Final Report on
"Airborne Studies of the Emissions from the Redoubt
Volcano, Alaska, 1990"
to
MIT Lincoln Laboratory for Contract BX-3703
and
National Oceanographic and Atmospheric Administration for Agreement Nos.
NA85ABH0031 and NA90RAH00073
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APRIL 1991
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SUMMARY

Airborne in situ and remote sensing (lidar and correlation spectrometer) measurements of the volcanic emissions from Mt. Redoubt, Alaska, in January and June 1990, are described. The lidar provided excellent real-time information on the distribution of the volcanic effluents. In post analysis, the lidar observations were used to determine cross-sectional areas of the plumes of emissions which, together with the airborne in situ measurements, were used to derive the fluxes of particles and gases from the volcano. For the intraeruptive emissions, the ranges of the derived fluxes were: for water vapor ~160–9440 kg s⁻¹; for CO₂, ~30–1710 kg s⁻¹; for SO₂, ~1–140 kg s⁻¹; for particles (<48 μm diameter), ~1–6 kg s⁻¹; for SO₄, <0.1–2 kg s⁻¹; for HCl, <0.01–2 kg s⁻¹; and for NOₓ, <0.1–2 kg s⁻¹. Independent measurements of SO₂ from a correlation spectrometer on March 20–24, 1990, gave fluxes of ~18–75 kg s⁻¹.

The particles in the intraeruptive emissions consisted primarily of silicate rock and mineral fragments devoid of any sulfuric acid coating. Very little of the SO₂ (~0.1%) was oxidized to sulfate in the cold, dark conditions of the arctic atmosphere. During a large eruption of Mt. Redoubt on January 8, 1990, the particle (<48 μm diameter) emission flux averaged ~10⁴ kg s⁻¹. During posteruptive emissions on June 11, 1990, the fluxes of both particles and gases were either close to or less than our lower detection limits (except for water vapor, which had a flux of ~6 x 10³ kg s⁻¹).

This study has indicated the potential of airborne lidar for both detecting volcanic ash and for distinguishing it from other atmospheric targets. Recommendations are made for a second generation lidar for this purpose and for its testing and evaluation.
PART I

AIRBORNE MEASUREMENTS OF PARTICLE AND GAS EMISSIONS FROM THE 1990 VOLCANIC ERUPTIONS OF MOUNT REDOUBT

1. INTRODUCTION

On December 14, 1989, after 21 years of quiescence, the Redoubt Volcano, located 180 km southwest of Anchorage, Alaska, erupted violently, sending an ash cloud to a peak altitude of over 12 km. This eruption was the seventh eruptive sequence since Captain James Cook named the volcano in 1798. On December 15, 1989, the four turbofan engines of a new Boeing 747-400 stalled when the aircraft encountered the ash cloud while descending for a landing in Anchorage. The aircraft fell for about 8 minutes, losing more than 3 km of altitude, before the crew restarted two of the engines. Subsequently, the other two engines were started and the aircraft landed safely. However, $80 million of damage was done to the nearly new aircraft. On the same day, two other aircraft were damaged by encounters with the ash cloud. During the next month or so, air traffic in Anchorage area was severely disrupted by the emissions from Mt. Redoubt.

Following requests from the Federal Aviation Administration (FAA), the National Ocean and Atmospheric Administration (NOAA), and Senator Ted Steven's office, our research group deployed its Convair C-131A research aircraft to Anchorage on January 3, 1990, for the purpose of studying the emissions from Redoubt. This airborne research facility has been used to study the emissions from many volcanoes, including Mt. Baker, Washington [Radke et al., 1976], St. Augustine, Alaska [Hobbs et al., 1977], Mt. Mageik and Mt. Martin [Stith et al., 1978], and Mt. St. Helens [Hobbs et al., 1981, 1982]. Descriptions of the instrumentation and techniques that we use for obtaining airborne in situ measurements of volcanic emissions may be found in these papers.

The principal goals of our studies of Mt. Redoubt were to characterize the physical and chemical nature of the volcanic emissions and, in particular, to test the suitability of a new
airborne lidar system aboard the Convair C-131A for remotely detecting clouds and plumes of volcanic ash. In Part I of this report we describe the results of our measurements of the nature of the particles and gases in the emissions from Mt. Redoubt. Part II is concerned with the airborne lidar and our preliminary evaluation of the suitability of lidar for the remote detection of volcanic ash. The report concludes with a summary of the results of this study and recommendations for future work on evaluating the utility of airborne lidar for detecting volcanic ash.

2. VOLCANIC ACTIVITY

After a series of vent-cleaning eruptions of Mt. Redoubt (peak elevation 3.08 km MSL) on December 14 and 15, 1989, the volcano entered a phase of dome-building that lasted until January 2, 1990, when the paroxysmal eruption in the 1989–90 sequence destroyed more than 80% of the dome [Alaska Volcano Observatory Staff, 1990; Brantley, 1990]. During the first period of our airborne measurements, from January 4–12, 1990, Mt. Redoubt largely vented steam and small amounts of ash, which produced a plume that could generally be seen to extend more than 100 km downwind. On January 4, there was vigorous steaming, with the top of the plume reaching to ~4.6 km above mean sea level (MSL). The emissions were less vigorous on the morning of January 5, but by the middle of the afternoon the activity was punctuated by steam explosions and an increase in ash emissions. On January 6 a comparatively large steam explosion occurred, which reached a height of ~6 km MSL. This was followed by minor explosions and venting. On January 8 there was another major volcanic eruption that destroyed the remainder of the dome. Ash was carried to more than 10 km MSL, and about 1 cm of ash was deposited in Kenai which is located about 80 km NE of Mt. Redoubt. By the afternoon of January 8, the volcanic activity looked much the same as it did on January 4, except that the plume was more opaque. The volcano continued to vent steam and, to a lesser extent, ash. Another explosion of steam occurred on January 11. We sampled these emissions, but our
operations were hampered by snow and cloud. The following day (January 12), the volcanic plume was not obscured by clouds and it was sampled at 3.3 km MSL.

On June 11, 1990, we again sampled the effluents from Mt. Redoubt at 1–2 km MSL under partly cloudy conditions. At this time, it was markedly less active than it was during our measurements in January. This period of sampling coincided with the end of observable growth of the Mt. Redoubt lava dome [Brantley, 1990] with the volcano markedly less active than during our January measurements.

With the exception of the measurements that we obtained just after midday on our first flight on January 8, we will refer to all of the measurements obtained in January as being intraeruptive emissions. After our last measurements on January 12, another major eruption occurred on January 16, and Mt. Redoubt continued to erupt periodically through April 1990. The last eruption was on April 26, 1990. This was followed by slow growth of the lava dome until early June. We will refer to the measurements that we obtained on June 11, 1990, as being posteruptive emissions.

3. INSTRUMENTATION AND SAMPLING STRATEGY

The University of Washington's Convair C-131A research aircraft was equipped with in situ samplers for measuring continuously the concentrations and size distributions of airborne particles in the size range 0.05–4500 μm, the concentrations of SO₂, NO, NO₂, CO, CO₂ and O₃, and for measuring (with the aid of chemically treated filters) the concentrations of SO₄²⁻ and HCl (and in June H₂S) in the air. Also aboard the aircraft was a recently built dual-wavelength Nd-YAG laser lidar. The lidar was mounted within the aircraft fuselage and pointed directly upwards through a window. The receiver was a 35.6 cm Cassegrainian telescope with a photomultiplier tube detector at 0.532 μm and an avalanche photodiode detector at 1.064 μm. The lidar was operated at a vertical resolution of 7.5 m and a horizontal resolution of 8 m. Previous airborne lidar measurements of volcanic clouds were in quiescent plumes containing little or no solid silicate ash particles.
One of the principle goals of our study of the volcanic emissions from Mt. Redoubt was to investigate how well this lidar could detect ash particles.

A correlation spectrometer (Model COSPEC IV, Barringer Research, Toronto) belonging to the Alaskan Volcano Observatory has been used regularly to measure sulfur dioxide emission rates at Mt. Redoubt since March 1990. This same instrument was operated aboard the Convair aircraft on June 11, 1990, simultaneously with lidar and other in situ sampling methods.* Using near-UV radiation from the sun as a source, the column density of SO$_2$ was measured remotely by comparing spectral absorption by SO$_2$ with spectral regions where absorption by this gas is negligible [Hoff and Millán, 1981]. The sampling strategy was similar to that which we [Stith et al., 1978; Radke, 1982; Hobbs et al., 1982] and others [Casadevall, 1990] used in previous studies of volcanic plumes. Measurements in quiescent plumes were made in and beneath the vertically stabilized portion of the plume, with the aircraft penetrating the plume normal to its axis (i.e. normal to the mean direction of the wind) at distances of ~7 to 176 km from the mountain. In the large eruption of January 8 we focused primarily on the remote sensing of the emissions with the lidar, since in-plume flying was potentially hazardous.

Mass fluxes of particles, water vapor, SO$_4$$^-$, CO$_2$, HCl, SO$_2$, and NO$_x$ were calculated from the measurement of the cross-sectional areas of the plumes obtained with the lidar, the in situ measurements of the concentrations of these constituents, and average wind speeds. Wind speeds were obtained from the National Weather Service rawinsondes launched from Anchorage, King Salmon, and Kodiak, Alaska, and from a VLF/Omega navigational system aboard the research aircraft. In situ measurements of constituents in the plumes were matched for various ranges downwind of the volcano with corresponding lidar (and hence plume cross-sectional area) measurements by flying the aircraft beneath the plume.

Mass concentrations of particles were determined from particle sizing instruments aboard the aircraft assuming spherical particles with a density of 2 x 10$^3$ kg m$^{-3}$ [Hobbs et
al., 1982] for all of the samples except those taken during the large eruption of January 8 when a density of $3 \times 10^3$ kg m$^{-3}$ was used [Stith et al., 1978]. Masses of particles $<5$ μm diameter were measured directly by weighing 37 mm diameter Teflon filters that had been exposed to the volcanic plumes. Aerosols were collected for sulfate analysis on 47 mm Teflon filters followed by LiOH impregnated backup filters for HCl collection [Kritz and Rancher, 1980]. Particles were also collected on 0.2 μm Nucleopore filters for scanning electron microscope analysis. In addition, during the June 11 flight, AgNO$_3$ impregnated filters were exposed for H$_2$S measurements [Saltzman and Cooper, 1988].

Water vapor in and out of the plumes from the volcano was determined from a high resolution (20 Hz) infrared absolute humidity sensor (Ophir Model 2000). These measurements showed great variability in water vapor content, with standard deviations equal to the mean value in some cases.

All of the measurements listed above, with the exception of water vapor, were obtained by collecting a "grab bag" sample of the plume air [Hegg et al., 1987] and then supplying this sample to various instruments aboard the aircraft. The time to fill the "grab bag" ranged from ~5–15 sec. Since the time taken to penetrate the plume was generally longer than this, the sample was often representative of only a portion of the plume. Therefore, to obtain a better estimate of the fluxes of materials in the plume, the various measured parameters were scaled to the Aitken nucleus concentrations, which were measured continuously in the free airstream and provided a good indication of the spatial structure of the plume along the flight path. Thus, the cross-sectional area of the plume determined from the lidar, the structure of the plume as indicated by the Aitken nucleus measurements, and species concentration measurements were all used in determining the flux of species in the plume.
4. LIDAR OBSERVATIONS

The dual wavelength lidar proved to be excellent for determining the locations of the particulate emissions from Mt. Redoubt. Also, the lidar was of great value in providing measurements of vertical cross-sectional areas of the volcanic plume, which were used in post analysis to determine the fluxes of particles and gases from the volcano.

Satellite imagery detected the paroxysmal eruption on January 8 as a roughly oval cloud drifting downwind of Mt. Redoubt, but it provided very little detailed structural information and no information on the depth of the plume. The airborne lidar, on the other hand, showed the volcanic plume in great detail.

Shown in Figure 1a is a depiction in false color imagery of a vertical cross section of the lidar backscattering measurements from the volcanic plume about 3 h after the paroxysmal eruption on January 8 and at a distance of ~130 km from the volcano. The plume is seen to be about 50 km wide and 2 km thick. Ash veils, produced by the fallout of ash particles from the plume, can also be seen. At higher levels, the lidar detected another layer of volcanic materials (8.6 km MSL) near and beyond the edges of the main volcanic plume. However, due to attenuation of the lidar beam, the upper layer was not detected above the denser central regions of the lower volcanic plume.

The intraeruptive emissions observed from January 4-7 were nearly continuous but very variable in intensity and showed considerable complexity in their cross sections. For example, Figure 1b shows a plume cross section, as detected by the lidar, at ~1432 Alaskan Local Time (ALT) on January 4 at ~18 km from Mt. Redoubt. It can be seen that the plume was separating into two portions. About 20 minutes later the aircraft passed under the plume at a range of ~50 km from Mt. Redoubt (Figure 1c). The plume was now considerably more extended laterally, and the breakup into two portions was nearly complete. This example (and many others not shown here) reveal that it cannot be assumed that volcanic plumes are simply cone-shaped, with an approximately bell (or Gaussian) shaped variation in density across their widths.
Figure 1. Vertical cross-sections of false-color imagery of lidar backscatter measurements across the widths of volcanic plumes from Mt. Redoubt. All examples are at a wavelength of $\lambda = 1.06 \mu m$, except (e) and (f) which are at $\lambda = 0.53 \mu m$. The false colors have been processed to remove the effects of range. Black/red indicates the largest backscatter values and blue/white the least. The same color may represent different backscatter values for the six cross sections shown. (a) January 8, 1990, at 12:46:05–12:57:03 ALT and ~130 km downwind of Mt. Redoubt. (b) January 4, 1990, at 14:30:10–14:33:45 ALT and ~18 km downwind. (c) January 4, 1990, at 14:50:10–14:57:45 ALT and ~50 km downwind. (d) January 6, 1990, at 11:19:30–11:24:35 ALT and ~56 km downwind. (e) January 11, 1990, at 13:07:30–13:09:00 ALT and ~172 km downwind. (f) Same as (e) with additional computer processing.
Another complex plume cross section is shown in Figure 1d. Here frequent steam explosions were superimposed on more continuous emissions that lofted some ash particles and submicron sized aerosol to ~4.5 km MSL. Visual observations, even from the aircraft and by experienced observers, failed to reveal the complexity of the volcanic plumes that the lidar depicted so well.

Lidar appears to be capable of detecting volcanic particulates even under some adverse meteorological conditions. For example, on January 11, 1990, ice crystal aggregates were falling from a deep cloud system over the Cook Inlet. However, the volcanic plume from Mt. Redoubt was still detectable at $\lambda = 0.534 \, \mu m$ in the real-time lidar display (Figure 1e), and with some additional computer processing (Figure 1f) the plume is readily apparent. However, an intervening water cloud a few hundred meters deep would certainly attenuate the lidar beam to the point that a volcanic plume on the other side of the cloud would not be detectable.

A more detailed evaluation of the use of lidar for the remote detection of volcanic ash is given in Part II of this report.

5. FLUXES OF PARTICLES AND GASES

Our estimates of the mass fluxes of various constituents from Mt. Redoubt are summarized in Table 1. Water vapor was the dominant constituent (by mass) in the Redoubt emissions, followed by $CO_2$ and $SO_2$. For the intraeruptive emissions the water vapor flux averaged $\sim 4300 \pm 3600 \, kg \, s^{-1}$, $CO_2$ averaged $\sim 480 \pm 600 \, kg \, s^{-1}$, and $SO_2$ averaged $\sim 70 \pm 60 \, kg \, s^{-1}$. There was essentially no $CO$ in the plume. Mass fluxes for $SO_4^{2-}$, $HCl$ and $NO_x$ were all $\leq 3 \, kg \, s^{-1}$ and frequently $< 1 \, kg \, s^{-1}$. The mass fluxes of particles for the intraeruptive emissions averaged $3 \, kg \, s^{-1}$. From March 20–24, 1990, Dr. T. J. Casadevall of the U.S. Geological Survey measured $SO_2$ from Mt. Redoubt using the correlation spectrometer mounted on a light aircraft; the mass fluxes of $SO_2$ derived from these measurements ranged from $\sim 18–75 \, kg \, s^{-1}$. 
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<th>Time^ from volcano (km)</th>
<th>Distance &lt;48 μm in diameter</th>
<th>Particles &lt;5 μm in diameter</th>
<th>Sulfate</th>
<th>Water Vapor</th>
<th>CO2 (see footnote 3)</th>
<th>SO2</th>
<th>HCl</th>
<th>NOx (see footnote 4)</th>
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<td>08/31/1990 (Intraeruptive emissions)</td>
<td>14:13</td>
<td>18</td>
<td>3</td>
<td>4</td>
<td>0.2</td>
<td>5787</td>
<td>127</td>
<td>75</td>
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<td>05/10/1990 (Intraeruptive emissions)</td>
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<td>1</td>
<td>2</td>
<td>(4)</td>
<td>(3)</td>
<td>(0.2)</td>
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<tr>
<td>06/11/1990 (Post-eruptive emissions)</td>
<td>11:40</td>
<td>9</td>
<td>0.08</td>
<td>(0.8)</td>
<td>(1.4)</td>
<td>(0.1)</td>
<td>3296</td>
<td>(197)</td>
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1) Alaskan local time in hours and minutes
2) Particle density assumed to be 2x10^3 kg m^-3 except for the first two samples on January 8, when the density was assumed to be 3x10^3 kg m^-3.
3) After subtracting ambient values.
4) NOx flux based on an estimate of 98% NO2 and 2% NO.
   DL = detection limit
   *Underestimates due to leak in sample line
The SO$_2$ fluxes that we measured during the intraeruptive emissions from Mt. Redoubt are similar to those that we measured in intraeruptive emissions from the neighboring St. Augustine volcano in 1976, where the average value was $\sim$100 kg s$^{-1}$ [Stith et al., 1978]. Measurements at Mt. St. Augustine in 1986 by Rose et al. found an SO$_2$ flux of 24800 Tg day$^{-1}$ (278 kg s$^{-1}$) during the eruptive phase, but only 380 Tg day$^{-1}$ (4.4 kg s$^{-1}$) three months later. Similar emission rates were obtained by Greenland et al. [1985] at Kilauea at various stages in its eruption, and by Rose et al. [1986] at the White Is. volcano, New Zealand. The average SO$_2$ flux that we measured for the intraeruptive emissions from Mt. St. Helens, Washington, in 1980–81 was substantially lower at $\sim$2 kg s$^{-1}$ [Hobbs et al., 1982] and similar to Mt. Erebus, Antarctica, which is $\sim$1–3 kg s$^{-1}$ [Radke, 1982; Rose et al., 1985; Chuan et al., 1986].

The average water vapor flux ($\sim$3000 kg s$^{-1}$) that we measured in the intraeruptive emissions from St. Augustine [Stith et al., 1978] were similar to Mt. Redoubt ($\sim$4300 kg s$^{-1}$). Mt. St. Helens produced greater quantities of water vapor ($\sim$100,000 kg s$^{-1}$) during its intraeruptive emissions [Hobbs et al., 1982]. The average mass fluxes of particles <48 $\mu$m in diameter in the intraeruptive emissions from these volcanoes varied from $\sim$3 kg s$^{-1}$ for Mt. Redoubt, to $\sim$80 kg s$^{-1}$ for Mt. St. Helens, to $\sim$330 kg s$^{-1}$ for St. Augustine.

Measurements made in the large eruption of Mt. Redoubt on January 8, 1990, were limited to particles. The fluxes of particles with diameters <48 $\mu$m, derived from these measurements, ranged from $\sim$7000–12000 kg s$^{-1}$ and averaged $\sim$10$^4$ kg s$^{-1}$. For comparison, the particle flux that we derived for the paroxysmal eruption of Mt. St. Helens on May 18, 1980 was $\sim$6 x 10$^4$ kg s$^{-1}$ and for St. Augustine on February 8, 1976, it was $\sim$6 x 10$^5$ kg s$^{-1}$. However, it should be noted that due to differences in sampling locations with respect to the plumes, rapid variabilities in volcanic emissions, and other factors, comparisons of measurements between volcanoes should be treated with some caution. This is especially true for measurements made in large eruptions, which may be restricted by potentially hazardous flying conditions.
Measurements of particles and trace gases made in the posteruptive emissions from Mt. Redoubt on June 11, 1990, show a general decrease in the volcano's activity compared to January 1990 (Table 1). The average mass flux of particles with diameters <48 μm measured in June 1990 was <0.1 kg s\(^{-1}\) compared to average values as high as 8 kg s\(^{-1}\) in January. The average CO\(_2\) flux was \(-50\) kg s\(^{-1}\) in June compared to average values as high as 1714 kg s\(^{-1}\) in January. However, the average water vapor flux measured in June \((\sim 6400\) kg s\(^{-1}\)) was somewhat higher than the average value measured in January \((\sim 4300\) kg s\(^{-1}\)). Measurements of SO\(_2\) fluxes from the volcano on June 11, 1990, obtained from the correlation spectrometer aboard the Convair C-131A aircraft, averaged \(-23\) kg s\(^{-1}\). SO\(_2\) fluxes derived from the airborne in situ and lidar measurements ranged from 2–5 kg s\(^{-1}\), but due to a leak in the sample line feeding the in situ SO\(_2\) instrument the latter values were certainly underestimates. The H\(_2\)S flux, measured by the impregnated filter technique on June 11, was 0.09 kg s\(^{-1}\).

The particle fluxes measured in the posteruptive emission from Mt. Redoubt on June 11 were comparable to those measured by us in the posteruptive emissions from Mt. St. Helens \((<1\) kg s\(^{-1}\)) [Hobbs et al., 1982] and from three Central American volcanoes [Casadevall et al., 1984], but they were lower than those measured in St. Augustine in 1976 \((\sim 30\) kg s\(^{-1}\)) [Stith et al., 1978]. The posteruptive SO\(_2\) fluxes from Mt. Redoubt were similar to those measured from Mt. St. Helens \((\sim 10\) kg s\(^{-1}\) in 1980 and \(\sim 0.2\) kg s\(^{-1}\) in 1981) and from St. Augustine in 1976 \((\sim 20\) kg s\(^{-1}\)). These values are also similar to the SO\(_2\) fluxes measured from the quiescent Arenal volcano, Costa Rica, \((\sim 2\) kg s\(^{-1}\)), the Colima volcano, Mexico \((\sim 4\) kg s\(^{-1}\)), and the Poas volcano, Costa Rica, \((\sim 9\) kg s\(^{-1}\)) [Casadevall et al., 1984], and Kilauea \((\sim 5\) kg s\(^{-1}\)) [Chartier et al., 1988].

The fluxes of all the measured constituents from Mt. Redoubt varied considerably during the course of a flight and from one day to another, reflecting both variations of the position of the aircraft relative to the plume and the non-steady state nature of the volcanic activity (Fig. 2). The mass fluxes of particles measured in the large eruption of Mt.
Figure 2. Average mass fluxes of various constituents measured in plumes from the Redoubt volcano. The particle fluxes are for particles <48 μm diameter. Estimates of the mass flux of particles < 48μm in diameter in the paroxysmal eruption on January 8 ranged from ~7,000–12,000 kg s⁻¹.
Redoubt on January 8 (~7000–12,000 kg s⁻¹), were by far the largest that we measured from Mt. Redoubt (and are off the scale of Figure 2). With a few exceptions, higher mass fluxes of particles from Mt. Redoubt were accompanied by higher mass fluxes of the gases we measured. A similar pattern was observed following the May 18 and May 25, 1980, eruptions of Mt. St. Helens, Washington [Hobbs et al., 1982], and the February 8 and February 13, 1976, eruptions of St. Augustine, Alaska [Stith et al., 1978]. However, our observations of Mt. St. Helens and St. Augustine indicated that this trend did not continue during the posteruptive phase. For these two volcanic eruptions, the mass fluxes of water vapor and SO₂ in the posteruptive phases were highly variable, but these variations were not matched by corresponding changes in particle fluxes. We have not sampled the volcanic emissions from Mt. Redoubt sufficiently during its posteruptive phase to establish any pattern.

6. PARTICLE MEASUREMENTS

Four examples of particle size distributions measured in the emissions from Mt. Redoubt are shown in Figure 3: two for intraeruptive emissions (A and D) and two measured in the emissions (B and C) of the January 8 eruption. All four particle number distributions contain a nucleation mode (<0.1 μm diameter) and an accumulation mode (≈0.1–1.0 μm diameter), although these modes are most prominent in intraeruptive emissions.

The two intraeruptive spectra are very similar in shape, except that the intraeruptive emissions (D) sampled after the January 8 eruption are substantially depleted in accumulation mode particles. Both of the intraeruptive spectra have peak number modes at ~0.1 μm and ~0.8 μm diameters. The number mode at ~0.1 μm, seen in spectra A and D, was probably the product of a condensation process (primarily H₂SO₄ in equilibrium with H₂O), which may have been produced by homogeneous nucleation. SEM-EDAX analysis
Figure 3. Examples of particle number and volume size distributions in the emissions from Mt. Redoubt: (A) January 5, 1990, intraeruptive emission, 3.8 km MSL, 22 km downwind; (B) January 8, 1990, paroxysmal emission, 4.0 km MSL, ~130 km downwind and ~2 1/2 hours after the main eruption; (C) January 8, 1990, aged paroxysmal emission, 2.6 km MSL, ~170 km downwind and ~7 hours after the main eruption; (D) January 12, 1990, intraeruptive emission, 2.7 km MSL, 20 km downwind.
showed that a significant fraction of the particle mode at \( \sim 0.8 \mu m \) consisted of silicate fragments.

Although the duration of the large eruption on January 8 was only about 15 min [Brantley, 1990], the emissions produced an easily recognizable eruptive cloud for at least 7 hours (when darkness fell). Measurements made in this eruptive cloud \( \sim 2 \frac{1}{2} \) h after the start of the main eruption (spectrum B in Figure 3) contained mostly accumulation mode and large (\( > 1.0 \mu m \) diameter) particles and comparatively few nucleation mode particles. Particle spectrum C, sampled \( \sim 7 \) hours after the eruption, shows the effects of aging on particle sizes in the paroxysmal emissions. In the \( \sim 4 \frac{1}{2} \) hours separating spectrum B and C, particles of all sizes decreased in concentrations. However, nucleation mode particles were relatively more prominent in the older sample C.

Virtually all of the particle volume (or mass) in the intraeruptive emissions was contained in accumulation mode particles with diameters of \( \sim 0.8 \mu m \) (see volume plots in Figure 3). Most of the particle mass in the large eruption cloud on January 8 was composed of giant sized (10–100 \( \mu m \) diameter) particles predominately of diameters \( \sim 10 \mu m \) and \( \sim 30 \mu m \) (see double peak in spectrum B volume plot, Figure 3). These giant particles continued to make up a large fraction of the particle mass in the aged emissions (spectrum C in Figure 3).

The particle-number distributions described above for the emissions of Mt. Redoubt on January 8 show some marked differences from those measured in the emissions from Mt. St. Helens [Hobbs et al., 1982] and St. Augustine [Stith et al., 1978] – see Figure 4. The emissions from St. Augustine (spectrum X in Figure 4) and St. Helens (spectrum Y in Figure 4) contained large concentrations of nucleation mode particles, whereas, accumulation mode particles dominated the number distributions in the eruptive emission from Mt. Redoubt (spectrum B in Figure 4). In addition, the eruptive clouds of both Mt. St. Helens and St. Augustine produced two peaks in the number distributions between 0.3 and 2 \( \mu m \) diameter, which were not measured in the emissions from Mt. Redoubt. It is
Figure 4. Particle number and volume distributions in paroxysmal emissions from several volcanoes. (B) and (C) are as in Fig. 3 (for clarity the volume distribution for (C) is not repeated); (X) St. Augustine, February 8, 1976, ~55 km range; (Y) Mt. St. Helens, May 18, 1980, ~9 km range.
interesting to note that the aged emissions from Mt. Redoubt (spectrum C in Figure 4) show a second particle mode that looks very similar to that measured in the eruptive emissions from St. Helens and St. Augustine. All three volcanoes contained giant sized particles in their paroxysmal emissions. Also, they all produced significant emissions of millimeter-sized debris, but these had extremely short residence times in the atmosphere. In the eruptive emissions from Mt. St. Helens and St. Augustine, the particle volume (or mass) distributions were dominated by the giant sized particles; however, there is a suggestion of a mode in the volume distributions at ~8–10 μm diameter. The masses of the particles in the eruptive emissions from Mt. Redoubt was composed primarily of ~10 μm and ~30 μm diameter sized particles. Emissions from all three volcanoes produced a less significant volume mode centered at ~1–2 μm diameter.

The mass concentrations of particles and gases that we measured in the intraeruptive and post-eruptive emissions from Mt. Redoubt are listed in Table 2. The average value of the total mass concentrations of particles with diameters <5 μm was ~120 ± 60 μg m⁻³ (see Table 2). This is consistent with the mass concentration of particles < 3 μm diameter calculated from the particle volume distribution assuming a particle density of 2 x 10^3 kg m⁻³, which for the same samples averaged 135 ± 190 μg m⁻³. Only about 20% (usually much less) of the particle mass in the plumes consisted of sulfate, which was present in concentrations ranging from 1.5 to 53 μg m⁻³, with a mean value of 6 ± 20 μg m⁻³ (Table 2). Hence, most of the fine (< 3 μm diameter) particle mass in the emissions from Mt. Redoubt probably consisted of mineral materials. The two flights on which the highest mass concentrations of particles with diameters less than 0.3 μm were measured (January 5 and January 7) also had the highest sulfate concentrations, indicating that the strikingly prominent nucleation mode near 0.1 μm diameter consisted of H₂SO₄, which was produced either in the volcanic throat or by gas-to-particle conversion of SO₂ in the plume. A similarly predominant nucleation mode was observed in the plume from Mt. Erebus [Radke, 1982].

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Location</th>
<th>Mass concentration of &lt;5 μm diameter particles from 37 mm filters (μg m⁻³)</th>
<th>Calculated masses from particle sizing instruments</th>
<th>SO₄²⁻ (μg m⁻³)</th>
<th>HCl (μg m⁻³)</th>
<th>SO₂ (μg m⁻³)</th>
<th>NOₓ (μg m⁻³)</th>
<th>Sulfur in SO₄²⁻ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Jan 1990</td>
<td>1413</td>
<td>Plume</td>
<td>13.6</td>
<td>141 157</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1421</td>
<td>Plume</td>
<td>193</td>
<td>– – 4527 33.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1439</td>
<td>Under plume</td>
<td>34</td>
<td>0.1 0.2 605 4.9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1508</td>
<td>Plume</td>
<td>–</td>
<td>4.5 66 2064 18.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1548</td>
<td>Plume</td>
<td>122</td>
<td>5.9 75 81</td>
<td>3807 35.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Jan 1990</td>
<td>1243</td>
<td>Plume</td>
<td>287</td>
<td>45 667 718</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1321</td>
<td>Plume</td>
<td>159</td>
<td>30 220 251</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1428</td>
<td>Plume</td>
<td>120</td>
<td>18 207 226</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1510</td>
<td>Plume</td>
<td>–</td>
<td>43 293 342</td>
<td>53 39 &gt;5670 59.7 &gt;0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Jan 1990</td>
<td>1204</td>
<td>Plume</td>
<td>118</td>
<td>1.5 14 16</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1232</td>
<td>Plume</td>
<td>97</td>
<td>9.8 60 70</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1325</td>
<td>Plume</td>
<td>–</td>
<td>– – 1.5</td>
<td>3584 67.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Jan 1990</td>
<td>1348</td>
<td>Plume</td>
<td>89</td>
<td>– – –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1355</td>
<td>Plume</td>
<td>–</td>
<td>14 71 99</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>1441</td>
<td>Background (haze)</td>
<td>–</td>
<td>1.7 1.2 3.4 &lt;DL &lt;DL &lt;DL</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1506</td>
<td></td>
<td>–</td>
<td>21 145 181</td>
<td>15 &lt;DL &gt;5670 59.2 &gt;0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Jan 1990</td>
<td>1214</td>
<td>Plume in cloud</td>
<td>89</td>
<td>4.9 41 60</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1308</td>
<td>Plume in cloud</td>
<td>70</td>
<td>4.9 42 58</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>12 Jan 1990</td>
<td>1509</td>
<td>Plume</td>
<td>119</td>
<td>4.4 23 34</td>
<td>2.2 &lt;DL 1098 18.2 0.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1525</td>
<td>Plume</td>
<td>–</td>
<td>6.8 32 695*</td>
<td>3.5 &lt;DL 1281 19.2 0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1541</td>
<td>Background</td>
<td>53</td>
<td>– – –</td>
<td>0.1 &lt;DL &lt;DL 3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1602</td>
<td>Plume</td>
<td>–</td>
<td>11.8 28 54</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1612</td>
<td>Plume</td>
<td>37</td>
<td>– – –</td>
<td>1715 25.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Alaskan local time in hours and minutes

- No data

DC = detection limit

* Sample contains ash particles
Further insight into the nature of the submicron particles was gained from scanning electron microscope analysis of individual particles collected in the intraeruptive emissions from Mt. Redoubt. This showed generally pure ash particles devoid of any sulfuric acid coating (Figure 5a). Even the submicrometer particles showed little evidence of sulfur (Figure 5b); they usually had elemental compositions similar to the larger ash particles. These submicrometer particles were probably fragments of larger particles produced by a sand blasting process of the type that produces submicron-sized dust particles in high winds in the Sahara Desert [Gomes et al., 1990]. Volcanic particles from Mt. Erebus in Antarctica are also ash particles devoid of sulfuric acid coating [Chuan et al., 1986], as were particles from the 1986 eruption of Mt. St. Augustine [Rose et al., 1988]. This contrasts dramatically with the emissions from three Central American volcanoes in which even relatively large ash particles were heavily coated with sulfuric acid [Cadle et al., 1979; Casadevall et al., 1984]. It is likely that in the cold wintertime conditions of Alaska, relatively little of the SO₂ emitted is photochemically oxidized to H₂SO₄, which would then condense onto the ash particles. Indeed, comparisons of the mass concentrations of sulfate and SO₂ in the intraeruptive emissions from Mt. Redoubt show that only a fraction of 1% of the SO₂ had oxidized to sulfate during the first few hours following emissions from the caldera (Table 2). This contrasts with much lower SO₂ to SO₄²⁻ ratios found in Central American volcanic plumes by Cadle et al. [1979] and Lazrus et al. [1979], where several percent of the SO₂ was converted to sulfate.
Figure 5. a) Typical large (~10 µm) ash particle and corresponding elemental analysis showing pure mineral composition with no sulfuric acid coating. (The white line at the bottom represents 1 µm.) b) Several large and small ash particles. (The white line at the bottom represents 10 µm.) The elemental analysis is for one of the submicron particles (arrow), which shows a trace of sulfur and no sulfuric acid coating. Most other submicron particles contained only mineral elements with no evidence of sulfur.
PART II

USE OF AIRBORNE LIDAR FOR THE DETECTION OF VOLCANIC ASH

1. INTRODUCTION

In Part I of this report we described the results of our airborne measurements of the 1990 volcanic eruptions of Mt. Redoubt volcano. In addition to the in situ measurements of particles and gases, which are emphasized in Part I, we also tested for the first time the use of a prototype airborne dual-wavelength lidar (Light Detection and Ranging), mounted on our research aircraft, for remotely detecting the volcanic emissions. Lidars are rather like radars, but instead of using centimeter wavelength radiation (which detects large precipitation particles) they emit much shorter wavelength visible or near-visible radiation (which is capable of detecting much smaller particles, such as those which are present in high concentration in volcanic emissions). A portion of the energy in the lidar beam is scattered back from the target (volcanic ash in this case) to the lidar on the aircraft, where it is detected by optical sensors. A good review of the principles of lidars and their uses in probing the atmosphere has been given by Collis and Russell [1976].

We first describe the airborne lidar that we used in this project. We then consider two potential applications of airborne lidar for the identification and avoidance of airborne volcanic debris. The first of these, which could be used in a cloud and precipitation free atmosphere, utilizes the lidar backscatter signal to determine the spatial distribution of volcanic ash in the atmosphere. As illustrated by Figure 1 in Part I, the airborne prototype lidar that we used to study the emissions from Mt. Redoubt proved to be very effective for this purpose. If the lidar had been calibrated, the magnitude of the backscattered signal could have provided approximate measurements of the mass concentration of ash along the line of path of the lidar beam (see Section 3 below).

Another potential application of airborne lidar for aircraft safety is discussed in this report. This is to use a lidar to discriminate volcanic ash from other more common
atmospheric targets (e.g. clouds and precipitation). Based on our preliminary studies, this approach appears very promising, and we propose a tentative target identification algorithm for this purpose (see Section 4 below).

2. DESCRIPTION OF THE AIRBORNE LIDAR SYSTEM

The lidar described here is the result of a cooperative development project between the University of Washington and Georgia Tech Research Institute. The lidar was designed for airborne research applications and, as such, it is reasonably robust and compact; the entire system, including data recording and display, uses less than 1.5 kVA of power. However, it should be noted that this lidar was built as a prototype; many improvements are possible (see Part III).

Figure 6 shows a schematic diagram of the lidar system and Table 3 gives system specifications. Polarized, incoherent, monochromatic light is emitted from the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser simultaneously at the primary (1.064 μm) and frequency-doubled (0.532 μm) wavelengths. The beam is reflected through 90° by a mirror toward the center line of the telescope assembly. The beam is then reflected by another mirror and is sent upward along the axis of the telescope. Alignment of the laser beam with the telescope is controlled by adjusting the second mirror. The emitted laser pulse, which has a width of 20 ns (or 6 m) and energies of 70 mJ at 1.064 μm and 45 mJ at 0.532 μm, travels upward while diverging at an angle of approximately 1 mrad. The laser pulse interacts with targets (e.g. gas molecules, volcanic ash, cloud and precipitation particles), and returns a small fraction of the energy of the lidar beam (at the same wavelength as the transmitted radiation) back to the lidar. This return pulse is received and focused by the 0.356 m (14 in.) Casségrainian telescope.

After the light passes through the telescope, it strikes a dichroic mirror. This beam-splitting device allows the infrared wavelength (1.064 μm) radiation to pass without
Figure 6. Schematic of the University of Washington’s-Georgia Tech Airborne Lidar System.
### TABLE 3. THE UNIVERSITY OF WASHINGTON-GEORGIA TECH AIRBORNE LIDAR SYSTEM

(a) **Laser**

- Type: Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG)
- Wavelengths: 1.064 and 0.532 \( \mu m \)
- Energies: 70 and 45 mJ
- Pulse width: 20 ns
- Beam divergence: 1 mrad

(b) **Telescope**

- Type: Cassegrainian
- Diameter: 0.356 m (14 in)

(c) **Detection**

- Polarizing filters: selectable for parallel and perpendicular polarizations
- Detectors: 1.064 \( \mu m \)
  - Type: Silicon Avalanche Photodiode
- 0.532 \( \mu m \)
  - Type: Photomultiplier tube

(d) **Data acquisition/control system**

- Data input
  - Type: CAMAC crate
  - Manufacturer: DSP Technologies, Inc.
  - Digitization rate: 50 ns
  - Shot rate: 10 Hz
- Control/display computer: 20 MHz 80386 based IBM PC/AT compatible
- Data display: VGA monitor (640 x 480 pixels)
- Data storage: 80 megabyte hard disk, floppy disks, or 2.2 gigabyte mini-video cassettes
reflection; the visible light (0.532 μm), on the other hand, is reflected 90°. The 1.064 μm beam is detected by a silicon avalanche photodiode (APD), while the visible light is sensed with a photomultiplier tube (PMT). The signals from each of these detectors pass through separate preamplifiers (to convert current to voltage) and logarithmic amplifiers. The logarithmic amplifiers are needed to detect a wide range of signal strengths without electronic saturation or distortion.

The amplifier outputs are received by a data acquisition system, which has a variable signal digitization rate of 25 or 50 ns, corresponding to vertical resolutions of 7.5 and 15 m, respectively. During our studies of the emissions from Mt. Redoubt, the laser was operated at ~10 Hz which, for an aircraft speed of 80 m s⁻¹, gives a horizontal resolution of 8 m; the data acquisition system at 25 ns gave 7.5 m vertical resolution.

A 20 MHz IBM AT compatible computer performs both display and recording functions, recording on a 2.2 gigabyte Exabyte drive and displaying the data in a variety of real-time formats (e.g. see Fig. 1 in Part I of this report).

3. QUANTITATIVE EVALUATION OF LIDAR MEASUREMENTS

The lidar may be used to detect the presence of particles in the atmosphere through elastic backscattering (see Fig. 1 in Part I). Light emitted from a laser is directed outward into the free atmosphere, where it strikes aerosol particles and gas molecules. The photons in the beam are absorbed and scattered; some fraction of the scattered light is returned opposite to the initial direction of propagation of the beam. The returned signal is a function of the backscattering coefficient (β), which is an integral property of the particle size distribution, the complex refractive index of the particles, the density of molecules, and the wavelength of the incident beam. The signal received by the lidar is described by the lidar equation for single scattering [Collis and Russell, 1976]:

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In this equation, \( P \) is the power of the signal detected at range \( R \), \( P_0 \) the output power of the laser, \( c \) the speed of light, \( \tau \) the pulse duration, \( A_e \) the effective receiving area of the telescope, \( \beta_p \) and \( \beta_g \) the backscattering coefficients due to particles and gases, respectively, and \( \sigma_e \) the coefficient of extinction due to both gas molecules and aerosol particles. The first bracketed term on the right side of (1) can be combined into a single system constant \( C_{sys} \). The exponential term in (1) accounts for the extinction of the beam as it travels from the laser at range \( r_0 \) to the target at range \( r \) and back (hence the factor of 2). The variables \( \beta_p, \beta_g \) and \( \sigma_e \) are all functions of the wavelength (\( \lambda \)) of the laser beam.

Even in relatively clean air, the contribution to the received signal of molecular (Rayleigh) backscattering from air molecules is significant. The Rayleigh backscatter coefficient is given by:

\[
\beta_g = \frac{3\pi}{8} \sigma_g
\]

where, \( \sigma_g \) is the Rayleigh scattering coefficient. Since \( \sigma_g \) follows a \( \lambda^{-4} \) dependence and varies linearly with molecular density, so does \( \beta_g \).

Backscattering by aerosol particles can also contribute significantly to the total signal received by the lidar. This backscattering can be calculated from Mie theory, if the size distribution and refractive index of the particles are known and if the particles are homogeneous spheres. If these conditions are met, the backscatter coefficient due to particles (\( \beta_p \)) is [Collis and Russell, 1976]:

\[
\beta_p(\lambda) = \frac{1}{4\pi} \int_0^\infty \frac{\pi D^2}{4} Q_{\pi}(D, \lambda) F(D) dD
\]

where, \( Q_{\pi} \) is the backscattering efficiency (i.e., the ratio of the backscattering cross section to the geometric cross-sectional area of a particle of diameter \( D \)), \( F \) the particle size distribution function, and \( \lambda \) the wavelength of the laser light. The variable \( Q_{\pi} \) is not a
simple function of particle size, rather it is the sum of an infinite series of spherical Ricatti-Bessel functions that are used in the Mie solution of the scattering equation [e.g., van de Hulst, 1957].

Unlike radars, lidar systems must be calibrated each time they are moved. Repeated calibration is required because the divergence of the laser beam and the field of view of the telescope are both very small—less than 10 milliradians. Thus, small changes in alignment of the laser relative to the telescope can result in the laser beam passing out of the field of view of the telescope. Vibrations and temperature-induced expansion and contraction can also cause the lidar system to become misaligned, and can also result in reduced laser power.

To calibrate lidar systems, three techniques are commonly used—the "slope" method [Collis and Russell, 1976], calibration against an atmospheric target of known backscatter, and calibration against a hard target of known backscatter. During our expedition to Mt. Redoubt, a hard target was not available, and, because the lidar was fixed in a zenith-pointing mode, the "slope" method could not be used. Thus, we decided to try to calibrate the lidar using a region of the atmosphere with known backscatter characteristics.

Before this calibration could be attempted, errors in the lidar data had to be corrected. During the operation of the lidar in the cold weather encountered in January 1990, several electrical problems occurred. These difficulties resulted in spurious electronic signals (millivolts in magnitude) superimposed on the actual lidar return signal. Because the lidar amplifiers detect very small electrical signals, this noise resulted in ringing of the logarithmic amplifiers, as well as a linear signal superimposed on the backscattering profile. Most of this linear signal was removed by calculating the slope of the line and subtracting it from the raw signal.

After correcting the lidar signal in this manner, we attempted to calibrate the lidar by viewing regions of the atmosphere where the particle concentrations were low, and
therefore the backscatter signal approached the Rayleigh limit for scattering by air molecules. Unfortunately, because the signal strength from Rayleigh scattering was close to the detection limit of the lidar in daylight conditions, the uncertainty produced by the spurious electronic noise made it impossible to calibrate the lidar in this way. In future expeditions, refinements of the lidar should solve this problem and permit calibration of the lidar and hence quantitative backscatter measurements.

4. DISCRIMINATION OF VOLCANIC ASH FROM OTHER ATMOSPHERIC TARGETS

In this section, data obtained using the dual wavelength lidar aboard the University of Washington's C-131A research aircraft are examined to determine if this system appeared to be capable of distinguishing between steam and ash emitted by the Mt. Redoubt volcano and natural clouds and precipitation.

To differentiate between the volcanic effluents and natural clouds we rely on differences in the integral property $P_p$ described by Eqn. (3) for these different targets. Because the infrared (1.064 μm) wavelength of the lidar is most sensitive to large particles (diameter > 1 μm), while the green (0.532 μm) wavelength is most sensitive to accumulation mode particles (0.1 – 1 μm diameter), a change in the relative concentrations or compositions of these two particle modes should be reflected in a change in the backscattering at these two wavelengths of the lidar. Thus, it should be possible to use the ratio of the backscattering signal at the two wavelengths to distinguish different targets.

Kent [1978] showed that backscattering from a 1.064 μm lidar can vary by more than an order of magnitude for different realistic coarse particle refractive indices. However, variations in the refractive index of the particles produces much smaller variations in integrated backscatter at 0.532 μm. Thus, the ratio of backscattering at these two wavelengths should be very sensitive to changes in the refractive index of the coarse particles. Because volcanic ash eruptions produce many large particles, they should be distinguishable by examining the relative scattering of the infrared and visible wavelengths.
The lidar data that we used to test the above idea were obtained during two flights near the eruptive plume from the Mt. Redoubt volcano in southern Alaska – one on 5 January 1990 (UW flight 1414) and one on 8 January 1990 (UW flight 1417). During the first of these flights, the targets studied were submicron volcanic ash and steam, ice clouds, and clear air. During flight 1417 a dense, ash-laden, volcanic plume was observed and mapped by the airborne upward-pointing lidar.

Figure 7 shows false color imagery for three targets that were selected for analysis. Figure 7(a) shows a section of the ash and steam plume detected by the lidar on 5 January 1990. Figure 7(b) shows a section of the large ash plume detected by the lidar on 8 January 1990. This plume is much thicker (~2–5 km) than that shown in Fig. 7(a) and it produced a much stronger return signal. Fig. 7(c) shows the return signal from a naturally occurring ice cloud.

The return signals detected by the lidar are composed of 1000 data points per laser shot at each of the two wavelengths. These 1000 data points span the distance from the altitude of the aircraft to 7.5 km above the aircraft. No quantitative signal is received for the first 75 data points (corresponding to a distance of ~560 m) because of the optical configuration of the lidar.

After the electronic noise was removed from the raw data, the data were linearized to account for the logarithmic amplifiers behind the photon-counting detectors. Also, as shown by Eqn. (1), the signal received by the lidar is inversely proportional to the square of the distance (R) from the transmitter. The lidar data were corrected for this range-squared factor using an algorithm developed from a previous ground-based study with this lidar [Gramms, 1990]. In this former study, a correction routine was developed that accounted for the fact that the lidar signal was passed through logarithmic amplifiers that created a logarithmic signal. The algorithm corrects for background noise and the range-squared dependence of the signal. In subtracting off the background noise, it is necessary to treat this value as logarithmic as well. If X is the stored digitized signal, the equation is:
Figure 7. False color imagery of lidar cross sections of (a) submicron-sized volcanic ash particles and steam from the emissions of Mt. Redoubt on 5 January 1990 (at 0.53 μm wavelength); (b) volcanic ash from the large eruption of Mt. Redoubt on 8 January 1990. The ash particles were up to 1 mm in diameter (at 1.06 μm wavelength). The data chosen for detailed analysis are contained between the vertical lines.
Figure 7 continued.

(c) A natural ice cloud in the vicinity of Mt. Redoubt on 5 January 1990 (at 0.53 μm wavelength).
\[ X = A \ln(B/R^2 + N) - A \ln(N) \]  

where, A is a constant, B the desired return signal, and N the level of the background noise. Hence,

\[ B = N R^2 [\exp (X/A) - 1] \]

After corrections to the data, false-color imagery of time-height cross sections of the lidar return signal were produced for the portions of the flights of interest. Using these cross sections, regions of the plume were selected for more detailed analysis. For each of these regions, vertical profiles of the linearized, range-corrected lidar signal were produced for each wavelength. These profiles were offset so that the last few data points of the profile were at zero signal strength. Sections of these profiles, encompassing the lower portions of the targets before attenuation of the laser beam became important, were then selected. Using these profiles, the relative backscattering signals at the two wavelengths were compared, and regressions were calculated. The analysis procedure described above applied to four targets are described below.

**Case I: Submicron-Sized Volcanic and Steam Emissions from Mt. Redoubt on 5 January 1990**

In this case, we examined a thin volcanic plume layer (~150–200 m thick) that consisted mainly of submicron ash particles and steam. Shown in Fig. 8(a) and (b) are vertical profiles of the lidar return signals at 0.53 and 1.064 μm wavelengths for the uncorrected (raw) and corrected data, respectively. As can be seen from Fig. 8(b), the plume was detected a little better at 0.53 μm than at 1.06 μm wavelength. This difference is seen better in Fig. 8(c), which shows a scatter plot of the ratio of the lidar return signal at the two wavelengths: the 0.53 μm wavelength clearly shows a stronger return than the 1.06 μm wavelength. The slope of the line in Figure 8(c) is 1.91, and the correlation coefficient \( r^2 \) between the two signals 0.765.
Figure 8. Submicron-sized volcanic ash and steam emissions from Mt. Redoubt on 5 January 1990. (a) Vertical profiles of raw (uncorrected) lidar return signal at 0.53 \( \mu \text{m} \) (solid line) and 1.06 \( \mu \text{m} \) (dashed line) wavelengths.
Figure 8 continued.
(b) As in (a), but after range correction and correction for electronic noise.
Figure 8 continued.
(c) Lidar return signal at 0.53 μm wavelength versus 1.06 μm wavelength for the lidar plume indicated in (b).

Correlation coefficient \((R^2) = 0.765\)
**Case II: Volcanic Ash from the Large Eruption of Mt. Redoubt on 8 January 1990**

This was the largest volcanic ash plume from Mt. Redoubt that we encountered (see Part I). The portion of the eruptive plume that we chose to analyze was 2–2.5 km thick and consisted largely of ash, including some very large (~1 mm in diameter) sized particles. The quantitative results of our analysis of the returned signals at the two wavelengths are shown in Fig. 9. In this case, the slope of the line in Fig. 9(c) is 1.61 and $r^2$ is 0.89.

**Case III: Natural Ice Cloud Sampled on 5 January 1990**

This thin (~150–200 m) ice cloud layer consisted entirely of natural ice crystals. Surprisingly, in this case the return signal at 0.53 μm was about twice as strong as the signal at 1.06 μm (see Fig. 10). We have no immediate physical explanation for this result. Since the sample size in this ice cloud was rather small, it is possible that the results are not statistically significant. However, if they are, they indicate that the lidar can readily distinguish natural ice clouds from volcanic effluents, since the slope of Fig. 10(c) is 2.5 (compared to 1.6 and 1.9 for Fig. 8(c) and 9(c), respectively).

**Case IV: Clear Air Sample on 5 January 1990**

In this case, we examined the lidar returns from clear air. The corrected data show the returned signal to be close to unity for both wavelengths (Fig. 11b). Also, as can be seen by comparing Figs. 8(c), 9(c), 10(c) and 11(c), the plot for the clear air case is distinctly different. In fact, Fig. 11(c) displays primarily a noise pattern, with more variance at 0.53 μm than at 1.06 μm (the 0.53 μm wavelength is inherently more noisy than the 1.06 μm wavelength).

Table 4 summarizes the results discussed above. We see that the dual wavelength discrimination approach effectively delineates the volcanic plume that consisted of submicron particles and steam (slope 1.91), with its strong particle number size mode near 0.1 and 0.8 μm diameter, from the far more hazardous plume of much larger ash particles.
Figure 9. As for Fig. 8, but for the large volcanic eruption on 8 January 1990.
Figure 9 continued.
Correlation coefficient ($R^2$) = 0.891

Figure 9 continued.
Figure 10. As for Fig. 8, but for the natural ice cloud on 5 January 1990.
Figure 10 continued.

Ice cloud layer

- 0.53 μm
- 1.06 μm

Range from aircraft (km)

Logarithm of lidar return signal
Figure 10 continued.

(c)

Correlation coefficient ($R^2$) = 0.709

Logarithm of lidar return signal at 0.53 μm wavelength

Logarithm of lidar return signal at 1.06 μm wavelength
Figure 11. As for Fig. 8, but for a clear air sample on 5 January 1990.
Figure 11 continued.
Figure 11 continued.

Logarithm of lidar return signal at 0.53 μm wavelength vs. logarithm of lidar return signal at 1.06 μm wavelength.
TABLE 4. Statistics for Discriminating Between Different Targets Using a Dual-Wavelength Lidar

(a) Ash from a large volcanic eruption

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Date</th>
<th>Time Period of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope = 1.61±0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r² = 0.891</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Submicron-sized volcanic ash and steam emissions

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Date</th>
<th>Time Period of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>y intercept = -0.11±0.5</td>
<td>1/5/90</td>
<td>13:06:50–13:07:05 (UW Flight 1414)</td>
</tr>
<tr>
<td>slope = 1.91±0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r² = 0.765</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(c) Natural ice cloud

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Date</th>
<th>Time Period of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>y intercept = 0.24±0.09</td>
<td>1/5/90</td>
<td>12:15:25–12:15:45 (UW Flight 1414)</td>
</tr>
<tr>
<td>slope = 2.53±0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r² = 0.709</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(d) Clear Air Sample

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Date</th>
<th>Time Period of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>r² = 0.031</td>
<td>1/5/90</td>
<td>12:26:00–12:26:10 (UW Flight 1414)</td>
</tr>
</tbody>
</table>

* The statistical parameters listed here are based on the results shown in Figs. 8(c), 9(c), 10(c) and 11(c).
(slope 1.61), which had a strong particle number mode at just over 1 μm and a mass mode at ≥ 10 μm. It was our expectation that ice crystal clouds, especially cirrus, would be difficult to distinguish from the ash produced by large volcanic effluents. However, based on the very limited data that we have, it appears that such discrimination might be possible (see Table 4).

The clear air study was designed to see if a very noisy signal (target at extreme range) might be misinterpreted as a hazard. We see that the ratio test successfully identifies a noisy signal of this type (see Table 4).

Based on the above preliminary results, it appears that an airborne dual-wavelength lidar has considerable potential for detecting volcanic ash in the atmosphere and distinguishing it from other targets. Polarization capability should also help distinguish ice clouds from volcanic ash. However, it should be noted that the lidar signal can be strongly attenuated by dense clouds.
PART III

CONCLUSIONS AND RECOMMENDATIONS

In this report we have described airborne in situ and remote sensing measurements of
the volcanic emissions from Mt. Redoubt during the period January 4–12, 1990 and on
June 11, 1990. We have characterized the emissions in terms of particle and gas fluxes,
and particle size distributions, concentrations and compositions. We have also provided
examples of the horizontal and vertical structures of the ash-bearing volcanic plumes as
revealed by an airborne lidar.

The volcanic emissions during the eruptive period consisted mainly of water vapor
(\(-4300 \text{ kg s}^{-1}\)), followed by \(\text{CO}_2\) (\(-480 \text{ kg s}^{-1}\)) and \(\text{SO}_2\) (\(-70 \text{ kg s}^{-1}\)). In the intraeruptive
emissions, the fluxes of \(\text{SO}_4^{2-}\), \(\text{HCl}\), \(\text{NO}_x\) and particles were on average \(<3 \text{ kg s}^{-1}\); less than
20% of the particle mass consisted of sulfates. The sulfate appeared to be confined to the
0.1 μm particle mode. Very little of the \(\text{SO}_2\) (~0.1%) was oxidized to sulfate and the SEM-
EDAX analysis showed that nearly all of the particles lacked a sulfuric acid coating. This is
in sharp contrast to volcanic particles observed in more temperate locations where
photochemistry is much more active.

Measurements in one of Mt. Redoubt's major explosive eruptions in 1990 (January 8)
showed that the fluxes of particles <48 μm in diameter were \(~10^4 \text{ kg s}^{-1}\). This large flux
was due to large number of particles >1 μm diameter, with a peak mass concentration at
≥ 10 μm diameter. Few particles <1 μm diameter were found in the paroxysmal emissions
compared to the intraeruptive emissions.

The posteruptive emissions from Mt. Redoubt had smaller particle mass (≤0.1 kg s\(^{-1}\))
and \(\text{CO}_2\) fluxes (~50 kg s\(^{-1}\)) than the intraeruptive emissions (~3 kg s\(^{-1}\) and ~480 kg s\(^{-1}\),
respectively). Also, correlation spectrometer measurements showed a decrease in \(\text{SO}_2\) flux
(to \( \sim 23 \text{ kg s}^{-1} \)). The water vapor flux remained a large component of the posteruptive emissions (\( \sim 6400 \text{ kg s}^{-1} \)).

This study has demonstrated the great utility of lidar for determining the location and structure of volcanic plumes containing ash. Also, estimates of mass fluxes of particles and gases from the volcano were significantly improved by the use of the lidar to determine cross-sectional areas of the plumes of emissions. It must be noted however that our success in the use of the lidar was due in part to the clear weather that predominated during our studies. In the presence of natural clouds the utility of lidar for detecting volcanic plumes could be significantly reduced.

The lidar that we used in this study was a prototype research lidar. Based on our experience to date, we recommend that a new lidar be designed and built for the specific purpose of volcanic ash detection. Some of the desirable characteristics for such a lidar are listed in Table 5. The capabilities of this second generation lidar should be evaluated in airborne tests similar to those described in this report. It may be possible to design an airborne lidar system to detect both volcanic ash and wind shear hazards out to distances of about 10 km from the aircraft.
TABLE 5. Some Suggested Characteristics for an Airborne Ash-Detecting Lidar System

a) Transmitter
- An eyesafe frequency tripled YAG laser.
- ~200 mJ per pulse (>100 mJ per wavelength).
- More efficient pumping systems than flash lamps for electrical energy efficiency.
- Pulse rate 20 Hz or better for good spatial resolution.
- Pulse length of ~5-10 m (~20 ns).
- Co-axial R/T unit for ease of alignment.

b) Receiver
- 30-35 cm aperture Cassegrain or Dall-Kirkam telescopes.
- Photomultiplier for visible wavelengths and silicon avalanche photodiodes in the
  near IR. All sensors must be thermally stabilized.
- At least three orders of magnitude dynamic range (without significant distortion). (This
  will require high quality logarithmic amplifiers and 12 bit flash digitizers if satisfactory
  backscattering ratioing is to be achieved.)
- Polarization capabilities

c) Scanning
- Lidar should be capable of pointing in any direction (via a rotating mirror) and be
  capable of operating in a scanning mode.

d) Data Presentation and Recording
- Exabyte with a good high speed PC for both presentation, formatting and recording.
- Color-coded display of different targets (ash, water cloud, ice cloud, etc.).
ACKNOWLEDGEMENTS

The rapid deployment to Anchorage and the success of our field study was greatly aided by Senator T. Stevens and his aide D. Gibson, D. Hodgkins (FAA), J. Fletcher and B. Hicks (NOAA/ERL), J. Evans and M. Stone (MIT Lincoln Labs), B. Goldenburg, H. Hassel and J. Kemper (NOAA/NWS/Anchorage) and D. Keil (FAA/Anchorage). E. Saltzman (U. of Miami) provided filters and analysis of H₂S. We extend our sincere thanks to each of these individuals. We are also grateful to many others, too numerous to mention by name, who helped us in this work.

This work was supported by the Federal Aviation Administration and by contracts NA85ABH0031 and NA90RAH0073 from the National Oceanic and Atmospheric Administration (through their Pacific Marine Environmental Laboratories) and contract BX3703 from M.I.T. Lincoln Laboratory.
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