Real Time Tracking of Earthquake Swarms

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University of Alaska Fairbanks

1. Motivation
2. Method (Real-time system)
   - Event catalog
   - Swarm tracking module
   - Alarm manager
3. Results
   - Okmok 2008
   - Redoubt 2009
4. Conclusions

1. Background
2. AVO Swarm alarm system
   - Real-time catalog
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   - Alarm manager
3. Application to Redoubt 2009
4. Other applications
   - Okmok 2008
   - St Helens 2004
   - Yellowstone 2010
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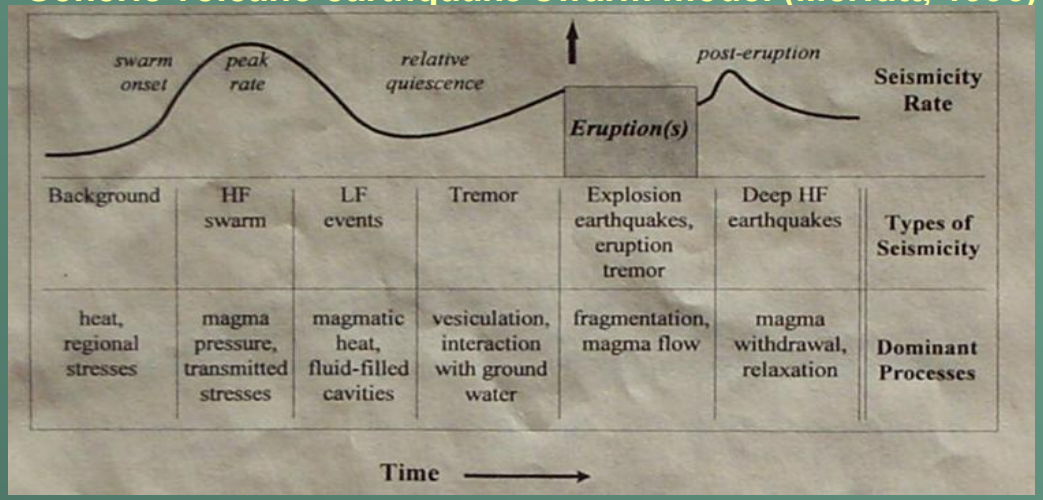
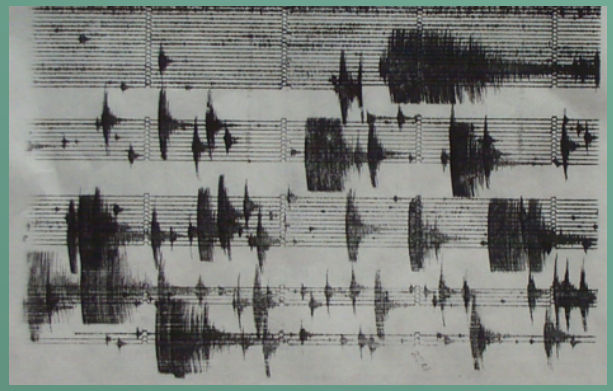
Why develop alarm systems?

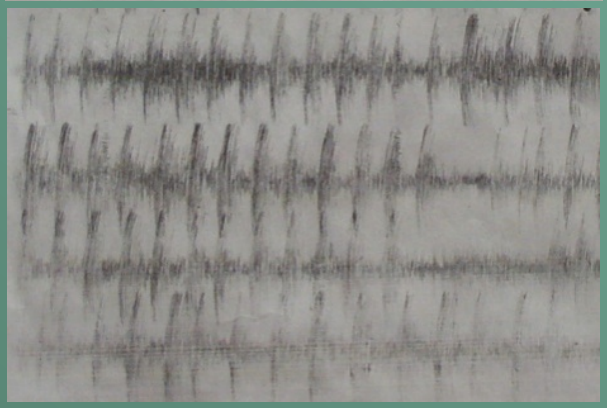
- Help prevent loss of life & injuries
- Rapid notification
- Mitigate burn out of observatory staff during prolonged unrest
- Inexpensive to operate
- Objective
- Effective replacement for periodic seismic checks (e.g. every 2 hours)
- Complementary to 24/7 visual monitoring
- Essential without it

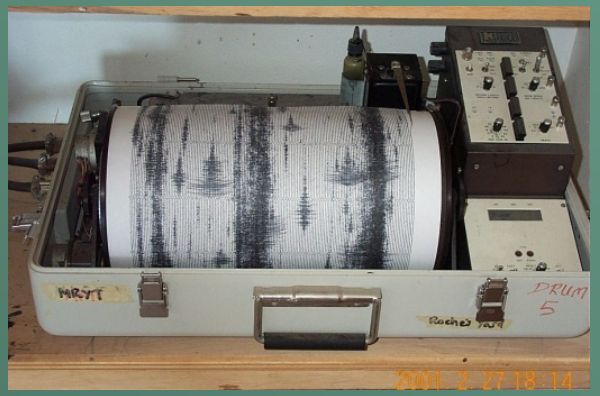
Seismic precursors to eruptions

Generic volcano earthquake swarm model (McNutt, 1996)









EYJAFJALLAJOKULL (SI/USGS Weekly Volcanic Activity Report 14-20 April 2010)

- **"This eruptive phase was preceded by a swarm of earthquakes and the onset of tremor"**
- **Ella-fyat-la-yo-kut (Island-Mountain-Glacier)**

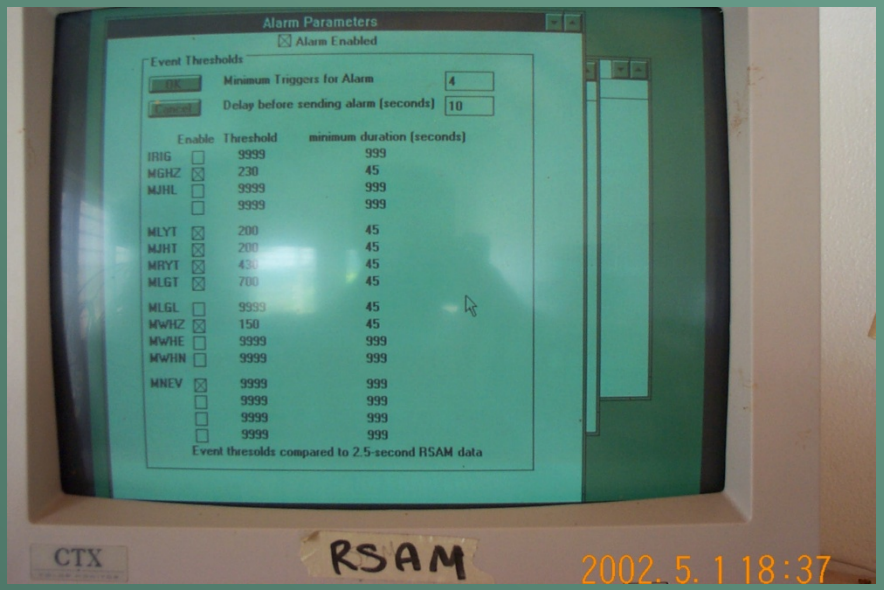
Early warning systems

Explosive eruptions

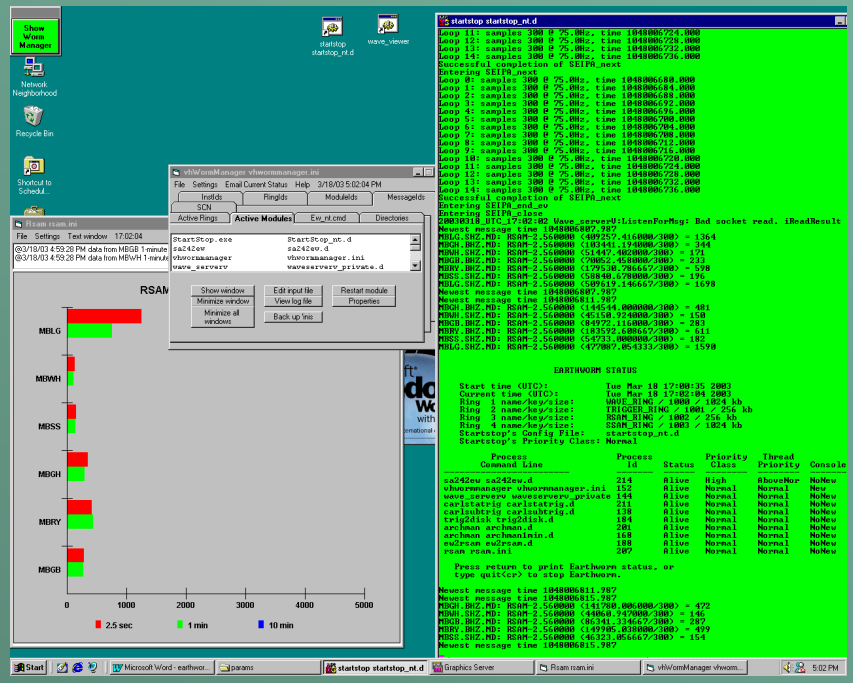
Pyroclastic flows & surges

Lahars

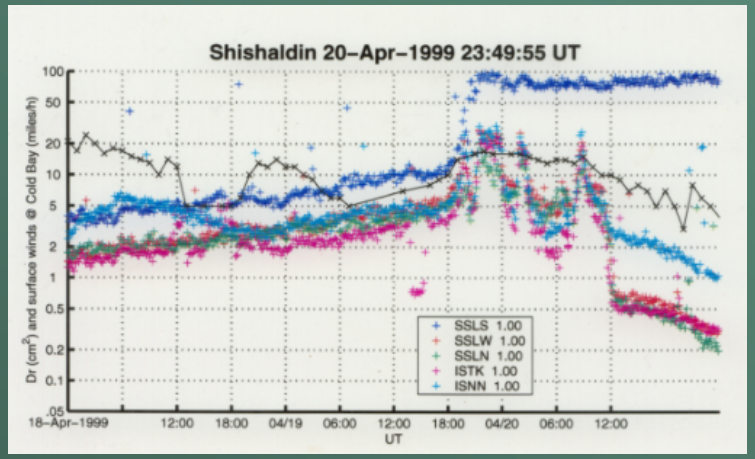
Minutes to sound sirens & inform local/aviation authorities



RSAM (?-2000)



Glowworm (2000-pres.)



IceWeb (1998-pres.)

Event classifier

↓

Real-time magnitude

↓

Amplitude-based location

MVO alarm system (2001-2003)

Okmok 12th July 2008

- VEI 4 eruption
- Less than 5 hours precursory seismicity
- Seismicity only ramped up significantly 1 hour prior to eruption
- AVO – visual data checks every 12 hours

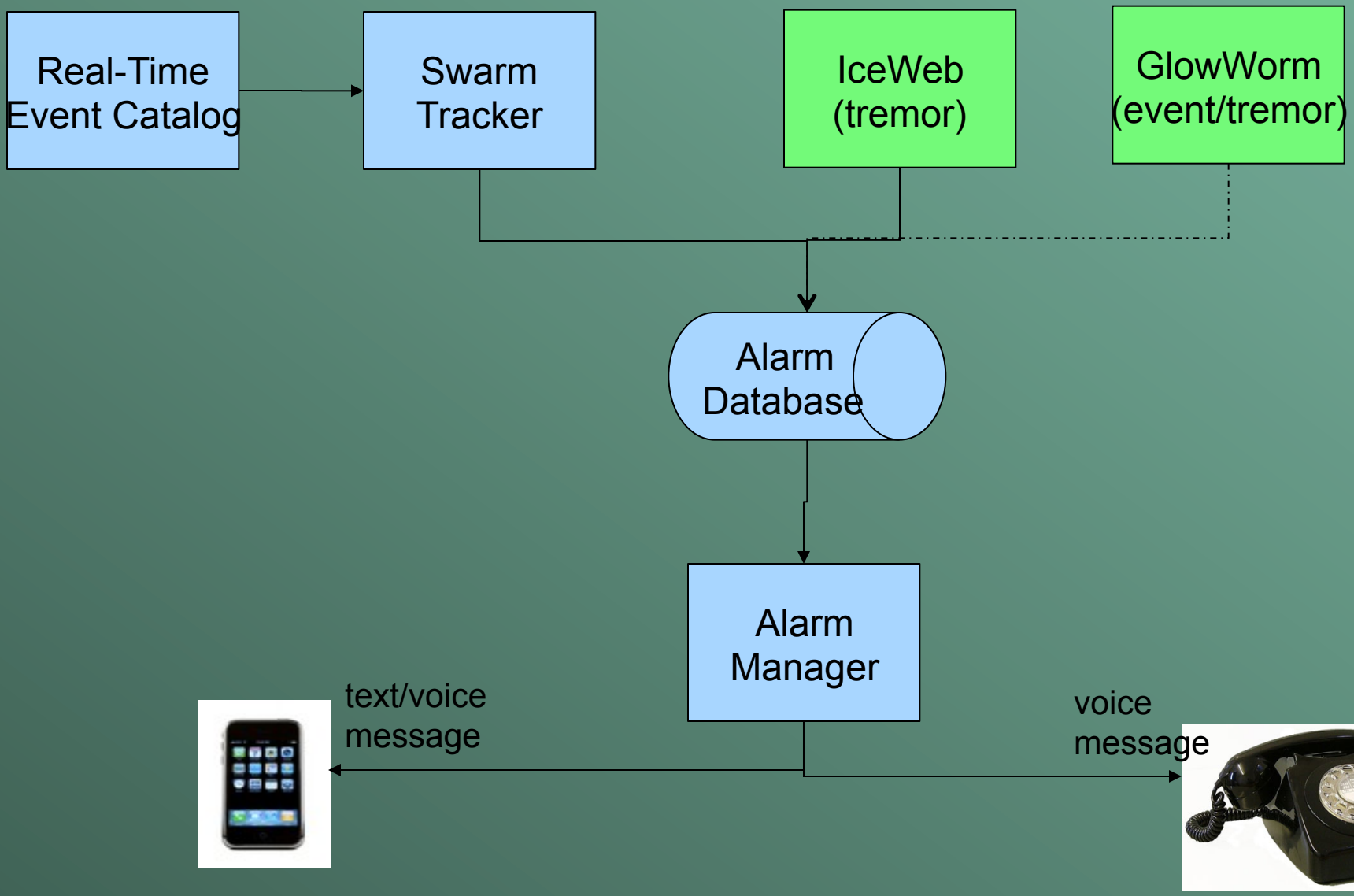
Swarms – what do we want to know?

We want to detect (significant) c*hanges*.

- **START of swarm**
- **END of swarm (merge into tremor / eruption imminent or occuring ?)**
- **Significant ESCALATION (intensification) of a swarm**
- **Reminder of an ongoing swarm?**

We don't care if the events are in the same place.

Real-time system



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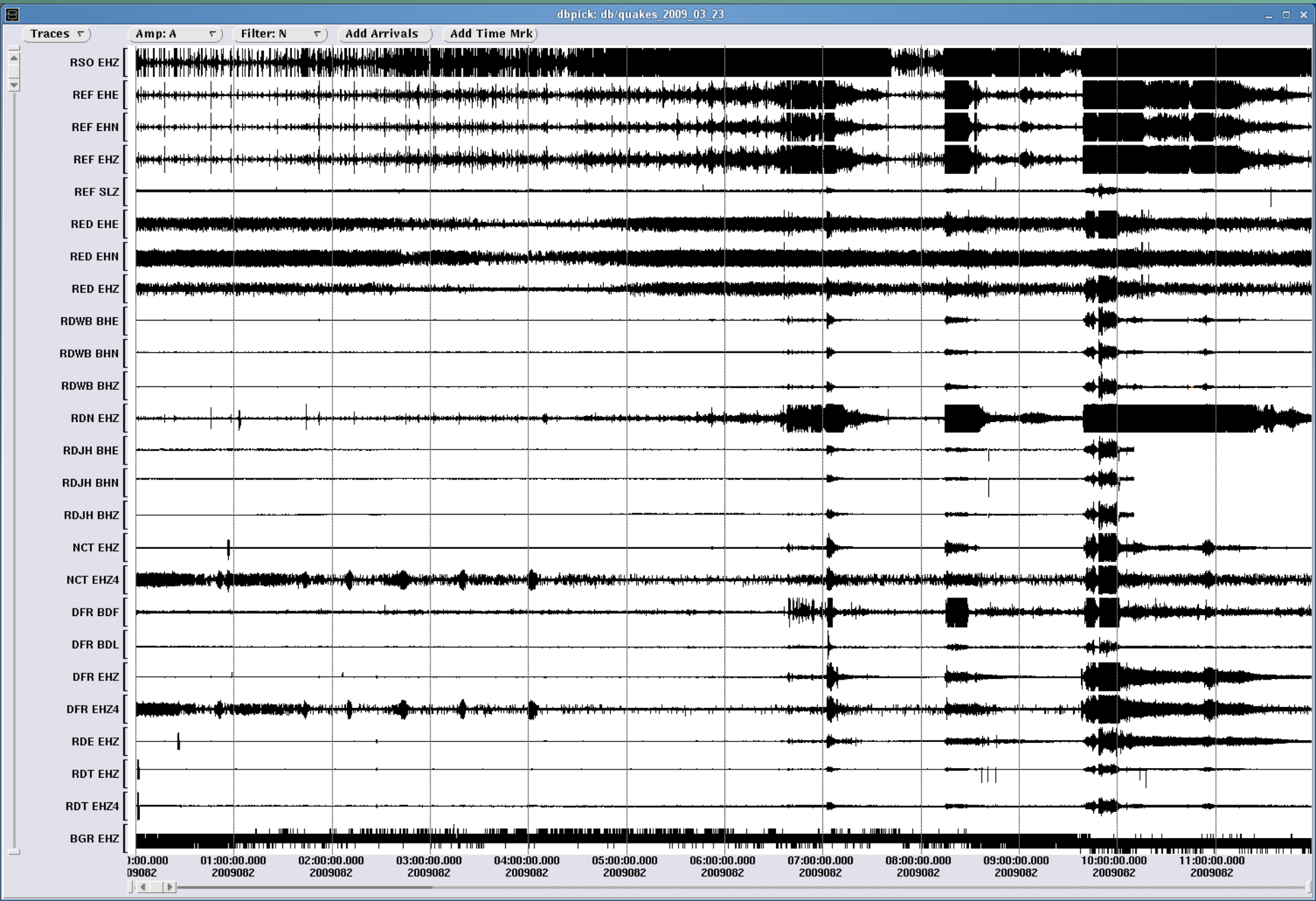
Real-time event catalog

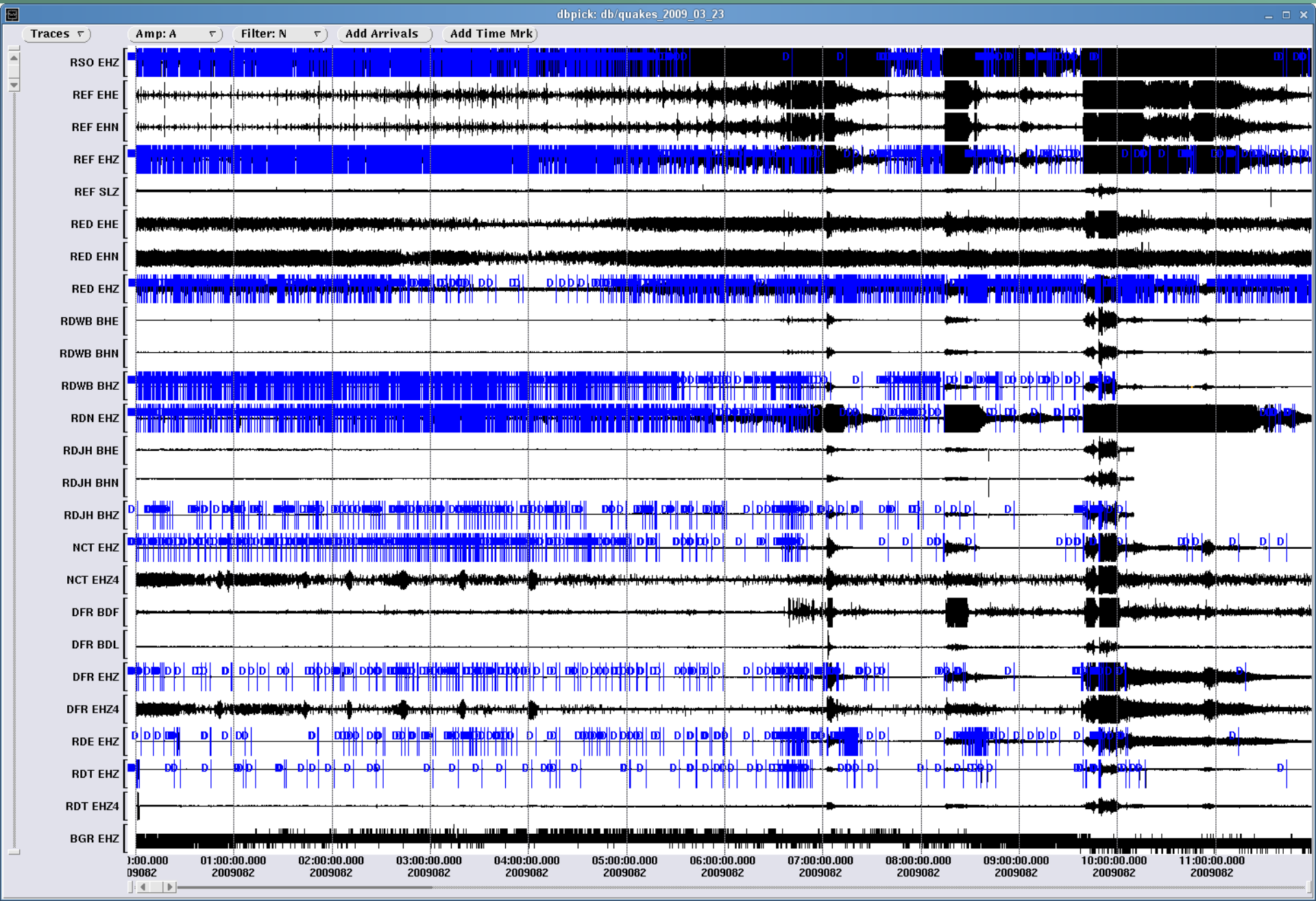
Provides:

- Event time
- magnitude
- location (which volcano)
- Quality control – minimise false alarms:
    - simultaneous detections on at least 4 stations, which locate within (say) 15 km of a volcano
    - AVO seismic data – lots of spikes/dropouts:
        - 12 bit analog telemetry
        - little solar energy for many months
        - harsh environment
        - long telemetry paths

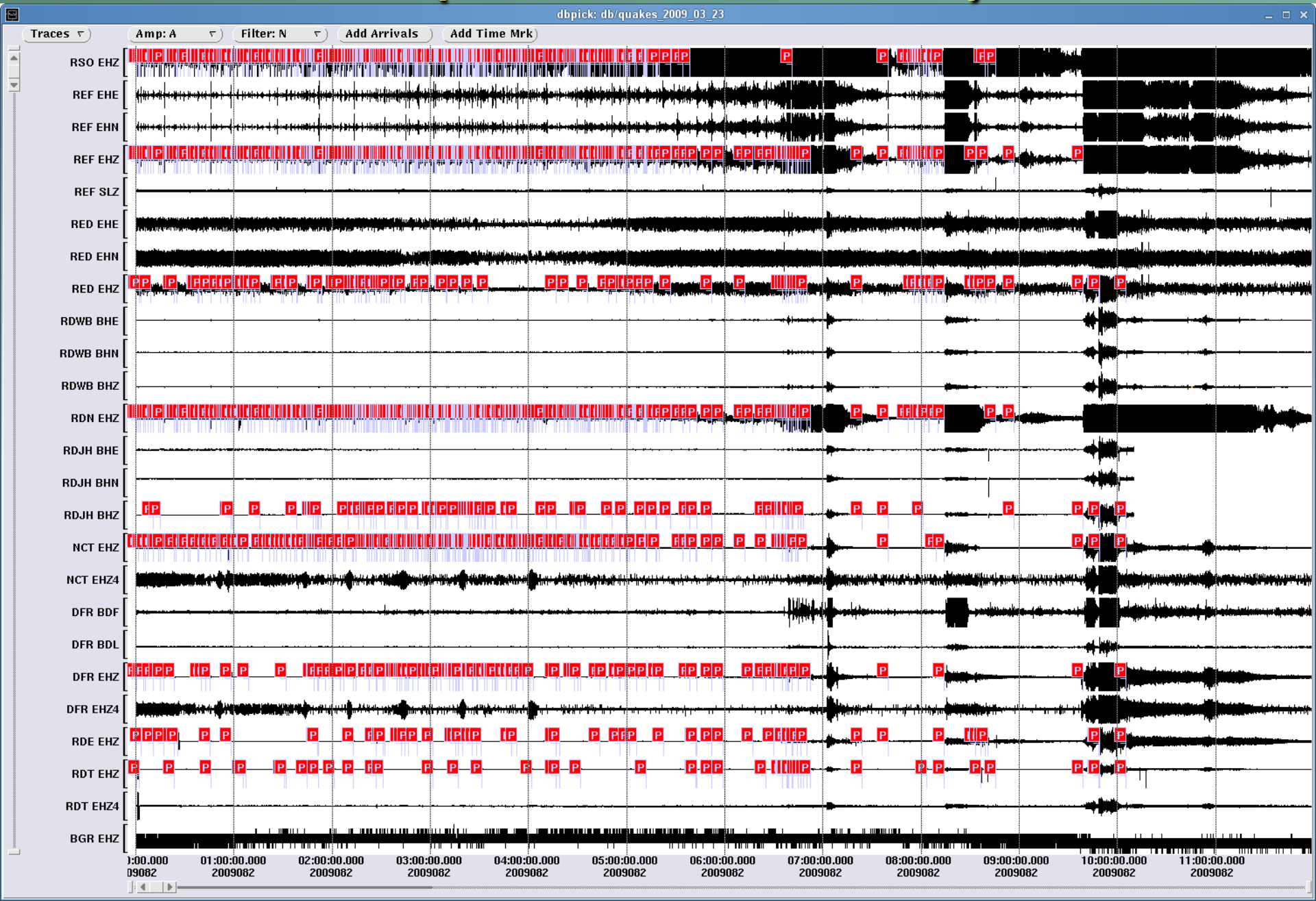
Waveform data



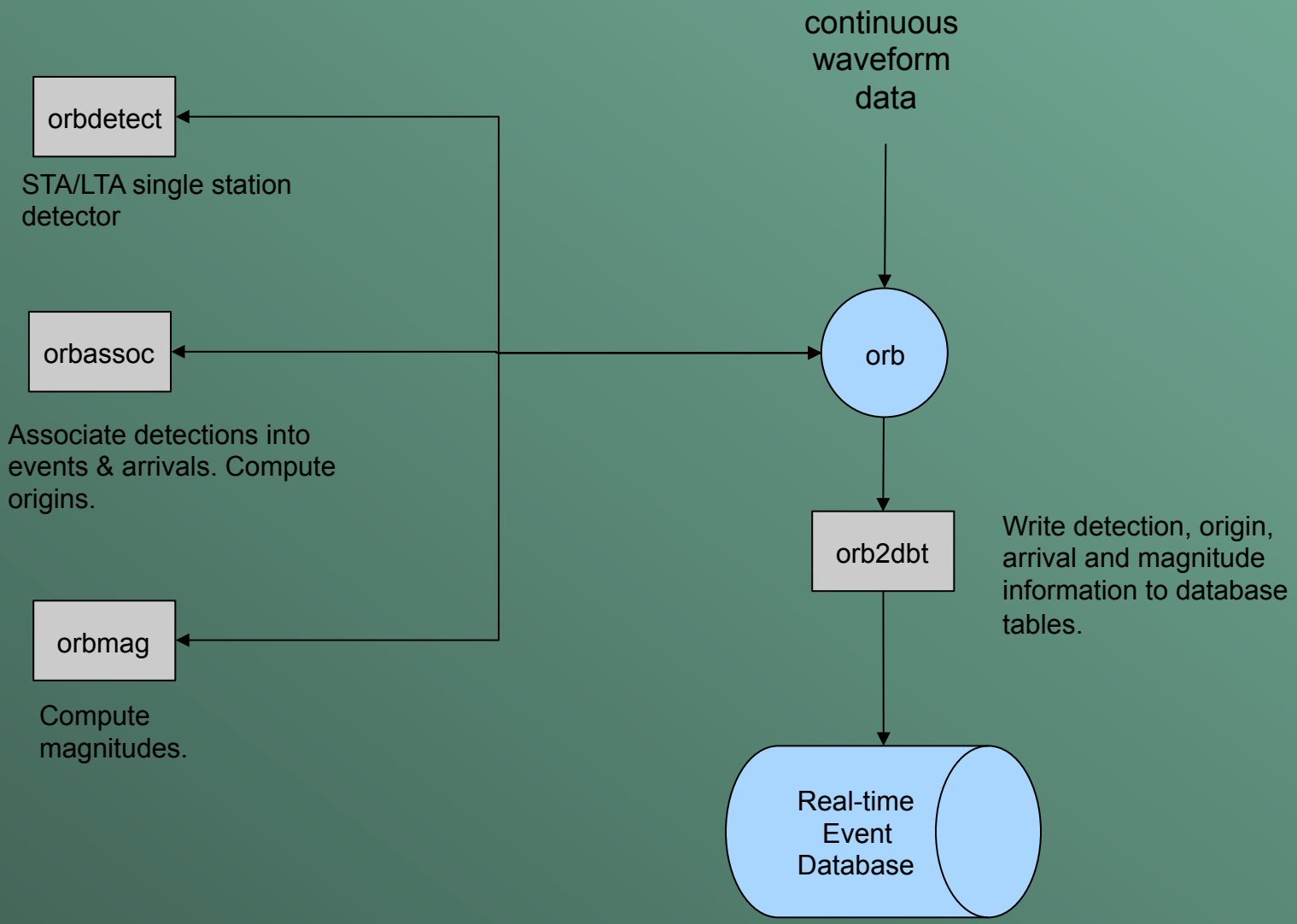
STA/LTA detector



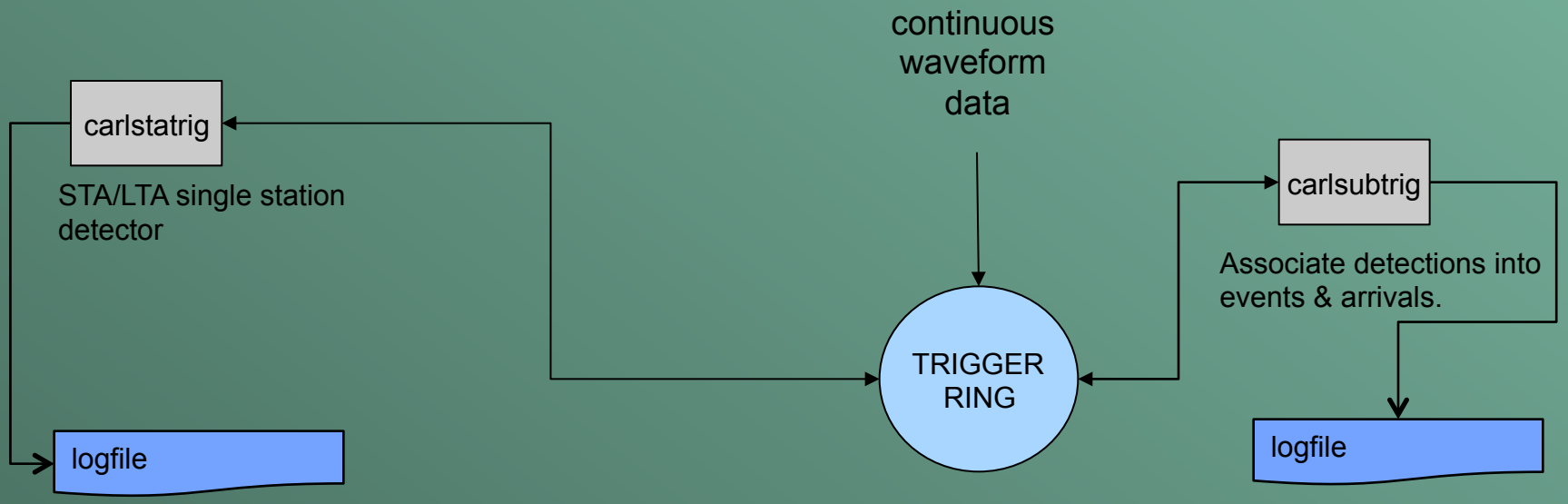
Associator (events + arrivals)



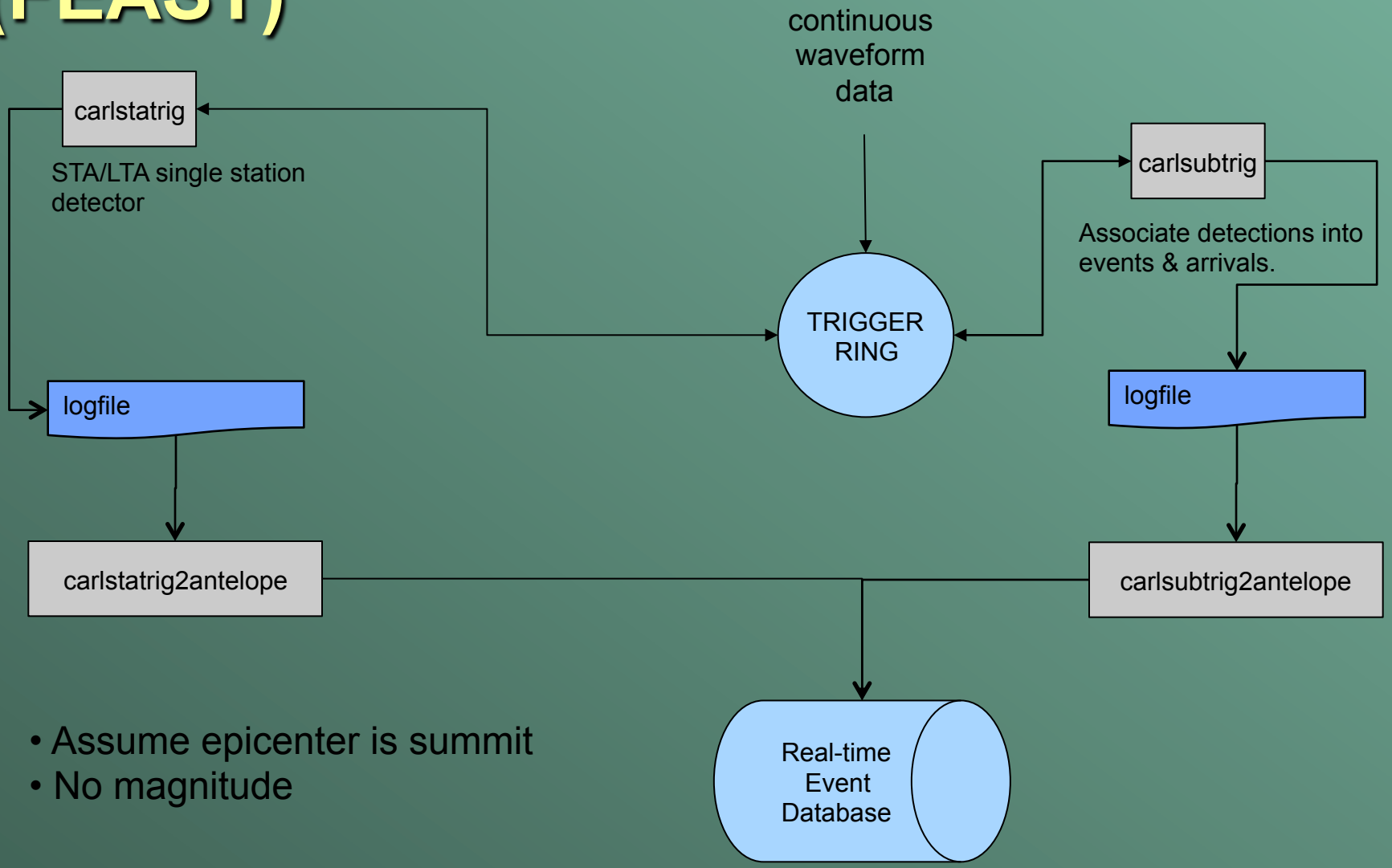
Real-time catalog: Antelope



Real-time catalog: Earthworm



Real-time catalog: Earthworm (FEAST)



- Assume epicenter is summit
- No magnitude

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5. Further work
   - FEAST swarm alarms
   - Single station alarms?
   - Generic alarm algorithm?

Swarm tracking system: Metrics

Every 5 minutes, read the last 60 minutes of the event catalog & compute:

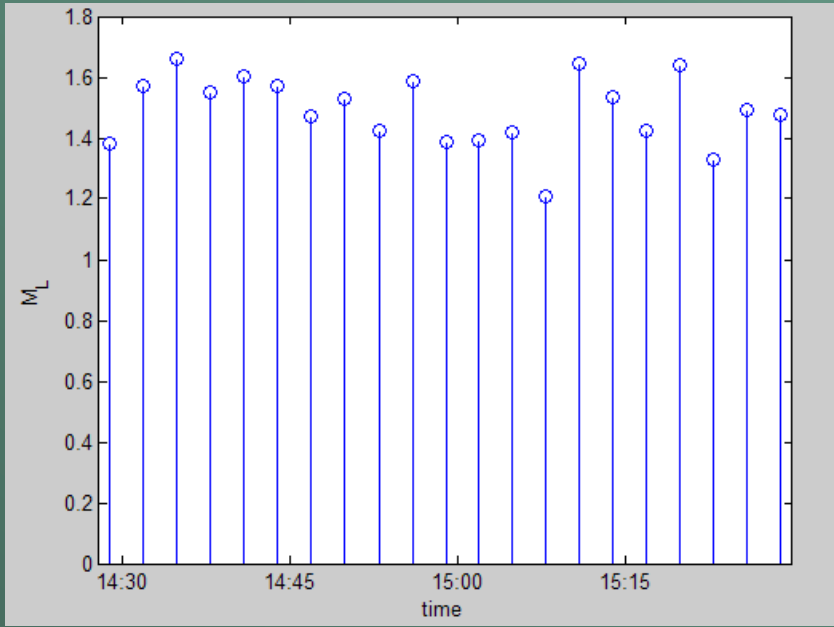
- **mean event rate**
- **median event rate (reciprocal of median event interval)**
- **mean magnitude**
- **cumulative magnitude**

$\log_{10}(\text{Energy}) = 1.5\ M_L + 4.7$

Energy release rate

Swarm tracking system: Metrics

20 events in 1 hour, 3 minutes apart
M_L 1.5 +/- 0.3



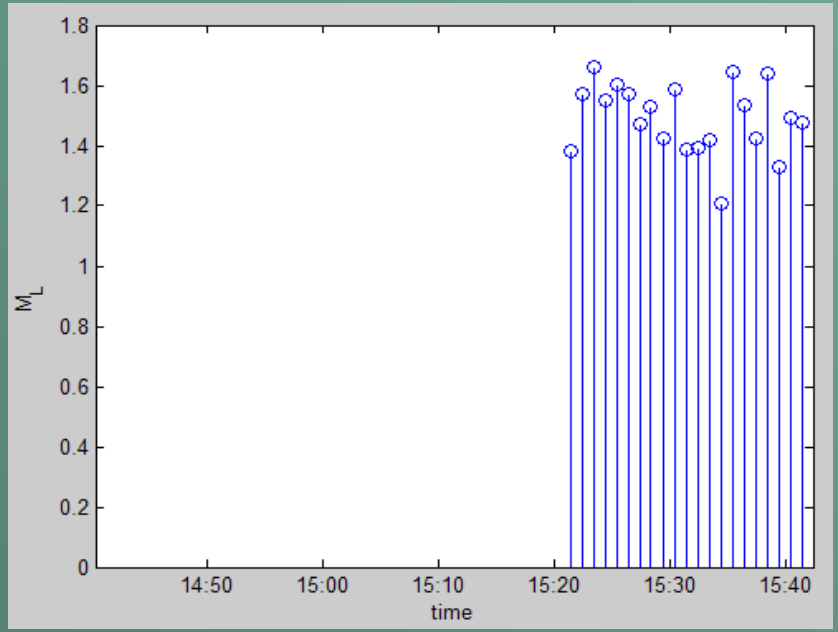
Mean rate = 20

Median rate = 20

Mean ML = 1.5

Cumulative ML = 2.4

20 events in 1 hour, 1 minute apart
M_L 1.5 +/- 0.3



Mean rate = 20

Median rate = 60

Mean ML = 1.5

Cumulative ML = 2.4

Swarm tracking system: Parameters

- Timewindow
- Thresholds for swarm start, escalation and end in terms of:
  - Mean rate
  - *Median rate (optional)*
  - *Mean magnitude (optional)*
  - *Cumulative magnitude (optional)*
- Reminder time

Alarm type	Mean rate	Median rate	Mean ML	Cumulative ML
start	16	32	1.0	1.2
end	8	16	0.8	1.0
Escalation 1	32	64	1.2	1.4
Escalation 2	64	128	1.4	1.6

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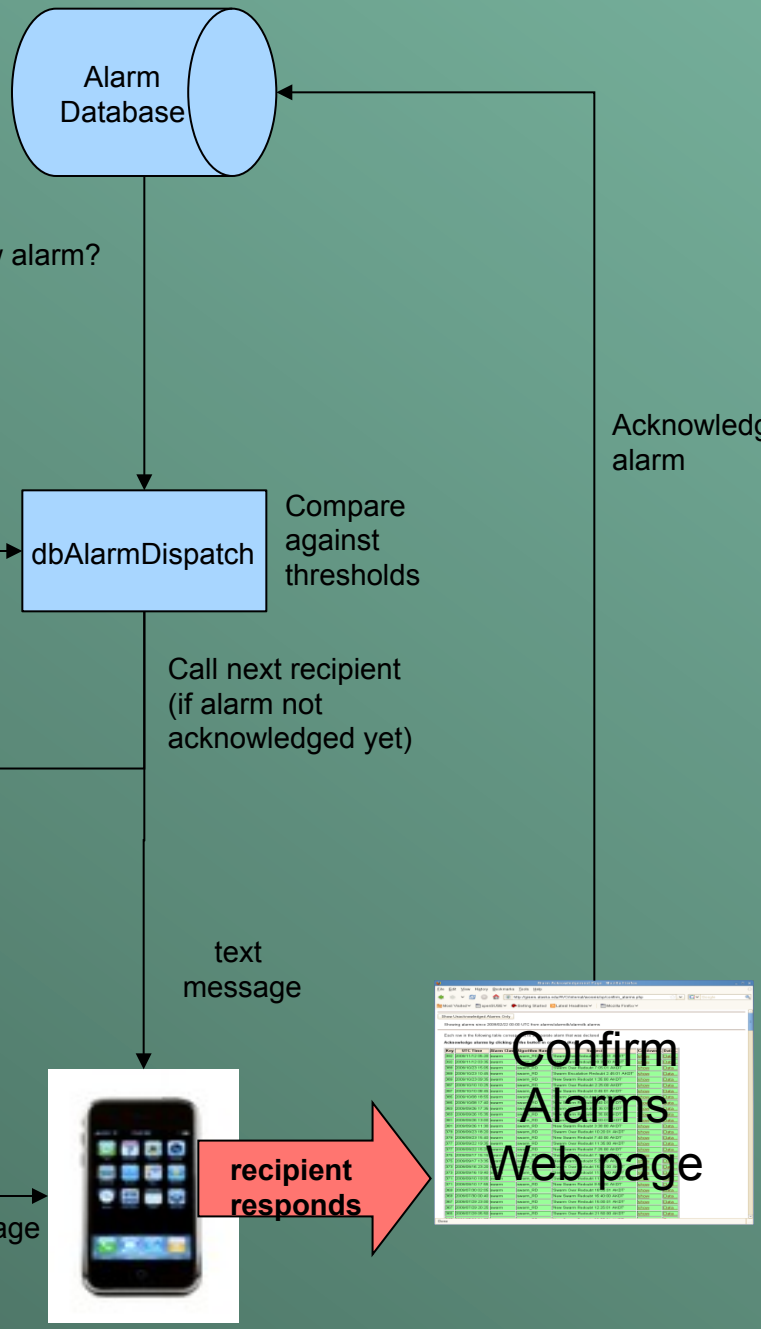
Alarm Manager

```
iceweb_tremor_Redoubt   &Arr{
  alarmclass      tremor
  recipients      &Arr{
    gthompson@alaska.edu
  }
}
swarm_RD        &Arr{
  alarmclass      swarm
  recipients      &Arr{
    # Duty Seismologist – delay 0 s
    9071234567@mms.att.net
    # Voice Message – delay 300 s
    seis_alarms@email2phone.net     300
    # Scientist-In-Charge – delay 600 s
    9071357913@msg.acsalaska.com    600
    # Co-ordinating scientist – delay 750 s
    9071470369@mms.att.net          750
    # Duty Scientist – delay 900 s
    9071593715@msg.acsalaska.com    900
  }
}
```

Parameter file for dbAlarmDispatch



Alarm Manager

- Generic (independent)
- Can handle alarms of any type (swarm, tremor, diagnostic, GPS, remote sensing…)
- Multiple recipients (cellphones)
- Progressive calldown
- First recipient – Duty Seismologist – changes weekly
- Any recipient can acknowledge alarm on a web page
- Once acknowledged, calldown is cancelled
- Information is logged
- Calls to landlines possible through 3rd party services

Progressive Calldown

recipient	address	delay time (s)
Duty Seismologist	9071234567@mms.att.net	0
Glenn	9071234567@mms.att.net	100
Mike	9071234567@mms.att.net	200
Ophelia	9071234567@mms.att.net	300
Helena	9071234567@mms.att.net	400
Celso	9071234567@mms.att.net	500
Duty Scientist	9071234567@mms.att.net	600
Scientist In Charge	9071234567@mms.att.net	700

```
iceweb_tremor_Redoubt   &Arr{
   alarmclass      tremor
   recipients      &Arr{
      gthompson@alaska.edu
   }
}

swarm_RD        &Arr{
   alarmclass      swarm
   recipients      &Arr{
      # Duty Seismologist – delay 0 s
      9071234567@mms.att.net
      # Voice Message – delay 300 s
      seis_alarms@email2phone.net     300
      # Scientist-In-Charge – delay 600 s
      9071357913@msg.acsalaska.com    600
      # Co-ordinating scientist – delay 750 s
      9071470369@mms.att.net          750
      # Duty Scientist – delay 900 s
      9071593715@msg.acsalaska.com    900
   }
}
```

Tremor alarms

Swarm alarms

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

Subject: 'Swarm Over Redoubt 22:13:00 AKDT'
2009/03/23 6:13:00 UTC
Span: 60 minutes
Evts: 14 (14 located)
Mean Rate: 13/hr
Median Rate: 17/hr
Mags: 0.2/0.9/1.6 (of 13)
Cum Ml: 1.9
RDN(12) REF(11) NCT(10) RSO(7) DFR(6) RDJH(6) RED(4) RDWB(0)

Confirm at: www.avo.alaska.edu/internal/confirm_alarms.php

Alarm manager: acknowledgement

Showing alarms since 2009/02/22 00:00 UTC from alarms/alarmdb/alarmdb.alarms

Each row in the following table corresponds to a separate alarm that was declared

Acknowledge alarms by clicking on the button in column 1 (Key)

Key	UTC Time	Alarm Class	Algorithm Name	Subject	Calldown...	Data...
32	2009/03/22 22:50	swarm	swarm_RD	'Swarm Continuing Redoubt 14:50:00 AKDT'	show	Data...
32	2009/03/22 19:45	swarm	swarm_RD	'Swarm Continuing Redoubt 11:45:00 AKDT'	show	Data...
32	2009/03/22 16:40	swarm	swarm_RD	'Swarm Continuing Redoubt 8:40:00 AKDT'	show	Data...
32	2009/03/22 13:35	swarm	swarm_RD	'Swarm Continuing Redoubt 5:35:00 AKDT'	show	Data...
32	2009/03/22 10:30	swarm	swarm_RD	'Swarm Continuing Redoubt 2:30:00 AKDT'	show	Data...
32	2009/03/22 07:25	swarm	swarm_RD	'Swarm Continuing Redoubt 23:25:00 AKDT'	show	Data...
32	2009/03/22 04:20	swarm	swarm_RD	'Swarm Continuing Redoubt 20:20:00 AKDT'	show	Data...
32	2009/03/22 01:15	swarm	swarm_RD	'New Swarm Redoubt 17:15:00 AKDT'	show	Data...
28	2009/03/21 18:35	swarm	swarm_RD	'Swarm Over Redoubt 10:35:00 AKDT'	show	Data...
28	2009/03/21 16:25	swarm	swarm_RD	'Swarm Continuing Redoubt 8:25:00 AKDT'	show	Data...
28	2009/03/21 13:20	swarm	swarm_RD	'Swarm Continuing Redoubt 5:20:00 AKDT'	show	Data...
28	2009/03/21 10:15	swarm	swarm_RD	'New Swarm Redoubt 2:15:00 AKDT'	show	Data...
25	2009/03/21 09:50	swarm	swarm_RD	'Swarm Over Redoubt 1:50:00 AKDT'	show	Data...
25	2009/03/21 08:55	swarm	swarm_RD	'Swarm Continuing Redoubt 0:55:00 AKDT'	show	Data...
25	2009/03/21 05:50	swarm	swarm_RD	'New Swarm Redoubt 21:50:00 AKDT'	show	Data...

Alarm calldown

Time (UTC)	Recipient	Delay (s)
2009/03/23 6:14:15	seis_alarms@avo.alaska.edu	15
2009/03/23 6:14:16	glennthompson197@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.

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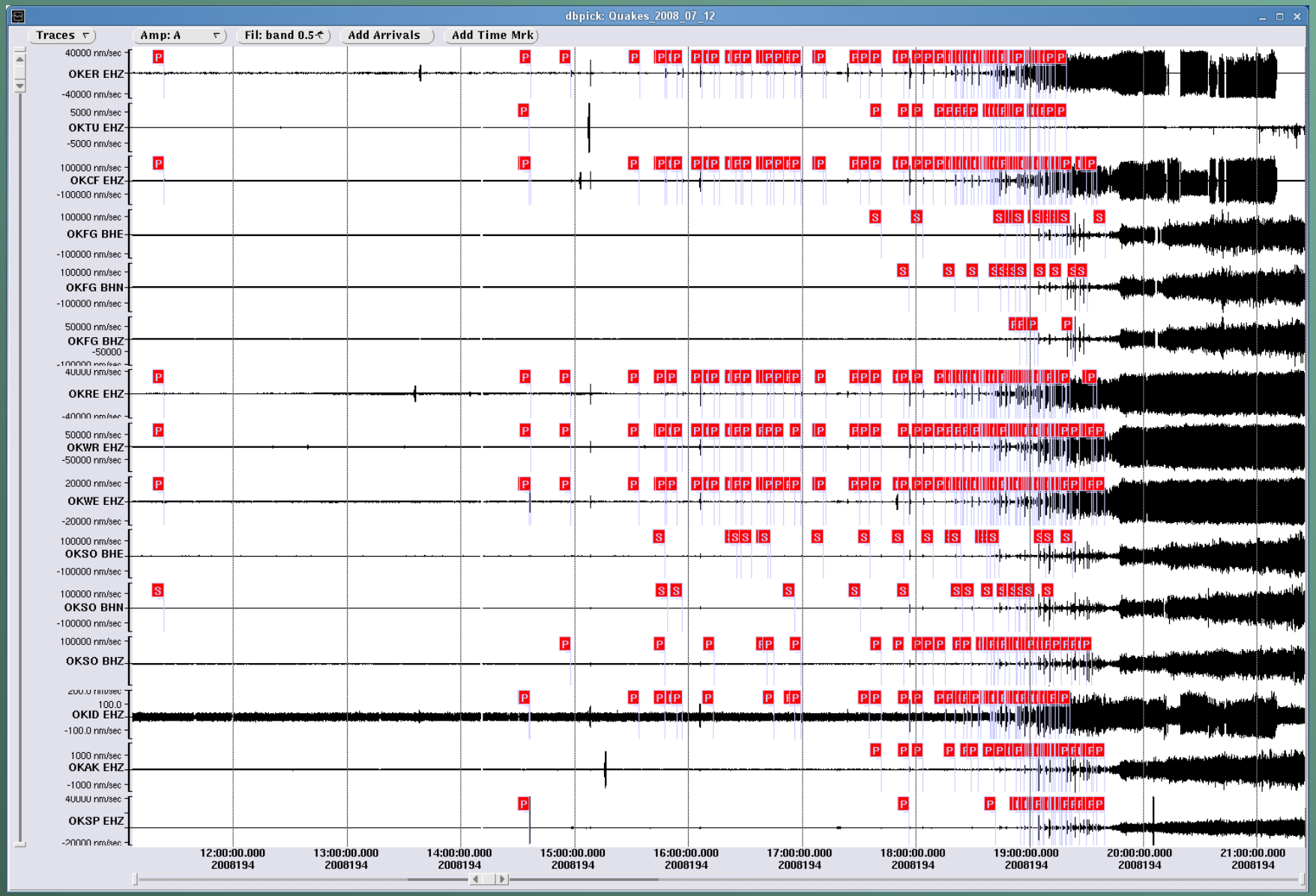
Okmok 2008: arrivals



Okmok 2008: Swarm tracking parameters

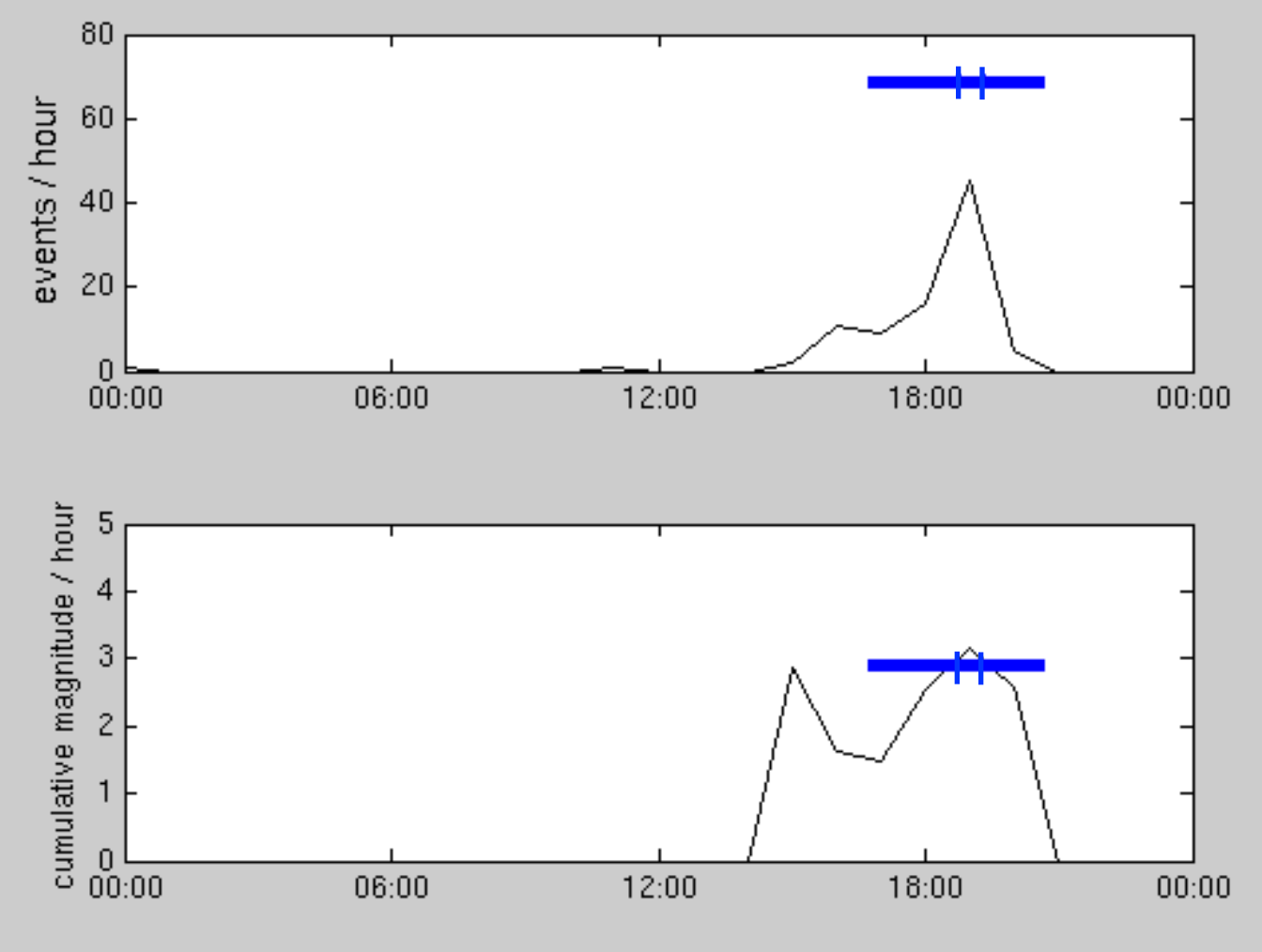
Timewindow = 60 minutes

Reminder time = 99999 minutes (none)

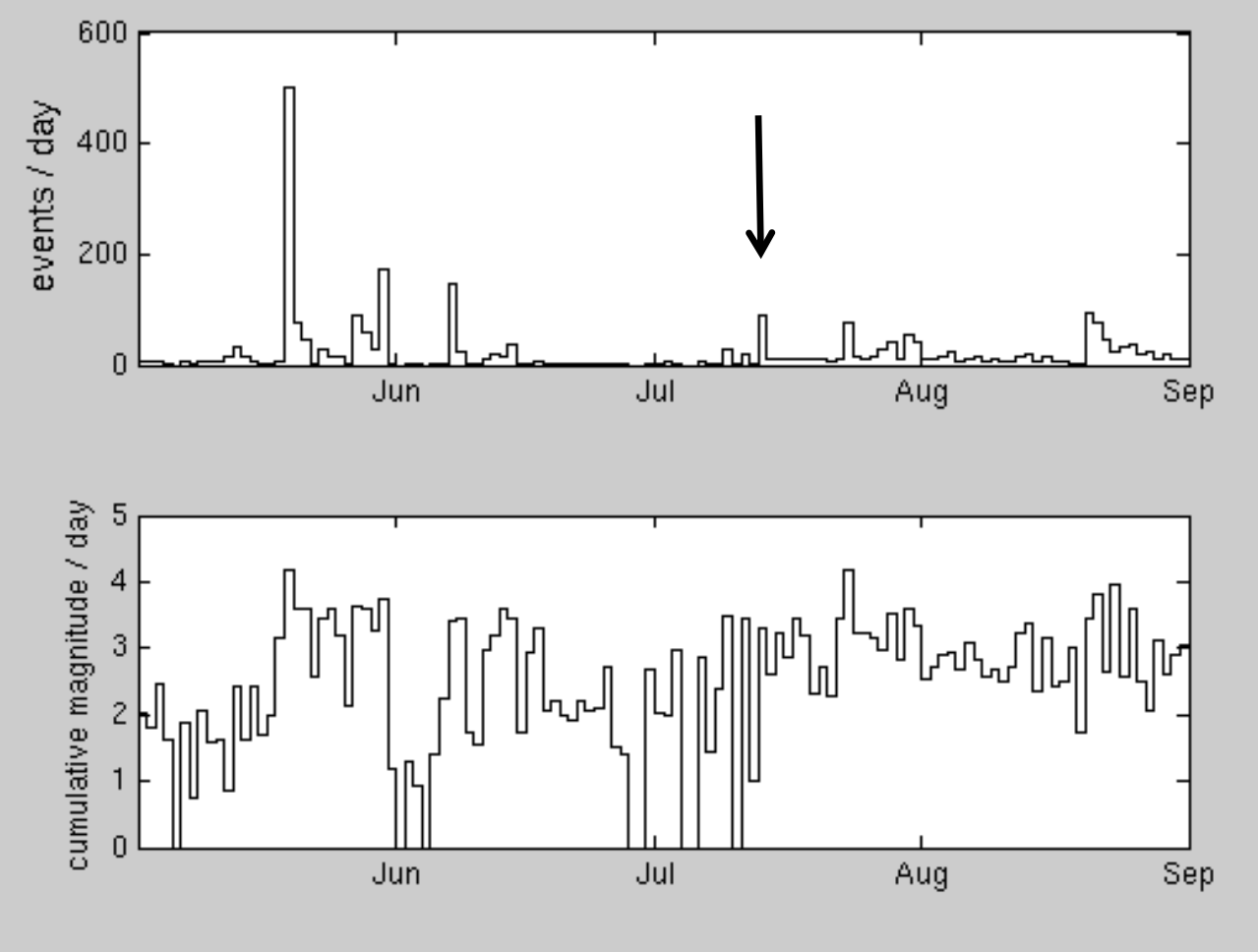
Alarm type	Mean rate	Median rate	Mean ML	Cumulative ML
start	12			
end	6			
Escalation 1	24			
Escalation 2	48			

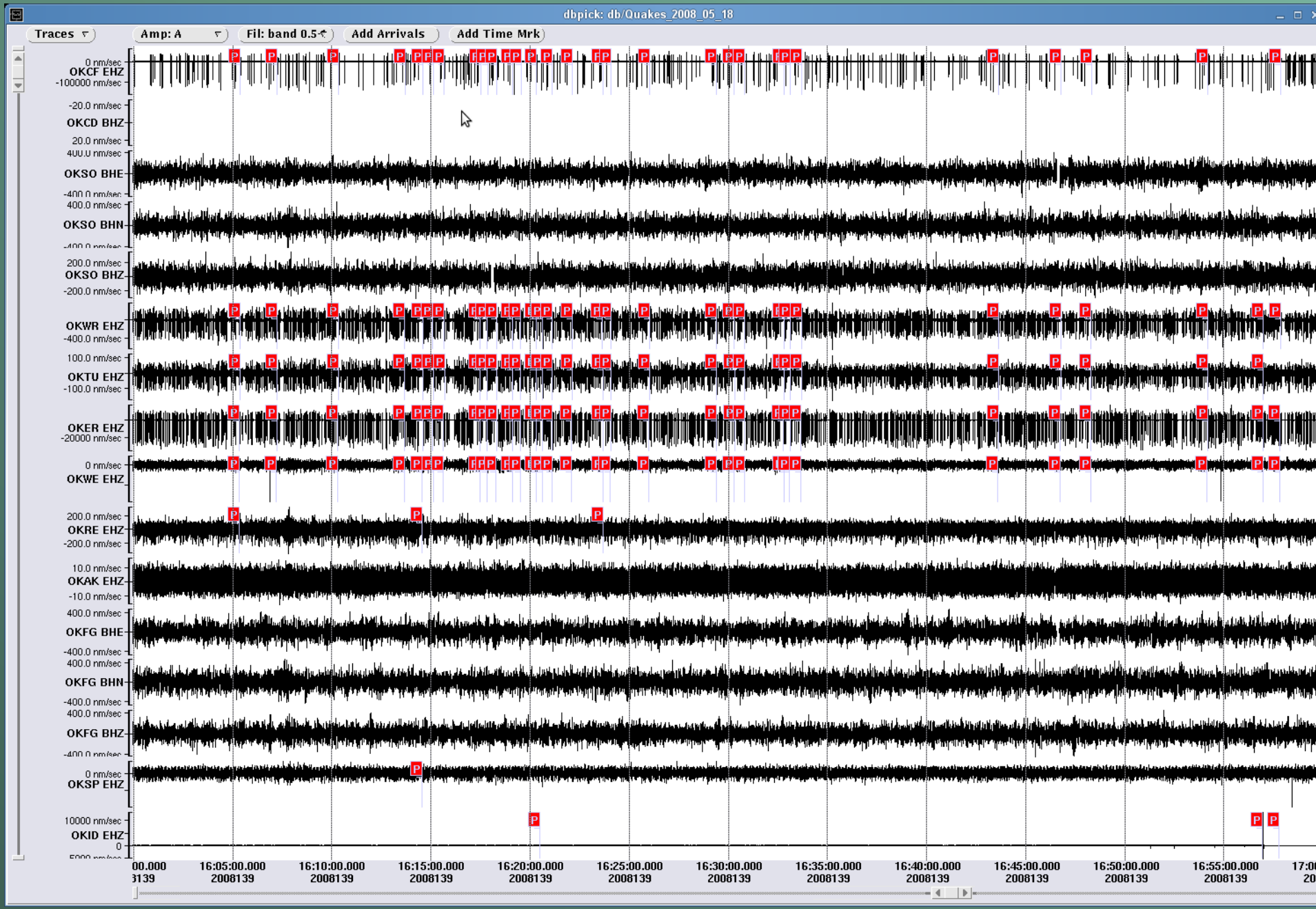
Okmok 2008: Results

12-Jul-2008 16:45:00 Start
12-Jul-2008 18:45:00 Escalation_1
12-Jul-2008 19:20:00 Escalation_2
12-Jul-2008 19:48:00 Eruption
12-Jul-2008 20:40:00 End



Okmok: event catalog May-Aug 2008




dbpick: db/Quakes_2008_05_18
Traces
Amp: A
Fil: band 0.5
Add Arrivals
Add Time Mrk
0 nm/sec
OKCF EHZ
-100000 nm/sec
-20.0 nm/sec
OKCD BHZ
20.0 nm/sec
400.0 nm/sec
OKSO BHE
-400.0 nm/sec
400.0 nm/sec
OKSO BHN
200.0 nm/sec
OKSO BHZ
-200.0 nm/sec
OKWR EHZ
-400.0 nm/sec
100.0 nm/sec
OKTU EHZ
-100.0 nm/sec
OKER EHZ
-20000 nm/sec
0 nm/sec
OKWE EHZ
200.0 nm/sec
OKRE EHZ
-200.0 nm/sec
10.0 nm/sec
OKAK EHZ
-10.0 nm/sec
400.0 nm/sec
OKFG BHE
-400.0 nm/sec
400.0 nm/sec
OKFG BHN
-400.0 nm/sec
400.0 nm/sec
OKFG BHZ
0 nm/sec
OKSP EHZ
10000 nm/sec
OKID EHZ
0
16:05:00.000
2008139
16:10:00.000
2008139
16:15:00.000
2008139
16:20:00.000
2008139
16:25:00.000
2008139
16:30:00.000
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16:40:00.000
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16:50:00.000
2008139
16:55:00.000
2008139

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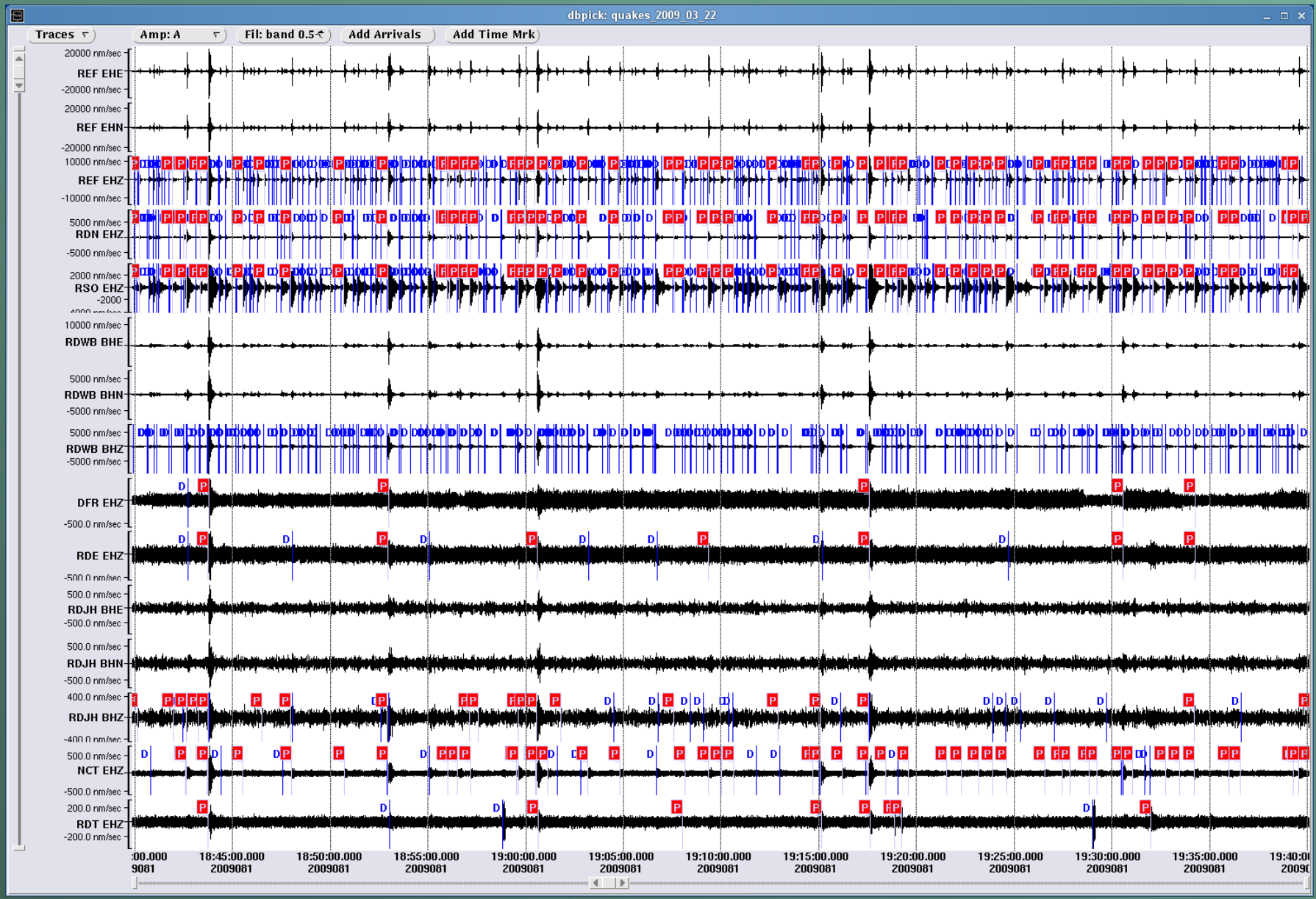
Redoubt 2009: event catalog



Redoubt 2009: Swarm tracking parameters

Timewindow = 60 minutes

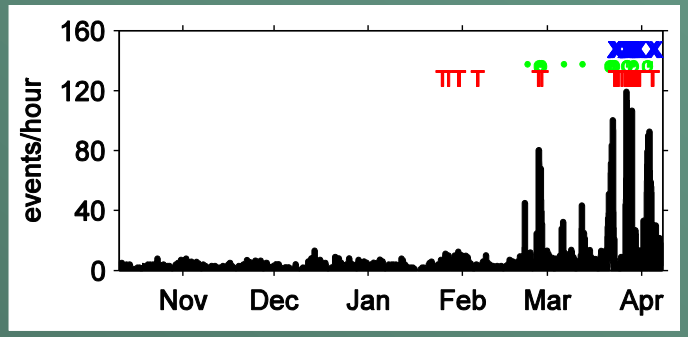
Reminder time = 99999 minutes (none)

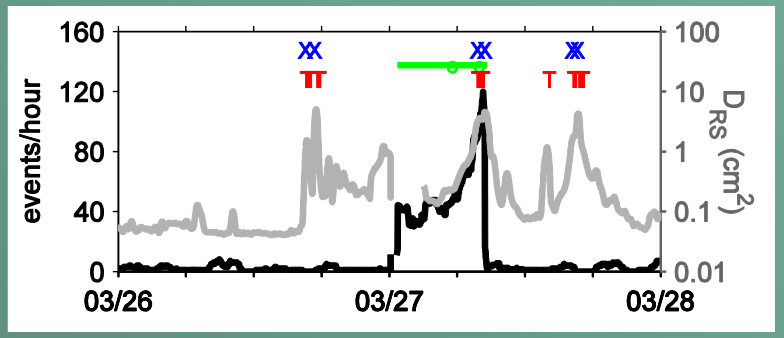
Alarm type	Mean rate	Median rate	Mean ML	Cumulative ML
start	16	32		
end	11	22		
Escalation 1	24	48		
Escalation 2	36	72		

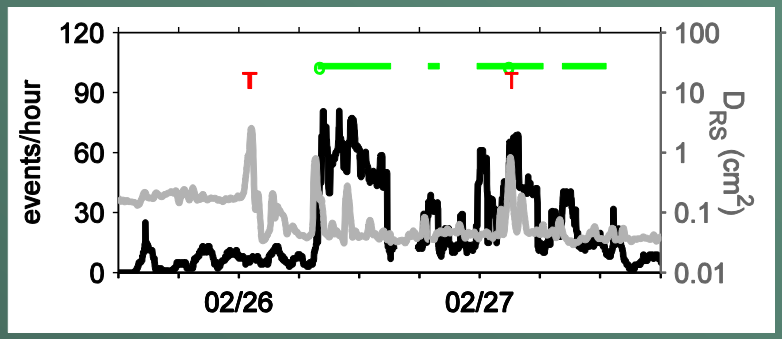
Redoubt 2009: Swarm episodes

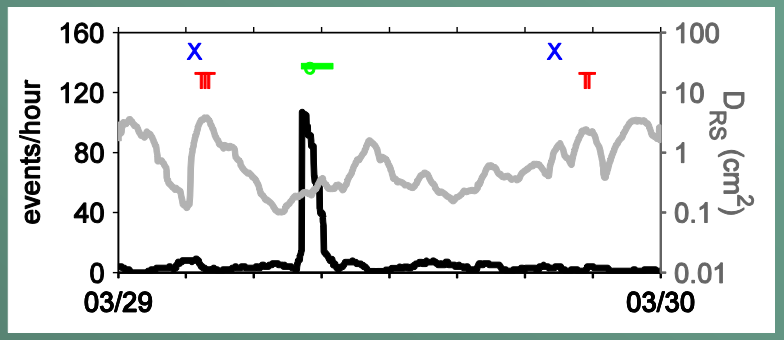
swarm	# events	Cumulative ML
25-28 Feb	815	3.3
19-25 Mar	1,793	3.7
26-29 Mar	410, 103	3.2
1-6 Apr	1,609	3.9

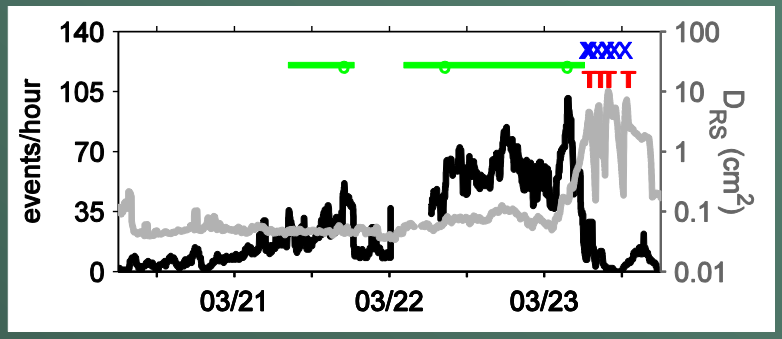
Redoubt 2009: swarms & tremor

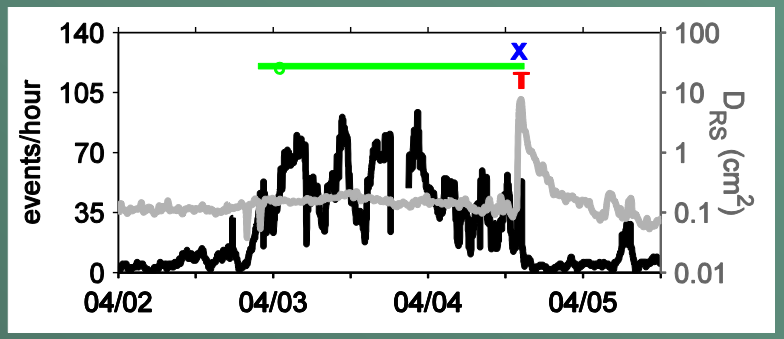




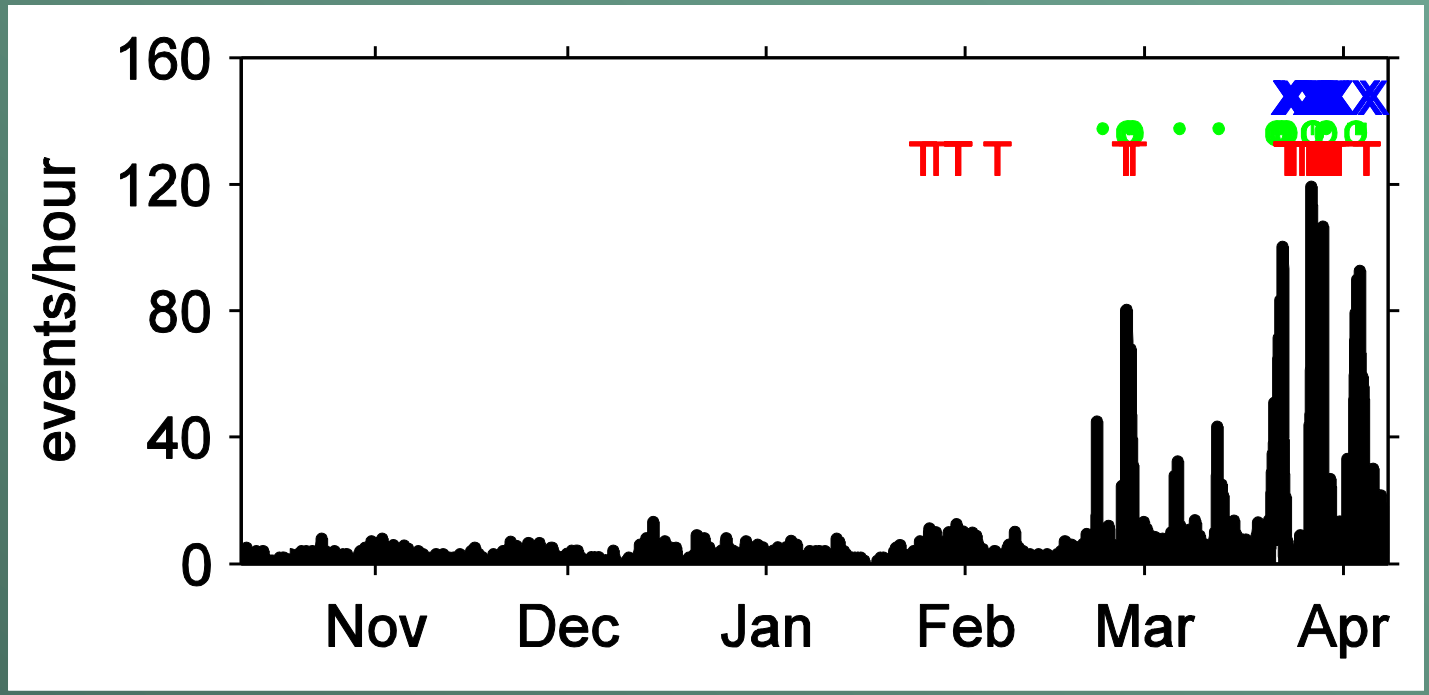








Redoubt: Oct 2008 – Apr 2009



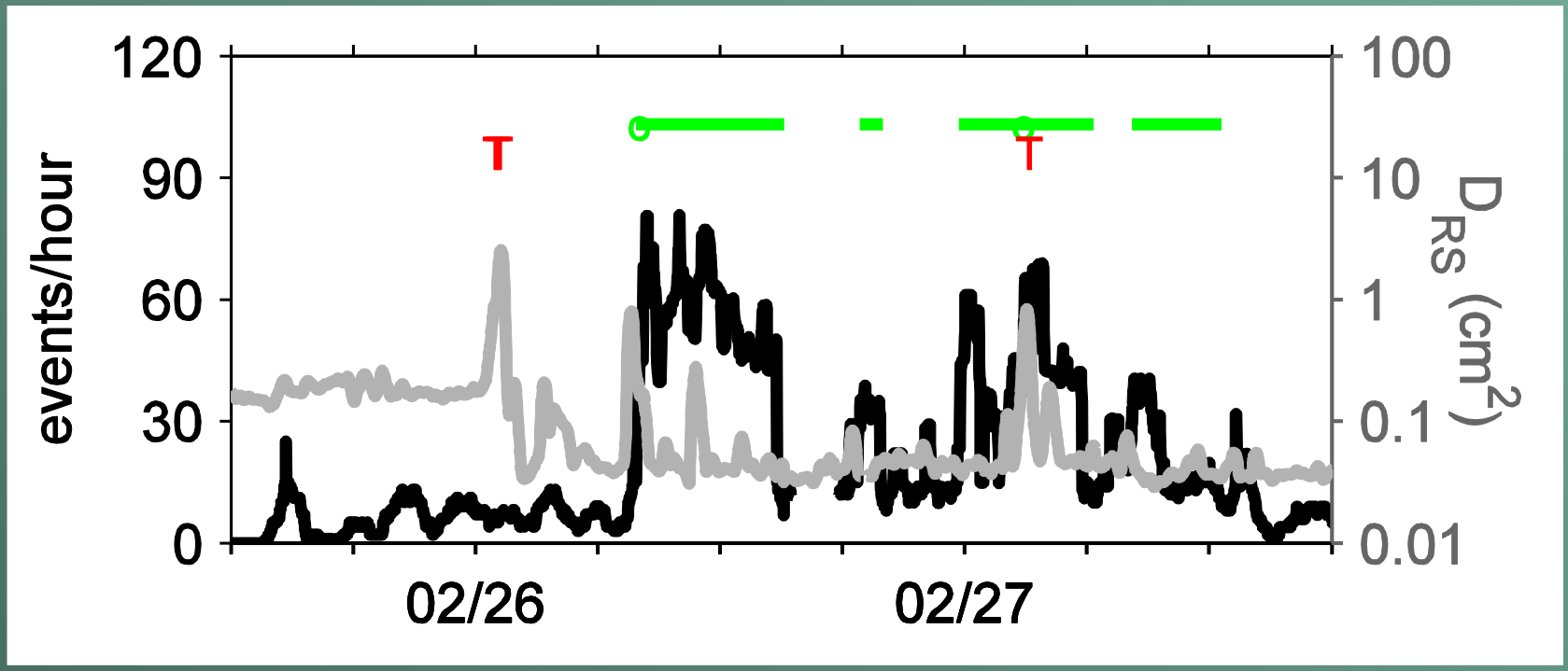
X Explosive eruption (ash > 5 km)

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

Redoubt: 26-27 Feb 2009



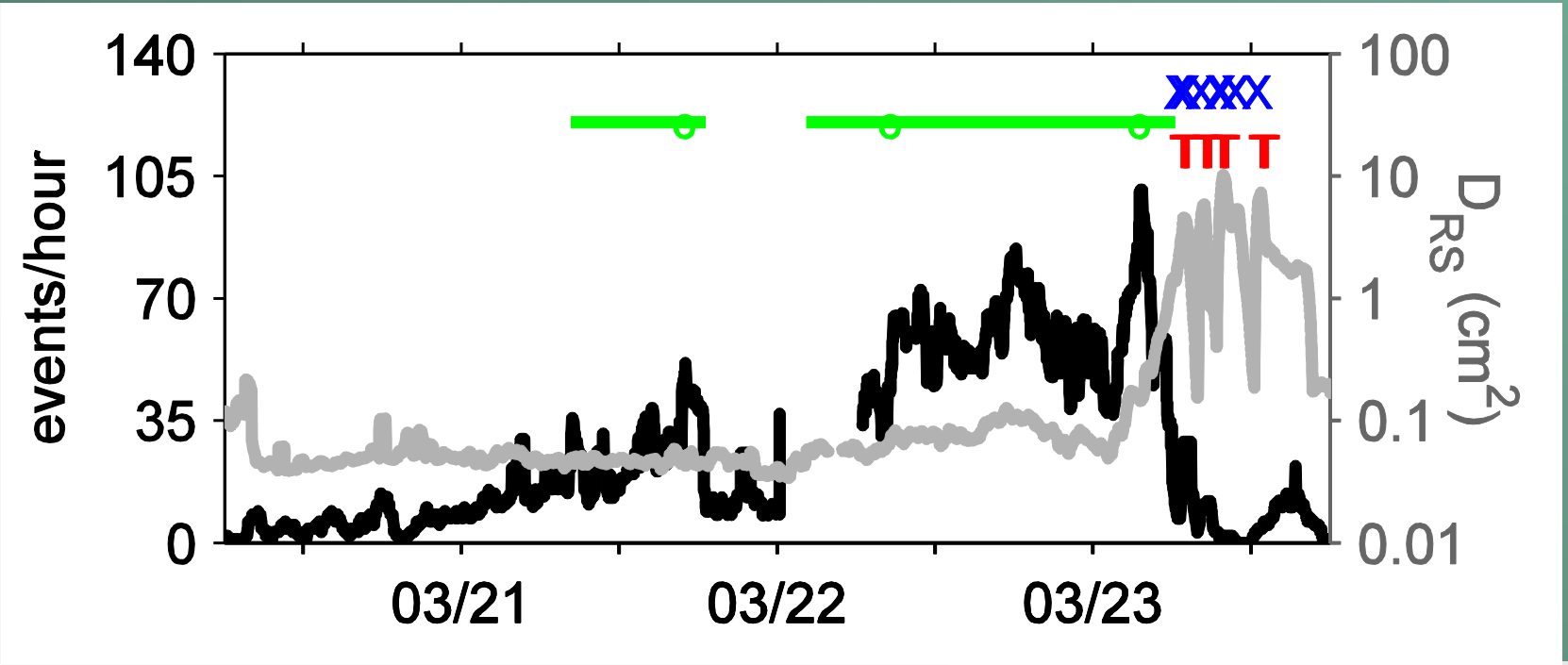
X Explosive eruption (ash > 5 km)

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

Redoubt: 21-23 Mar 2009



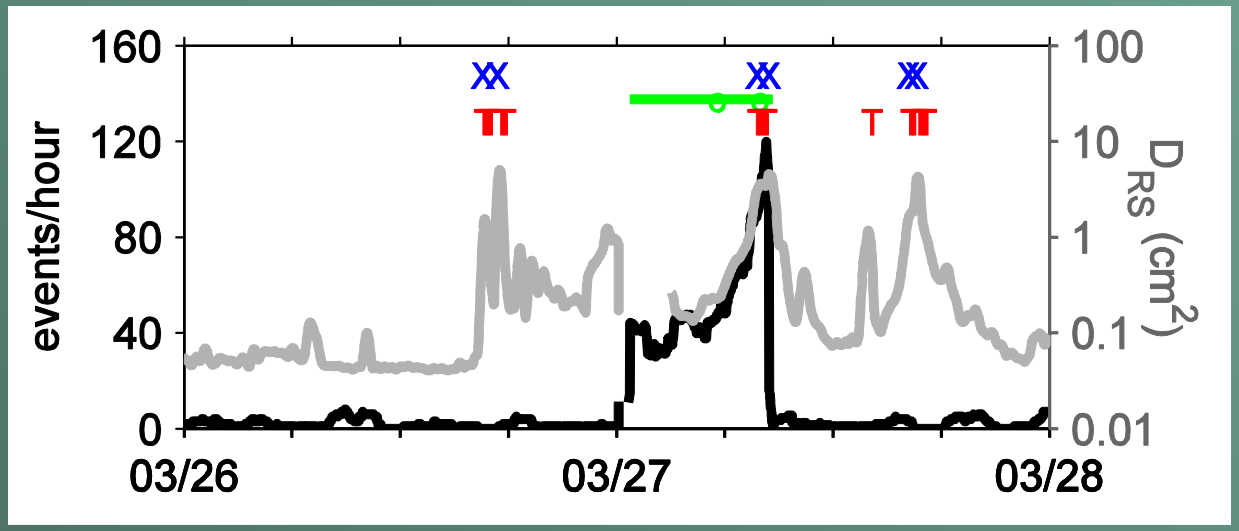
X Explosive eruption (ash > 5 km)

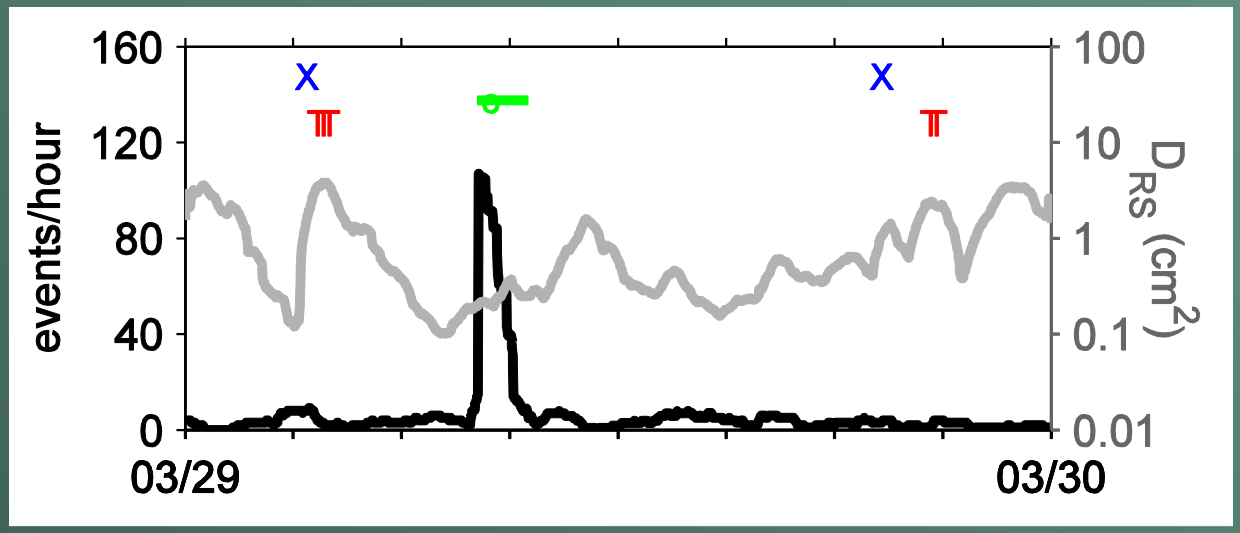
T Tremor alarm

Hourly event rate, from the real-time event catalog

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

Redoubt: 27 & 29 Mar 2009





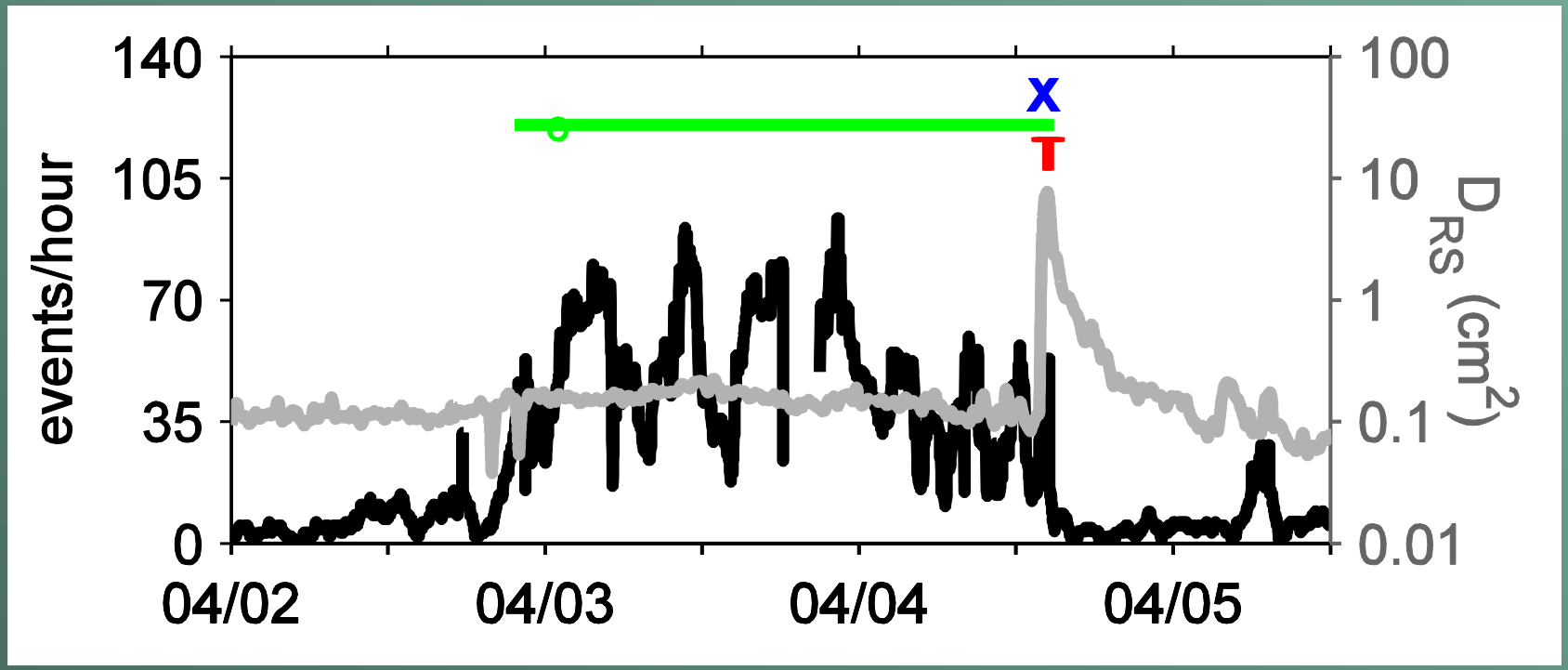
X Explosive eruption (ash > 5 km)

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

Redoubt: 2-4 Apr 2009



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

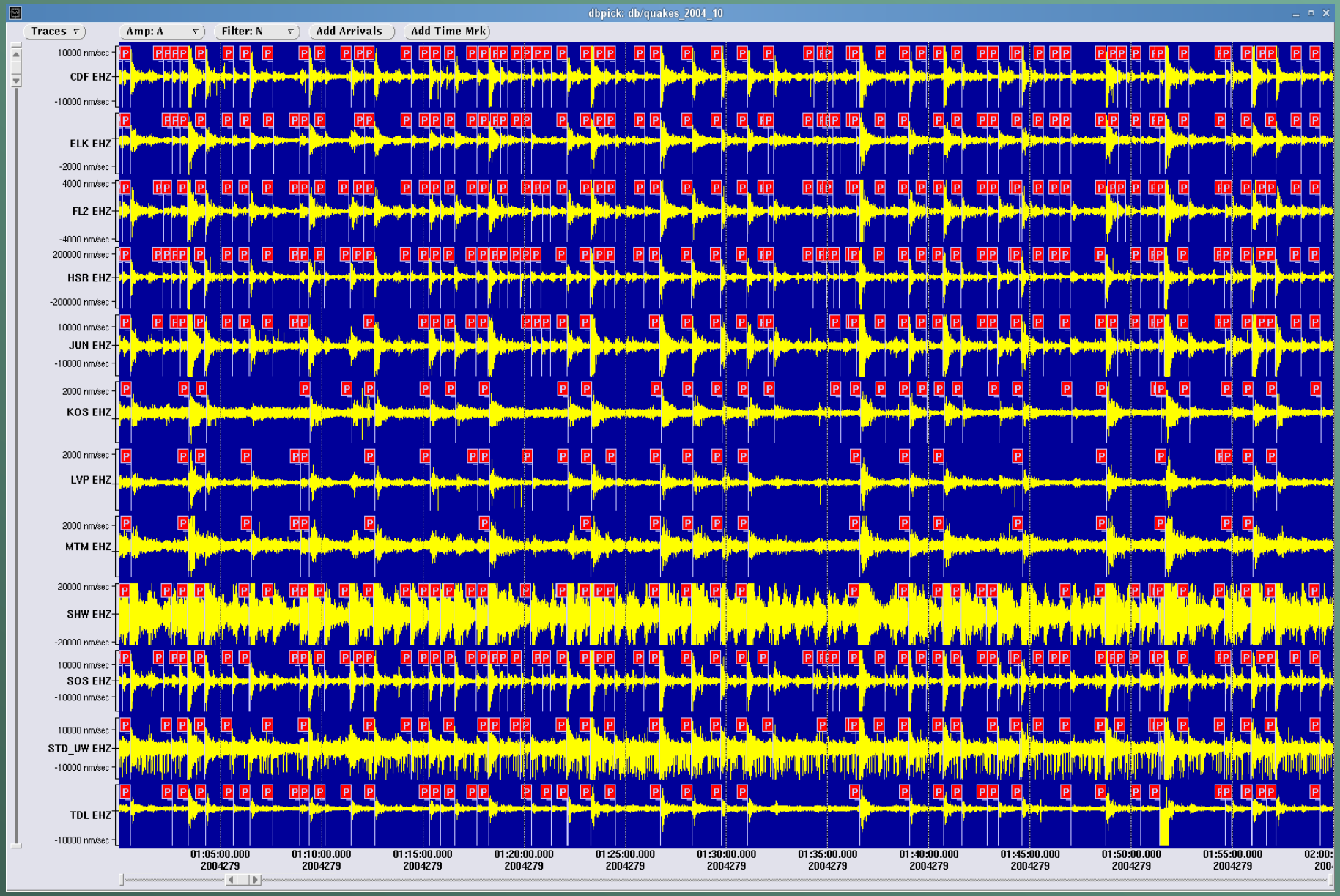
Swarm Alarm system

- Five swarm episodes were detected: 26-27 Feb, 21-23 Mar, 27 Mar, 29 Mar and 2-4 April.
- No false alarms (no garbage in event database caused by telemetry noise)

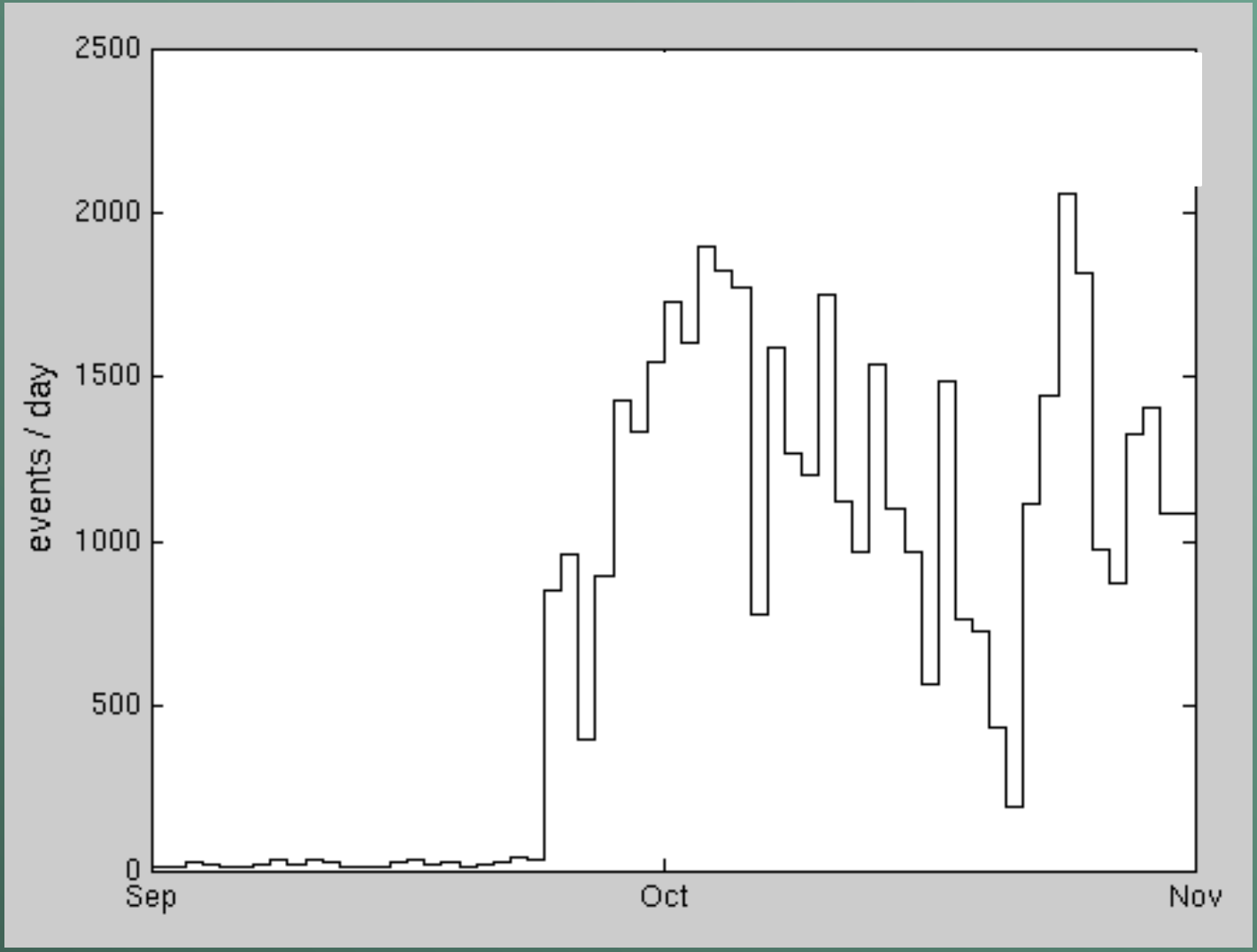
Tremor Alarm system

- Detected initial escalation in seismicity on 25 January
- Detected most of 31 explosive eruptions (based on infrasonic data)

St Helens 2004 swarms



St Helens 2004: daily event counts



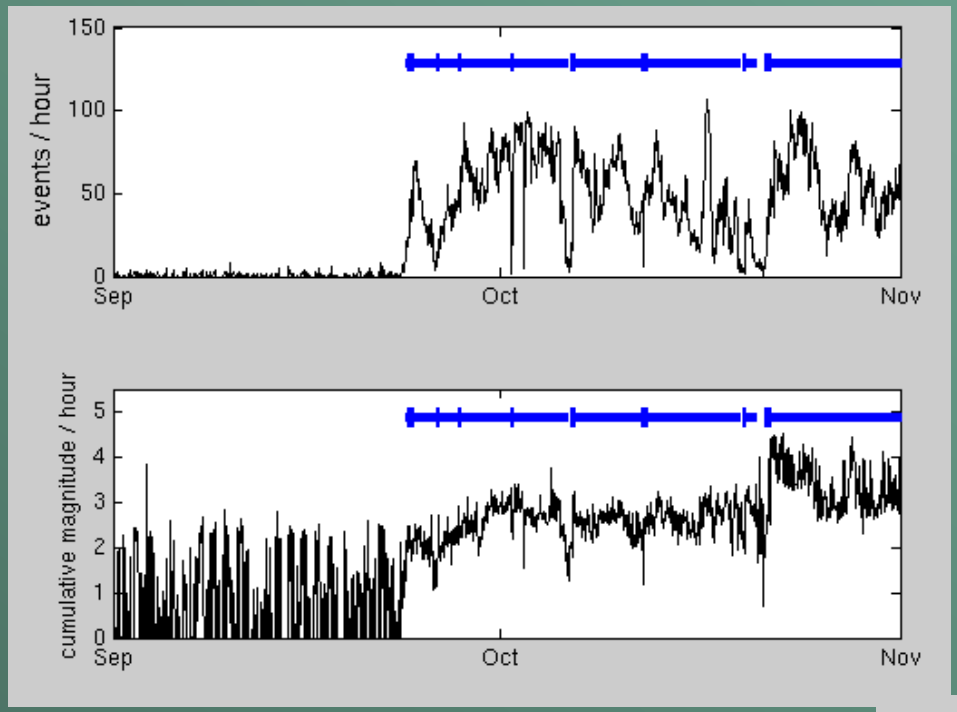
St Helens 2004: Swarm tracking parameters

Timewindow = 60 minutes

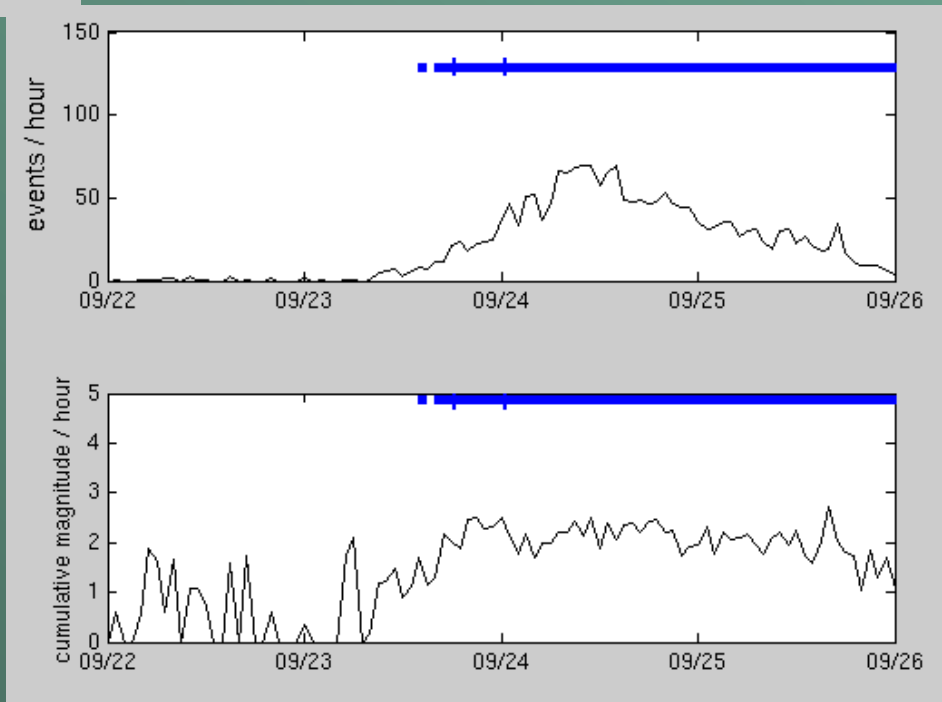
Reminder time = 99999 minutes (none)

Alarm type	Mean rate	Median rate	Mean ML	Cumulative ML
start	10			
end	5			
Escalation 1	20			
Escalation 2	40			

St Helens 2004



5 swarms
First alarm at 13:50 UT on 23-Sep-2004



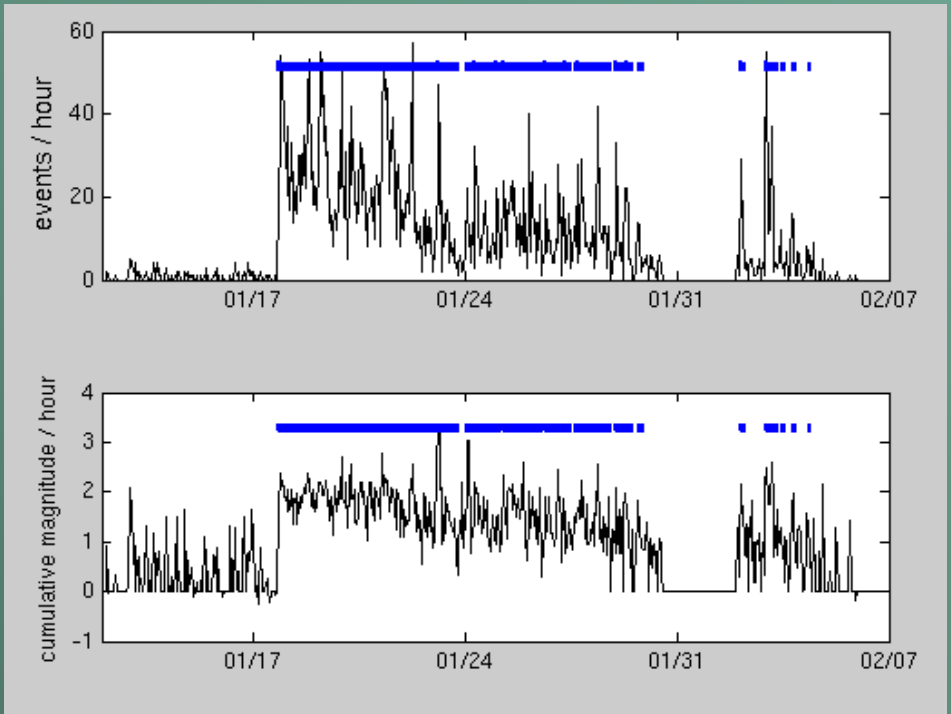
Yellowstone 2010: Swarm tracking parameters

Timewindow = 60 minutes

Reminder time = 99999 minutes (none)

Alarm type	Mean rate	Median rate	Mean ML	Cumulative ML
start	12			
end	6			
Escalation 1	24			
Escalation 2	48			

Yellowstone 2010 swarms



First alarm at 17-Jan 20:30 UT
Longest swarm 123 hours
16 swarms

Summary

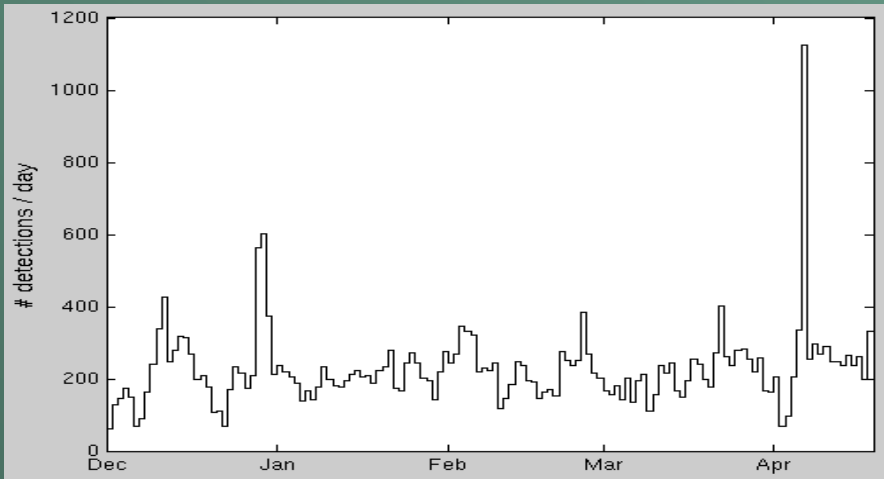
- Detect start, escalations and end of swarm
- Highly configurable – changes in event rates or energy release rate
- Generic alarm system – progressive calldowns for any alarm type
- Can work with carlstatrig/carlsubtrig
- Successful during Redoubt 2009 eruption – all 5 main episodes of swarms detected, no false alarms
- 3 hours warning for Okmok 2008 eruption

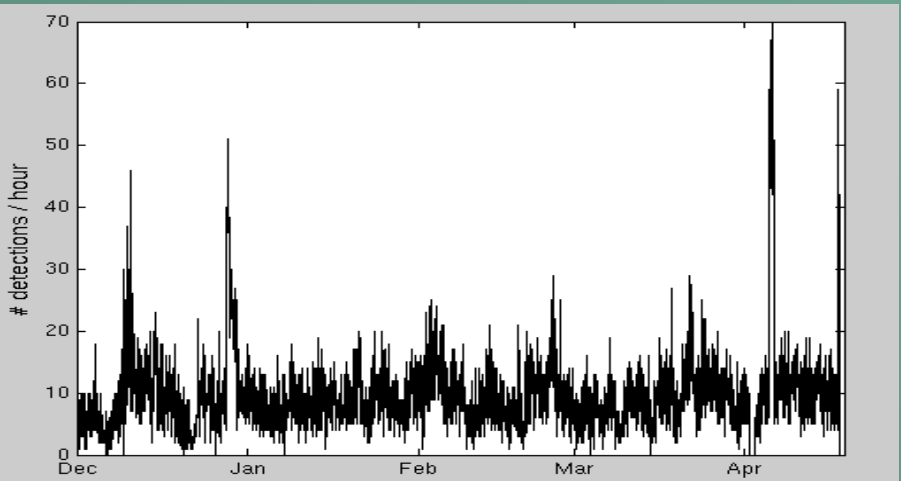
Further work:

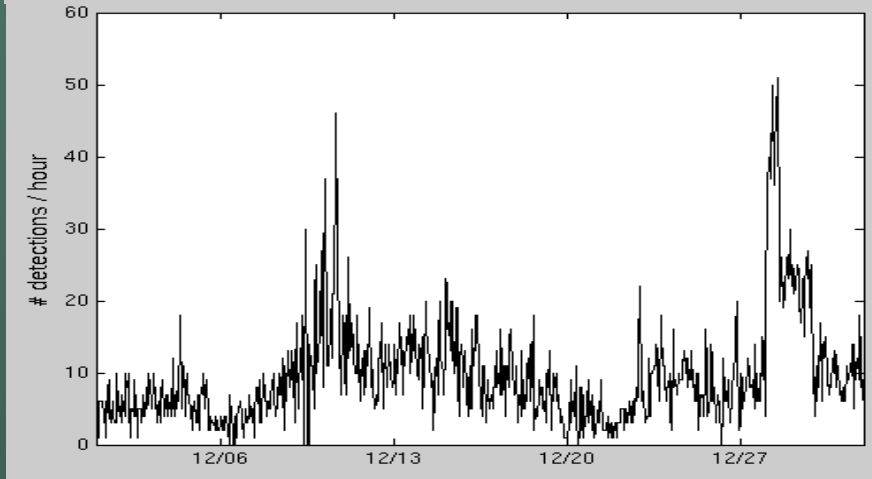
- More testing on previous eruptions
- Configure for all Alaskan volcanoes
- Run in parallel & add diagnostic system (robustness)
- Develop alarm response system / procedures

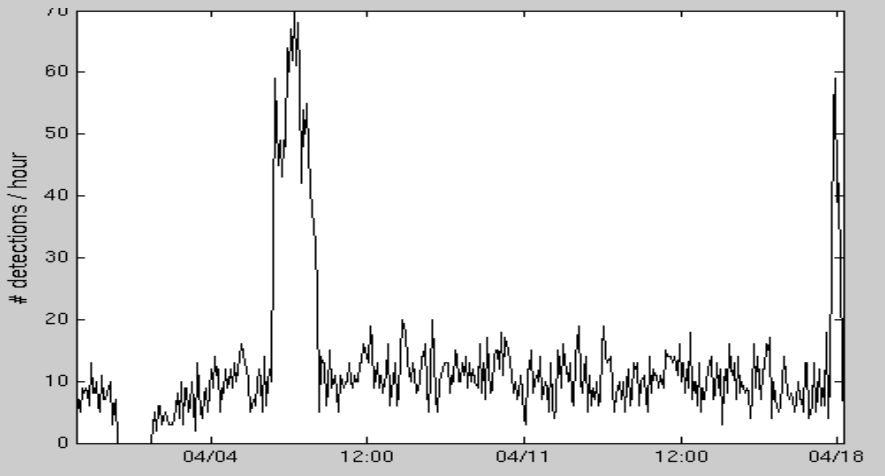
Redoubt swarms Dec 2009 / Apr 2009

- Show up only on RSO (too small)
- Alarm system based on detections?









Generic alarm algorithm: An alternative approach?

- Treat tremor & swarms same way
- Input a timeseries for any metric (e.g. RSAM, reduced displacement, mean event rate, median event rate, mean magnitude, cumulative magnitude, detection rate)
- Compute mean & standard deviation for each hour except the most recent
- Is current timewindow outside mean + 2 (or 3) standard deviations?
- Yes – alarm.

Advantages:

- notification of rapid changes in any metric
- no thresholds to set
- rapid implementation of new alarm types