Veðurstofa Íslands

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A new early-warning software, Tremv-ALERT, has been created to detect volcanic tremor at the onset of an eruption and trigger an audio warning. The module works in real-time and detects signal characteristics similar to previously observed eruptions using a three-fold detection procedure based on: 1) an amplitude threshold; 2) the signal-to-noise ratio; and 3) an emergent ramp-like shape. Data from six Icelandic eruptions was used to assess and tune the module, which can provide 10–15 minutes of warning for Hekla up to over two hours of warning for some other eruptions, depending on the sensitivity of the network, parameterization, and recent pattern of seismic activity. This software is a new module for Tremv, a program created by the same team in 2020 to calculate and plot RSAM data for real-time tremor and volcano monitoring. Additionally, improvements that increase accessibility and functionality were made to the Tremv-program itself this summer.

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Contents

1 Introduction

Responsive and reliable volcano monitoring agencies are crucial for the national security of volcanically active countries. In Iceland alone, eruptions occur with an average frequency of four years, and some of these eruptions occur at highly active, dangerous, and explosive volcanoes and in close proximity to infrastructure. The Icelandic Meteorological Office (IMO) monitors all natural hazards in Iceland and has the responsibility of issuing warnings and forecasting impending dangers, when possible. There is a constant stream of real-time seismic data coming into the monitoring office from over 80 seismometers located around the country, allowing the IMO to monitor over 30 active volcanic systems in Iceland as well as two major seismic fault zones. With the presence of so many active volcanic threats, effective monitoring and warning systems are essential.

Plots of Real-time Seismic Amplitude Measurement (RSAM) data are one of the most ***important*** tools utilized in volcano observatories worldwide. The IMO's monitoring office is no exception, as this type of real-time data shows mid- to long-term trends, which is especially important for monitoring active volcanic systems. The RSAM methodology was developed by the USGS in 1989 (Murray & Endo, 1989) to plot averaged amplitude values in near real-time instead of being tied to data-dense, highly-sampled traditional seismograms. While having high resolution data can be advantageous for identifying the sharp onset of individual earthquake events, simplifying data is often more helpful when it comes to recognizing more long-term trends, including volcanic tremor. A light data format is ideal for plotting long time series, allowing visualization of long-term changes that are not obvious on traditional heavy data streams, which usually only plot the most recent minutes or hours of data (see Figure 1). With RSAM, longer duration of tremor can be quickly and easily visualized, improving the capability of monitoring more gradual earth processes, including changes in the seismic wave amplitude and frequency that can give notice of e.g. an impending eruption.

Last summer, 2020, the Tremor Viewer (Tremv) was created by the same team as this project to replace the outdated RSAM processing software at the IMO. As far as we understand, this is the first time an RSAM, python-based software is made ***open access***. The software is available at github (http//:github.com/tremv) and facilitates the plotting of easily-visualized long time series seismic tremor data by using real-time streaming of waveform data and plotting its RSAM values. The "Tremor Viewer" Tremv is a modular software that processes and plots 24 hours RSAM data in real time, providing an easily interpreted overview of the current tremor activity within a region. Tremv was nominated to the 2020 President Award.

Different types of tremor vibrate the earth with different frequencies, so bandpass filters can be applied to RSAM data to enhance the signal from different tremor sources. The IMO's displays RSAM data within the frequency bands 0.5–1.0 Hz, 1.0-2.0 Hz, and 2.0–4.0 Hz, which are useful to identify weather and teleseismic events, volcanic and flood tremor, and local tectonic earthquakes. Volcanic tremor displays a coherent, emergent signal in RSAM data (see Figure 2), raising the question: Can RSAM data be empirically used to detect ***volcanic tremor*** events preceding eruptions?

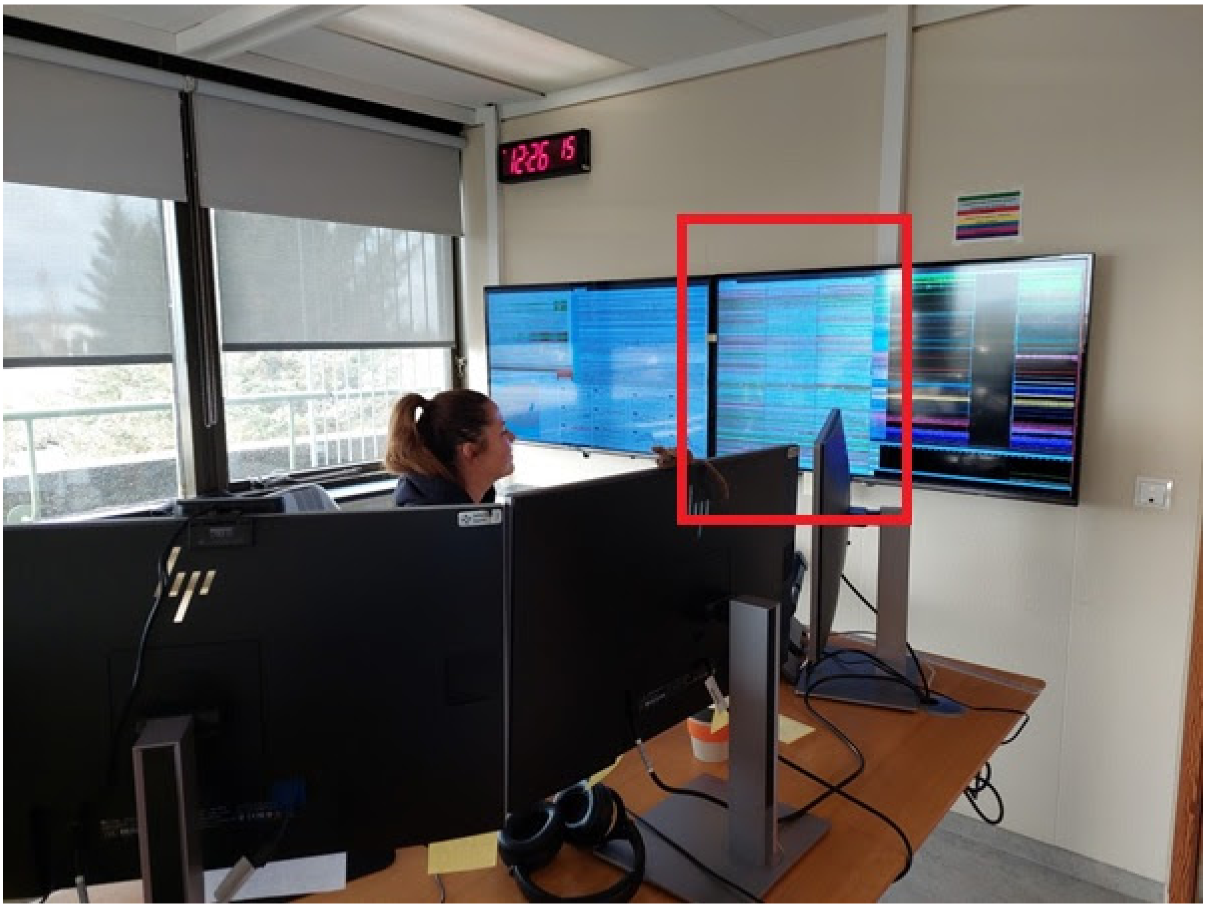

Figure 1. Photo of the monitoring setup in the IMO's natural hazards monitoring room. The right screen shows real-time earthquake and tremor data. Tremv output is displayed in red box with the last 24 hrs of all frequency bands from all seismic stations.

Until now, IMO's main automated early warning system is based on seismicity in different regions of Iceland. The country has been split into over 50 different areas based on location and volcanic system, each of which has defined thresholds for magnitude and number of earthquakes within a 24-hour period necessary to trigger different levels of ***warning***. If enough earthquakes or a single earthquake with a large enough magnitude are located within a specific area, based on the warning levels, an audio alarm warning will be played in the monitoring office. However, for detecting tremor there has only been a simple amplitude warning, and no "smart" warning system that automatically detects and warns of volcanic tremor, using the coherency of a signal recorded at different stations and identifying features of the signature of volcanic tremor.

The main objective of this project was to develop a new open source python- and RSAM-based early warning software that provides an audio alarm for the onset of volcanic eruptions, by using known signatures of seismic eruption tremor signals. The new module Tremv-ALERT, which is an addition to Tremv, analyzes real-time data and creates an alert or warning about volcanic tremor. The most difficult aspect of creating an efficient volcanic tremor detector is isolating the desirable signals from unwanted, non-volcanic sources that can appear at multiple frequency bands and trigger the warning module. For instance, a detector for volcanic tremor should avoid triggering with storm tremor, which rises very slowly and emergently in the lowest frequency band (0.5–1.0 Hz), and also not to trigger on individual earthquakes, which have a sharp, high amplitude onset in the highest frequency band (2.0–4.0 Hz). Volcanic tremor falls somewhere between these signals. Preceding explosive volcanic eruptions, tremor signals exhibit a ramp-like emergent shape and display coherence across a seismic network (see Figure 2). In other words, in this work the challenge was to not create false detections and at the same time not to miss any important events.

The python-based ***ALERT module*** was created with a three-fold tremor detection scheme in mind, based upon: 1) an eruption velocity threshold, 2) the signal-to-noise ratio, and 3) the shape of the emergent tremor signal. The module was tuned using data from six recent Icelandic eruptions: Hekla 2000, Eyjafjallajökull 2010, Fagradalsfjall 2021, and Grímsvötn 1998, 2004, and 2011. For tuning, data for these eruptions had to be converted from IMO's old in-house RSAM data format to the new Tremv csv format. In addition to developing the ALERT module, this project involved several updates to the original Tremv program.

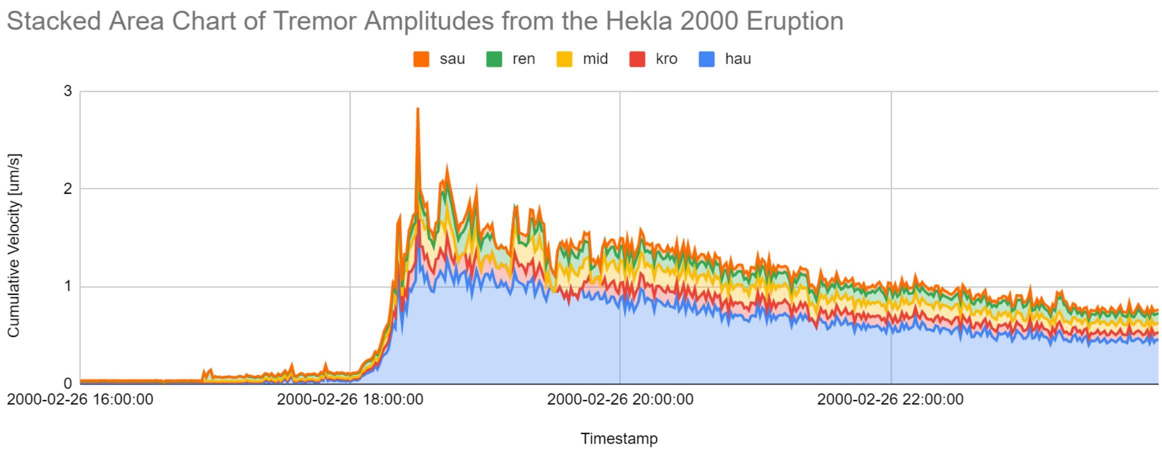

Figure 2. Stacked area chart of the cumulative tremor amplitude for six stations preceding the Hekla 2000 eruption. These stations are all WSW of Hekla, and data is plotted in the 2.0–4.0 Hz frequency band.

2 Methods

2.1 Tremv-ALERT routine

The ***Tremv-ALERT module*** follows a straightforward, robust routine of reading and processing data, detecting tremor events, and sounding an audio warning. Since the ALERT module is designed to detect tremor events, it uses RSAM data that has been output from the Tremv-logger program, which handles raw waveform data acquisition, data decimation and filtering, RSAM calculation, and the creation of a output files (in csv format) containing the time series RSAM data for each station's vertical component and each bandpass filter.

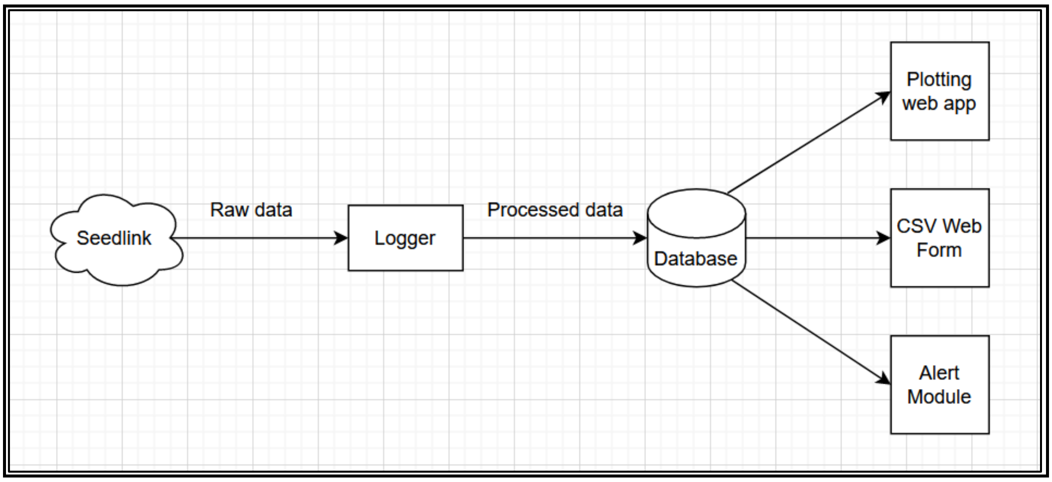

Figure 3. Schematic diagram of the updated Tremv routine, including the Tremv-ALERT module.

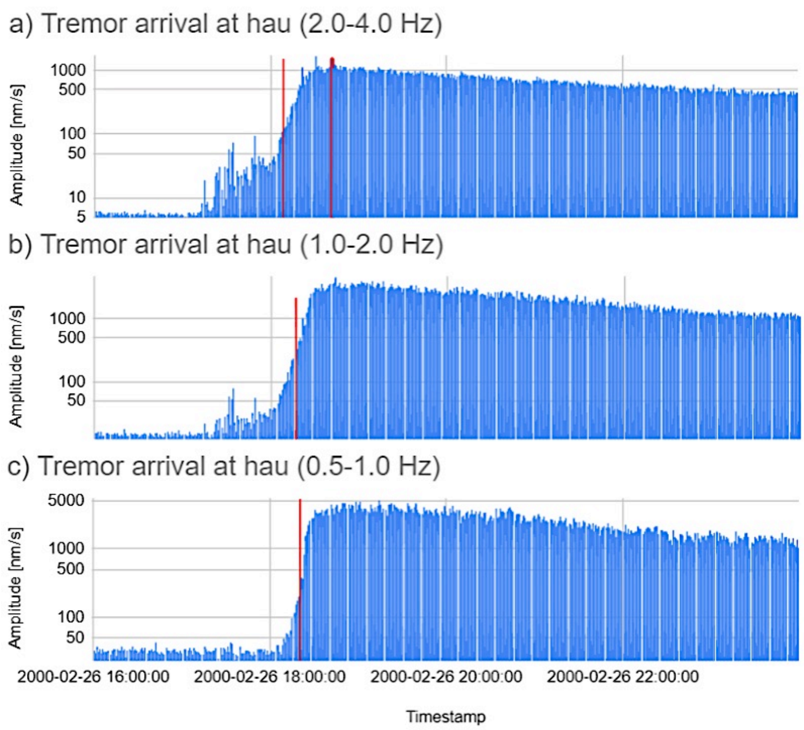

Figure 4. Graph of the tremor signal preceding the eruption of Hekla on February 26, 2000 for the station closest to Hekla (hau) in three frequency bands, a) 2.0–4.0 Hz, b) 1.0–2.0 Hz, c) 0.5–1.0 Hz. Tremor detections by Tremv-ALERT are shown by red lines.

Each minute, the ALERT module is called by the Tremv-logger program, effectively initializing the module every minute after the most recent minute of data has been processed (see Figure 3). Depending on the duration of the configurable windows (see section 2.2), one or two days worth of csv data will be read. The data is then split into three lists for each bandpass filter and station to be analyzed with the three-fold detection algorithm described in section 2.2. If a sufficient number of stations for a given filter satisfy all three tremor detection requirements (see section 2.2), the filter will enter a triggered state and a new tremor event will be identified. Filters are handled separately for calculations and trigger independently of each other because different bandpass filters preferentially show different types of tremor, and the tremor signals typically arrive much faster for higher frequencies than for lower frequencies. For example, Figure 4 shows the arrival of the volcanic tremor during the Hekla 2000 eruption, and it is clear that signal can be seen first in the 2.0–4.0 Hz bandpass filter, followed by the 1.0–2.0 Hz and then 0.5–1.0 Hz filters.

When a tremor event is first identified, a new entry is added to the tremor event catalog; one tremor catalog is created per month, containing information on the tremor event ID, the start time of the tremor, the filter triggered, and the stations triggered (see Figure 5). Each subsequent minute, if the filter remains in a triggered state, newly triggered stations will be appended to the existing event. Most importantly, when a tremor event is detected, the ALERT module connects to a computer in the natural hazards monitoring room to play an ***audio alarm*** warning. This warning serves to alert the monitoring team of an emergent tremor signal, indicating that immediate action may need to be taken. The audio alarm only rings when the tremor signal is first identified. If too few stations remain in a triggered state to keep a given bandpass filter in a triggered state, the event will end.

EventID	StartTime	Filter	Stations
1	2000-02-26T18:08:00.000000Z	[2.0,4.0]	gra,grv,hau,hei,hve,hvo,kri,kro,mid,ren,sau,sig,skr
2	2000-02-26T18:16:00.000000Z	[1.0,2.0]	gil,gra,grv,hau,hei,hla,hve,hvo,kri,kro,mid,ren,sau,sig,skr
3	2000-02-26T18:20:00.000000Z	[0.5,1.0]	gil,gra,grv,hau,hei,hla,hrn,hve,hvo,kri,kro,mid,ren,sau,sig,skr
4	2000-02-26T18:41:00.000000Z	[2.0,4.0]	gra,hau,hei,hve,hvo,kro,ren,sau,sig,skr

*Figure 5. Example **tremor catalog** for the month of February 2000.*

2.2 Tremv-ALERT triggering methodology (Parameterization and Trigger Requirements)

Tremv-ALERT utilizes a three-fold detection methodology, as illustrated in Figure 6. This triggering methodology is based on the current RSAM velocity amplitude, the signal-to-noise ratio, and the shape of the emergent tremor signal. These calculations are applied to the RSAM data for all seismic stations in all specified bandpass filters; each filter is handled separately and can be triggered, as different filters preferentially show different types of tremor events. The following three requirements must be satisfied for a station to detect a tremor event ***(three-fold detection program)***:

1. *Current velocity*: The RSAM velocity of the most recent minute must exceed a specified, configurable threshold amplitude in micrometers per second ($\mu m/s$). If the most recent RSAM value exceeds the amplitude threshold, the average velocity of ground movement is great enough to warrant eruptive volcanic activity.

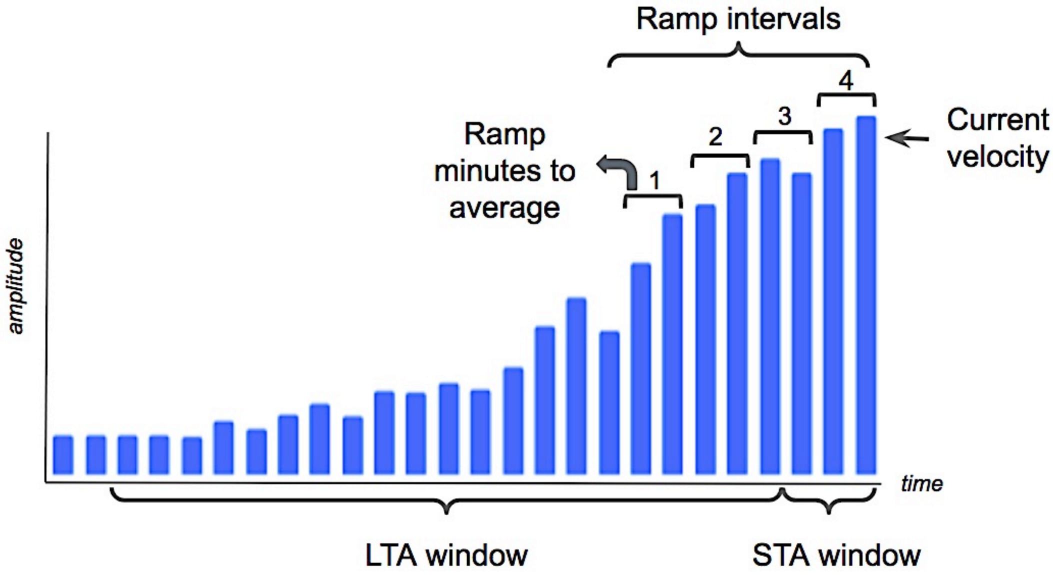

Figure 6. Diagram of Tremv-ALERT triggering routine on RSAM data (1 minute averages), labeling the main parameters Tremv-ALERT utilizes to detect tremor events.

2. *Signal-to-noise ratio*: The signal-to-noise ratio is calculated to determine how quickly the amplitude of the signal is changing. It is calculated by dividing the short-term average (STA) by the long-term average (LTA) to find the STA/LTA ratio, also known as the signal-to-noise ratio. In other words, the program continuously calculates the average values of absolute amplitude in two consecutively moving time windows, then divides these time windows. The user must define three parameters, including 1) the length of the STA window in minutes, 2) the length of the LTA window in minutes, and 3) the STA/LTA ratio. If the calculated STA/LTA ratio is high enough to meet or exceed the defined STA/LTA trigger ratio, the current averaged signal amplitude is significantly larger than the trailing window LTA, meaning that an eruption may be imminent.
3. *Ramp shape check:* Volcanic tremor exhibits an emergent signal in RSAM data leading up to an explosive eruption, as seen in Figure 2. To determine if the current data shows this ramp-like shape, several intervals of running averages are calculated and compared to ensure that the most recent average is larger than the previous. For example, in Figure 6, the average of ramp interval 4 must be larger than the average of interval 3, which must be larger than the average of interval 2, etc. It is beneficial to average several minutes worth of data for each interval in case earthquakes occur in certain minutes that skew the shape of the tremor signal. If the data exhibits step-like behavior of increasing data, a ramp shape similar to that during volcanic tremor episodes must be present.

These methods are applied to the csv RSAM data for all seismic stations and all specified bandpass filters. A station will "vote" if these three criteria are met. Since volcanic tremor preceding an eruption can be seen coherently across a seismic network (see Figure 2), several stations must identify this signal before an audio alarm is set off. If enough stations within a particular filter vote, a tremor event will be detected in that bandpass filter, and the filter will be put into a triggered state. At this point, the audio alarm will be sounded in the monitoring room, and a new tremor event will be added to the tremor catalog (see Figure 5). Section 2.4 describes the tuning process of these variables.

2.3 Additional ALERT parameters

The ALERT module can be additionally configured beyond the trigger parameterization to increase the ***functionality and flexibility*** of the module. These parameters control, among other things, which stations and filters contribute to audio alarms and how frequently audio alarms are permitted to ring.

- *Percent data*: This variable specifies the percentage of data (0–100%) that must be available for a station for its vote to count towards an event trigger. If there are large gaps in the data, a station could falsely set off a trigger. This parameter ensures that a specific amount of data is present before a tremor event is triggered.
- *Mute filters*: Bandpass filters can be muted so they will not cause an audio alert to be initiated. Tremor events detected for this filter will still be written into the event catalog.
- *Mute stations*: Stations can be muted for all bandpass filters so their votes will not count towards an audio alarm. These stations will vote as usual for a tremor event to be initiated in the tremor catalog, but they will not be used to set off an audio alarm. This feature is especially useful when there is an ongoing eruption (i.e. Fagradalsfjall 2021), as the stations around this eruptive area can be muted to enhance signals from other regions in Iceland.
- *Remove stations*: Stations can be removed from the trigger calculations for all bandpass filters. Removed stations will not be accounted for in the tremor catalog or for the audio alarm.
- *Silence audio*: The audio alarm can be silenced for the ALERT module if this variable is changed from “False” to “True.” This is useful if the ALERT module is desired to be used for research instead of monitoring purposes.
- *Max audio per hour*: The number of audio alarms triggered per hour can be limited within this variable. This is especially useful if there is an ongoing eruption that is setting off many unwanted triggers.
- *Minimum minutes between events:* Sometimes, after an event has been triggered, there are several minutes during which too few stations remain in the triggered state to keep the tremor event active. The event will thus untrigger. However, if the event retriggers after several minutes, it may be preferential to treat this as a continuation of the previously triggered event instead of treating it as a new tremor event. Thus, a minimum amount of minutes between the start of new tremor events can be defined.

2.4 Defining thresholds: Testing and tuning the ALERT module

The ***goal of tuning*** the ALERT module is to detect a tremor event only during volcanic tremor, not triggering on weather or earthquake events. Tremor due to weather emerges slowly, so the signal-to-noise ratio threshold must be higher than the signal-to-noise ratio seen preceding storm tremor. Additionally, the ramp shape check of the signal should prevent earthquakes from individually triggering events; earthquakes usually cause one large spike in the RSAM data for only one minute-worth of data, so there should not be a gradual increase in average amplitude over several minutes due to a single earthquake. This is a perfect example of why the triggering algorithm cannot be based purely on an amplitude threshold.

To tune Tremv-ALERT, the dataset from the most recent ***Hekla eruption*** on February 26 at 18:08 (cite source) is first analyzed to get a general sense of acceptable tuning parameters. This eruption provides a very clear signal that is ideal for initial tuning efforts because there are no complications, unlike the explosive, subglacial ***Grímsvötn*** and ***Eyjafjallajökull*** eruptions, whose signals are far more convoluted due to glacier interaction during the eruptions. After the parameters are generally defined from the Hekla 2000 eruption, the code will be tested on more complicated explosive scenarios including Eyjafjallajökull 2010 and Grímsvötn 1998, 2004, and 2011. Additionally, the module will be tested on data from the current effusive eruption at Fagradalsfjall from the beginning of the year to mid-September 2021 to assess its performance.

Three variables are involved in tuning the signal-to-noise ratio threshold, including STA window length, LTA window length, and the STA/LTA threshold value. The STA/LTA methodology is widely utilized by many automatic earthquake detectors, but instead of having window lengths on the order of minutes, like the ALERT module, they have window durations on the order of seconds. A longer STA window duration will make the module less sensitive to small signals (Trnkoczy, 1999). Additionally, the total duration of the STA and LTA windows may not exceed 24 hours, as the ALERT module will only read a maximum of two days worth of data; averaging windows that are too long will decrease the overall ***sensitivity of the module*** and make it very difficult to detect tremor events reliably. For Tremv-ALERT, based on the Hekla 2000 dataset, the proper length of the STA window is on the order of several minutes, while the LTA window can be on the order of several tens of minutes. Depending on the specific window lengths, the appropriate triggering signal-to-noise ratio falls somewhere between 1.1 and 1.4.

Logarithmic scaling on the vertical axis enhances weak tremor signals, making them easier to identify at an early time. When logarithmic scaling was applied to the STA and LTA averages, however, it became clear that this would require very fine tuning, as many ***false triggers*** were set off. Perhaps this is something to be investigated more in the future, but for now, non-logarithmic scaling appears to work more reliably and was thus chosen.

The number of minutes for each running average interval and the number of intervals to compare must be tuned to determine the ***shape of the signal***. The idea is to ensure amplitudes are steadily increasing with a ramp-like shape due to emergent volcanic tremor, attenuating amplitude spikes caused by earthquakes. This means that the number of minutes to average per interval should exceed one minute, yet not be so many that the early onset of the ramp is missed. There must also be more than one interval to compare, but the number of intervals should be limited. Based on Hekla 2000 analysis, the number of minutes to average per interval should be around 2–3 minutes, while the number of intervals should be between 3–4. It should be noted that it is advantageous to check that the average amplitude of each interval is greater than each previous interval instead of only comparing the first and last intervals; this minor change in data handling noticeably decreases the amount of false triggers.

Defining the ***amplitude threshold*** introduced some unexpected challenges. Volcanic tremor occurs with seismic velocities between 0.3 and 0.5 *μm/s*, as demonstrated by Figure 7. However, when this amplitude threshold was applied to the ALERT module, no trigger would occur until the eruption had already begun. For example, the Hekla 2000 RSAM data showed no significant increase in velocity across the network on the order of 0.1 *μm/s* until 18:19, the time of the summit eruption (see Figure 4, note that amplitudes are written in *nm/s* instead of *μm/s*). Thus, a lower amplitude threshold is necessary to provide an early warning. An amplitude threshold of 0.03 *μm/s* was selected because many velocities recorded across the network before volcanic tremor is visible are below 0.03 *μm/s*.

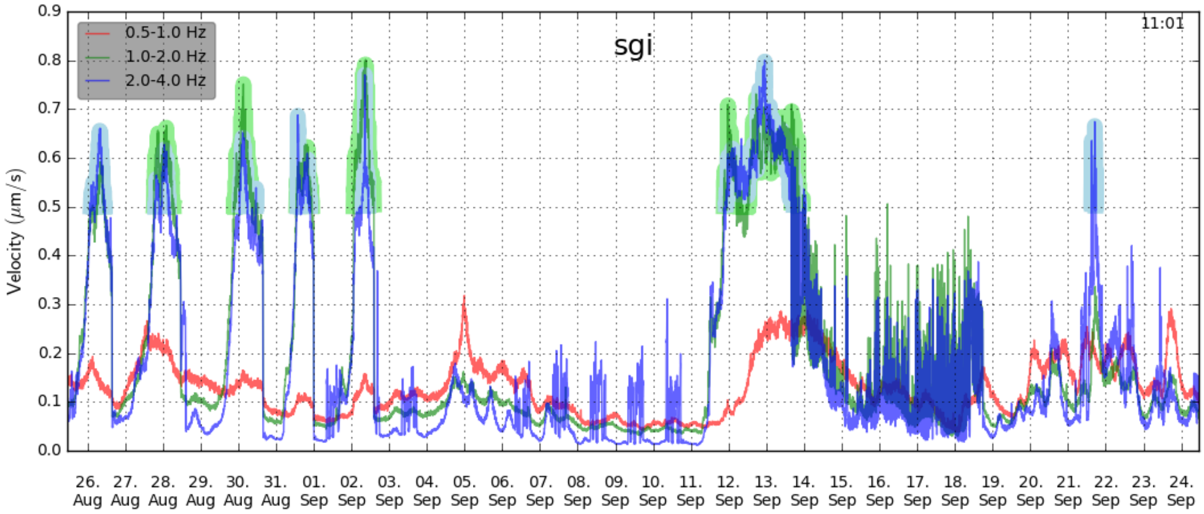

Figure 7. Example of long-term eruption tremor data from a station (sgi) 4 km SW of the Fagradalsfjall eruption site. The periods of high amplitude represent the eruptive sequence during which lava is visible in the crater, followed by low amplitude quiet periods with little to no active lava fountaining.

The number of stations that should be required to vote before a tremor event is detected is highly variable and depends on the density and sensitivity of the ***seismic network***. At the IMO, the sensitivity of the seismic network increased over the past couple decades, meaning that more small earthquakes and faint seismic signals can be detected. Thus, the older eruptions require fewer stations to vote than newer eruptions. The number of station votes needed to detect a tremor event should be roughly somewhere between 4 and 10, but this number is highly variable depending on the network setup. Ideally, however, this number could be configured specifically for different regions.

For the results section below, the ***parameters*** are as follows: sta window length = 3 minutes, lta window length = 60 minutes, sta/lta trigger ratio = 1.4, number of ramp intervals = 3, minutes to average for each ramp interval = 3 minutes, and amplitude threshold = 0.03 $\mu m/s$. For the 1998 and 2000 trials, only 4 stations needed to meet the triggering criteria to detect a tremor onset. This number was increased to 6 for 2004, 2010, 2011, and 2021.

3 Results

3.1 Tremv-ALERT test results for six Icelandic eruptions

The ALERT module was tested on the following six Icelandic eruptions to assess its behavior with different types of eruptions and to determine the expected warning times:

1. Grímsvötn 1998
2. Hekla 2000
3. Grímsvötn 2004
4. Eyjafjallajökull 2010
5. Grímsvötn 2011
6. Fagradalsfjall 2021

For eruptions 1–5 above, Table 1 displays the manually picked visual arrival time of the tremor signal, the Tremv-ALERT tremor detection time, and the summit eruption time for the station closest to each relevant volcano in all three standard frequency bands. Additionally, ***maximum warning times*** from the ALERT module are noted.

Table 1. Tremv-ALERT detection times for six Icelandic eruptions. Summit eruption times defined by Soosalu & Einarsson (2005) and by Einarsson (2018). Note that some events have multiple tremor arrival/ALERT detection times because two distinct types of tremor were seen preceding the eruption.

Volcano Name and Date of Summit Eruption	Stat.	Visual tremor arrival			ALERT tremor detection			Summit Eruption Time	Max Warning Time
		2.0-4.0 Hz	1.0-2.0 Hz	0.5-1.0 Hz	2.0-4.0 Hz	1.0-2.0 Hz	0.5-1.0 Hz		
Grímsvötn Dec. 28, 1998	skr	03:35, 09:12	03:36, 09:01	03:35, 08:58	*03:40, 08:21*	*03:40, 08:21*	03:49, n/a	09:20 UTC	59–340 minutes
Hekla Feb. 26, 2000	hau	17:13	17:21	18:08	18:08	18:16	18:20	18:19 UTC	11 minutes
Grímsvötn Nov. 1, 2004	skr	19:08	19:09	19:48	*19:35*	*19:35*	19:53	~20:00 UTC	~25 minutes
Eyjafjallajökull April 14, 2010	mid	02:38, 08:03	02:36, 08:00	02:32, 07:59	n/a, 08:14	*03:05,* 08:14	n/a, 08:55	~06:50 UTC	~258 minutes
Grímsvotn May 21, 2011	skr	17:35	17:52	18:02	*18:04*	*18:04*	*18:04*	19:00 UTC	56 minutes

3.1.1 Hekla Results

The tremor at the onset of the Hekla 26, 2000 eruption is a very clear signal, uncomplicated by glacier interactions, unlike Grímsvötn and Eyjafjallajökull. This makes it an ***ideal volcanic tremor for analysis***. Figure 4 shows the arrival of the tremor and the ALERT detection times at the station closest to Hekla in all three frequency bands. It is clear that this signal first arrives in the highest frequency band, then the middle and lower frequency bands. It should be noted that the detection times may be influenced by an increase in earthquake activity preceding the eruption onset. The earliest tremor signal is detected by the ALERT module in the 2.0–4.0 Hz frequency band at 18:08, providing 11 minutes of warning time before the eruption.

The tremor signal emanating from Hekla travels outwards in a radial pattern, starting at stations closest to Hekla and then traveling outwards towards the borders of Iceland. Figure 8 shows the tremor amplitude plots for stations with a NE bearing from Hekla (Figure 8a) and a WSW bearing from Hekla (Figure 8b). Figure 9 shows the locations of these stations. In both cases, the tremor signal first arrives at stations closest to Hekla, and then propagates outwards; the visual arrival time of the tremor signal at each of these stations in each bandpass filter is recorded in Table 2.

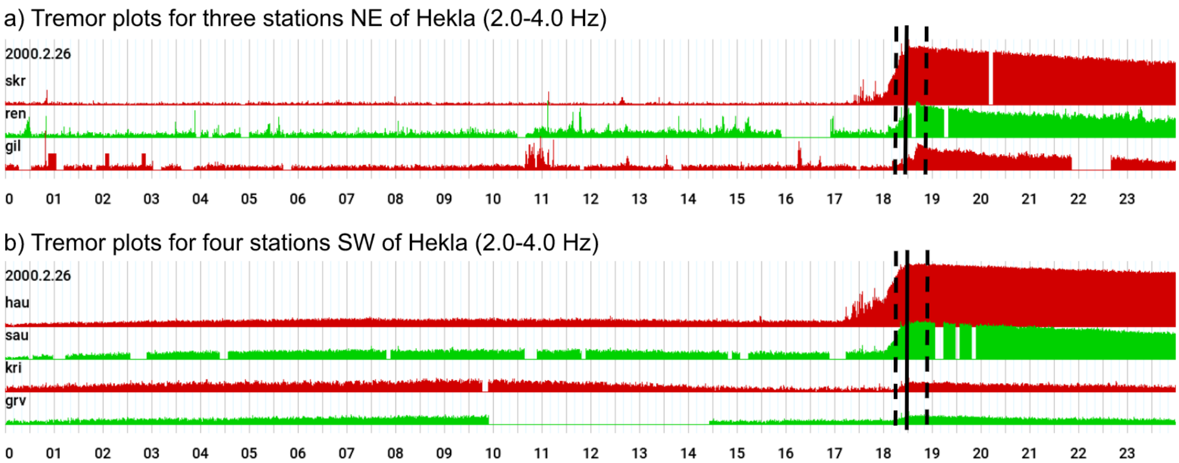

Figure 8. The emergent tremor signal and detection times in the 2.0–4.0 Hz frequency band preceding the Hekla eruption at 18:19 on February 26, 2000. a) stations along a WSW radial path away from Hekla, hau, sau, kri, grv; b) stations along a NE radial path away from Hekla, skr, ren, gil. NOTE that the 2.0–4.0 Hz frequency band is being used instead of the 1.0–2.0 Hz frequency band because the tremor is first detected in the 2.0–4.0 Hz range, although 1.0–2.0 Hz is the typical frequency range for volcanic tremor.

A simple calculation using the tremor "wave" arrival time at each station and the distance from Hekla can be used to approximate the propagation speed of the tremor signals. This approximation assumes that the stations for each radial (NE and WSW) are in a perfectly straight line and have the same bearing with respect to Hekla. While neither of these assumptions are quite true, an approximation can be made. Table 2 shows the results of this analysis, recording calculations of the tremor travel time between stations. Although RSAM data is very low resolution, meaning that the exact arrival times of the tremor cannot be precisely pinpointed, most travel time values for Hekla agree to be on the order of 100's of meters per second. Preliminary results suggest that these values correlate nicely with the speed of sound, as well as the plume exit velocity of Eyjafjallajökull volcano calculated by Ripepe et. al., 2013, indicating that the first tremor that can be seen is actually caused by an ***acoustic wave*** travelling through the air.

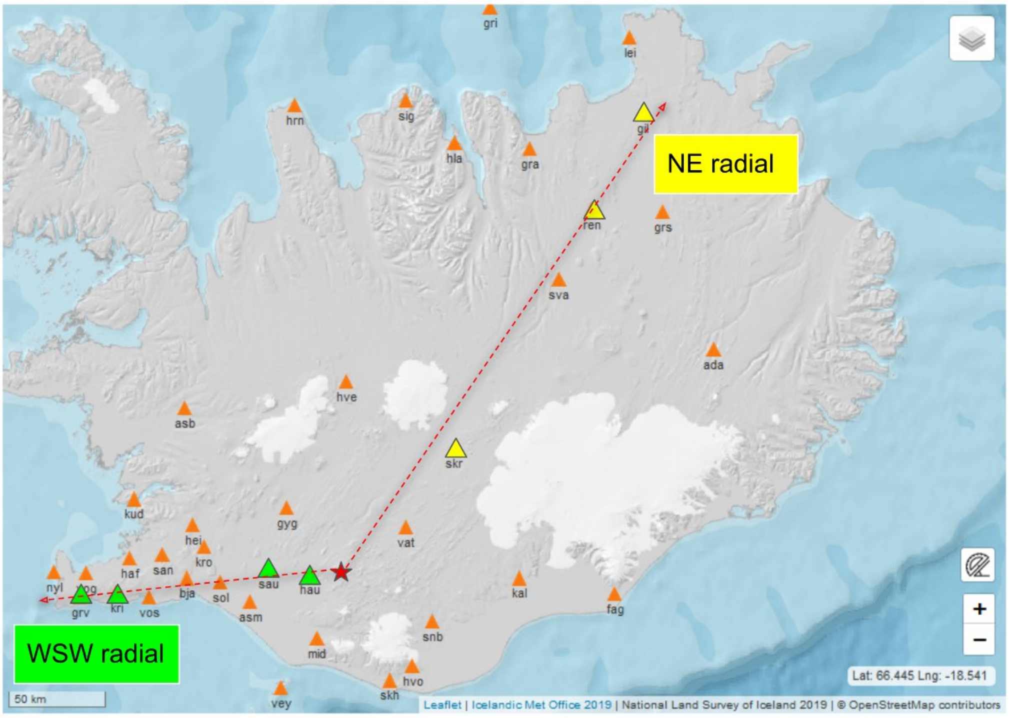

Figure 9. Seismic network maintained by the IMO as of February 26, 2000. The location of Hekla is marked by a red star. The four stations to the WSW plotted in Figure 8a are colored green, while the three to the NE plotted in Figure 8b are colored yellow.

Table 2. Table of the visually picked arrival times of the Hekla 2000 eruption tremor to stations WSW of the volcano (hau, sau, kri, grv) and NE of the volcano (skr, ren, gil). Tremor velocities are with respect to the previous station.

Bearing from Hekla	Station Name	Distance from Hekla [km]	Tremor Arrival Time			Tremor Velocity [m/sec]		
			2.0-4.0 Hz	1.0-2.0 Hz	0.5-1.0 Hz	2.0-4.0 Hz	1.0-2.0 Hz	0.5-1.0 Hz
WSW	hau	14.75	17:13	17:21	18:08	n/a	n/a	n/a
	sau	36.50	17:30	18:05	18:11	21.3	8.2	120.8
	kri	118.40	17:55	18:22	18:24	54.7	80.3	105.0
	grv	137.12	18:12	18:24	18:25	18.3	156.0	312.0
NE	skr	88.45	17:24	18:00	18:13	n/a	n/a	n/a
	ren	225.72	18:06	18:13	18:21	54.5	175.8	286.0
	gil	279.27	18:11	18:21	18:26	178.5	111.6	178.5

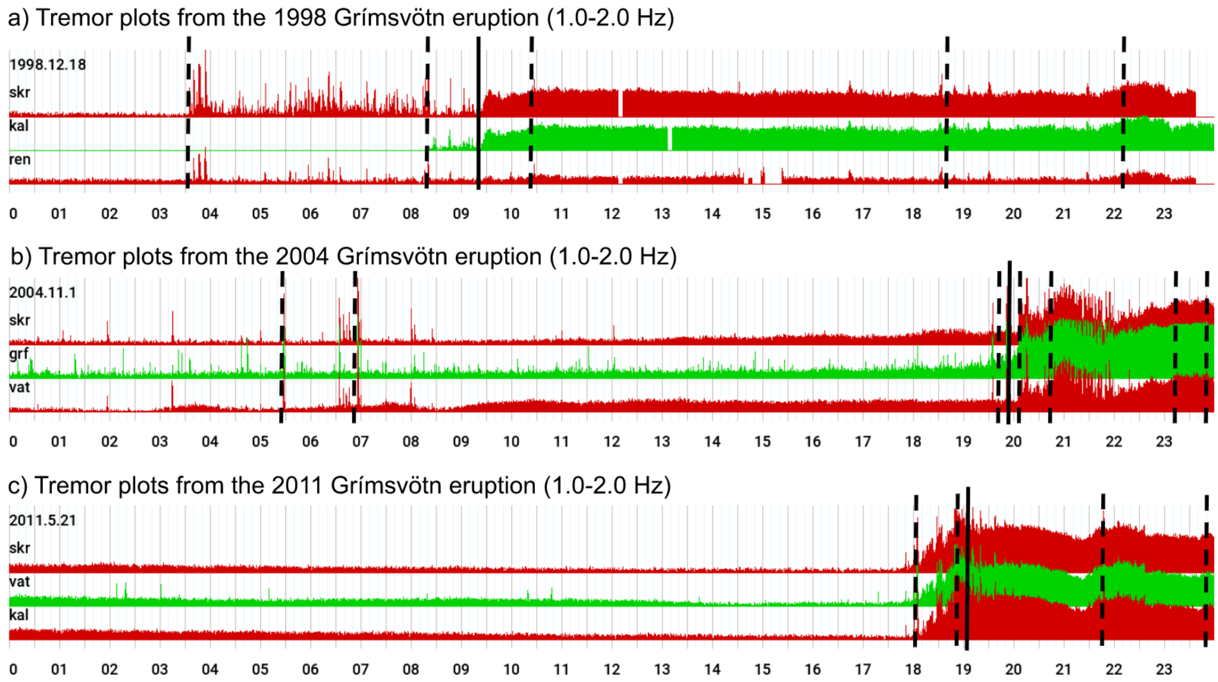

Figure 10. Tremor amplitude plots of three stations in the 1.0–2.0 Hz frequency range for Grímsvötn eruptions in the years a) 1988, b) 2004, and c) 2011. ALERT tremor detections are marked by dashed red lines, while the time of summit eruption is marked with a solid red line.

3.1.2 Grímsvötn Results

Figure 10 shows tremor amplitude plots for three of the most recent Grímsvötn eruptions, which occurred on December 18, 1998 (Figure 10a), November 1, 2004 (Figure 10b), and May 21, 2011 (Figure 10c). The station skr is plotted and can thus be compared for all three eruptions, exhibiting differing types of pre-eruptive tremor signal for each year. The warning times provided by Tremv-ALERT range between 25 minutes and 5.6 hours (Table 1), but it should be noted that the 5.6 hour warning time is only seen for the 1998 eruption.

3.1.3 Eyjafjallajökull Results

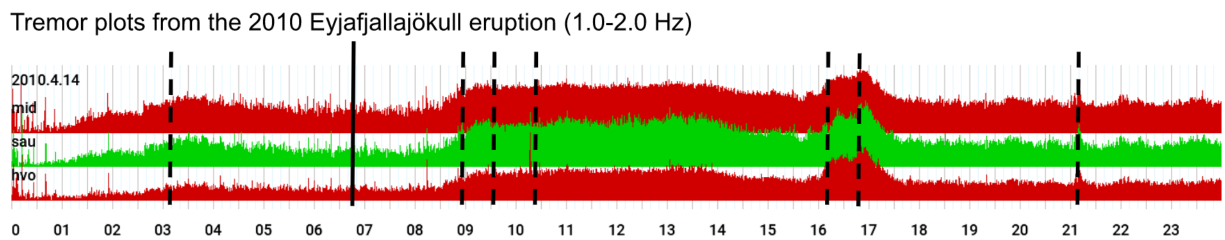

Figure 11. Tremor amplitude plots of three stations in the 1.0–2.0 Hz frequency range for the April 14, 2010 Eyjafjallajökull eruption. ALERT tremor detections are marked by dashed black lines, while the time of summit eruption is marked with a solid black line.

The summit eruption of Eyjafjallajökull on April 14, 2010 occurred after months of unrest and volcanic activity in the region. The interaction of the glacier and the eruptive activity complicates the tremor signal, as seen in Figure 11. As seen in Figure 11, there are approximately four or five different pulses of tremor. Table 1 looks at tremor arrivals from the pulse around 3:00 and the pulse around 9:00, between which the eruption occurs without a clear tremor signal. Data from Table 1 indicates that these tremor signals were visibly seen in the lowest frequency band, 0.5–1.0 Hz, before they could be seen in the 1.0–2.0 Hz or 2.0–4.0 Hz frequency bands. This may indicate that the early tremor was not due to earthquake activity or volcanic tremor, but rather the propagation of a jökulhlaup. Regardless of source, the first tremor signal detected by the ALERT module provides ***over two hours of warning*** (see Table 1), depending on the actual start time of the summit eruption, which is dubious.

3.1.4 Fagradalsfjall Results

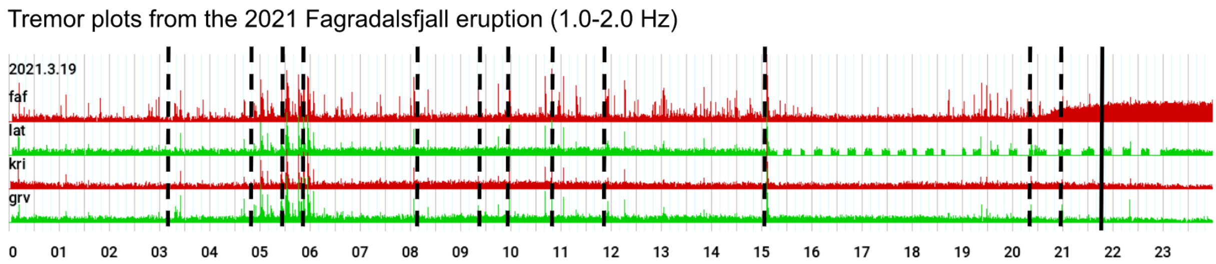

Figure 12. Tremor amplitude plots of four stations closest to the eruption site in the 1.0–2.0 Hz frequency range during the start of the Fagradalsfjall eruption.

After a prolonged earthquake swarm, eruptive activity commenced at Fagradalsfjall on March 19 around 21:40. Figure 12 shows that an emergent tremor signal is only visible at the station closest to the eruption site (faf), and there are far ***too many triggers*** occurring due to the earthquake swarm for this detection to be useful in a monitoring setting. Figure 13 illustrates the frequency of event detections for the first eight months of 2021, coinciding with the period of volcanic and eruptive activity on Reykjanes. The ALERT module additionally triggers with the lava fountaining events, which is clear by the trends in Figure 13.

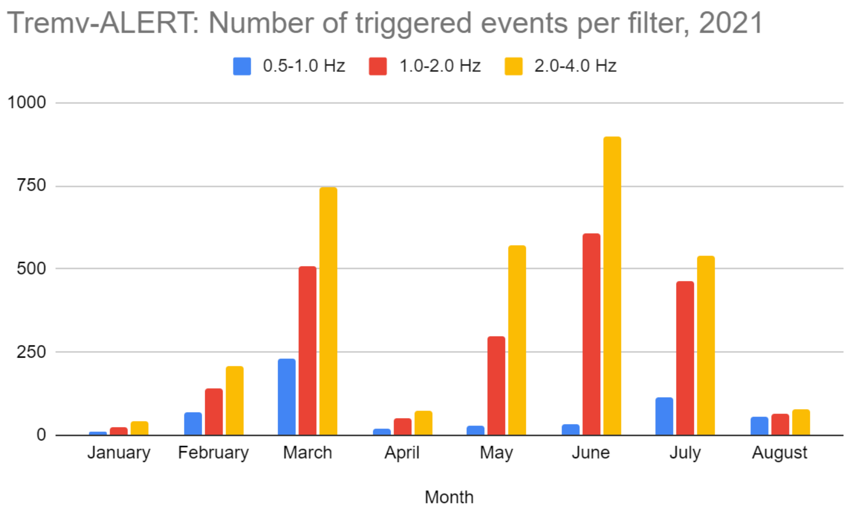

Figure 13. Number of triggered events for all filters from January to August, 2021. This analysis was conducted before the amplitude threshold was added to Tremv-ALERT and with slightly different parameterization values.

3.2 Updates to the original “Tremor Viewer”, Tremv

In addition to the development of the ALERT module, the Tremv program underwent numerous upgrades and additional development this summer. Tremv consists of a set of backend and frontend processes, which handle data acquisition and processing and data plotting, respectively (see Figure 3). The highlights of these upgrades include a conversion from the IMO’s previous RSAM data file format (tremlogs) to csv files, an HTML data request website, a web-based HTML plotting interface, and an instrument correction that converts the csv output data from counts to velocity. Currently the HTML websites with IMO data can only be accessed in-house, but they may be made public in the future.

3.2.1 Conversion of old RSAM data to CSV

The IMO has almost ***25 years of continuous RSAM data*** from 1996 to 2021, output by the original in-house RSAM processing program written by Einar Kjartansson. This is the program that Tremv was first created to replace during last summer’s project. This tremor data represents the IMO’s only continuous seismic data from 1996–2015, as storing high-resolution waveform data was once very expensive, and therefore records were only kept for identified earthquakes. These files, called tremlogs, are vital to analyzing volcanic tremor preceding eruptions during this time period, including Grímsvötn 1998, Hekla 2000, Grímsvötn 2004, Eyjafjallajökull 2010, Grímsvötn 2011, and the Holuhraun 2014–2015. This summer, 2021, a conversion code was developed that converts these archaic, binary tremlogs to a standardized csv format, which can be plotted with any type of meteorological or volcano monitoring data, including gas measurements, number of earthquakes, rainfall measurements, etc. This conversion of data was vital for tuning the ALERT module and may be very useful for further investigation into tremor signals in Iceland.

In addition to this ***tremlog to csv converter***, which is limited to the IMO’s historical data, a conversion code was created to convert the widely-used seismic data format mini-SEED to RSAM data. This code reads local mini-SEED files, processes 1-minute windows of seismic data to calculate RSAM, and outputs the Tremv standard csv files. This conversion program may be very useful to other observatories and research institutions that would like to analyze RSAM csv data without being in an active monitoring situation.

A ***new web-based plotting interface*** was additionally added to Tremv this summer, replacing the python-based plotting program written in 2020. This HTML web interface increases accessibility of the Tremv plotting program; instead of downloading the plotting software on a local device, a user can simply type in a URL linking directly to a plot of the most recent RSAM data. This plotting program retains the original features of the original 2020 version of Tremv-plot, which is based on Sjátrem, the IMO’S original RSAM plotting program, and displays the RSAM data for all stations in the IMO’s seismic network and all bandpass filters (see Figure 14). The webpage is interactive, allowing the user to select the stations and filters he or she desires to plot. The data is plotted and updated in real-time, with a 24-hour window of the most recent RSAM data visible. There is logarithmic scaling on the vertical axis to enhance emergent tremor signals. Operational tests began in IMO’s monitoring office on July 22, 2021.

3.2.2 Web-based data request portal and plotting interface

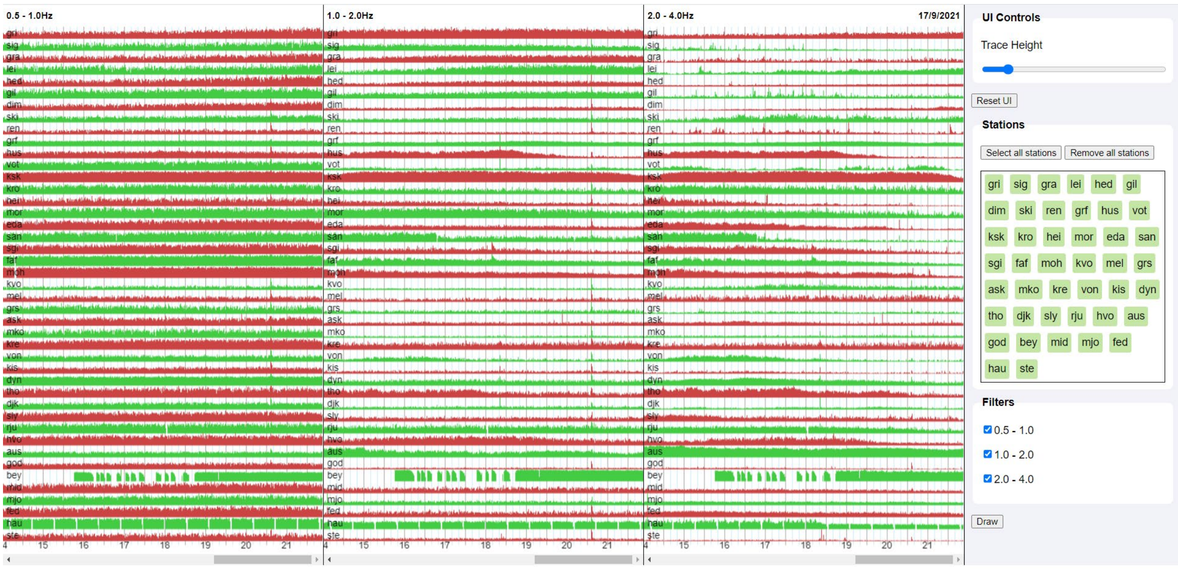

Figure 14. Screenshot of the updated web-based Tremv plotting program on September 20, 2021. Stations and filters to plot can be selected by the user.

The HTML plotting interface includes a "live" cursor showing the exact timing (see Figure 15), which is a ***major improvement*** and which the analysts have been using since they received the link this summer. The cursor provides the exact minute of the onset of the "main" events seen in Tremv. For the person on duty, they will quickly identify the main features (events) for the past 24 hours, and with the cursor, they have the exact timing of those events. This allows them to do a check if the automatic system has detected those events, and if not, the exact timing allows them to quickly search in the raw data for further analysis. The plots with the cursor option have been used, now for a couple of months, at civil-protection meetings to provide an overview of the activity at the eruption site in Fagradalsfjall. While the analyst shares his or her screen of Tremv, the cursor option allows them to quickly identify the timing of various events and features, such as increase and decrease in eruptive activity, individual earthquakes, and even man-made noise linked to on-site maintenance and operations.

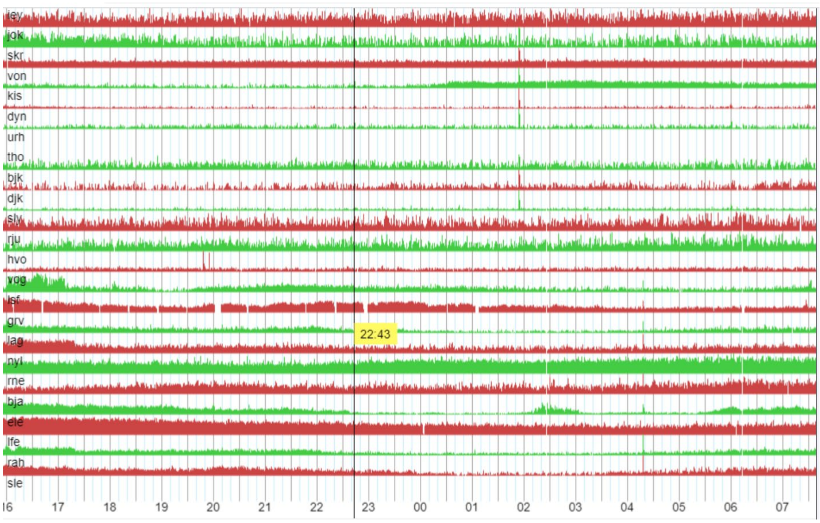

Figure 15. Screenshot of Tremv's "live" cursor feature.

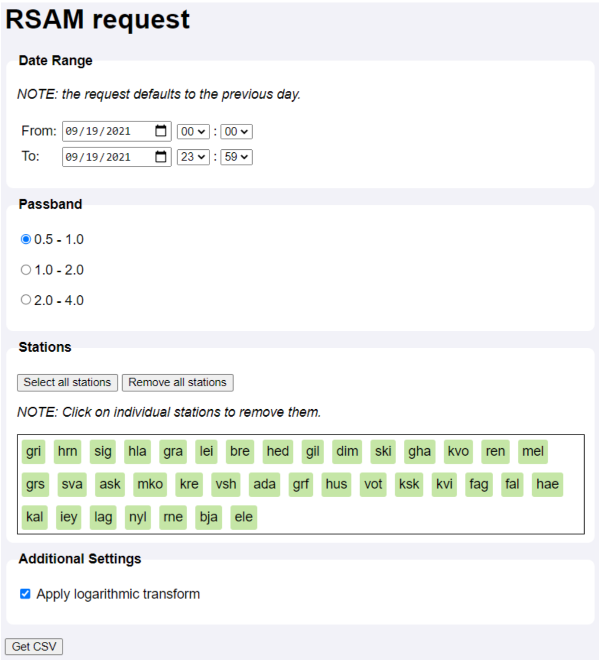

Figure 16. Example of web-based RSAM data request form. For a selected data range, passband filter, and list of stations, the web page will download a csv file of RSAM data by user request.

In addition to this new and improved web-based plotting program, there is ***a new web portal*** accessible to all research staff at the IMO to request and download csv RSAM data (see Figure 16). Currently, the web page can provide RSAM data from 1996 to the present day. This tremor data can be easily plotted with other volcano monitoring and meteorological data to observe the correlation between different types of data, for example, a correlation between RSAM tremor data and gas emission data.

3.2.3 Instrument response correction

An important step forward in Tremv development is that instrument response is now accounted for in the calculations before RSAM data is written to csv. Previously, Tremv recorded amplitude averages in counts, which are the actual values of the raw data read directly off of the instrument. These counts are arbitrary numbers that vary based on the tuning and type of sensor, meaning that the count values cannot be quantitatively compared between different types of instruments. Information on the response of a seismometer is necessary to convert this unit of counts to ***SI units*** of velocity, which is the ideal measurement for this RSAM data. The sensitivity of a seismometer describes the response time of a particular seismic sensor, which can be adjusted by a technician.

By using an FDSN server connection to ***SeisComP***, one of the most widely-used open source programs for real-time earthquake monitoring software, information about the instrument response data can be gathered. Although the instrument response information of a station should not be changed frequently, Tremv updates the response numbers twice per day to ensure that the constants being used for the conversion are correct. Response information about historical data can additionally be collected and applied to the tremlogs with historic RSAM data. It should be noted that this historical inventory sometimes assigns the incorrect type of sensor to some stations, so not all of the data is properly corrected.

A seedlink server connection via SeisComP can also be utilized to connect to the real-time stream of seismic data directly via SeisComP, facilitating faster, more reliable data acquisition. Additionally, stations with available data are now ***automatically detected***, so the user does not need to manually provide a list of stations.

4 Discussion

4.1 Performance of the ALERT module

Overall, the Tremv-ALERT module performs well and ***successfully detects the onset of volcanic tremor*** events. It does not trigger on quiet days, and the false triggers that do occur often coincide with large earthquakes and earthquake swarms, which may have the same mathematical properties as eruption onset tremor: an increase in amplitude, a significantly higher signal-to-noise ratio, and a coherent signal in several stations across the network. Often there are several smaller spikes in amplitude--presumably smaller earthquakes--preceding these larger earthquakes that satisfy the ramp shape checks. More testing and tuning will be needed to find an ideal balance between ignoring these false triggers and detecting volcanic tremor at an early time preceding the eruption.

As Table 1 shows, the ALERT module can detect eruption tremor in both simple subaerial (i.e. Hekla) and complicated subglacial eruption scenarios with a maximum warning time exceeding 2 hours (Grímsvötn 1998 and Eyjafjallajökull 2010). Comparing Tremv-ALERT's performance between three years of Grímsvötn eruptions can be enlightening. The eruption onset tremor for Grímsvötn in 1998, 2004, and 2011 looks quite different for each eruption. Regardless of this, Tremv-ALERT manages to provide ***25 to 340 minutes of warning***, depending on the precursor signals. However, it must be acknowledged that the source of tremor detected at the onset of subglacial eruptions will not necessarily always be attributed to volcanic tremor, which was likely the case for the early morning tremors of April 14, 2010 that provided such an early warning time for the Eyjafjallajökull eruption. There is not a definitive start time in the literature for the Eyjafjallajökull summit eruption on April 14, but best estimates of the eruption place it around 06:00 between two pulses of low-frequency dominant tremor (see Table 1); visually, there is no tremor pulse directly coinciding with this estimated time. This indicates that the ALERT module was likely detecting flood tremor, which triggered the warning so soon. It is acceptable and even beneficial for the ALERT module to detect tremor sources outside of the volcanic realm, however, further testing should be carried out to better observe and understand the ALERT module's response to jökulhlaups, which may improve understanding and tuning of the module to eruptive scenarios.

Another issue to consider is that immediate response may not be taken by the monitoring office due to one single ALERT detection, dependent upon the recent amount of activity and associated tremor triggers for the previous several days, weeks, or even months. For instance, volcanic activity associated with the 2010 Eyjafjallajökull eruption lasted for roughly 2.5 months, and the ALERT module recognizes many of these signals as volcanic tremor. In this case, barring more precise tuning, the detection on April 14th may not have seemed unique or pressing enough for the monitoring team at the IMO to take immediate action. In contrast, there was only one detection at 22:16 on December 17, 1998--one day before the Grímsvötn eruption--so the ALERT detections at 03:40 and 08:21 of December 18 may have been taken more seriously, providing ample response time before the 09:20 summit eruption.

The onset of the ongoing 2021 effusive eruption at Fagradalsfjall is more nuanced and difficult to distinguish in the tremor event catalogs. While there was an emergent, coherent tremor signal seen in the closest station to the eruption site, there were too many false triggers during the earthquake swarms earlier in the year to distinguish between the swarms and an eruption. When Tremv-ALERT is officially implemented in the IMO's volcano monitoring office, stations near the volcano will be muted so that potential signals from other volcanoes--including Grímsvötn, Hekla, Katla, and Askja--will not be drowned out in a flurry of ongoing detections, as the ALERT module recognizes the lava fountaining events as volcanic tremor, too. Clearly, the ALERT module, which was designed specifically for explosive eruptions, requires drastically improved tuning to effectively detect the onset of effusive eruptions like Fagradalsfjall.

Finally, Tremv-ALERT provides just over 10 minutes ***warning time*** (triggering at 18:08) for the 2000 eruption of Hekla. Hekla notoriously shows very few precursors until the hour before an eruption (Soosalu & Einarsson, 2005). While this seems to neglect the early tremor that was only seen in the highest frequency band, it should be noted that the ALERT module was able to detect the early tremor signal at 17:20, which began approximately an hour before the eruption started at 18:19, when logarithmic scaling was applied to the STA and the LTA. However, this made the ALERT module so sensitive that there were many false triggers. Logarithmic scaling has much potential for this application, but a large effort will be necessary to tune it. Also of note, the Hekla dataset that was used in this project only consisted of 24 usable stations. Comparatively, the current seismic network streamed to the IMO includes 85 usable stations, meaning that the sensitivity of the network overall has drastically increased. Thus, it is likely that, if the current network existed during the 2000 Hekla eruption, the early tremor signal would have been detected, giving almost an hour warning time. This can be compared to the earthquake-based alarm system, currently running in the monitoring office. This system provides 23-79 minutes of warning for Hekla eruptions, based on data from several Hekla eruptions (Barsotti et. al., 2019). Tremv-ALERT has a great potential to be on par with this, with some additional tuning, trials for logarithmic scaling, and the increasingly sensitive seismic network.

4.2 Addressing Advantages and Limitations

The main advantage of the Tremv-ALERT protocol compared to earthquake-based alert systems is that long term trends of RSAM data can be identified. This allows the ***detection of emergent signals*** such as volcanic eruptive tremor to be detected, which would otherwise be missed by high-resolution waveform data. The main limitations of the module relate to the tuning, not the ALERT detection protocol itself. Since the density of the ***seismic network*** varies around the country, it would be useful to set different thresholds for different regions of the country, many of which display different types of eruptive activity.

4.3 Future Work

While Tremv and the ALERT module are currently ***available and ready to be used*** for volcano monitoring in their current stage of development, several improvements could be made to improve the software.

To begin with, there are several ways to increase the convenience and usability of the ALERT module. First and foremost, the ALERT module could be integrated with the HTML plotting program to visually represent which stations and filters have been triggered. Currently, there is only an audio warning stating that a tremor event has been detected, and it does not detail the specific stations or filters that have detected this tremor; to acquire this information now, the tremor catalog must be checked. In the future, the plotting interface could highlight stations and filters that are currently in a triggered state, making it easier for the volcano monitoring team to quickly and ***efficiently locate*** where the unrest is concentrated based on visual cues. Similarly, the audio warning itself could be tuned and play additional audio files that audibly state the region of unrest when a tremor event is detected. This could be achieved by sorting the stations into different regions, based on geographic location, proximity to a volcanic system, etc. Then, if stations within a particular region detect a tremor event, the audio warning can state the name of the region. Another consideration is that the density of Iceland's seismic network is not homogeneous, meaning that there are more stations in some regions than others. Thus, the number of stations it takes to detect a tremor event may vary with region for different volcanic systems. To account for this, the ALERT module could be ***fine-tuned*** to require different numbers of station votes for different regions before a tremor event is triggered. Finally, since the ALERT module performed well based on the three-fold detection process described in section 2.2, data from the 2000 Hekla eruption was not analyzed with cross-correlation as stated in the grant proposal. Thus, this is something that could be subsequently investigated to determine its potential for eruption monitoring.

In addition to ***integration*** of the ALERT module into the web-based plotting interface, many improvements can be made to the plotting interface itself. Currently, only real-time RSAM data with a 24-hr trailing window is displayed. However, it would be very beneficial to plot old RSAM data using this HTML interface, as well. Since the plotting program already connects to the data server, older data could be acquired in the same way and plotted statically. Several other features would improve the user experience of the plotting interface, including a zoom window to enhance and allow inspection of detailed parts of the data, a configurable option to plot more than 24-hours worth of data at a time, and a toggle for scaling that allows user to plot the values either as relative or absolute values, meaning that either 1) each station's data is scaled to the largest value for that particular station, or 2) that all stations are scaled to the largest amplitude seen at any station, in the standard SI units of velocity. Additionally, a designated pre-configured Tremv HTTP server could be created so that users will not have to set up their own HTTP server to host an HTML website to run the plotting program. This drastically increases accessibility, as it cannot be assumed that all volcano observatories running Tremv will have IT support staff to set up such a server.

The final step is officially incorporating Tremv into the SeisComP3 software package (http://seiscomp.org). The updated version of Tremv is already configured to connect to an FDSN SeisComP server to retrieve waveform data, the list of active stations, and instrument response information for each station. The IMO has already hired contracting services from Gempa to aid in software handling at the IMO, so it is a possibility for Gempa to handle this final integration of Tremv and the ALERT module into SeisComP3, making it available for other volcano observatories running SeisComP3. Once Tremv and Tremv-ALERT are integrated into SeisComP, they will be the very first RSAM code and tremor-based warning module intended for SeisComP users and will be open source under the GNU public license. Since SeisComP is the most downloaded seismic analyzing system in recent years, with users around the globe, the addition of an open source RSAM and tremor-detection module would be invaluable. It would become available to a large number of users, including volcano observatories in poor countries that depend on freely available monitoring tools, and it would introduce the possibility for observatories from around the world to compare RSAM plots. This opens a door for the scientific community to learn new information about the similarities and differences from volcanoes and other natural phenomena in systems around the world.

Two presentations about the new module were given at the IS-TREMOR two day kick-off meeting September 6-7 this year and raised several discussions. The Tremv-ALERT project nicely links with the ***Rannís Grant of Excellence project IS-TREMOR***, which started in May 2021 and aims at detecting, classifying, and locating emergent tremor events for the past 6 years in Iceland. In addition to getting a glimpse of the aims of the project, it has also been a great opportunity for the Tremv-team to connect with scientists in the field, both from Iceland as well as from Belgium and France. Indeed many of the problems that came up during this summer's work were tackled at meetings together with the IS-TREMOR team. One future aspect is to use the simple but robust Tremv-ALERT detector to compare with more advanced waveform detectors that are underway in the IS-TREMOR project.

4.4 Innovation and Implications

Tremv-ALERT is an innovative volcano monitoring tool that provides a new RSAM-based warning algorithm for detecting volcanic tremor preceding explosive eruptions. It holds the ***potential*** to greatly improve the monitoring capabilities at both the IMO and other volcano observatories worldwide. Currently, at most volcano observatories including the IMO, eruption warnings are only based on earthquake frequency and magnitudes. To our knowledge, there is currently no open-source, platform-independent RSAM tremor warning available to seismologists and the volcano monitoring community. Thus, Tremv-ALERT will be the first eruption tremor audio-alert at the IMO, and is therefore an important step towards more reliable natural hazards monitoring. Since the software is open source on GitHub, it will be available to all observatories across the globe, including those with limited funding. Implementation of the updated version of Tremv, including the user-friendly web-based plotting program, and Tremv-ALERT is scheduled for the end of September or early October.

5 Conclusion and Outlook

Tremv-ALERT is a new python-based software that detects the onset of volcanic eruptions in real-time by applying a three-fold detection scheme to RSAM data. This detection methodology was designed to identify known characteristics of volcanic tremor and is based upon: 1) an amplitude threshold, 2) the signal-to-noise ratio, and 3) the shape of the emergent tremor signal. Based on tests using data from six Icelandic eruptions--Hekla 2000, Eyjafjallajökull 2010, Fagradalsfjall 2021, and Grímsvötn 1998 2004, and 2011 eruptions--the ALERT module can provide over two hours of warning. The earliness of the warning is highly dependent upon the sensitivity of the seismic network and the amount of tremor activity preceding the eruption, which means that it works for the onset of explosive eruptions. When a volcanic tremor event is detected, an audio warning alarm will be played in the volcano monitoring room of the IMO, and an event will be added to a tremor event catalog. This innovative software is, to our knowledge, the first python-based, open-source software ever created to detect eruption onset tremor using RSAM data. Tremv-ALERT is a module of the program Tremv, an RSAM processing and plotting software created in 2020 by the same team to monitor tremor activity.

In addition to the development of the ALERT module, its parent program Tremv underwent numerous upgrades and improvements this summer. These improvements include a web-based real-time plotting program, a web-based data request form, converting old RSAM data to csv format, and an instrument response correction that converts data to standard SI units. The new HTML plotting interface allows anybody with access to the server to plot data directly in their web browser without installing software on their computer, improving accessibility and ease of use. This feature is being utilized by the monitoring team at the IMO and during Civil Defense meetings. Additionally, data can be requested for any length of time using a new in-house web portal. Old RSAM data from the IMO can be requested via this portal, as it was converted to

Tremv's csv standard. This historical data is very important, as it is the only continuous seismic data record at the IMO from 1996 to 2015 and was used to tune the ALERT module. Additionally, now that data has been converted to standard SI units, the amplitudes of the RSAM tremor data can be directly compared to one another.

Tremv and its various updates have a great potential to increase the scientific community's understanding of tremor on a whole, and the ALERT module has a great potential to improve the national security of volcanically active countries. The ALERT module and updated version of Tremv will be published on the main branch of the Tremv Github in the coming weeks (http://github.com/tremv), but they can currently be found under the development branch. An outreach effort will be initiated to contact observatories and present this new, innovative volcano monitoring software. Hopefully, this will allow Tremv and the ALERT module to have a significant impact by improving the capabilities of the global volcano monitoring community. In Iceland, several large explosive volcanoes threaten to re-awaken, so it is the ideal time to implement the ALERT module, hopefully increasing the response time of the IMO to handle the impending disaster.

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