VOLCANIC ASH AND AVIATION SAFETY:
Proceedings of the First International Symposium
on Volcanic Ash and Aviation Safety
U.S. GEOLOGICAL SURVEY BULLETIN 2047

AN AIRCRAFT ENCOUNTER WITH A REDOUBT ASH CLOUD (A SATELLITE VIEW)

By Kenneson G. Dean, Lawrence Whiting, and Haitao Jiao

ABSTRACT

Satellite images, wind measurements, and ground observations were used to track and map gas clouds and ash clouds emitted by Redoubt Volcano, Alaska, on 15 December 1989. This eruption resulted in a nearly catastrophic encounter between airborne ash and a Boeing 747 jet aircraft (most of southern Alaska was completely covered by clouds on that day). Four satellite images were analyzed using complex digital-processing techniques to locate geographic features and to distinguish eruption-related gas clouds from meteorological clouds. The technique of subtracting thermal infrared bands to detect ash clouds was applied to three images but was only successful on the 13:42 Alaska Standard Time (AST) image. The 13:42 image revealed the presence of two ash clouds near Fairbanks and Delta Junction that may have been involved in the encounter with the 747 aircraft earlier that morning. Ground samples from the two ash clouds help quantify the characteristics of ash clouds detected by satellite sensors. The eruption at 10:15 AST appears to be the origin of the ash involved in the aircraft encounter.

INTRODUCTION

On 14 December 1989, Redoubt Volcano, located 177 km southwest of Anchorage, Alaska (fig. 1), erupted and expelled a huge eruption cloud composed of ash and gas to altitudes greater than 10 km (Brantley, 1990). For the next 4 months, 24 additional eruptions resulted in the deposition of ash throughout southern Alaska (Scott and McGimsey, 1991). Clouds of ash and gas from Redoubt Volcano drifted hundreds of kilometers to locations beyond Fairbanks, Delta Junction, and Glennallen.

The danger to airline traffic posed by airborne ash was exemplified on 15 December at 11:45 Alaska Standard Time, when a Boeing 747 jet flew into an ash cloud at an altitude of 7,600 m (25,000 ft) northeast of Talkeetna, Alaska. All four engines shutdown within minutes after the aircraft entered the cloud but were restarted about 8 minutes later, narrowly averting a catastrophe (Brantley, 1990; Casadevall, in press). The ability to detect, monitor, and predict the movement of volcanic plumes and ash clouds would help to minimize the possibility of aircraft encounters with ash. Satellite images are one potential source of this information. The 15 December 1989 chronology of events and National Oceanographic and Atmospheric Administration (NOAA) advanced very high resolution radiometer (AVHRR) satellite images used in our analysis are given in table 1.

NOAA AVHRR satellite images have been used to monitor and analyze eruption clouds from Redoubt (Dean and others, 1990; Kienle and others, 1990); from Augustine (Holasek and Rose, 1991); from Colo, Indonesia (Maligreau and Kaswanda, 1986); from Mt. Galunggung, Indonesia (Hanstrum and Watson, 1983); from El Chichón, Mexico (Matson, 1984); and from Mount St. Helens (Matson and Staggs, 1981). Techniques have been developed to distinguish ash clouds from meteorological clouds and other airborne volcanic constituents (Prata, 1989; Holasek and Rose, 1991). Images from the Earth observing system (EOS) spacecraft will become an additional source of data for analyzing volcanoes in the near future (Mouginis-Mark and others, 1991).

Images from the AVHRR sensor aboard the polar-orbiting NOAA-10 and NOAA-11 (N-10, N-11) satellites are recorded for the Cook Inlet region more than 10 times per 24-hour period. This high temporal resolution is unique to high latitudes due to extensive overlap on each image swath from adjacent orbits. The data have a spatial resolution of 1 km and a swath width greater than 2,000 km. The images are recorded in five wavelengths: visible band 1 (0.58–0.68 pm), near-infrared band 2 (0.72–1.1 pm), thermal-infrared band 3 (3.55–3.93 µm), thermal-infrared band 4 (10.3–11.3 pm), and thermal-infrared band 5 (11.5–12.5 pm). However, on even-numbered NOAA satellites up to but not including N-12, band 5 is a duplicate of band 4. The five-band coverage can detect both volcanic and non-volcanic cloud formations during both day and night.

In this paper, clouds composed of gas and ash emitted by a volcano are referred to as eruption clouds. Eruption clouds may have a conical shape with an apex ending at the

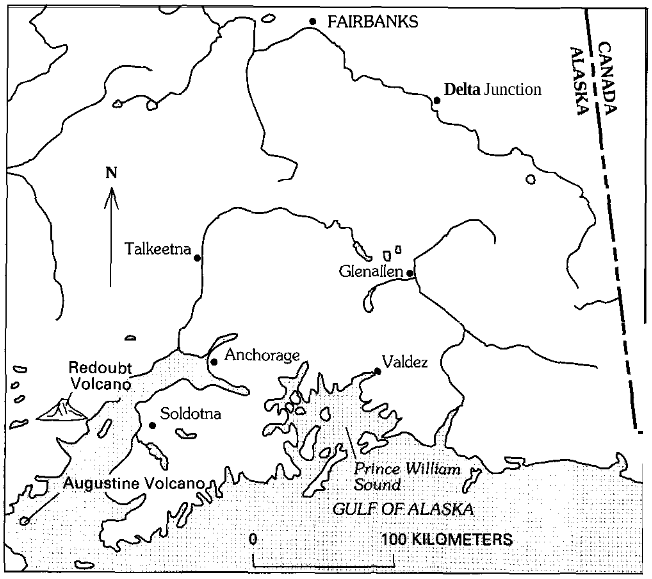

Figure 1. Location map of south-central Alaska.

Table 1. Chronology of Events on 15 December 1989.

[AST, **Alaska** Standard Time]

Time (AST)	Event
01:40	Eruption, 12 minutes duration
03:28	Image: NOAA-11; orbit no. 6305
03:48	Eruption, 10 minutes duration
05:09	Image: NOAA-11; orbit no. 6306
09:28	Image: NOAA-10; orbit no. 16851
10:15	Eruption, 40 minutes duration
11:45	Aircraft–ash cloud encounter
13:27	Image: NOAA-11; orbit no. 6311

volcano indicating that it is still being emitted, or the apex may be adrift and not connected to the volcano. An ash cloud is that portion of an eruption cloud containing volcanic ash that damages aircraft and other mechanical devices. Both ash and gas components of eruption clouds can be detected on satellite images, but they may not always be distinguishable from each other.

OBJECTIVES

The objective of this analysis is to use satellite images to identify and monitor eruption clouds, including the ash clouds responsible for the near-downing of an aircraft on 15 December 1989. AVHRR images are used to distinguish eruption clouds from surrounding meteorological clouds, to map the trajectory and distribution of eruption clouds, and to detect and track the movement of the ash cloud that the aircraft encountered.

METHODS

SATELLITE ANALYSIS

Three eruptions occurred on the morning of 15 December: at 01:40, 03:48, and 10:15 AST. Four satellite images were recorded at 03:28, 05:09, 09:28, and 13:27 AST (table 1) and show that most of southern Alaska was completely covered by clouds. To relate cloud structures to ground locations, the images were registered to an Albers equal-area map projection, and geographic features were digitally superimposed. The values of individual pixels were transformed to temperature and albedo using coefficients provided with the data as described in the NOAA polar orbiter data users guide (Kidwell, 1991). Contrast was enhanced to optimize the detection of eruption-related gas clouds and ash clouds. Individual bands of satellite data were combined to distinguish gas clouds, ash clouds, and other plume constituents from meteorological clouds using established experimental techniques. These included:

- Subtraction between bands 5 and 4 to distinguish ash clouds from meteorological clouds,
- Subtraction between bands 2 and 1 to help distinguish the water-vapor portion of eruption clouds from other plume constituents, and
- Principal-component analysis to distinguish eruption clouds from meteorological clouds.

Color composite images were generated using various combinations of raw images, band subtractions, and principal component images.

Images that result from the subtraction of two bands of data may detect distinct properties of eruption clouds. The image that results from subtracting the two thermal infrared bands on AVHRR data (bands 4 and 5 on NOAA-9, 11, and 12 satellites) detects ash clouds (Prata, 1989; Holasek and Rose, 1991). The image that results from subtracting visible and near-infrared bands may help to distinguish water vapor from other plume constituents (Dean and others, in press). These band-subtraction techniques were used in this analysis to help distinguish plume components.

The principal-component-analysis technique creates new images by performing coordinate transformations that recognize the maximum variance in multispectral data. This technique generates new images referred to as "principal-component images" (PC1, PC2, PC3, etc.). The first principal-component image is a weighted-average picture: the remaining principal-component images are similar to pairwise differences between bands (Sabins, 1987; Siegal and Gillespie, 1980). The principal-component images were used to help distinguish subtle eruption-cloud signatures from meteorological clouds.

Altitudes of the eruption clouds were estimated by comparing their temperatures with the temperature profile of the atmosphere. The eruption cloud, which is hot when first emitted by the volcano, will rise due to buoyancy hut is also mechanically lifted by the force of the eruption. These two factors often propel eruption clouds to altitudes higher than many cloud masses (Sparks and others, this volume; Woods and Kienle, this volume; Dean and others, in press) where they rapidly cool to the temperature of the surrounding air. The temperature of the upper surface of the eruption cloud is derived from the thermal-infrared (band 4) satellite images. The thermal profile of the atmosphere is derived by the National Weather Service (NWS) from radiosonde observations and compared to the eruption-cloud temperature to determine an estimate of eruption-cloud height. These estimates are subject to errors (Woods and Self, 1992). The perspective view of the upper cloud surface was generated based on these principles and is shown in figure 2.

Eruption clouds have some attributes that distinguish them from many meteorological clouds. They are often higher and, hence, colder; they often have a larger albedo and are thus brighter; and, eruption clouds often have an apex starting at a volcano. A perspective view to the northeast was generated to show some of these differences (fig. 2) based on the 13:27 AST satellite image using a combination of the visible (band 1) and thermal-infrared (band 4) bands. In this example, the volcanic plume seen emanating from Redoubt Volcano was not at a greater height than the surrounding clouds, even though it is shown that way on this image, but it was brighter due to its high albedo on the visible-band data.

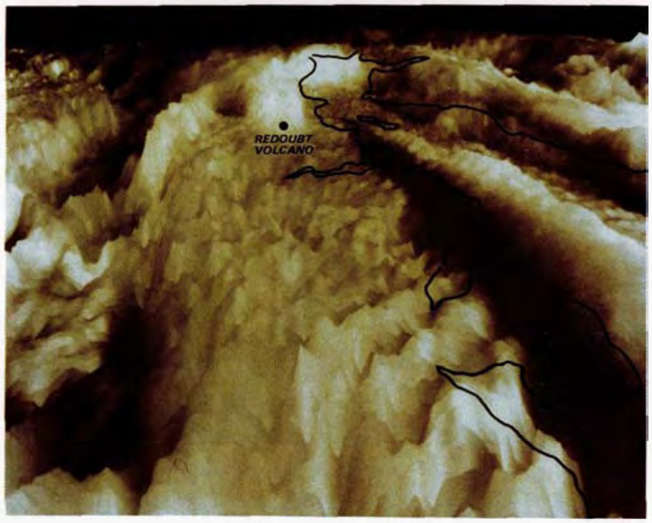

Figure 2. Perspective view, looking approximately northeast, of cloud tops generated from an AVHRR satellite image of south-central Alaska, 13:27 AST, 15 December 1989. The plume extends from Redoubt Volcano to the northeast and is brighter (high albedo) than most of the surrounding clouds. Cook Inlet is outlined on the right-hand side of the figure; refer to figure 1.

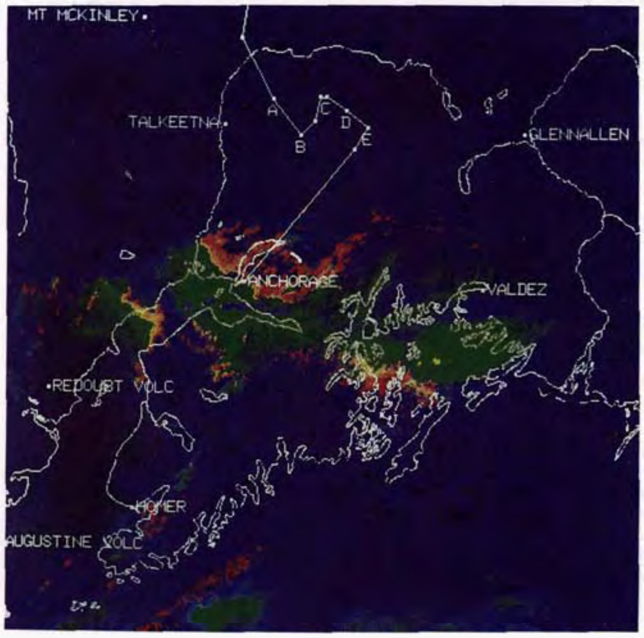

Figure 3. AVHRR satellite image of south-central Alaska, 03:28 AST, 15 December 1989. Suspected eruption clouds appear as green and red across the center of the image. The image is approximately 500 km on a side. The flight of the aircraft that encountered the ash cloud is shown as straight line segments in the upper and central parts of the figure. See text for explanation of A, B, C, D, and E.

The flight path of the aircraft that encountered the ash cloud is shown on figures 3 through 7. Labels along the flight path indicate the position of the aircraft at the time of critical events (Casadevall, in press):

- A—(11:46 AST)—Ash cloud encountered at 7,600 m (25,000 ft),
- B—(11:48 AST)—Engine shutdown at 7,600 m (25,000 ft),
- C—(11:50 AST)—Exit ash at 6,000 m (20,000 ft),
- D—(11:52 AST)—Restart two engines at 5,200 m (17,200 ft),
- E—(11:55 AST)—Restart two engines at 4,100 m (13,300 ft).

RESULTS

The first AVHRR image (NOAA-11, orbit no. 6305), was recorded at 03:28 AST, 2 hours after the 01:40 AST eruption. A color composite image was generated to optimize differences in morphology and spectral response within the overlying cloud layer using PC3 as red, thermal-infrared band 3 as green, and PC1 as blue (fig. 3). This image shows a cloud structure (green and red) that may be an eruption

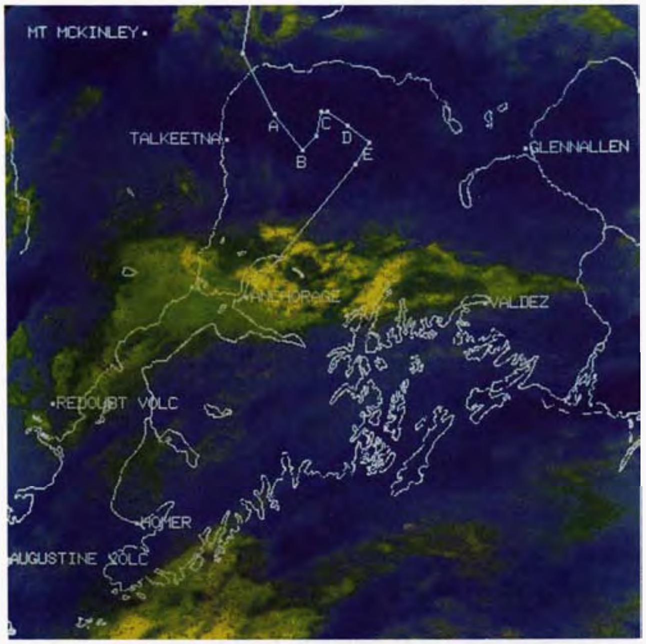

Figure 4. AVHRR satellite image of south-central Alaska, 05:09 AST, 15 December 1989. The suspected eruption cloud has an apex at Redoubt Volcano and appears as yellow across the center of the image. The image is approximately 500 km on a side. The flight path of the aircraft that encountered the ash cloud is shown as straight line segments in the upper and central parts of the figure. See text for explanation of A, B, C, D, and E.

cloud that starts northeast of Redoubt Volcano and extends to the east over Anchorage and beyond, to Prince William Sound, south of Valdez. The suspected eruption cloud was presumably emitted by the 01:40 AST eruption and appears to be in three segments, possibly indicating a discontinuous event comprised of three distinct eruptions. A subtraction of bands 5 and 4 was not successful in detecting the ash clouds.

The second AVHRR image (NOAA-11, orbit no. 6306) was recorded at 05:09 AST, 1.5 hours after the 03:48 AST eruption. A color composite image was generated to optimize differences in the morphology and spectral response within the overlying cloud layer. The optimal combinations used the thermal-infrared band 3 as red, thermal-infrared band 4 as green, and PC1 as blue (fig. 4). This band combination shows a suspected eruption cloud (yellow), with an apex near Redoubt Volcano, extending to the northeast and east, beyond Valdez. The eastern portion of this cloud is slightly detached and may be a remnant from the 01:40 AST eruption. A subtraction of bands 5 and 4 was not successful in detecting the ash clouds.

The third AVHRR image (NOAA-10, orbit no. 16851) was recorded at 09:28 AST, 6 hours after the 03:48 AST eruption and about 45 minutes before the 10:15 AST eruption. A color composite image was generated to optimize differences in the morphology and spectral response within the overlying cloud layer with PC1 as red, thermal-infraredband 4 as green, and thermal-infrared band 5 as blue (fig. 5). This image shows a suspected eruption-cloud (green and yellow) northeast of Redoubt Volcano that extends beyond Talkeetna and across the flight path of the aircraft that encountered an ash cloud. This cloud does not have an apex at Redoubt Volcano. Two possible volcanic-related clouds (yellow) can also be seen south of Glennallen and between Talkeetna and Fairbanks. Detection of ash clouds using the subtraction between bands 4 and 5 could not be applied because these bands are identical on the NOAA-10 satellite.

The fourth AVHRR image (NOAA-11, orbit no. 6311) was recorded at 13:27 AST, 3.25 hours after the start of the 10:15 AST eruption. A color composite image was generated to detect the plume and ash clouds using PC3 as red, subtraction of band 1 from 2 as green, and subtraction of band 4 from 5 as blue (fig. 6). This is the first 15 December image that unquestionably shows a volcanic plume despite the cloud layer and reveals an eruption cloud still emanating from Redoubt Volcano (yellow and green in the lower left portion of fig. 6) 2.5 hours after the end of the seismic event defining the 10:15 AST eruption. This plume trends northeast and east, ending just short of Anchorage, and is brightest

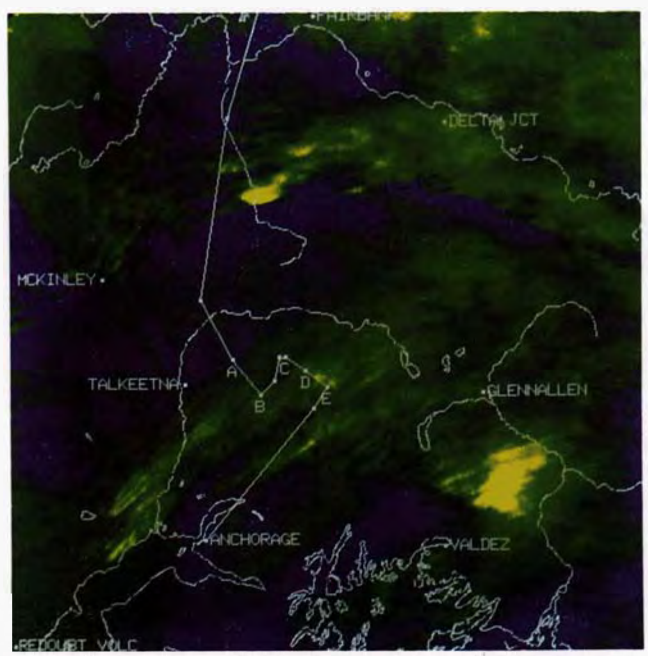

Figure 5. AVHRR satellite image of south-central Alaska, 09:28 AST, 15 December 1989. The suspected eruption clouds are green and yellow features that extend from Redoubt Volcano to Glennallen. The yellow features across the upper third of the figure may also be volcanic emissions. The image is approximately 500 km on a side. The flight path of the aircraft that encountered the ash cloud is shown as straight line segments in the central part of the figure. See text for explanation of A, B, C, D, and E.

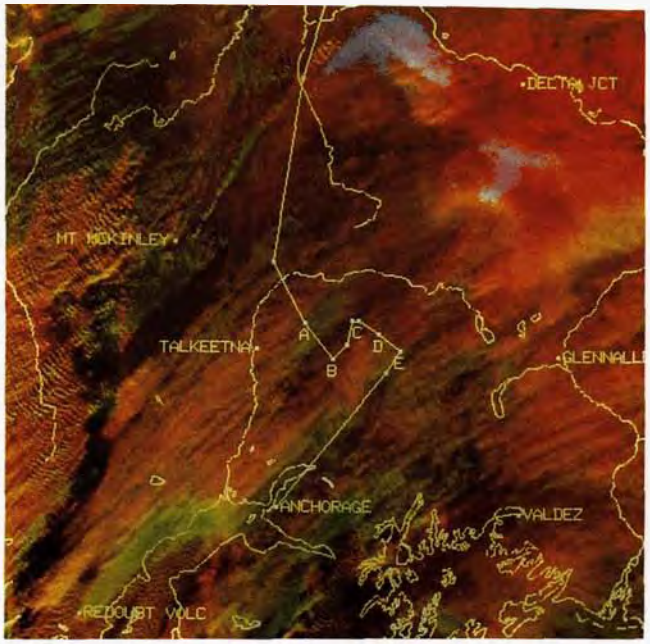

Figure 6. AVHRR satellite image of south-central Alaska, 13:27 AST, 15 December 1989. The eruption cloud (light green) has an apex at Redoubt Volcano and extends to Anchorage. The ash clouds (purple), which are south of Fairbanks and Delta Junction, may have been involved in the aircraft encounter. The image is approximately 500 km on a side. The flight path of the aircraft that encountered the ash cloud is shown as straight line segments in the central part of the figure. See text for explanation of A, B, C, D, and E.

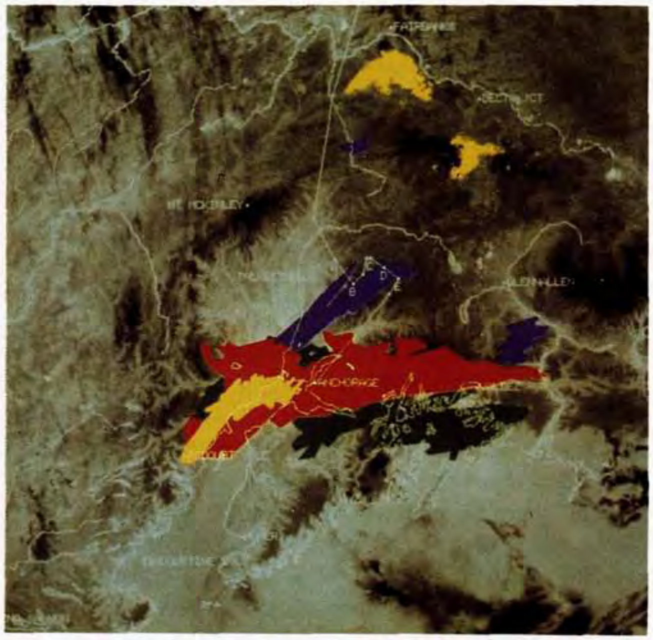

Figure 7. Artificially integrated satellite image that shows all of the possible eruption clouds on 15 December 1989. Colors designate the image from which the eruption clouds were extracted: green, 03:28 AST image; red, 05:09 AST image; blue, 09:28 AST image; yellow, 13:27 AST image. The flight path of the aircraft that encountered the ash cloud is shown as straight line segments in the upper and central parts of the figure. See text for explanation of A, B, C, D, and E.

on the band-2-minus-band-1 image, suggesting that its composition is something other than water vapor (Dean and others, in press). To the north, near Fairbanks and Delta Junction, two clouds (purple and pink) were observed in the band-5-minus-band-4 image, suggesting that they are composed of ash, as indicated by the signature generated by this band combination (Prata, 1989; Holasek and Rose, 1991).

DISCUSSION

GROUND ASH DISTRIBUTION AND ERUPTION-CLOUD TRAJECTORIES

To show more clearly the scenario of events on 15 December 1989, a summary image was compiled that integrated all of the "eruption clouds" observed on satellite data. The maximum extent of these clouds was extracted from individual images and transferred to a cloud-free reference image (fig. 7). Colors designate the image from which the suspected eruption clouds were extracted: green, 03:28 AST image; red, 05:09 AST image; blue, 09:28 AST image; yellow, 13:27 AST image. This integrated image shows that three of the four suspected eruption clouds have an eastward trajectory and that there is a northward progression in the trajectory of the early-morning eruption cloud, a northeast trend at 09:28 AST, and a northeast to eastward trend at 13:27 AST.

The predominantly eastward trajectory of the suspected eruption clouds does not agree with the distribution of surface ash collected by the U.S. Geological Survey (Scott and McGimsey, 1991). Surface ash deposited by the 15 December 1989 eruption is found northeast of Redoubt Volcano, not to the east, as the eruption cloud seen on the images would indicate. This suggests that either the suspicious clouds are not volcanic or that, as the ash falls from the plumes, it is swept northward by winds at a different altitude and that the clouds seen on the images do not contain ash. The elongated shape of the clouds with apexes at Redoubt Volcano (possibly two of four suspected plumes), geographic position, soft texture, and spectral signatures of these cloud structures indicate that they may be plumes, although absolute quantifying data is not available.

The second explanation is possible because winds below about 7-km altitude are to the north; at 7 to 12 km, the winds are to the northeast; and at 12 to 28 km, the winds are to the northeast and east (03:00 AST, 15 December 1989, Anchorage radiosonde data). The wind directions indicate that the ash is in the lower air mass (below 7 km) and is being swept northward, whereas the eruption clouds seen on the images are in a higher air mass and are being transported northeast and east.

AIRCRAFT–ASH CLOUD ENCOUNTER

Redoubt Volcano erupted three times during the morning of 15 December 1989: at 01:40, 03:48, and 10:15 AST. In order to identify which eruption cloud was involved in the encounter with the jumbo jet, we compare the velocity required to transport an ash cloud from Redoubt Volcano to the site where the encounter occurred to the wind velocity and direction obtained from radiosonde data from Anchorage International Airport. The required azimuth from Redoubt Volcano is approximately 40°, and the encounter occurred at an altitude of 7.6 km (25,000 ft).

The 10:15 AST eruption occurred 90 minutes prior to the aircraft-ash encounter at a point approximately 280 km northeast of Redoubt Volcano (Casadevall, in press). Based on these conditions, the ash cloud requires a velocity of 55 m/s to reach the site. The wind at 8 km altitude has a velocity of 55 m/s and a heading of 47° (15:00 AST sounding, 15 December 1989, Anchorage). Thus, measured wind parameters closely correlate with the transport of ash emitted by the 10:15 AST eruption.

ASH CLOUD AT FAIRBANKS AND DELTA JUNCTION

The 13:27 AST AVHRR image (fig. 6) shows two ash clouds near Fairbanks and Delta Junction, approximately 3 hours after the 10:15 AST eruption. One or both of these ash clouds may be the one that the aircraft encountered near Talkeetna, 1.75 hours earlier. Back-tracking of cloud movement using wind data from Fairbanks atmospheric soundings were used to test this hypothesis.

The aircraft encountered ash at 7.6 km (25,000 ft) altitude (point A, figs. 3–7), 200 km from Fairbanks and Delta Junction. Temperature-height correlations of the cloud in the Fairbanks area range from 1.5 to 7 km (5,000 to 23,000 ft), and the height of the Delta cloud range from 2.5 to 13.5 km (8,000 to 44,500 ft) (15:00 AST sounding, 15 December 1989, Fairbanks). The range of heights of the cloud at Delta Junction spans the height of the encounter, and the upper height of the cloud near Fairbanks is slightly lower.

To transport the ash clouds from point of the encounter with the aircraft, to the Fairbanks and Delta Junction area, a velocity of 32 m/s and a northeast-blowing wind are required. Velocity calculations based on ground reports of ash fall are 31 m/s and show a northeast direction of movement (R. McGimsey, oral commun., 1992).

Meteorological measurements indicate that wind direction at approximately 7-km altitude would move the ash cloud that the aircraft encountered to either the Fairbanks or Delta Junction position. Wind at that altitude has a velocity of 31 m/s, with the wind blowing to the northeast. It does appear that either or both of these ash clouds were involved in the aircraft encounter, although the height of the cloud near Fairbanks is slightly lower than the altitude of the encounter.

Ground samples of ash from these ash clouds collected in the Fairbanks area had a mass of 0.1 g/m^2 (C. Nye, oral commun., 1991). Approximately 85 percent of the ash particles that fell from the Delta Junction cloud were in the 0.0039- to 0.0625-mm size range, based on two samples (R. Combellick, oral commun., 1991), and were composed predominantly of very angular glass and plagioclase (C. Nye, oral commun., 1991). The glass shards made up greater than 75 percent of the total ash weight.

CONCLUSIONS

The 15 December 1989 eruption of Redoubt Volcano resulted in a near-fatal encounter of a jumbo jet passenger aircraft (Boeing 747) with the ash cloud from the 10:15 AST eruption. Despite the almost total cloud cover over south and central Alaska, eruption clouds were observed on several satellite images. However, the position of the clouds seen on the images did not always agree with ground observations of fallen ash, probably due to height differences between the ash component and gas component of the eruption cloud (and the air masses that transported those parts). A technique of using multiple thermal bands to distinguish ash clouds from other clouds was successful on only one out of three possible images (fig. 6). This image, recorded at 13:27 AST, detected ash clouds near Fairbanks and Delta Junction. One or both of these ash clouds were very likely involved in the aircraft encounter at 11:45 AST.

Validation analyses of eruption clouds observed on satellite images have been minimal. It is not known how opacity, plume composition, particle size, and particle density affect the signatures observed on the satellite images. A thorough understanding of these factors would significantly improve the utility of satellite images for tracking and monitoring eruption clouds.

REFERENCES CITED

Brantley, S.R., ed., 1990, The eruption of Redoubt Volcano, Alaska, December 14,1989–August31,1990: U.S. Geological Survey Circular 1061, 33 p.

Casadevall, T. J., in press, The 1989–1990 eruption of Redoubt Volcano, Alaska: Impacts on aircraft operations: Journal of Volcanology and Geothermal Research.

Dean, K.G., Bowling, S.A., Shaw, G., and Tanaka, H., in press, Satellite analysis of movement and characteristics of the Redoubt Volcano plume: Journal of Volcanology and Geothermal Research.

Dean, K.G., Guritz, R., and Garbeil, H., 1990, Near-real time acquisition and analysis of satellite images of Redoubt Volcano [abs.]: Eos, Transactions, American Geophysical Union, v. 71, p. 1701.

Hanstrum, B.N., and Watson, A.S., 1983, A case study of two eruptions of Mount Galunggung and an investigation of volcanic cloud characteristics using remote sensing techniques: Australian Meteorological Magazine, v. 31, p. 171–177.

Holasek, R.E., and Rose, W.I., 1991, Anatomy of 1986 Augustine Volcano eruptions as recorded by multispectral image processing of digital AVHRR satellite data: Bulletin of Volcanology, v. 53, p. 420-425.

Kidwell, K.B., ed., 1991, NOAA polar orbiter data users guide (TIROS-N, NOAA-6, NOAA-7, NOAA-8, NOAA-9, NOAA-10, NOAA-11, and NOAA-12): Washington D.C., National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service, National Climatic Data Center, Satellite Data Services Division.

Kienle, J., Dean, K.G., Garbeil, H., and Rose, W.I., 1990, Satellite surveillance of volcanic ash plumes; application to aircraft safety: Eos, Transactions, American Geophysical Union, v. 71, p. 266.

Maligreau, J-P., and Kaswanda, O., 1986, Monitoring volcanic eruptions in Indonesia using weather satellite data: The Colo eruption of July 28, 1983: Journal of Volcanology and Geothermal Research, v. 27, p. 179–194.

Matson, M., 1984, The 1982 El Chichón eruptions—A satellite perspective: Journal of Volcanology and Geothermal Research, v. 23, p. 1–10.

Matson, M., and Staggs, S.J., 1981, The Mount St. Helens ash cloud: Bulletin of the American Meteorological Society, v. 62, p. 1486.

Mouginis-Mark, P., Rowland, S., Francis, P., Friedman, T., Garbeil, H., Gradie, J., Self, s., and Wilson, L., 1991, Analysis of active volcanoes from the Earth observation system: Remote Sensing of the Environment, v. 36: p. 1–12.

Prata, A.J., 1989, Observations of volcanic ash clouds in the 10–12 µm window using AVHRR/2 data: International Journal of Remote Sensing, v. 10, p. 751–761.

Sabins F.F., 1987, Remote Sensing: Principals and Interpretations (2nd ed.): New York, W.H. Freeman and Company, 449 p.

Scott, W.E., and McGimsey, R.G., 1991, Mass, distribution, grain size, and origin of 1989–1990 tephra-fall deposits of Redoubt Volcano, Alaska [abs.], in Casadevall, T.J., ed., First International Symposium on Volcanic Ash and Aviation Safety, U.S. Geological Survey Circular 1065, p. 39.

Siegal, B.S., and Gillespie, A.R., 1980, Remote Sensing in Geology: New York, John Wiley and Sons, 702 p.

Woods, A.W., and Self, S., 1992, Thermal disequilibrium at the top of volcanic clouds and its effect on estimates of the column heights: Nature, v. 355, p. 628–630.