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Continuous Tracking of Lava Effusion Rate in a Lava Tube at Kilauea Volcano Using Very Low Frequency (VLF) Monitoring

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by

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ABSTRACT

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Measurement of lava effusion rates is a key objective for monitoring basaltic eruptions because it helps constrain geophysical models of magma dynamics, conduit geometry, and both deep and shallow volcano processes. During these eruptions, lava frequently travels through a single "master" lava tube. A new method and instrument for continuously monitoring the cross-sectional area of lava streams in tubes and estimating the instantaneous effusion rate (IER) is described. The method uses 2 stationary very low frequency (VLF) radio receivers to measure an unperturbed VLF signal and the influence of highly conductive molten lava on that signal. The difference between these signals is a function of the cross-sectional area of molten lava and the IER. Data from a short test of the instrument are described. This methodology represents a breakthrough in the continuous monitoring of IER because it provides higher temporal resolution than competing methods at a fraction of the cost.

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CHAPTER 1

MEASUREMENT OF LAVA EFFUSION RATES BY REMOTE SENSING - A REVIEW

Introduction

Volcanoes grow and their shape is defined by the endogenous and exogenous addition of magma and lava. Measurement of lava effusion rates is a primary objective of volcano monitoring because it places limits on the subsurface processes associated with lava supply and constrains models for a volcano's plumbing system. The volume of lava flowing from a volcano is generally referred to as the effusion rate (Harris et al. 2007) and is expressed as some number of cubic meters per second, but this number may represent an instantaneous flux or an average flux computed over minutes, weeks, or an entire eruption.

The effusion rate of an ongoing eruption may indicate whether the eruption is waning, waxing, or remaining constant (Harris et al. 2000). It may also indicate whether the current or possible future eruptions represent a hazard to people and their property. There are a number of methods used to measure or estimate lava effusion rates. These methods include monitoring lava streams flowing from the volcano, monitoring the growth of the volcano, and monitoring other volcanic processes that can be correlated to some extent with the emplacement of lava, such as emissions of SO_2 gas exsolved from magma and erupted at the surface. While the various methods produce results that are in general agreement, significant errors are not uncommon. Some disagreement is to be expected if scientists use different methodologies or different assumptions about the lava and its emplacement. A significant limitation of the current methods is the use of a few observations to average the effusion rate over periods of time from days to months, so that the study of volcanic processes on small time scales is not currently possible. Furthermore, current methodologies have inherent temporal constraints, such as satellite revisit intervals that make it difficult to increase temporal resolution or achieve continuous monitoring.

Ground-Based Measurements of Lava Effusion Rates

When magma approaches the Earth's surface it may be emplaced in a number of ways that contribute to the growth of a volcano. New lava may be emplaced within a lava flow and cause the flow to inflate or the lava may contribute to the growth of a volcanic dome or may simply flow out upon the surface. Basaltic lava reaches the Earth's surface at approximately 1150°C (Pinkerton et al. 2002). These high temperatures require scientists to use a variety of remote sensing techniques to monitor lava effusion rates. While basic field observations made by geologists, such as measuring distances, thicknesses, and elapsed time, are not normally considered remote sensing, they are important to this paper because they are the techniques that are used to calibrate and validate more elaborate remote sensing strategies.

Lava Confined In Streams

As lava flows onto the Earth's surface it is frequently confined by a lava tube or channel, and the effusion rate can be found as the product of the flow's velocity and cross-sectional area. The cross-sectional area is the width multiplied by the average depth. Standard surveying techniques, including GPS, can be used to measure the width of a lava flow. The classic method to find the depth of a lava flow is to force a piece of steel "re-bar" (normally used to reinforce concrete) into the lava and measure the length used to reach bottom (Pinkerton and Sparks 1976).

An average depth can be determined by measuring the depth at multiple points along a line perpendicular to the lava flow. However, approaching an active lava flow is not always safe or practical, so other methods of determining the flow depth are necessary. The depth of a lava flow can be more safely estimated by first measuring the height of the levees that confine the flow and then subtracting the distance from the top of the lava flow to the top of the levee (Calvari et al. 2003). Finally, the flow velocity can be found by timing the movement of a feature on the flow surface between 2 points that are separated by a known distance. The flow velocity can also be measured using a radar speed gun (Kauahikaua et al. 1998) or measured from high resolution photographs.

In some cases it is possible to monitor a lava flow with a time lapse camera that records a photograph at a fixed interval, normally a few seconds or minutes. The camera is positioned to image the lava surface against a levee wall so that depth information can be extracted from the photographs. Simultaneously, the camera field-of-view is set sufficiently wide so that features on the flow surface can be observed as they move from frame to frame against a background of fixed features of known separation. Thus, cross-section and velocity information can be extracted from the photographs and an effusion rate calculated. This approach was used by Patrick et al. (2011) by positioning a time lapse camera to record images, once per minute, of an active lava channel on Kīlauea Volcano. The camera was placed at a sufficient distance to monitor depth against the channel wall and derive flow velocities by monitoring the movement of pieces of lava crust on the flow surface as they moved in the time between images. In addition to allowing an estimate of lava effusion rate, the relatively high temporal resolution of this technique yielded other beneficial results. Cyclic spattering and seismic tremor caused by gas pistoning within a volcano were observed in a lava flow for the first time (Patrick et al. 2011). This discovery was made because of the continuous monitoring of the volcano's effusion of lava at a high temporal rate and suggests that other discoveries may also be possible if high resolution monitoring of volcano effusion rates can be achieved.

The mean flow velocity of a lava flow is dependent on the lava density, viscosity, channel dimensions, and slope. The mean velocity can be calculated using the Jefferys equation (Jeffreys 1925):

$$v = \rho g d^2 \sin\theta / \eta b \qquad (1.1)$$

where ρ is lava density, g is acceleration due to gravity, d is depth of the molten lava stream, θ is slope of the stream in degrees, η is the viscosity, and b is a constant dependant on channel geometry (8 for a semicircular channel, and 3 for a broad flow such as a typical lava stream) (Harris et al. 2007).

When using field measurements as inputs to the Jefferys equation, small errors in the measured depth can produce significant errors in calculated mean velocity. Mean velocity can be measured in several ways, but for a typical lava flow the mean velocity has been found to be about 50% of the maximum velocity (Kauahikaua et al. 1996). However, it is simpler to measure maximum velocity and then calculate mean velocity (Kauahikaua et al. 1998).

Lava Emplaced in a Dome

For a lava dome, the time-averaged discharge rate is obtained by measuring the change in volume of a lava dome or lava flow and then dividing this volume by the time in seconds (Harris et al. 2007). Measuring the volume of a lava dome or lava flow is conceptually straightforward. An appropriate combination of surveying techniques can be used based on each volcano's unique situation. Precise leveling, GPS, triangulation, photogrammetry, and laser-range finder measurements are commonly used options.

Lava in an Open Flow Field

Finding the volume of a dispersed and complicated flow field is more difficult than finding the volume flowing within a confined stream. One approach is to measure the area of newly emplaced lava on a daily or weekly schedule. The area of the lava can be multiplied by an average thickness to obtain a volumetric estimate (Pinkerton and Sparks 1976) and then dividing by the time interval produces the time-averaged discharge rate (Harris et al. 2007). The new lava is easily distinguished from older lava by its high temperature and, in the case of pahoehoe, by a shiny glass appearance. Carrying a GPS unit that has been programmed to record location once per second around the new lava either by foot or by helicopter is a simple method for obtaining the area of newly emplaced lava. The volume and time-averaged discharge rate can then be calculated.

Lava in a Pit, Caldera, or Crater

Occasionally, new lava will be emplaced into a pre-existing feature with known dimensions (crater, pit, or other depression) and the effused volume can be determined by periodically measuring the lava level against a sidewall and applying the appropriate equation of volume.

Effusion Rates by Remote Sensing

Sulfur Dioxide Emissions

Magma contains dissolved volatiles that represent approximately 0.5% to 1.5% of its total weight and includes a mixture dominated by carbon dioxide (CO_2), water (H_2O), and a relatively small quantity of sulfur dioxide (SO_2). The ratios of these 3 volatiles vary but generally represent about 98% of all volatiles emitted (Symonds et al. 1994). Of these, CO_2 is the least soluble and first gas to exsolve as magma approaches the surface (Schwandner et al. 2010). This makes CO_2 an important indicator of new magma and a precursor to volcanic eruptions. As magma nears the surface and erupts, degassing of lava continues. By periodically measuring the released volatiles, particularly SO_2, it is possible to estimate the quantity of magma necessary to produce that volume of volatiles (Sutton et al. 2003). If it is assumed that all the degassing magma is erupted as lava, then it is possible to calculate a time-averaged discharge rate.

Sulfur dioxide gas in the atmosphere absorbs ultraviolet light in proportion to the SO_2 concentration. This property of SO_2 is used in correlation spectrometers (COSPEC) to measure SO_2 emissions. COSPEC was developed by Resource Ltd. (Canada) in the 1960s to monitor SO_2 emissions from the smokestacks of coal-fired power plants (Horton et al. 2006). The instrument includes an optical system to deliver light to a spectrometer sensitive to the UV portion of the electromagnetic spectrum and 2 calibration cells containing SO_2 at known concentrations. The

COSPEC instrument automatically self calibrates by periodically inserting these calibration cells into the field of view. By pointing the instrument skyward near midday, and traversing under a gas plume, it is possible to obtain a concentration profile of the SO_2 in the atmosphere. Combining this profile with wind velocity allows the SO_2 effusion rate to be calculated.

First applied to volcanoes by Moffat and Millan (1971), COSPEC remains the principal method for measuring SO_2 emissions within volcanic plumes. The instrument is mounted onto a suitable platform, typically a car or airplane, and then driven or flown under the volcanic plume. Modern units include a GPS receiver to obtain accurate location and time information and a laptop computer to automatically log instrument readings. The vehicle transporting the instrument may also measure the wind velocity or the wind velocity may be obtained from a separate weather station located on the volcano. The SO_2 profile is combined with the wind velocity to obtain an SO_2 effusion rate that is normally represented as tonnes per day. Lava effusion rates are computed from SO_2 effusion rates by use of a constant that relates the quantity of SO_2 released per tonne of lava erupted (Sutton et al. 2003). As an alternative, the SO_2 effusion rates can be compared with lava effusion rates determined by other methods and a conversion factor established.

Carn and Bluth (2003) were able to measure SO_2 emissions using space-based sensors on board the Total Ozone Mapping Spectrometer (TOMS) platform for 2 dates at the Nyamuragira Volcano, D.R. Congo. Although they did not attempt to estimate lava effusion rates, this would be a logical extension of their work.

VLF Method

Various governments operate very low frequency (VLF) radio stations for military communications. Operating at frequencies from 15 kHz to 30 kHz, with transmitter power up to 1.8 million watts, these stations provide worldwide one-way communication to submerged submarines (King et al. 1997). Primary signals from these powerful VLF stations penetrate deep into the Earth and produce secondary electromagnetic signals by inducing electrical currents in buried conductors. This phenomenon is used in the design of Electromagnetic (EM) instruments to study the Earth's subsurface. In 1962 Vaino Ronka and Alex Herz were inspired to invent the EM-16. This device measures the local tilt and ellipticity of the secondary VLF signal, and resolves the secondary VLF signal into in-phase and out-of-phase (quadrature) components (Paterson and Ronka 1971). The EM-16 and more modern EM devices can be used to locate buried electrical conductors and estimate their size, depth, and conductivity.

Molten lava in lava tubes is a much better electrical conductor than the surrounding solidified lava, and this makes the molten lava a good subject for VLF investigation. Researchers have been able to use EM-16 data from a VLF survey conducted perpendicular to an active lava tube to model the "wet area" of the lava tube and obtain an estimate of the lava effusion rate (Zablocki 1978). This is possible because the secondary radio signal received from the lava tube varies as a result of changes in the cross-sectional area of the flow within the tube.

Between April, 1991 and April, 1992 Kauahikaua et al. (1996) used the VLF method to investigate a lava tube on Kīlauea Volcano, Hawai'i. At the time, this lava tube carried all of the lava from a vent on Kīlauea's East Rift Zone to the ocean, a distance of approximately 12 km. A study site was selected along the lava tube approximately 1 km from the vent and 5 m upslope from a skylight. Permanent survey stations were marked along a 60 m line perpendicular to the path of the lava tube at intervals of 1.5 m. Each EM-16 survey consisted of measurements at 41 survey stations with station 21 directly over the lava tube and required approximately 30 minutes to complete. During the year a total of 38 VLF surveys were made at intervals of a few days to a few weeks. Data from each survey was mathematically reduced to the cross-sectional conductance of the lava within the lava tube. Samples of lava were collected from the lava tube at the nearby skylight and remelted so that the lava's conductivity could be measured in the laboratory. The researchers were then able to convert the cross-sectional conductance into an estimate of the cross-sectional area of the lava within the lava tube. This "wet area" estimate was multiplied by a velocity obtained at the skylight using a hand-held radar speed gun to give an estimate of the lava effusion rate. Measurements of the width and depth of the lava within the lava tube were made at the skylight to verify the results obtained by the VLF surveys. This research represented a refinement in the VLF method by simplifying the computations needed to convert VLF survey data into cross-sectional conductance and lava effusion rate.

The VLF research at Kīlauea was conducted on one of the most accessible and studied volcanoes in the world, and the home of the US Geological Survey, Hawaiian Volcano Observatory (HVO). Despite the advantages of resources at HVO, proximity and accessibility to an active basaltic volcano, the VLF method has some shortcoming and limitations. For example, only 38 VLF surveys were conducted during the year of the study (Kauahikaua et al. 1996). Furthermore, the VLF method requires researchers to work alongside an active lava flow for prolonged periods of time and visits are normally restricted to daylight hours. Finally, even if VLF surveys could be made continuously, the fact that each survey requires 30 minutes to execute would severely limit its usefulness for investigating phenomena with temporal durations shorter than this.

Sutton et al. (2003) compared estimates of lava effusion rates for Kīlauea derived from COSPEC SO_2 monitoring with estimates from VLF surveys for the 20-year period between January 1983 and May 2002, including the VLF data of Kauahikaua et al. (1996).. Both of these methods (VLF and COSPEC SO_2 profiling) are logistically challenging and they each averaged only about 15 measurements per year. There were 261 COSPEC SO_2 measurements made over 16 years and 217 VLF surveys made over 15 years. Each method was used to estimate the volume of lava erupted annually. The 2 methods disagreed by as much as 85% with an average disagreement of 30%. However, the 20 year "grand total" estimates for volume of erupted lava were in agreement within 10%. The best agreement between the 2 methods was observed to be in the years with the most data points.

Thermal Methods

Newly erupted lava at the Earth's surface is far hotter than its surroundings. Over time the lava cools primarily by conduction, convection, and radiation (Harris et al. 1998). Heat is lost by radiation and convection at the surface of the flow and by conduction at points where the flow is in contact with solidified materials. Solidified, vesicular basaltic lava is a relatively good insulator (Kauahikaua et al. 2003), so heat loss is dominated by those losses occurring at the flow surface (Harris et al. 1998). A heat loss model can be developed that accounts for all types of heat loss and, in particular, isolates that portion of the heat loss due to radiation. By measuring the heat loss due to radiation, and knowing the proportion of heat lost by radiation, it is possible to calculate the area of molten lava currently in the flow field (Harris et al. 1998). With repeated measurements the time averaged lava effusion rate can be calculated.

Harris et al. (1998) computed a time averaged lava effusion rate for Kīlauea for July 23 and October 11, 1991 using 30 m Landsat Thematic Mapper (Landsat TM) data. The researchers first developed detailed thermal flux budgets for lava flowing onto the surface, within lava tubes, and into the ocean. These budgets included convection, radiation, wind, rain, skylights, and the latent heat of crystallization. The effusion rate estimates reported by the authors were in agreement with measurements made on the ground for the given dates. However, the author's estimates had an uncertainty of ± 33% while measurements made on the ground had an uncertainty of ± 10%. The authors were also able to use lower resolution data from the Advanced Very High Resolution Radiometer (AVHRR) onboard a National Oceanic and Atmospheric Administration (NOAA) weather satellite to estimate lava effusion rates for an additional 26 dates with similar uncertainties. Harris et al. (2000) built a data set of 391 lava effusion rate measurements for Mt. Etna and Krafla volcanoes from 1980 to 1999 using ground and satellite based sensors to compare the relative percentages of erupted and intruded lava. Their data set of approximately 21 observations per year would be inadequate to investigate phenomena that varied on a weekly timescale. Lava effusion rates have also been calculated using Landsat Enhanced Thematic Mapper Plus (ETM+) data (Harris et al. 2004), although the thermal flux budgets were later modified to include conduction into the ground (Harris et al. 2005).

Wright et al. (2004) and Hirn et al. (2005) developed a state of the art software package to automatically compute instantaneous lava effusion rates from thermal data obtained from any

1 of 6 different satellite based sensors including Landsat TM and ETM+, TERRA, and SPOT. Even with this convenient technology, their published data for Kīlauea only amounted to approximately 6 observations per year over a 3-year period.

Wooster and Kaneko (1998) used a combination of satellite thermal data and COSPEC $S0_2$ monitoring at Unzen Volcano, Japan to analyze lava emplacement in a lava dome. Eleven COSPEC measurements were made over 36 months and SO_2 effusion rates were calculated. No attempt was made to estimate lava effusion rates based on these data but it would be a logical next step. Because it would seem desirable to carefully monitor SO_2 emissions, the extremely infrequent COSPEC observations may reasonably be interpreted as a weakness in the COSPEC method.

Thermal images from multiple satellites have been used in an effort to overcome resolution versus revisit trade-offs encountered during many investigations using satellite based sensors. Murphy et al. (2013) used MODIS images with high temporal resolution (daily) and low spatial resolution (1 km^2) combined with ASTER images with moderate spatial resolution (90 m) and low temporal resolution (16 days) to investigate thermal activity at 4 volcanoes.

Lombardo et al. (2009) measured spatial variations in lava flow field thermal structures and computed lava effusion rates from data acquired by a very high spatial resolution airborne 82 band hyperspectral sensor at Mt. Etna. Ten measurements were made over an 8-week period, once again illustrating the temporal limitations of the thermal approach as it is routinely applied to volcano monitoring. Steffke et al. (2011) also investigated lava effusion rates at Mt. Etna with a combination of sensors, COSPEC, and satellite thermal data. They observed that 24% of the degassed magma never erupted as lava thus casting suspicion on one or both of these methodologies. Forward looking infrared (FLIR) is a thermal approach similar to the previously discussed satellite approach. FLIR cameras can provide continuous high resolution thermal data over small areas. They can also be used to collect thermal data for an entire flow field or an entire volcano with a temporal resolution constrained only by one's ability to transport the device by foot or by helicopter. Calvari et al. (2005) used FLIR to collect near daily temperature measurements of the 2002-2003 Stromboli eruption at a resolution of approximately 2 m. FLIR was also used to monitor daily lava effusion rates at Stromboli during June 2003 (Harris et al. 2005). Because the FLIR provided unsaturated temperature data, it was possible to accurately calculate heat loss on a pixel by pixel basis and compute daily lava discharge rates.

InSAR

Interferometric Synthetic Aperture Radar (InSAR) is a computationally complex method of combining the phase information from multiple Synthetic Aperture Radar (SAR) images to produce an interferogram that displays increases and decreases in the distance between the radar unit and the ground that occurred during the time between radar images. Wadge (2003) discussed the measurement of lava effusion rates with InSAR. He observed that the size of most lava flows fall somewhere along a continuum with lava domes that seldom exceed 1 km^2 in area, as one end member, and large flow fields with areas of about 10 km^2, as the other end member. Wadge then evaluated the performance of InSAR at Soufrière Hills volcano, Montserrat. InSAR appeared to work well on the flanks of the volcano and poorly on forested areas and extremely poorly on the lava dome. Even when there was no volcanic activity, the lava dome was poorly imaged with InSAR because of rock falls, thermal contraction, and block rotation of the dome.

Each of these processes acts to decorrelate the surface of the dome during the time between InSAR images. Wadge suggested that one-pass InSAR would be required to produce interferograms of lava domes. In a second example, InSAR was shown to produce useful digital elevation models (DEM's) of Arenal Volcano, Costa Rica. Wadge concluded that, in general, InSAR works best with long wavelengths, short repeat intervals, and large baselines.

Zebker et al. (1996) used images acquired on 4 successive days by the Space Shuttle Imaging Radar (SIR-C) experiment in October, 1994 to estimate the lava effusion rate for Kīlauea. The researchers compared 15 m x 15 m pixels within images of Kīlauea's flow field with the same pixels from images recorded the previous day. Pixels inundated with lava between images would scatter radar signals differently in each image and be decorrelated. Undisturbed pixels would scatter radar signals the same way in each image and be correlated. Thus the researchers were able to measure the land area that was covered with fresh lava each day by counting the number of uncorrelated pixels. Multiplying this area by an assumed average thickness of 0.5 m they were able to estimate daily lava effusion rates of 1.94, 2.13, and 2.06 m^3 per second. This approach is elegant in its simplicity and it would be extremely useful on dangerous or remote volcanoes. InSAR has also been used to measure posteruptive inflation, compaction, and subsidence of lava flows (Stevens et al. 2001). The InSAR method is limited by the sensor revisit interval and the difficulty in measuring changes in flow field height.

Difficulties with the Current Methods

Current methods for estimating lava effusion rates are fraught with difficulties. Direct measurements made in the field require geologists to visit active volcanoes, which can be timeconsuming, expensive, dangerous and, normally, only possible during daylight hours. Because of these problems, effusion rate estimates based on field measurements are made on a daily basis, at best, and, more typically, on a weekly or monthly basis. Effusion rate estimates using ground based remote sensing techniques such as COSPEC or time lapse photography require sunlight for illumination and cannot be used at night.

The mean duration for volcanic eruptions on Earth is about 7 weeks (Siebert et al. 2010). High resolution satellite-based sensor systems have revisit intervals that are typically in the range of 2 to 10 days (Schowengerdt 2006) and are therefore not particularly useful for studying many volcanic eruptions and volcanic processes. Satellite imagery is affected by cloud cover and vegetation which may further reduce its availability. Even daily, high resolution satellite remote sensing is inadequate for studying volcanic processes with short temporal duration.

The notion of estimating lava effusion rates by measuring the thermal energy radiated from a lava flow field has had its detractors. Wright et al. (2001) wondered how measuring heat lost across an entire lava flow field for 1 second could be used to determine the volume of lava erupted from a distant vent during that same period of time. They suggested that the apparent success of the thermal heat budget method was a numerical coincidence and was no more precise than simply multiplying the area of the lava flow field by a constant. Pieri and Baloga (1986) had confirmed a linear relationship between effusion rate and lava flow field area for a number of eruptions at Kīlauea. Dragoni and Tallarico (2009) identified 11 underlying assumptions in the heat budget method that limited its usefulness. In particular the assumption of uniform surface temperature across the flow field was contradicted by field measurements. These assumptions and limitations were acknowledged by Harris and Baloga (2009) who had developed much of the satellite based thermal sensor approach. Coppola et al. (2010) used a high resolution handheld thermal camera to compare surface radiance of lava flows to the radiance recorded by the satellite based Moderate-resolution Imaging Spectroradiometer (MODIS) sensor. They found that the presence of clouds strongly affected the radiance reaching the MODIS sensor and that ground based thermal data should be used to improve the interpretation of satellite measurements of time averaged lava effusion rates.

Using a combination of long term satellite-based observations and 3 days of frequent ground based observations, Lautze et al. (2004) identified variations in the lava effusion rate from Mt. Etna on timescales of minutes to months. This clearly suggests a need for a methodology able to measure lava effusion rates far more frequently than is typically done at this time, which is essentially monthly to weekly at best.

Conclusions

More research is needed to develop methodologies that can continuously estimate lava effusion rates at time intervals of a few seconds to a few minutes. This article has demonstrated that the world's leading volcanologists, publishing their best research in the most prestigious peer-reviewed journals, lack a methodology to continuously measure or accurately estimate lava effusion rates on a timescale measured in seconds. When scientists have been able to increase the temporal resolution of their observations, new phenomena have been discovered. Sensors and computers are becoming faster and cheaper, so there is hope that new devices and methods can be developed.

CHAPTER 2

CONTINUOUS TRACKING OF LAVA EFFUSION RATE IN A LAVA TUBE AT KĪLAUEA VOLCANO USING VERY LOW FREQUENCY (VLF) MONITORING

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Abstract. Measurement of lava effusion rates is a key objective for monitoring basaltic eruptions such as those of Kīlauea Volcano, Hawai'i, because it helps constrain geophysical models of magma dynamics, conduit geometry and both deep and shallow volcano processes. A variety of methods are currently used to estimate average effusion rates and while they produce results that are in basic agreement, significant discrepancies are common. Furthermore, current methods do not permit the study of events with short temporal durations of seconds to days. During basaltic eruptions, lava frequently travels through a single, master lava tube. A new method and instrument for continuously monitoring the cross-sectional area of lava streams in tubes and estimating the instantaneous effusion rate (IER) is described. The method utilizes two stationary very low frequency (VLF) radio receivers and is designated the Freeman DVLF method. One receiver has its antenna placed over the tube to measure the influence of highly conductive molten lava on a VLF signal transmitted from a remote transmitter. The second receiver's antenna is placed off the tube to measure the unperturbed VLF signal. The mathematically normalized difference between these signals is the Differential VLF (DVLF) and is a function of the cross-sectional area of molten lava and the IER. Data from a short (4-hour) test of the instrument are described. The Freeman DVLF methodology represents a breakthrough in the continuous monitoring of IER because it provides orders of magnitude higher temporal resolution than competing methods at a fraction of the cost.

Keywords: Lava Tube, Effusion Rate, VLF

1. Introduction

A variety of methods, both direct and indirect, are currently used to measure lava effusion rates, but these measurements are intermittent and have temporal scales of days to months or greater and have errors of up to 50% [*Harris et al.*, 2007]. For example, the correlation spectrometer (COSPEC) which measures SO_2 emissions can only make measurements in strong sunlight, while remote sensing thermal methods using satellites are limited by revisit intervals that are typically days to weeks [*Schowengerdt*, 2006]. Methods that require geologists to visit the volcano to conduct line-of-sight measurements, which is sometimes a high risk situation, can also have significant cost and logistical constraints. In general, current techniques only provide a measurement once every few days or few weeks, which is insufficient for the study of many volcanic processes that have time scales of minutes to hours. Examples of processes that cannot currently be easily monitored include the cyclic spattering and tremor caused by gas pistoning of lava at Kīlauea [*Patrick et al.*, 2011] and cyclic activity at Soufrière Hills Volcano, Montserrat [*Voight et al.*, 1999].

Recently, Harris et al. [2007] provided a review of the wide and varied use of terms related to the eruption of lava over different time scales and the advantages and disadvantages of each in understanding both short- and long-term volcano processes. These terms included *effusion rate*, *instantaneous* effusion rate (IER), *time averaged discharge rate*, *eruption rate*, and *mean output rate*. The IER and *mean output* rates represent two ends of a temporal spectrum of lava effusion.

Previously the general term "*effusion rate*" was made more specific by Lipman and Banks [1987] by using it to refer to instantaneous values. Harris et al. [2007] went on to define IER as a measure of the volume flux of erupted lava that is feeding a flow at any particular point in time, whereas the *time averaged discharge rate* is defined as volume fluxes averaged over a given time period. They define *eruption rate* as the total volume of the lava emplaced since the beginning of the eruption divided by the time since the eruption began and the *mean output* rate as the final volume of erupted lava divided by the total duration of the eruption. One advantage [*Harris et al.*, 2007] identified for the *time averaged discharge rate* over the IER was, "…that short-term variations caused by short-lived changes in measurement conditions or bias introduced by the time of measurement can be minimized." Quantifying lava eruption rates of all types (i.e., across all temporal scales ranging from seconds to months or years) is essential for better understanding volcano processes, interpreting a suite of volcano monitoring data, and forecasting hazardous processes, yet existing methodologies do not allow the measurement of IER at time scales below minutes to hours and these can only be made intermittently, not continuously. The utility of existing IER measurements is therefore limited. The objectives of this study are to describe instrumentation and methods that have the capability to determine the IER at intervals of seconds to minutes and to overcome the *time averaged discharge* rate's advantage over IER.

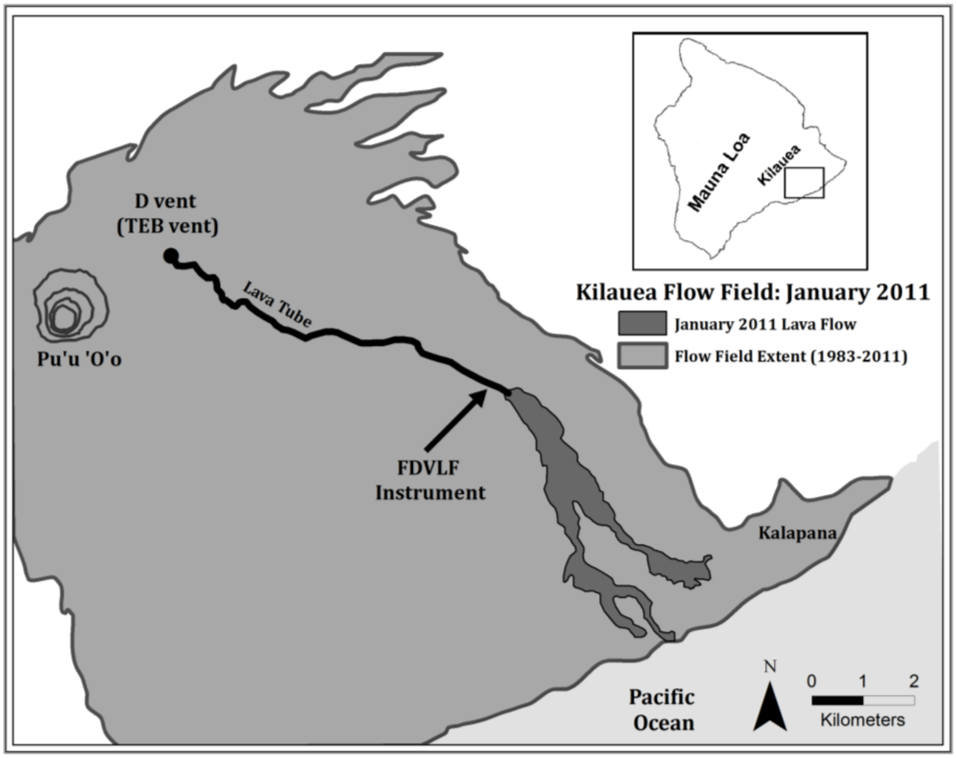

Figure 2.1. January 2011 map of Kīlauea flow fields showing Pu'u 'Ō'ō vent, Fissure D vent, Kupaianaha, lava tube and the location of the FDVLF instrument (USGS Hawaiian Volcano Observatory).

2. Background

Molten lava flowing through a lava tube has a much lower electrical resistance (2 ohm-metre) [*Zablocki*, 1978] than surrounding, cold, solidified country rock (3 - 20 x 10^3 ohm-metre) [*Keller and Rapolla*, 1974]. This large contrast in resistance allows subsurface molten lava to be studied with a variety of electromagnetic (EM) techniques in both the time and frequency domains. Among the EM frequency domain techniques is the very low frequency (VLF) method.

The VLF method takes advantage of military VLF transmissions from radio stations operated by various governments. Transmitting at frequencies from 15 to 30 kHz and with transmitter power up to 1.8 million watts, these stations provide worldwide one-way communication to submerged submarines. Signals from these powerful VLF stations penetrate deep into the earth and make an excellent source of EM energy for an otherwise passive remote sensing instrument. In 1962, Vaino Ronka and Alex Herz invented the EM-16 instrument [*Catalano*, 2009] which measures VLF interference caused by conductive material. Paterson and Ronka [1971] explained the theoretical basis of the VLF method and operation of the EM-16, which basically measures the local tilt and ellipticity of VLF broadcasts, and resolves the inphase and quadrature components of the VLF response. The EM-16 is a widely used geophysical instrument [*Olsson*, 1980] and has been used to discover metal ore bodies and water-filled fractures [*Ogilvy and Lee*, 1991].

Kīlauea (Figure 2.1) has been the subject of VLF investigation for the past 40+ years [*Anderson et al.*, 1971]. Sandberg and Connor [2000] investigated two active lava tubes on Kīlauea with a suite of EM techniques and reported that the VLF method was particularly useful for locating active lava tubes because the high electrical conductivity of the molten lava allowed the conspicuous identification of molten lava in a tube. Jackson et al. [1988] used data from a VLF survey conducted perpendicular to an active Kīlauea lava tube with an EM-16 instrument to model the “wet cross-sectional area” of the lava tube and estimate the lava effusion rate. This was possible because the VLF radio signal received from the lava tube varies as a result of changes in the cross-sectional area of molten lava in the lava tube. The EM-16 VLF approach was improved by simplifying the conversion of survey data into cross-sectional area Kauahikaua et al. [1996]. Other VLF instrumentation could be substituted for the EM-16, as long as changes in the VLF signal at the lava tube can be monitored. Previous VLF techniques are all campaign style (brief visits with long intervals between) whereas the main advantage of this technique is that it is continuous, and therefore more appropriate for real-time hazard monitoring. The instrument described in this paper has a stationary receiver which has the advantage of allowing continuous monitoring of IER at a scale of minutes to hours.

Currently, lava effusion rates are measured by a variety of methods, but each of them are limited in terms of their ability to provide accurate observations of effusion rates and on short temporal scales. These include surface mapping with handheld GPS instruments, ground deformation, and gas correlation spectrometry (COSPEC). Sutton et al. [2003] showed that the very low frequency (VLF) method and COSPEC SO_2 profiling, in addition to ground-based GPS surveying, can be used to independently estimate Kīlauea lava effusion rates with long-term agreement within about 10%. They compared estimates of lava-effusion rates derived from infrequent SO_2 emission measurements (17.4 yr^{-1}) and VLF measurements (14.5 yr^{-1}) made during 15 years of observations.

3. Methods

3.1 The Freeman DVLF Instrument (FDVLF)

The current EM-16 method of conducting a VLF survey requires moving the instrument to multiple survey points along a line crossing the lava tube at right angles. At each survey point, the EM-16 is rotated and adjusted to measure the vector components of the VLF radio signal response. Our new stationary instrument utilizes a method which we will refer to as the Freeman Differential VLF (FDVLF) method. A DVLF receiver consists of two stationary VLF radio receivers. One receiver has an antenna placed over the lava tube (the *on-tube* antenna) and measures the influence of highly conductive lava flowing in the tube on a VLF signal transmitted from a powerful remote transmitter. The second receiver has its antenna placed some distance from the tube (*off-tube* antenna) so that it can measure the ambient and unperturbed VLF signal from the same transmitter. These receivers use multi-turn air-core loop antennas and measure the amplitude of the magnetic field component of VLF signals from remote VLF transmitters (the closest being 400 km northwest of Kīlauea at the US Navy Lualualei Naval Base on the island of O'ahu, Hawai'i). The amplitude of the received signals are digitized and recorded by a data logger housed within the new instrument.

The received VLF signal at both antennas will vary due to changes in the propagation path such as the diurnal cycle of the lower ionosphere [*McRae and Thomson*, 2000]. The signal received by the *on-tube* antenna will also vary due to changes in the quantity and proximity of molten lava. By comparing the VLF signal received by the *off-tube* antenna with the VLF signal received by the *on-tube* antenna, variations due to changes in propagation can be eliminated and changes due to variations in lava flow will be detected.

The *off-tube* antenna and its VLF receiver capture the magnetic component of the primary signal from the remote VLF transmitter. The *on-tube* antenna and its VLF receiver capture the magnetic component of the sum of the primary VLF signal from the remote VLF transmitter and the secondary VLF signal that is radiated from the molten lava in response to the primary signal. After calibration, the normalized difference between the signals received by the two VLF receivers can be interpreted as the "wet" cross-sectional area of molten lava in the lava tube. The effusion rate can then be calculated by multiplying this cross-sectional area by the velocity of the flowing lava, which may be measured with a standard radar instrument where the lava is visible (e.g., at a sky light) or calculated from existing models of lava flow velocities in lava tubes [*Kauahikaua et al.*, 1998]. Both the velocity of the lava within a lava tube and the dimensions of the lava stream currently cannot be directly measured with the DVLF method so calibration with existing methodologies such as establishing the IER by measurements of velocity and molten flow dimensions at a nearby skylight [*Kauahikaua et al.*, 1998] is necessary.

To be practical, the design of an instrument measuring continuous effusion rates on an active volcano should be low cost so that destruction by lava or longer-term corrosion by magmatic gases and aerosols does not unduly impact a monitoring program budget. Similarly, its power consumption should not exceed a few watts so that it can be easily powered at a remote site for a few days by batteries or for long durations by a combination of batteries plus a small solar panel. With a total cost of US $700 and power consumption 0.9 watts the FDVLF instrument (Figure 2.2) satisfies these requirements.

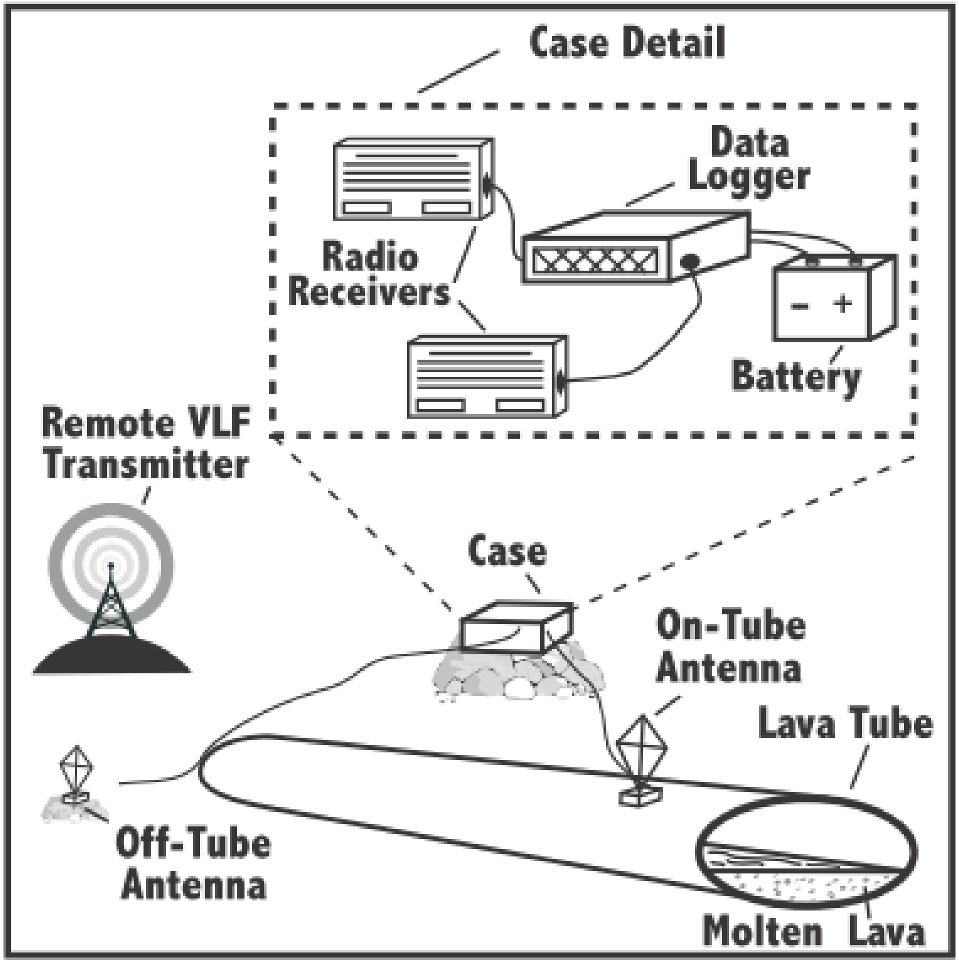

Figure 2.2. Diagram showing the major components of the Freeman Differential VLF instrument. A VLF signal is transmitted from a remote and stationary transmitter. The signal is received by the on- and off-tube receivers and the difference in the received signals reflects the VLF interference by molten lava in the lava tube. Temporal variations in this difference reflect change in the cross-sectional area of lava flowing in the tube, which primarily occurs as the level of lava rises and falls in the tube.

The FDVLF instrument uses a low-cost VLF radio receiver system developed by the UK Radio Astronomy Association (UKRAA). Their device utilizes distant VLF radio signals to monitor solar activity [*UKRAA*, 2010]. UKRAA's VLF receivers detect Sudden Ionospheric Disturbances along the signal propagation path as a proxy for solar weather. The UKRAA VLF receiver system consists of three basic components: a VLF radio receiver, a multi-turn air core loop antenna and an antenna tuning unit (Figure 2.3). The loop antenna responds to the magnetic component of the VLF signal and converts it into a voltage at the antenna terminals. The antenna tuning unit is a combination of fixed and variable capacitors attached directly to the antenna and adjusted to bring the antenna into resonance at the desired frequency, which increases the voltage at the antenna terminals. The UKRAA VLF radio receiver is a single board, highly tunable AM radio receiver which can be connected to an external data logger [*Reeve*, 2010].

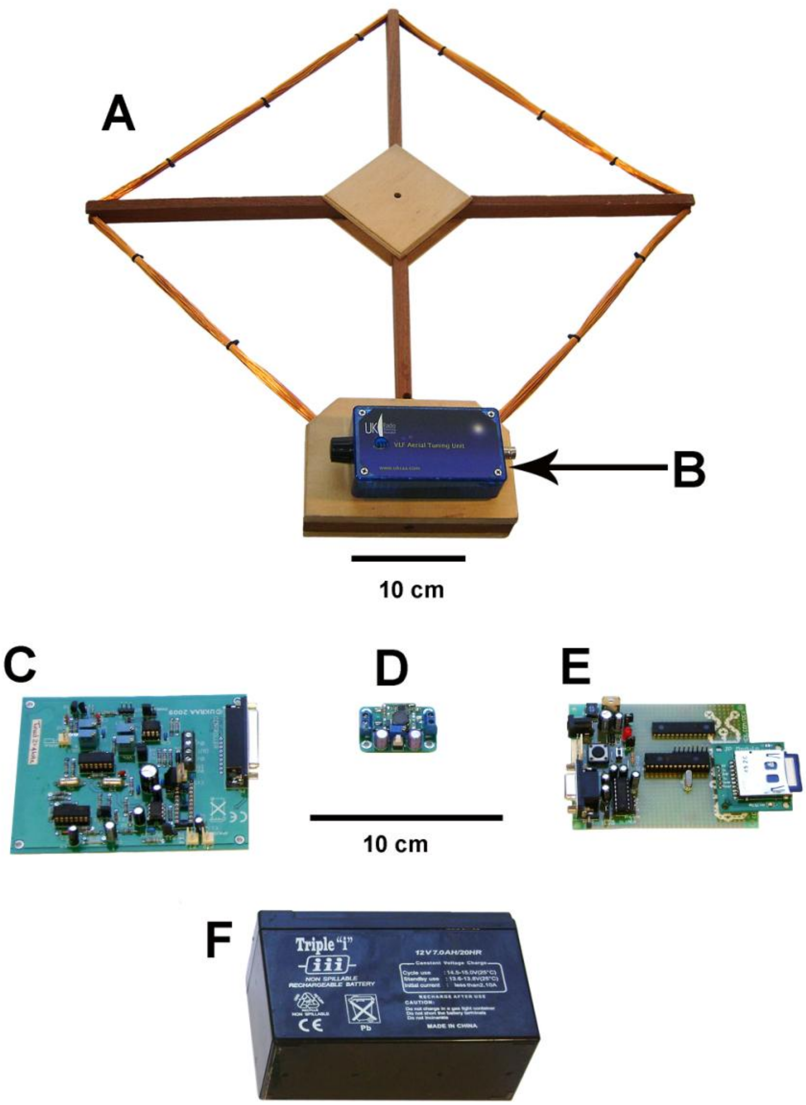

Figure 2.3. The UKRAA VLF Receiver system consisting of a multi-turn loop antenna (A) with Antenna Tuning Unit (B) and VLF Receiver (C), with additional components used in the FDVLF instrument consisting of power supply (D), data logger (E) and battery (F).

The FDVLF instrument combines two of the UKRAA VLF receiver systems with additional components adapted for volcano monitoring. To construct the FDVLF instrument, we assembled a custom data logger that included a 14 bit analog to digital converter with a programmable gain amplifier, a Microchip PIC single chip microcomputer and a non-volatile flash memory card. Power for the instrument is provided by two sealed lead acid 7 amp hour 12 volt batteries and a small, high efficiency, switching power supply. The UKRAA VLF radio receivers, batteries, power supply and data logger were housed inside a watertight protective case manufactured by Pelican™ Products. These were used in combination with the UKRAA multi-turn air-core loop antennas and antenna tuning units to complete the FDVLF instrument.

3.2 Determining Lava Effusion Rates by FDVLF

The IER of lava flowing in a lava tube is the product of the cross-sectional area of the lava flowing in the tube and lava flow velocity. In a stable lava tube the flow velocity can remain relatively constant for months at a time [*Kauahikaua et al.*, 1996]. Flow velocity may change when the flow pauses or surges during large deflation-inflation cycles [*Poland et al.*, 2011]. The IER may also vary in the short-term by temporary interruption of the flow due to collapse of the wall or roof of the tube or by a pulse of lava entering the tube. Sometimes a lava pulse may exceed the tube's lava transfer capacity and result in failure of the roof or levee of the tube and a break-out of lava [*Orr*, 2011].

It should be noted that the VLF signal is influenced by the cross-sectional area occupied by all of the molten lava in the tube. This includes the lava flowing downslope and any molten lava coating the inner walls of the tube −above, below and beside the flowing lava. Figure 2.4 depicts how these coatings form on the ceiling and walls above the flow surface as: a) a veneer of molten, juvenile lava resulting from a surge of lava filling the tube to capacity and then declining or b) previously solidified lava which has re-melted due to exposure to intense heat caused by accumulation of exsolved volcanic gasses and radiative and convective heat transfer from the flowing lava onto the inner walls and ceiling. Furthermore, the coating forms below and beside the flowing lava by conductive heat loss from the molten lava to the colder solidified lava, and occasionally results in thermal and mechanical erosion of the substrate and hence change in slope (see Figure 2.4). See Harris et al. [1998] for a complete discussion of heat loss and heat gain parameters in lava tubes.

The thickness of the molten veneer is unknown, but it is assumed to be considerably less than that of the flowing lava. The thickness and circumference of this veneer influences the cross-sectional area of molten lava available at any one point to influence the received VLF signal. The cross-sectional area of the flowing lava and the veneer is the "wet" area discussed above. The area of the veneer is one source of error in any VLF study of lava flows; however when the flow of lava temporarily ceases as is sometimes observed during large deflation/inflation (DI) events, it is possible to measure the "wet" area of the veneer so that it can be removed from measurements of the flowing lava (Equation 2.1). The veneer would be at a minimum when the lava tube has a slope that drains lava and avoids ponding. Ponding of lavas sometimes occurs in areas of very low to no slope and has been described on the coastal plain of Kīlauea where it is responsible for forming P-type (pipe vesicle bearing) lavas [*Wilmoth and*

Walker, 1993]. In such areas the measured wet area veneer is thicker than on sloping topography because of the thickness of the stagnant, ponded lava. However, even in these conditions, the veneer can be removed from the measurement if the veneer can be measured during a cessation of effusion. Current VLF methods do not consider this veneer because it may account for only a small proportion of the total "wet" cross-sectional area or because of the logistical difficulty in obtaining a VLF survey during the brief and unpredictable period when lava effusion has paused.

$$A_{(\text{flowing lava})} = A_{(\text{total})} - A_{(\text{veneer})} \qquad (2.1)$$

where:
$A_{(\text{flowing lava})}$ is the cross-sectional area of lava flowing within a lava tube.
$A_{(\text{total})}$ is the total cross-sectional area of molten lava measured by VLF.
$A_{(\text{veneer})}$ is the cross-sectional area of molten lava measured during an eruptive pause.

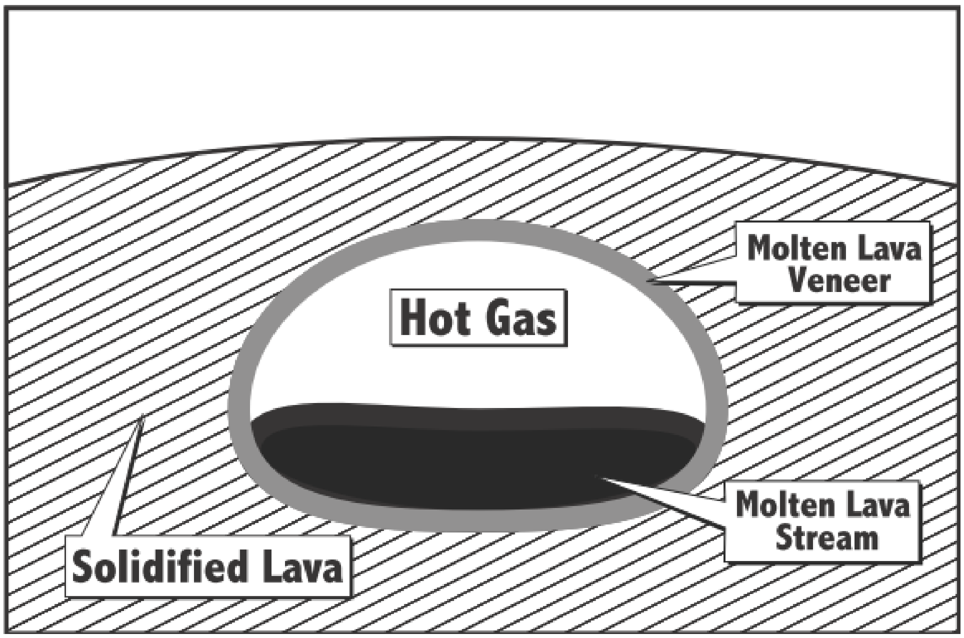

Figure 2.4. Simplified model of a typical basaltic pahoehoe lava tube consisting of gas headspace and a molten veneer of lava around a stream of molten lava which is surrounded by solidified lava. The veneer is often thin to absent on the flow surface. The ceiling commonly displays stalactitic formations so the veneer is in no way of uniform thickness.

The VLF radio signal received at a point along the lava tube varies as a result of changes in the cross-sectional area of molten lava in the tube, which is primarily related to the depth of the lava as a consequence of changing volume flux of lava in the tube. Kauahikaua et al. [1998] compared three lava tube models that related cross-sectional area of a lava stream in a tube to its velocity. They measured lava stream width, depth and velocity at skylights and found that lava velocity varied inconsistently with the depth of the lava stream. They further observed that the use of lava stream velocities measured at skylights is often unreliable and high, because skylights are often found at areas of steep increases in slope, such as when a lava tube flows over a fault escarpment. Even with these limitations, direct measurement is currently the best source of velocity data. Alternately, the mean flow velocity can also be found mathematically. The mean flow velocity (v) for a lava flow is dependent on the lava density, viscosity, channel dimensions and slope and can be calculated using the Jefferys equation for laminar flow [*Jeffreys*, 1925] (Equation 2.2):

$$v = \rho g d^2 \sin\theta / \eta b \tag{2.2}$$

where ρ is lava density, g is acceleration due to gravity, d is depth of the molten lava stream, θ is slope of the stream in degrees, η is the viscosity, and b is a constant (8 for a semi-circular channel and 3 for a broad flow such as a typical lava stream).

While flowing in a stable lava tube, molten lava flowing past any single point along the tube would likely maintain the physical properties of density and viscosity through time. Thus, if the flow velocity changes then the changes in the received VLF signal may still be mathematically related to changes in the IER. For example, an increase in the IER will result in greater flow depth, cross-sectional area of molten lava and velocity, while a decrease in the IER will have the opposite effect.

When the velocity of lava flowing in a lava tube is constant then the effusion rate is directly proportional to the cross-sectional area of molten lava in the tube. If the velocity of lava flowing in a lava tube is not constant or unknown then the velocity is likely a function of the depth of the lava in the lava tube. This depth cannot be estimated based solely on the VLF derived cross-sectional area of molten lava within the lava tube but instead must rely on some form of calibration to establish a width to depth ratio or velocity. The FDVLF method currently relies on the Geonics-EM16 and measurements made at skylights to provide this calibration following the method of Kauahikaua et al. [1996]. With calibration, the effusion rate can be estimated from the cross-sectional conductance measured with our new instrument.

3.3. Field Deployment

Kīlauea has been erupting nearly continuously since 1983 [*Orr et al.*, 2012] with a significant percentage of lava flowing as a stream through a long-lived, master lava tube on the East Rift Zone (ERZ; see Figure 2.1). These tubes witness events such as episodes of inflation and deflation which have become increasingly frequent since March 2008 [*Poland et al.*, 2011] and thus provide an ideal test-bed for an instrument designed to continuously monitor the IER for the purpose of studying events of both short- and long-term temporal duration.

On the afternoon of 10 January 2011, the FDVLF instrument was deployed on an active pahoehoe lava tube of Kīlauea's ERZ 6.0 km southeast of the TEB vent (Figure 2.1) and tuned to radio station NPM Lualualei, Hawai'i, transmitting at 21.4 kHz. Readings were collected every 5 seconds for a total duration of 4.5 hours. The relatively short duration was unintended and due to the failure of one of the instrument's coaxial cables, probably due to a flaw in the wire or thermal expansion in sunlight. The antenna for one of the VLF receivers was placed in a remote area of the lava flow field and directly above an active lava tube. It is referred to as the "on-tube" antenna (see Figure 2.2). The antenna for the second VLF receiver was placed approximately 35 m east of the on-tube antenna (i.e., perpendicular to the tube). This antenna was beyond the edge of the lava tube and is referred to as the "off-tube" antenna. Both antennas were connected to the VLF receivers that were housed in a water tight Pelican™ case with a data logger and power supply.

A VLF transmitter, on strike with the long-axis of the lava tube, will induce a larger secondary VLF signal from the molten lava than one off-strike. The relatively nearby Lualualei VLF transmitter on O'ahu was utilized because it is favorably oriented for investigating lava tubes on Kīlauea's ERZ, including the one measured in this study. While the FDVLF instrument was being deployed, a Geonics EM-16 was used to conduct a VLF survey perpendicular to and across the lava tube from 13:45 to 14:30 Hawai'i Standard Time (HST). Using the methodology of Kauahikaua et al. [1996], the wet cross-sectional area was estimated to be 11.7 m^2. A second EM-16 survey was performed from 15:00 to 15:25 HST and the estimated wet cross-sectional area was found by the EM-16 to have reduced by 5% to 11.1 m^2. This reduction in area established that the lava tube was not completely full when the FDVLF instrument began collecting data and that detectable variations in IER were occurring. The FDVLF instrument was turned on at the approximate midpoint of the second VLF survey (15:12 HST).

4. Results

Data were collected every 5 seconds for 5.0 hours by the receivers connected to both the on-tube and off-tube antennas. To remove high frequency noise typically produced by switching power supplies and the analog to digital process, samples were averaged over 1 minute intervals and shown in Figure 2.5. The output of the instrument was then computed as the normalized difference between the on-tube and off-tube signals as follows:

$$d = (R_{ps}-R_p) / (R_{ps}+R_p) \tag{2.3}$$

where d is the normalized DVLF; R_{ps} is the on-tube receiver, which receives the primary and secondary VLF signals and R_p is the off-tube receiver, which receives only the primary VLF signal.

Figure 2.5 is a plot of the amplitude of the VLF signals received by the FDVLF instrument and the normalized difference between these two signals. A portion of the variation shown in Figure 2.5 can be reasonably attributed to component and adjustment differences in the on-tube and off-tube receivers, temperature drift and errors in the analog to digital conversion process. However, these factors are, in total, very small and unlikely to produce the variations observed. Therefore, the normalized signal in Figure 2.5 is a relative measure of the lava tube "wet area". The slope and cross-section of the lava tube should not vary significantly within a day, so the normalized DVLF signal in Figure 2.5 can also be interpreted as proportional to lava IER. Some of the variations observed in Figure 2.5 have time scales of 5 to 60 minutes and are likely caused by fluctuating volume of lava in the tube. The fluctuations may represent changes in the lava effusion rate at a temporal scale not normally observed in lava tubes, but which are consistent with observations of open channel flow described by Bailey et al. [2006] at Mt. Etna and others.

Data collection began in the early afternoon and the data from the on-tube receiver shows a typical "U" shaped diurnal pattern as the path between the transmitter and receiver nears sunset, which occurred at approximately 18:00 local time. After sunset the received signals are less predictable. Data from the off-tube receiver shows a similar shape; however the slope is less. The normalized differential signal (shown in red) declines slightly between 15:25 and 19:55. Localized minimums of this differential signal can be observed at 17:05, between 17:40-17:55 and 18:35. Corresponding localized differential signal maximums can be observed at 16:35, 17:20 and between 18:12-18:20. These represent cycles with periods of approximately 40 minutes. The observed cyclicity in our VLF data likely reflects changes in the IER. Alternately, the variations in our VLF data may be caused by the formation and clearing of partial blockages of the lava stream by rafted pieces of solidified lava or other phenomena.

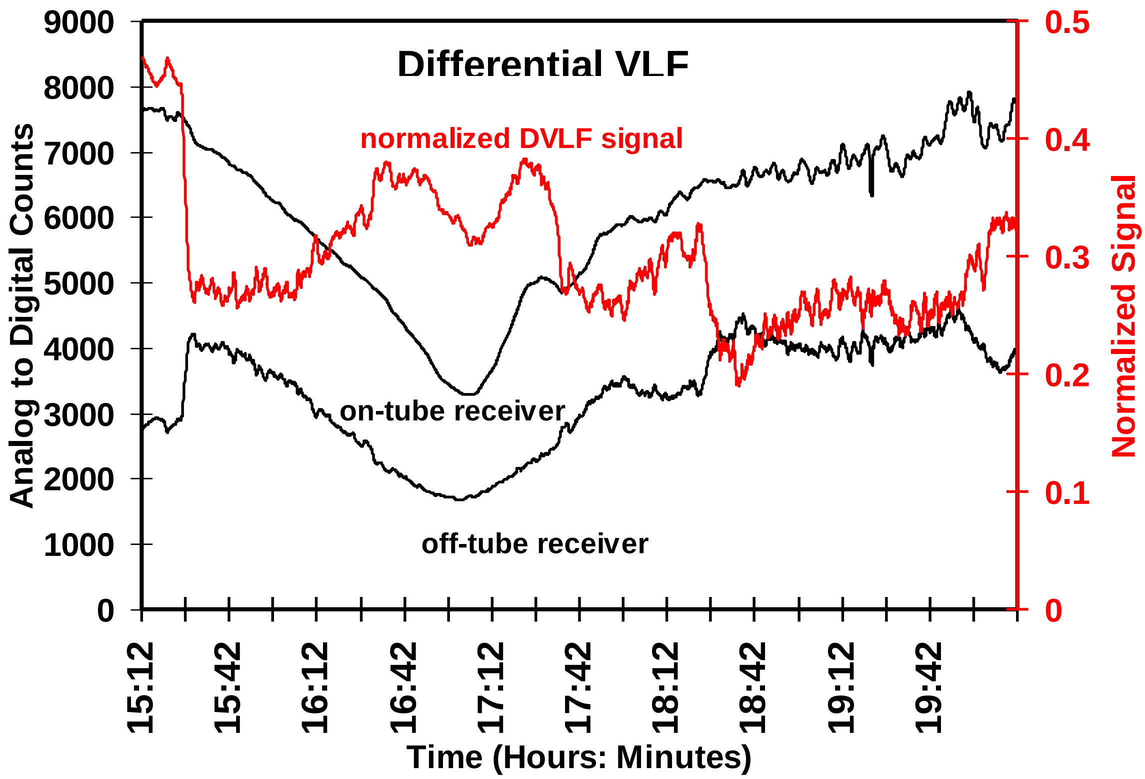

Figure 2.5. Uncalibrated conductance measurement. X-axis is 5 seconds per count. The on-tube receiver is located directly over the tube. The off-tube receiver is located 35 m east of and perpendicular to the lava tube. The “Signal” (in red) is the normalized difference between the signals received by the on-tube and off-tube receivers.

For relatively short time intervals, changes in the differential VLF signal are directly proportional to changes in lava effusion rate and the differential signal shown in Figure 2.5 is thus directly proportional to lava effusion rate. The uncalibrated data shown in Figure 2.5 can be converted into an estimate of effusion rate by first using the cross-sectional area of the molten lava within the lava tube determined by EM-16 survey as an initial starting point. The EM-16 survey data produces a cross-sectional area of 11.1 m^2. A contemporaneous measurement of the lava velocity was not available. However, assuming a velocity for the molten lava equal to that of lava flows in tubes observed at ERZ skylights with similar cross-sectional area and similar ground slope, then an approximate estimate of IER can be calculated by multiplying the cross-sectional area by this velocity. In our case a 3 degree ground slope would suggest a maximum lava flow velocity of 0.6 m sec^{-1} and an average lava flow velocity of 0.3 m sec^{-1}.

To further illustrate the utility of our FDVLF method, we present Pu'u 'Ō'ō tilt data and a running average of the estimated lava effusion rate in Figure 2.6. The running average of lava effusion rate simplifies the identification of localized peaks. The effusion rate shown in Figure 2.6 has a minimum of 1.4 m^3 $sec.^{-1}$, a maximum of 3.3 m^3 $sec.^{-1}$, time averaged rate of 2.1 m^3 $sec.^{-1}$ and standard deviation of 0.39, which are all within the reported range of values for Kīlauea [*Sutton et al.*, 2003]. Five peaks in lava effusion are observed at intervals of approximately 45 minutes, which is on a time scale similar to the gas pistoning observed by Patrick et al. [2011]. Furthermore, the estimated lava effusion rate has a cross correlation with tilt value of -0.55, which suggests a possible relationship between the two.

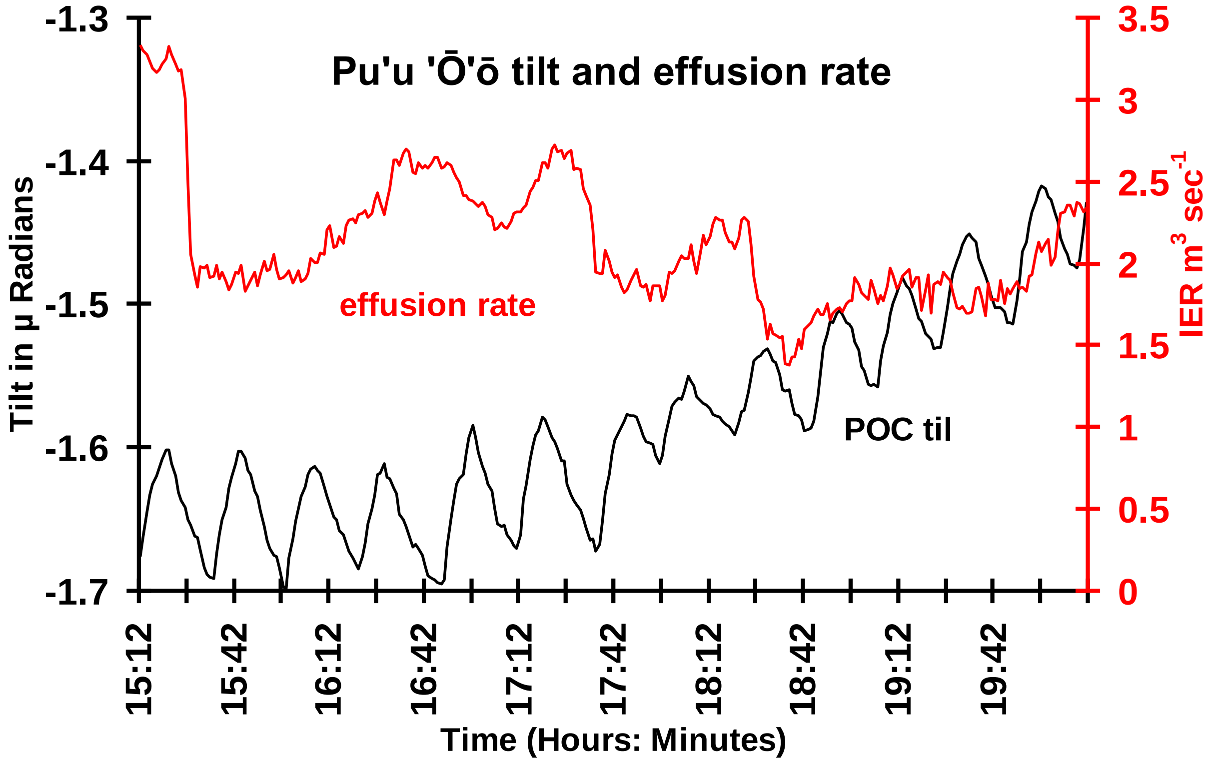

Figure 2.6. Graphs of effusion rate and tilt showing Pu'u 'Ō'ō (POC) tilt (black) as monitored by the Hawaiian Volcano Observatory and estimated lava effusion rate (red) for 300 minutes on the afternoon of 10 January 2011.

5. Discussion

Current methods for measuring lava effusion rates have high errors and measurements are made too infrequently to capture volcano processes with short temporal scales. For example, the work of Sutton et al. [2003] and Kauahikaua et al. [1996] showed that annual estimates of effusive volume using these COSPEC SO_2 profiling and VLF methods disagreed by as much as 85%, and had an average disagreement of 30%. Furthermore, the dynamics of lava flowing in a tube are still not completely understood. For example, molten lava flowing in a channel or partially filled lava tube has been assumed to behave as a Newtonian fluid, yet Kauahikaua et al. [1996] observed lava maintaining near constant velocity, even while the IER and presumed depth of the lava varied. By collecting more measurements of IER and cross-sectional area of flowing lava using the FDVLF method, we hope to improve our understanding of lava flow physics on temporal scales orders of magnitude greater than currently possible and reduce error in estimates of IER. Even in situations where a velocity cannot be measured or calculated, data from the FDVLF instrument will provide an indication of relative changes in effusion rate. Knowing if the effusion rate is waxing, waning or remaining constant over various timescales would be a significant advance in volcano monitoring.

In recent years, the ongoing Kīlauea eruption has been characterized by deflation/inflation (DI) events. These DI events often facilitate or at least coincide with pulses and pauses in the IER along the ERZ and summit. Up rift from our study area on the ERZ and at the summit caldera, Kīlauea began an ongoing eruption in March, 2008. Since then, the number of DI events has increased from 5-10 per year to 50-60 per year [*Poland et al.*, 2011]. We propose that some of the disagreement in estimates of effusive volume is related to the relatively infrequent number of VLF measurements compared to the number of DI events and that this disagreement can be reduced by increasing the number of measurements per year.

During our study many small fluctuations in the differential signal were observed. They started with periods of ca. 10 min., became more frequent throughout the test, and ended with periods of ca. 3 min. We suspect that these fluctuations may represent small slugs of molten lava being added to the lava stream. Our data indicates that variations in IER, with timescales of minutes to tens of minutes, are observable in the lava stream using the low cost FDVLF instrument. Furthermore, if variations in IER with time scales of minutes can be reliably monitored with the FDVLF instrument then multiple FDVLF instruments placed at known intervals along a lava tube may be able to measure the relative arrival times of these variations and allow near real-time accurate determination of the velocity and IER of molten lava flowing in a tube.

6. Conclusion and Future Work

Kīlauea is one of the world's most active and studied volcanoes, yet critical questions remain about shallow and deep geophysical processes linked to variations in magma supply and effusion rate. Continuous, real-time measurement of lava effusion would greatly enhance our interpretation of volcano processes at Kīlauea and elsewhere. Here we demonstrate that the low-cost Freeman Differential VLF (FDVLF) instrument is capable of providing a continuous estimate of the cross-sectional area of a pahoehoe lava tube, which, over short time intervals, is a function of instantaneous effusion rate (IER). Further, we demonstrate how the low cost FDVLF instrument can measure small changes in the flow of lava in a tube on time scales covering over three orders of magnitude. While we cannot conclusively demonstrate that the observed changes are correlated with magma supply to the surface, this study indicates a need to collect data over longer durations to encompass events associated with gas emissions (measured by COSPEC) or ground deformation (measured by tilt) or seismicity.

The short duration of time over which these data were collected is a major limitation to conclusively establishing a connection between the received VLF signal and known volcano processes with long duration from days to months, such as periods of deflation and inflation (DI events). We are currently developing a more robust power supply to test the FDVLF over longer time periods that would capture DI events recorded by multiple instruments (e.g., SO^2, tilt, strain, EM-16, etc). While the EM-16 survey provided a useful calibration for the FDVLF method described here, Stanford University has developed a research-quality, broad band, extremely low frequency/very low frequency (ELF/VLF) receiver known as the Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) receiver [*Cohen et al.*, 2010]. This receiver has several features which will aid further investigation of lava streams in tubes at Kīlauea. The AWESOME instrument has a mature, reliable design, 16-bit sensitivity, selectable gain and filtering options, and an extremely accurate time stamp for collected data derived from an internal GPS receiver. It has up to three independent loop antennas, each with the ability to simultaneously monitor the amplitude and phase of the magnetic signal component from multiple VLF transmitters (from US and international military sites). Side-by-side comparison of the AWESOME and FDVLF instruments requires a robust solar power source for remote field deployment. We envision a second generation FDVLF instrument that will include a third receiver with an antenna placed above the lava tube and up-flow from the on-tube antenna to calculate velocity. We will also investigate how the off-tube antenna and receiver might be eliminated from the FDVLF instrument and replaced with data from a remote VLF monitoring station which would simplify the deployment and reduce the power consumption of the FDVLF instrument.

A Stanford ELF/VLF receiver was placed in an HVO underground instrumentation vault at Kīlauea's summit and powered by utility mains to collect baseline data in early 2013. The Stanford ELF/VLF receiver was designed to use a desktop personal computer as the supervisory and data logging element and uses utility mains as a power source. We are modifying and repackaging a second Stanford ELF/VLF instrument for outdoor deployment and plan to test it side-by-side with a FDVLF, with both initially connected to a utility main. If successful, the instruments would then be deployed in the field with their power supply modified for battery/solar panel operation. The Stanford ELF/VLF receiver, modified for field deployment on Kīlauea's remote ERZ, would cost approximately US $6000. Its power requirements are approximately 70 W, which is significantly more than the 0.9 W required by the FDVLFR and near the practical limit of solar powered volcano monitoring instruments. We plan to place this second Stanford ELF/VLF receiver, with two antennas, above an active lava tube on Kīlauea's ERZ in tandem with a FDVLF receiver, as part of a dedicated campaign to characterize the secondary VLF signal from a lava stream within a tube and calibrate the FDVLF. Frequent estimates of IER would be made over multiple DI cycles using EM-16 surveys, COSPEC plume measurements and a time lapse camera located at a skylight near the VLF radio receivers. The data collected as part of this study would be combined with other data sets routinely collected by HVO, such as seismicity and tilt, in order to understand our observations in the context of Kīlauea's ongoing eruption. Until then, our current data suggest that the FDVLF receiver is capable of detecting changes in cyclicity of IER over several orders of magnitude of time and hence is a strong candidate for providing continuous, real-time observations of IER that will provide new insight into deep and shallow volcanic processes at Kīlauea.

Acknowledgments Data supporting Figure 2.5 is available upon request from the authors.

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CHAPTER 3

DISCUSSION AND CONCLUSIONS

Introduction

This section provides a detailed discussion of the components of the Freeman Differential Very Low Frequency (FDVLF) instrument. The section begins with a discussion of the Antenna and Antenna Tuning Unit and is followed by discussions of: Antenna Position, Battery, Power Supply, UKRAA Receiver, Data Logger, Packaging, Design Limitations, and Coaxial Cables. This is followed by a discussion of other monitoring capabilities for estimating effusion rates of basaltic volcanism. The chapter closes with a discussion of the applicability of the FDVLF Method and conclusions.

Design of the Freeman DVLF Instrument

Antenna and Antenna Tuning Unit

Electromagnetic radiation radiating from a vertically polarized transmitting antenna propagates with a vertical electric field and a horizontal magnetic field. In order to receive the magnetic component of the transmitted signal it is necessary to use an antenna that is sensitive to magnetic fields. The 2 common options for this purpose are air core loop antennas and ferrite core antennas, both of which feature a coil of copper wire to convert the magnetic signal into a voltage signal (Voogt n.d.). For the air core loop antenna, sensitivity is based on the number of turns of wire in the coil and the area enclosed by the coil. They are thus relatively large with many turns of wire in their coil. In contrast, the ferrite core antenna, also referred to as a ferrite rod antenna, is a coil of copper wire wound around a magnetic core with high permeability such as an iron ferrite. The ferrite core raises the radiation resistance of the antenna and, hence, reduces the loss of signal due to the resistance of the copper wire. The ferrite core antenna has greater antenna quality (Q) and can be made much smaller than an air core antenna. The magnetic domains within the ferrite must reverse polarity each half cycle as the received magnetic signal reverses each half cycle. Reversing the domains absorbs a portion of the received signal and represents a loss of efficiency and reduction in signal-to-noise ratio that increases with the frequency of the received signal. In spite of its lower efficiency, the ferrite core antenna has been adopted for modern amplitude modulation (AM) portable radio receivers. Ultimately it may be possible to construct a FDVLF instrument with ferrite core antennas; however, at the current time we are using the more efficient air core loop antenna in order to maximize the signal-to-noise ratio.

The VLF signal propagates as a continuously varying sine wave. This ever-changing magnetic component of the VLF signal produces a small electrical current in the coil of the air core antenna, which produces a small voltage at the antenna terminals. This small voltage can be increased either by increasing the number of turns of wire used in the antenna coil or by increasing the area enclosed by the antenna coil. In general, the performance of the antenna is improved more by increasing the area enclosed by the antenna coil than by increasing the number of turns. The resistance of the wire forming the antenna's coil acts to reduce the voltage at the antenna terminals. To increase the voltage at the antenna terminals, the resistance of the antenna can be decreased by using larger diameter wire (wire with smaller gauge number). The inductance and capacitance of the antenna act to form an electrical circuit that resonates when receiving a narrow range of frequencies. When receiving radio signals at the resonant frequency, the antenna produces a significantly higher voltage at its terminals. The antenna can be tuned to resonate at a frequency lower than its initial resonate frequency by connecting external capacitors or additional wire to the antenna. The antenna tuning unit is a combination of fixed and variable capacitors attached directly to the antenna and adjusted to bring the antenna into resonance at the desired frequency and increase the voltage at the antenna terminals by a factor of 10 to 100. This tuning process has the goal of creating an antenna that produces a peak voltage at the same frequency as the remote VLF transmitter.

Reeve (2010) described the UKRAA antenna (Figure 2.3) as a square antenna with 0.4 m sides and constructed with 125 turns of 24 gauge magnet wire. The antenna has 17 ohms of resistance, an inductance of 22.5 mH and a self-resonant frequency of 52.2 kHz. The Antenna Tuning Unit shown in Figure 2.3 can be used to tune the antenna to a frequency less than this self-resonant frequency.

Antenna Positioning

Two air core loop antennas are deployed in the field in a vertical orientation where the plane of the antenna coil is perpendicular to the plane of the Earth's surface. The antennas are rotated so that the plane of the antenna coils is pointed at the remote VLF transmitter. This places the antenna coils perpendicular to the magnetic component of the VLF signal. Ideally, the lava tube is also oriented in the direction of the remote VLF transmitter so that the lines of force of the transmitted VLF signal will cut the electrically conducting molten lava in the lava tube and a maximum strength secondary signal will be produced. If the orientation of the lava tube is not in-line, or along strike, with the propagating VLF signal then care should be taken to identify a section of the tube that is most in-line with the VLF signal. If possible, the antennas should be located well away from interference produced by electrically conducting objects such as power lines, fences, and piping (whether buried or exposed) as these objects also produce strong secondary magnetic signals. In terms of placement of the on- and off-tube antennas, the on-tube antenna is placed directly above the lava tube because at this location the secondary VLF signal is horizontal and optimally oriented for reception by the loop antenna. The off-tube antenna is placed a short distance away from the lava tube (25 to 100 m) so that the antenna is beyond the influence of the secondary signal from the molten lava. A VLF survey with a Geonics EM-16 can be conducted as part of the process. The survey would locate buried fences or other man-made sources of interference as well as establish the minimum distance from the lava tube for locating the off-tube antenna.

Battery

The battery shown in Figure 2.3 is a deep-cycle, sealed, lead-acid battery that uses a gelled electrolyte and is rated at 7 amp-hours (Ah) at 12 V. Weighing 2.10 kg, this battery provides 40 watt hours per kilogram (Wh/kg). Lead-acid batteries are used extensively in volcano monitoring because they are sturdy, inexpensive, easy to recharge, and available in a wide range of sizes. When compared to other battery chemistries, the lead-acid battery has a low energy to volume ratio and, of greater concern, a low energy to weight ratio. If the weight of the required lead-acid battery is unacceptable, the designer should consider a nickel-metal hydride battery (95 Wh/kg) or the more difficult to recharge lithium-ion battery (128 Wh/kg).

In a remote setting, deep-cycle lead acid batteries are connected to a solar panel and battery charging unit so that they can be used to power experiments indefinitely. Repeatedly discharging lead-acid batteries beyond 50% of their rated capacity can significantly reduce their lifespan. Batteries and solar panels are routinely sized so that the batteries are not normally discharged beyond 50% level, even during extended periods of cloudy weather or volcanic plumes. Battery charging units are available that will automatically power down an experiment when the battery charge level drops below 50%, but this means the experiment will not operate and no data will be collected. If the experiment and data collection are of a critical nature, a battery charging unit can be selected that will allow the batteries to discharge completely. This may shorten the lifespan of the batteries but it increases the probability that power will be available for a high priority experiment even in the presence of extended cloudy weather or the failure of the solar panel.

Power Supply

Batteries are available in a variety of voltages. The nominal output voltage of lead-acid batteries typically used in volcano monitoring is 12 volts. Depending on a battery's state of charge, this voltage may vary from 11.5 to 13.8 volts. A power supply is used to convert this unregulated battery voltage into a precise and consistent voltage to power an experiment.

Power supplies are of 2 basic designs. The linear power supply uses a voltage regulator circuit to reduce the input voltage to a desired voltage by dissipating excess energy as heat.

Linear power supplies have typical efficiencies of 40 to 60%. The second design is the switching power supply in which high frequency on-off switches (transistors) and energy storage devices (inductors and capacitors) "chop" the input voltage down to the desired voltage. When operating at their rated capacities, switching power supplies have efficiencies greater than 92%. This efficiency is reduced if the switching power supply is operated with a connected load smaller than its rated capacity; so the switching power supply should be sized to closely match its connected load. Switching power supplies, such as the one connected to the Freeman DVLF instrument (shown in Figure 2.3) or the one within a battery charging unit, emit electromagnetic interference. A combination of inductors, capacitors, and ferrite beads can be used to filter out this interference.

The FDVLF instrument was deployed without solar panels or a battery charging unit, so a switching power supply was selected to extend the hours of operation from the two lead-acid batteries. The two 12 V, 7.0 Ah deep cycle lead acid batteries were wired in series to produce a 24 V, 7.0 Ah power source. This voltage was necessary because the UKRAA VLF receiver (shown in Figure 2.3) has a power input requirement of 15 V. This 24 V, 7.0 Ah power source was sufficient for a brief deployment of up to 72 hours.

UKRAA Receiver

The UKRAA VLF radio receiver is a highly tunable amplitude modulation (AM) radio receiver that operates in a frequency range of 10-35 kHz. The small signal from the antenna is initially amplified and then sent through a bandpass filter to remove unwanted frequencies. The signal continues on through another amplifier and then into an envelope detector. The envelope detector converts the high frequency, alternating current radio signal into a low frequency, direct current radio signal. Finally this signal is smoothed and buffered to produce an output signal. The output signal is available in a voltage range of 0 to 5 V or 0 to 2.5 V in order to simplify connection to a data logger.

The UKRAA VLF receiver includes a temperature sensor and provision to install a Maxim MAX186 low resolution 12-bit analog to digital converter. These provisions allow the UKRAA receiver to be connected to a computer printer port so that the computer can be used as the data logging device. The difference between the signal received by the on-tube receiver and the off-tube receiver is small so a resolution greater than 12 bits is required. Also, the FDVLF instrument does not require a measure of ambient temperature. The FDVLF instrument does not use the temperature sensor or the 12-bit analog to digital converter option of the UKRAA receiver; however, these 2 capabilities are available if needed.

Datalogger

The data logger acquires and stores voltage readings from the 2 VLF receivers at programmed time intervals. High-performance commercial data loggers are readily available; however, they are expensive and could easily double or triple the cost of the FDVLF instrument. A custom data logger was assembled from off-the-shelf subsystems. The data logger consists of 4 components; a control microcomputer, analog to digital converter, SD memory card controller, and software to control the data logging process.

The control microcomputer was an Olimex PIC-P28-20MHz circuit board with a Microchip PIC18F2553 single-chip microprocessor. The Olimex circuit board has all of the circuitry necessary to power and download software to the single-chip microprocessor. The microprocessor is a 12 million instructions per second computer with 32 Kb of program storage and 2 Kb of data memory as well as a number of input and output peripherals. Among the peripherals is a 10-channel, 12-bit analog to digital converter that could be used as the input device for a low resolution data logger. Initial testing of the FDVLF instrument revealed that the 12 bit analog to digital converter did not provide sufficient resolution, so a separate 14-bit analog to digital converter chip was added to the design.

The analog to digital converter for the data logger is the FLEXEL-1 chip manufactured by Integrated Micro Systems LLC. This chip retails for less than $10 and features a 4-channel 14-bit analog to digital converter with programmable gain amplifier. The programmable gain amplifier performed poorly during testing and was not used. The chip's default configuration with a 14 bit analog to digital converter was sufficient for the FDVLF instrument.

The JP Module, manufactured by Jianping Electronics, was selected as the SD memory card controller. The JP Module is a MMC/SD card controller that can read and write Microsoft Windows compatible files to flash memory cards. The JP Module uses the FAT-16 file system which limits the flash memory card size to 2 gigabytes. A 2 GB flash memory card would provide about 5 years of data storage for the FDVLF instrument, which is much more than adequate for this type of study.

The control software for the data logger was written using the C programming language and the Microchip MPLAB® Integrated Development Environment (IDE). MPLAB® IDE is a software program that runs on a Windows® PC used to develop applications for Microchip single-chip microprocessors.

The control software performs several tasks. When power is applied to the FDVLF instrument, the control software first initializes the microprocessor, FLEXEL-1 chip and the JP Module. A Windows compatible file is then created on the JP Module. Every 5 seconds the FLEXEL-1 chip is commanded to read the 2 analog to digital channels connected to the 2 UKRAA VLF receivers. The analog to digital readings are then sent to the JP Module where they are written to the Windows© compatible file in a format easily imported into Microsoft Excel©. Data acquisition and logging continues until power is removed from the instrument.

Packaging

Assembling the FDVLF instrument involves placing two UKRAA VLF receivers, 2 batteries, a power supply and a data logger inside a Pelican^{tm} brand watertight plastic case. Pelican cases feature an "O"-ring gasket around their hinged lid and are commonly used to house instrumentation in harsh environments such as Kīlauea. Belden P-235 coaxial cables connect the 2 VLF receivers to the Antenna Tuning Units at the 2 antennas via a hole drilled in the side of the Pelican^{tm} case. The opening around the coaxial cables was temporarily sealed with foil tape placed on the outside and the inside of the case. Preferably a permanent connection should be fashioned using epoxy cement around the cables entering the case or a high reliability military grade connector could be mounted through the case.

Design Limitations

The FDVLF instrument was constructed as a proof-of-concept device to demonstrate the capability of differential VLF. Some engineering trade-offs were made in order to build the unit in a timely fashion with a modest budget. Testing and initial field deployment of the instrument revealed that refinements to the design are desirable. Also, new components are now available that would improve the instrument's performance.

Power Consumption

Power consumption is a critical specification for the components of any battery-powered instrument. Low power consumption is desirable because it allows batteries and solar panels to be smaller and less intrusive in the environment, lighter, more transportable, and less expensive. Because the experiment was conducted in Hawai‘i Volcano National Park and equipment was flown in by helicopter, it was necessary to keep equipment small to avoid aesthetic issues with the National Park Service and lightweight to keep transportation costs low.

The UKRAA VLF receiver was designed to be powered by utility mains and hence does not contain any of the design choices that would have been incorporated into a battery powered receiver. In particular, the receiver uses 2 small linear power supplies to produce voltages used within the receiver. Although these receivers were purchased preassembled, they are also available for purchase as a kit. When constructing the receiver from a kit, it would be simple to substitute a more efficient switching power supply for the linear power supplies. The input voltage could also be modified so that a 12 volt power source could be used.

Likewise, the Olimex circuit board used to construct the data logger also uses a small linear power supply to produce the power used by the Microchip microprocessor. This power supply could also be replaced with a high efficiency switching power supply. The software could also be modified to place the microcomputer into a sleep mode between data samples to reduce power consumption. Sample collection is currently controlled by a software clock within the microprocessor. A software clock is not precise and might gain or lose as much as a minute per day. A better option would be to use a dedicated clock-calendar chip with battery backup. If extremely precise timing was desired, a low-power GPS module could be added to the data logger.

The FLEXEL-1 chip and the JP Module do not have low-power standby modes, and for simplicity no attempt was made to use the low-power options available on the PIC microcomputer. Commercial data loggers normally enter a low-power standby mode between samples so that their average power consumption is only a few milliwatts.

The OpenLog SD memory card controller manufactured by Sparkfun Electronics could be substituted for the JP Module with a resulting power savings of 80%. The OpenLog unit also features an automatic idle mode that further reduces its power consumption.

The FLEXEL-1 chip with its 14-bit analog to digital converter can be replaced with 2 Linear Technology LTC2400 24-bit analog to digital converter modules. Two of these modules have a combined power consumption that is 95% less than the FLEXEL-1 chip and would provide 10 additional bits of analog to digital resolution. These modules are designed for precise analog to digital sampling and are far more noise immune than the hand wired construction of the current data logger.

Once the changes described above have been made to reduce power consumption, the data logger used within the FDVLF instrument would be a key component in other low cost volcano monitoring instrumentation such as a thermocouple based temperature logger for volcanic fumaroles. The construction of a data logger from prefabricated subassemblies is relatively straightforward, but it may be beyond the capabilities of some researchers because geoscientists may lack the engineering background necessary to evaluate and select the components or write the software to control the components. In cases where researchers do not have the necessary skills, they should consider purchasing a preassembled high resolution battery powered data logger.

Coaxial Cables

Care should be taken in the selection of coaxial cables. One of the initial Belden coaxial cables connected to the 2 VLF receivers failed within a few hours of field deployment in our experiment. The copper wire within the cable separated and became electrically "open" about 2 m from the Pelican case. The copper wire may have contained a flaw that failed when the cable was subjected to thermal expansion and contraction in the afternoon and evening of the deployment. No useful data were collected after this failure, which effectively ended our field testing. Only the most rugged coaxial cables should be used in the harsh volcano environment.

Reducing EM Interference

Significant electromagnetic interference was observed in the prototype FDVLF instrument. Several simple steps could be taken to reduce this "electronic noise". The 2 VLF receivers were mounted side by side with the other electronics inside the Pelican case. Each of the 2 UKRAA VLF receivers could be wrapped in aluminum foil or mounted inside its own metal enclosure to protect it from electromagnetic interference. Reducing the power consumption of the various components comprising the FDVLF instrument will have the dual purpose of increasing the number of hours of battery operation and reducing the electromagnetic interference from those components.

Cost

The FDVLF instrument was constructed for a cost of approximately $700. This price compares very favorably with an alternate instrument such as a ultra-violet sensitive camera system to monitor SO_2 emissions, which might cost $12,000 and only operate in daylight hours. The changes envisioned would not change the price of the FDVLF instrument by more than $100. So a final version of the FDVLF instrument will be a relatively inexpensive volcano monitoring instrument.

Measures of Eruption Rate

Conceptually, the most straightforward way of measuring IER would seem to include sending a single geologist into the field to make a direct measurement of the quantity of lava flowing from a volcano. This prospect remains tenuous at best because lava may be emplaced on or intruded into vast areas of a volcano measuring tens of thousands of square meters. Notwithstanding these limitations, once a reliable method was identified, the procedure could be repeated anytime there was a need to measure the effusion rate and, by extension, one might envision a legion of geologists continuously making observations of how much lava is erupting from the volcano. In reality, nothing approaching this is possible. To begin with, traveling to the volcano may only be possible during daylight hours and many of the observations are only possible during daylight. At times the volcano may be off limits because of safety concerns and finally the logistics and expense of placing a team of geologists in the field for an extended period of time would in most cases be cost prohibitive.

Satellite Remote Sensing

Geostationary satellites maintain a constant position relative to the Earth and would be a reasonable choice for an instrument to continuously monitor a volcano (Wooster and Kaneko 1998). Current geostationary satellites do not provide coverage of Polar Regions and their sensors cannot resolve objects smaller than several thousand square meters. This resolution is insufficient for monitoring the IER of a basaltic volcano because there may be tens to hundreds of small flow features too small to be resolved, thus underestimating the IER. In contrast, sensors mounted on low earth orbiting (LEO) satellites can resolve objects smaller than 1 square meter but they have revisit intervals that are typically 2 to 10 days (Schowengerdt 2006). This is too long for monitoring IER. Furthermore, cloud, vegetation, and other ground cover as well as precipitation will limit the effectiveness of space-based sensors. In summary, satellites will continue to provide long-term volcano monitoring at temporal resolutions of days or months but they will have little application in measuring IER for the foreseeable future.

Cameras

Cameras that are sensitive to the electromagnetic spectrum from the infrared to the ultraviolet are available. Some cameras can capture images at speeds in excess of 100 frames per second and, with an intervalometer, lower speed photography such as one frame per second or one frame per week is possible. Photography is a widely employed tool for volcano monitoring and in certain situations can be used to monitor IER (Harris et al. 2007).

Recently emplaced lava provides a convenient thermal signature for tracking lava with infrared photography. Considerable research has focused on converting changes in the infrared image of a volcano into time averaged effusion rates (Harris et al. 2005). The subject is complex and the results debatable (Dragoni and Tallarico 2009); but at this time no reliable method for obtaining continuous measurements of IER from infrared imagery has been demonstrated.

Photography using the visible spectrum can be used to monitor flowing lava during daylight hours and obtain estimates of IER. Field measurements are normally required to calibrate size of objects within the images. Measurements are then extracted from the images by hand and an IER computed. Use of this methodology is not common because all the prerequisite requirements are seldom found together. Also, a lack of automation in the image analysis process limits the usefulness of this strategy.

Regardless of the type of monitoring camera, they all have the same disadvantages in environments typical of volcanoes. For example, their performance may be reduced by dynamic weather conditions such as rain, fog, or fumaroles. Moreover, volcanic gases, aerosols, and ash fall from plumes or fountains are moderately to highly corrosive and abrasive.

Acquiring ultraviolet images is a special case of daylight photography that is particularly useful in volcano monitoring. Sulfur dioxide absorbs ultraviolet light and images of a volcano's plume can be calibrated to measure SO_2 emissions in tonnes per day. Research using COSPEC has demonstrated a relationship between SO_2 emissions and the time averaged discharge rate of lava (Sutton et al. 2003). Magma and lava degassing are the source of SO_2 at a volcano

(Symonds et al. 1994). Some magma may be stored in the shallow plumbing system of the volcano where it might degas and never erupt. Likewise, previously degassed magma might eventually erupt without releasing additional SO_2. Thus, SO_2 emissions can overestimate or underestimate lava emplacement (Sutton et al. 2003) and, until this can be understood and accounted for, there seems little point in attempting to use SO_2 emissions to estimate IER. So far, no attempt has been made to measure or interpret SO_2 emissions on the temporal scale needed to estimate IER.

Freeman DVLF Method

The VLF method is a remote sensing technique that uses a multipoint survey to map subsurface electrical conductors (Paterson and Ronka 1971). Volcanologists have used the VLF method to estimate the cross-sectional area of a stream of molten lava flowing in a lava tube (Jackson et al. 1988). If the velocity of the stream can be directly measured or estimated from existing equations, it is possible to compute the IER (Kauahikaua et al. 1996). The technique is applicable to the relatively small number of volcanic eruptions that form lava tubes such as the ongoing eruption at Kīlauea. As the cross-sectional area of molten lava in a lava stream varies, the measurements made in the VLF survey also vary. Instead of making a series of low resolution measurements of the magnetic component of the VLF signal along the survey line, the FDVLF instrument measures the magnetic component of the VLF signal at a single point with very high resolution. The single point used by the FDVLF instrument is directly above the lava tube where the magnetic component of the VLF field contributed by the molten lava is horizontal and easily received by the instrument's vertical antenna.

To illustrate the FDVLF method, consider the simple case of a lava tube with rectangular cross-section. Changes in the cross-sectional area of the molten lava stream in the lava tube must include a change in depth of flowing lava. The measurement made by the FDVLF instrument will therefore vary as a function of the depth of the molten lava stream. From Jeffreys's equation ($v = \rho g d^2 \sin\theta / \eta b$) it is clear that d is the only variable likely to change on time scales of seconds to minutes (and possibly days to weeks). At those timescales the velocity of the stream will vary with the square of the depth. And because the effusion rate is the product of the width, depth, and velocity of the stream then the effusion rate must vary as a function of the cube of the measurement from the FDVLF instrument. A lava tube must have finite width, so the previous argument that relates effusion rate to the cube of the measurement from the FDVLF instrument will hold for lava tubes of any geometry. Even in situations where a velocity cannot be measured or calculated, data from the FDVLF instrument will tell researchers if the effusion rate is waxing, waning, or remaining constant. This is an important scientific result in itself.

Data shown in Figure 2.6 suggest that variations in IER, with timescales of minutes to tens of minutes, are observable in the lava stream using the low cost FDVLF instrument. Furthermore, if variations in IER with time scales of minutes can be reliably monitored with the FDVLF instrument, multiple FDVLF instruments placed at known intervals along a lava tube may be able to measure the relative arrival times of these variations and allow near real-time accurate determination of the velocity and IER of molten lava flowing in a tube. Alternatively, another method of obtaining the lava flow velocity would be a second generation FDVLF instrument with a third receiver and antenna. The third antenna would be placed above the lava tube and up-flow from the on-tube antenna. The off-tube antenna and receiver might be eliminated from the second generation FDVLF instrument and replaced with data from a remote VLF monitoring station that would simplify the deployment and reduce the power consumption of the FDVLF instrument.

Conclusions

Kīlauea is one of the world's most active and studied volcanoes, yet critical questions remain about shallow and deep geophysical processes linked to variations in magma supply and effusion rate. Continuous, real-time measurement of lava effusion would greatly enhance our interpretation of volcano processes at Kīlauea and elsewhere. Any method for the long-term monitoring of IER that involves the continuous activity of a researcher is simply not practical. Satellites cannot measure features small enough or frequently enough to monitor IER and camera systems are normally useful only during daylight hours and their performance may be reduced by weather or volcanic emissions.

This project demonstrated that the low-cost FDVLF instrument is capable of providing a continuous to nearly continuous estimate (we sampled at 5 sec intervals) of the cross-sectional area of a pahoehoe lava tube. Over short time intervals this is a function of IER. Further, we demonstrated how the low cost FDVLF instrument can measure changes in the flow of lava in a tube on time scales covering over 3 orders of magnitude. Our data indicate cyclic changes in IER that appear to cross correlate with changes in volcanic tilt. An overall decrease in IER was observed in our data that is in agreement with the observed behavior of Kīlauea Volcano during the time of our field deployment.

While we cannot conclusively demonstrate that the observed changes are correlated with magma supply to the surface (they could be caused by conditions of supply within the shallow conduit, vent, or tube), the data suggest a need to collect data over longer durations to encompass events associated with gas emissions (measured by COSPEC) or ground deformation (measured by tilt) or seismicity (measured by an array of seismometers). Ideally, the next test would be of a second generation FDVLF instrument capable of measuring velocity and would continue through several deflation/inflation (DI) events at Kīlauea, which have occurred with increasing frequency in recent years.

The short duration of time during which these data were collected is a major limitation to conclusively establishing a connection between the received VLF signal and known volcano processes, such as the periods of DI events. Notwithstanding this, data from our 5-hour test suggest that the FDVLF receiver is capable of detecting changes in cyclicity of IER over several orders of magnitude of time and hence is a strong candidate for providing continuous, real-time observations of IER that will provide new insight into deep and shallow volcanic processes at Kīlauea.

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