Alarm systems detect volcanic tremor and earthquake swarms during Redoubt eruption, 2009

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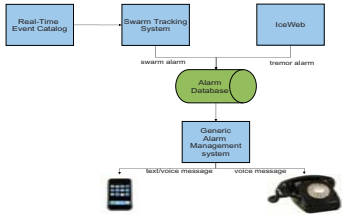
SUMMARY 1

Volcanic ash clouds are hazardous to aviation, so we need to warn the authorities before they are likely occur, and when they do occur. The most reliable precursors to volcanic eruptions are earthquake swarms and (escalating) volcanic tremor. Our goal is to create robust alarm systems to detect these swarms and tremor episodes, and notify observatory scientists.

We present encouraging results from swarm and tremor alarm systems we operated during the 2009 Redoubt eruption. We successfully detected all the major swarms and almost all of the explosive eruptions.

INTRODUCTION 2



The Alaska Volcano Observatory seismically monitors 27 volcanoes. Sometimes volcanoes erupt with little precursory seismicity (Okmok erupted in 2008 after less than 5 hours of "unrest"), so alarm systems are needed which can detect earthquake swarms and volcanic tremor at all 27 volcanoes. We trialed two alarms systems during unrest at Redoubt volcano:

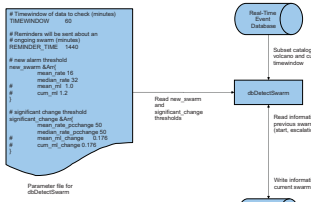
(1) A swarm alarm system, which comprised a real-time event catalog and swarm tracking system.

(2) A tremor alarm system which is a component of the IceWeb system.

Whenever an alarm from either system was added to the alarm database, it was detected by a generic alarm management system, and dispatched accordingly to a call-down list. The alarm call-down stops when a recipient acknowledges the alarm via a confirmation webpage.

Further details on these systems are presented in the *orange panels below*. Data and results are presented in the *panel to the right*.

SWARM ALARM SYSTEM



The real-time event catalog (a database) is constantly monitored by dbDetectSwarm which computes four parameters: mean hourly event rate, median hourly event rate, mean magnitude and cumulative magnitude.

These parameters are compared with pre-defined thresholds from the dbDetectSwarm parameter file which provide a flexible way to define swarm start, swarm escalation and a swarm end. When a threshold condition is met an alarm of the appropriate type is written to the alarm database.

THE 2009 REDOUBT ERUPTION 3

The 2009 eruption of Redoubt volcano can be summarised through two continuous parameters: (1) **the hourly event rate** detected by the real-time event catalog (ideal for highlighting swarms), and (2) the reduced displacement (D_{RS}) which is like RSAM, but corrected but instrument response and geometrical spreading (ideal for highlighting tremor). These data are shown in figures 1-8.

Seismicity first became elevated on 25 January 2009 [Figure 3]. The onset of tremor was followed on 27 January by a significant increase in event rate. Seismicity declined after 3 February. There was a brief swarm on 22 February.

Seismicity increased again on 26 February with an abrupt tremor band followed 5 hours later by an abrupt increase in event rate to almost 80 events per hour [Figure 4]. Elevated levels of seismicity continued through 27 February, then declined. Small swarms occurred on 6 and 12 March [Figure 1].

A gradual increase in event rate began on 21 March and this swarm episode continued through 23 March [Figure 5]. The event rate declined sharply in the hour before the first explosive eruption at 06:34 UTC on 23 March as the swarm merged into continuous tremor [Figure 9].

KEY FOR FIGURES 1-8

X Explosive eruption (ash > 5 km)

T Tremor alarm

Hourly event rate, from the real-time event catalog

Reduced displacement (like RSAM, but corrected for instrument response and geometrical spreading) on station REF

PLOTS OF **HOURLY EVENT RATE** AND REDUCED DISPLACEMENT (D_{RS})

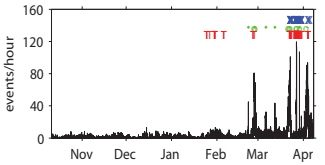


Figure 1: Event rate from the real-time catalog from 10 October 2008 - 5 April 2009. Explosions, swarm alarms and tremor alarms are also plotted (see key, below left). No false alarms (e.g. nothing before 25 January). First tremor alarm on 25 January 2009, when AVO raised the Aviation Color Code to "Orange". First swarm alarm on 26 February. There are five periods when the event rate exceeded 60 events per hour: 26-27 February, 21-23 March, 27 March, 29 March and 2-4 April.

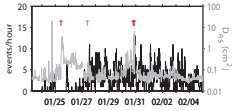


Figure 3: Seismicity at Redoubt first escalated on 25 January 2009. Reduced displacement (D_{RS}) abruptly increased from about 0.05 to 3 cm^2, triggering the first tremor alarm. Repeated on 27 and 30 January. Event rate increased to ~ 10 events per hour on 27 January.

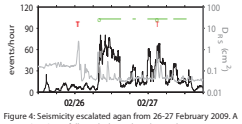


Figure 4: Seismicity escalated agan from 26-27 February 2009. A tremor band was followed 5 hours later by an abrupt increase in event rate (black) to 80 events/hour. Four swarms were declared by the swarm alarm system.

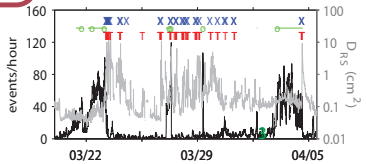


Figure 2: Detail for the explosive period 23 March - 5 April 2009. Looking at the explosions (X) and tremor alarms (T), the tremor alarm system 'detects' all but one of the explosions, and there is one tremor alarm that does not seem to correspond to an explosion. Explosions shown here based on infrasonic, lightning and seismic data [spreadsheet by Steve McNutt] and sent ash to at least 5 km height.

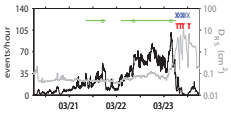


Figure 5: A gradual increase in event rate (black) began on 21 March, rising to about 100 events per hour at around 03:30 UTC on 23 March. As events began to merge into continuous tremor [Figure 9] the STA/LTA detector broke down and there is an abrupt decline in event rate, causing an end of swarm alarm to be issued about 20 minutes before the first explosive eruption at 06:34 UTC. The tremor alarm system does a good job of detecting explosion-related tremor, though latency is evident.

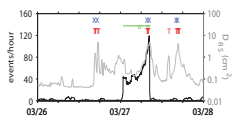


Figure 6: Elevated tremor was recorded from 15:00 UTC on 26 March for a period of 24 hours, during which 6 explosions occured. All were detected by the tremor alarm system. Within this period a swarm occurred with a rapid onset and end. This swarm escalated significantly causing two swarm escalation alarms to be issued.

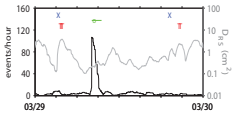


Figure 7: An even more abrupt swarm occurred on 29 March, lasting about 1.5 hours. This is probably the example that best shows the latency that can result. The swarm start and swarm escalation alarms are clearly late. Tremor alarms are issued late because the timewindow of 60 minutes includes previous peaks in D_{RS}.

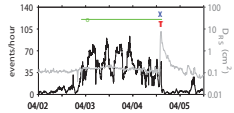


Figure 8: The swarm episode from 2-4 April was similar to that on 21-23 March with a gradual onset, duration of about 2 days, and a transition from swarm to tremor (marked by a swarm-end and tremor alarm) immediately before an explosive eruption.

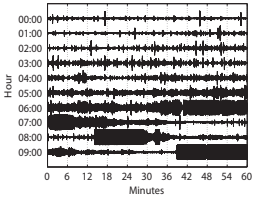


Figure 9: IceWeb pseudo-helicorder plot showing the transition from intensifying swarm to continuous tremor and explosive eruptions on 23 March 2009. Station REF.

RESULTS 4

The tremor alarm system detected the escalation in seismicity on 25 January, further escalations on 26 and 27 February, and then 30 of the 31 explosions between 23 March and 4 April.

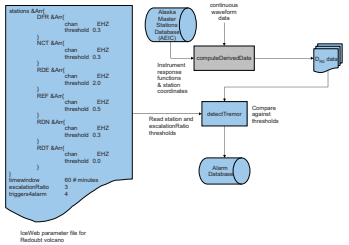
The swarm alarm system detected the 5 main swarm episodes which occurred 26-27 February, 21-23 March, 27 March, 29 March and 2-4 April.

There were no false alarms. Noise has to affect multiple stations before it can cause swarm or tremor alarms to be falsely declared.

FURTHER WORK 5

- Do these volcano-seismic alarm systems work well for periods of unrest at other Alaskan volcanoes?
- Reduce the latency between significant seismicity occurring and an alarm being issued, without increasing the alarm rate.
- Make it easier to "tune" thresholds.

ICEWEB TREMOR ALARM SYSTEM



IceWeb is a web-based real-time seismic monitoring system which has been operational since July 1998. It was designed for the AVO Duty Seismologist. detectTremor compares thresholds to real-time reduced displacement (D_{RS}) data. A station triggers when the threshold defined in the parameter file is exceeded and there has been a factor of 3 increase within the past 60 minutes. If at least 4 stations trigger simultaneously, detectTremor declared a tremor alarm, and writes it to the alarm database. (All these parameters are configurable).

IceWeb includes several pre-generated image-based products which then allow the Duty Seismologist to respond rapidly, from the comfort of home:

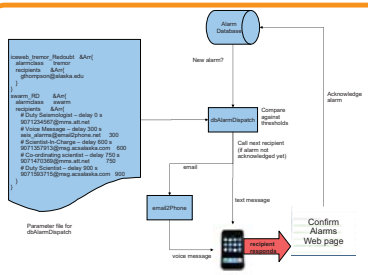
- Reduced displacement plots (for multiple time periods)
- 10-minute multi-stations spectrograms
- Spectrogram mosaics
- Daily spectrograms
- Pseudo-helicorder plots (optional)
- Sound files of the seismic data linked to spectrogram panels (optional)

The entire system was designed to be configurable via a web interface called the "IceWeb Setup Utility". The idea of this is to allow the Duty Seismologist to switch off a noisy station, that is generating false alarms. Or to raise the thresholds during a period of increasing seismicity.

IceWeb has been used to monitor up to 32 Alaskan volcanoes, and the 10-minute spectrograms have been a primary monitoring tool used by AVO scientists since 1998.

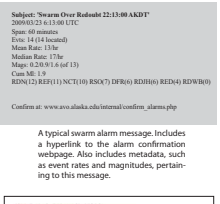
The tremor alarm system was not used between 2000 and 2008 - though activated, the alarm messages were going to an unmonitored email account. During the early stages of Redoubt unrest it was modified to write alarm messages into the alarm database so they would be managed by the generic alarm management system.

GENERIC ALARM MANAGEMENT SYSTEM



The program dbAlarmDispatch monitors the alarm database, and whenever a new record is added which matches one of the alarm names specified in the dbAlarmDispatch parameter file, that alarm message is dispatched. The recipients list describes a call-down sequence. In the case of a swarm_RD alarm shown in the parameter file, the message is sent immediately to the Duty Seismologist, and includes a link to the alarm confirmation webpage. If he/she acknowledges the alarm promptly have elapsed, further calldown is cancelled. Otherwise further recipients will be contacted after 300, 600, 750 and 900 seconds, or until the alarm is acknowledged.

The email2phone service allows the text message to be converted to a voice-mail message and left on a landline or cellphone.



A typical swarm alarm message. Includes a hyperlink to the alarm confirmation webpage. Also includes metadata, such as event rates and magnitudes, pertaining to this message.

The alarm confirmation webpage first prompts the recipient to enter their name, and take responsibility for responding to this particular alarm.

The alarm confirmation webpage shows in red any alarms that have not been acknowledged. Clicking on the button in the 'Key' field, acknowledges it. All swarm alarms relating to the same swarm have the same key.

Time (UTC)	Recipient	Delay (s)
2009/03/23 6:14:15	avo_alarms@avo.alaska.edu	15
2009/03/23 6:14:16	glennthompson1971@gmail.com	74
2009/03/23 6:16:29	9074747424@mms.att.net	207

This alarm was acknowledged by jpdixon at 2009/03/23 06:19:24 UTC

By clicking on the 'show' hyperlink, the calldown for a particular alarm can be displayed, as well as name of the person who acknowledged it.