



# Article Detection and Avoidance of Atmospheric Aviation Hazards Using Infrared Spectroscopic Imaging

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**Abstract:** Atmospheric aviation hazards due to turbulence, poor visibility, high-altitude ice crystals and volcanic ash and gases are known problems for aviation and can cause both economic damage to engines and airframes as well as having the potential to cause the engines to stall in flight with possible loss of the aircraft. Current space- and ground-based assets allow observations of some of these hazards and their detection and movement can be forecast using modern computer weather forecasting and dispersion models. These largely strategic resources have proved very valuable but somewhat limited in the tactical sense, where commercial aviation must make rapid decisions in order to avoid an undetected or un-forecast hazardous cloud or atmospheric condition. Here we investigate the use of multi-spectral (two channels or more) infrared imaging from an aircraft perspective, and show that it is possible to use this information to provide tactical awareness tools for use by aviators and other stakeholders. This study has a strong focus on volcanic ash as an aviation hazard but also includes applications to some forms of clear air turbulence (CAT), to high-altitude ice crystals (HAIC) and windblown desert dust. For volcanic ash detection, the research shows that current two-channel satellite-based infrared techniques provide acceptable discrimination and quantification, but two-channel infrared imaging airborne solutions have significant drawbacks. Because of the limitation of two-channel methods, infrared spectroscopic techniques are investigated and it is shown they can significantly reduce the confusion caused by meteorological hydrometeors and potentially provide information on other atmospheric hazards to aviation, such as HAIC and some forms of turbulence. Not only are these findings important for on-going efforts to incorporate IR imaging onto commercial aircraft, but they also have relevance to the increasing use of drones for hazard detection, research and monitoring. Uncooled infrared bolometric imaging cameras with spectroscopic capabilities are available and we describe one such system for use on airborne platforms.

Keywords: airborne remote sensing; volcanic ash; aviation hazards

# 1. Introduction

There are several important hazards that affect aviation due to changing atmospheric conditions. The most severe of these is clear air turbulence (CAT), which can cause significant damage to airframes and to impact passenger and crew safety. CAT is undetectable by aircraft radar but can, in certain favourable circumstances, be forecast by numerical weather forecasting models (NWPs). High-altitude ice crystals (HAIC) are also a significant threat to aviation safety due to the potential for ice to clog-up important avionics instruments and because small ice crystals are invisible to current aircraft radar systems.

It is well known that volcanic ash presents a significant hazard to in-flight jet-powered commercial and military aviation. A detailed up-to-date discussion of the problem and relevant references to prior work can be found in the 2nd Edition of the Encyclopedia of Volcanoes [1]. The research work

described here stems from almost 30 years of investigating the problem of detecting and discriminating airborne volcanic ash using passive infrared observations that are on satellite-based, ground-based and airborne platforms. Other important and relevant work on the volcanological, chemical-physical properties of ash, effects on airframes and engines, modelling perspectives, regulatory environment and complementary observation systems are not discussed here but details of these may be found in some of the papers in Reference [2] and references therein.

There have been very few experimental programs devoted to the use of infrared imaging systems on board airborne platforms and so the work here must rely largely on inferences from satellite and ground-based measurements augmented by theoretical and modelling studies. Smith et al. [3] developed an infrared interferometer for probing the atmosphere from the ground and have also used the instrument on airborne and ship-borne platforms. The Atmospheric Emitted Radiance Interferometer (AERI) uses cooled detectors and can measure the infrared (IR) spectrum from 3.3–19.2 µm in a single field-of-view [4–6]. Some studies [7–10] have employed commercial IR thermal cameras, mounted onto light aircraft for looking downwards to measure upwelling radiation and infer surface temperature and other factors related to it. Other uses of thermal IR sensing from aircraft include high resolution measurements of methane and ammonia [11,12], chemical pollution [13], for mapping aquatic environments [14] and for mapping geological structures [15]. All of these instruments are either looking upwards or downwards and for the good reason that investigating infrared radiation works well when either the feature of interest is emitting (against a cold background) or absorbing (against a warm background). Gimmestad et al. and colleagues [3,16,17] used an airborne interferometric instrument to look in the forward direction in studies of atmospheric turbulence. The problem of viewing the atmosphere along a horizontal path or towards the horizon comprises both emission and absorption processes and is thus complicated and can lead to ambiguity.

In this work, the problem of viewing under different geometries is addressed using a new radiative transfer model that incorporates the widely used MODTRAN [18] model, an infrared scattering module, a database of refractive indices relevant to volcanic ash and other airborne particulates and a module that considers characteristics of the imaging camera. This study reviews and investigates multi-spectral infrared methods for measuring particulates and gases as atmospheric aviation hazards. The case for adopting a multi-spectral approach is made by considering the limitations of two channel systems and highlighting the need to optimise wavelength selection depending on the altitude of observation. To support these ideas, simulations using the new radiative transfer model are provided and extended to include other atmospheric hazards of interest to aviation, including some forms of clear air turbulence and high altitude ice crystals. Because of the limited amount of airborne data available, examples using high spectral resolution satellite infrared measurements are used and the configuration of a suitable airborne spectroscopic hazards imager (ASHi) is described.

## 2. Observations

#### 2.1. Satellite Observations

Passive multi-spectral (two-channel) infrared (IR) remote sensing to detect and discriminate volcanic clouds was first suggested by Prata [19]. The radiative transfer theory and some observations using the Advanced Very High Resolution Radiometer (AVHRR) were described. Prior to that study, Sawada [20] utilized single-channel infrared and visible (daytime only) imagery from the Japanese Geostationary Meteorological Satellite (GMS) instruments to infer volcanic clouds from meteorological clouds through differences in spatial and temporal effects. Since these studies, many improvements have been made and more sophisticated approaches have been applied to advanced satellite instruments, such as the MODerate Resolution Imaging Spectrometer (MODIS), the Along-Track Scanning Radiometers (ATSR, ATSR-2, AATSR), the Spin-stabilised Enhanced Visible and InfraRed Imager (SEVIRI), sensors on board the Japanese geostationary platform series (GMS), more recently Himawari-8, and the Suomi-NPP instrument on board the NOAA Polar Platform (NPP),

among others. An illustration of the ability of IR satellite instruments to detect ash clouds is shown in Figure 1, where the optical depth (see later) at 10.8  $\mu$ m is shown for an ash cloud from an Eyjafjallajökull eruption in May 2010 using MODIS imagery.



**Figure 1.** MODIS/Aqua optical depth retrieval for the plume from the Eyjafjallajökull volcanic eruption of 8 May 2010 at 13:35 UTC.

In the earth observation satellite era (beginning in the 1970s) studies of volcanic clouds had previously detected them using ultra-violet (UV) measurements relying on absorption by sulphur dioxide gas, as elegantly first demonstrated by Arlin Krueger [21] using Total Ozone Mapper Spectrometer (TOMS) data. Krueger et al. [22] provides an up-to-date review of the satellite-based UV accomplishments in quantifying volcanic SO<sub>2</sub> emissions. While these types of data have proven extremely useful and remain invaluable, they have two drawbacks: the measurements pertain to SO<sub>2</sub> gas and they are only useful when there is sufficient sunlight–monitoring during the nighttime and during high-latitude wintertime conditions is not possible or is difficult. The first limitation is ameliorated somewhat by noting that quite often ash and SO<sub>2</sub> are collocated [23], but not always [24] and so an indication of SO<sub>2</sub> may be associated with potential collocated ash. TOMS and its successor (the Ozone Monitoring Instrument–OMI) can also measure absorbing aerosols. Thus when the UV sensors detect SO<sub>2</sub> and anomalously high, collocated aerosol absorption, confidence of positive ash detection is much higher. There is little that can be done during low sunlight conditions.

Satellite-based instruments most often orbit in two configurations—polar orbits (usually sun-synchronous) with 1–16 day repeats, and geostationary orbits that have a fixed view of the Earth's surface and high temporal frequency (up to 5 min in some cases, but more typically 30–60 min). Polar instruments orbit ~700–1000 km above the Earth's surface while geostationary instruments are located at ~36,000 km above the Earth's surface. The Earth's atmosphere is located between ~0–18 km above the surface, but the large majority of absorption within the IR window (8–13 µm) is due to water vapour and 99% of this is contained in the first 5 km of the atmosphere. Clouds also strongly perturb IR radiation and these exist almost from the surface to the very top of the atmosphere. Generally, an

optically thick cloud will conceal radiation from below it and restrict satellite observation of ash and gas below, accordingly. IR instruments on both polar and geostationary platforms are able to see right down to the surface when conditions allow (e.g., low water vapour concentrations and clear skies) and hence even at distances of more than 1000 km, micron-sized ash particles can be detected if mass loadings (mass per unit area) are sufficiently high. It has been demonstrated that mass loadings as small as 0.2 g m<sup>-2</sup> are detectable by current IR satellite instruments [25,26].

Of interest to aviators are particles and gases that intercept air-routes and that remain in the atmosphere for protracted periods of time (hours–10 s hours). Volcanoes are capable of sending particles and gases, principally  $SO_2$  up to and above the tropopause and thus can affect aviation. Aged particles from volcanic eruptions in the atmosphere tend to be of low concentration and small  $(<1 \,\mu m radius)$ —most of the larger particles have fallen out and generally it is believed these aged clouds are less hazardous to aviation. For  $SO_2$  gas it is less clear. This is because the  $SO_2$  is transformed chemically into sulfate aerosols that are acidic and can damage airframes and windows. It has also been suggested that the acid formed from oxidation and hydration of volcanic SO<sub>2</sub> can affect engine parts and contaminate fuel [27,28]. At very high concentrations SO<sub>2</sub> is harmful to the respiratory system and causes eye irritation so if sufficiently high amounts of SO<sub>2</sub> are circulated within the cabin of a commercial aircraft there is potential for adverse effects on passengers. Hence SO<sub>2</sub> may be regarded as an atmospheric hazard and importantly, because it is often (but not always) accompanied by ash and because detecting it is somewhat easier than detecting ash, SO<sub>2</sub> may be regarded as an indicator of ash. Since it is unlikely that an aircraft would encounter a cloud of SO<sub>2</sub> at low altitudes, the main concern would be for an encounter at cruising altitudes and from a drifting cloud that had not travelled far from source. An interesting example of the potential for such an encounter arose during the February 2000 Hekla (Iceland) eruptions when a NASA research aircraft mistakenly flew through a cloud of SO<sub>2</sub> gas and was able to make concentration measurements [29]. An illustration of the use of infrared measurements made at a wavelength of  $\sim$ 7.3 µm from MODIS satellite data which clearly show good detection and quantification of the Hekla  $SO_2$  cloud, is provided in Section 4.3. It is not clear whether there was significant ash in the plume [29] but the use of data at 7.3  $\mu$ m for detecting the location of the plume is demonstrated. A method for detecting  $SO_2$  from aircraft is described in Section 4.3.

#### 2.2. Ground-Based Observations

Passive IR instruments can also be utilized to monitor volcanic emissions from the ground [30,31] and when placed near a volcano can provide useful warning of an ash eruption. There are some attractive reasons for using passive IR sensing close to volcanoes, not least from the perspective of safe observation. Unlike the satellite instruments, a ground-based instrument can be customized to detect gases and particles of interest, for example by using tailor made filters to isolate absorption features of  $SO_2$  gas or ash particle effects. Temporal and spatial resolutions also greatly exceed those that can be achieved from an orbiting satellite and because the instrument can be placed where needed there is no latency in obtaining data. Prata and Bernardo [30] demonstrated that ash detection was possible provided that there were at least three channels available and preferably five. The instrument they built-the Ground-based InfraRed Detector (GbIRD) has since been improved but the fundamentals of the technique are the same. Figure 2 illustrates the use of GbIRD and some retrieval results when viewing ash clouds from an erupting volcano a few kilometres away. Because viewing from the surface entails optical paths that contain most of the water vapour, there is a severe constraint on how far an IR instrument can "see" and most of the ground-based measurements were made from just a few kilometres from the source. Figure 3 shows radiative transfer calculations for an IR instrument with a relatively broad band (10–12  $\mu$ m) viewing upwards from the surface towards a target in the atmosphere. At ranges in excess of 20 km the atmosphere becomes so opaque that the signal from an ash cloud or any other cloud is obscured, making detection at these ranges unlikely or impossible. At ranges of more than 50 km it is likely that no detection is possible at all. This somewhat counter intuitive situation, where detection from

space at 36,000 km is adequate but ground-based detection from just 50 km is not possible, occurs because 99% of the water vapour is contained in the first few kilometres of the Earth's atmosphere and the long ground-based paths include all of the water vapour. Infrared camera providers (e.g., FL-IR, see http://www.flir-direct.com/content/thermal-imaging-how-far-can-you-see-with-it) are quick to point out the range limitations for detection, recognition and identification when used from the ground. Claims of detection ranges of 100 km from ground-based trials must be treated with extreme skepticism, see for example https://nicarnicaaviation.com/successful-ground-trials-of-volcanic-ash-detection-with-elbit-systems-clearvision-evs-system/, which is clearly an erroneous claim.



**Figure 2. Left (a)** and **(b)**: The Ground-based Infra-Red Detector (GbIRD) with five filters used for detecting ash from the ground. Note that at least three wavelengths are required and four is preferable. **(c)** A calibration rig is installed in front of the camera module to ensure accurate temperature readings. **Lower right:** GbIRD placed ~1 km from Tavurvur volcano, Rabaul, PNG. **Upper right:** Ash mass retrieval from the ground-based camera.

# 2.3. Airborne Observations

Prata [32] reported successful ash detection from the ground using a two-channel single-pixel radiometer from distances of a few kilometers at Sakurajima volcano, in southern Japan. Following this success the same instrument was flown on board a Cessna light aircraft to assess whether the system could detect emissions from Sakurajima and a neighbouring active volcano, Unzen. These experiments showed the limitations of using a single-pixel radiometric device from an airborne platform, where fast-sampling and large spatial views (imagery) are necessary. In 2003 further ground trials were conducted at Etna, Rabaul and Anatahan volcanoes using a multi-spectral (5-channels) imaging device using state-of-the-science uncooled VO<sub>x</sub> bolometric arrays. A helicopter-mounted imaging camera flying towards an ash plume from Anatahan volcano, showed for the first time that volcanic ash detection using airborne passive IR imaging was feasible. By mid-2010, following the April/May 2010 Eyjafjalljökull eruption, there was renewed interest in airborne detection and easyJet PLC, together with AIRBUS funded a scientific experiment in October 2013 demonstrating that ash detection was feasible from a range of ~70 km at 10,000–12,000 ft (The use of feet for specifying altitude is done here to be consistent with aviation terminology. Wherever appropriate SI units of m

is that the only view of importance is the view aligned with the aircrafts' heading-essentially the limb view to the horizon. This differs significantly from the mostly nadir view obtained from a satellite-based instrument and the upward view to space obtained from a ground-based instrument. It is not trivial to extrapolate measurements from satellite or from the ground because of these different viewing configurations. The successful AIRBUS/easyJet experiment, as is often the case in science, revealed some new and interesting problems as noted in Reference [33]. The demonstration to 12,000 ft, while a good first step, cannot be extrapolated to typical cruise altitudes of 20,000 ft and higher. At 38,000 ft the atmosphere is essentially transparent to IR radiation and a detection range to the horizon ( $\sim$ 300 km) is possible, in principle. If demonstrated detection up to 38,000 ft could be achieved then all cruise altitudes are included. However, while range is no longer an issue, the extreme cold (target temperatures of -50 °C or less) make sensitivity and proper in-flight calibration essential. The AIRBUS/easyJet trial used a pre- and post-calibrated system, with no on-board calibration module. This proved adequate for a scientific proof-of-concept demonstration, but for an operational instrument, such a system is likely to be extremely unreliable or at worst unsafe. This is concluded because ash detection algorithms rely on measuring temperature differences precisely. Differences as small as  $\sim$ 0.2 °C must be detectable and errors of this magnitude can lead to the mis-identification of a potential hazard and confusion with meteorological clouds-see the following Sections.



**Figure 3.** Transmission as a function of path distance for a thermal IR imager sensing from the ground along a slant path to an object–in this case a volcanic plume. Beyond 60 km the transmission falls below 10% making imaging the plume extremely difficult.

Measurements were also made of various types of clouds and for a low-level dust outbreak over the Atlantic ocean. The meteorological cloud measurements are important because they provide information on false-positives and also help validate the radiative transfer modelling.

The detection of low-level windblown dust using multi-spectral infrared measurements is anticipated from theory and has been verified through satellite detection [34]. Detection by this method from an airborne platform at 10,000 m is new and lends further support to the usefulness of on-board IR imaging from commercial aircraft. The dust layer observation by the AIRBUS A340

(see Figure 4) was made near the Canary Islands, off the coast of Western Sahara between 13:00–14:00 UT on 19 July 2012. At 13:55 UT on the same day the MODIS/Aqua satellite imaged the same region and the presence and extent of the dust outbreak can be seen in true-colour visible imagery (Figure 5). The location of the A340 and approximate viewing direction is also shown on the figure. Quantitative retrievals of dust loadings are, in principle, possible using these data, but accurate knowledge of viewing geometry and aircraft attitude are needed and these were not logged during this flight. However, proof-of-concept has been demonstrated.



**Figure 4.** Infrared data obtained from an A340 aircraft at  $\sim$ 10,000 m viewing clouds and windblown dust off Western Sahara on 19 July 2012. **Left:** Single-channel brightness temperatures–note the low level clouds and haze layer. **Right:** Dust index determined by combining 11 and 12 µm images, and accounting for differential gaseous absorption.



**Figure 5.** MODIS/Aqua true-colour image showing a dust outbreak off the coast of Western Sahara on 19 July 2012 at 13:55 UT. The location of the A340 is shown and the approximate viewing direction of the IR cameras is indicated by the blue-coloured lines.

Several airborne campaigns were conducted using the AIRBUS A340 aircraft in order to test on-board IR imaging cameras and collect data for meteorological clouds and refine algorithms (to reduce false detections), culminating in an elaborate test with an artificially-generated ash cloud over the Bay of Biscay, France, mentioned earlier. Details of the experiment are described more fully in Reference [33], so here just the important results and conclusions are presented.

Approximately 1000 kg of fine ash was sourced from recent volcanic ashfalls in Iceland and transported to AIRBUS in Toulouse France where it was loaded on to an AIRBUS A400 transport aircraft. A mechanism was developed to eject the ash into the atmosphere in a controlled manner and

a test flight was made to verify the system, in this case using a non-toxic powder with particles of similar sizes to the Icelandic ash. Further flights were conducted with the IR cameras mounted on to the side of an A340 to test the mechanical stability of the mounting and check that the cameras could function correctly during accelerations, high vibrations and the low temperates encountered at altitudes up to 25,000 ft. These test flights also afforded the opportunity to collect data. The experiment itself consisted of a single flight campaign on 30 October 2013 that consisted of four main runs at different altitudes from 5000 ft up to 12,000 ft. The purpose of these was to observe the ash cloud close to its actual altitude, a horizontal view, and from above and below. The ash was distributed into the atmosphere from the A400 by executing a spiral flight path upwards. Figure 6 shows the A400 while the ash was streaming into the atmosphere and a view of the IR cameras mounted into a pod on the side of the AIRBUS A340 test aircraft. Apart from these aircraft a smaller light aircraft (DA42) operated by the University of Dusseldorf was used to measure the ash in situ using optical counters. Since this was a controlled experiment the exact amount of ash, its composition and size distribution was known. The dispersion of the ash could not be controlled but the conditions selected were favourable and the ash could be detected up to 40 min after its release, although it was not easily perceptible by eye. The IR cameras could detect the ash from  $\sim$ 70 km and the best results were obtained when the aircraft was flying below the ash cloud centred at about 11,000 ft. For various reasons, explained later, poorer detectability was found at other altitudes. The ash cloud remained more or less at the same location but some layering did occur. The concentration of the ash was quite low  $\sim 200 \ \mu g \ m^{-3}$ , which is considered at the low end of detectability from modern infrared satellite instruments.



**Figure 6. Top:** AIRBUS A400 dispensing ash into the atmosphere. **Bottom:** AIRBUS A340 in flight with the IR cameras mounted in a pod and onto the forward lefthand side of the aircraft.

In summary, airborne detection using a two-channel imaging system has been demonstrated to detect ash mass loadings (concentration x path length) down to 0.2 g m<sup>-2</sup> and at flight altitudes to 10,000 ft and ranges up to  $\sim$ 70 km. The limb view case was not investigated in any detail as the artificial ash cloud remained at 12,000 ft while the aircraft altitude was  $\sim$ 5000–10,000 ft and so the view was essentially a slant-path view through the ash cloud to space. A schematic of the viewing geometry from an aircraft is shown in Figure 7.



**Figure 7.** Schematic showing an airborne instrument viewing ahead of the aircraft. A wide horizontal field of view is useful but the important view is along the limb, indicated by the dashed line. It is preferable to have a restricted vertical field of view.

## 3. Analysis and Results

# 3.1. Limitations of Two Channel Systems

Two-channel systems, typically using  $\sim$ 0.5–1 µm narrow band channels centred at 11 and 12 µm have proved to be very useful from satellite-based instruments. The actual choice of centre wavelengths is driven by what is available from satellite and is not optimal for ash detection (none of the current or past IR sensors were designed specifically for ash detection). The success of the satellite two-channel technique relies on near nadir viewing and more importantly works best for ash that is high in the atmosphere over a warm surface, above the clouds and where water vapour is much less concentrated. Ash detection near the surface is much less reliable from satellite instruments. Experience with multi-spectral IR ground-based cameras [30,35] shows that two-channel algorithms fail because of water vapour interference and because quite often there are other gases present, such as SO<sub>2</sub>. Another problem for ground-based observation, which is also relevant for airborne and satellite sensing, is the problem of thermal contrast. A simple model for the brightness temperature of a non-scattering, homogeneous, planar cloud of particles may be written:

$$T_i = \epsilon_i T_c + (1 - \epsilon_i) T_b, \tag{1}$$

where  $\epsilon_i$  is the emmisivity of the cloud in channel *i* (within some small bandwidth) and  $T_c$ ,  $T_b$  are the cloud (brightness) temperature and background (brightness) temperature, respectively. It can be seen immediately that if  $T_c = T_b$  then this isothermal system reveals nothing about the emissivity of the target. The thermal contrast of this measurement setup is defined as the temperature difference between the cloud and the background. The larger this quantity is, the greater is the sensitivity of the measurement. In order to infer some compositional property of the target, for example whether it is ash, SiO<sub>2</sub>-based, or a meteorological cloud, H<sub>2</sub>O-based, the target radiation must be absorbed or scattered in some way. IR imagers or radiometers measure radiance (or brightness temperature) that is wavelength dependent. A single channel can only tell you the brightness temperature of the target.

If the emissivity of the target is known then it is possible to infer more things (e.g., type of target). The emissivity (wavelength dependent) cannot be inferred using a single atmospheric measurement, but if another measurement or several more measurements at different wavelengths are available then it is possible to infer more details of the target. No matter how many spectral (wavelength dependent) measurements are made it is not possible to uniquely determine the temperature and emissivities of the target–there is always one more unknown than measurements available. For a perfect blackbody where the emissivity is independent of wavelength and has a value of one, a single measurement provides an estimate of the temperature of the target (in this ideal case the brightness temperature and actual radiative temperature are the same). Departure from blackbody behaviour is the norm and in the case of atmospheric targets is generally caused by decreased opacity of the target (a cloud). Atmospheric scientists generally prefer to describe this behaviour using transmittance ( $\tau$ ), where for a non-scattering cloud,

$$\tau = 1 - \epsilon. \tag{2}$$

The transmittance can be related to the optical depth (opacity) of the cloud through the relation:

$$\tau = \exp(-\delta),\tag{3}$$

$$\delta = kL\rho,\tag{4}$$

where  $\rho$  is the ash concentration (g m<sup>-3</sup>),  $\delta$  is optical depth, *L* is the geometrical depth (in m) of the cloud in the viewing direction and *k* is an absorption coefficient, with units of m<sup>2</sup> g<sup>-1</sup>. These equations illustrate how the properties of a cloud of particles can be inferred from measurements of the optical depth. It can be seen that as  $\delta$  increases the transmittance decreases and the cloud becomes opaque. In the limit of an infinite optical depth, the transmittance is zero and the cloud acts like a blackbody ( $\epsilon = 1$ ). For small optical depths it is possible, in principle, to determine the transmittances from a set (e.g., two) brightness temperature measurements and then infer the optical depth. It is important to note that the optical depth includes the product of an absorption coefficient and a length. The same cloud of particles can have very different optical depths if the geometrical path length is different. From two independent IR measurements, two quantities can be inferred; usually these are the transmittances at the two wavelengths. By using a radiative transfer model (adding more information to the system) quantities such as the optical depth and the mean effective particle radius can be derived.

A corollary of the physics of this problem is that a laboratory verification of the technique is surprisingly difficult. There is the problem of suspending micron-sized particles in a large chamber (it must be large to achieve a reasonable optical depth) and using optical components that are transparent to IR radiation (Germanium and Zinc Selenide are possible choices). The particles must be continuously agitated and in a dry environment to prevent aggregation. Most problematic of all is that a large thermal contrast is needed, and for realism the background temperature must be low (at 38,000 ft the background temperature maybe be as cold as -90 °C). No such laboratory trial has been undertaken and its usefulness for the airborne problem is doubtful, considering that it is difficult to simulate the aircraft environment in this way.

As mentioned, the wavelengths used in the two-channel technique are dictated by what is available from satellite instruments. In ground-based studies it has been found that other choices might be better. When selecting wavelengths there are two parameters to optimize. The first is discrimination. There is a need to discriminate volcanic ash from all other possible airborne substances, and the most common of these are hydrometeors. Once this condition is met it is then desirable to optimize in terms of sensitivity to ash. It is not obvious that both parameters can be optimized simultaneously. For example, the optimal discriminator may not yield the most sensitive wavelengths for ash quantification, since discrimination may depend on particle composition whereas quantification may depend more on effective particle radius. It is more likely that wavelengths for the best ash quantification are similar to or the same as those for ice or water cloud quantification. Beside these two constraints, the IR window is not open to all narrow wavelength band choices because of the ubiquitous nature of water vapour absorption and other gases also have absorption features (e.g., O<sub>3</sub> and SO<sub>2</sub>). With only two channels available the problem of optimization is compromised.

#### 3.2. Discriminating Power for a Two-Channel Imager

In order to describe the problem in a mathematical framework we introduce the concept of discriminating power. The discriminating power ( $D_p$ ) defines the ability of a dual-camera imaging system to distinguish two or more substances in the atmosphere. A higher value of  $D_p$  implies better discrimination.

$$\mathcal{D}_p = 4 \left[ \frac{k_{a,\lambda_1}(r) - k_{a,\lambda_2}(r)}{k_{n,\lambda_1}(r) - k_{n,\lambda_2}(r)} \right],\tag{5}$$

where  $k_{a,\lambda}(r)$  are absorption coefficients for ash as a function of the effective radius *r* and wavelength  $\lambda$ and  $k_{n,\lambda}(r)$  are corresponding absorption coefficients for a different substance denoted by the subscript *n*. The factor 4 is a scaling value and contains no physical meaning. In calculating  $\mathcal{D}_p$  the absorption coefficients are integrated over the filter response functions and  $\lambda_1$  represents the centre-weighted wavelength of the filter or channel. Likewise it is necessary to calculate the absorption coefficients at appropriate wavelength values to achieve sufficient accuracy for the integrations.  $\mathcal{D}_p$  is largest when the difference between the absorption for ash at the two selected wavelengths ( $\lambda_1$  and  $\lambda_2$ ) is largest and the corresponding difference in absorption for the second substance is smallest. Since the absorption coefficients are strong functions of r,  $D_p$  cannot be optimal at each effective radius but can be tuned such that it is greatest over a range of radii. Figure 8 illustrates the discriminating power against ice (n = ice) and water (n = water) for filters at 10.8 and 12  $\mu$ m (the standard arrangement) and an optimal pair chosen by analysing 1000 s of radiative transfer simulations. It can be seen that the standard filters are sub-optimal for radii above  $\sim$ 3  $\mu$ m, which is the typical size range found in dispersing ash clouds. The optimal filter pair (shown by the red-coloured lines) have been tuned to maximise the discriminating power for effective radii in the range  $1-10 \mu m$ . The standard set of filters only work well for very small particle sizes, when the ash has a low concentration. The optimal filters on the other hand work much better up to radii of  $\sim 15 \,\mu\text{m}$  or so and hence work best in higher ash concentrations that are more hazardous to aircraft. Beyond radii of 20 µm neither of the filter pairs have good discrimination power. Clouds with larger particle radii are likely also to have high concentrations. Whilst discrimination is not possible, identification of the cloud is. Whether this kind of identification (without discrimination) is sufficient for aircraft safety is not known.



**Figure 8.** Discriminating power as a function of effective radius for two different pairs of filters when the interfering substance is ice (left-hand side), and when the interfering substance is water (right-hand side). The black lines show the current sub-optimal *standard* filters (used in the AIRBUS experiment) and the red-coloured lines show a new pair of filters selected using radiative transfer simulations. Also shown are size distributions for ash used in the AIRBUS experiment and for a sample from the recent Puyehue eruption in Chile.

## 3.3. Simulations

A sophisticated radiative transfer model (ART–Ash Radiative Transfer model) has been developed to better understand the problem of sensing from an airborne platform using a multi-spectral IR imager. It is beyond the scope of this paper to describe the model here, but the essential details are that the model couples the MODTRAN radiative transfer code with a detailed microphysical ash cloud model that includes spectral refractive indices for ash, realistic size distributions and scattering effects. The scattering model uses the discrete ordinates method and the scattering parameters are determined from a Mie code for spherical particles and the T-Matrix method for non-spherical particles. A fast parametrisation scheme is used to calculate the complex spectral refractive indices of ash based on compositional measurements of fresh ash samples. A new aspect of the model is that non-spherical particles with sharp edges and asperities or aggregations of smaller particles can be considered. The model also incorporates a camera module that traces the radiation through the camera, considers aberrations and takes into account parasitic radiation. Since the camera measures extremely low radiances, the radiometric model also models noise sources and assumes a good calibration. An example of one simulation (1000 s were performed) is shown in Figure 9.



**Figure 9.** Ash Radiative Transfer (ART) model simulation for an aircraft cruising at 9 km (~29,500 ft) and viewing an ash cloud slightly above. **Top-left:** Temperature difference image (12.1–10.9  $\mu$ m). **Top-right:** Vertical profiles of the temperature difference—the right-hand panel shows a normalised temperature difference. **Bottom panels:** Individual temperature images. The mean effective particle radius is 3  $\mu$ m typical of dispersing ash clouds in the atmosphere and a mass loading of 0.2 g m<sup>-2</sup> is assumed. The mean anomaly is -0.40 K; the minimum anomaly is -2.23 K and the maximum anomaly is 1.07 K. The aircraft altitude is 9 km (29,527 ft).

The example shown uses a standard set of filters with central wavelengths at 10.9 and 12.1  $\mu$ m (it makes little difference if these are slightly different). An aircraft is at a cruising altitude of 29,500 ft and views a cloud ~3000 ft above at a range of 100 km. The top-left panel shows the brightness temperature difference image ( $\Delta T = T_{12.1} - T_{10.9}$ ). The thin layer of ash (layer depth of 1 km) is just visible in this difference image. An effective particle radius of 3  $\mu$ m has been used. All parameters are typical of what is expected from a dispersing ash cloud some distance from its source. The mass loading is 0.2 g m<sup>-2</sup> which is the lower detection limit for a satellite-based sensor. The simulated ash layer is assumed to be homogeneous but some random noise (based on the NE $\Delta$ T of the detector) has been added for realism. The two bottom panels show brightness temperature in each of the channels. The top-right panel shows a vertical transect through the image: the "normalised" transect is constructed by removing the profile mean. The greyed region indicates the location of the ash layer. A mean anomaly (averaged over the ash layer) of -0.4 K is found for this simulation. The NE $\Delta$ T for the channels sensing at these cold high altitudes is of the same order of magnitude as the ash signal. Because of noise and lack of sensitivity of this two-channel combination, detection of the ash layer is

A second simulation is shown in Figure 10 for exactly the same parameters except now an optimised filter choice is used. In this case it is seen that the anomaly is easily detected with a mean of -1.9 K.

very poor and in fact an automated system would not be able to identify this layer.



**Figure 10.** As for Figure 9 but using an optimised channel selection. The detection is superior and the anomaly signal is above the noise level.

The problem of accurately discriminating ash clouds from ice and water clouds is essential before attempting to quantify the amount of ash (its mass loading) in the cloud. In these examples the layer is prescribed as ash; in practice this is not known *a priori*. Discrimination requires optimisation of the filter channels while quantification is a problem of information content. For the second problem (quantification) at least five pieces of information are needed: the temperature of the ash cloud, the background and foreground temperatures and the emissivities in at least two wavelengths. This implies that at least five independent measurements are needed. A two channel system does not meet these criteria.

## 3.4. Confusion with Ice Clouds

Infrared imaging the atmosphere ahead of an aircraft will reveal any cloud within the field of view of the instrument, provided it is warmer or colder than the background. Clouds usually inhabit regions of the atmosphere below cruise altitudes, but in the tropics convective clouds (ice clouds) can reach up to the tropopause ( $\sim$ 18 km) and can therefore be intercepted along the flight route. Most of the time the imager will see clouds or clear skies—the lifetime of ash particles with radii > 1 µm is short, in the order of a few days to a few weeks following an eruption. Small ice crystals within convective clouds are also a hazard to aviation [36–38] and detection of ice is therefore of some interest. Here we show how two-channel systems perform in the presence of ash and ice.

The ART model was used to investigate the altitude-concentration space when both ash and ice clouds were present. The ice parameters were taken from References [39,40]. Figure 11 shows the results for the standard filter set (as used on many satellite instruments). The plot shows regions of the atmosphere that are amenable to ash detection (green-coloured), with areas where there is ice confusion in blue. Red signifies no detection is possible. The abscissa shows ash concentrations on a logarithmic scale and the ordinate shows altitude in kilometres. The dashed red-coloured contour lines are isolines of constant NEAT in K. The top-left of the plot is a region of low ash concentration and cold temperatures, while the bottom right is a region of high concentrations and warm temperatures. The current recommended concentration limits of 0.2, 2 and 4 mg m<sup>-3</sup> are shown as vertical lines. Three flight levels are also indicated as are the freezing levels for temperate and tropical atmospheres. The plot shows that there is a region where ash can be detected up to about 15,000 ft provided concentrations are between  $\sim$ 0.4 and 1 mg m<sup>-3</sup>. Detection at higher altitudes fails because of confusion with ice and for optically thin ash clouds no detection is possible below  $0.4 \text{ mg m}^{-3}$  and FL200. At all flight levels above FL200 the standard filter set will not detect ash because of confusion with ice. The AIRBUS experiment [33] was conducted at flight altitudes below 10,000 ft and with mean ash concentrations  $< 1 \text{ mg m}^{-3}$ . The region of the plot where the experiment was conducted is indicated by two horizontal red lines. It is apparent that the simulations suggest ash detection is possible, in agreement with the experimental results. It is possible to relax the detection criterion ( $\Delta T = -5$  K was used here) and this permits ash detection at lower concentrations but at the expense of larger noise. The NEAT isolines suggest that the camera must be very well characterised as NE $\Delta$ Ts in this regime are > 1 K.

An optimised filter set does much better (see Figure 12) and, in particular, performs extremely well at FL250 for moderate ash concentrations ( $<2 \text{ mg m}^{-3}$ ). There remains a region of the atmosphere at high altitudes (FL200 and above) with ash concentrations  $> 2 \text{ mg m}^{-3}$  where confusion with ice is still a problem. The ART model simulations could not find any combination of channels that optimised quantitative ash detection without ice confusion, but using more than two channels and having the ability to change channels at different altitudes can provide better discrimination. Something that is not possible with a two channel system.



**Figure 11.** Discrimination against ice.  $r = 3 \mu \text{m}$ ;  $\Delta T = -5 \text{ K}$ . The plot shows ash concentration vs. altitude for the filters used on the AIRBUS experiment (10.9 µm and 12.1 µm). The red-coloured region shows where no detection is possible. The blue-coloured regions are parts of the atmosphere where the system is unable to discriminate ash from water, that is, these substances appear the same. Green-coloured regions are where ash detection is possible. The red-coloured dashed contour lines indicate the calculated noise temperatures for the algorithm. A discrimination level of  $\Delta T = -5 \text{ K}$  has been used (indicated by the black-coloured contour line). Less stringent levels ( $\Delta T = -3 \text{ K}$ ) improve the detection range to lower concentrations but do not alter lack of detection with altitude; while more stringent levels compress the region of good detection. The solid red lines show the region of the atmosphere/ash concentration space sampled during the AIRBUS experiment. Three flight levels (FL) are shown and the locations of the freezing level is shown for a tropical and temperate atmosphere.

It is concluded that a reliable ash detection system requires more than two channels and preferably 10 s or even 100 s of channels in order to eliminate false detections and avoid ice confusion.



**Figure 12.** Discrimination against ice.  $r = 3 \mu m$ ,  $\Delta T = -3 K$ . The plot shows ash concentration vs. altitude for the optimised (NF). The red-coloured region shows where no detection is possible. The blue-coloured regions are parts of the atmosphere where the system is unable to discriminate ash from ice, that is, these substances appear the same. Green-coloured regions are where ash detection is possible. The red-coloured dashed contour lines indicate the calculated noise temperatures for the algorithm. The white-coloured contours are isolines of  $\Delta T$ . A discrimination level of  $\Delta T = -3 \text{ K}$  has been used (indicated by the black-coloured contour line). Less stringent levels ( $\Delta T > -3 \text{ K}$ ) cause greater confusion; while more stringent levels compress the region of good detection. The solid red lines show the region of the atmosphere/ash concentration space sampled during the AIRBUS experiment. Three flight levels (FL) are shown and the locations of the freezing level is shown for a tropical and temperate atmosphere.

# 3.5. Confusion with Water Clouds

ART model simulations were also conducted for a range of water clouds, also using the data of Stephens [39]. Similar problems arise when trying to discriminate ash clouds from water clouds given varying atmospheric conditions, altitudes, viewing geometry and concentrations. Figure 13 illustrates the size of the problem for the standard filter set and for an optimised set. While the

standard set fails—the anomaly is of similar size to that found for ash, the optimised set performs better. More research is required in order to better model these complex situations. What can be concluded here is that a two-channel imager using the standard set of filters (or similar) will fail to discriminate ash from ice cloud and water cloud in many situations.



**Figure 13. Left:** Simulations for the standard set of filters for a water cloud ahead on an aircraft flying at 7 km ( $\sim$ 23,000 ft). The mean anomaly is -3 K and is of the same sign and magnitude as the signal obtained from an ash cloud. **Right:** The same scenario but using optimised filters. The anomaly is now positive and can be discriminated from an ash cloud.

## 3.6. Calibration

The model simulations and experimental data suggest that any IR imaging system used at aircraft cruise altitudes will need careful and continuous calibration. The AIRBUS experiment demonstrated that calibration of the system was essential. For this experiment the flight duration was <2 h and the instrument was pre-calibrated. However, during the mission real-time detection was difficult or impossible because it was found that the instrument response had drifted during the flight. The main cause of this was the effect of the radiative environment around the detector coupled with rapidly changing scene temperatures. Without further processing and post-calibration the experimental results were inconclusive. Figure 14 shows pre-calibrated, uncorrected imagery obtained during the AIRBUS experiment for filters at 10.8 µm and a broadband channel (the 12 µm filter originally selected was replaced with a broadband filter because of the large noise sensitivity of the 12 µm filter)—the ash signal is concealed by noise in this case. A vertical transect of the temperature difference shows that the ash anomaly signal is within the noise—the layer is noticeable on the broadband image as a warm temperature anomaly but is indistinguishable from the meteorological cloud below. The ash anomaly can only be inferred in the temperature difference image through spatial pattern recognition.



Aircraft Lon: -2.097° Lat: 44.990° Alt: 5006.0ft Pitch: 2.6904° Heading= 9.946°

**Figure 14.** Broadband temperature image acquired by the instrument when the aircraft altitude was 5000 ft and the instrument was viewing upwards and ahead of the aircraft. The solid black line is a vertical temperature difference transect (Broadband-10.8  $\mu$ m filter) through the ash layer. The horizontal scale for the transect is in Kelvin and the noise level is  $\sim \pm 1$  K. The white circle shows the location of the position of the ash layer at the transect location. The ash layer can be discerned in the broadband image through spatial pattern recognition but cannot be discriminated from the meteorological clouds lower down.

The noise equivalent temperature difference (NE $\Delta$ T) for a resistive bolometric device is proportional to both the detector temperature and the background temperature [41–43]. The NE $\Delta$ T changes as the pixel and background temperatures change and a change in the pixel temperature is indistinguishable from a change in the background temperature. Keeping the pixel temperature low (e.g., cooling the detector) reduces the noise fluctuations, but there is a limit to how low the NE $\Delta$ T can be maintained because of the background temperature. For the unstable temperature environment of an aircraft, the noise fluctuations are dominated by background effects and lead to the high noise seen in the temperature images. The problem is exacerbated further by the fact that the signal response of the detector is proportional to  $T_B^{5/2}$  so that uncontrolled changes in the background temperature change the gain of the instrument and lead to erroneous calibration. The radiance received at the detector is registered as a voltage, *V*. The background noise component of the mean squared fluctuation of this signal is [41]:

$$\overline{V_B^2} = A_D \eta \sigma k (T_D^5 + T_B^5) \mathcal{R}, \tag{6}$$

where  $\mathcal{R}$  is the responsivity of the detector. Changes in  $T_B$ , the background temperature must be monitored in order to gauge the size of the background noise signal. The power incident on the detector from an external source causes a change in the bolometric resistance, which is registered as a voltage change across a load resistor. The incident power is usually confined to a small bandwidth and

can be calculated by integrating over the Planck function corresponding to the scene temperature,  $T_s$ . Thus the calibration of the detector, defined here as establishing a relationship between the output voltage (or digitised counts) and the radiant power intensity is non-linear with respect to scene temperature (the voltage is proportional to  $T^n$ , where n > 1 and depends on the wavelength interval). Generally for scene temperatures encountered at typical flight altitudes ( $T_s < 240$  K) the absorbed power will be small, so that the signal-to-noise (SNR) ratio is also small. A change in the scene temperature of 1–2 K may be indistinguishable from the background noise temperature fluctuations at

typical broadband bolometer with a noise figure (NEΔT) of 50 mK at 280 K. It is essential therefore that a bolometric imager used in an aircraft environment be continuously calibrated, preferably by using a two-point blackbody calibration before and after each scene measurement. The environment around the detector, and the temperature of the detector itself must be monitored continuously. An aircraft instrument without an on-board calibration module will be unreliable and likely to give erroneous signals.

the detector. Figure 15 illustrates the amplification of noise with respect to scene temperature, for a



**Figure 15.** Noise characteristics for an uncooled bolometer measuring atmospheric radiation at various altitudes in the atmosphere. The top-panel shows the noise amplification (SNR ) and NE $\Delta$ T (temperature error) as a function of scene temperature.

#### 4. Airborne Spectroscopic Hazards Imager

Several researchers [44–46] and Reference [26] have shown that hyperspectral sensors on board satellites provide much greater ability to detect and discriminate volcanic ash than the two channel

configured for both quantitative ash detection and discrimination. Furthermore, because of the ability to choose amongst many channels the same instrument can be used to detect high altitude ice clouds, windblown dust, some gases (notably SO<sub>2</sub>) and some types of turbulence. The system comprises a sensitive (NE $\Delta$ T < 50 mK) broadband (8–12  $\mu$ m) imager coupled with an uncooled static Fourier Transform Spectrometer (FTS) with a two-dimensional detector providing a single line of spectral data. The spectral resolution of the detector is customized for airborne platforms and a proprietary rocking/flip mirror is incorporated into the instrument to allow the FTS to scan the broadband image. An example of how the system will determine the type of atmospheric cloud ahead of the aircraft is shown in Figure 16.



**Figure 16.** Simulations and measurements for the ASH imager. **Top:** Simulation set-up for the model calculations of an altostratus cloud. **Bottom-left:** ART model calculations for altostratus cloud emissivity as a function of wavenumber for three different optical depths (or concentrations, as the path length is the same for all three situations). **Bottom-right:** Broadband image made during an AIRBUS A340 flight trial of an altostratus cloud.

The engineering principles governing the design and development of an IR spectroscopic imager (the Airborne Spectroscopic Hazards imager—ASHi) for use on commercial aircraft are currently being investigated with detailed studies of the design and examples of the detection and discrimination of airborne hazards. Here we have discussed the limitations of a two channel system and shown, through simulations and experimental work that a hyperspectral system will outperform a two channel system in both discriminating power and quantification. A very valuable advantage of the

ASH imager is that it will simultaneously provide information on high altitude ice crystals as well as several other potential aviation hazards by exploiting the spectral dependence of cloud emissivity, or characteristic spectral shapes. Figure 17 shows two more example of how ASHi can detect both ash and ice simultaneously—in this case the simulations use satellite data and the viewing geometry is appropriate for an instrument viewing downwards through the atmosphere.



**Figure 17.** Satellite measurements illustrating the spectral discrimination capability of the Airborne Spectroscopic Hazards (ASH) imager. **Left:** Satellite measurements for an ash cloud–cloud emissivity vs. wavenumber. **Right:** Satellite measurements for high altitude cirrus cloud generated by a tropical cyclone.

For other viewing geometries (e.g., upwards or along the limb) the characteristic shapes will be different. Since from an airborne platform all viewing geometries are potentially available, an efficient discrimination algorithm has been developed based on ART model simulations. These simulations provide a library of characteristic spectral shapes that have dependency on cloud composition (complex spectral refractive indices), altitude, viewing geometry, particle size distribution and particle shape. Allowance is also made for the noise characteristics of the imager and static FTS.

# 4.1. CAT

Clear air turbulence (CAT) is a catch-all term used to describe any kind of in-flight turbulence that occurs with little warning and often in what appear to be cloud-free or storm cloud-free areas [47]. Aircraft radar seldom indicate typical rain cloud signatures during CAT events but more commonly high wind speeds and or vertical wind shear are present [48,49]. Neither of these parameters (wind speed and shear) can currently be directly sensed remotely, and so the first indication of the severity of these factors appears as violent shaking of the aircraft or, in severe cases, the aircraft may undergo sudden altitude changes [50]. Many cases have led to aircraft damage and more importantly caused injuries to passengers and crew [51–53]. CAT is predicted to increase by up to 149% due to changes in wind pattern waviness and strengthening of the jet stream caused by climate change [54]. Currently aviation relies on pilot reports, numerical weather predictions and seasonal patterns to reduce the possibility of CAT encounters.

As CAT is frequently associated with strong winds, wind shear and stronger than usual jet streams, it may be possible, under some circumstances to remotely detect vertical wind shear indirectly through changes in temperature. The vertical acceleration associated with a temperature anomaly T in an ambient atmosphere of temperature T is,

$$\frac{\partial^2 w}{\partial t^2} = -g(\frac{T'-T}{T}),\tag{7}$$

$$\frac{\partial u}{\partial z} = -\frac{g}{f\overline{T}}\frac{\partial T}{\partial y},\tag{8}$$

where  $\frac{\partial u}{\partial z}$  is the rate of change of the horizontal wind component with height, *z* is height (altitude), *f* is the Coriolis parameter, *T* is temperature,  $\overline{T}$  is the layer mean temperature and *y* is a horizontal distance. Thus by continuously (in time) measuring the horizontal thermal gradient over a vertical layer using thermal imaging, the rate of change of the horizontal wind component can be estimated. If this is done for several layers, the presence of wind shear can be detected. A two-dimensional thermal camera image provides an estimate of  $\frac{\delta T}{\delta y}$  by relating the horizontal distance *y* to pixel number (*p*) through the characteristics of the optical system employed.  $\delta T$  is the change in brightness temperature across  $\delta p$  pixels. In discrete form (8) may be written:

$$u_1 - u_2 = k(T_2 - T_1) \frac{(z_2 - z_1)}{y_2 - y_1}.$$

where  $u_1$  and  $u_2$  are layer wind speeds at altitudes  $z_1$  and  $z_2$ , respectively,  $T_1$  and  $T_2$  are temperatures at pixel positions  $p_1$  and  $p_2$  respectively and k is a constant with a value of  $\sim 5.6 \times 10^3$  m s<sup>-1</sup> K<sup>-1</sup> at 45° latitude. For a layer thickness of 100 m, and a horizontal temperature gradient of  $10^{-2}$  K m<sup>-1</sup>, the wind shear is  $\sim 5.6$  s<sup>-1</sup>. This corresponds to moderate turbulence.

CAT is also often associated with the outflows from large storms that are either not directly in the line of sight of the aircraft or too distant to be observed, or perhaps in low light conditions and not perceptible. These outflows are often associated with tenuous cirrus clouds that, although invisible to the eye (sub-visual cirrus), can be detected by IR imaging. To illustrate this, the example of convectively induced cirrus band structures [55] observed in data from MODIS is used. The MODIS data have been downloaded and processed for one of the cases studied by Reference [55] in order to compare areas of cirrus clouds and thick cumulonimbus clouds. Transects were plotted through these regions (Figure 18) and show the spatial temperature variability is high across the cirrus band structures. Reference [55] showed that transverse bands were often associated with thunderstorm outflow, that they were relatively long-lived (~9 h) and that turbulence occurred in 93% of the cases investigated.



**Figure 18. Left:** MODIS/Aqua 11 µm brightness temperature image showing a large cloud formation and outflow cirrus clouds. **Right:** Temperature transects across the cloudy region and outflow region (red) showing a high temperature variation across the outflow region.

## 4.2. HAIC

High altitude cirrus clouds (HAIC) are a known aviation hazard that came to prominence during investigations into the crash of Air France flight 447 bound for Paris from Rio de Janeiro on 1 June 2009. The flight crashed into the Atlantic ocean with loss of all passengers and crew. The main conclusion from the investigators report was that the crash was likely due to erroneous airspeed indications caused by blockage of the pitot static tubes by ice crystals. Approximately 150 aviation incidents have been recorded since 1989 where HAIC has been a factor in causing engine problems and instrument malfunction (pitot static tubes). The basic mechanism is that very small ice crystals (radii  $\sim$ 50 µm or smaller) can be lofted to high altitudes in large numbers where they are essentially undetectable by aircraft radar and invisible to the pilot (especially in low light conditions). In sufficient numbers the ice crystals can cause engine power loss including engine surge, stall, flameout and rollback, and even engine blade damage. The main generation mechanism for HAIC arises from thunderstorm activity, where small ice crystals can form in the vicinity of the anvil and in the cirrus outflow region (see also Section 4.1). Aircraft radar and on-board ice detectors, mainly designed to assess airframe icing, are unable to detect HAIC.

Thermal measurements at 3.7 µm and in the infrared window between 8–14 µm are well suited to detect thin cirrus clouds and satellite data have been used in numerous studies to quantify sizes and measure abundances of small-sized cirrus particles [56–58]. For an imager with just two bands centred at 8.6 and 11 µm it is possible to easily detect and quantify cirrus particles [59]. Essentially, small ice crystals absorb IR radiation more strongly at 11  $\mu$ m than at 8.6  $\mu$ m, leading to a strongly positive temperature anomaly when the two channels are differenced. Figure 19 illustrates the detection of ice in the cloud from the eruption of Anak Krakatau in December 2018. The ice cloud was large and generating large amounts of ice that remained in the area for several days. The ice cloud reached altitudes in excess of 15 km and so was hazardous to aviation. Data from Himawari-8 was analysed to determine the amount and and size of the ice cloud and microphysical properties (effective radius, optical depth and mass loading). The ART model was employed assuming oblate spheroidal ice particles. From an aircraft, the detection of ice using an instrument like ASHi would be relatively easy. Indeed because the temperature differences get larger as particle sizes decrease, the sensitivity of the instrument is excellent. As the cloud particles get larger or the cloud becomes optically thick, sensitivities decrease and quantitative retrievals are difficult, however cloud detection is still possible. One issue with using the 8.6  $\mu$ m channel to detect ice is that it is also sensitive to SO<sub>2</sub>. Thus once again the value of high spectral resolution data can be seen, as using another channel at 7.3 µm would allow both SO<sub>2</sub> and ice to be unambiguously identified (see next).

## 4.3. SO<sub>2</sub>

SO<sub>2</sub> has a strong absorption feature centred near to 7.3  $\mu$ m and satellite band measurements across this feature have been highly successful at detecting and quantifying volcanic SO<sub>2</sub> at mid- to high-altitudes in the atmosphere. Water vapour also absorbs across this band and precludes use of this band at lower altitudes, where most of the water vapour resides. For long horizontal paths, relevant to the aircraft case, even small amounts of water vapour can obscure or confuse a retrieval of SO<sub>2</sub>. To reduce these effects, a correction for water vapour is necessary. ASHi is able to do this by using three 'micro' channels located on the SO<sub>2</sub> band and a short distance either side of the absorption. The near linearity of the Planck function over a small interval of wavelengths can be exploited to interpolate the radiance between the shorter and longer wavelength micro-channels, that are not substantially affected by SO<sub>2</sub> absorption, to obtain a pseudo-radiance at 7.3  $\mu$ m that is unaffected by SO<sub>2</sub>. A comparison between the presence of SO<sub>2</sub>. Off-line modelling under different atmospheric conditions can be used to relate the radiance difference to SO<sub>2</sub> slant-column abundance. In practice, detection of SO<sub>2</sub> from a commercial aircraft may be all that is required and rather than determine the slant column amount it would be sufficient to use the radiance difference to signal an alert for the pilot to heighten awareness

of a potential volcanic cloud. Note that detecting  $SO_2$  by itself is not sufficient to assume that ash is present, but can be used to be reasonably certain that a cloud of gas of volcanic origin is present.



**Figure 19.** Analysis of ice particles from the eruption cloud of Anak Krakatu on 23 December 2018 at 03:00 UTC. **Top:** Ice mass retrievals using the ART model with oblate spheroidal ice particles. **Bottom left:** Temperature difference curves using 8.6 and 11.2 μm brightness temperatures. **Bottom right:** Retrieved effective radius particle size distribution. Satellite data are from Himawari-8 courtesy of JAXA/JMA.

Currently there are no operating airborne instruments designed to measure  $SO_2$  using infrared 'micro' channels. However, the principle of the method can be demonstrated using satellite data. The  $SO_2$  plume caused by the 28 February 2000 eruption of Hekla volcano, Iceland reached high altitudes (~8–10 km), was measured by a NASA aircraft [60] and imaged by the MODIS/Terra satellite instrument. This case is therefore a good example to demonstrate IR detection and quantification of  $SO_2$ . The Hekla eruption started on 26 February 2000 and lasted about 12 days [61] but the explosive period occurred on 27 February and the emission reached high altitudes where it was observed by MODIS and measured (coincidentally) by NASA research aircraft [60]. For the purpose of illustrating detection of  $SO_2$  using windows near the 7.3 µm absorption feature a MODIS retrieval is provided in Figure 20.

The MODIS channels used are centred at 6.7  $\mu$ m, 7.3  $\mu$ m and 12  $\mu$ m. The off-band channels should ideally be much closer to the absorption band, but these are the optimal channels based on what is available The channel at 8.6  $\mu$ m cannot be used because there is another SO<sub>2</sub> absorption feature centred there; the 9.6  $\mu$ m channel suffers from absorption by ozone and the 11  $\mu$ m channel has ash absorption. The retrieval procedure follows the recipe provided above, namely: a radiance interpolation is used between 6.7 and 12  $\mu$ m radiances to obtain an SO<sub>2</sub> 'free' radiance (a pseudo-radiance). The difference between the measured 7.3  $\mu$ m radiance and the pseudo-radiance indicates the degree of absorption by  $SO_2$  and the ART model is used to generate a function that relates the  $SO_2$  slant column amount (in suitable units) to the radiance difference. In the modelling case, the  $SO_2$ -free case is calculated for an atmosphere without  $SO_2$ , and modelled radiances are then computed by introducing more  $SO_2$ in the form of a profile, with a prescribed peak and plume thickness. In practice, the actual height of the plume is often not known and must be guessed or determined independently. In the Hekla case because there was independent data, the height of the plume is well constrained. Using this technique from an aircraft has an advantage that it is possible to estimate both the height and the thickness using image analysis methods.



**Figure 20.** MODIS/Terra SO<sub>2</sub> retrieved concentrations for a plume from the 28 February 2000 eruption of Hekla, Iceland. Concentrations were determined using independent NASA DC-8 aircraft observations of the plume height and thickness and validated against in situ aircraft SO<sub>2</sub> data.

The NASA aircraft measured SO<sub>2</sub> concentrations at the top of the plume of 0.5–1 ppmV and the plume thickness at half-the maximum of the Rayleigh extinction observed (see Figure 6 of Reference [60]) is estimated to be ~1 km, which, at ~10 km gives partial column densities of 50–100 DU. These values match the retrievals remarkably well and provide good confidence that high altitude SO<sub>2</sub> plumes can be detected and quantified in this way. Using the NASA data it is possible to convert the column densities to concentrations and an example is given in Figure 20, where the approximate flight track of the NASA DC-8 is also shown. It is worth noting that even though the concentrations may be as large as ~2000 µg m<sup>-3</sup> in some places, the probability of passenger exposure to concentrations ~500 µm m<sup>-3</sup> for 15 min is ~0.1% [62].

## 4.4. Range Information

Passive infrared systems cannot directly measure the range to an object in the scene being sensed. This is may be a significant drawback for using such systems on aircraft that are moving fast (typical cruise speeds are  $\sim 30 \text{ ms}^{-1}$ ) as the time to intercept the hazard is short ( $\sim a$  few minutes). There are not many alternative ways to measure the range to a hazard in front of an aircraft; radar works well for clouds containing large hydrometeors, but is unable to detect volcanic ash, HAIC and CAT. Lidar is another possible *active* remote sensing method that can sense range but its use on commercial jet aircraft is compromised by the need to be able to range to distances of  $\sim$ 50–100 km which requires a high-powered laser and hence a large instrument and potential safety issues. There are ways to indirectly measure range using passive infrared. For clouds of particles or gases of sufficiently high concentration, the opacity difference from an undisturbed background will be noticeable at all wavelengths within the interval 7–14  $\mu$ m. Since some gases (e.g., CO<sub>2</sub>) are well-mixed in the atmosphere, it is possible to determine the range to the anomaly by measuring the radiation at certain wavelengths where the opacity is sufficiently high. In the  $CO_2$  band between 13.5 and 14.5  $\mu$ m effective ranges of 1–100 km can be obtained. The method relies on spectroscopic measurements and proceeds by comparing the brightness temperature spectra to pre-computed spectra based on altitude and external environment conditions (the background atmosphere); information that is available in real-time on board the aircraft. The range is estimated by minimising the difference between the measured and computed spectra for different specified ranges. Accuracies of 5–10 km in range are probably sufficient, since in general the hazard is detectable at ranges of 50–100 km. This method of range detection is similar to the CO<sub>2</sub>-slicing method used from satellites and described by Reference [63].

As an example of one implementation of the algorithm to determine the distance to a volcanic ash anomaly Figure 21a shows a sequence of satellite images at different wavelengths from the AIRS instrument. A small volcanic ash plume (circled) from Kambalny volcano, Kamchatka is noticeable in these images. As the wavenumber decreases within the  $CO_2$  band, the plume gradually becomes less visible as the absorption strength increases. Figure 21b shows the approximate heights measured from the surface for the same wavenumbers. The actual height of the volcanic plume was estimated to be ~7 km (flight level FL230) and Figure 21b shows the plume is no longer visible at wavenumber 721.5 cm<sup>-1</sup>, at a height of ~6.9 km. The height-temperature relationship was determined from an analysed temperature profile used in a numerical weather forecast. While this example is from a satellite platform, the same principle applies when viewing along the limb. An advantage of viewing along the limb is that both the opacity of the object and of the atmosphere are increased due to the longer viewing paths.

Another way to obtain information about the range to an object in the scene from an aircraft is to utilise the geometry of the measurement. Referring to Figure 7 it can be seen that with judicious choice of the total angular field of view (fov) of the instrument it is possible to know the range to the earth's limb given the altitude (h) of the aircraft. For example if the total fov is  $6^\circ$ , then at an aircraft altitude of 10 km the earth's limb is  $\sim$ 357 km away. Assuming that there are no clouds obstructing this limb view, then it can be detected in the image because the ground is usually considerably warmer than the atmosphere above. Simple geometry can be used to find that the top of an object at the height of the aircraft altitude, for example a volcanic ash cloud, is first sensed in the image when it is  $\sim$ 714 km away. At that distance, assuming the object's motion is much less than the aircraft, at a cruise speed of 1000 km h<sup>-1</sup> the limb point is reached in  $\sim$ 21.4 min. If the cloud height has not changed then at this limb position, the position (line and pixel coordinates) in the image can be calculated. Note that the only object ahead of the aircraft of importance is the one that is on a collision course with the aircraft, that is, it is at the same flight level as the aircraft. Objects below or above the aircraft are avoided. While this is just one scenario possible during flight, it is the most common. If an aircraft makes a turn and finds a hazardous object ahead already in the image then the assumptions above are no longer valid and there will be no range information available. The aircraft can still manoeuvre to avoid intercepting the object.



Figure 21. (a) Sequence of satellite images showing a small volcanic plume in different channels from the AIRS instrument measured at different infrared wavenumbers (values shown on each panel) all at the same time. Each image was individually histogram stretched to increase the contrast.(b) Temperature at the centre of the plume plotted against wavenumber for the same satellite image. The dashed lines correspond to the wavenumbers of the images shown in (a).

The assumptions are usually good for a dispersed volcanic ash cloud, but may not hold for a developing thunder cloud generating HAIC or for turbulence. For a cloud object that is not changing its shape, specifically its thickness and width, with time (over several minutes) it is possible to infer the rate of change of the range from the rate of change of the apparent size of the object in the image. It is tempting also to consider the use of two cameras to estimate range using parallax but the error in range is inversely proportional to the square of the parallax angle, which will be small for a commercial jet aircraft since the maximum separation of the cameras is limited by the wingspan.

While range is an important parameter, for the volcanic ash hazard and perhaps HAIC and CAT, the priority for a commercial jet aircraft will be to avoid the hazard. As long as the hazard can be detected within some time-frame, typically 5–10 min, the aircraft will be able to manoeuvre around the hazard. The ability to image the hazard in real-time and at rapid intervals greatly assists this tactic.

# 5. Conclusions

This study demonstrates that proposed two-channel imaging systems for use on aircraft have limited ability to discriminate ash from other meteorological hydrometeors. The standard filter set,

as used in satellite instruments and proposed for the system used on the AIRBUS experiment, fail to discriminate ash from ice clouds and water clouds in many common atmospheric situations, leading to serious false detections and potentially putting an aircraft at risk. It was shown that the situation can be improved using an optimal filter set. A new, sophisticated radiative transfer model was used specifically for simulating the problem of viewing ash, water and ice clouds from an aircraft at altitudes from and above 5000 ft. The model takes into account background and foreground radiation from the atmosphere and includes the effects of scattering from a layer of non-spherical particles. The fast parametrisation scheme to calculate refractive indices from ash compositional measurements means that different filters can be selected to provide optimal ash discrimination for different types of ash. A radiometric and optical camera module is used to estimate the radiation reaching the bolometric detector array, accounting for optical aberrations, bolometric and background noise sources. The analysis shows that an extremely accurate and stable calibration of the imager is needed in order to detect small temperature differences from very cold sources. It is concluded that an on-board calibration module is a necessity.

The inability of a two-channel imager to discriminate ash suggests the need for a multi-spectral instrument for detecting airborne hazards. A proposed instrument, the Airborne Spectroscopic Hazards imager (ASHi) uses a single broadband imager that allows good SNR and spatial sensitivity coupled to a spectroscopic array that provides 100s of channels in the IR window along a single co-registered line of pixels on the broadband (BB) image. A rocking mirror is used to scan the line through the BB image so that the spectrum of any feature identified in the image can be studied. The advantage of this system over others is that arbitrary combinations of channels can be used to identify clouds, thereby providing optimisation of the filter combinations for ash, for water clouds or for ice clouds. In this configuration false detections are minimised or eliminated. ASHi also includes an on-board blackbody calibration module, which is a necessity for an airborne microbolometer imager viewing very low radiation sources.

An illustration of the ability of ASHi to detect and discriminate ash was provided by using measurements from an airborne broadband imager coupled with spectra from a spectroscopic satellite instrument, modified for viewing from an airborne platform. These simulated measurements show the greatly improved discriminating power of a spectroscopic imager over a two-channel system and also show that such an instrument can also detect high altitude ice crystals and potentially some forms of turbulence. If precise quantification is not needed, then the instrument can be made much smaller and re-designed for mounting on a drone or ultra-light aircraft where weight may be a problem. The calibration module can be removed and for short flights, pre- and post-calibration procedures performed. ASHi should be used to complement existing technology and warning systems, including weather forecasts, pilot reports and volcanic ash advisories. In this respect ASHi should be seen as a tactical device to assist the pilot in real-time situations adding to the strategic information already available. In the future, launching a small drone into airspace contaminated with volcanic ash may provide strategic information and a viable way to ensure that aviation can fly along safe corridors and hence minimise the kind of disruption experienced during the Eyjafjallajökull eruption event of April and May 2010.

The proposed ASHi instrument and its design are described in greater detail in a forthcoming paper.

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