Final Report for Computer Skills Class

Introduction

Tremor signals are interesting because volcanic tremor is indicative of fluid movement (either magmatic or hydrothermal) and is associated with volcanic eruptions, *e.g.* (Aki & Koyanagi, 1981; Yamamoto, Kawakatsu, Yomogida, & Koyama, 2002; McNutt S. R., 1986; Soosalu, Einarsson, & Jakobsdottir, 2003; Ukawa, 1993). The amplitude and duration of tremor has been used as a proxy for determining possible ash-plume heights and possible explosivity (McNutt S. R.; Benoit, McNutt, & Barboza, 2003). Tremor can also be used to determine the mechanism of flow within the conduit, *e.g.* (Thompson, McNutt, & Tytgat, 2002). Knowing the depth and location of the tremor source may provide physical constraints on the processes involved in tremor generation.

These tremor signals are often difficult to locate. They emerge gradually from background noise and maintain their irregular signal for minutes to days. In some cases, such as the non-volcanic tremor found in Cascadia, the envelope of strong tremor signals can be correlated across vast regional networks. The lag times from these correlations can then be treated as phase picks, which can be used to locate the source of the signal as though it were a traditional earthquake (Kao & Shan, 2004; Kao, Shan, Dragert, Rogers, Cassidy, & Ramachandran, 2005). This study will primarily try to locate volcanic tremor at Okmok volcano, a well instrumented volcano which has exhibited years of interesting tremor signals.

Okmok is a basaltic to basalt-andesitic volcano located on the northeastern half of Umnak Island, approximately 800 mi west of Anchorage. It is defined by a 2050 ± 50 year-old caldera 10 km diameter. This caldera contains multiple cinder cones, the youngest of which is Cone A, active since 1818. The most recent eruption issued from Cone A in February - April 1997, extruding basaltic lava flows into the caldera floor. Visits to Okmok during the summers of 2002, 2003, and 2004 for seismic station installation and geologic studies revealed vigorous steaming of Cone A (Beget, Larsen, Neal, Nye, & Schaefer, 2005; Grey, 2003). During fieldwork in 2002, incandescence was noted within Cone A's vent (McNutt, Larsen, personal communication). The seismic stations used for this project are shown in figure 1.

I have opted to use a location technique that takes advantage of amplitude distributions across the network to wrangle out the likely source location. As a signal is transmitted through the ground, its amplitude is controlled by geometric spreading and energy loss due to the earth not being perfectly elastic. The basic equation governing amplitude A at distance r for body-wave decay (waves travelling within the earth) is $A(r) = A_0 \frac{e^{-Br}}{r}, B = \frac{\pi f}{Q\beta}$, while that for surface-wave decay is $A(r) = A_0 \frac{e^{-Br}}{\sqrt{r}}$. A_0 is the source amplitude, f is the signal frequency, Q is quality factor (describing attenuation within rocks), and β is the propagation velocity. The source is assumed to have no directionality.

Because the amplitude fluctuates strongly on short timescales, because the signal decay is frequency dependent, and because the signal is within a limited band of frequencies, I opt to use RMS amplitude ratios for time windows for frequencies between 1-5 Hz, windowed for 20.48 seconds, examined at 20 second intervals.

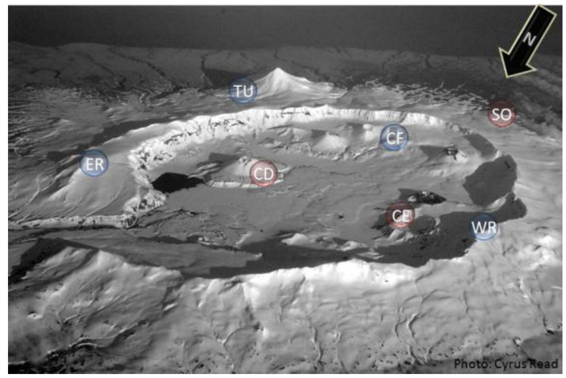

Figure 1 Closeup of Okmok volcano's caldera. Stations in blue are short-period stations, used with this study. Stations in red are broadband instruments.

I have existing code, written in MATLAB, which comes up with best-fits for the observed signal. It takes advantage of station to search grid distances being constant to then calculate expected decay to each search grid point. I invert that to get expected signal strength A_{calc} at each station. These values are then compared against the observed amplitudes A_{obs} to come up with a best-fit location (and amplitude)

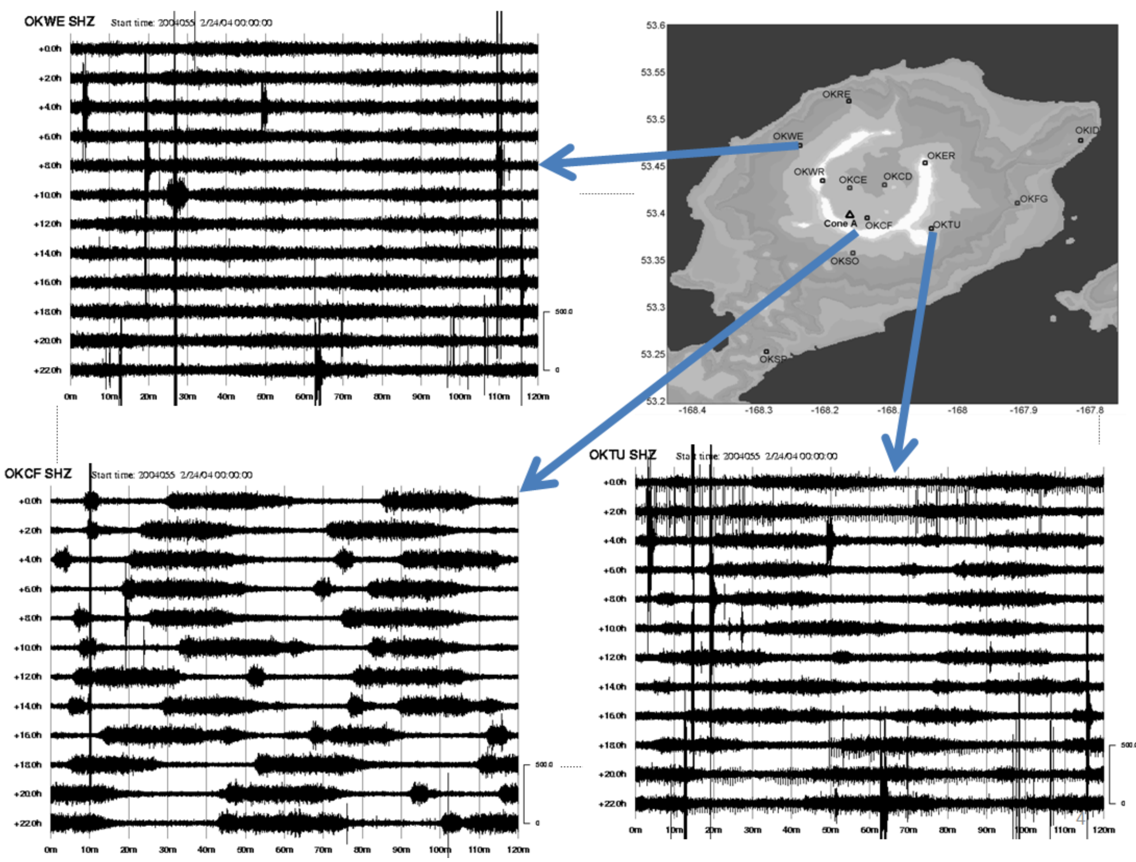

Figure 2 – Sample seismic traces for a variety of stations at Okmok volcano for February 24, 2004.

Origin/purpose of serial code

Code for this project originated in MATLAB (written by the author). In its entirety, the code reads continuous seismic data, and then preprocesses it to create RMS data files. These files, which consist of RMS amplitudes for each 20 seconds at each station, are read into the tremor location program along with vital statistics for the volcano of interest. This includes station locations and topography. In the future, input may include a velocity model, as well. The location program then cycles through possible signal origin locations, determining where the best source location and strength exist.

MODULES

The tremor location code was rewritten into fortran 95 for this class, with the ultimate goal of parallelizing it. The serial code was converted into several fortran modules, as follows:

cr_math : math routines, such as mean, variance, $\sin^2$, and linspace.

cr_string: a string manipulation routine that will convert to uppercase for use with SELECT statements

cr_geo : containing routines used to determine great-circle distances as well as point-locations and such. Much time was spent working on this section. It is critical to the location code to have accurate distances between possible event locations and the event. In MATLAB, this was handled by the mapping toolbox; in Fortran, the Haversine formula was used, as discovered on the web. Issues with precision and optimization caused this to be a much worked-on series of routines.

waveform : a module that handles the waveform object, including get /set, I/O, and minor manipulation. This was based on work I've done in MATLAB.

A "waveform" is an object that has information about the seismic station (station name, channel, frequency) and the data associated with it (start time, data samples). I have a whole suite of routines based on this MATLAB object.

Time was wasted trying to keep the waveform module generic. Even though the sample file had a pre-defined length, I attempted to allow waveform to grow in real-time. Unfortunately, Fortran 90 has limitations that kept allocatable objects from being used within user-defined types.

stationlocation : module containing presets (seismic station information) and geographical information about Okmok Volcano.

tremorlocator : the workhorse module that puts it all together ("main"). It is in here that the data is loaded, and the signal decay values and misfits are calculated.

.takes the continuous seismic data at several seismic stations around Okmok Volcano, band pass filters it (1-5 Hz), then extracts ~20 second windowed RMS values.

For actual tremor location, a Lat-Lon-Depth grid is created. For each station, this grid is converted from location to distance-to-station. These distance grids are then turned into calculated signal decay from that point to that station.

Now with a RMS values at each time-step at each station, and with signal-decay at our grid calculated, I invert to find the best location. (I'm just minimizing variance between Observed an Calculated RMS amplitudes)

Mostly, I'm concerning myself with single days of activity, concentrating on 2/24/2004. At this point, I have MATLAB files containing the calculated RMS values for each day. The data spreads 4320 RMS values over a grid that encompasses ~35km^2 (real rough guess).

Everything that can be calculated once is precalculated before looping through the day. Still, processing a day may take roughly 10 minutes with a not-so-big grid and a fast computer. However, I'd love to cover multiple frequency bands, and calculate tremor locations for a year.

Output

The fortran code would generate three output files:

1. ASCII Header file used by tremloc_misfits_to_v5d.f90 (.hdr)
2. Binary output of all calculated misfits (.bin)
3. ASCII file containing the preferred locations and amplitudes (.best)

Sample	Longitude	Latitude	Depth	Best Amp	Misfit
1	-168.1398	53.4667	5.00	285.3	124.6
2	-168.1284	53.4747	5.00	295.2	77.9
3	-167.7646	53.4384	5.00	2430.2	45.1
4	-167.7646	53.4424	5.00	2348.1	39.4
5	-168.0488	53.4263	5.00	164.1	29.6
6	-168.0488	53.4222	5.00	177.6	32.0
7	-167.7646	53.4343	5.00	2312.7	39.0
8	-168.0261	53.4182	5.00	164.9	19.4
9	-167.7646	53.4545	5.00	2263.8	31.0
10	-168.0375	53.4182	5.00	133.3	31.1

Table 1 example of best fit location output found in the .best file

Visualization

The visualization plan wasn't fully implemented due to time constraints. I'd spent time working with Vis5D, trying to massage the data into the proper format for display.

I'd like to have had several bits of data available and visible...

1. Best-Fit Locations. (Lat, Lon, Depth, - one per sample)
2. Best-Fit Source Amplitudes (RMS value, one per sample)

3. Calculated Amplitudes (best fit) at each station (for each sample)
4. Misfit data (for volume visualization). Every point in the search grid will have an associated misfit for each sample.

In the end, I think I'd like to have a movie that shows how the best-fit source moves over time, with an associated volume representing the area of higher probablility (I haven't chosen a cutoff, yet), perhaps colored according to source strength at that point in time.

All this information should be presented underneath a 3-D topographic map of Okmok Volcano and vicinity. Early attempts to do this were complicated by the apparent need for both the topographic map and the data grid to share the same grid locations and spacing.

Two additional panes that I'd liked to display include detailed best-fit and continuous data with a marker. The detailed best-fit would have bars that show how my modeled amplitudes match observed amplitudes at each of the stations. The continuous data would be displayed as rms-envelopes for each station used for the complete timeframe. This data would have some sort of visual representation of the moment in time that is displayed.

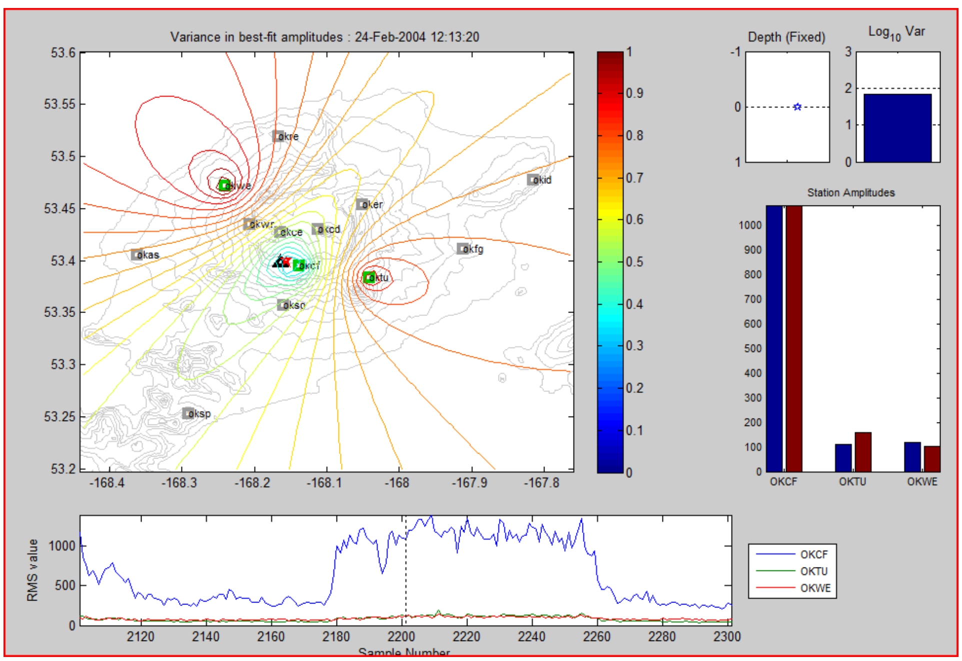

Figure 3 – Output window from the MATLAB version of the tremor locator.

Profiling the data

What follows is the output from profiling the serial code locally on the linux machine.

```
Each sample counts as 0.01 seconds.
  %   cumulative   self            self     total
 time   seconds   seconds    calls  Ks/call  Ks/call  name
 83.37   2909.83  2909.83 2145790004     0.00     0.00  __waveform__load_waveform
 16.38   3481.57   571.75        1     0.57     3.48  MAIN__
  0.00   3481.63     0.06   240000     0.00     0.00  __cr_geo__havsn
  0.00   3481.65     0.02   960000     0.00     0.00  __cr_geo__deg2rad
  0.00   3481.65     0.00   240000     0.00     0.00  __cr_geo__arc2km
  0.00   3481.65     0.00   240000     0.00     0.00  __cr_geo__earthdistance_km
  0.00   3481.65     0.00     4320     0.00     0.00  __waveform__get_sample_r1
  0.00   3481.65     0.00       12     0.00     0.00  __waveform__display_a_waveform
  0.00   3481.65     0.00        8     0.00     0.00  __waveform__make_waveform
  0.00   3481.65     0.00        3     0.00     0.00  __cr_math__linspace
  0.00   3481.65     0.00        2     0.00     0.00  __waveform__display_multi…
  0.00   3481.65     0.00        1     0.00     0.00  __cr_math__julian_day
  0.00   3481.65     0.00        1     0.00     0.00  __cr_string__upcase
  0.00   3481.65     0.00        1     0.00     0.00  __stationlocation__getokmokinfo
  0.00   3481.65     0.00        1     0.00     0.00  __waveform__get_waveform_int
  0.00   3481.65     0.00        1     0.00     0.00  __waveform__warn_if_uninitialized
```

It follows that there is one obvious routine that may benefit the most from parallelization. Oddly, the slowest section of code is not at *waveform__load_waveform*, as suggested by this profile results, as this function is called only once. The profiler on ICEFLYER, shows the true results, though.

```
ngranularity: Each sample hit covers 4 bytes. Time: 5274.88 seconds
                                    called/total     parents
index  %time    self descendents  called+self                    name         index
                                    called/total     children
          394.41    3205.36         1/1                          .__start [2]
[1]     68.2  394.41    3205.36     1                            .main [1]
         3174.09       0.00         569586599/569586599          .@7@calculate_misfit [3]
           29.47       0.00         4320/4320                     .__waveform_NMOD_get_sample_r1 [6]
            1.80       0.00         4320/4320                     .@7@calculate_bestfit [10]
            0.00       0.00         240000/240000                .__cr_geo_NMOD_earthdistance_km [40]
            0.00       0.00         4322/4334                    .__free [58]
            0.00       0.00         6/4335                       .__malloc [57]
            0.00       0.00         2/2                          .__waveform_NMOD_display_multiple_waveforms
            0.00       0.00         1/1                          .__stationlocation_NMOD_getokmokinfo
```

Calculate_misfit becomes the primary candidate for parallelization. It is uncertain why result from the linux box is inaccurate. Calculate_misfit was then parallelized.

Parallelization Methods

Time restraints dictated the extent to which the data was parallelized.

Two obvious aspects of this code lend themselves to parallelization.

1. Tremor location uses a grid search, with results from one grid section (depth, for example) completely independent of results from other grid sections.

2. There are reams of data to process. That is, over two years of data for 8 stations at this volcano, sampling at 100Hz. Should this technique be fruitful, it may be enlightening to examine tremor episodes at other volcanoes, resulting in approximately 30 times more data.

Loops that lend themselves to parallelization:

- Do DATE (single value)
- Do SAMPLE (4320) – This is an excellent candidate for MPI parallelization, but without careful consideration, it may generate file output issues.
- Do Points (60 x 100 x 10) – Plenty of work to be done, unknown number of iterations per point.

For results of the parallelization, see figures 3 and 4. Figure 3 shows how the processing time dropped from an hour (series) to approximately 7 minutes using eight processors. The percentage speedup was nearly linear with the number of processors..

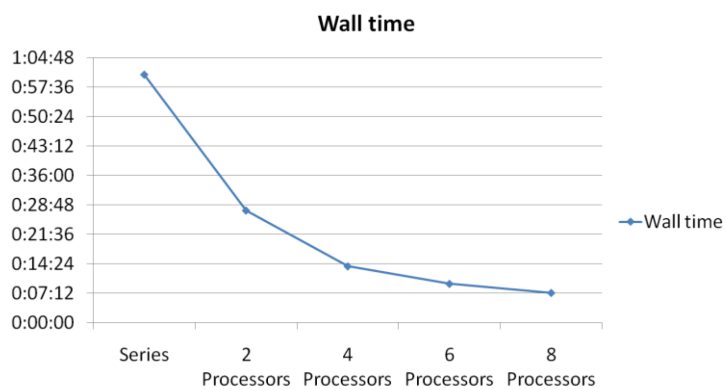

Figure 3 – Effect of the number of processors upon wall time.

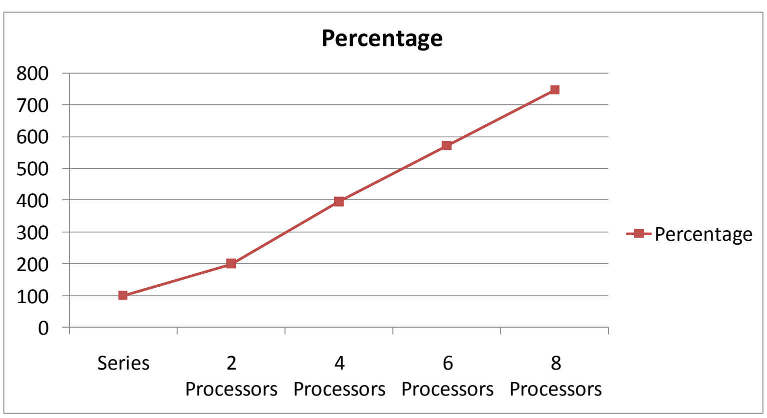

Figure 4 – Speed up is nearly linear with the number of processors. This indicates that the parallelization routine was effective.

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