenous charging. But charging is probably more often generated by the triboelectric effect, as airborne volcanic ash particles strike the airframe [15]. This electrostatic phenomenon has been long known to occur with precipitation particles (mainly ice crystals), and is called P-static (precipitation static) [17].

Uncontrolled discharge can result from corona breakdown at aircraft extremities, through streamers across insulating dielectric surfaces or by means of sparks across unbonded conductive parts [18]. Reports of St. Elmo's fire indicate this occurrence. The discharges generate broadband electromagnetic noise which can couple into aircraft antennas and interfere with navigation and communication systems.

Wave attenuation and refraction are not expected to significantly change the operation of navigation and communication systems. In severe conditions, antennas may become so eroded that systems could stop working properly. In the case of electrostatic discharges, noise or interruption in communication systems have already been reported, but navigation systems may suffer degradation or denial of service as well. Although misleading information is theoretically possible on navigation systems which use signal phase or amplitude ratio of modulated signals, it is very unlikely to occur.

6. SUMMARY AND RECOMMENDATIONS

Our compilation shows that flights into volcanic ash or gas clouds are not uncommon. They may pose a considerable threat to the aircraft and its occupants. Therefore, we must understand its impact on all aircraft systems, not only on engines but also avionics and other aircraft systems. Even if the effects on other systems do not normally lead to risks as high as those posed by engine failures, flight safety may be considerably compromised. Our analysis of selected volcanic ash encounters shows that even flight in or near airspace with low modeled volcanic ash concentration may significantly impact aircraft systems. Flying into volcanic ash or volcanic gas-contaminated airspace can also affect the health of the aircraft occupants. A more efficient information flow and presentation of volcanic ash and volcanic gas-contaminated airspace to the flight crew may help increase the situational awareness and minimize risk.

We have shown that combining different data sets can help engineers to understand the impact of volcanic ash on the aircraft systems, and scientists in the volcanic ash advisory centers to verify and improve their dispersion models. In addition, information from past occurrences can help improve air traffic management as a whole, e.g. the information flow to the flight crew [19].

Encounters of aircraft with volcanic ash clouds are not reliably reported. Many reports omit essential information such as encounter location, time, and duration. Although some mechanisms exist for reporting encounters, such as pilot reports (PIREPS) and ICAO Volcanic Activity Reports, the reporting could be strengthened through establishment of a well-publicized, online reporting system that captures all the relevant information.

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LIST OF ACRONYMS

A	
ALPA	Air Line Pilots Association
D	
DDR	Demand Data Repository
DLR	German Aerospace Center
E	
EASA	European Aviation Safety Agency
EVAIR	EUROCONTROL Voluntary ATM Incident Reporting
F	
FAA	Federal Aviation Administration
FATS	Future Air Traffic Simulator
FL	Flight Level
I	
ICAO	International Civil Aviation Organization
ISD	InSufficient Data
P	
PIREP	Pilot Report
U	
UK	United Kingdom
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
V	
VAA	Volcanic Ash Advisory
VAAC	Volcanic Ash Advisory Center
VolcATS	Volcanic ash impact on the Air Transport System