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HAZARDS CAUSED BY VOLCANIC ASH ON AVIONIC SYSTEMS

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Abstract

Volcanic ash can have a serious impact on flight safety. A safety risk assessment is currently accepted as a means to increase air operation in areas contaminated with volcanic ash while minimising risks. Several aircraft systems can be affected by volcanic ash; safety analyses should thus consider hazards associated to all of them. This paper provides an overview of interfering mechanisms and modes of failure of avionic systems of aircraft exposed to volcanic ash. A focus is laid on navigation and communication systems, for which possible disturbing processes are discussed, in particular the electrostatic discharges caused by triboelectric charging. Examples are shown to stress the severity of possible failures of avionic systems. In addition, important aspects to be considered in a safety risk assessment of flights in areas contaminated with volcanic ash are presented.

1. INTRODUCTION

Interest on the impact of volcanic ash on air traffic systems has recently increased due to large aviation disruptions during the last years. Since the well-known case of the volcano Eyjafjallajökull in April and May 2010, flights were also delayed, cancelled or diverted due to eruptions such as of the Mount Merapi in 2010, Grímsvötn in 2011, Puyehue-Cordón Caulle in 2011, Kelut in 2014, Popocatépetl in 2015, and Raung in 2015.

Airspaces in which aircraft can be operated safely could be defined based on volcanic ash concentration and duration of exposure: the limit values are derived mainly from tests and incidents with engines. However, past reports show that there are effects of volcanic ash on other aircraft systems as well [1], which per se or in conjunction with other conditions may threaten the flight safety. Electrical systems, air data sensors and navigation and communication systems are also susceptible to failure or damage [1], [2], [3], [4]; it is therefore of interest to investigate how they are affected by volcanic ash.

After recent volcanic eruptions, emphasis of regulatory agencies for the management of air traffic during such events has been increasingly laid on a risk-based approach by operators. According to EASA [5] and ICAO [3], flight operations in areas with forecasted volcanic ash are to be conducted based on a safety risk assessment. Furthermore, susceptibility of aircraft features to volcanic ash hazards is to be addressed for new aircraft and engines, as stated in regulations [6], [7]. The objective of this paper is therefore to identify hazards and risks caused by volcanic ash on avionic systems, paving the way for a more comprehensive safety risk assessment of the complete aircraft and possible mitigating procedures. A special focus is laid on the impact of volcanic ash on the navigation and communication systems (NAV/COM systems).

The paper is organised as follows. Section 2 addresses past reports of volcanic ash encounter related to avionic systems and the severity of the incidents. Hazards associated with functional failure conditions of some systems are identified in Section 3, based on the investigation of interfering mechanisms. Additional considerations on the safety risk assessment of flights in areas contaminated with volcanic ash are made in Section 4, and a conclusion is presented in Section 5.

2. ANALYSIS OF INCIDENTS

2.1. Past Reports

Although studies of the effect of volcanic ash on aircraft have been predominantly carried out in the last years, encounters of aircraft with volcanic ash as early as 1953 have been reported. In [1], a compilation of 129 encounters of aircraft with volcanic ash between 1953 and 2009 is presented. The database contains information about the volcanic source of ash, encounter location, date, conditions of flight as well as observed effects on the aircraft. Currently, a list with reported encounters from 2010 onwards is being prepared [8], in a collaboration between authors of the present paper and of the original compilation. The updated encounter database will be published soon as a U.S. Geological Survey digital data series like the original [1].

As a first step for investigating the possible impact of volcanic ash on avionic systems, the available information of each encounter presented in [1] was analysed. TAB 1 presents a summary of electrical effects and occurrences with avionic systems found in the 129 encounters until 2009.

The figures shown in TAB 1 are minimum numbers of occurrences. Firstly, only reports that contain sufficient information to determine the type of incident were considered. For instance, reports mentioning “sparks on the windshield” were insufficiently detailed to identify whether grinding effects or electrostatic discharges occurred. It is also possible that effects on avionic systems were not included in some of the reports, either due to the greater attention devoted to engine problems or because interference went unnoticed by the pilot. In this context, it is important to mention that if misleading information occurs (incorrect information is displayed but is not

Type of Incident	Number of Occurrences
Antenna abrasion	3
Radio interference	3
Electrostatic discharge	16
Ash deposit on avionics	1
Electrical or computer failure	2
Contamination or clogging of pitot tubes	8
Problems with speed indication	1

TAB 1. Aircraft encounters with volcanic ash clouds: electrical incidents and incidents involving avionic systems (total of 129 encounters assessed)

detected as false), catastrophic consequences might result (e.g. false information of instrument landing system during CAT II/III precision approach). Finally, the number of occurrences can be larger since there is no systematic reporting of encounters.

Encounters with volcanic ash clouds involving at least one of the effects listed in TAB 1 amounted in total to 23. Therefore, several of these encounters were characterised by more than one type of electrical or avionic incident.

Electrostatic discharge is the most frequently reported effect in TAB 1. This category includes St. Elmo's fire (visual display of electrostatic discharges), which is one of the first indicators of aircraft encounter with volcanic ash [2], [3], [9]. Even considering that St. Elmo's fire is more easily seen during night, the fact that it was not reported more often in the database of [1] suggests that descriptions of other encounters may be indeed incomplete.

2.2. Severity of Incidents

In addition to the encounter data, a severity class is also attributed in [1] to each encounter in accordance with an existing severity index, ranging from class 0 (less severe) to class 5 (failure or damage leading to crash, which has fortunately never happened) [1], [2].

The types of incident listed in TAB 1 can be correlated with the existing criteria and severity classes presented in TAB 2.

Electrostatic discharge (class 0) and antenna abrasion (class 2) can be directly classified according to the criteria of TAB 2. In addition, other effects listed in TAB 1 can be sorted as follows:

- ash deposit on avionics is related to contamination of air conditioning systems (class 2), but could also lead to avionics damage (class 3);
- electrical or computer failures, even if not related to physical damage, have similar consequences to damage to electrical or computer systems (class 3);
- contamination or clogging of pitot tubes can be either assigned to class 2 or class 3, depending on the consequences;
- problems with speed indication are related to class 3 ("erroneous instrument readings").

Class	Criterion
0	Electrostatic discharge (St. Elmo's fire) on windshield, nose, or engine cowls.
2	Contamination of air handling and air conditioning systems requiring use of oxygen.
2	Abrasion damage to exterior surfaces, engine inlet, and compressor fan blades.
2	Minor plugging of pitot-static system, insufficient to affect instrument readings.
3	Plugging of pitot-static system to give erroneous instrument readings.
3	Damage to electrical or computer systems.

TAB 2. Severity class of electrical incidents and incidents involving avionic systems according to existing index

As with other types of incident, radio interference is not associated to any existing criterion, therefore prompting a revision of the severity classification [8]. After being asked to classify the incident "interference of navigation or communication systems", five different experienced pilots assigned a class between 2 and 4, with an average of 2.9 [8].

Although engine problems due to volcanic ash may pose more apparent risks, it is clear at this point that failures of avionic systems can also deteriorate the flight safety during or after encounters with volcanic ash clouds.

While the severity index gauges the general impact on the aircraft, a more detailed analysis of functions and modes of failure can deliver exact hazards to the flight safety. In many cases, understanding causes and mechanisms is necessary for the identification of hazards. This is addressed in the next section.

3. IDENTIFICATION OF HAZARDS

In this section, the causes for the types of incident listed in TAB 1 are analysed in more detail. This is done in separated subsections. In Subsection 3.1 (NAV/COM Systems), antenna abrasion and radio interference are assessed jointly; electrostatic discharge is additionally considered as a consequence of a common mechanism that also causes radio interference. Ash deposit on avionics and electrical or computer failure are regarded in Subsection 3.2 (Electrical or Computer Failure). Contamination or clogging of pitot tubes and problems with speed indication are analysed in Subsection 3.3 (Air Data Systems). In addition to the analysis of interfering mechanisms, possible failure conditions associated with the systems' functions are identified.

3.1. NAV/COM Systems

3.1.1. Interfering Mechanisms

Navigation and communication systems of aircraft may be affected in different ways during an encounter with volcanic ash. Possible mechanisms are: abrasion of aircraft antennas; attenuation and refraction of waves in volcanic ash clouds; and electrostatic discharges following exogenous charging or triboelectric charging. They are analysed next.

The first mechanism, perhaps the most evident one, is the abrasion of the antennas of navigation and communication systems. Volcanic ash particles are highly abrasive because of their sharp edges and their hardness [2], and can thus damage any external parts of the airframe, including the aircraft antennas. Indeed, in both reported cases of antenna abrasion, other external components of the aircraft were damaged as well (e.g. windshields, windows, stabilizers, leading edges and other probes). Antennas generally require a ground plane (normally the fuselage); impacts on the bonding may therefore change the antenna performance. Nonetheless, bonding is usually accomplished at the antenna base or through antenna components which are protected by other parts of the antenna. It is expected that these surfaces are not significantly affected by volcanic ash. There are normally no noticeable effects of ageing antennas subjected to aggressive environmental conditions during the lifetime of aircraft. In especial, the radiating element of the antennas is not directly exposed to volcanic ash. However, erosion of antennas with conductive volcanic ash (acidic ash or damp ash [2]) might partially block the view of the radiating element and change the antenna radiating pattern, with an impact on the range and direction of wave transmissions.

Another possible interfering mechanism is the electromagnetic behaviour of volcanic ash. Radar measurements of volcanic clouds exploit the backscattering of waves to monitor eruptions and clouds [10], [11], [12]. Reflectivity characteristics of volcanic ash have been investigated for these purposes [11], [13], [14], but the operating ranges of most NAV/COM systems lie beneath the studied frequencies, and additional analysis should be carried out concerning propagation and refraction of waves in volcanic clouds. This mechanism could act not only when the aircraft is flying through volcanic ash, but also when transmitted waves traverse volcanic ash-contaminated zones. Consequences may be connected with the attenuation and the propagation direction of signals.

In addition, volcanic ash is usually electrically charged itself, not only near the vent – where spectacular lightning activity can sometimes be seen – but also in regions distant from the source volcano [15]. One of the self-charging mechanisms of volcanic ash is interestingly the triboelectric charging (also seen later concerning the friction of ash with the aircraft), which depends on the size distribution of particles and their material [16], [17]. The charging process in the volcanic cloud can lead to an electric field which induces charges on the surface of the aircraft. Depending on the local field strength generated around the charged surfaces, electrostatic discharges can occur.

The generation of charges can also happen due to the triboelectric effect, as airborne volcanic ash particles strike the airframe (the particles and the airframe develop opposite charges after the shock) [18]. This electrostatic phenomenon in the aircraft has been long known to occur with precipitation particles (mainly ice crystals), and was therefore given the name of P-static (precipitation static) [19].

The discharge of accumulated charges can happen with corona breakdown at aircraft extremities (where stronger local electric fields are formed), through streamers across insulating dielectric surfaces (windshields, radomes, composite components) to the conductive airframe or by means of sparks across unbonded conductive parts [20], [21]. These discharges generate broadband electromagnetic noise which can couple into aircraft antennas and produce interference with NAV/COM systems. According to [22], corona discharge pulses are higher on composite aircraft; as a consequence of this, modern aircraft using more composite material might be more subjected to NAV/COM interference.

FIG 1 depicts the possible processes taking part in the interference with navigation and communication systems of aircraft.

In order to reduce the electromagnetic noise generated by precipitation static, static dischargers (also known as static wicks) are installed on the airframe, facilitating low-energy, more controlled discharges at multiple places [9], [21], [23]. The oft-recurring St. Elmo's fire during encounters with volcanic ash clouds suggests that the amount of triboelectric charging generated with volcanic ash particles may be more intense than with precipitation particles. This may be aggravated by the impact of volcanic ash particles which are already charged [15], [16], [17], [18] or by the

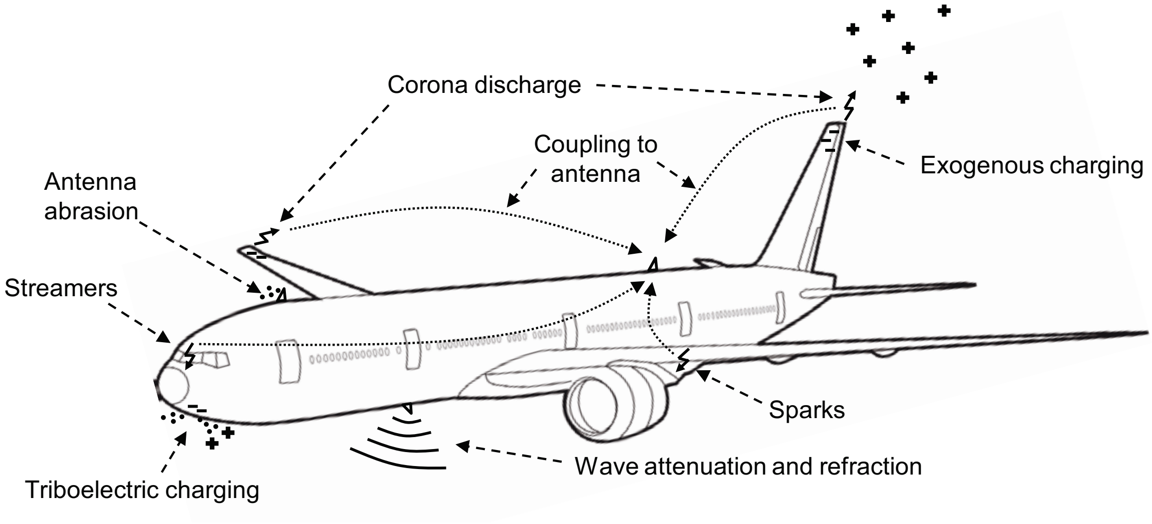

FIG 1. Processes involved in the interference with navigation and communication systems

fact that ice crystals can be formed in volcanic ash clouds [24], [25] and contribute to the triboelectric charging. As a result, static wicks are not able to discharge efficiently the charge accumulated and keep the aircraft potential below the corona threshold at other points. This can cause undesired corona breakdown which generates interfering electric noise into the NAV/COM systems.

Of all the above-mentioned mechanisms of NAV/COM interference – antenna erosion, wave attenuation and refraction, and electrostatic discharge –, the latter is presumably the most significant one. Indeed, radio interference is related to electrostatic discharges [2], [6], [9], [21], [26]. Thus, despite the larger number of reported events of electrostatic discharges in comparison to that of radio interference (TAB 1), it is expected that both effects are largely connected. The discrepancy can be attributed to the following causes:

- a higher level of awareness for visual effects (especially St. Elmo's fire on the windshield);
- interference on radio systems can go unnoticed if they are not being used at the moment;
- the phenomena corona and windshield-streamers get started at different field threshold levels (electrical noise generated by streamers is less of a problem for radios than corona-generated noise [20], while most observations of St. Elmo's fire occurred directly on the windshield, i.e. due to streamers); static wicks do not mitigate streamers along insulating surfaces;
- radio interference depends not only on the electrostatic discharge itself, but also on the level of coupling into the antenna and the sensitivity of the avionic receiver.

In order to provide additional support to the relation between electrostatic discharges and radio interference, a search for reports containing a description of St. Elmo's fire was performed on the database of the NASA ASRS (Aviation Safety Reporting System) [27]. A total of 52 reports, independent of volcanic ash, were analysed, and 12 of them (23%) also included NAV/COM problems. Even though this portion is not large, all of the 12 concerned reports described that both St. Elmo's fire and NAV/COM interference occurred together, when the aircraft was flying through clouds or storms. The bullet points mentioned above could also explain the accounts without NAV/COM problems.

It is important to notice that, whereas the radio interference reports of TAB 1 are related to communication systems, some descriptions found in the NASA ASRS also include navigation systems. Moreover, some navigation systems operate in frequency ranges close to that of VHF (Very High Frequency) communication, so that possibility of interference to navigation systems cannot be excluded.

There is unfortunately little information available to analyse in a more precise way the behaviour of navigation and communication systems under volcanic ash. In particular, different conditions, like volcanic ash concentration and duration of exposure, can affect the system's response. More knowledge could be gained with tests. In [28], for example, a design of a test-rig is presented in which aircraft components can be subjected to accelerated volcanic ash, allowing for investigations on the triboelectric charging and erosion.

3.1.2. Failure Conditions

Failure conditions of navigation and communication systems can be basically categorized into [29]:

- denial of service (the system does not operate);
- degradation of service (the system operates in a degraded way);
- misleading information (the system delivers false information, and the crew is not able to identify that there is a failure).

The mechanisms of abrasion and attenuation/refraction of waves change the behaviour of transmission, propagation or reception. Differences between the effects on the different frequency channels inside one given NAV/COM range are negligible. In extreme cases, for instance severe erosion of antennas with conductive ash, denial of service might occur. However, it is more expected that range and direction of transmission are changed, most possibly leading to slight degradation of service. In the case of strong refraction of waves, misleading information might occur for navigation services which depend on the direction of incoming waves for determining the aircraft bearing (e.g. ADF – Automatic Direction Finding) or on the time difference between transmitted and received signals for providing distance (e.g. Radio Altimeter, DME – Distance Measuring Equipment). Yet, significant refraction depends on large volcanic ash concentrations and volcanic ash cloud volume through which waves propagate; the probability of occurrence of such errors is therefore expected to be very low. Finally, it should be mentioned that erosion could also affect the optimum operation of static wicks, and increase of electrostatic discharges could thus follow.

Electrostatic discharges generate broadband electromagnetic noise [20], [21], [30] which may fall into the operating range of NAV/COM systems. This increases the noise floor of the NAV/COM receivers and can distort low-level signals until no useful signal can be distinguished or processed anymore. Therefore, both degradation of services (audible noise for communication, signal instability, data dropouts, or intermittent failure flags for navigation services) and denial of service (high noise interference for communication, loss of indication, or failure flag for navigation services) can happen [29].

Broadband noise introduced by electrostatic discharges can also cause misleading information [29]. It is possible only for some systems, e.g. VOR (VHF Omnidirectional Range) and ILS (Instrument Landing System), which rely respectively on the signal phase and on the amplitude ratio of modulated signals for providing guidance information. For other systems, misleading information is not possible (VHF communication) or extremely unlikely (systems that operate with particular signals, for which the generated noise would have to introduce a combination of very specific pulses of certain shape, frequency or synchronisation to alter the conveyed information).

3.2. Electrical or Computer Failure

3.2.1. Interfering Mechanisms

In one of the past encounters with volcanic ash clouds, there was complete electrical failure with loss of flight instruments and air data. The report of a second incident describes failure of the electronic engine controls and the flight management computer. From the information of these two reports, no conclusions can be drawn on the precise causes of failure. However, both reports also have descriptions of smoke and/or volcanic ash entering into the aircraft. Moreover, another report gives account of volcanic ash deposit on avionics. This indicates the direct influence of ash inside the aircraft. Three mechanisms involving volcanic ash which could cause electrical or computer failure are raised here: reduced cooling, short circuit and electrostatic discharge.

Volcanic ash has small particles that can penetrate aircraft filter systems [2]. Unfiltered volcanic ash ingested into air conditioning and cooling systems can therefore reduce the cooling efficiency of equipment [2], [3], [6]. This can happen either by the clogging of flow holes, therefore reducing air flow, or because volcanic ash particles in or on equipment can render the heat exchange more difficult.

Secondly, volcanic ash particles are able to penetrate equipment enclosures. As ash can easily absorb water and turn more conductive, small arcing and short circuits could happen [2], [3].

Thirdly, semiconductor devices present in electronic equipment can be very sensitive to electrostatic discharges. Charged volcanic ash particles ingested into the cooling systems of avionic compartments may therefore contribute to the risk of failure of avionic equipment [2], [18].

Finally, there is another possible cause of failure associated to volcanic ash. Contaminated fire-warning systems can generate false fire warnings by mistaking the volcanic ash in the air for smoke from a fire [2].

3.2.2. Failure Conditions

Insufficient cooling can lead to overheating and decreased performance of electrical and electronic equipment (degradation of service), or to complete unavailability or even damage (denial of service). Short circuits and electrostatic discharges can cause similar modes of failure, ranging from intermittent deficiencies, deteriorated operation to complete system loss.

A wide variety of failures can happen, since there is a large number of electrical and electronic components and systems, especially in modern aircraft which largely rely on such pieces of equipment. The effect on the flight safety depends on the system affected and functions performed.

It is important to mention that overheated equipment, even if not displaying damage or any failure during the encounter itself, can have its lifetime significantly reduced. In addition, charged particles stick to equipment and are more difficult to remove [2]. This may affect future operations of aircraft systems, even if the aircraft is not subjected to volcanic ash clouds anymore.

3.3. Air Data Systems

3.3.1. Interfering Mechanisms

Volcanic ash can contaminate air data sensors and lead to erroneous indications, in particular of airspeed [2], [3], [6]. Some reports of past encounters with volcanic ash indeed indicate blocking of pitot systems and problems with the 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 yields 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 the barometric altitude and the vertical speed of the aircraft. However, differently from 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. Due to air vents allowing the airflow to exit, blocking of temperature probes is less expected. Additional insight into the behaviour of air data sensors when subjected to volcanic ash could be gained by means of tests. Reference [28] shows a concept for a test-rig in which pitot tubes and other sensors can be exposed to air flow containing volcanic ash.

3.3.2. Failure Conditions

Possible effects of the contamination of pitot tubes comprise fluctuations and unreliable airspeed indications, erroneous warnings, and loss of airspeed information. For air data systems there is thus the risk of degradation of service, denial of service and misleading information.

The indicated airspeed is used by the Auto Flight System, which, in order to try to maintain a target speed, can change engine thrust and/or pitch. This may bring the aircraft closer to the stall limit or to the structural stability limit [28].

4. CONSIDERATIONS ON THE SAFETY RISK ASSESSMENT

Since the volcanic crisis posed by the eruption of Eyjafjallajökull in 2010, efforts have been made to allow more aircraft to fly in areas contaminated with volcanic ash but with reduced safety risks. One of the most noticeable developments is the introduction of the safety risk assessment methodology [3], [5], by means of which operators have to show authorities that flights can be executed safely with controlled risks in areas with forecasted volcanic ash in different concentrations.

While engine failures are the most prominent risk, other aircraft systems can also be affected by volcanic ash. As seen throughout this paper, failure and damage can happen to avionic systems as well, with different effects on the flight safety. Some of the possible resulting failure conditions of avionics might even be catastrophic, as they could cause multiple fatalities of occupants or loss of the aircraft. Examples for this are:

- total loss of electronic primary flight control systems;
- misleading information of ILS signals (localiser or glide-slope) during CAT II or CAT III precision approach [29];
- loss of all airspeed displays (including standby display) or misleading airspeed information on one primary display combined with a standby failure (e.g. loss or incorrect airspeed) [31].

Even if not leading to catastrophic events, many failures can contribute to reduced flight safety margins, for instance by increasing crew workload in a situation which is already stressful. Indeed, a potential hazard may arise from a combination of failures, malfunctions, external events or errors [32]. These hazards can only be identified by means of a thorough analysis, e.g. with a risk matrix. Events dependent on 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 this context, a volcanic crisis can cause problems in the air traffic management (ATM) as a whole. Differently from the assumption of risks in one given aircraft, as in the general guidance provided for system safety analysis [32], this might lead to consequences on different aircraft flying in the same area contaminated with volcanic ash.

In addition, safety assessments in many cases presuppose that failure conditions of different systems are independent. Volcanic ash may be in fact a common source of failure conditions. Considering this, it is possible that primary and backup systems may fail simultaneously, invalidating redundancy. For some navigation systems, for example, there are sometimes two antennas which are located in close proximity. Antenna coupling from points of electrostatic discharge is therefore similar, and common modes of failure for this system are possible. In contrast, VHF antennas positioned on the top and on the bottom of the aircraft in different fuselage stations may be differently exposed to electrostatic discharges and erosion.

After the identification of hazards and of the impact on the flight safety, a safety risk assessment basically contains an assessment of the probability of risks and determines whether they are acceptable. In a final stage, mitigation measures are developed in order to minimise risks. It is therefore important to consider all possible hazards and their combination in order to perform a refined safety risk assessment and determine efficient and comprehensible mitigations and controls.

5. CONCLUSION

Volcanic ash clouds pose a serious threat to the flight safety. While engines are usually viewed as the major affected component in aircraft, other systems can suffer damage or failure as well, as past reports of aircraft encounters show. This paper provides an overview of possible hazards caused by volcanic ash on avionic systems.

Concerning navigation and communication systems, mechanisms of interference are abrasion of antennas, wave refraction and attenuation, and electrostatic discharges. In particular, the triboelectric charging of the airframe can play an important role in radio interference. Computer, electrical and electronic systems can suffer from overheating, short circuits and small electrostatic discharges. Erosion and blocking of air data sensors can affect their operation.

Different failure conditions can arise from these mechanisms. The fact that avionic systems affected by volcanic ash can deteriorate significantly the flight safety is highlighted by examples of catastrophic consequences that may result from failures. In order to assess the overall impact on the aircraft, multiple failure conditions as well as their interdependency have to be assessed. Furthermore, it has to be considered that volcanic ash impacts not only single airplanes, but the complete air traffic management, so that mitigating actions have to be thought and applied in different layers of the air traffic system.

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