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Project Summary

Collaborative Research: Characterizing Small-scale Lightning Discharges Associated with Explosive Volcanic Activity at Sakurajima Volcano

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Overview: Volcanic lightning discharges have length scales ranging from tens of meters to tens of kilometers. Most small discharges occur proximally to a volcanic vent concurrent or within a few minutes of an explosive volcanic eruption. Large scale discharges typically occur throughout a mature plume formed 5 or more minutes subsequent to an explosive eruption. The proposed work focuses on studying the small, proximal discharges that occur concurrent with explosive volcanic eruptions. The main goal is to better characterize the proximal electrical activity within the context of the eruptive activity to gain a better understanding of the eruptive conditions that are required to produce different types of small-scale discharges. This characterization will be accomplished by making high-resolution 3-D lightning mapping observations of lighting discharges during small explosive eruptions of Sakurajima Volcano located in the Kyushu region of southwestern Japan. Other instrumentation (infrasound, video cameras, electric field change sensors) will be used to monitor the explosive activity, plume development, and changes in electric field caused by lightning. The data will be used to determine when different types of electrical discharges occur relative to the onset of an explosive eruption and in relation to the ascent of volcanic ejecta. Electrical discharges will be characterized by determining the length scales, speeds, and polarities of the discharges, as well as by locating where the discharges initiate.

Intellectual Merit: The proposed research would be the most detailed study of volcanic lightning to date, combining measurements of volcano infrasound, electric field changes, and plume development with high-resolution LMA data and high-speed video observations of volcanic lighting. The inclusion of electric field change measurements, high-speed video, and visual plume observations distinguishes this proposal from previous research. The proposed research will increase knowledge of electrical activity that occurs as a direct result of an explosive volcanic eruption. This will contribute to our understanding of the eruption processes that are responsible for producing electrical activity proximally to a volcanic vent.

Broader Impacts: Because small-scale discharges frequently accompany volcanic eruptions of a large range of sizes, the results of the proposed research will be applicable to developing an eruption monitoring system that utilizes VHF observations of lightning and electrical activity. In addition, the results of the proposed research will be used to determine if one can predict eruption magnitudes or ash plume heights based on observations of electrical activity. The proposed research will also provide training for an early career researcher from an underrepresented group for her development in academia. Co-PI Behnke will gain experience organizing fieldwork in a foreign country, managing a research project, and learning how to use new scientific instruments, which will benefit her development as an interdisciplinary researcher in the fields on atmospheric physics, atmospheric electricity, and volcanology. Three graduate students (two from NMT and one from USF) will function as field assistants and gain experience deploying scientific instruments. They will participate in gathering, organizing, archiving, and analyzing the data. This will provide Behnke with her first opportunity to mentor a graduate student.

Collaborative Research: Characterizing Small-scale Lightning Discharges Associated with Explosive Volcanic Activity at Sakurajima Volcano

Project Description

1 Introduction

Volcanic lightning research has been substantially advanced due to recent detailed studies of lightning in electrified volcanic plumes using the Lightning Mapping Array (LMA). The LMA is a network of VHF sensors that locates sources of electromagnetic radiation produced by lightning (*Rison et al.*, 1999; *Thomas et al.*, 2004). The 3-dimensional images of lightning produced by the LMA reveal detailed structure of individual discharges. The LMA was developed with NSF support to study lightning in thunderstorms, and the recent construction of portable versions of the instruments has enabled the study of lightning in volcanic plumes.

The most recent volcanic lightning mapping studies, undertaken by the Principal Investigators (see section 6: Results of Prior NSF Support), focused on two volcanic eruptions: Redoubt Volcano in Alaska during March–April 2009, and Eyjafjallajökull volcano in Iceland during April–May 2010. Both studies were very successful and have provided rich data sets that have been applied to the study of plume electrification, plume dynamics, and volcano monitoring. Part of the success of this research was due to good timing and a bit of luck: both volcanoes were located in regions that are reasonably accessible for instrumentation deployment, and, in the case of Redoubt, the volcano became active with sufficient warning to safely deploy the instrumentation in advance of the eruption onset.

It was also fortuitous that the eruptions were different sizes and thus exhibited different styles of electrical activity to study. The peak plume height from Redoubt was 19 km, while the peak plume height from Eyjafjallajökull was 10 km, barely reaching the tropopause. During the eruption of Redoubt, isolated and intense lightning storms drifted downwind in volcanic clouds produced by the larger events (*Behnke et al.*, 2012, 2013). By contrast, the lightning observed in Eyjafjallajökull's plume was always localized to a relatively small region around the vent (*Behnke et al.*, 2014). As we discuss in further detail below, the somewhat marginal electrification of Eyjafjallajökull's plume led to significant differences in the behavior of the electrical activity, particularly with the small-scale discharges. While we are confident that an eruption producing a plume higher than tropopause will always produce substantial electrical activity, we can not measurably predict what will happen when peak plume heights are lower than the tropopause. Understanding how the electrical activity could vary in a small eruption is important because lightning is an indicator of explosive volcanic activity, and lightning monitoring can be used to detect and monitor eruptions.

Though the prior studies were successful, the reactionary strategy of waiting for a good candidate volcano to become active has some disadvantages. In the case of Redoubt, which is located 80 km west of the sparsely-populated Kenai Peninsula, there were only a limited number of good station sites, in part due to the requirement of AC power for the stations; the geometry of the stations resulted in the data being limited to providing two dimensional locations (latitude and longitude). In Iceland there was a better selection of station sites available around Eyjafjallajökull, but installing the stations was somewhat of a race against time: we arrived in Iceland on the day the explosive eruption began, and we hurried to install our equipment. As a result, fully 3-D data were only recorded during the latter half of the five-and-a-half week eruption.

With this proposed research project we intend to study small-scale (sub-km to several km) electrical activity that occurs proximally to a volcano during an explosive eruption in order to improve our understanding of the types of electrical activity that occur during an explosive eruption and how changes in eruptive activity affect the electrical activity. We plan to take a new approach by studying a currently active volcano with a predictable eruption style. Sakurajima volcano, located in Kyushu (southwestern Japan), is currently very active (it has been erupting since 1955), historically produces volcanic lightning (*Aizawa et al.*, 2010), and typically exhibits low-level eruptive activity (up to 5 km plume height). In the unlikely event that the eruption of Sakurajima ceases in the near future, we will select another currently erupting volcano with similar eruptive style, e.g., Suwanosejima, Japan; Tungurahua, Ecuador; Colima, Mexico; or Popocatépetl, Mexico. Sakurajima is well monitored by the Sakurajima Volcano Observatory (SVO), which has the facilities to support our research (we have included a letter of support from SVO as a supplementary document); the region around Sakurajima is very accessible, and the topography in the surrounding area will allow for the LMA station sites to be located at both high and low altitudes while having a line-of-sight view to the vent, providing the highest resolution LMA data of any volcanic lightning yet recorded. The LMA stations we will use are a newer, solar-powered design, which will give us more freedom in their placement. In addition, we will deploy acoustic sensors to monitor the explosive activity and visual cameras to monitor the development of the plume; electric field change sensors will be deployed to determine the polarities of lightning discharges and a high speed video camera will help determine physical characteristics of small discharges. These additional sensors will help us characterize the small-scale electrical activity within the context of the eruptive activity. The high-resolution LMA, electric field change data, and high speed video data combined with the eruption and plume monitoring data will provide the most detailed study of volcanic lightning to date.

2 Background

The first LMA study of volcanic lightning took place during the 2006 eruption of Augustine Volcano in Alaska. From this study, the first descriptions of small-scale discharges that occurred or initiated proximally to the vent during explosive eruptions were made and led to the grouping of discharges into two general categories: vent discharges and near-vent lightning. Vent discharges were inferred to be small discharges (order 10-100 m) that occur simultaneous with the onset of an explosive eruption, and near-vent lightning were larger discharges ranging in size from hundreds of meters to several km that occur within 1–2 minutes following the onset of an explosive eruption. Both types of discharges occurred or initiated at low altitude in the eruption column. In addition, a third type of lightning was identified, referred to as plume lightning, which encompasses all the discharges that occur at higher altitudes within the plume. Plume lightning is generally large scale (10 km or more in length) and most resembles intracloud and cloud-to-ground lightning in thunderstorms (*Thomas et al.*, 2010).

The distinction between vent discharges and near-vent lightning was largely based on the characteristic appearance of the radiation produced by each type of discharge. During one relatively energetic explosive eruption, VHF radiation was recorded that manifested as continual impulsive

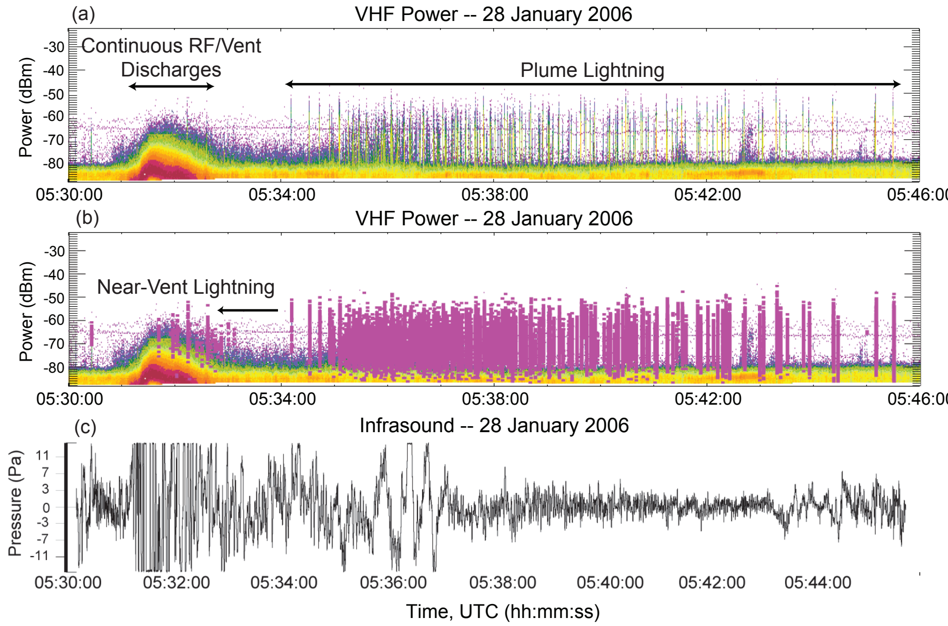

Figure 1: Time series of LMA and infrasound data for an explosive eruption of Augustine Volcano on 28 January 2006, showing distinction between continuous RF and discrete plume discharges and near-vent lightning. Continuous RF is believed to be caused by high rates of small (10–100 m) 'vent discharges.' Continuous RF is unique to volcanic eruptions (i.e. it has never been observed in non-volcanic thunderstorms), making the occurrence of it an unambiguous indicator of explosive volcanic activity, as opposed to the larger plume lightning, which is not unique. (a) Power of VHF signal (unprocessed data) received by the 'Homer' LMA station, shown as a 2-D histogram of the event density. Colors indicate relative density of events, red being most events and purple being least. (b) Same as (a), but with magenta coloring indicating the radiation events that were detected by both LMA stations in operation. (c) Infrasound data for the explosive event on 28 January, recorded approximately 3 km from Augustine. Infrasound data have been time shifted to the left to account for the approximate 10 second travel time delay.

radiation events that looked like an increase in the background radiation and that lasted for 30 seconds or more (Figure 1) (*Thomas et al.*, 2007). The continual character of the radiation contrasts with the discrete character of radiation from typical lightning discharges. We note that this type of continual radiation has not been observed in meteorological thunderstorms. Now often referred to as continuous radio frequency (RF), the distinctive signal produced by the continual radiation events was also observed during subsequent explosive events of the Augustine eruption. During this period of eruptive activity there were only two LMA stations in operation, and the continuous RF signal was always detected by the same LMA station, which had a line of sight view to the vent. The second LMA station did not have a line of sight view to vent, thus it was hypothesized that this unique radiation signature was originating at the vent of the volcano, at low altitude, below the horizon of the second LMA station. This hypothesis was confirmed by observations of continuous RF made during the eruption of Redoubt Volcano in 2009. Correlation of the data between multiple stations at Redoubt confirmed that the sources of continual radiation events were located above the vent (data were only 2-D), and comparison with radar data showed that they were located at low altitude. The estimated source powers of the continual radiation events were comparable to that produced by typical lightning discharges, thus it was inferred that this characteristic radiation was caused by high rates of small-scale discharges that were termed "vent discharges."

Near-vent lightning, on the other hand, was distinguishable from vent discharges because in addition to producing discrete rather than continual bursts of radiation, it was also detected by both LMA stations, which indicated that these discharges were occurring or extending to higher altitudes than vent discharges. In Figure 1b, magenta coloring shows the radiation events that were detected by both stations. The azimuthal locations of the correlated discharges were determined from the two-station data, revealing that these discharges were located at the azimuth of Augustine Volcano. Additionally, while vent discharges were observed simultaneous with the onset of a large explosive event, near-vent lightning did not occur until 1–2 minutes after the onset of the event, suggesting that distinct processes may have been involved in creating each type of discharge.

The existence of both vent discharges and near-vent lightning are evidence that volcanic ejecta are electrically charged as a consequence of explosion processes. There are two silica-based processes that have been hypothesized to charge volcanic ejecta: fractoemission and tribocharging. Fractoemission is the ejection of electrons, positive ions, and neutral ions during material fracture (*Dickinson et al.*, 1988). This process is believed to occur when magma fractures into silicate particles, leaving the particles with a net charge. Laboratory experiments with pumice samples showed that silicate particles were imparted with a net charge after fracturing, while the opposite charge was emitted as ions (*James et al.*, 2000). Tribocharging is the transfer of electric charge between two particles after a rebounding collision. Laboratory experiments of tribocharging of volcanic ash showed that the span of the particle size distribution affected the amount of charging; in particular, wider spans had more charging, while narrower spans had less charging (*Houghton et al.*, 2013). This result is important because volcanic eruptions typically produce silicate particles with a wide range of sizes.

Subsequent studies of volcanic lightning have revealed that continuous RF does not always occur during an explosive volcanic eruption, and this revelation raises questions about how continuous RF is generated. For example, continuous RF was was only observed during part of the the 2010 eruption of Eyjafjallajökull. This eruption consisted of two multi-day periods of explosive activity that were separated by two weeks of relative quiescence. Interestingly, continuous RF was frequently observed during the first explosive period (when only one, and at times two, stations were recording data), but was never observed during the second explosive period (when 3-D data were recorded), even though a substantial amount of other electrical activity did occur, including frequent small discharges (up to 2 km in length; an example of near-vent lightning) at low altitude in the region above the vent (*Behnke et al.*, 2014). It is not clear why continuous RF was not observed during the second explosive period, but we speculate that changes in the eruptive activity were responsible. Based on ground-based ash measurements it is known that the eruptive activity during the second explosive period was less strong than the first (*Gudmundsson et al.*, 2012); thus, there could have been less silicate-based charging during the second explosive period. The lack of continuous RF and the observation that the eruption was less strong during the second explosive period implies that there might be a threshold on the intensity of the eruptive activity (i.e. mass eruption rate) required to produce continuous RF.

The occurrence of continuous RF may also be linked to other factors of an eruption, such as the amount of gas released, the distribution of gas, the ascent rate of ejecta, or possibly magma composition. It is possible that the dynamics of the volcanic ejecta may also play a role. PIs Thomas and Behnke witnessed lightning during the eruption of Eyjafjallajökull during the first

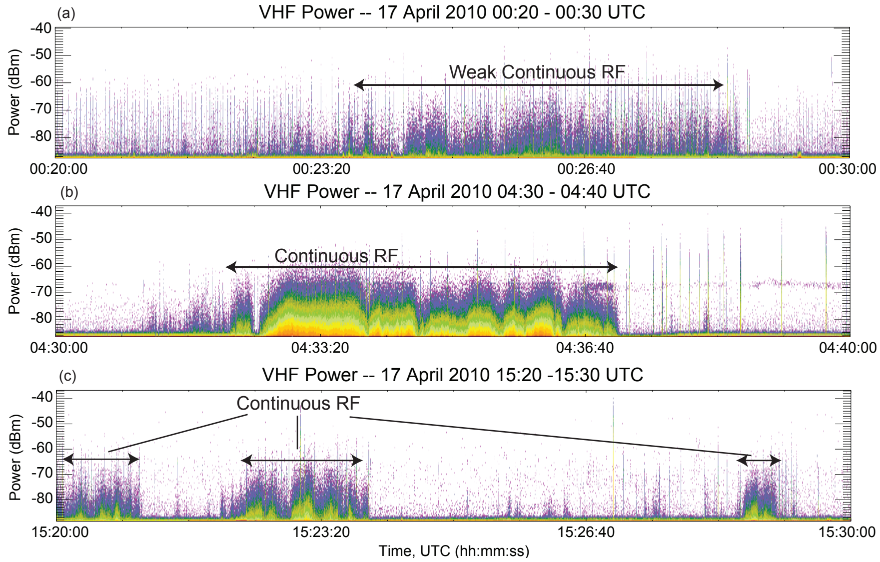

Figure 2: Three 10-minute examples of unprocessed LMA data showing varying intensity of continuous RF during the first explosive phase of the 2010 Eyjafjallajökull eruption. There were two phases of explosive activity during the eruption, and continuous RF was only observed during the first explosive phase; presumably differences in mass eruption rate are responsible for the lack of continuous RF in the second explosive phase (mass eruption rate was lower during the second explosive phase (Gudmundsson et al., 2012)), though other factors in the eruption may have played a role, such as the amount of gas released, the distribution of gas, the ascent rate of the ejecta, the magma composition or the dynamics of the plume/ejecta.

explosive period. They observed a discrete explosion of ejecta, which would rise above the plume for a few seconds in a laminar fashion before transitioning to turbulent flow. Once the flow was turbulent, the ejecta would light up for several seconds as if it were sparkling. Distinct discharges were not perceivable. Less than a minute after the sparkling, obvious large lightning discharges were observed throughout the plume. Unfortunately, these observations were not recorded in a manner that could be used as data, so it is not known if continuous RF occurred during the time when the observations were made or if there were other discharges that occurred prior to the observation that were completely obscured from view by the dense plume. Nonetheless, the observations suggest turbulence is involved in the creation of proximal electrical discharges, perhaps by forming clustered regions of charge (see section 3: Relation to Other Previous Studies).

When continuous RF was observed during the eruption of the Eyjafjallajökull, it was noticed that the intensity of continuous RF could vary, perhaps due to variations in eruptive vigor, or other differences in eruptive processes discussed above. Figure 2 shows three examples of continuous RF in the unprocessed data from the first explosive period. Of these three examples, continuous RF was the most intense from 04:30–04:40 (panel b), while it was least intense from 00:20–00:30 (panel a). Unfortunately, we lack other detailed observations with which to compare these data (e.g., acoustic or high-resolution radar data) that could indicate if the varying intensity of continuous RF correlated with changes in eruptive conditions. There were some acoustic measurements collected during the eruption, but only during the second explosive period. The only radar data obtained during the eruption were collected with a weather radar, and the scanning strategy employed

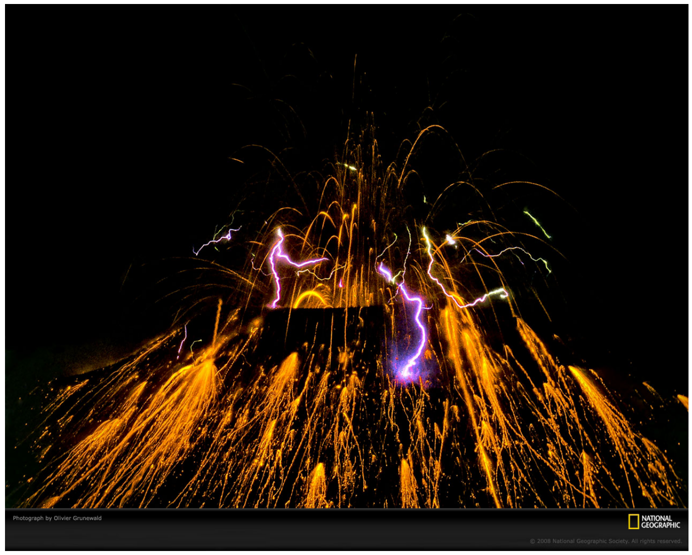

Figure 3: Small-scale discharges at the vent of Tavurvur volcano in Papua New Guinea. The discharges are on the order of a few tens of meters, which is the length scale vent discharges are inferred to have from LMA observations. However, since only a small number of discharges are visible in the photo, it seems unlikely that continuous RF would have been produced by these discharges, which raises questions about our understanding of continuous RF and small-scale electrical activity. Photograph by Olivier Grunewald, copyright 2008 National Geographic Society.

resulted in large uncertainties in the height of the plume.

Since the rate of continuous RF has been observed to vary, it is also possible that vent discharges might sometimes occur at rates that are too low to produce continuous RF. Peak rates of recorded radiation events during periods of continuous RF can be higher than 50 thousand per second, implying that vent discharges occur at rates of thousands per second, and this high rate persists for several seconds. Several thousand discharges per second is a somewhat surprisingly large number that does not reconcile with photographs that have been obtained of small discharges near a volcanic vent. In Figure 3, for example, the diameter of the vent is 100 m, so the small discharges are on the order of tens of meters, which is similar to the length scale that we infer vent discharges to have. However, assuming that the exposure time of this image was several seconds or less, we do not expect that the discharges shown in the figure would have produced continuous RF; there just aren't that many discharges present. This observation raises several questions about the nature of vent discharges. For example, can vent discharges occur at low rates that don't produce continuous RF? Or, are the discharges shown in Figure 3 fundamentally different than the continuous RF-producing vent discharges? By making detailed observations of small-scale discharges at Sakurajima over a 4–6 month time period we expect to see a large enough range of eruption sizes and types to address these questions.

Further insight about continuous RF and vent discharges as well as near-vent lightning is limited without a detailed set of electrical and eruptive observations. Out of the three, the Redoubt eruption was probably the best monitored eruption; however, the geometry of the LMA stations yielded only two-dimensional locations from the data. At Eyjafjallajökull, the LMA data gave

3-D locations during only part of the eruption, and not during the time when continuous RF was observed. With simultaneous measurements of lightning and eruptive activity at Sakurajima, we plan to collect data that will contribute to a growing data set that can inform the thresholds needed to produce continuous RF and electrical activity of any type. We will use detailed measurements to provide more concrete definitions of vent discharges and near-vent lightning as well as address questions regarding these discharges. For example, are near-vent lightning just larger vent discharges? Can near-vent lightning be attributed to a different charging process or a different phase in development of an eruption column? How do small discharges in volcanic eruption columns compare to small discharges in meteorological thunderstorms? Do turbulence processes that occur during the transition from a jet to a convective plume control lightning production? Understanding how and why electrical discharges occur in a volcanic plume is valuable because this knowledge could potentially be used in a real-time monitoring situation to estimate mass eruption rate or ash plume heights from lightning measurements.

In addition to providing more insight about small-scale electrical activity, the data from the proposed research will also be useful for learning more about volcanic processes. Similar to meteorological thunderstorms, lightning and electrical activity are closely linked to the dynamics of an eruption column and ash cloud. For example, the lightning data from the Redoubt eruption have revealed possible variations in eruptive processes leading to plume formation. Typically, the first several minutes of electrical activity following an explosive event would be contained within a roughly circular region of a few km diameter centered directly over the vent; however, on some occasions the electrical activity would instead be offset from the vent. This exception may indicate a difference in how the eruption column formed: the first minute of electrical activity being centered over the vent suggests that a typical, upward-directed explosive event occurred, while the electrical activity being offset suggests that a plume was formed as a result of a pyroclastic flow (a dense flow of volcanic ejecta directed downslope from a volcano). Preliminary comparisons between a high-resolution plume model and the LMA data have shown some evidence that these different types of eruptive activity were correlated to differences in lightning behavior.

3 Relation to Other Previous Studies

Most of the previous studies of volcanic lightning have been limited to detection of high current electromagnetic pulses that are produced by strong cloud-to-ground discharges (e.g., Redoubt 1990, *Hoblitt* (1994); Mt. Spurr 1992, *McNutt and Davis* (2000), Eyjafjallajökull 2010, *Arason et al.* (2011); *Bennett et al.* (2010); Sakurajima 2009, *Aizawa et al.* (2010)) and, in some cases, strong intracloud discharges as well (Grimsvötn 2004, *Vogfjörd* (2005)). Though these studies have significant value in documenting electrical activity in volcanic eruptions and have been important for understanding charging mechanisms in volcanic plumes, the methods employed, at best, can determine the time and 2-D point-source location of the discharges. Because only the high-current pulses are detected, these methods preclude, in general, the study of small scale electrical activity. For example, the lightning detected in the *Hoblitt* (1994) and *McNutt and Davis* (2000) studies was substantially delayed in time from the onset of the explosive eruptions (5–15 minutes for Redoubt; 21–26 minutes for Spurr), thus, these discharges were most likely plume lightning. All of the studies did reveal, however, that substantial lightning occurred during these eruptions and that lightning is a significant consequence of explosive volcanic activity.

There has been one recent study of experimental generation of volcanic lightning that is relevant to our proposed studies. In this study, electrical discharges occurred in a shock-tube experiment where a mixture of gas and silicate particles was rapidly decompressed, resulting in the particles being ejected through a nozzle into a tank containing air at atmospheric conditions (*Cimarelli et al.*, 2013). Experiments were performed that used sieved ash, monodisperse silica beads of two different sizes (500 and 50 microns), and bimodal blends of silica beads. Electrical discharge only occurred when silicate particles were entrained in the turbulent portion of the flow. In experiments with monodisperse 500 micron silica beads, the particles formed a collimated flow and no electrical discharge occurred. When 50 micron beads were used, the flow was turbulent and electrical discharge occurred. In all other experiments, the smaller silicate particles formed a turbulent shell around the collimated portion of the flow and electrical discharge occurred. These results lead *Cimarelli et al.* to conclude that particle clustering in turbulent regions promoted collisions between particles resulting in triboelectric charging. This is an interesting result, showing the role of turbulence in producing electrical discharges. In our proposed research we plan to make video observations to track the development of the plume so that we can correlate potential changes in electrical activity to the transition from the momentum-driven jet phase of a plume to the turbulent, convective phase.

Other researchers have used Sakurajima to study the electrification of its plume. These studies used ground-based electric field measurements to infer the electrical charge structure in small plumes (*Lane and Gilbert* (1992), maximum plume height 3 km; *Miura et al.* (2002), maximum plume height 5 km). *Lane and Gilbert* inferred a positive-over-negative dipole charge structure, while *Miura et al.* inferred a positive-negative-positive tripole structure. Both studies hypothesized that distinct charge regions formed due to gravitational separation of charged ejecta. *Lane and Gilbert* suggested that lighter gas/cloud particles carried net positive charge and ash carried net negative charge. *Miura et al.* made the same assignment, but suggested that there were two layers of charged ash; the lighter ash carried net negative charge and heavier ash carried positive charge. With our proposed study of 3-D LMA observations, we will also be able to infer the dominant charge regions in Sakurajima's plume using the methods employed for Eyjafjallajökull (*Behnke et al.*, 2014), and to observe how the charge regions change over time.

4 Proposed Studies

4.1 Goals and Objectives

The overarching goal of the proposed research is to better characterize the electrical activity that occurs proximally to the vent of a volcano during and shortly after an explosive eruption. By characterizing the electrical activity within the context of the eruptive activity we will be able to address the following question: What eruptive conditions are required to produce the different types of small-scale discharges that may occur proximally to a volcanic vent simultaneous with and within the first several minutes following the onset of an explosive eruption? A related question is: what are the thresholds of the various measures of eruptive activity (e.g., infrasound, plume height, plume ascent rate) for the different types of proximal electrical discharges to occur?

To address these questions we plan to do a temporary deployment of electrical, acoustic, and optical instruments around Sakurajima Volcano in southern Japan, which is located near an urban region in an easily accessible area. Sakurajima is one of Japan's most active volcanoes, which produced over 1000 vulcanian-style explosive events in 2013 alone (source: Tokyo Volcanic Ash

Advisory Center (VAAC)). During 2013 ash plume heights typically reached altitudes of 3–5 km, though higher plumes heights were observed on occasion (source: Smithsonian Global Volcanism Program). Volcanic lightning has been frequently observed at Sakurajima during these relatively small explosive events, and there has been one recent study of lightning at Sakurajima (*Aizawa et al.*, 2010). Because the plume heights are relatively low, the charging mechanisms responsible for electrification in Sakurajima's plumes should be limited to the dry, silicate vent charging processes described in section 2. The frequent, but overall low level volcanic activity of Sakurajima and its accessibility make it a good candidate volcano for intensive research of small-scale electrical activity.

We plan to take measurements to address the following objectives for the discharges that may occur within a nominal 5 minute time window following the onset of an explosive event. In each case we will determine

1. when electrical discharge occurs relative to the onset of an explosive event and in relation to ascent of volcanic ejecta as it transitions from a jet to a convective plume,

2. where the electrical discharges initiate (either from the ground or from above the vent in the eruption column) and which direction they propagate,

3. the length scales and speeds of the discharges,

4. the polarities of the discharges,

5. which discharges produce continuous RF radiation.

The Lightning Mapping Array (LMA) is the primary instrument that will be used to address each of these five objectives. The 3-D locations of VHF sources from lightning will directly address objectives 2 and 3. The high-resolution timing of the located sources (typical timing errors are 25–30 ns) will aid in addressing objectives 1 and 4. Supporting instrumentation (high and regular speed video, infrasound sensors, and electric field change sensors) will also be used to address objectives 1, 4, and 5, as discussed below.

The project success will be measured by making all of the determinations outlined by the above objectives. By addressing these objectives we will be able to classify the observed electrical activity into categories such as vent discharges, near-vent lightning, or plume lightning, though it is possible that our definitions of these discharges will change or that new categories will be created. In addition, we will be able to link the occurrence of these discharges to specific eruptive conditions and phases of plume development based on our planned visual and infrasound measurements; we will make use of any available complementary monitoring data from the Sakurajima Volccano Observatory as well. We will have a better understanding of the eruptive conditions or stages of plume development in which these discharges occur.

4.2 Work Plan

We will measure electrical and eruptive activity at Sakurajima over a 4–6 month period in year 1 of the project. Several autonomous instruments (9 station LMA network, one slow antenna, 4-sensor acoustic array, one autonomous daylight camera) will be deployed and operated for the duration of the entire observation period (hereafter referred to as the long observation period). During a shorter, 2–3 week period, additional non-autonomous instrumentation (low-light video camera, fast antenna, modified LMA station to record log-RF waveform, high-speed video camera) will be deployed at one of the Sakurajima Volcano Observatory stations during a time when eruptive activity is heightened. This will require us to be flexible with the timing of this short observation period. Following the conclusion of the field campaign, we will devote year 2 and the remainder of year 1 to analyses of the data and publication of our results.

All of the instruments are available for use from either New Mexico Tech or University of South Florida, except the low-light and daylight video cameras, which will be purchased. Since much of this equipment is already in use during the summer storm season in New Mexico, we plan the observation period to occur from October 2014 – April 2015, when the equipment will be available, though there is some flexibility with this proposed scheduled; we could push the start date farther into the future.

4.3 Instrumentation

The instrumentation to be used is categorized based on its purpose; these categories include mapping of electrical discharges (lightning mapping), electric field measurements, optical lightning observation, explosion monitoring, and plume observation.

4.3.1 Lightning Mapping

The Lightning Mapping Array (LMA) – A 9-station LMA will be deployed around Sakurajima Volcano to locate in three dimensions sources of VHF radiation produced by electrical activity. We plan to use 9 stations because we will be using a particular set of instruments used for temporary deployments that happens to consist of 9 stations. Nine stations provide a good balance between data quality and installation time/ease. The LMA will record data from the 60–66 MHz band, which is currently unused by television or radio broadcasting in Japan, so no interference in that band is expected. This is the primary instrument to be used in this field project for the duration of the long observation period, and data from the LMA will be used to address the objectives 1–5.

Figure 4 shows proposed LMA station sites. About half of the stations will be located on Sakurajima itself, within several km from the vent; the rest will be located east and north east of Sakurajima up to 40 km from the vent where population density is relatively low, offering a low-noise environment for the LMA stations. To help provide low uncertainties in VHF source altitudes, station sites ranging in altitude from near sea level to 990 m are proposed. Station sites will have a line-of-site view to the vent. Figure 5 shows predicted uncertainties in altitude, azimuth, and radial distance for radiation sources located at 1 km altitude using the proposed station locations. At the vent the predicted uncertainties would be 12.5, 4.9, and 12.0 meters for azimuth, radial distance, and altitude. Stations will be operating in 10 microsecond mode and enhanced processing methods recently developed by Harald Edens of New Mexico Tech will be employed during times of interest to increase the number of located VHF lightning sources. Flashes will be identified both by visual inspection and by automated algorithms.

Log RF Waveform – One LMA station will be modified to record the filtered log RF waveform from the antenna in addition to the waveform peaks that are normally recorded by the LMA. This data is not needed to directly address any of the objectives; however, if continuous RF does occur, the log RF waveform will be able to show how impulsive the sources of continuous RF are.

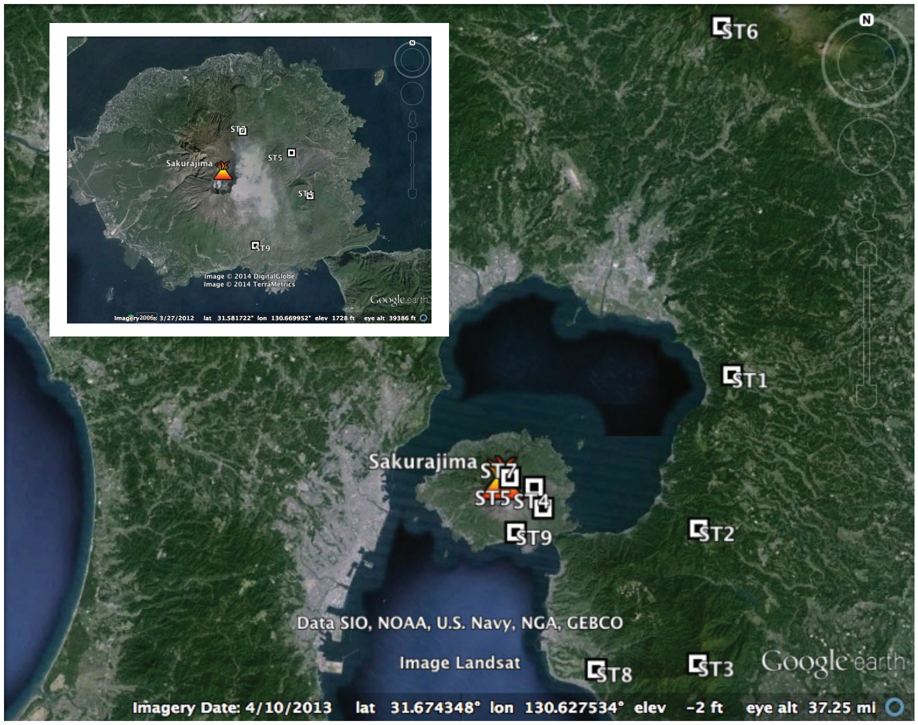

Figure 4: Preliminary locations of 9 proposed LMA station sites in the region surrounding Sakurajima in Japan. Inset shows close-up view of stations sites on Sakurajima itself. Topography of the area surrounding Sakurajima will allow for stations to be located at elevations ranging from near sea level to about 1000 meters, which is important for achieving low uncertainties in altitude of the located VHF sources. Final locations will be made in consultation with SVO staff.

This will improve our understanding of the distinction between discharges that produce continuous RF (i.e. vent discharges) and discharges that do not.

4.3.2 Electric Field Measurements

Slow Antenna – An autonomous slow antenna will be used to record slow changes in the surface electric field caused by lightning and electrical activity during the long observation period. These data reveal the polarity of lightning discharges. Data from the slow antenna will be used to address objective 4.

Fast Antenna – During the short observation period an additional instrument will be deployed at one of the observing sites to record electric field changes. Different from the slow antenna, this instrument records fast electric field changes. This instrument will have more sensitivity than the autonomous slow antenna, which will allow it to record the field changes from vent discharges, which we expect to be small. Data from this instrument will be used to address objectives 4 and 5.

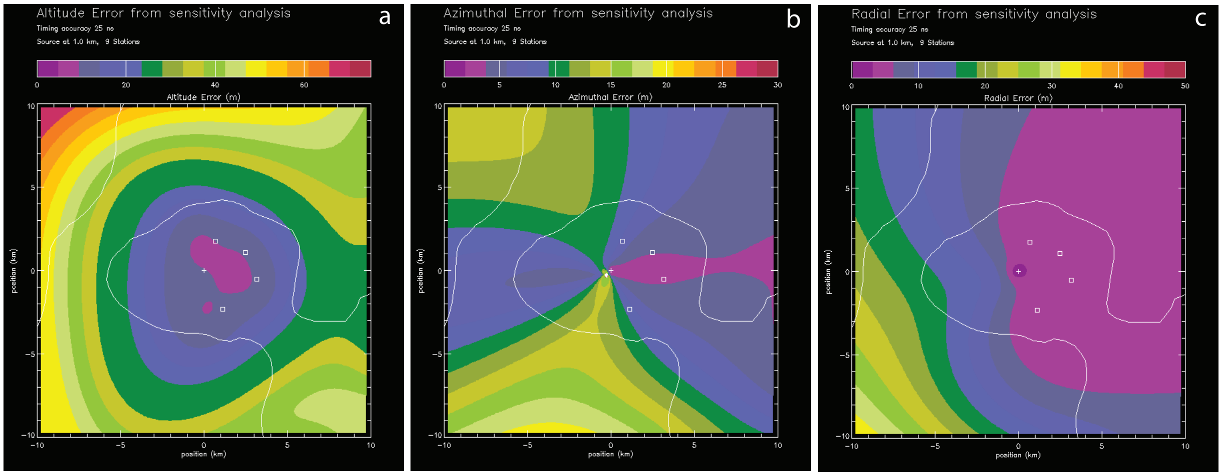

Figure 5: Predicted uncertainties of located VHF sources in (a) altitude, (b) azimuth, and (c) radial directions using stations sites shown in Figure 4 and assuming 25 ns timing errors. Uncertainties of 12.5, 4.9, and 12.0 meters for azimuth, radial distance, and altitude are predicted for VHF sources located at the vent, which is more than an order-of-magnitude improvement on altitude uncertainty from our previous deployment at Eyjafjallajökull.

4.3.3 Optical Lightning Observation

High-Speed Video Camera – A high-speed video camera (6400 fps at full [800 x 600 pixels] resolution; up to 100,000 fps at low resolution) with GPS timing will be located at one of the observing sites and data recording will be triggered with the fast antenna. We will record high-speed video of lightning during the short observation period and correlate these observations with the LMA and electric field data to address objectives 2, 3, and 5. In particular, we hope to record video when continuous RF occurs because no correlation has been made before between visual and electrical observations of continuous RF.

4.3.4 Explosion Monitoring

Acoustic Array – A 4-sensor array of acoustic sensors will be used to record infrasound (low frequency sound waves; below 20 Hz) produced by explosive activity during the long observation period. The data will provide timing, duration, and relative intensity of discrete explosive eruptions. Acoustic data will be used to address objective 1. Our acoustic array will be complementary to the existing SVO infrasound instrumentation.

4.3.5 Plume Observation

Autonomous video camera – An autonomous, low-cost, fixed video camera will be installed at one of the observing sites to make a visual record of eruptive activity during the long observation period. This camera would only provide data during daylight conditions. Data from this camera will be time-tagged with a GPS time inserter, and will be used to estimate plume heights, ascent rates, and observe plume development (e.g., jetting or turbulent motions) during explosive events.

The video images will be correlated with LMA and acoustic measurements to address objective 1.

Low-light Video Camera – A low light video camera (Watec 910HX/RC) will provide plume surveillance at night, complementing the video recorded by the autonomous video camera during the day. Because this camera is not designed to run autonomously, it will only be used during the short observation period. Video frames will be accurately tagged with GPS time using a time inserter. These data will be used to address objective 1.

4.4 Expected Outcomes

Based on our experience with many LMA deployments all over the world (see section 6: Results of Prior Support), we expect to successfully deploy a 9 station LMA network in Japan and obtain 3-D data with low location uncertainties (5–13 m). We also expect that explosive activity will occur while the instruments are deployed and that we will record electrical activity in Sakurajima's plume based on its historical and recent record of frequent explosive activity. Expected outcomes include successful recording of data of both electrical and eruptive activity on each of the appropriate sensors as well as addressing all five objectives as outlined above. We think that it is likely that continuous RF will occur (and that we will record data of it on the LMA in conjunction with other sensors measurements) based on results of the Augustine Volcano study, which showed that continuous RF occurred even for low plume height eruptive events (minimum plume height when continuous RF was detected was 3.8 km), and was recorded at LMA sensors 110 km from the source (*Thomas et al.*, 2010).

Additionally, though we plan to specifically address small-scale discharges, the data we will collect will have value for studying other aspects of volcanic lightning, such as examining the charge structure in the plume. Identification of the charge structure can be used to interpret charging mechanisms in the plume, as was done for the Eyjafjallajökull eruption (*Behnke et al.*, 2014). With the high level of detail we expect to obtain in the LMA data, we should be able to resolve the dynamic behavior of the charge structure. Since charge is carried on silicate particles, the evolution of the charge structure would shed light on the history of silicate particle formation and transportation in the plume.

5 Broader Impacts

Lightning is known to be an integral part of explosive volcanic eruptions (*McNutt and Williams*, 2010) and can thus be used as an independent indicator of explosive activity in a monitoring situation. Lightning observations could serve as a confirmation that an eruption occurred or as a means of primary detection. The only lightning detection system that is currently used to detect eruptions is the World Wide Lightning Location Network (WWLLN). Though this is a good and novel use of WWLLN, it is limited in its ability to detect eruptions because the network currently detects only about 10% of total lightning. WWLLN primarily detects lightning discharges that have high current pulses like energetic cloud-to-ground discharges, thus it misses the small-scale electrical activity that happens simultaneously with an eruption. WWLLN's response time to an eruption is thus delayed by several minutes, which is a large amount of time considering it only takes a few minutes for an ash plume to reach aircraft cruising altitudes (*Casadevall* (1994), *Behnke and McNutt*, in review). Another drawback to using lightning detection systems like WWLLN is that the origin (meteorological or volcanic) of large scale lightning could be ambiguous in regions prone to thunderstorms.

In contrast, the small-scale lightning that is detected by the LMA is a better indicator of explosive activity for two reasons: it occurs simultaneously with the onset of an eruption and the continuous RF signal is unique to volcanic eruptions. Thus, by monitoring for small-scale lightning much faster detection of a potentially hazardous ash plume can be achieved. The results of the proposed research (1) will be directly applicable to developing an eruption monitoring system using the LMA based on observations of continuous RF and other small-scale discharges. In addition, (2) by better characterizing the electrical activity in the context of the eruptive activity we may learn how to predict eruption magnitudes or ash plume heights based on lightning observations.

The proposed research will also (3) provide valuable training for an early career researcher (co-PI Behnke) from an underrepresented group. This is the first grant where co-PI Behnke will take a lead role in the investigations. Behnke will gain experience organizing field campaigns overseas and managing a project involving collaboration among several researchers with different areas of expertise. She will also gain experience deploying and using new instruments for volcano monitoring and lightning studies (infrasound sensors, slow and fast antennas), which will benefit her development as an interdisciplinary researcher in the fields of atmospheric physics, atmospheric electricity, and volcanology. Further, this proposed research will provide Behnke with her first opportunity to mentor graduate students, both in the field while deploying instruments and collecting data and in the laboratory analyzing data.

Moreover, (4) three graduate students (two from NMT and one from USF) will function as field assistants during the initial deployment and short observation period. The students will gain experience with field work and will learn how to deploy the LMA and the other instruments. The students will participate in gathering, organizing, archiving, and analyzing the data.

6 Results from Prior NSF Support

Note: Co-PI Behnke is an early career researcher and has no history of prior NSF support.

1. Collaborative Research: Lightning and Associated Electrical Activity at Erupting Volcanoes. Award No.: 0739085; PIs: R.J. Thomas, P.R. Krehbiel, W. Rison; Org: New Mexico Institute of Mining and Technology; NSF Org: AGS; Award Date: 02/15/2008; Award Amount: $ 500,987.00.

and:

2. Collaborative Research: Lightning and Associated Electrical Activity at Erupting Volcanoes. Award No.: 0739114; PI: S. McNutt; Org: University of Alaska, Fairbanks; NSF Org: AGS; Award Date: 02/15/2008; Award Amount: $ 104,243.00

These grants supported study of volcanic lightning during four volcanic eruptions: the 2008 eruption of Chaitén in Chile, the 2009 eruption of Redoubt Volcano in Alaska, the 2010 eruption of Eyjafjallajökull in Iceland, and the 2011 eruption of Grimsvötn in Iceland. These studies gave us valuable experience installing the LMA and other instruments in remote regions in the US and foreign countries. The LMA stations we used during these deployments required access to AC power and, ideally, a broadband internet connection, so deploying these instruments involved identifying residential homes or businesses that could offer these resources and also have a line-of-sight view of the volcano. We achieved this by using our personal, local contacts and community agencies in the area to find individuals who would allow us to use their homes or businesses as our station sites. We also had success finding sites by simply knocking on doors and explaining our needs and goals to homeowners. We found that many people were very generous in offering their support and land.

These studies discovered that there were two components or phases of electrical activity in a volcanic lightning storm. First, as ash and gas are ejected from a volcano, large quantities of small discharges occur due to the volcanic ejecta being charged. We discovered that high rates of very small "vent discharges" produced a characteristic "continuous RF" signal. Second, once a high altitude plume forms, thunderstorm-like lightning occurs throughout the plume. We also found some evidence that the quantity of small discharges and plume discharges correlated with the size of an eruption.

Co-PI Behnke was supported as a graduate student under the first of the two grants and received a PhD for her research on volcanic lightning. Graduate student and later post-doc Harald Edens was also supported with this grant and participated in the Redoubt and Eyjafjallajökull field campaigns. Several undergraduate students were also supported at New Mexico Tech contributing to data analysis and writing analysis software.

Related publications: *Behnke et al.* (2012, 2013, 2014), and numerous AGU, AMS, IAVCEI, and ICAE conference presentations. Currently in review is a chapter on volcanic lightning authored by PIs McNutt and Thomas in the 2nd edition of the Encyclopedia of Volcanoes, edited by Haraldur Sigurdsson, Bruce Houghton, Hazel Rymer, John Stix, and Steve McNutt.

3. Volcanic Lightning: Observations and Constraints on Mechanisms. Award No. 0538319; PI: S. McNutt; Co-PI E. Williams; Org: University of Alaska, Fairbanks; NSF Org: AGS; Award Date: 01/01/2006; Award Amount: $54,227.00

This grant supported investigation of volcanic lightning on a global scale that focused on the role of water and ice in electrification.

Related publications: (*McNutt and Williams*, 2010), and several conference presentations at AGU.

4. Collaborative Research: Investigating the Relationship Between Pluton Growth and Volcanism at Two Active Intrusions in the Central Andes. Award No. 0739114; PI: S. McNutt; Org: University of Alaska, Fairbanks; NSF Org: EAR; Award Date: 09/01/2009; Award Amount: $1,517,928.00.

This award is currently active and investigations are in progress. A large anomalous magma body exists from 10-20 km depth. We are characterizing its geometry using receiver functions and attenuation properties using both local and teleseismic data. We are also characterizing the local seismicity based on study of magnitudes, swarm parameters, b-values, and other criteria. One paper has been published on Uturuncu seismicity (Jay et al., 2011). Broader impacts include education and international field experience for graduate students Alexandra Farrell (PhD) and Heather McFarlin (PhD), insight into controls on mid-crustal growth, and improved basis for determining caldera eruption potential.

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Biographical Sketch: Stephen R. McNutt

Professional Preparation
PhD, Volcanology, Columbia University, 1985
M.Phil, Geological Sciences, Columbia University, 1984
MA, Geological Scienes, Columbia University, 1982
BA, Earth and Environmental Science, Wesleyan University, 1977

Appointments
Professor, School of Geosciences, University of South Florida, Tampa, FL, 2012–present
Research Professor, Geophysical Institute, University of Alaska Fairbanks, AK, 1991–2012
Senior Seismologist, California Division of Mines and Geology, Sacramento, CA, 1984–1991
Graduate Research Assistant, Lamont-Doherty Geological Observatory of Columbia, 1979–1984
Research Assistant, Lamont-Doherty Geological Observatory of Columbia, 1977–1979
Research Assistant, Woods Hole Oceanographic Institution, June 1977–August 1977

Publications
Related Publications

1. Behnke, S.A., R.J. Thomas, S.R. McNutt, D.J. Schneider, P.R. Krehbiel, W. Rison, and H.E. Edens (2013), Observations of volcanic lightning during the 2009 eruption of Redoubt Volcano, *J. Volc. Geoth. Res.*, 259.

2. McNutt, S.R. and E.R. Williams (2010), Volcanic Lightning: Global observations and constraints on source mechanisms, *Bull. Volcanol.*, v. 72, no. 10, p. 1153, doi: 10.1007/s00445-010-0393-4.

3. Thomas, R.J., P.R. Krehbiel, W. Rison, G. Aulich, H. Edens, S.R. McNutt, G. Tytgat, and E. Clark (2007), Electrical activity during the 2006 Mount St. Augustine volcanic eruptions. *Science*, v. 315, p. 1097.

4. Thomas, R.J., S.R. McNutt, P. Krehbiel, W. Rison, G. Aulich, H. Edens, G. Tytgat, and E. Clark (2010), Lightning and Electrical Activity During the Eruptions of Augustine Volcano. *USGS Prof. Paper 1769.*

5. McNutt, S.R. and C.M. Davis (2000), Lightning Associated with the 1992 Eruptions of Crater Peak, Mount Spurr Volcano, Alaska, *J. Volcanol. And Geotherm. Res.*, v.102, p.45- 65.

Other Significant Publications

1. Fee, D., S.R. McNutt, T. Lopez, K.M. Arnoult, C.A.L. Szuberla, J.V. Olson (2011), Combining Local and Remote Infrasound Recordings from the 2009 Redoubt Volcano Eruption. *J. Volcanol. Geotherm. Res.*, doi:10.1016/j.volgeores.2011.09.012.

2. De Angelis, S., S.R. McNutt and P.W. Webley (2011), Evidence of atmospheric gravity waves during the 2008 eruption of Okmok volcano from seismic and remote sensing observations. *Geophys. Res. Lett.*, v.38, doi:10.1029/2011GL047144.

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4. West, M., J.J. Sanchez, and S.R. McNutt (2005), Periodically-triggered seismicity at Mt. Wrangell volcano following the Sumatra-Andaman Islands earthquake. *Science*, v. 308, p. 1144-1146.
5. Behnke, S.A., R.J. Thomas, P.R. Krehbiel, S.R. McNutt (2012), Spectacular Lightning Revealed in 2009 Mount Redoubt Eruption. *EOS, Trans. Amer. Geophys. Un.*, v. 93, no. 20, p. 193-194.

Synergistic Activities

Development of databases on volcanic earthquake swarms and volcanic tremor to support research and education. Service as Secretary-General of the International Association of Volcanology and Chemistry of the Earth's Interior (1999-2007). Development of the graduate course Volcano Seismology, GEOS 672. Development of automated algorithms for analyzing volcano seismicity and posting results to the World Wide Web. Development of databases on volcanic earthquake swarms and volcanic tremor to support research and education.

Collaborators & Other Affiliations

Collaborators: Ken Arnoult, University of Alaska Fairbanks; Cere Davis, University of Washington; Ken Dean, University of Alaska Fairbanks; Jon Dehn, University of Alaska Fairbanks; Dan Dzurisin, US Geological Survey; John Eichelberger, US Geological Survey; Jeff Freymueller, University of Alaska Fairbanks; Roger Hansen, University of Alaska Fairbanks; Zhong Lu, US Geological Survey; Doerte Mann, Stanford University; Richard Moore, US Geological Survey; Seth Moran, US Geological Survey; Vilma B. Moreira, Universidad Nacional Costa Rica; Christina Neal, US Geological Survey; John Power, US Geological Survey; Angela Roach, Brown University; Hazel Rymer, Open University; David Schneider, US Geological Survey; Scott Stihler, University of Alaska Fairbanks; John Stix, McGill University; Wayne Thatcher, US Geological Survey; Guy Tytgat,New Mexico Tech; Charles Wicks, US Geological Survey; Ron Thomas, New Mexico Tech; Paul Krehbiel, New Mexico Tech; Earle Williams, MIT; John Olson, University of Alaska Fairbanks; Charles Wilson, University of Alaska Fairbanks.

Graduate and Postdoctoral Advisors: Klaus Jacob (primary), Chris Scholz (faculty), both at Columbia University; No Post-Doc, 1st supervisor - Brian E. Tucker, California Division of Mines and Geology.

Thesis Advisor: None. John Benoit, Chevron Corporation (PhD 1998); Arthur Jolly, Leeds University (PhD 2000); John Sanchez, Universidad de Guadelajara (PhD 2005); Tanja Petersen, Geol Survey New Zealand (PhD 2006); Katrina Jacobs, University of Wellington (M.S. 2008); Celso Reyes, University of Alaska Fairbanks (PhD 2012 planned); Nicole DeRoin, University of Alaska Fairbanks (PhD 2012 planned); Branden Christensen, (M.S. 2010); Milton Garces, University of Hawaii (post doc 1996-1998); Glenn Thompson, University of South Florida (post doc 1999-2000); Jackie Caplan-Auerbach, Western Washington University (post doc 2001-2003); Silvio De Angelis, Montserrat Volcano Observatory (post doc 2004-2006).

Biographical Sketch: Sonja Behnke

Professional Preparation
PhD, Physics with disseration in Atmospheric Physics, New Mexico Tech, Socorro, NM, 2003
BS, Physics with Astrophysics Option, New Mexico Tech, Socorro, NM, 2013

Appointments
Postdoctoral Scholar, School of Geosciences, University of South Florida, Tampa, FL 2013–present
Research Scientist, Langmuir Laboratory, New Mexico Tech, Socorro, NM Jan–Apr 2013
Graduate Research Assistant, Physics Department, New Mexico Tech, Socorro, NM 2008–2012

Publications

Related Publications

1. Behnke, S.A., R.J. Thomas, H.E. Edens, P.R. Krehbiel, and W. Rison (2014), The 2010 eruption of Eyjafjallaj okull: lightning and plume charge structure, *J. Geophys. Res.*, doi:10.1002/2013JD020781.

2. Behnke, S.A., R.J. Thomas, S.R. McNutt, D.J. Schneider, P.R. Krehbiel, W. Rison, and H.E. Edens (2013), Observations of volcanic lightning during the 2009 eruption of Redoubt Volcano, *J. Volc. Geoth. Res.*,259.

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5. Behnke, S.A. and S.R. McNutt (2014), Using lightning observations as a volcanic eruption monitoring tool, *Bull. Volcanol.*, in review.

Other Significant Publications

1. Edens, H.E., K.B. Eack, E.M. Eastvedt, J.J. Trueblood, W.P. Winn, P.R. Krehbiel, G.D. Aulich, S.J. Hunyady, W.C. Murray, W. Rison, S.A. Behnke, and R.J. Thomas (2012), VHF lightning mapping observtions of a triggered flash, *Geophys. Res. Let.*, 39 L19807.

2. Behnke, S.A., R.J. Thomas, P.R. Krehbiel, and W. Rison (2005), Initial leader velocities during intracloud lightning: Possible evidence for a runaway breakdown effect, *J. Geophys. Res.*, 110, D10207.

3. Behnke, S.A., R.J. Thomas, S.R. McNutt, P.R. Krehbiel, W. Rison, and H.E. Edens (2013), Using volcanic lightning measurements to discern variations in explosive volcanic activity, Eos Trans. Am. Geophy. Union, Abstract V43B-2861.

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5. Behnke, S.A., R.J. Thomas, S.R. McNutt, P.R. Krehbiel, W. Rison, and H.E. Edens (2011), Using VHF lightning observations to monitor explosive volcanic activity, Eos Trans. Am. Geophy. Union, Abstract V43F-05.

Synergistic Activities

1. Judge – Sixth Annual Graduate Student and Postdoctoral Scholar Research Symposium, USF

2. Session Chair – Atmospheric Physics 1, Annual Meeting of the Four Corners Section of the APS

Collaborators & Other Affiliations

Collaborators: Eric Bruning, TTU; Alexa Van Eaton, University of Arizona; Harald Edens, NMT; Paul Krehbiel, NMT; William Rison, NMT; Dave Schneider, AVO/USGS; Ronald Thomas, NMT; Mark Woodhouse, University of Bristol.

Graduate and Postdoctoral Advisors: Ronald J. Thomas, New Mexico Tech; Stephen R. McNutt, USF

Thesis Advisor: None.

Budget Justification

A & B. Personnel

We request funding for PI S.R. McNutt and co-PI S.A. Behnke for support and execution of the project. The salary requested for PI McNutt is for 0.5 months summer salary per year. The salary requested for co-PI Behnke is 6 months salary per year. Both salary rates assume an increase of 3% per fiscal year.

We also request funding to support a graduate student for 12 months salary per year. The student will participate in field work and data analysis.

C. Fringe Benefits

Fringe benefits have been budgeted at 16.09% of salaries and wages for faculty (PI McNutt), 1.85% of salaries and wages for postdocs (co-PI Behnke), and 0.5% of salaries and wages for graduate students. The fringe rate for postdocs and graduate students does not include health insurance, so for co-PI Behnke an additional amount equal to 6 months per year (12 months total) of the yearly premium (1747.20) has also been requested in addition to an amount equal to two years premium (2078.00 per year) for one graduate student. These estimates are in agreement with USF policies and procedures.

D. Equipment

We request funding to buy a small amount of equipment for plume monitoring. We plan to acquire a low-light video camera for night time use, an autonomous surveillance-style video camera for daylight use, two GPS time-inserters to accurately time-tag the video images, and a DVR for recording the video data. We also request funding for a rugged Toughbook laptop to use to communicate with the LMA stations during setup and to support the short observation period. The Toughbook is water and dust resistant and has a sunlight-viewable screen. Three quotes were obtained for each item.

E. Travel

A substantial portion of our requested budget includes funds for foreign travel to Sakurajima in year one of the project. We have budgeted for four trips: (1) the deployment of the autonomous instrumentation, (2) the short observation period, (3) an emergency maintenance trip, (4) equipment removal. We have travel funds budgeted for three people to participate in the (1) deployment and (2) short observation trips (McNutt, Behnke, and one student), and for 1 additional person to participate in (4) equipment removal, all of which will be complemented by personnel from NMT. Based on our past experiences with the Redoubt and Eyjafjallajökull projects, we have also included funds for two people to each make one (3) emergency trip to repair and maintain equipment as needed. The LMAs will be connected to the internet through cell phone modems, which will allow us to monitor the operating status of the instruments and determine if repairs are necessary.

We also requested funding for domestic travel for McNutt and Behnke to present preliminary research results annually at professional conferences such as the week-long Fall Meeting of the

American Geophysical Union. In addition to disseminating results of the project, participation in professional conferences will facilitate collaborative possibilities. Fund are also requested for Behnke and McNutt to travel to New Mexico Tech to meet with co-PI Thomas in year two of the project.

Foreign and domestic travel costs are based on current estimates and will be conducted in accordance with the State of Florida Travel Regulations.

F. Participant Support

None requested.

G. Other Direct Costs

Materials and Supplies: The deployment of the LMA stations requires several supplies: 12 V deep cycle batteries, 150 W solar panels, cables, cell phone modems, cellular data service/subscription from Japanese provider, as well as miscellaneous hardware. The batteries and solar panels will be purchased in Japan and our estimates are based on Japan prices. We plan to use a model of cell phone modem we have used in other projects therefore these will be purchased in the U.S. Rates for a cellular data subscription were estimated from rates advertised online by a Japanese provider.

Publications: Funds are requested to offset anticipated publication charges for two publications in the second year of the project in appropriate journals, such as *Journal of Geophysical Research* and *Bulletin of Volcanology.*

Expenditures reflected in these categories are based on best estimates now available.

H. Indirect Costs

The latest indirect cost rate approved by the cognizant government audit agency for the University of South Florida is 49.5% of modified total direct costs. This rate has been used in the budget calculations. The cognizant government audit agency for the institution is DHHS, Darryl Mayes, 301-492-4855.

Facilities, Equipment, and Other Resources

USF Facilities

Seismology Laboratory: The seismology lab at USF is under development. We are in the process of purchasing seismometers and infrasound sensors. The seismology lab has a data server and 40 TB of data storage, two high-end workstations for data analysis, and two computers that support graphical display of real-time seismic data. USF is a member of IRIS.

Computing Facilities: The School of Geosciences at USF maintains or accesses four computing facilities. Several workstations and supporting software are available to PIs for basic analysis of GPS and EM data. Second, the Volcano Research Group within the School of Geosciences maintains a 32-element node cluster for computationally intensive models, satellite InSAR analysis, and global GPS solutions. Third, the university has a multi-user Supercomputer system, and we are currently negotiating software additions to this system that will support detailed 3D finite element models. Fourth, the university recently invested in a high-end 3D visualization system that interfaces with the University's Supercomputer. The School of Geosciences has been selected as a beta tester for this system.

MT/EM: USF has modern MT/EM equipment, including an EM-31 instrument from Geonics, Inc. These data are logged with a recently purchased data logger that can accept a GPS input stream. Data processing can be done for individual profiles on a desktop computer.

GPS: USF currently operates a total of 8 state-of-the-art Trimble GPS receivers with Zephyr antennas, and 0.5 m spike mounts, which T. Dixon designed a decade ago and which are now in common use in the community. Dixon also operates a 15-station continuous GPS network in Central America for studies related to episodic tremor and slow slip events. New stations will complement this network; the analysis of the new stations will be "folded in" to the analysis of the existing stations. USF is already a member institution of UNAVCO. UNAVCO will be in charge of maintaining sets of stations, including data archiving. It is likely that the operation of both of these networks will be subsumed into the COCO-Net network (NSF's network of permanent GPS stations in the Caribbean) in the next few years.

The University of South Florida System is one of the nation's top 50 public research universities and one of the 39 community-engaged, four-year public universities as designated by the Carnegie Foundation for the Advancement of Teaching. USF was awarded $411 million in research contracts and grants in FY 2010/2011. The system offers 232 degree programs at the undergraduate, graduate, specialist and doctoral levels, including the doctor of medicine. It has a $1.5 billion annual budget, an annual economic impact of $3.7 billion, and serves more than 47,000 students on institutions/campuses in Tampa, St. Petersburg, and Sarasota-Manatee. USF is a member of the Big East Athletic Conference. For information regarding the USF system, please visit our website at http://system.usf.edu/

Data Management Plan

Expected Data

New observational data will be collected during the 4–6 month field campaign. In total, we expect to generate ∼6 TB of new primary data products including

1. time series data:
   - slow antenna,
   - fast antenna,
   - log-RF waveform,
   - infrasound array,
2. processed LMA data,
3. video recordings (high speed and regular).

In addition, secondary data products will be produced during data analysis including

1. time series of lightning statistics,
2. animations of LMA lightning and video data.

Data Storage and Archiving

All primary data will be archived for long-term use by both the USF Seismology Laboratory and the LMA Laboratory at NMT. Secondary data products will be made available for other researchers on Vhub (http://vhub.org), an online resource for collaboration in volcanology. A website will be created and maintained by the USF PIs that will be used to share details about the field campaign and research results with the general public.

Data Sharing and Access Policies

Primary data products will be made available to other researchers on a request basis through the above mentioned website. Secondary data products will be available to other researchers through the Vhub website on a request basis. Primary and secondary products will be made available beginning one year after the end of the award period. The data is expected to remain available for 5 or more years. LMA and time series data will be available in ASCII format. Video and animations will be provided in mp4 format. The university and investigators will retain intellectual property as applicable to all NSF funded research.