Benefits of NPOESS for Commercial Aviation – Volcanic Ash Avoidance

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January 2001

Introduction

Volcanic ash clouds represent a threat to commercial aviation. Excessive ingestion of volcanic ash can cause jet engines to shut down, and ash can damage other components of aircraft such as windshields and external sensors. Satellite data plays a role in helping aircraft avoid volcanic ash. This paper summarizes the problems volcanic ash presents to commercial aviation and considers the potential contribution of data provided by the planned National Polar-Orbiting Operational Environmental Satellite System (NPOESS) to the mitigation of these problems.

The methodology we use to estimate these benefits is to quantify the "costs" to civilian aviation from volcanic ash historically, and project how these costs might change in future years with and without NPOESS. Due to the nature of the hazard, this estimation deals with relatively rare events (4 or 5 significant eruptions per year), only some of which seriously affect aviation. Available information on the actual cost of these events is incomplete. However, in part because of the threat to human lives and the prominent role of commercial air travel in modern life, the problem has received considerable attention, as illustrated by an extensive literature.

We begin with a description of the physical hazard and historical costs. We then discuss the present response to volcanic ash threats to aviation, and role of satellite data in the mitigation of these threats. Finally, we address the possible contribution of NPOESS.

Description of the Problem

Volcanic ash presents two immediate problems to commercial aviation. The first, and most serious, is direct encounters of aircraft in flight with volcanic ash clouds. The second arises when aircraft are caught on the ground in a volcanic ash "rain", and are unable to resume service until runways and the aircraft themselves have been cleaned.

Volcanic eruptions produce ash clouds that sometimes rise to commercial jet cruising altitudes (10,000 meters), and can extend from sea level to altitudes as high as 50,000 meters. These ash clouds consist of rock and mineral particles and glass shards generally less than 0.5 mm in size and often mixed with acid gases or coated with acid droplets (Miller and Casadevall 1999; Heiken 1994). They are difficult for pilots to distinguish from water clouds in good visibility, and may be impossible for pilots to detect at night. Ash clouds are not identifiable by aircraft radar or any other current on-board instrument.

When a jet aircraft flies through an ash cloud, ash particles are ingested into the engines. This can lead to loss of power and, in some cases, to complete engine shutdown. Other damage to aircraft includes abrasion of windows, including the windshield, to the point of opaqueness; clogging of sensors external to the aircraft; ash contamination of the ventilation system and cabin interior. Electrostatic properties of ash cloud also interfere with radio communications.

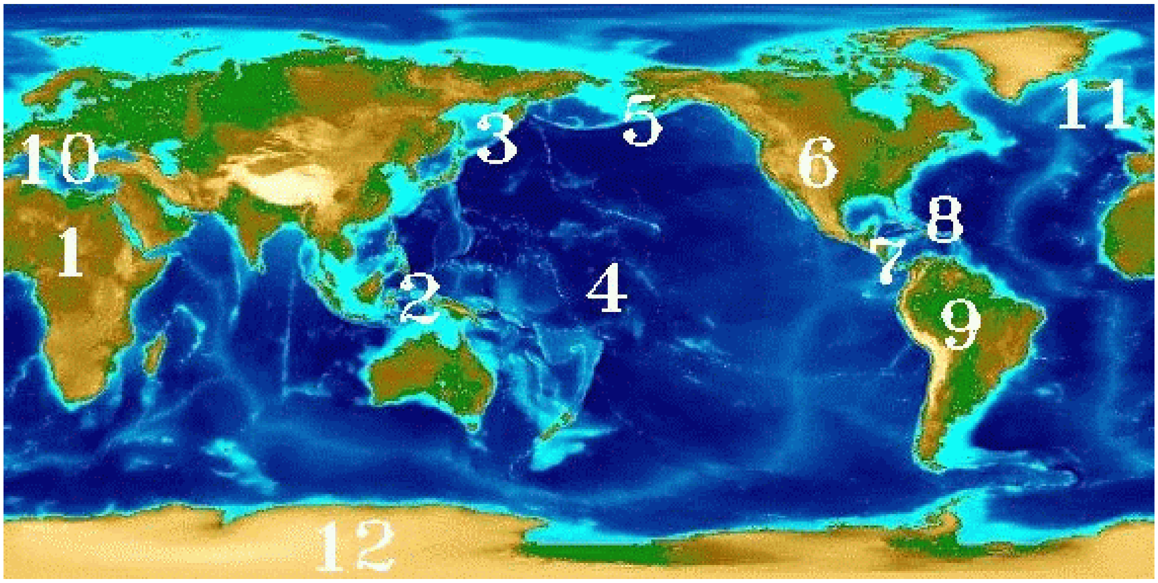

Figure 1: The world's volcanic activity zones.
Source: Michigan Technological University.

Figure 2: Active volcanos and flight paths in the northern Pacific.
Source: U.S. Geological Survey.

The problem of ash clouds is most severe where the world's volcanic activity zones (Figure 1) intersect major commercial flight paths. This happens prominently in the northern Pacific (Figure 2) and in the Indonesian-Australian region (Johnson and Casadevall 1994). However, the problem is not limited to these zones. Ash clouds that rise to commercial aviation cruising altitudes can move with the wind over many hundreds of miles in the course of several days (see Figure 3). Ash cloud encounters have taken place 3000 miles away from the source eruption.

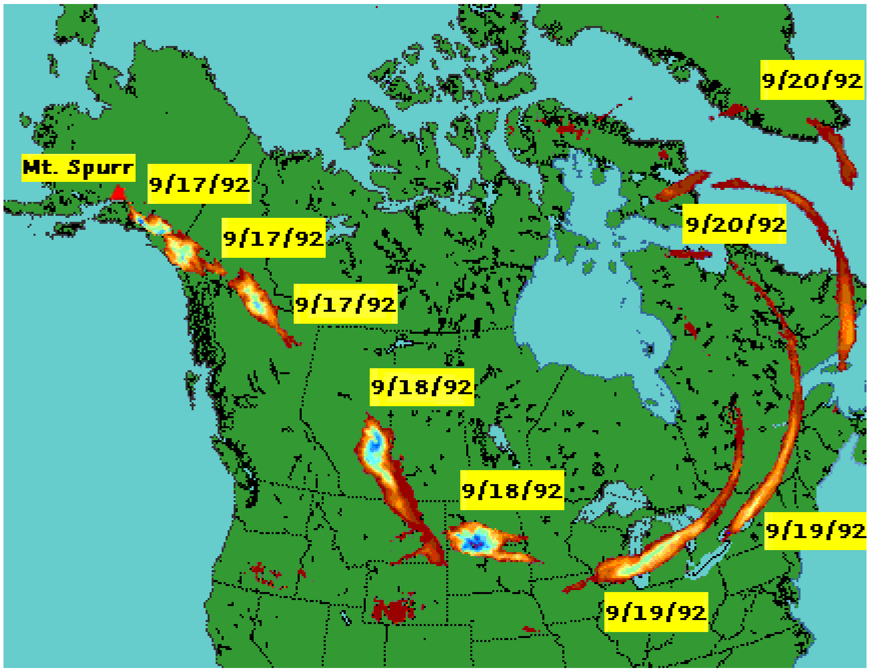

Figure 3: Movement of ash cloud from 1992 eruption of Mt. Spurr, Alaska.
Source: David Schneider, U.S. Geological Survey.

Physical Hazard

The greatest hazard from volcanic ash is compromised aircraft propulsion. When volcanic ash is ingested into jet engines (Przedpelski and Casadevall 1994), it abrades compressor fan blades. In addition, volcanic glass in the ash has melting temperatures within the operating range of modern jet engines (over 700 degrees C). Molten glass can accumulate on turbine nozzle guidevanes, causing compressor stall and ultimately complete loss of engine power. Engines are particularly susceptible during high-thrust operations during takeoff and climbing. Sulfate deposit accumulation from SO_2 in ash clouds can also lead to loss of engine power. Engines can loose power completely within about one minute in "young" ash clouds (within hours of eruption) due to high particle concentrations. Modern high-temperature jet engines are more susceptible than older jets. Reciprocating engines are not affected as badly as jet engines.

In addition to compromising engines, volcanic ash causes other damage to aircraft in flight. SO_2 and acid aerosols can etch or craze aircrafts' acrylic windows and damage exposed metal, rubber, and plastic (leading edge erosion/abrasion). Air speed sensors on the outside of the aircraft can be clogged. Radio communications can be compromised by static electricity.

Volcanic events were not a major concern to aviation before the 1970s, because air travel was less common and because reciprocating engines are not as badly affected.

1953	Mt. Spurr Alaska	at least one military F-94 jet intentionally flew through ash cloud; Plexiglas cockpit canopy "frosted"; Elmendorf Air Force Base closed to traffic due to ash for 8 days; no known records of commercial plane effects (Kienle 1994)
1976	Augustine Volcano Alaska	two U.S. Air Force F-4E Phantom jets encountered an ash cloud during training exercises; canopies were scoured and paint at wing tips was sandblasted off; also three Japan Airlines planes encountered ash clouds, one DC-8 windshield had to be replaced
1980	Mt. St. Helens Washington	C-130 lost two engines climbing through ash clouds at 3400 m and suffered damage to two other engines; $500,000 damage; other aircraft suffered minor surface damage; seriousness of threat fully recognized
1982	Galunggung Indonesia	(BA 747, 11,300 m, lost 4 engines; Singapore Air 747, 9000 m, lost 3 engines). Both at night; casualties narrowly averted; extensive damage to aircraft. Also: Garuda Airlines (Indonesia domestic) DC-9 and a Singapore Airlines 747 encountered ash but reached their destinations without significant damage.
1983	Colo Volcano Indonesia	British Airways 747 encountered eruption cloud, returned to Singapore for inspection, no significant damage.
1985	Soputan Volcano Indonesia	Quantas Airways 747 nighttime encounter. Aircraft withdrawn from service for 5 days after landing in Melbourne; engines removed and cleaned (Johnson and Casadevall 1994).
1986	Augustine Volcano Alaska	affected airline traffic in Anchorage area. U.S. Air Force evacuated planes from Anchorage for three days. Alaska Airlines cancelled 40 out of 68 Anchorage arrivals and departures on 28 March and deleted the Anchorage stop of its Seattle-Anchorage-Fairbanks flights 27-29 March. United cancelled 35 flights 27 to 29 March. Western Airlines cancelled all flights to and from Alaska 27-28 March and some flights 29 March. Other carriers, like Northwest, also cancelled Europe-Asia flights over the north pole.
1989/90	Redoubt Volcano Alaska	(KLM 747, 8500 m, lost all engines; engines restarted 1-2 minutes before impact). $80 million in damage to aircraft (Steenblik 1990). Six additional ash cloud encounters (four in Alaska, two over west Texas) did not result in loss of engine power (Casadevall 1994).
1991	Mt. Pinatubo Philippines	at least 20 commercial jets affected: 3 within 200 km/3 hours; 12 720-1740 km away/12 to 24 hours. Damage may have exceeded $100 million (Miller and Casadevall 1999).
1991	Mt. Hudson Chile	interfered with air traffic over the Atlantic Ocean
1992	Mt. Spurr Alaska	August 18 eruption deposited 1-3 mm of ash at Anchorage airport, resulting in closure and reduced operations for several days. Ash removal and associated costs estimated at $680,000; revenue loss due to flight cancellations at $276,000. September 17 eruption sent ash cloud 5000 km over Canada and United States, which caused major disruption of commercial air traffic over the U.S. some 48 hours after the eruption.
1993	Lascar Chile	interfered with air traffic over the Atlantic Ocean
1994	Klyuchevskoy Kamchatka	aircraft rerouted for 48 hours; no incidents
1994/95	Rinjani Indonesia	interfered with air traffic, particularly terminal operations at several nearby airports, leading to extensive rerouting
1996-98	Soufriere Hills Montserrat	disrupted air traffic in the Caribbean and adjacent Atlantic Ocean.
2000	Etna Italy	Air Europe Airbus 320 encountered ash shortly after takeoff, windshield cracked, plane returned safely to airport

Table 1: Selected eruptions and their effects on aviation. Various sources.

By the late 1970s, several jet aircraft had flown into ash clouds over Alaska and Japan, but suffered only minor damage to leading edges. When wide-body jets (747, DC-10, MD-11, etc.) with bigger, hotter engines entered commercial service in large numbers in early 1980s, both the incident frequency and severity of volcanic ash interactions increased. The eruption of Mt. St. Helens in 1980 is seen by many as a watershed event that accelerated concern over volcanic ash in the aviation community. Table 1 lists selected eruptions and their interactions with aviation in the history of volcanic ash and aviation. To date, seven of about 100 aircraft known to have encountered volcanic ash in flight lost power as a result.

There are 534 active volcanos worldwide. The geographic regions most at risk from volcanic ash are the North Pacific, Southeast Asia (including Japan), central and northern South America, Mexico, the Caribbean, and Iceland (the North Atlantic). North Pacific air routes cross or are downwind of some 100 historically active volcanos, or 20 percent of world's total. Collectively, the North Pacific volcanos produce on average 5 to 6 eruptions per year. On an estimated 4 to 5 days per year, volcanic ash is present in the region's air above 9000 m; on an additional 10 to 12 days per year, it is close enough to the routes to be of concern to aviation (Miller and Casadevall 1999).

Economic Effects

In estimating the economic effects of volcanic ash on aviation, it is useful to distinguish between two main categories: "airborne" effects due to aircraft encounters with ash clouds, and "airport" effects due to flight delays and cancellations.

Each year from 1980 to 1995, on average, five commercial jets encountered ash clouds in flight. About 10 percent of these encounters resulted in loss of power. The total reported damage to engines, avionics, and airframes from such encounters (1980 to 1998) is about $250 million. Some ash damage may not have been reported; it is likely that this number underestimates the actual costs.

Fortunately, no ash encounter to date has led to loss of aircraft or fatalities. However, observers agree that several encounters (Galunggung 1982; Redoubt 1989/90) had the potential for disastrous consequences. It seems reasonable, therefore, to suggest that there has been about a 1 percent chance of total aircraft loss in the event of an ash cloud encounter.

To estimate the economic risk of "airborne" effects, we add the expected annual equipment damage (some $15 million/year based on historical data), and the estimated annual risk of a total aircraft loss. Assuming 200 passengers and crew, and a value per human life of $5 million (see Gramlich 1990), plus $100 million for the aircraft, the cost of a total aircraft loss is $1.1 billion. The economic risk of total aircraft loss is 1 percent of 5 encounters per year, or $55 million. Thus, the overall economic risk from "airborne" effects historically is a about $70 million per year.

On the ground, additional costs are incurred when airports are shut down and flights are delayed or cancelled because of ash clouds and ash deposition. (Aircraft may be moved to avoid ash contamination on the ground.) Between 1980 and 1998, over 35 airports in 11 countries (USA, Japan, New Zealand, Mexico, Guatemala, Colombia, Argentina, Indonesia, Japan, New Guinea, Philippines, Falkland Islands) have been shut down or severely affected by ash falls (Miller and Casadevall 1999). The historical average in the jet aviation age, therefore, has been about two "airport" events per year.

Although the particular effects vary from one incident and airport to another, most fall into one of three categories: (1) lost revenue to airlines because of cancelled passenger and freight service, (2) lost revenue to airports from cancelled traffic, and (3) delay costs incurred by passengers. Other costs include the removal of ash from airport facilities, the relocation of aircraft to avoid stranding them (for example, a Boing 767 was stranded at Manila airport for 6 days due to ash contamination from Mt. Pinatubo in 1991), and delays associated with rerouting flights around potential ash hazards, among others.

Tuck and Huskey (1994) summarize the economic effects of the 1989/90 Redoubt eruption on the aviation industry. In addition to $80 million in damage to aircraft, they identify some $21 million in economic losses due to disruption of air travel at Anchorage International Airport (see Table 2). This is a lower bound estimate of overall losses, as it does not include the cost of disruptions in international passenger traffic.

domestic passenger traffic	$1.7 million
international passenger traffic	[not quantified]
domestic freight	[minimal]
international freight	$15.0 million
Anchorage Int'l Airport revenues (landing fees, concessions, fuel flowage fees)	$1.6 million
airport support industries (fuel distribution, ground crews and service, catering, concessions)	$1.0 million
passenger waiting time	$1.8 million

Table 2: Estimated economic effects from the 1989/90 Redoubt eruption.
Sources: Tuck and Huskey (1994); Casadevall (1994).

Using the Anchorage Airport figures as a representative example, we assume "airport" losses in the event of ash fall of about $20 million. Historically, two airports per year have been affected, for a historical loss of $40 million per year in "airport" losses.

Thus, the historical losses to commercial aviation from volcanic ash over the baseline period 1980 to 1995 have been on the order of $110 million per year. This baseline historical "exposure" can serve as a starting point for the evaluation of benefits from NPOESS. However, before it can be used as a baseline (no NPOESS) exposure level for future years, it must be adjusted to reflect changes that have taken and will take place. Among the former is a significant ramping up in the response to volcanic ash threats to aviation since the mid-1990s.

Response

Current Response/Mitigation

Response efforts have focused on improved detection of eruptions, forecasting of ash cloud movements, and warning and training of pilots. At present, it includes monitoring of volcanos for eruptions and ash clouds (in part by satellites), a system to generate and disseminate warnings specific to commercial aviation, and systematic ash avoidance training for commercial pilots.

Efforts to safeguard commercial aviation against volcanic ash hazards have centered around a global network of nine Volcanic Ash Advisory Centers (VAACs; Figure 4). Each VAAC is responsible for monitoring volcanic clouds in its region and issuing Volcanic Ash Advisory Statements (VAAS) to pilots. The VAAC network was established in 1995 as part of the World Meteorological Organization's International Airways Volcano Watch.

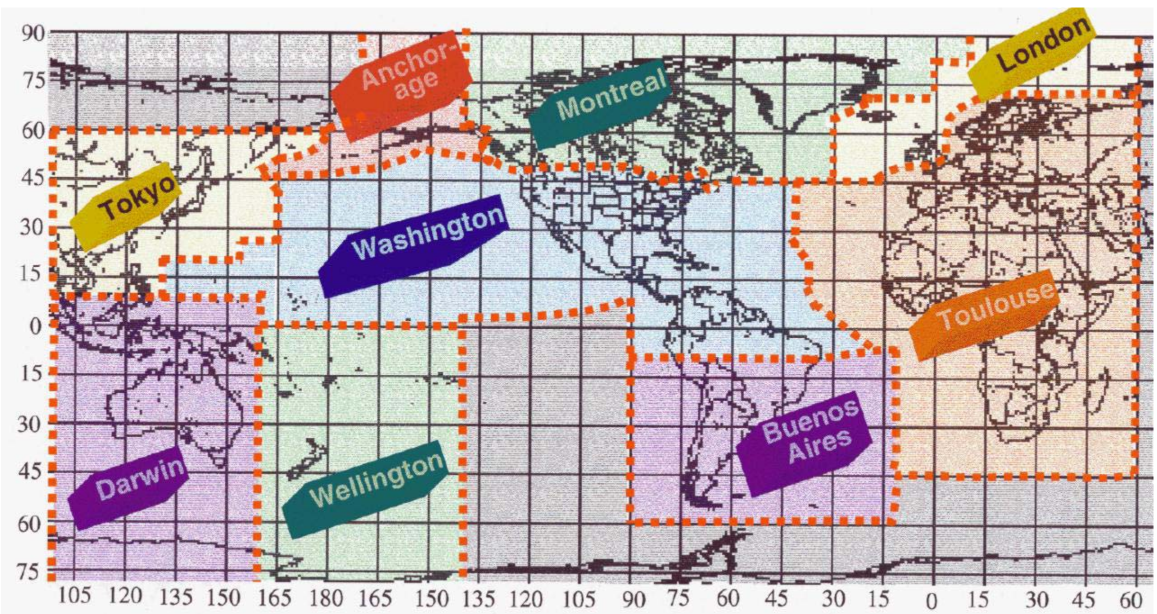

Figure 4: Vocanic Ash Advisory Center (VAAC) coverages.
Source: National Oceanic and Atmospheric Administration.

The VAACs utilize information from volcano observatories, airline pilots, satellite observations, and ash cloud trajectory models. The satellite data available varies from one VAAC to another (CEOS 1999).

Seismic monitoring (detection of earthquakes and tremors) remains the most useful and reliable means of detecting eruptions. Seismic systems have been used in some cases specifically for aviation warnings (for example, on Sakurajima Volcano, 22 km from Kagoshima City, Japan, since 1991). However, less than 20 percent of world's active volcanoes are effectively "wired" for seismic. The numbers are better in the

United States -- 20 of 44 are wired in Alaska -- and slowly increasing elsewhere (Schneider, p.c.; Miller and Casadevall 1999). Satellite data links (ARGOS, Cauzac *et al.* 1994) may be useful in extending direct monitoring to remote volcanos in a cost-effective way.

In addition to seismic data, eruptions can be detected by GPS networks and radar (deformation) (Stone 1994), microgravity changes monitoring, thermal emissions (thermal IR), gas emissions (SO_2, CO_2 – UV, IR), and acoustic monitoring. The most useful satellite data are thermal IR measurements. Thermal IR is used to detect both the heat associated with an eruption and the subsequent ash cloud itself. Remote sensing technologies employed in Alaska volcano debris monitoring include Doppler wind profilers, non-Doppler (C-band) weather radar, and polar satellite data (Hufford 1994).

An extensive literature exists on the use of satellite observations in support of volcano monitoring (see general discussions by Matson *et al.* 1994; CEOS 1999; and Schneider *et al.* 1999). Table 3 lists the satellite data that have been used for volcanic monitoring. Satellite data come from both polar (Schneider *et al.* 1999) and geostationary (Sawada 1994) satellites. Typical image frequency is 30 to 60 minutes for geostationary satellites (15 mins for GOES over the continental United States), and 2 to 6 hours for polar satellites. Image resolution ranges from 1 to 8 km (Matson *et al.* 1994).

data/product	***references***
"split window" IR (11-12 micron temperature difference)	Prata (1989); Scheider *et al.* (1995)
ultraviolet (UV) backscatter and absorption (Total Ozone Mapping Spectrometer (TOMS) – 0.4 micron) - sulfur dioxide concentrations - aerosol index (0.34-0.38 micron bands)	 Krueger *et al.* (1995) Seftor *et al.* (1997)
visible band (0.5-1.0 micron)	Holasek and Self (1995); Holasek *et al.* (1996)
thermal IR band (11 micron)	Holasek and Self (1995); Holasek *et al.* (1996)
thermal IR mid-wave band (8.5 micron)	Realmuto *et al.* (1997)
water vapor absorption band (6-7 micron)	Lunnon and McNair (1999)
reflectivity (3.9, 11 micron)	Ellrod and Connell (1999)
experimental 3-channel IR products (3.9, 11, 12 micron)	Ellrod and Connell (1999)
passive microwave data (85 GHz)	Delene *et al.* (1996)
infrasonic techniques	(nuclear test ban proposal)

Table 3: Satellite data and products useful in volcanic ash detection.
Source: CEOS (1999).

The most widely used, and most useful, satellite data for volcanic ash detection and tracking is "split window" two-band IR. By computing the brightness temperature difference between 11 micron and 12 micron infrared radiation, it is often possible to distinguish volcanic from water clouds (Ellrod 1999; Ellrod and Connell 1999; Dean *et al.* 1994). The Advanced Very High Resolution Radiometer (AVHRR) on current polar satellites and IR sensors on GOES satellites provide split window data (a similar sensor has also been proposed for use onboard aircraft (Honey 1994)). Split window IR imagery is particularly effective for established ash clouds with low moisture content, and with a relatively dry atmosphere and volcanic plume. It is more difficult to distinguish ash from water clouds with a single IR channel or when the volcanic plume is moist.

The Total Ozone Mapping Spectrometer (TOMS) detects aerosols and SO_2, and has been used experimentally to detect volcanic ash (Krueger *et al.* 1994). However, it suffers from low resolution, and is available only during daylight hours, and for a few passes per day.

Once an eruption or ash cloud has been detected, the emphasis shifts to plume tracking/forecasting. Satellite imagery (single channel visible, IR, or multi-spectral IR) is used to track the horizontal extent of ash clouds; vertical tracking relies on IR imagery, pilot reports, ground-based observations, air temperature measurements, and wind information (CEOS 1999).

Predictive models initialized by ash cloud detection data are used to provide aviators with information about likely ash cloud trajectories. NOAA's Volcanic Ash Forecast Transport and Dispersion (VAFTAD) model (developed by NOAA's Air Resources Laboratory) (Stunder and Heffter 1999), is associated with the Washington VAAC. Other models include the PUFF dispersion model (Anchorage VAAC), CANadian Emergency Response Model (CANERM, Montreal VAAC), Modele Eulerian de Dispersion Atmsopherique (MEDIA, Toulouse VAAC), and Nuclear Accident Model (NAME, London VAAC) (CEOS 1999). International Civil Aviation Organization (ICAO) requires updates to be issued during significant volcanic events at least every six hours.

Limitations of Present and Future Satellite Data

The Committee on Earth Observation Satellites (CEOS 1999) has highlighted the limitations of existing satellite data in the detection of volcanic eruptions and ash clouds. For eruption detection, the major limitations are (1) coarse pixel size (4 km), (2) geographic limitation (western hemisphere), (3) low data frequency (30 minutes to several hours between observations), and (4) poor precision (high false alarm rate) of GOES IR data. For ash cloud detection, major limitations are (1) imagery obscured by clouds or ambient moisture, (2) reduced imagery at night, (3) limited ability to detect small-scale events; eruption detection.

CEOS makes detailed recommendations for future operational requirements (see Table 4), including:

- better resolution for geostationary data, approaching polar resolution of 1 km from AVHRR
- access to "split window" geostationary data at 30 minute intervals for all VAACs
- IR SO_2 absorption channel available 24 hours/day
- global UV and high resolution thermal IR data available

Toward this end, CEOS recommends:

- all future satellites to include dual longwave IT (11-12 micron), dual shortwave thermal IR (3-5 micron), and SO_2 absorption IR (8.5 micron)
- both IR and UV (0.3-0.4 micron) sensors on future geostationary satellites
- minimum frequency of multispectral data from geostationary satellites of 30 minutes
- IR resolution at least 5 km

Phenomenon	*Data*	*Resolution (Threshold/Optimum)*	*Frequency (Threshold/Optimum)*
ash cloud	IR	5 km / 1 km	30 min / 15 min
ash cloud	visible	1 km / 0.5 km	30 min / 15 min
ash cloud	sounder	10 km / 2 km	30 min / 15 min
SO_2 cloud	UV	20 km / 10 km	2 hr / 15 min
thermal anomaly (persistent)	IR	1 km / 30 m	2 hr / 15 min
thermal anomaly (transient)	IR	1 km / 30 m	30 sec / 10 sec

Table 4: CEOS (1999) recommended data requirements for improved volcanic ash cloud detection for commercial aviation.

Similarly, Harris *et al.* (1999) recommend image acquisition intervals of 15-30 minutes, multiple IR bands, and better satellite coverage to improve satellite detection of volcanic eruptions. Existing and planned geostationary satellites provide adequate coverage up to 55 degrees latitude. Some 12 AVHRR-like polar satellites would be needed to provide equivalent coverage of areas north of 55 degrees. Existing NOAA polar orbiting satellites provide AVHRR sensor coverage at 1 km resolution (Dean *et al.* 1994).

CEOS (1999) summarizes the value of planned future satellite capabilities to volcanic ash monitoring as follows:

> Future geostationary and polar satellite systems will result in overall improvements in our ability to monitor volcanic ash, except in the western hemisphere. The replacement for GMS (MTSAT) and the METEOSAT Second Generation (MSG) will both have shortwave IR (3.9 micron), and split window IR (12.0 micron) with a sub-point resolution of 4 km and 5 km, respectively. MSG will also have a 9.0 micron ozone channel that could be useful for monitoring SO2 concentrations. Polar satellite coverage will be enhanced with the European ENVISAT (late 1999), which has a near clone of the AVHRR, the European METOP (2002) with SO2 detection capabilities, and Japan's sophisticated ADEOS-II (late 1999), a thirty-nine channel, high resolution imager. Data from an Advanced Interferometric Radiometric Sounder (AIRS) will be available from NASA's Earth Observation System (EOS) beginning 2000. A future GOES imager is being planned (for circa 2011) that will have eight to ten bands (including a 12 and possibly 8.5 micron wavelength) at higher temporal and spatial resolution (2 km IR, 0.5 km visible).
>
> **The one major weakness of the future global satellite network with respect to volcano monitoring is the loss of the "split window" (12.0 micron) channel on all GOES spacecraft launched from 2002 to possibly as late as 2010.** That channel will be replaced by a 13.3 micron CO2 absorption band at 8 km resolution, to be used for more accurate height assessment of wind vectors and cloud tops. [Emphasis in the original.]

The GOES sounder and polar AVHRR are cited by CEOS as less desirable alternative sources of split window data. Ash cloud detection rates have been estimated at around 10 percent for single frequency imagery (Sawada 1994) and as high as 80 percent for split window data (Ellrod 1998). The GOES sounder (see Ellrod 1999) has low spatial and temporal resolution (10 km and 1 hour (at best)), and provides coverage only of low and mid latitudes. Polar satellites currently provide coverage at 2 to 6 hour intervals. Polar satellite coverage is particularly poor for low latitude volcanos in Central America, the Caribbean, and South America.

In recent years, attention has begun to shift from encounters at cruising altitude to encounters in terminal flight. Engines – particularly large, high-temperature modern jets – are more susceptible to ash damage during high-power climb and descent maneuvers. A number of active volcanoes are located in the immediate vicinity of important airports, including Mexico City (Popocatepetl); Catania, Sicily (Mt. Etna); Quito, Ecuador (Pichincha Volcano), and Montserrat (Soufriere Hills). Satellite data are of limited use in providing the very short term warnings necessary in these situations.

Improved Mitigation with NPOESS

Five NPOESS satellites are to replace existing NOAA POES (Polar-Orbiting Environmental Satellite) and DoD DMSP (Defense Meteorological Satellite Program) polar orbiters starting in 2007 (NPOESS/IPO 1998a). A Visible Infrared Imaging Radiometer Suite (VIIRS) on NPOESS will replace the civilian AVHRR and military Operational Line Scan (OLS) instruments on current polar orbiters.

NPOESS data elements relevant to the detection and tracking of volcanic ash plumes are described in Table 5.

	EDR 3 *imagery (visible, IR)*	*EDR 5* *sea surface wind*	*EDR 13* *suspended matter*
horizontal resolution	1.0 km (global) 0.4 km (regional)	20 km	3 km
mapping accuracy	3 km	5 km	3 km
refresh	4 hours average 6 hours maximum	6 hours	12 hours

Table 5: Thresholds for NPOESS data records of concern to volcanic ash detection and monitoring. Source: NPOESS/IPO (1998b).

In summary, NPOESS will provide IR imagery, including split window, at horizontal resolution desired by volcanic ash monitors but not at the desired refresh rate. The horizontal resolution and refresh rate will be somewhat better than that available from AVHRR on existing polar satellites. It will partially make up for the loss of split window IR in future geostationary satellites from 2007 to 2010. NPOESS EDR 13 (suspended matter) may be useful in some instances but is provided at a 12 hour refresh rate, limiting its use as an early warning tool.

Estimate of NPOESS Benefits

The benefit from NPOESS data to volcanic ash avoidance in commercial aviation is the difference between expected losses without NPOESS (the future baseline) and expected losses with NPOESS.

The Future Baseline

The future baseline here is a projection of the historical baseline exposure with some allowance for changes in underlying conditions. These changes include:

- the operation of the VAAC network and other measures
- the growing volume of air traffic
- changes in aircraft characteristics and long-distance routing
- the loss of GOES 2-channel IR data

The rate of volcanic activity around the world is expected to remain about constant in the coming decades (Miller and Casadevall 1999).

Pilot training in ash avoidance and the operation of VAACs is thought by some observers to have already lowered the risk of airborne encounters from pre-1995 levels. Assuming that VAACs continue to refine their operations for the next two decades, this should contribute to a reduction in the baseline exposure.

Air traffic volume is growing worldwide at about 5 percent/year, and more rapidly on trans-Pacific and trans-Atlantic routes that are particularly vulnerable to volcanic ash problems.[1] North Pacific routes were used by more than 200 flight/day in 1999, with 20,000 passengers and more than 12 million pounds of cargo. This volume is expected to triple by 2017 (Miller and Casadevall 1999). Some 800 flights per day now cross the northern Atlantic; and this number is growing at 10 percent/year. Air traffic to Australia is also growing fast; most of this must cross the volcano region of Indonesia. A higher volume of air traffic might be expected to increase the exposure of civilian aviation to volcanic ash risk.

As noted, the trend toward large, efficient twin-engine jets with high-temperature, high-throughput engines has increased the vulnerability of aircraft engines to damage from ingested ash. Reliance on two engines (instead of four) on transoceanic flights also generally requires these aircraft to be at all times within 3 hours of an emergency airport. Eruptions that close airports designated as emergency landing sites for long-distance twin-engine aircraft (Reykjavic on North Atlantic routes, Adak Island on North Pacific routes) may affect increasing numbers of flight schedules in the future. These trends suggest increased future exposure in both airborne and airport risk categories.

Finally, the elimination of 2-channel IR imagery from future GOES satellites is seen as detrimental to volcano and ash cloud monitoring, and thus as leading to increased risk at least through 2010.

It is impossible to translate these changes in underlying conditions precisely into changes in the baseline risk. On balance, however, most observers argue that the risk exposure will increase in the future (see, for example, Miller and Casadevall 1999). The main factor working to reduce future baseline risk – the VAAC network – addresses

[1] The world's civilian air fleet consisted of about 13,000 aircraft in 1999.

mostly the airborne component of exposure, which is roughly half of historic baseline exposure. In view particularly of rapidly rising traffic volumes and the greater vulnerability of modern twin-engine planes to shutdown of emergency landing sites, it is likely that the baseline "airport" exposure in the decades following the activation of NPOESS will be greater than historic exposure.

Assuming that the VAACs are able to reduce airborne exposure by half (even in the face of loss of GOES 2-channel IR), and that future baseline airport exposure increases linearly with traffic volume, we obtain future baseline exposure of $35 million per year airborne and about $100 million on the ground by 2020. This suggests a future baseline (no NPOESS) exposure of $100 to $200 million per year during NPOESS' lifetime.

Future Exposure with NPOESS

The main difference for volcanic ash monitoring activities between a future without NPOESS and a future with NPOESS is the availability of polar satellite 2-channel IR data. This is particularly important in the early years of NPOESS (2007 to 2010, and perhaps beyond), when GOES will not be equipped to provide 2-channel IR.

The polar satellite IR data is most useful in addressing airborne exposure, and thus may reduce $35 million out of the $100 to $200 million annual future baseline exposure. Satellite data in general of limited use in reducing "airport" loss exposure, except by minimizing delays and repositioning costs via reduced uncertainty. Exactly how much of this $35 million airborne exposure polar IR data can eliminate is impossible to predict with accuracy. An estimate of $10 million is likely to in the right ballpark.

These future costs and benefits are rough estimates in year 2000 dollars. Future costs and benefits have not been explicitly inflated or discounted in this analysis. The fraction of the total benefit realized by citizens and corporations of the United States is difficult to estimate. U.S. airlines have a significant presence on transatlantic and transpacific routes most likely to be affected by volcanic ash, and U.S. citizens make extensive use of international air travel.

Summary/Conclusion

Satellite data play a role in volcanic ash monitoring and aviation warning processes. The most important satellite data to this process at present is 2-channel (split window) IR imagery. The preferred source is a geostationary, as opposed to polar, satellite because of more frequent refresh.

NPOESS will be a useful source of 2-channel IR data, particularly during the years (2007 to 2010 and possibly beyond) when GOES cannot provide 2-channel IR. These data will help mitigate an estimated $35 million exposure in annual airborne encounter losses in the two decades following the launch of NPOESS in 2007. The benefits of NPOESS to civilian aviation volcanic ash avoidance during that period can be expected to be at best on the order of $10 million per year.

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