Chapter 25

Lightning and Electrical Activity during the 2006 Eruption of Augustine Volcano

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Abstract

Lightning and other electrical activity were measured during the 2006 eruption of Augustine Volcano. We found two phases of the activity, the explosive phase corresponding to the explosive eruptions and the plume phase. We classified the lightning into three types, vent discharges, near-vent lightning, and plume lightning. Vent discharges are small, 10 to 100 m sparks, that occur at rate as great as 10,000 s^{-1} at the mouth of the volcano during the energetic explosive eruptions. The vent discharges were observed six different times. Near-vent lightning appears to develop upward from the volcanic cone into the developing column during explosions. This lightning is small, in the range of 1 to 7 km, and short, 0.01 to 0.1 s. The behavior of the near-vent lightning indicates an overall positive charge in the ejecta. The plume lightning resembled intracloud thunderstorm lightning. Often it was branched, spanned more than 10 km, and lasted more than 0.5 s.

Introduction

Throughout recorded history, spectacular lightning discharges have been observed in and from the ash clouds produced by large volcanic eruptions. Lightning has also been observed and photographed during much smaller eruptive activity. Early investigations of volcanic lightning were made during the Surtsey and Heimay eruptions in Iceland in 1963 and 1973 (Anderson and others, 1965, Brook and others, 1974). Lightning associated with eruption of Redoubt in 1989–90 (Hoblitt, 1994) and Spurr 1992 (McNutt and Davis, 2000) occurred in the ash cloud beginning 5 or more minutes after the explosion onsets. (This appears to represent only one type of volcanic lightning, referred to below as plume lightning.) The worldwide observations of volcanic lightning have recently been tabulated, encompassing more than 200 cases associated with 74 volcanoes (Mather and Harrison, 2006; McNutt and Williams, unpublished data), showing that lightning occurs for volcanoes with a wide variety of magma compositions, eruption types, and ash column heights. However, despite increasing interest and additional studies in recent years (reviewed in Mather and Harrison, 2006), volcanic lightning continues to be poorly understood.

Volcanic lightning is at the same time spectacular, dangerous, and interesting. It presents danger that most people close to the eruption will not be expecting. Its interests to science include its roll in the origin of life, similarities and difference to thunderstorms, and why the plume becomes electrified. Observing and monitoring lightning during an eruption opens many possibilities. First it could show where there may be danger to people and where fires could be started. The measurement techniques that we present, can detect lightning at a safe distance even when there is bad weather and visual observations are not possible. Thus, the occurrence of an eruption could be confirmed in remote locations or poor conditions if lightning signals were detected. The location of lightning in the drifting plume would show the location of the ash plume. Measurement of lightning and electrical activity can be another tool to help understand the processes occurring during the eruption.

Here we report observations of lightning during the 2006 eruption of Augustine Volcano, Alaska (Thomas and others, 2007), that have provided a much more detailed picture of volcanic lightning than heretofore available. The observations were obtained with a portable lightning mapping system that was recently developed at New Mexico Tech (NMT),

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and was deployed in cooperation with the Alaska Volcano Observatory (AVO).

We have designed and built a lightning mapping system which produces three-dimensional images of lightning discharges by measuring the arrival time of RF (radio frequency) radiation, at multiple ground stations (Rison and others, 1999; Thomas and others, 2004). The radiation is produced as the lightning channels form or are reionized. To make the system more versatile, we recently built a portable version for rapid deployment in field operations. In addition to studies of thunderstorm lightning, the portable version was built in anticipation of using it for studies of volcanic lightning. A few weeks after the construction of the first portable stations (December 2005), the recent eruption of Augustine began. After consultations about logistics between the New Mexico and Alaska groups, we moved quickly to deploy two stations to observe lightning from possible further explosive eruptions. These stations were installed on the east coast of Cook Inlet near Homer and Anchor Point (see fig. 1). Although more stations surrounding and closer to the volcano were desirable, the remoteness, the lack of power, and the winter conditions made this impossible in the short term. Installation of the two stations was completed only hours before the series of explosive eruptions that began on 27 January, 2006. In this paper, we report on the lightning observations made during these explosions.

In February of 2006, we installed two battery powered stations in remote locations, one on Augustine's informally named West Island (about 7 km from the vent) and one at Oil Point (520 m above Cook Inlet and about 34 km north of the volcano; see fig. 1). The stations operated automatically and unattended on battery power for a period of 1 to 1.5 months. Only a small amount of useful data from West Island was recorded, because the volcano went into a dome-building phase, with substantially decreased explosive activity. Also, due to an electronics problem, much of the data from the West Island station was unusable. On a few occasions during the effusive phase of the eruption, the remote systems recorded signals that were correlated to the signals received at the

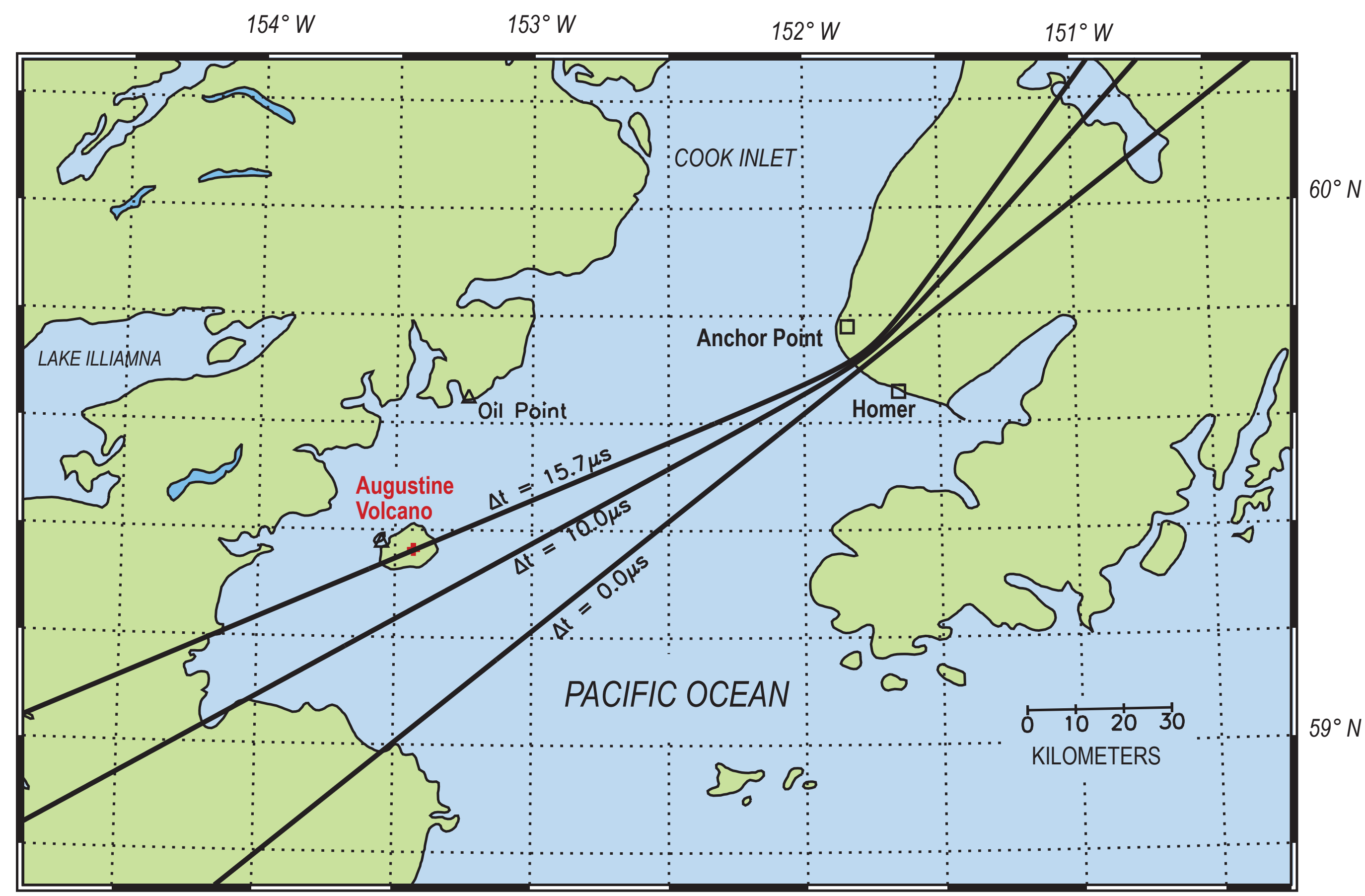

Figure 1. Map of the area surrounding Augustine Volcano and the locations of the lightning mapping stations. Anchor Point and Homer stations (squares) operated from January 27 to May 12, 2006. Oil Point station (triangle) operated from February 20 to March 16 and West Island (Augustine) station (triangle) operated from February 18 to April 2. The three hyperbola show the possible source location for different arrival time differences for the Homer and Anchor Point station pair.

Homer and Oil Point stations. These observations are also reported in this paper.

Other Observations of Lightning January 2006

Before the installation of the NMT Lightning Mapping Array (LMA) stations, lightning was observed accompanying 6 of the 9 explosions from January 11–17, 2006 (table 1). The data are from quite varied sources. A lightning detection system operated by the Bureau of Land Management (BLM) in central Alaska recorded two flashes during the January 13 explosions at 0424 AKST (1324 UTC) and one flash during the January 14 explosion at 0014 AKST (0914 UTC). As the primary use of the BLM system is to monitor summertime cloud-to-ground lightning, which may start forest fires, winter operation is not a high priority. Only four stations of the nine station network were operational during the Augustine eruption (T. Weatherby, written commun., 2006). Figure 3 of McNutt and Davis (2000) shows the locations of the BLM stations. The January 13 lightning flashes were both of positive polarity (as they transferred positive charge to ground) and occurred 10 and 12 minutes after the beginning of the explosion. This time difference is similar to intervals during the Redoubt eruption in 1990 (Hoblitt, 1994). One flash was cloud to ground (CG) and the other intracloud (IC) (T. Weatherby, written commun., 2006). The January 14 flash occurred 8 minutes after the explosion onset and was a CG flash with negative polarity. This event was also recorded on five seismic stations as an irregular spike, due to the interaction between the broadband lightning pulse and the seismic system electronics. The three Augustine flashes were the only lightning flashes recorded by the BLM system in all of Alaska for the first 2 weeks of January 2006.

The explosion on January 14 at 0847 AKST (1747 UTC) was observed by airline pilots flying 100 to 150 miles to the west. They state that they saw the eruption column rising “totally vertically, visibly growing as we watch it, probably 10–15 thousand feet above us now, static lightning discharges within the cloud, cloud is growing very fast…”

One other explosion on January 13 had lightning witnessed by ground observers within the radio station KDLG Dillingham listening area. We infer this to be the 1122 AKST (2022 UTC) explosion or the January 13 1858 AKST (January14 0358 UTC) explosion. Viewing conditions were favorable for both these explosions. The other report is from the January 17 explosion at 0758 AKST (1658 UTC).

During the explosions of January 27–29 there were no visual reports of lightning or detections by the BLM network.

Table 1. Observations of lightning during the Augustine Volcano, January 11-28, 2006, explosive eruption events.

[CG, cloud-to-ground; IC, Intarcloud; BLM, Bureau of Land Management; PIREP, Pilot Report; NMT, New Mexico Tech]

Event			Lightning	Data source	Plume Height (km)	Comments
Number	Date, 2006	Onset UT				
1	11-Jan	1344	No	-	6.5	
2	11-Jan	1412	No	-	10.2	
3	13-Jan	1324	Yes	BLM	10.2	2 flashes, positive polarity, 10 and 12 min after eruption onset, CG and IC
4	13-Jan	1747	Yes	PIREP	10.2	IC, viewed from aircraft 100-150 mi to the west
5	13-Jan	2022	Yes	Ground obs	10.5	telephone call from radio station KDLG Dillingham
6	14-Jan	0140	No	-	10.5	
7	14-Jan	0358	Yes	?	13.5	
8	14-Jan	0914	Yes	BLM	10.2	1 flash, negative polarity, 8 min after eruption onset, CG; also recorded on 5 seismic station
9	17-Jan	1658	Yes	?	13.5	
10	28-Jan	0524	Yes	NMT	10.5	365 flashes; 2 flashes showed up on pressure sensor at station AUE as interference with the pressure sensor electronics
11	28-Jan	0837	Yes	NMT	3.8	1 flash
12	28-Jan	1104	Yes	NMT	7.2	28 flashes
13	28-Jan	1642	Yes	NMT	7.0	6 flashes

Poor weather conditions at these times made for unfavorable viewing conditions.

Measurement Technique

The NMT LMA detects VHF (63 MHz) radio signals from electrical impulses that are produced by lightning and other sources. The arrival times of the signals are measured with 40 ns accuracy using a timing signal from a GPS receiver. With this timing accuracy a multistation LMA can determine the source location with 10-m horizontal error and 30-m vertical error, depending on the geometry of the station and source locations (Thomas and others, 2004). The system is a time-of-arrival system similar to the ones used to locate the source of seismic signals, except the radio signals travel at the speed of light in straight lines (as with light a clear path is needed between the source and receiver; however clouds will not block the signal but solid objects will). A system using eight or more stations spaced 10 to 20 km apart (fig. 2) can locate several thousand sources (in 3 dimensions; 3D) for a single lightning flash. Impulsive RF radiation is emitted as a lightning channel develops. A lightning channel develops in a bipolar manner, with negative breakdown at one end of the channel and positive breakdown at the other (Behnke and others, 2005). The radiation from the positive end of the channel is much weaker than that from the negative end, and the LMA detects primarily the breakdown associated with the extension of the negative end of the channel.

The LMA digitizes the log of the received power at a 25 MHz rate. If the peak amplitude in a short time interval exceeds the local noise level, the time and 8-bit amplitude of the strongest source is recorded. In this experiment this time interval (time window) was either 80 µs or 10 µs. Also, the number of events above the local noise threshold is recorded. This above threshold value will be between 1 and 2,000, with high value indicating continuous breakdown and a small value indicating that only one or a few impulsive events occurred in the 80 µs interval. The threshold is adjusted automatically so that during quiet periods background noise triggers the system about 10 percent of the time. If a source produces radiation strong enough to be detected by six or more stations, the 3D location of the source can be determined.

Figure 3 shows the LMA image of a lightning flash with a complex structure that is lower in altitude (2 to 6 km) and lasts a little longer (about 1 second) than a more typical discharge (6 to 10 km altitude with a duration of about half a second). This flash was selected because its characteristics are similar to the lightning in the Augustine plume after the initial explosion on January 27.

Due to time constraints and logistics, we were able to install only two receiving stations for the initial Augustine observations. The stations were located about 17.1 km apart and about 100 km north-northeast the volcano (see fig. 1). The line joining the stations was close to perpendicular to the direction to Augustine. The southern station was at the AVO field station north of Homer and the northern station was at the Anchor Point Public Library. The receiving antenna at the Homer station was located on the edge of a high (220 m) bluff overlooking Cook Inlet, with direct line of sight to Augustine. The Anchor Point station was located at 125 m altitude about 1.5 km inland from the coast and did not have a direct view of Augustine.

With this system we could determine the azimuthal direction to the radio source. Under these conditions it is a good approximation to assume that the arriving radio wave is a plane wave as shown in figure 4. The azimuthal direction θ to the source is given by $\sin(\theta) = c\,T_{13} / D$, where T_{13} is the difference in arrival times at the two stations, c is the speed of light, and D is the separation distance of the stations. An arrival time difference of 15.7 µs corresponded to signals arriving from the direction of Augustine's summit; signals originating in a southward direction from Augustine had decreased time differences as indicated in figure 1. The 40 ns resolution of the system

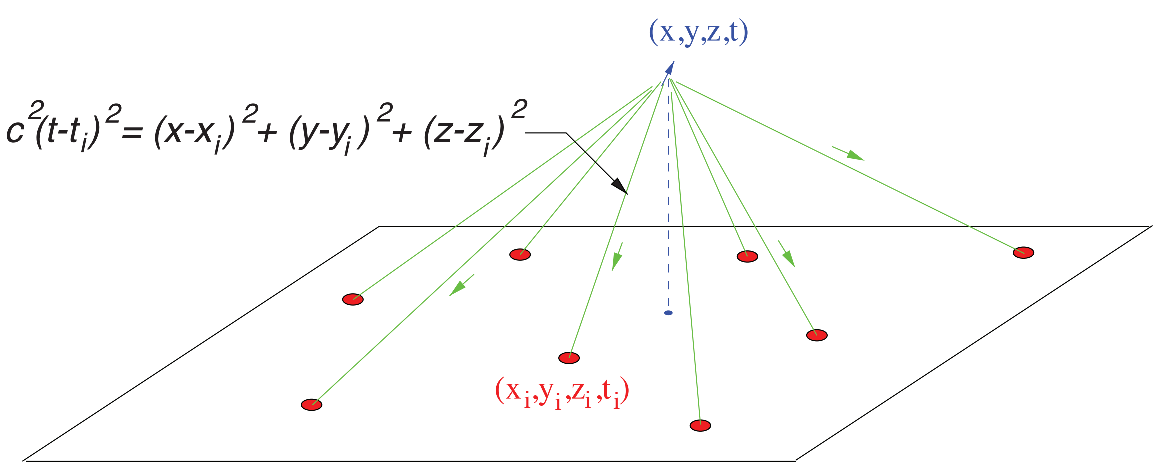

Figure 2. Diagram showing how lightning is located. The multiple station lightning mapping array locates the position of impulsive radio sources in three dimensions by carefully measuring the arrival times at each station.

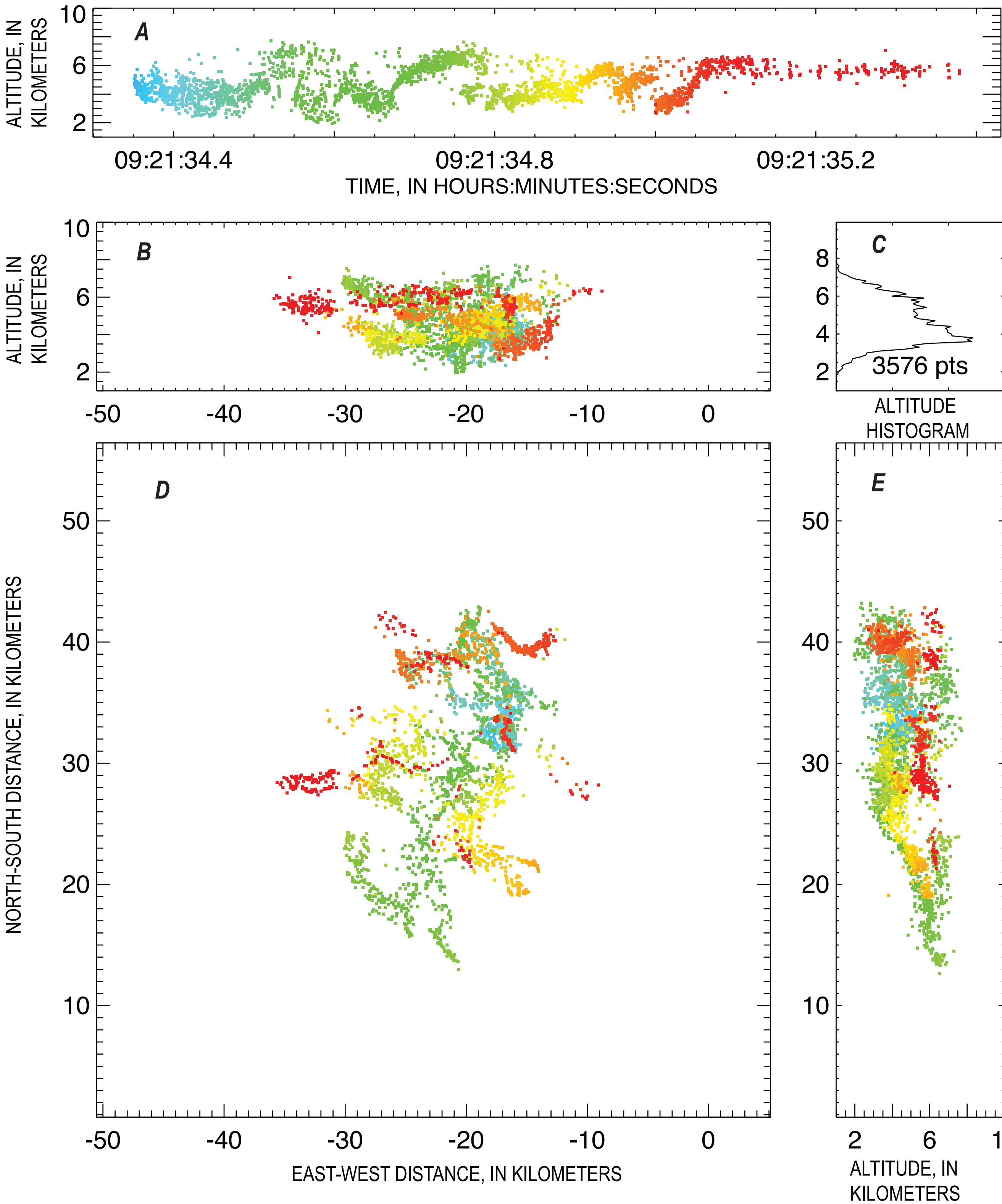

Figure 3. Three dimensional (3D) views of a low altitude intracloud lightning flash observed in eastern Colorado by the lightning mapping array (LMA). This flash was between a negative layer above 6 km and a positive layer below 6 km. The flash did not go to ground. *D* shows a plan view. Colors show the time development, beginning with blue and ending with red. *B* and *E* are vertical projections showing the altitude development. Part A shows the altitude versus time. *C* is an altitude histogram.

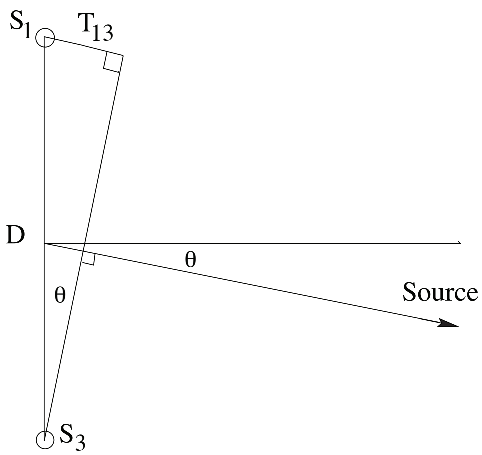

Figure 4. Diagram showing how the direction to a source is determined. Radio waves at an azimuth θ from the source in the distance arrive at station S_3 first and later at station S_1. T_{13} is the difference in arrival times at the two stations. *D* is the separation of the stations.

translates to 75 m (transverse distance, that is in a horizontal direction perpendicular to the line of sight, about north-south) resolution at the distance of the volcano. More precisely, using two stations, a measured time difference constrains the source to lie on a hyperbola (see fig. 1), and at large distances from the stations the azimuthal angle can be determined from the above relationship.

For comparison with the Augustine Volcano results, figure 5 shows the 3D locations of the thunderstorm lightning of figure 3 as they would be observed by a two station network. The top panel shows north-south position as a function of time as would be seen from the west or east. Branches that form continuously appear as lines; the slope can be used to determine the component of velocity perpendicular to the line between the stations and the lightning discharge. The second panel shows how the channels would look as observed from the north or south. The third panel shows the power emitted by the source in the 6 MHz bandwidth of the receivers. The fourth panel shows the number of points above threshold in

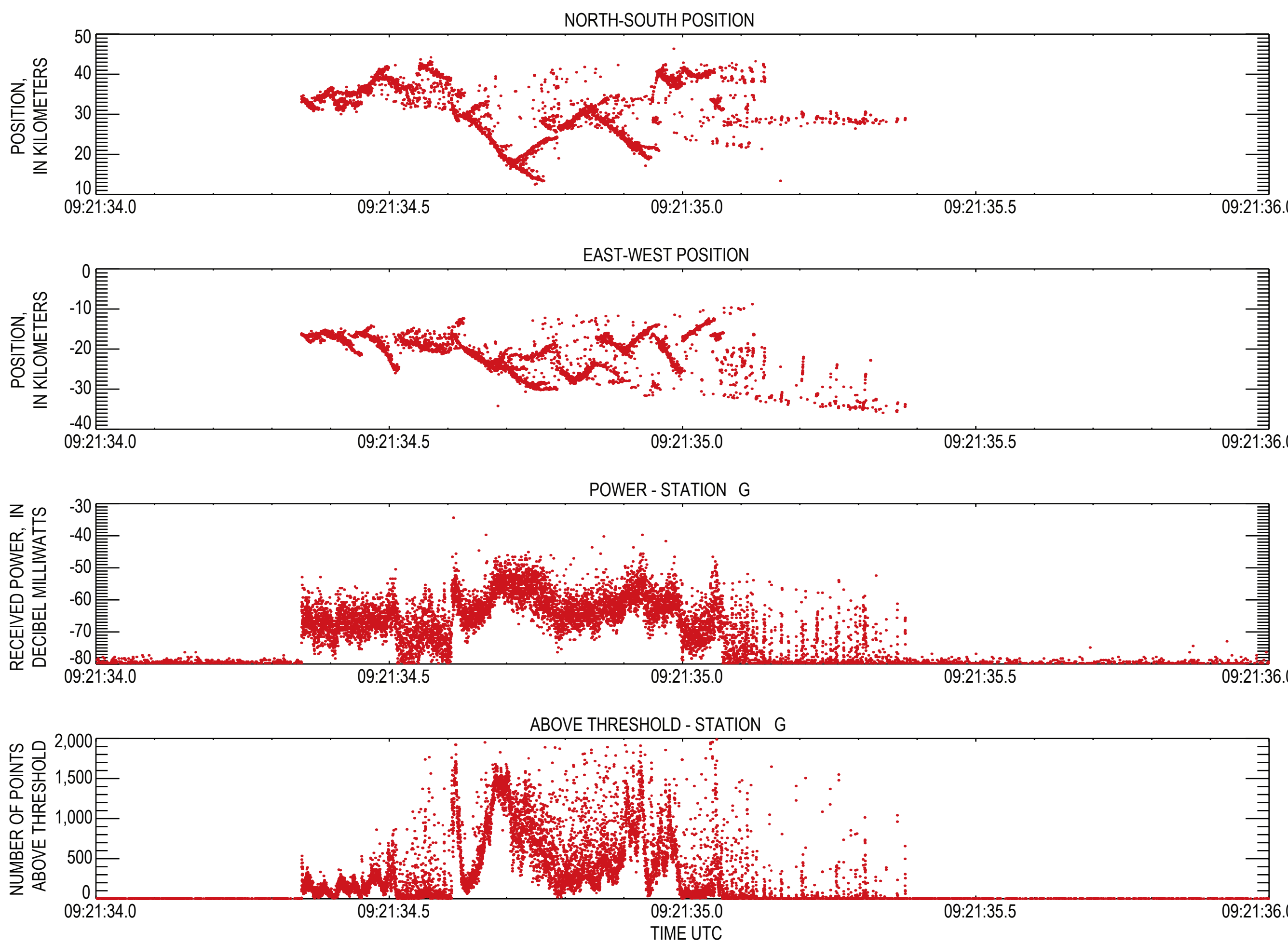

Figure 5. This set of plots show how the flash in figure 3 would appear to a two station network. The top two panels are the x and y positions versus time. The bottom two panels are raw data (power and number of points above threshold) from one station about 100 km from the flash. The times in this plot are in universal time (UTC).

each 10 μs window of the system. In this plot the flash divides into three parts of about equal lengths. During the middle phase of its development, RF radiation was mostly continuous (because the above threshold is near the maximum), and during the final phase, it consisted mostly of isolated impulses (since the above threshold is small).

Explosive Eruption at 2024 AKST on January 27, 2006

LMA Data

The raw data for the 2024 AKST (0524 UTC) explosion on January 27 (January 28 for UTC time) are shown in figure 6. The top panel shows the peak received power of the strongest event detected in each 80 μs interval (the time window was reduced to 10 μs at 1236 AKST (2136 UTC) for Homer and 1443 AKST (2343 UTC) for Anchor Point). In the top plot the color represents the relative density of the number of points at each power level. Several bands of background signals are observed. Most of these are due to local sources such as computers, other high speed electronics devices, motors, and transformers. The best way to identify signals caused by lightning is to correlate the signals from the two stations by looking for differences in arrival times consistent with sources near Augustine. (Peaks due to local sources will not correlate, because sources local to one station will not be detected at the other.) For this explosion we were interested only in time differences close to 15 μs (see fig. 1). Events we identify as correlated are marked with magenta in figure 7. We identified correlated points as groups of at least three points close in both time and arrival time difference.

The second panel shows number of points above threshold in each time window. The bottom panel displays the time between the strong events. During lightning flashes the rate increases and the time between events decreases. The three panels help to identify interesting events. Most of the events identified as correlated appear as vertical lines. Because lightning flashes generally last less than a second, have many high

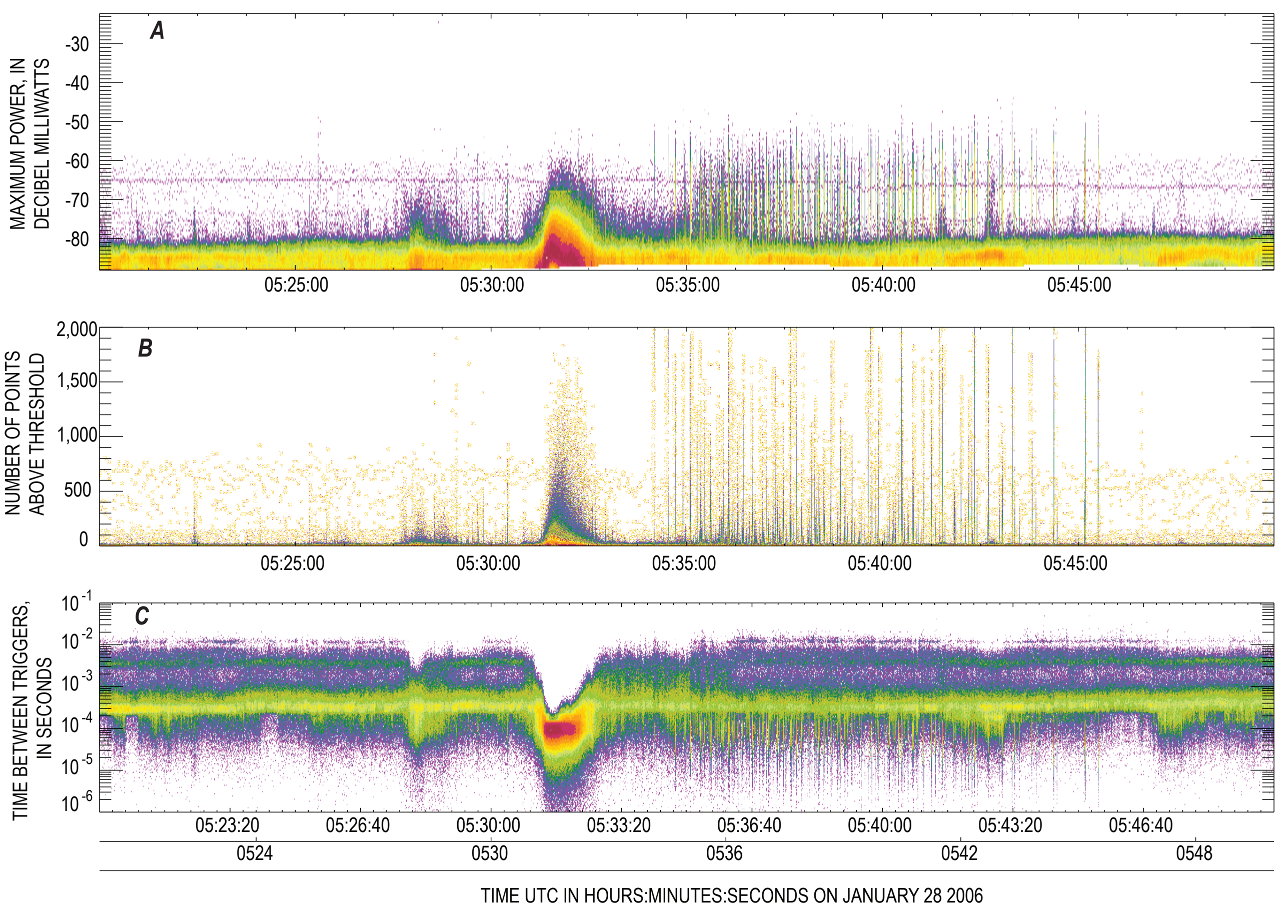

Figure 6. Plots of the raw lightning mapping data of the first explosive eruption on January 27 at 2031 AKST (January 28 at 0531 UTC) from the Homer station. The signature of the explosion is clearly visible as the bright red area. The power, the number of points above threshold, and the time between peaks are shown in the three panels as density plots; the color indicates the number of events with red being the most and blue-purple the least. The dates and times in this plot are in universal time (UTC).

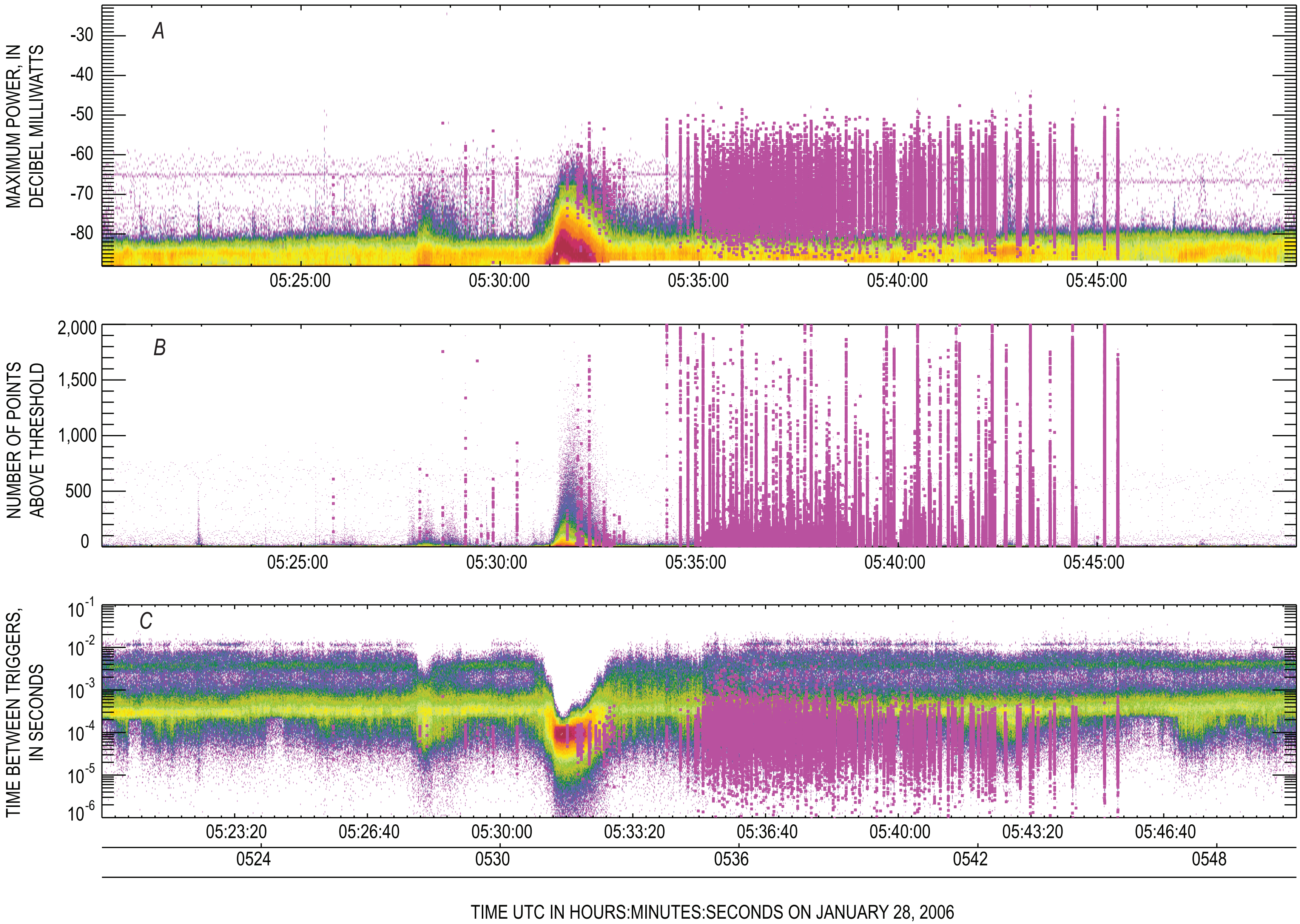

Figure 7. The raw data shown in figure 6 has been marked with magenta points to show events that are seen with both station and are correlated. The difference in the times of arrival show that these are from the volcano. The dates and times in this plot are in universal time (UTC).

power events, and many point above threshold, they should appear as vertical lines in plots with this time scale.

The explosion began at about 2024 AKST (0524 UTC), and was small at first. At 2027 AKST (0527 UTC) an increase in the energy of the explosion occurred, which can be seen as an increase in the LMA signal levels. At about 2031 AKST (0531 UTC) the largest eruptive pulse occurred as an enhancement lasting about two minutes and seen in all 3 panels of LMA data. This enhancement appears to have been caused by the explosion, as it is concurrent with the most intense part of the explosion based on seismic and infrasound data (see fig. 11 below) but is not correlated with data from Anchor Point. Because the station at Anchor Point was somewhat inland, was in a noisier radio frequency environment, and did not have line of sight to the Augustine summit, it was less sensitive to signals from Augustine than the Homer station. Although Anchor Point functioned well for higher-altitude events, it did not detect the noisy radiation during the explosive phases, even though the Homer data showed this radiation to be as strong as or stronger than that of more organized discharges. This indicates that the explosive-phase radiation originated at relatively low altitude at or slightly above Augustine's summit vent. The signals from the vent would have been more strongly attenuated at Anchor Point. The radiated source powers ranged from about 0 dBW up to 30 dBW (1 to 1,000 W) in the receiver passband, typical of values observed for ordinary lightning (Thomas and others, 2001). Because we saw similar enhancements during five other eruptive events (documented below), we conclude that the signals are due to electrical events at the vent during explosive eruptions. We will refer to these as vent discharges.

We have not observed similar electrical activity in thunderstorms (we have observed many thunderstorms with the same equipment and have not seen similar electrical signals). This type of electrical activity appears to be unique to volcanic explosions.

During the 2.2 minutes of enhanced signals starting at 2031 AKST (0531 UTC) there are 26 groups of events that correlate with Anchor Point. During this period only 573 events out of about 810,000 were correlated between the stations. The 810,000 events can be compared to the background of about 140,000 noise events in the same interval 10 minutes earlier. The correlated events are thought to be due to lightning higher up in the eruption column. The first lightning that is seen at both Homer and Anchor Point occurred much earlier, at 20:25:48.8 AKST (05:25:48.7 UTC), and was associated with the first phase of the explosion that began at 2024 AKST (0524 UTC). These lightning flashes have short durations (less than about 0.1 sec) and are few in number; we call these near-vent lightning.

Several minutes after the explosive phase signals ended (2033 AKST (0533 UTC)), there was a sequence of about 300 well-defined lightning discharges that continued for about 11 minutes (20:34:11 to 20:45:31 AKST (05:34:11 to 05:45:31 UTC); fig. 7). We believe that most of these were in the plume as the time differences slowly became smaller indicating a movement to the south in accordance with the wind direction and with radar images of the plume (Schneider and others, 2006). The transverse position of each source is shown in figure 8. The difference in the time of arrival of each correlated event gives the direction to the event, which can be translated to the distance from the summit of Augustine Volcano perpendicular to the

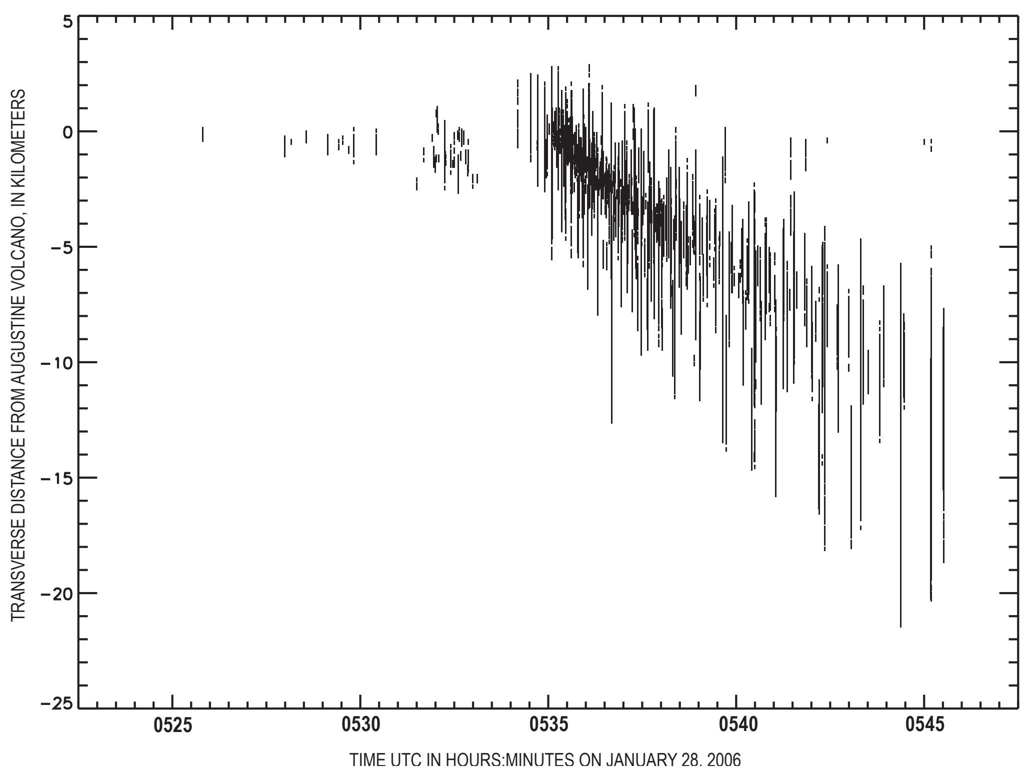

Figure 8. A plot of the transverse position of all the correlated points versus time. The position transverse to the line of sight at Augustine Volcano is found from the difference in the arrival times at the two stations and the distance to Augustine. During the explosion all the points are close to Augustine Volcano. After the explosion ended the location of the lightning drifted to the southeast. The transverse position is the distance from Augustine Volcano in a horizontal direction perpendicular to the line-of-sight from the station at Homer, about north-south. The dates and times in this plot are in universal time (UTC).

line of sight. It can be seen that during the explosion all the events are within 2 km of the volcano. After the explosion ended, the lightning is seen to drift to the south-east during this plume phase.

One of the final discharges lasted 650 ms and had a transverse extent of 15 km, extending to 22 km away from the volcano (fig. 9). The discharges undoubtedly occurred within the volcano's plume, which reached an altitude of 8 to 10 km. Hence we term this plume lightning. The lightning in both figures 8 and 9 undoubtedly also moved along the line of sight both toward and away from us. We were very fortunate that the movement of the plume and its elongation by the winds were mostly perpendicular to the line-of-sight.

The raw data for a plume lightning flash that occurred about a minute earlier are shown in figure 10. The format is similar to that of the thunderstorm flash of figure 5. Similar to the thunderstorm flash, numerous branches are observed, and both impulsive and continuous phases were present. The top panel of figure 10 shows the transverse source positions inferred from the differences in arrival times. The noisy background is a due to correlations which include a noise point at one of the stations which result in a time similar to the difference expected for events in the vicinity of Augustine. These noise correlations are easily removed, and the remaining points are assumed to be correlated.

Seismic and Acoustic Data

The relative timing between the signals from lightning (and other electrical activity) and the explosion as seen by the seismic and acoustic signals is key to understanding the mechanism for the production of lightning. In figure 11 lightning, seismic, and acoustic data are compared. The measured times are displayed, and signal propagation delays must be considered when comparing the two types of data. The lightning signals travel at the speed of light, which produces a delay of about 0.3 ms. The seismic signals travel at about 3 km/s, which produces delays of about 1.1 sec for the signals measured at Augustine Volcano and 6 sec for the signal measured at Oil Point (OPT). The acoustic signals travel more slowly in the air (about 330 m/s), resulting in a 10 s delay. All these delays are small compared to the time resolution of figure 11 and can be ignored here, but will be important for comparisons discussed later. The seismic signals from some of

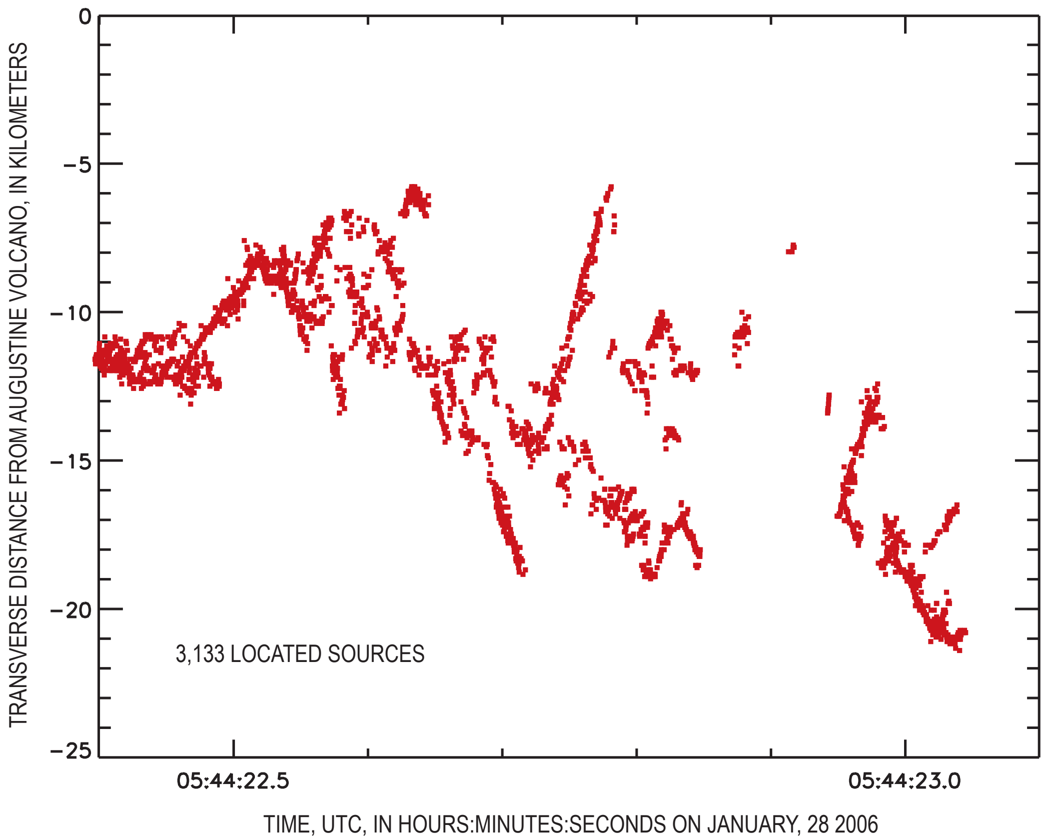

Figure 9. A plot showing the transverse position of the located points of single lightning flash near the end of the plume lightning on January, 27 AKST (January 28 UTC), 2006, during the eruption of Augustine Volcano. The transverse position shows it started about 12 km from Augustine and initially moves toward it. Later branches were as far as 21 km away from the volcano. The dates and times in this plot are in universal time (UTC).

the Augustine instruments saturated during the explosion. The seismic signal from Oil Point did not saturate, and making it suitable to compare seismic amplitudes with lightning signals throughout the explosion (Augustine station AU14 did not saturate and is very similar to that at OPT , see figure 4*B* in McNutt and others, this volume).

The seismic data indicate that the explosion lasted about 11 minutes, from 2025 to 2035 AKST (0524 to 0535 UTC), with a particularly energetic explosive pulse between 20:31 and 2033 AKST (0531 and 0533 UTC). A smaller explosive event occurred at about 2028 AKST (0528 UTC). An enhancement in the lightning background signal is observed at this time. These correlations in time and the similarities in the shapes in intensity are good evidence that the vent discharges are a result of small discharges occurring within the superheated ejecta as it exits the volcano. It also suggests that the number of discharges and their RF power is in some manner proportional to the explosion intensity. Further evidence of such vent discharges is shown by a spectacular photograph published in the September 2007 National Geographic (Grunewald, 2007). This time exposure of an eruption at Tavurvur Volcano, Papua New Guinea, shows about a dozen small electrical discharges that are spread throughout the ejecta. Most of these discharges are tens of meters long

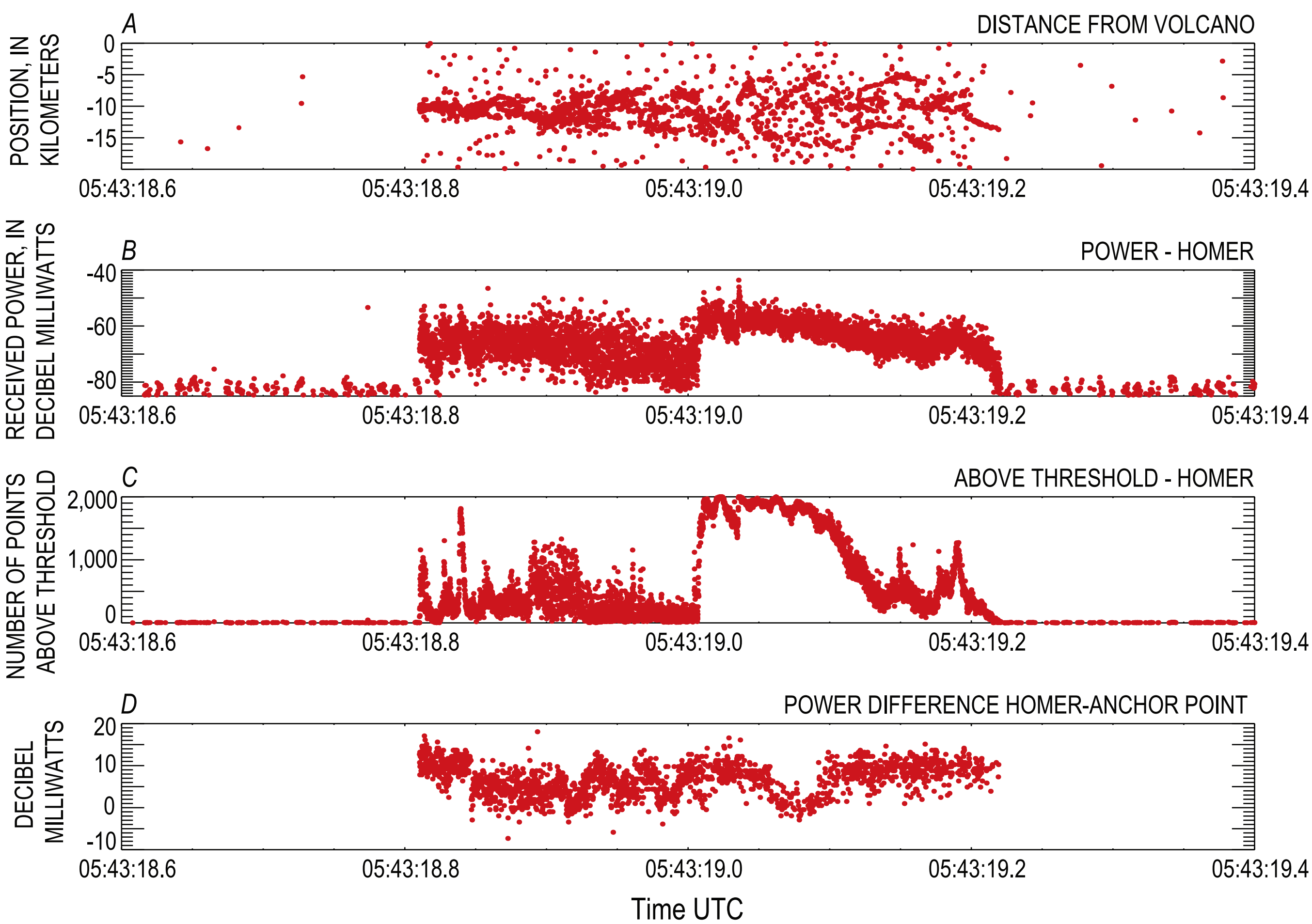

Figure 10. A set of plots showing how another flash from the plume phase evolves on January, 27 AKST (January 28 UTC), 2006, during the eruption of Augustine Volcano. It occurred about a minute before the one in figure 9. The format is similar to that of the thunderstorm lightning in figure 5. For the first 0.1 second the signals are just continuous enough to make the above threshold points reach values of several hundred. For the second 0.1 second the signals are more impulsive and the locations spread out. Beginning at 19.0 s the signals become very continuous and more powerful. In the top three panels all the raw data are included. The transverse positions (top panel) are a linear function of the arrival time differences at the two stations. The top panel also includes a noise background caused by one or both of the sources being a noise source. In the previous figure the noise points were removed by keeping only points that are in clusters. The lowest panel is the ratio of power measured in each station. Because the power is measured on a logarithmic scale the ratio is found by differencing the two measurements. The dates and times in this plot are in universal time (UTC).

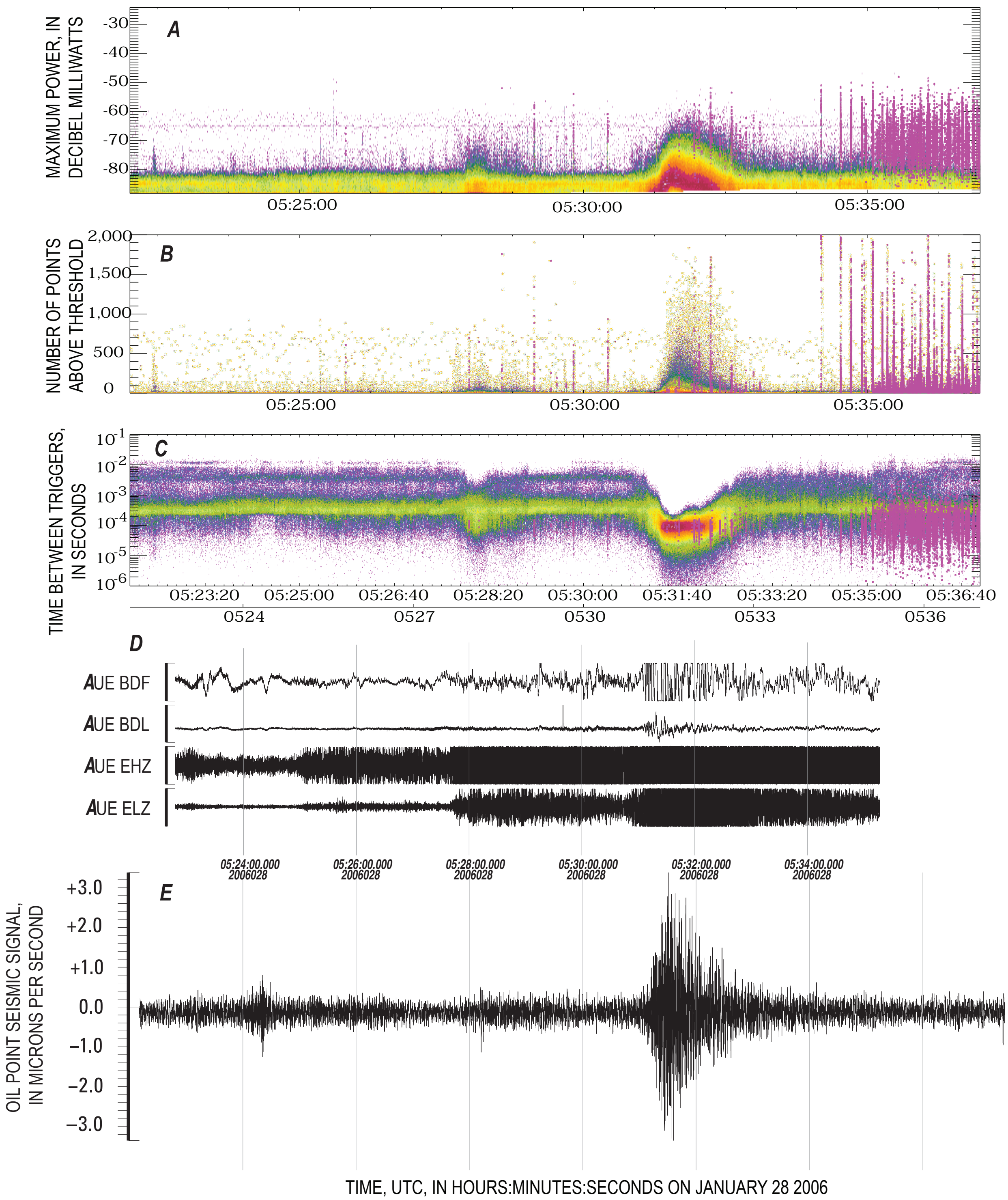

Figure 11. Seismic and acoustic data for the Augustine Volcano on January 27 AKST (January 28 UTC), 2006, are added to the plots of figure 7. The measured times for all the signals are aligned in this and following figures. Acoustic signals are from stations referred to as AUE BDF (high gain) and BDL (low gain). Seismic traces are from stations referred to as AUE EHZ (high gain) and ELZ (low gain). Station AUE is located 3.5 km east of Augustine Volcano's vent. The lowest trace is the seismic signal from Oil Point, about 34 km north of the volcano. The power, the number of points above threshold, and the time between peaks are shown in parts *A*, *B*, and *C* as density plots; the color indicates the number of events with red being the most and blue-purple the least. Units for acoustic and seismic data in part *D* are the same as shown in figure 17. The dates and times in this plot are in universal time (UTC).

and occur within a few tens of meters of the vent. Such small structures are compatible with our observations at Augustine, even though the details of the eruptions may differ.

LMA as an Interferometer

The station near Homer, on a bluff 220 m above the Cook Inlet, received radio signals directly from the lightning sources above the volcano and from their reflections off the sea surface. Because the reflected signal traveled slightly farther, the two signals were out of phase with each other when detected by the Homer station. Although we did not plan for or anticipate the effect, once recognized it allowed us to determine information about the altitudes of the sources. The same effect has been used by radio astronomers to infer the location and structure of astronomical radio sources (Bolton and Slee, 1953). Because the difference in path length varies with the altitude of the source, the interference pattern depends on source altitude. A path length difference that is exactly an integral number of wavelengths will result in constructive interference, whereas a path length difference of N + ½ (a phase change of π) will result in destructive interference. These effects were clearly present for a radiation burst at 20:32:14 AKST (05:32:14 UTC), during the main explosion.

Figure 12 shows how the Homer station functioned as a sea interferometer. The relatively simple discharge at 20:32:14 AKST (05:32:14 UTC) (a near-vent flash) produced received power values versus time that showed clear evidence of interference fringes. The raw data for this flash are shown in figure 13. Figure 13*A* shows the arrival time differences. The points due to the flash are tightly clustered while those associated with noise in one or both stations are scattered randomly, which illustrates how we identify our "correlated" events. Panels B and C show the received power of all points at the two stations.

While most of the high power points are from lightning, some of the high power points are due to weak local sources close to the station's antenna. The correlation allows us to reject high power noise points and identify weak lightning

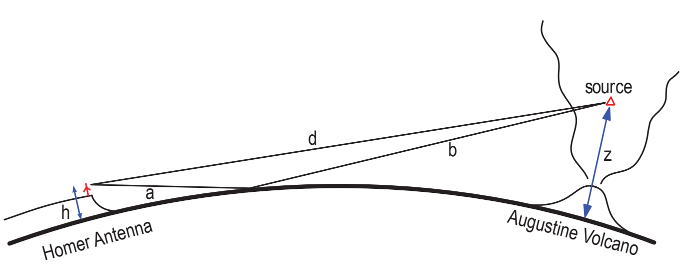

Figure 12. A diagram of the "sea-surface" interferometer. Signals could reach the antenna at the Homer station after bouncing off the water of Cook Inlet. Because the length of the two signal paths were slightly different the two signals interfered with each other depending on the altitude of the source. (From Thomas and others, 2007.)

events. To remove the effect of variations in the source power itself, the Homer power values were referenced to those of the same events at Anchor Point, which did not experience interference effects (fig. 14*C*). With the noise removed, the variations in the power ratio clearly show an interference effect.

The predicted interference pattern is shown in figure 14*D* along with the results of fitting the measurements to the predicted pattern. To obtain the predicted pattern it was necessary to take into account the curvature of the Earth, as well as the fact that seawater is a reasonably good conductor, with a phase shift close to π on reflection. Because of the extreme grazing nature of the reflections (the incidence angle varied between ~0.5 and 2.0 degrees from horizontal for the discharge of figure 12), the path length difference for the direct and reflected signals was only about 0.6λ for signals originating at Augustine's summit (1,260 m altitude) and increased at a rate of about 0.9λ per kilometer above Augustine. Thus, in going ~2 km upward, the discharge at 20:32:14 AKST (05:32:14 UTC) showed two complete interference fringes (fig. 14*D*).

Several steps were taken to fit the observed data to the predicted values. First, the logarithmic power differences needed to be shifted downward by 15 dB to compensate for the attenuation of the Anchor Point signals. Second, to match the depth of the interference minima, the reflection coefficient of the sea surface was adjusted to an effective value of 0.7 (versus 1.0 for an ideally smooth conducting surface). Finally, a piecewise-linear approach was used to map temporal intervals in the observed data to spatial intervals on the predicted interference fringes (figs. 14*A*, *C*). To accomplish this, a particular set of points in the temporal data was assumed to originate at heights that gave reasonable "eyeball" fits between the observed and predicted power values. The resulting time-height conversion (fig. 14*B*) was then used to convert the transverse distance versus time data of figure 14*A* to a 2-dimensional vertical projection plot.

Figure 15 shows the resulting vertical projection of the flash. The discharge appeared to begin about 250 m above Augustine's summit and progressed upward and leftward (southward) along a single, 4-km long path. The average speed of progression was about 0.7×10^5 m sec^{-1} vertically and about 1×10^5 m sec^{-1} overall in the transverse plane. Such propagation speeds are characteristic of negative polarity breakdown propagating toward or through net positive charge (Behnke and others, 2005). Lightning emits radio frequency radiation primarily from developing negative-polarity breakdown, which propagates into positive charge regions, rather than from positive breakdown, which propagates into negative charge regions. The upward radiation sources of figure 15 are similar in character to the initial breakdown observed in intracloud discharges in thunderstorms, which are of negative polarity and propagate into and through regions of net positive charge (for example, Behnke and others, 2005). (The propagating radiation segments seen in figures 9 and 10 are also produced by negative breakdown through positive charge regions.)

The origin of the upward discharge in figure 15 is only an apparent location that corresponded to the time that the

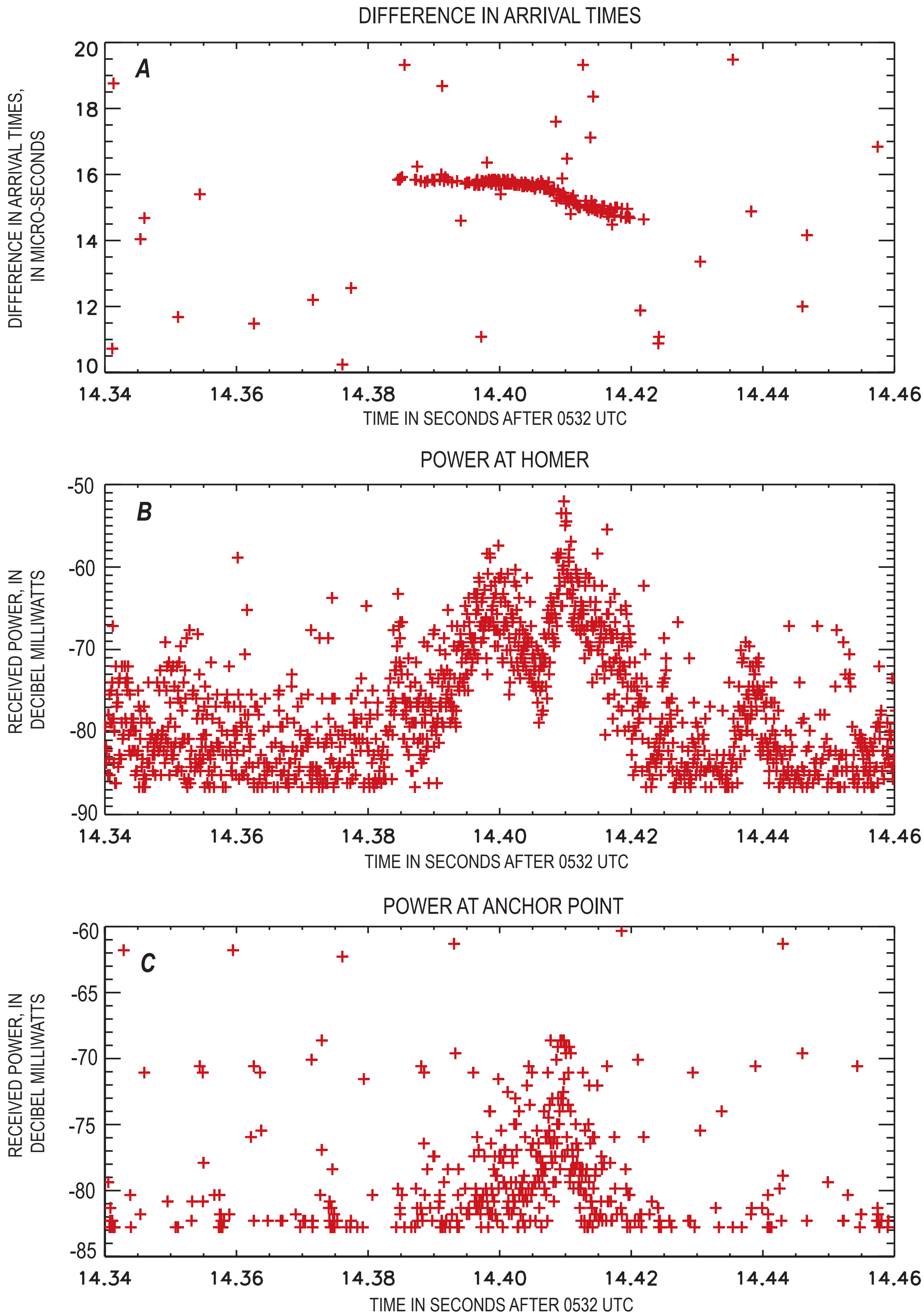

Figure 13. Plots of the raw data from a small lightning flash during the main explosion of the Augustine Volcano at 2032 AKST on January 27 AKST (0532 on January 28 UTC), 2006. All the measured power values are shown for the Homer and Anchor Point stations. The Anchor Point station is less sensitive as it is inland about 1.5 km. The power varies differently at each station. The dates and times in this plot are in universal time (UTC).

sources from the flash were strong enough to be detected by the Anchor Point station. The single-station power data from Homer show clear evidence of propagating breakdown prior to signals being detected at Anchor Point, indicating that the discharge began at lower altitude, almost certainly on the ground in the vicinity of the summit. Because the choice of the initial fringe is ambiguous, we cannot strictly rule out the possibility that the discharge began an integer number of fringes higher in altitude. However, this is considered unlikely in view of the above physical interpretation of the observations. There is also an ambiguity as to whether the discharge developed downward or upward, but this is readily resolved from the fact that downward development would give a physically incorrect picture of the discharge relative to the plume.

No cloud-to-ground discharges were detected by the BLM Alaska Lightning Detection System during the January 27–28 explosions. Upward-initiated discharges from the ground would not be detected by the BLM system because such networks locate the strong "sferic" produced by return strokes initiated by downward leader breakdown (Cummins and others, 1998). Low-frequency lightning location networks occasionally detect intra-cloud flashes, as the BLM network did for January 13 explosion. The BLM network detected cloud-to-ground discharges only during the early January explosions—one that

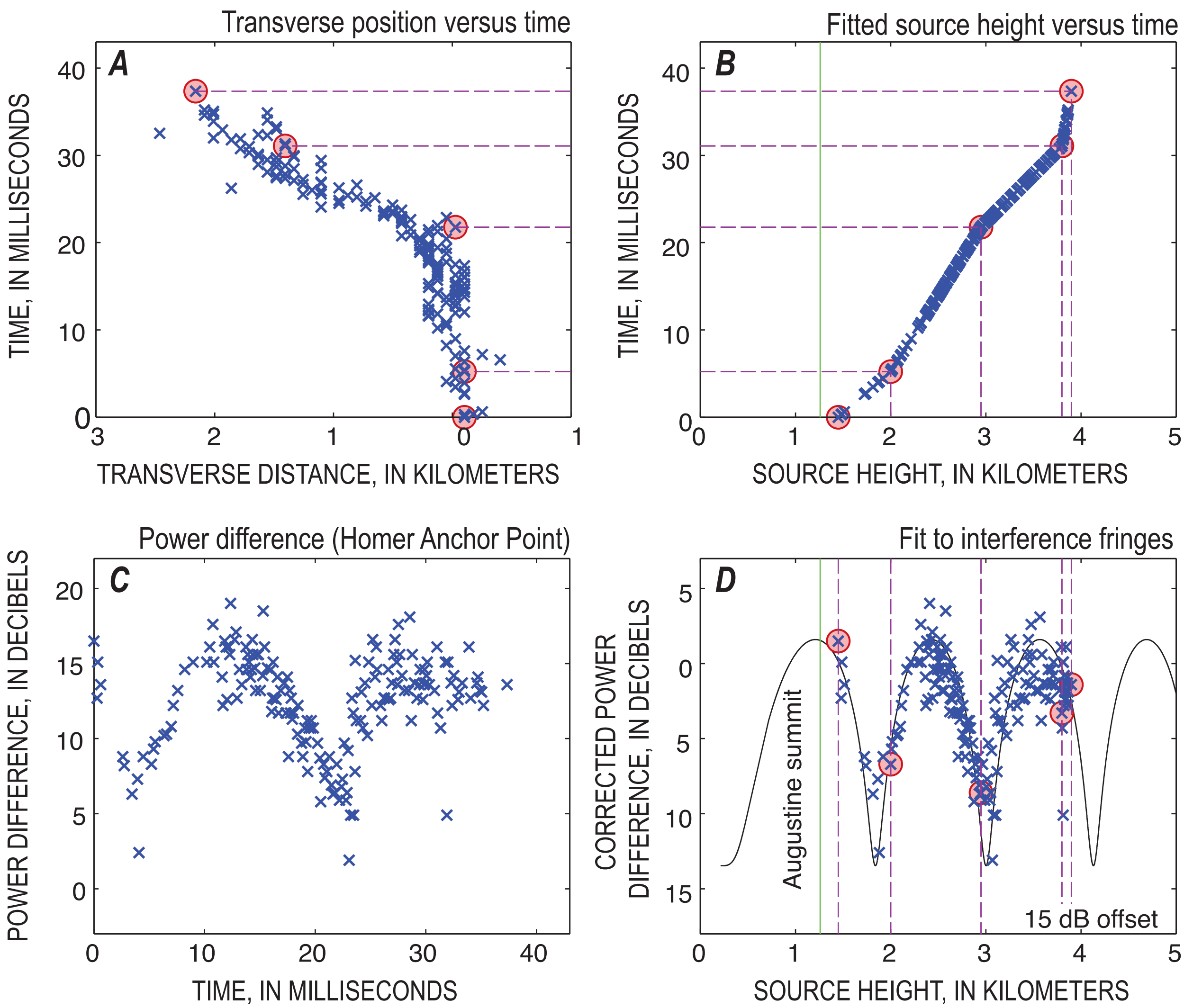

Figure 14. Four plots showing how the interference pattern is deciphered. This pattern is from a small lightning flash during the main explosion of the Augustine Volcano at 2032 AKST on January 27 AKST (0532 on January 28 UTC), 2006. *A*, Transverse distance versus time. *B*, Fitted source height versus time. *C*, Power difference between Homer and Anchor Point versus time. *D*, Corrected power difference versus height with interference fringes also shown. The pink circled points and dashed lines indicate breaks in the piecewise-linear fits. (from Thomas and others, 2007).

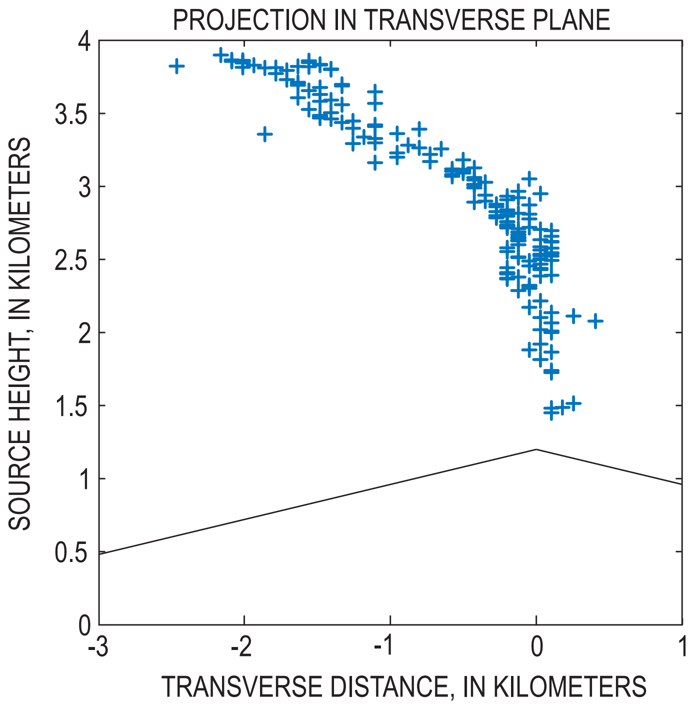

Figure 15. Plot showing the path of the lightning channel above Augustine Volcano. This lightning occured during the main explosion of the Augustine Volcano at 2032 AKST on January 27 AKST (0532 on January 28 UTC), 2006. The lightning began at the summit of Augustine and went up and then to the southeast where the wind was moving the plume. The volcano is represented by a simple line drawing. (from Thomas and others, 2007).

lowered positive charge to ground during the initial explosion (January 13 at 0424 AKST (1324 UTC); table 1), and one that lowered negative charge to ground during a later explosion (January 14 at 0014 AKST (0914 UTC)).

Flash Durations

Various aspects of the flash durations are plotted in figure 16. Initially the flashes lasted only a few milliseconds (fig. 16*A*); these are near-vent lightning discharges. During the explosion they increased in length to about 70 milliseconds. With a typical velocity of 10^5 m/s this implies a total length of less then 7 km. During the main eruptive phase, many of the flashes in the plume last several hundred milliseconds. During the initial part of this phase there are many fast small flashes, but their numbers decrease with time. figure 16*B* shows that most of the small flashes appear to be near the volcano vent, most likely in the rising plume column. Initially the flashes are separated by 10 or more seconds (fig. 16*C*), similar to what is seen in a small thunderstorm. As the plume lightning begins at about 2035 AKST (0535 UTC) the rate is more than 5 flashes per second. Such high rates are generally seen only in large thunderstorms, such as those produced by meos-scale systems in the Great Plains (MacGorman and Rust, 1998). At the end of the plume lightning phase the flash rate is typical of rates observed in similar sized thunderstorm in New Mexico. Interestingly, the number of points per millisecond seems to increase with the flash size (fig.16*D*).

Explosion at 2337 AKST on January 27, 2006

A very short and impulsive second explosion on this day occurred at 2337 AKST on January 27, 2006 (0837 UTC on January 28). Infrasound measurements show a short burst (20 s) with the highest peak acoustic pressure (105 Pa) for the entire eruption [Peterson and others, 2006]. The plume height was estimated to be 3.8 km (Schneider and others, 2006). Lightning, infrasound and seismic data are shown in figure 17. Both the signals from the electrical and acoustic sources begin very abruptly and last about 20 seconds. Because both the signals began so quickly their onsets can be determined to $\pm$0.1 seconds. Using the time delay for the acoustic signal from Peterson and others (2006) of 9.4 s would indicate that the electrical activity began about a second before the acoustic signal. However, Peterson and others (2006) based their acoustic delay on an assumed atmospheric acoustic velocity of 340 m/s, which is velocity at room temperature. Correcting the velocity to a temperature of −10°C indicates that the onset of both signals was simultaneous within the measurement error of 0.1 s. This supports the argument that electrical activity is generated at the vent of the volcano and is produced by the high velocity ejecta. Both the electrical and acoustic signals indicate activity above ground. The strong seismic signal of the main event appears to begin several seconds before indicating the beginning of the explosion, deeper in the vent. A small seismic subevent began about 15 s before the main phase (fig. 17).

Plots of the electrical activity recorded at the Homer station (fig. 18) show about 10 vertical lines consistent with small lightning flashes. Only one of these flashes, a 10-ms-long flash at 23:38:19.36 AKST (08:38:19.36 UTC on January 28), correlated with signals at Anchor Point. Using an average velocity of lightning of about 10^5 m/s, we can estimate a length of 1 km for this flash. This indicates that the flash is near-vent lightning. It can be seen that there are very few vertical lines both before and after the minute of eruptive activity (fig. 18). Thus, it is very likely that the vertical lines during this period were produced by other small near-vent lightning flashes (lasting 5 to 10 ms).

A summary of parameters for the various types of lightning and electrical activity is given in table 2 for all the events in this study.

Table 2. Summary of lightning parameters measured by the Lightning Mapping Array for the Augustine Volcano eruptions in January 2006.

Date January 2006	Time UTC	Plume Height (km)	Vent Discharges		Near-Vent Lightning			Plume Lightning		
			Max power (dBm)	Duration (sec)	Number of flashes	Duration (min)	Delay (sec)	Number of flashes	Duration (min)	Delay (sec)
28	0524	10.5	-50	120	22	7.4	108	300+	11.4	10.5
28	0837	3.8	-70	20	1	-	42	0	-	-
28	1104	7.2	-65	30	28	1.2	60	0	-	-
28	1642	7.0	none	-	6	2	300	0	-	-
29	0040	3.8	none	-	35	18	n.a.	0	-	-
29	2019	7.2	-65	120	2	0.05	118	0	-	-
30	1228	7.2	-70	132	0	-	-	0	-	-
30	1522	7.2	-72	25	2	0.1	25	0	-	-

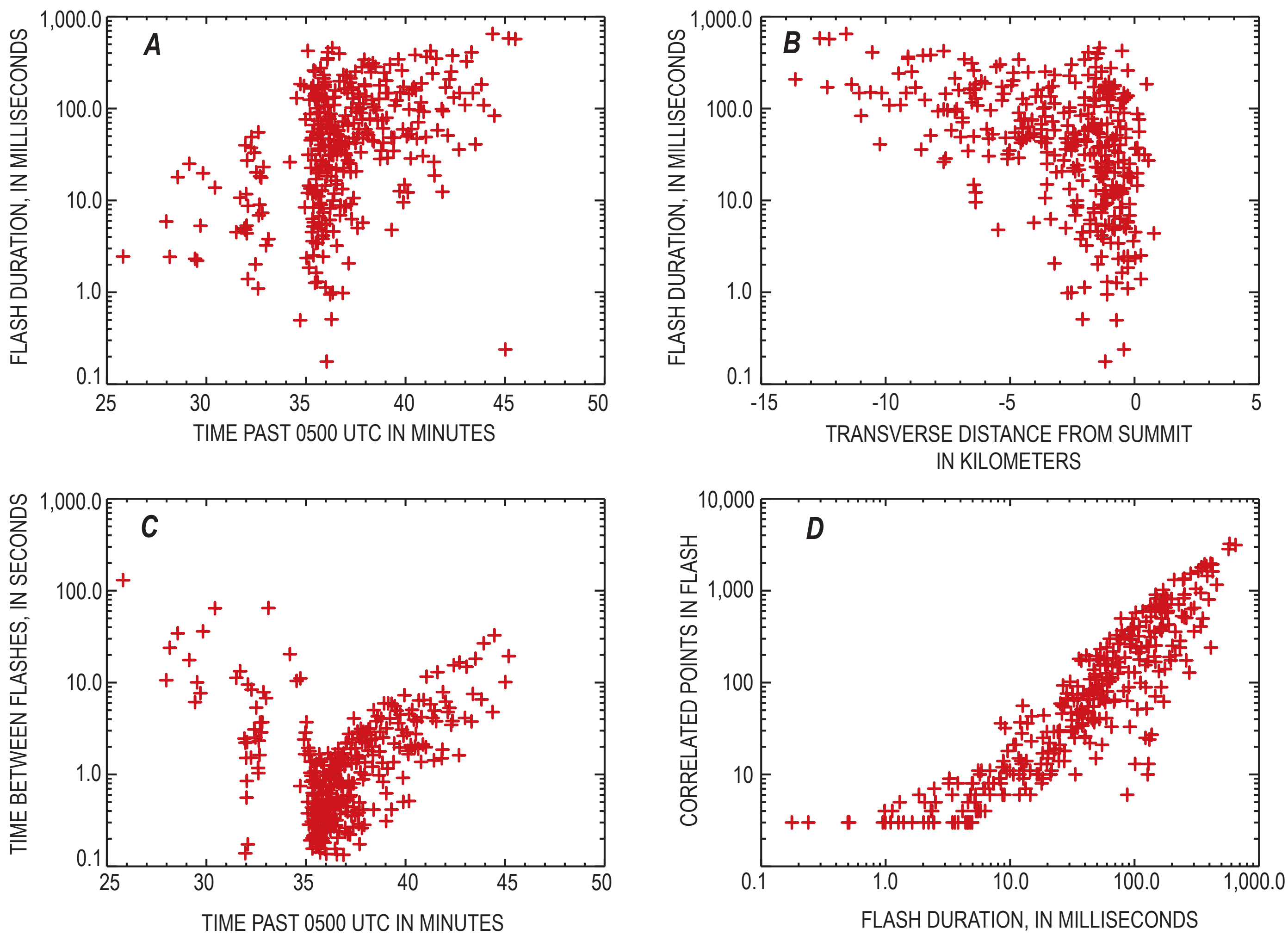

Figure 16. Plots showing the flash durations as a function of other parameters for the Augustine Volcano eruption on January 27 AKST (January 28 UTC), 2006. The panels show (*A*) the duration of each flash versus time, (*B*) the duration versus position, (*C*) the separation of flashes versus time, and (*D*) number of points in the flash versus duration. The dates and times in this plot are in universal time (UTC).

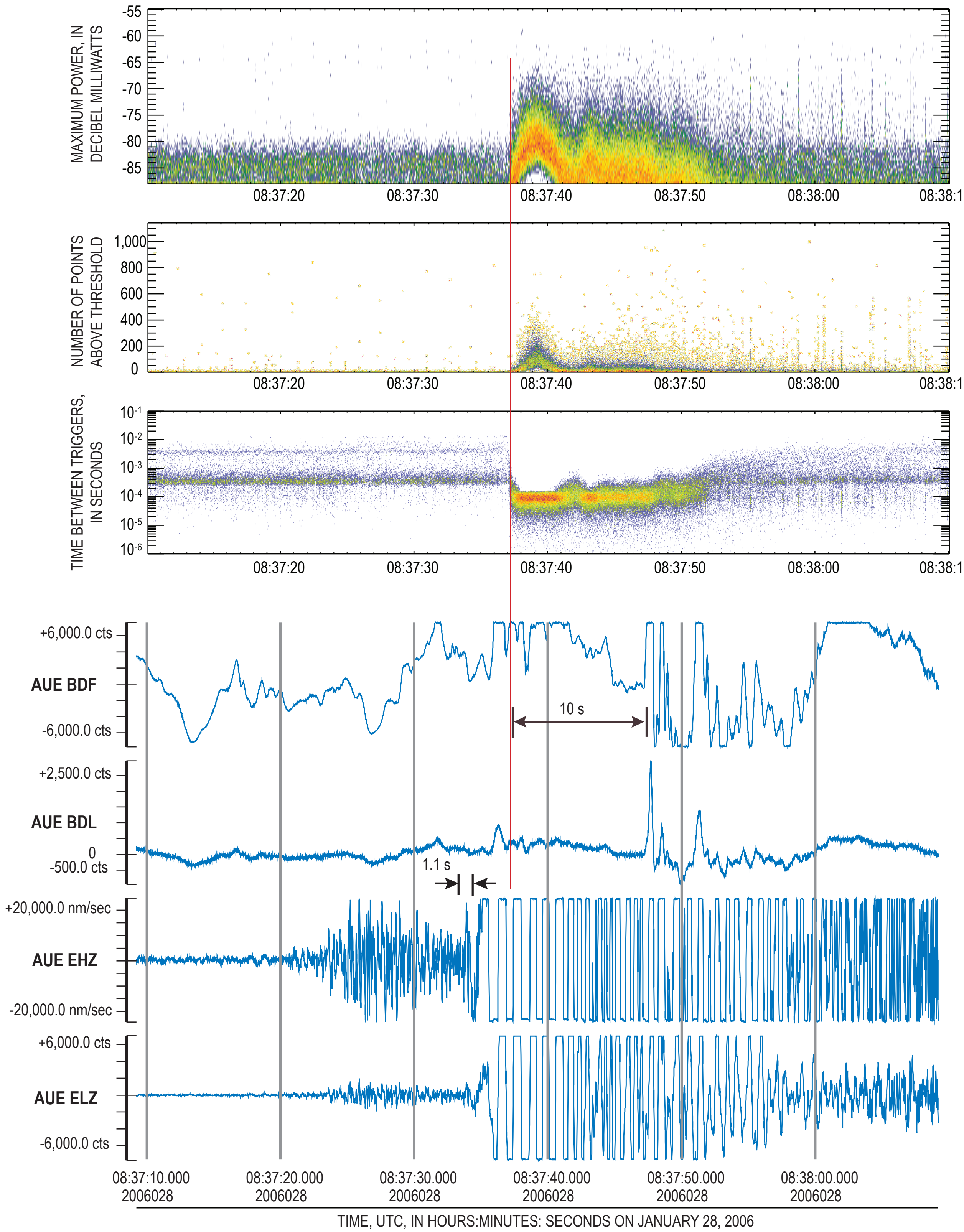

Figure 17. Plots of the data from Augustine Volcano's explosion at 2337 AKST on January 27 (0837 UTC on January 28), 2006 showing lightning mapping, seismic, and acoustic signals. When the acoustic travel time of 10 seconds is taken into account the beginning of the electrical and acoustic signals are coincident (vertical red line). Upper three panels show electrical data and lower four show acoustic and seismic data. See figure 11 caption for details. The dates and times in this plot are in universal time (UTC).

Explosion at 0204 AKST on January 28, 2006

The explosion at 0204 AKST (1104 UTC) on January 28, had smaller acoustic and seismic amplitudes than the previous two events. The peak acoustic pressure was 66 Pa and the plume height was 7.2 km. The seismic duration was longer than the 2337 AKST (0837 UTC) event but shorter than the 2024 AKST (0524 UTC) event (Petersen and others, 2006; McNutt and others, this volume). The data in figure 19 show similar behavior in the electrical, acoustic, and seismic signals. As in the previous explosions, we see both continuous background activity due to vent discharges and correlated signals indicating the development of lightning channels upward into the erupting column. All the correlated lightning appears to be near-vent lightning.

Figure 20 shows that most of the flashes lasted less than 10 ms and, therefore, had lengths of less than a km. A few could have been several km long. These are similar to the events in the first few minutes of the 2024 AKST (0524 UTC) explosion (fig. 16) that occurred before the plume lightning began at 2034 AKST (0534 UTC).

Explosion at 0742 AKST on January 28, 2006

The explosions at 0742 AKST (1642 UTC) on January 28, was smallest of the four explosive eruptions of this day in terms of the acoustic and seismic amplitudes (Petersen and others, 2006; McNutt and others, this volume). The duration (see fig. 21) was similar to the 0242 AKST (1104 UTC) event and was much longer than the earlier 2337 AKST (0837 UTC) event. This explosion began with a weak phase at 0742 AKST (1642 UTC), followed by a stronger phase starting at 0748 AKST (1648 UTC). We did not see the enhanced radiation

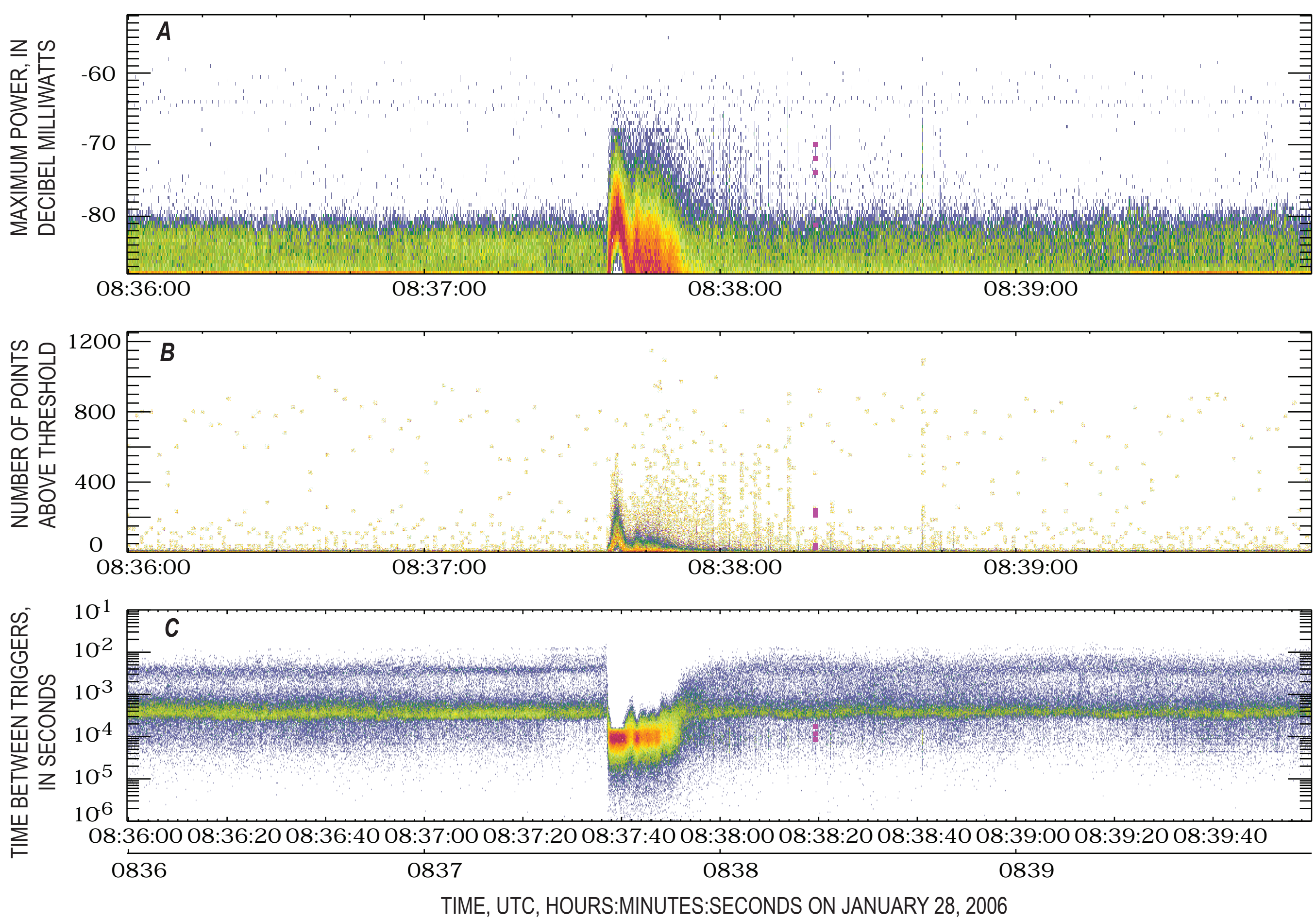

Figure 18. Data from Augustine Volcano's explosion at 2337 AKST on January 27 (0837 UTC on January 28), 2006. Because the background is small (easiest to see in panel *B*) both before and after the explosion, the vertical lines of signal points are probably small lightning flashes. See the captions of figures 6 and 7 for details. The dates and times in this plot are in universal time (UTC).

from electrical activity at the vent, but there were 6 small lightning flashes with correlated points. Most of the lightning occurs just before the major seismic event; this suggests it is near-vent lightning caused by the initial 0742 AKST (1642 UTC) event. It also implies that the large phase at 0748 AKST (1648 UTC) may have been mostly gas with little tephra. Figure 22 shows that all the flashes were very small and of short duration, similar to the near-vent lightning flashes associated with the other three explosions on January 28, 2006.

Lightning and Vent Discharges during the Continuous Phase on January 29 and 30, 2006

The explosive phase of the eruption ended with the event on January 28 at 0742 AKST (1642 UTC). This was followed by a transitional event that began at 1430 AKST (2330 UTC)

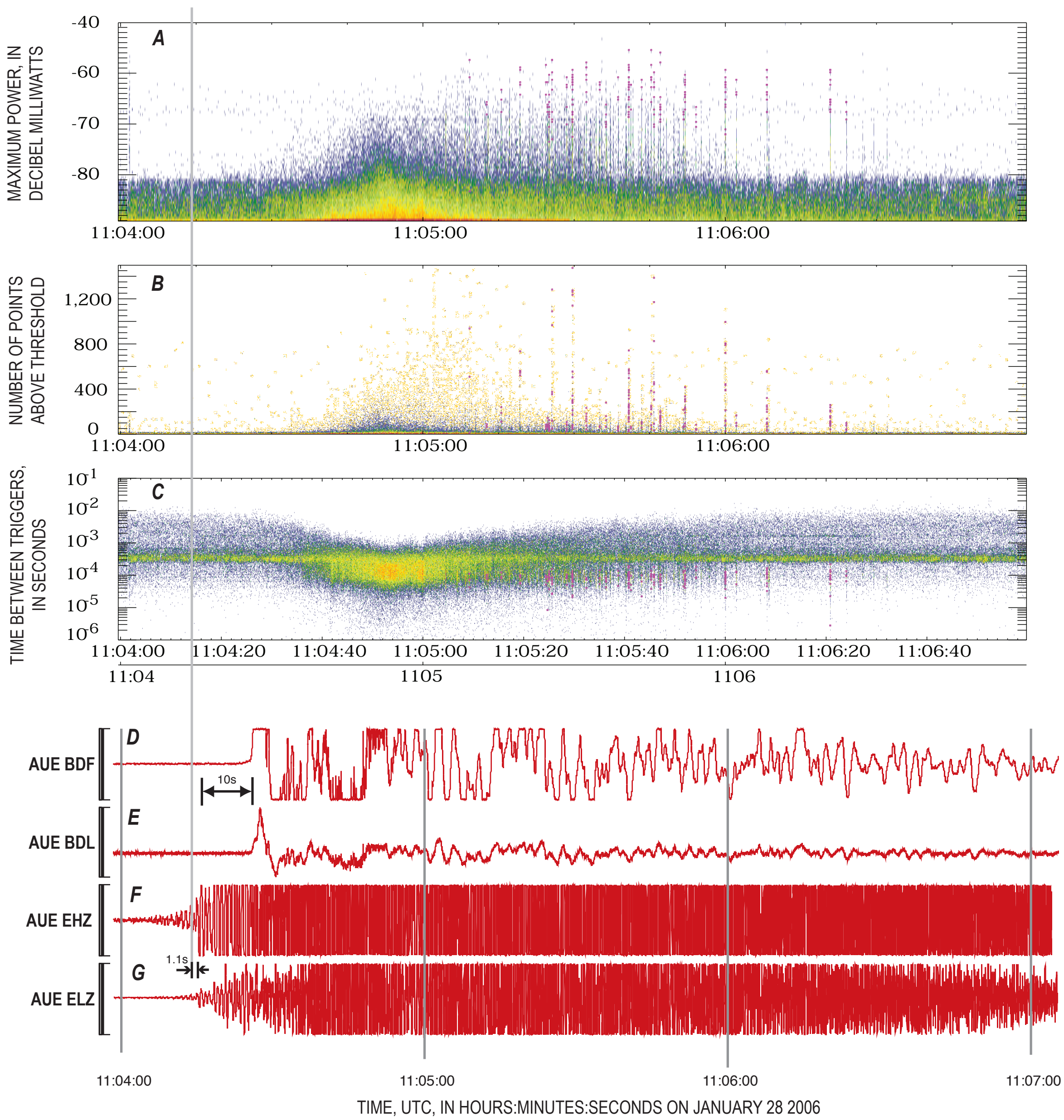

Figure 19. Data from Augustine Volcano's explosion at 0204 AKST (1104 UTC) on January 28, 2006. Panels *A* through *C* show electrical data, *D* and *E* acoustic data, and *F* and *G* seismic data. See figure 11 caption for details. Units for acoustic and seismic data in parts *D*, *E*, *F*, and *G* are the same as shown in figure 17. The dates and times in this plot are in universal time (UTC).

on January 28 (McNutt and others, this volume) and signaled the beginning of the continuous phase. The continuous phase was characterized by many small explosions that occurred a few minutes apart, so that ash was in the air continuously for several days. During this continuous phase, several larger explosions occurred. These were smaller than all 13 of the numbered explosive events (Petersen and others, 2006) but were larger than the small events that occurred every few minutes. Lightning was associated with several of these moderately large explosions.

Between 1540 and 1600 AKST on January 28 (0040 UTC and 0100 UTC on January 29), we saw electrical signals from about 28 lightning discharges (fig. 23). These occurred late during the transitional explosive event that began at 1530 AKST on January 27 (2330 UTC on January 28). This event had a seismic and acoustic duration of about 1 hr 45 min, and moderate amplitudes (McNutt and others, this volume). The lightning rate is much smaller here than in the previous events. Many of these flashes are as large as those in the big explosion at 2031 AKST on January 27 (0531 UTC on January 28), with 6 flashes lasting between 20 and 80 ms each (fig. 24). Several

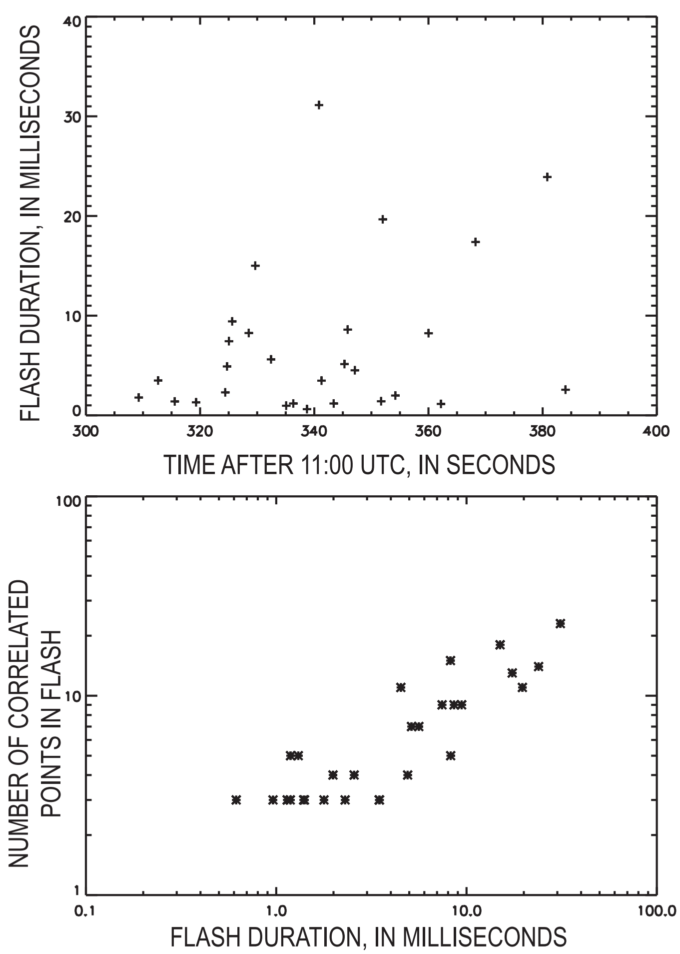

Figure 20. Durations of flashes during the 0204 AKST (1104 UTC) explosion of Augustine Volcano on January 28, 2006. The dates and times in this plot are in universal time (UTC).

of these show interference patterns and altitude analysis may be possible. Thus, we interpret the lightning to be composed of upward propagating near-vent flashes. The total number of flashes was small presumably because the amount of tephra and height of the ash column were smaller than the 2031 AKST, January 27 (0531 UTC, January 28), explosion. Radar data indicate that the ash plume height was about 3.8 km during this event (Schneider and others, 2006).

On January 29 between 11:19:30 and 12:21:18 AKST (20:19:30 and 21:21:18 UTC) (fig. 25) there was an increased electrical background signal similar to that seen during the explosive eruptions. At the same time a large increase was seen in the radar reflectivity at 7.2 km, indicating an impulse of ash injected into the atmosphere (Schneider and others, 2006). Seismic and acoustic data indicate that a moderately strong explosive event began at 11:17:54 AKST (20:17:54 UTC) and lasted 340 s. The signals were strongest from 1119 to 1121 AKST (2019 to 2021 UTC), corresponding to the time of the continuous electrical signal. Two flashes of near-vent lightning occurred 2 minutes after the start of the continuous electrical signal. These were both short duration flashes. No plume lightning was observed.

On January 30 between 0128 and 0130 AKST (1228 and 1230 UTC) (fig. 26) there was an increased electrical background signal due to vent discharges, similar to that seen during the explosive eruptions. Seismic and acoustic data indicate an explosion starting at 1:25:18 AKST (12:25:18 UTC), strongest from 1:28:40 to 1:29:10 AKST (12:28:40 to 12:29:10 UTC), and lasting 340 s total. At the same time an increase was seen in the radar reflectivity at 7.2 km indicating an impulse of ash injected into the atmosphere (see Schneider and others, 2006). No near-vent or plume lightning occurred in association with this explosion.

On January 30 between 6:22:25 and 6:22:50 AKST (15:22:25 and 15:22:50 UTC) (fig. 27) there was another increased background signal similar to that seen during the explosive eruptions. Seismic and acoustic data show a moderate explosion beginning at 6:19:42 AKST (15:19:42 UTC) and lasting 290 s, strongest from 6:21:20 to 6:23:50 AKST (15:21:20 to 15:23:50 UTC). This event was less than half the amplitude of the 0128 (1228 UTC) event. At the same time an increase was seen in the radar reflectivity at 7.2 km indicating an impulse of ash injected into the atmosphere (Schneider and others, 2006). Two flashes of near-vent lightning occurred just after the continuous signal ended (table 2). No plume lightning was associated with this explosion.

Electrical Events in March 2006

During the dome building phase in March we had the two additional stations operating, one on West Island and one at Oil Point (fig. 1). During this time we found 6 periods where there were signals from two stations that were correlated. Almost all the correlations were between signals received at the Homer station and Oil Point. Figure 28 shows the possible

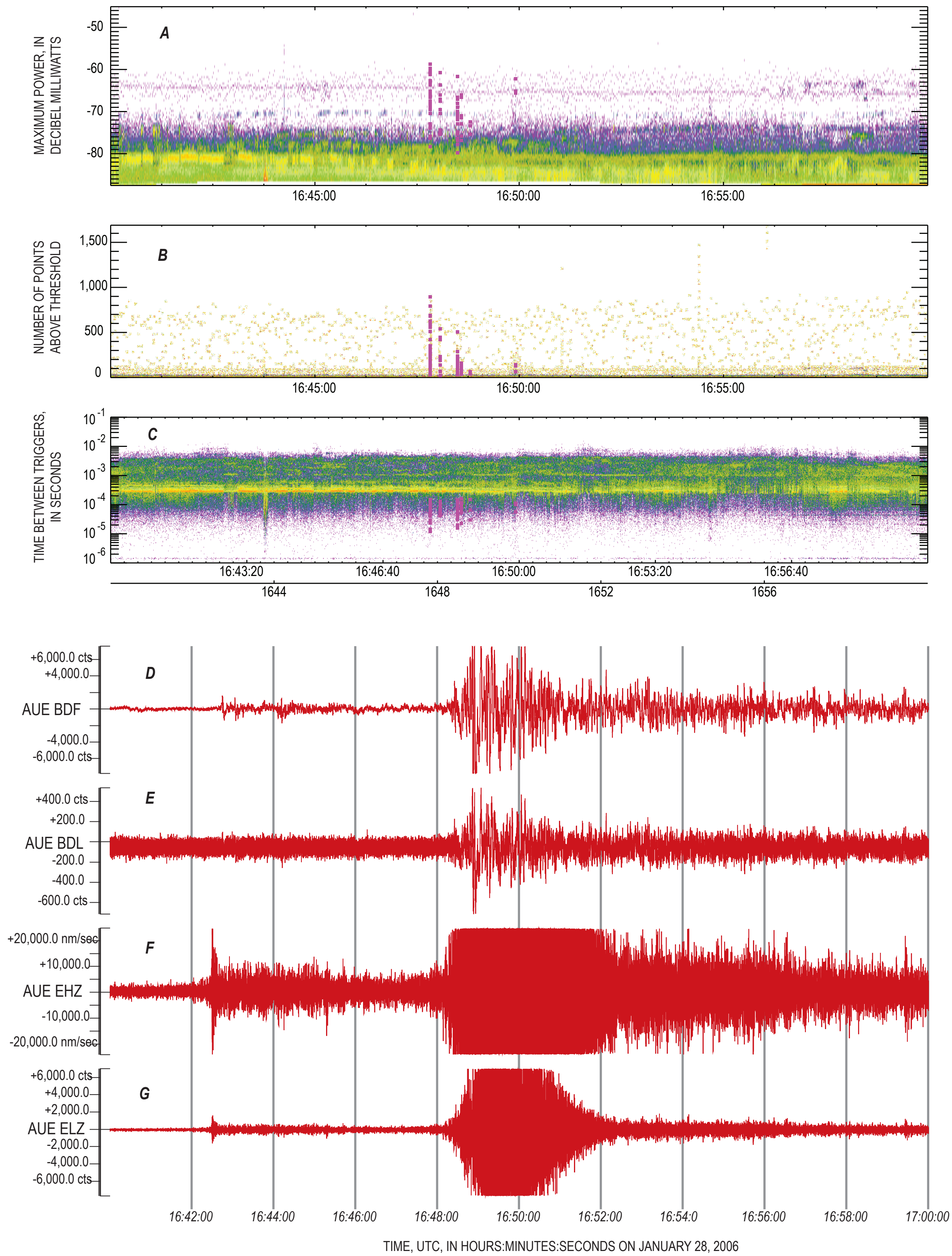

Figure 21. Data from Augustine Volcano's explosion at 0742 AKST (1642 UTC) on January 28, 2006. Panels *A* through *C* show electrical data, *D* and *E* acoustic data, and *F* and *G* seismic data. See figure 11 caption for details. The dates and times in this plot are in universal time (UTC).

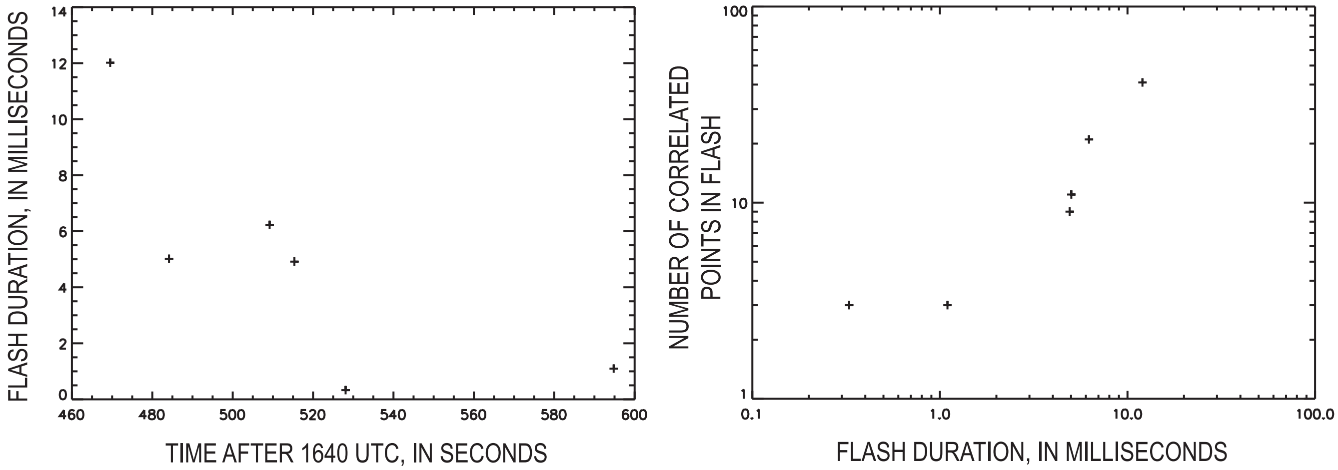

Figure 22. Durations of flashes during the 0742 AKST (1642 UTC) explosion of the Augustine Volcano on January 28, 2006. The dates and times in this plot are in universal time (UTC).

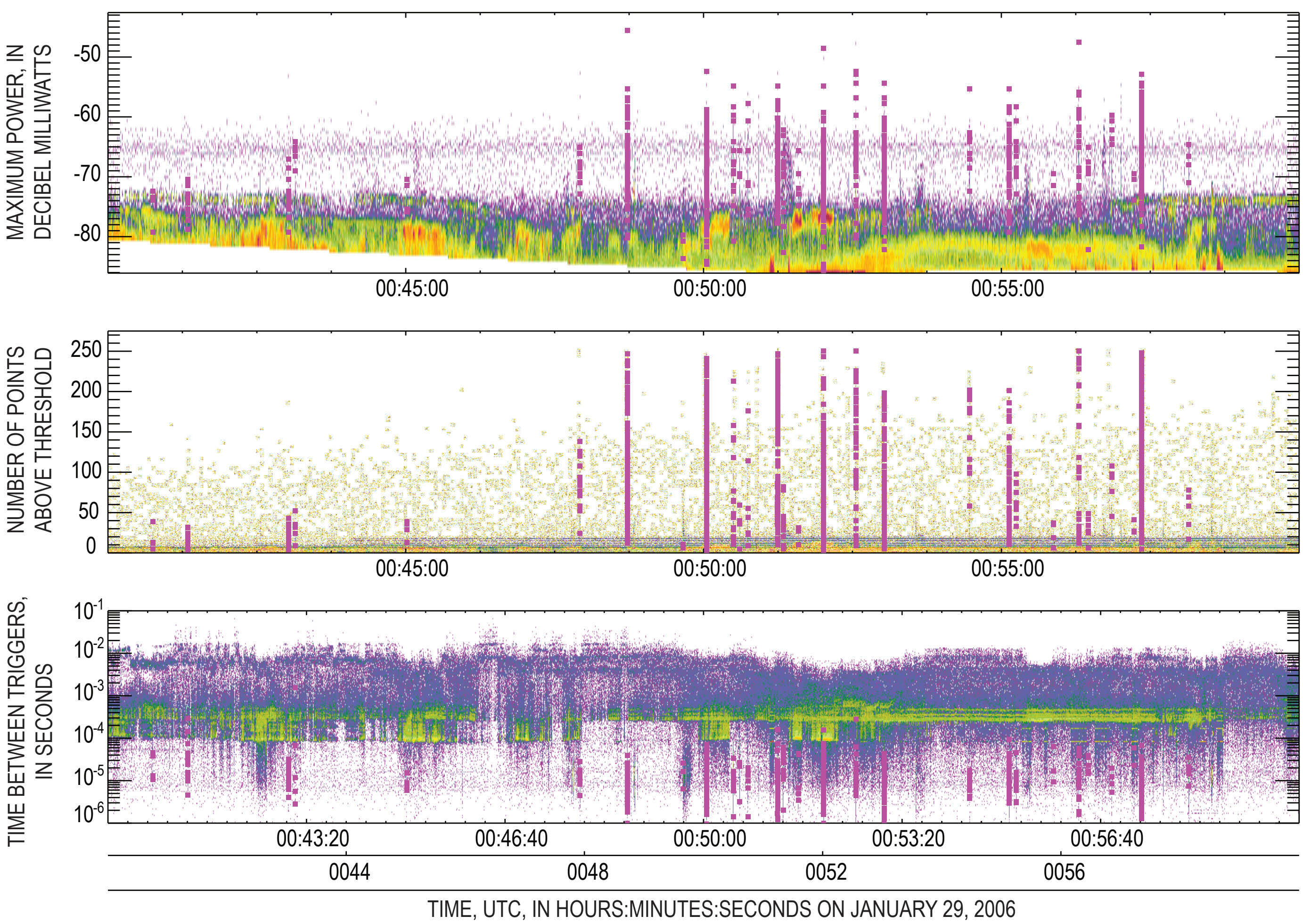

Figure 23. Lightning during Augustine Volcano's continuous eruptive phase, 1540 to 1600 AKST on January 28 (0040 to 0100 UTC on January 29). See the captions of figures 6 and 7 for details. The dates and times in this plot are in universal time (UTC).

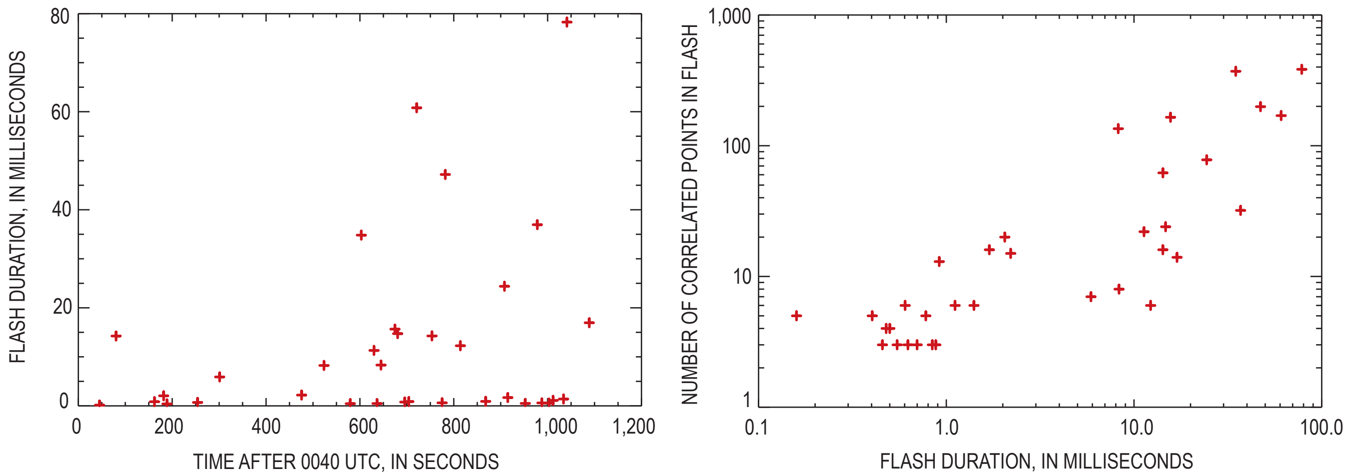

Figure 24. Durations of flashes between 1540 and 1600 AKST during Augustine Volcano's eruption on January 28 (0040 and 0100 UTC on January 29, 2006). The dates and times in this plot are in universal time (UTC).

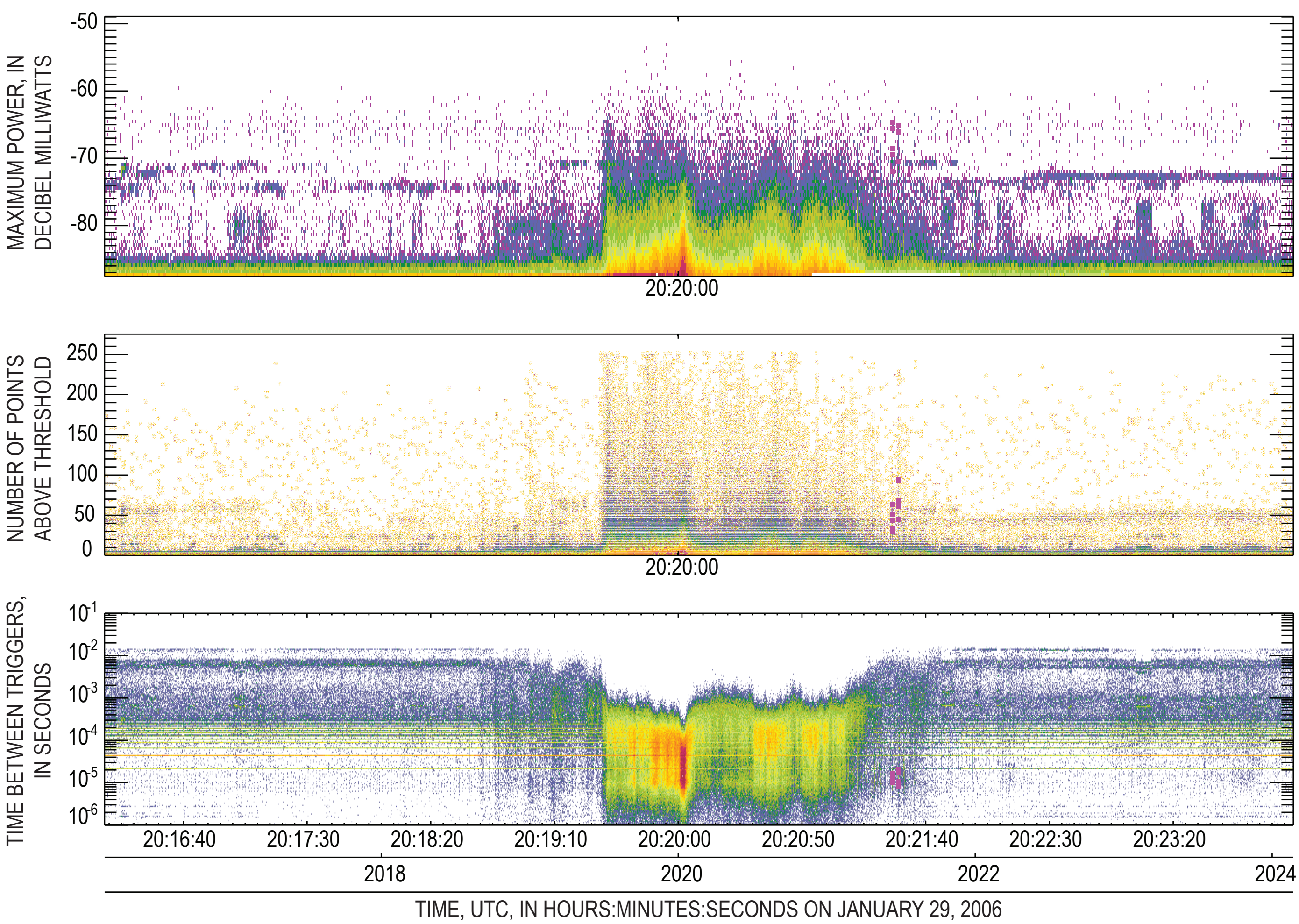

Figure 25. Lightning and electrical signals during Augustine Volcano's eruptive pulse at 1120 AKST (2020 UTC) on January 29, 2006. See the captions of figures 6 and 7 for details. The dates and times in this plot are in universal time (UTC).

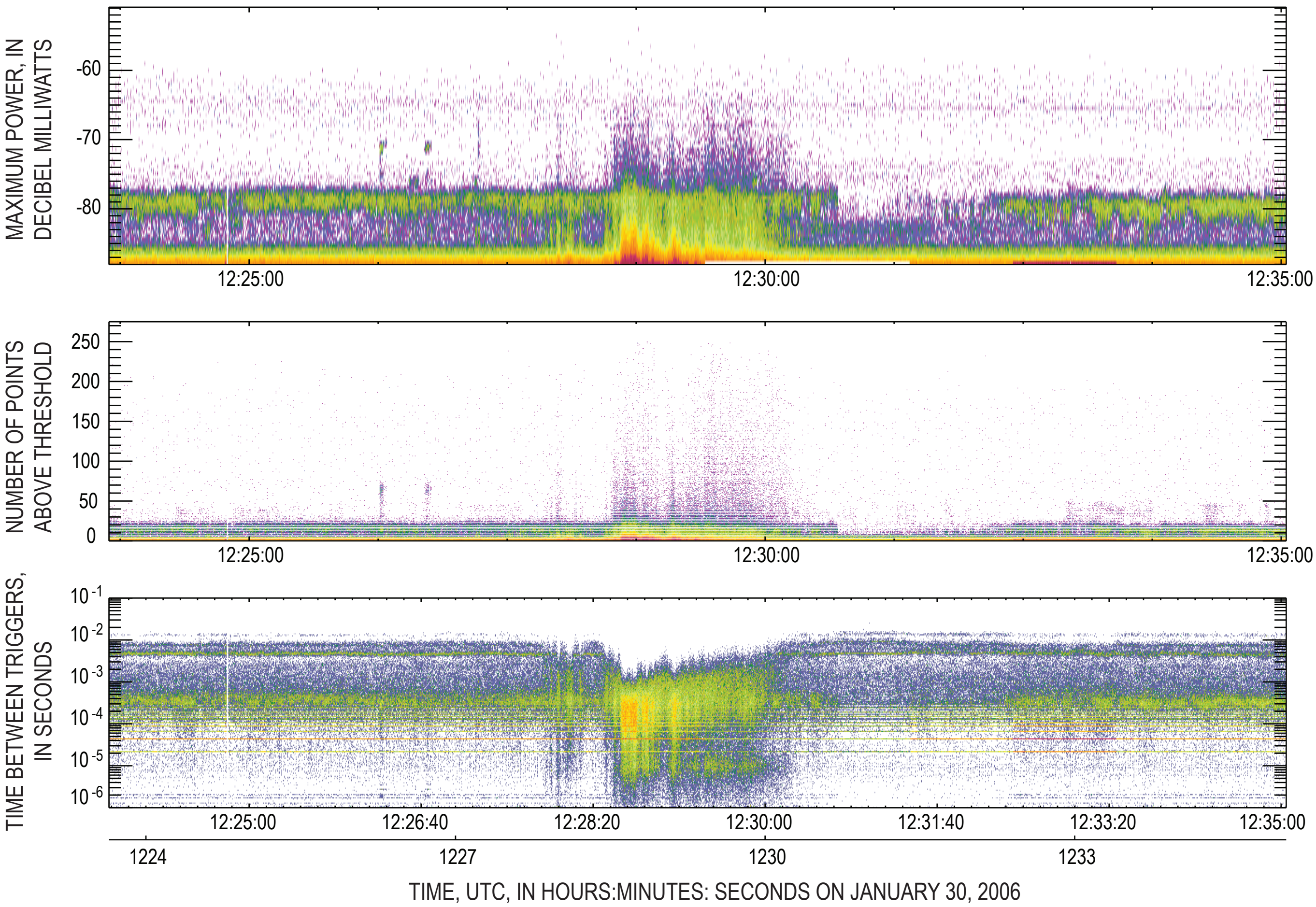

Figure 26. Lightning and electrical signals during Augustine Volcano's eruptive pulse at 0328 AKST (1228 UTC) on January 30, 2006. See the captions of figures 6 and 7 for details. The dates and times in this plot are in universal time (UTC).

location of sources for different time of arrival differences. Table 3 shows the time differences for the 6 periods. Because the signals were weak and coming from close to the volcano we would not expect to receive them at Anchor Point. The station at Oil Point was in a good location to observe signals arising from lava and pyroclastic flows on the north and east sides of Augustine. Because the station on West Island was very close (5 km), we expected to see many correlations in its data. However, we found correlations only during one period (table 3). There are two possible reasons for this. First we found a defective part in the antenna that could have intermittently blocked the signals, but we don't know when the part failed. Second, most of the other correlated signals seemed to come from the east side of Augustine Volcano and not visible to the station. Most of the ash and lava flows were also on the east side of the volcano (Coombs and others, this volume).

All these electrical emission are thought to be the result of charging of ash or gas during extrusion and flow of lava and pyroclastic materials. The breakup of material during pyroclastic flows can cause particles to become charged by fracto-emission (Hoblitt, 1994; Miura and others, 1996) (this mechanism will be discussed below). Additionally the interaction of hot volcanic material and water has been observed to produce charged particles (Vogfjörd and others, 2005).

For the event on March 5 there were several thousand correlated points received by the stations at Homer and Oil Point between 10:08:50 and 10:09:40 AKST (19:08:50 and 19:09:40 UTC). Their time difference were within a few tenths of a micro second of 240.0 μs. Figure 28 shows that these electrical signals came from the northeast side of Augustine Volcano along lava and ash flows. Neither the seismic data nor acoustic data give an indication that anything unusual occurred to give the electrical signals. Thus, it is likely they were associated with some sort of gravitationally driven flow event. Although the time difference could be due to events on the volcano's southwest side, neither station could have seen events occuring in this location.

On March 7 there was an event that produced a small number of correlated points between the Homer and West Island stations, with a duration of about 15 seconds. As this signal ended there were 10 seconds of correlated points between Homer and Oil Point. There were no points from Homer that correlated with both Oil Point and West Island. A possible explanation for this could be that initially the flow or eruptive material was near the summit and visible from both the east and the west but not the north. As the material came down the north east side it became visible from the north but not the west. This event was the only one which produced correlation between the West Island station and one of the other stations that we found. The locations of the events giving rise to these signals are close to the intersection of the 240 µs and 327 µs lines on figure 28.

Several more events were seen on March 9, 10, and 11 (see table 3). The time differences of 237.2 µs to 238.5 µs indicate that they came from the west or south faces of Augustine. The south face can be excluded as it would not be visible from Oil Point to the north. The most likely source is the avalanche channel on the northeast face.

Discussion and Conclusions

The electrical activity measured during the eruption of Augustine Volcano has given us a wealth of new information on volcanic lightning. We have classified the lightning and smaller discharges into two phases and three types. The phases are the explosive phase and the plume phase, and the types are (1) small and very short vent discharges, (2) small near-vent lightning, and (3) thunderstorm-like plume lightning. A continuous variation of phenomena spanning these three classifications is very likely. The three types are shown as simple drawings in figure 29.

The nearly continuous signals from the vent discharges do not consist of a continuous radio signal but of impulses that occur about every 10 to 100 µs. A developing lightning channel could emit a similar series of impulses, but the impulses would form a long channel in the process. The vent discharges appear to remain localized at the vent. If they went much

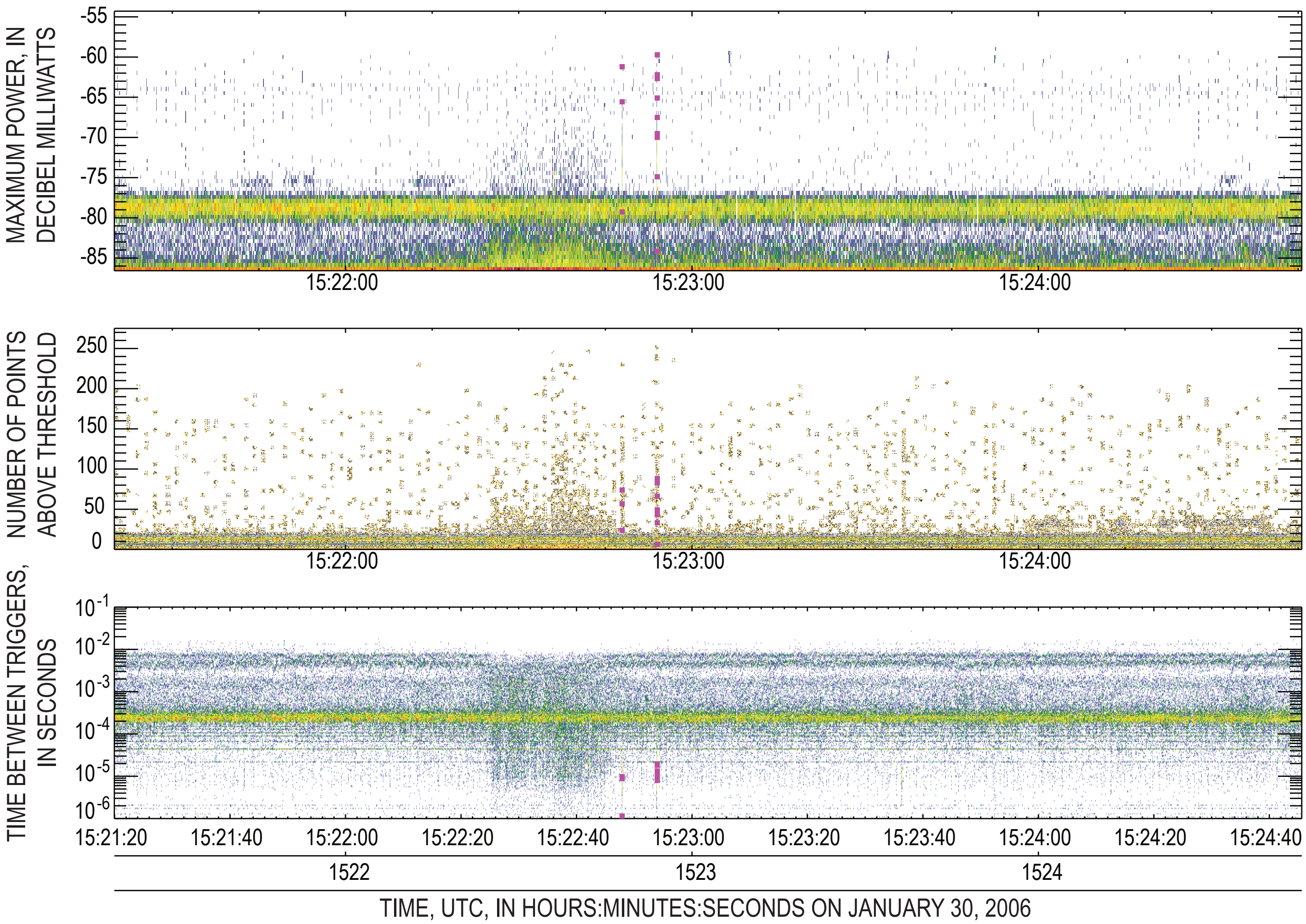

Figure 27. Lightning and electrical signals during Augustine Volcano's eruptive pulse at 0622 AKST (1522 UTC) on January 30, 2006. See the captions of figures 6 and 7 for details. The dates and times in this plot are in universal time (UTC).

Table 3. Electrical activity at Augustine Volcano detected during March 2006.

Date UTC	Time UTC	Homer-Oil Point Δt (arrival time difference) (μs)	Δt spread half-width (μs)	Duration (s)	Comments
March 5	1909	240.0	0.3	50	This correlation has the most points, also a suggestion of a Homer-Anchor Point correlation at 15.4 μs.
March 7	1241	240.0	0.3	10	Also a good 15 s of Homer-West Island correlations at 327.0 μs (0.3 μs wide).
March 9	2212	238.5	1.0	60	
March 10	0058	237.65	0.25	50	
	0059	237.7	0.1	10	
	0840	237.7	0.2	30	
March 11	0311	237.4	0.6	50	Time difference progressed from 237.8 to 237.2 μs.

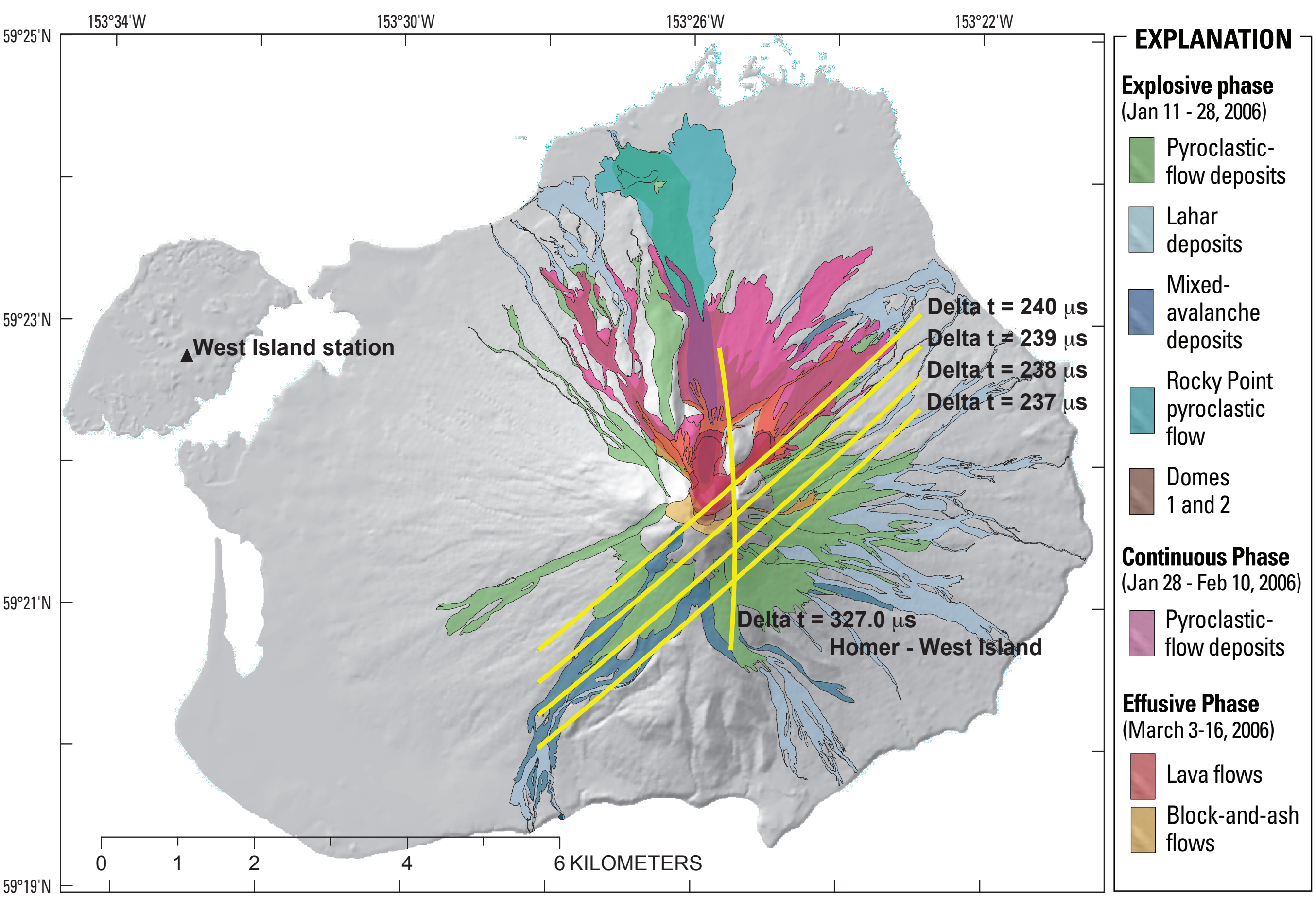

Figure 28. Simplified geologic map of Augustine Volcano deposits from the 2006 eruption with arrival time difference hyperbolas for March 2006. The time differences of 237 to 240 μs are for a combination of the Homer and Oil Point stations. Signal correlations were seen between Homer and West Island stations with a time difference of 327 μs. Base map courtesy of M.L. Coombs.

above the vent they would have been detected by the station at Anchor Point. In the large explosion on January 27 at 2031 AKST (January 28 at 0531 UTC) these impulses continued for 3 minutes. The discharges appear to be disconnected and independent. The RF power emitted by the impulses during vent lightning events is similar in magnitude to the power emitted during the formation of leader channels in thunderstorms (Thomas and others, 2001). This indicates that the sizes of the discharges that produce the RF are about the same as the steps during leader formation, about 10 to 100 m. The onset of the discharges coincided with the onset of the explosion indicating that the particle charging is due to processes associated with the explosion itself, rather than a delayed process such as particle interactions in a developing plume.

The charge is probably generated as the magma expands and fractures into ash particles in the volcanic conduit. The micro-physical properties of the ash and the other particles in the conduit will determine the sign of the charge transfer. This type of process is referred to as fracto-emission and leads to charged particles and emission of light in laboratory experiments. It was proposed by Lane and Gilbert (1992) as the mechanism charging ash rich plumes at Sakurajima Volcano in Japan. James and others (2000) conducted laboratory experiments fracturing pumice samples and found that charged particles were generated. Once the charged particles are generated in the conduit the positive and negative charge must be separated to produce the high electric field and discharges. In the upper part of the plume, as in thunderstorms, gravitational separation divides the particles by size and weight; however, in the conduit, jet flow dynamics could separate the particles. The observed vent discharges may be between different regions in the ejecta or between the ejecta and the vent of the volcano. Our observations of the upward development of the near-vent lightning indicate that the developing plume has a net positive charge. This indicates that much of the negative charge remains attached to the vent or is on large particles that fall back almost immediately. These vent discharges may be similar to the lightning photographed during Strombolian eruptions, such as those at Sakura-jima or Tavurvur. During the Augustine eruption there was probably much more ash, and these new-vent discharges could have been obscured by the ash cloud and would not have been visible even with good weather conditions.

During the explosions there were small near-vent lightning flashes that developed upward for several kilometers into the erupting column. These were observed as organized sets of impulses correlated between the Homer and Anchor Point stations. We were able to determine the altitude development of one of these near-vent discharges from the interference between the direct RF signal and the signal reflected from the sea surface received at the Homer station. Thunderstorm lightning that strikes the ground almost always begins in the cloud with a downward propagating leader channel forming a conducting path to ground, followed by a high current return stroke back up the channel. This return current pulse produces the bright flash as well as a low frequency electromagnetic pulse that can be used to locate the ground strike point by a network like the one operated by the BLM in Alaska. Occasionally lightning begins with a leader channel that develops from a tall tower and propagates upward into the thundercloud, with no associated return stroke. We suspect that most of the near-vent flashes begin at the summit and propagate upward into the developing column. This is consistent with the fact that no return strokes were detected by the BLM network during the explosions we observed. The near-vent lightning began 25 to 300 seconds after the onset of the explosion, during which time period an eruptive column formed (see table 2). The near-vent

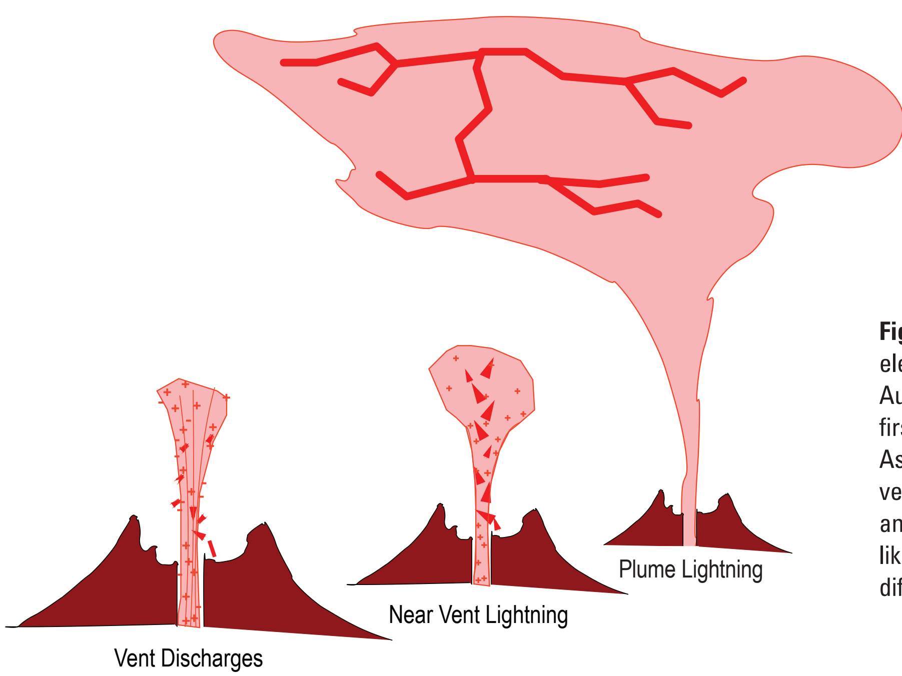

Figure 29. The three types of lightning or electrical discharges seen in the 2006 eruption of Augustine Volcano. The vent discharges are seen first, occurring as soon as the explosion begins. As the eruptive column develops upward near-vent lightning begins. After the plume develops and some charge separation occurs, thunderstorm like lightning begins; it is probably between two different charge regions at different altitudes.

lightning discharges ended several minutes after the end of the explosion. Charge generated by fracture in the conduit can account for these discharges. In other eruptions we would expect to see similar lightning discharges in or very close to the erupting column. The vent discharges indicate the electric field is the largest at the vent and this is where the near vent lightning would start and develop up into the plume.

One clear sequence of plume lightning was observed after the large explosion at 2031 AKST on January 27 (0531 UTC on January 28). The lightning began about 4 minutes after the onset of the large explosion and a minute after the explosion stopped. All the lightning during this period was intracloud (IC) lightning or upward lightning from the summit. There were no CG flashes detected by the BLM network. Data from the NEXRAD radars indicated that the plume extended to an altitude of 10.5 km (a typical height for thunderstorms) and drifted to the south east. It is very likely that the volcano injected a large volume of hot moist air into the cold winter atmosphere, producing conditions similar to those that exist in a small summertime thunderstorm (Williams and McNutt, 2004). As the buoyant air rises and mixes with surrounding air and cools, water droplets and ice are formed, that fall back through the rising air. This is the basis of the mechanism that is thought to produce charge separation in thunderstorms (Williams, 1985). A natural thunderstorm will typically last longer than this volcanic plume as it will have a much longer lasting source of rising warm moist air. A rough estimate of the amount of water injected into the atmosphere during the main explosion on January 28, 2006, can be made assuming that each cubic meter of magma had 100 kg of water (Williams and McNutt, 2005). About 17×10^6 m^3 of magma was erupted (Coombs and others, this volume). Thus there was about 1.7×10^9 kg of water vapor was injected into the atmosphere. Simulation of a small thunderstorm required about 10^9 kg (T. Mansell, oral commun., 2009). Thus all the components that generate and separate charge in a thunderstorm seem to be present in this plume.

After the ash, tephra, and gases have been injected into the plume by the initial velocity and buoyancy, the larger particles will settle out faster than the light ones. Cooled by entrained air, the particles will serve as condensation nuclei and the large quantities of water vapor will become coated with water or ice. The different sized particles falling at different speeds will collide, exchange charge, and separate. Because many of the particles are ice or water coated charge will be separated as in a thunderstorm. Volcanic plumes may have charge separation mechanisms not present in thunderstorms, because of collisions between different sizes and types of ash particles in the plume or collisions between ash particles and water droplets. If the large particles fall at 5 m s^{-1}, a plume could produce lightning for as long as 20 minutes as the particles fell 6 km.

Many of the particles were electrically charged during the ejection process (as evidenced by the vent discharges). If enough of these particles charged by fracturing in the conduit were not neutralized by the vent discharges and reach high altitudes and if the positive and negative charge were on different sized particles, subsequent settling could separate the charge and lead to lightning discharges. Lane and Gilbert (1992) proposed that electric fields (no lightning) observed during ash eruptions at Sakurajima were the result of this fracto-emission in the volcanic conduit and that the particles were charged negative and the positive charge was on gas. Our observations verify their idea that charged particles are generated in the explosion before they leave the vent of the volcano.

We can estimate the amount of charge needed if this mechanism was responsible for plume lightning we observed. A typical IC lightning flash discharges 10 to 40 C of charge. There were about 150 big flashes in the 10 minute sequence that would require 1,500 to 6,000 C. This implies a current of 2.5 to 10 A. The charging current produced by the settling of one type of charge particle is the charge density times the fall speed times the plume area. An 100 km^3 area (a square 10 km on a side) and a fall rate of 5 m s^{-1} indicates a charge density of 5 to 20 C km^{-3}. In thunderstorms charge densities are several C km^{-3} with a maximum of 10 C km^{-3} (MacGorman and Rust, 1998). Although this mechanism seems possible it is hard to understand why there was not charge separation and lightning during the period that the plume was forming.

It seems unlikely that gravitational separation of the different sized ash particles charged during the explosion could separate a sufficient amount of charge to produce the series of lightning flashes. Continued charge generation by a process such as the thunderstorm ice mechanism is needed for all but a brief series of flashes. More observations are needed to determine the roll of each charging mechanism in volcanic plumes.

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