GeoClaw Model Tsunamis Compared to Tide Gauge Results

Final Report

November 3, 2017

Loyce M. Adams and Randall J. LeVeque
University of Washington

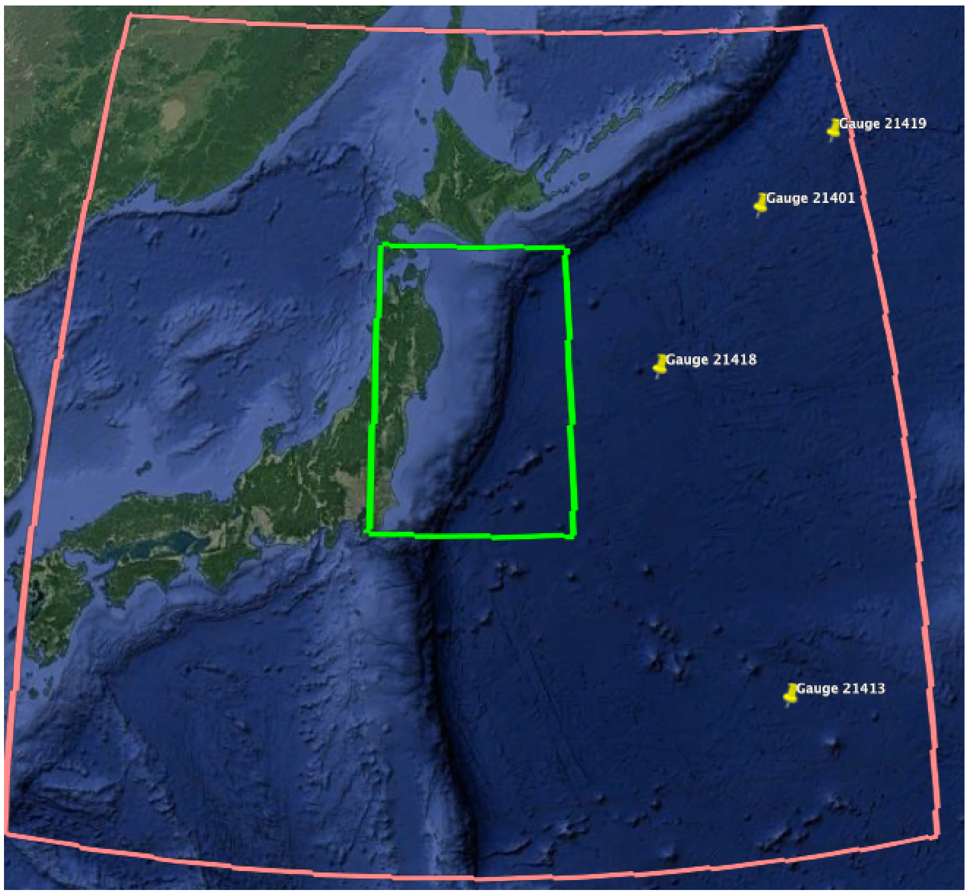

Photo Source: Google Earth

Study funded by PMEL
(website: http://depts.washington.edu/ptha/GeoClawMOSTcomparison/)

Contents

1 Introduction **4**
- 1.1 Source deformation (dtopo) files . . . 4
- 1.2 De-Tiding gauges . . . 4
- 1.3 GeoClaw refinement . . . 4
- 1.4 Maximum amplitudes summary . . . 4
- 1.5 Maximum amplitude differences summary . . . 7
- 1.6 Wave train summary . . . 9
- 1.7 Executive summary . . . 11

2 Japan 2011 Tsunami **12**
- 2.1 Comparisons with Detided DART Locations . . . 12
- 2.2 Hilo . . . 18
- 2.3 Crescent City . . . 21
- 2.4 Arena Cove . . . 26
- 2.5 Port Orford . . . 30
- 2.6 Midway Island . . . 35

3 Samoa 2009 Tsunami **41**
- 3.1 Hilo . . . 42
- 3.2 Crescent City . . . 45
- 3.3 Arena Cove . . . 50
- 3.4 Port Orford . . . 53
- 3.5 Midway Island . . . 56
- 3.6 PagoPago . . . 59

4 Chile 2010 Tsunami **63**
- 4.1 Hilo . . . 64
- 4.2 Crescent City . . . 67
- 4.3 Arena Cove . . . 72
- 4.4 Port Orford . . . 75

5 Kuril 2007 Tsunami **78**
- 5.1 Hilo . . . 79
- 5.2 Crescent City . . . 82
- 5.3 Arena Cove . . . 88
- 5.4 Port Orford . . . 91

6 Haidi Gwaii 2012 Tsunami **94**
- 6.1 Hilo . . . 95
- 6.2 Crescent City . . . 98
- 6.3 Arena Cove . . . 103
- 6.4 Port Orford . . . 106

References **109**

Appendices **110**

A De-Tiding **110**
A.1 De-Tiding Method . . . 110
A.2 De-Tiding comparisons . . . 114
A.2.1 Japan 2011 De-Tiding comparisons . . . 114
A.2.2 Samoa 2009 De-Tiding comparisons . . . 115
A.2.3 Chile 2010 De-Tiding comparisons . . . 117
A.2.4 Kuril 2007 De-Tiding comparisons . . . 118
A.2.5 Haida Gwaii 2012 De-Tiding comparisons . . . 119

B Timing **121**
B.1 Japan2011 - Crescent City . . . 121
B.1.1 Wave tolerance flagging: 1/3sec run . . . 122
B.1.2 Wave tolerance flagging: Additional 1/3sec run . . . 123
B.1.3 Adjoint flagging: Additional 1/3sec run . . . 125
B.2 Japan2011 - Midway Island . . . 127
B.3 Japan2011 - Port Orford . . . 128
B.4 Samoa2009 - Crescent City . . . 130
B.5 Samoa2009 - Arena Cove . . . 131
B.6 Samoa2009 - Port Orford . . . 133
B.7 Samoa2009 - Midway Island . . . 134
B.8 Samoa2009 - Pago Pago . . . 136
B.9 HG12 - Hilo . . . 137
B.10 Kuril 2007 - Crescent City . . . 139
B.11 Chile 2010 - Arena Cove . . . 140

1 Introduction

The purpose of this project is to compare GeoClaw tsunami model results to detided tide gauge results at multiple destinations for each of several tsunamis. In particular, we are interested in the suitability of GeoClaw for calculating tsunami amplitudes with enough precision to be used for forecasting, especially in the context of ensemble modelling. In each of our comparison plots, we also include a sample MOST tsunami result which is useful to see the reasonableness of GeoClaw in regions where tide gauge data is missing or has insufficient resolution. The methodology behind GeoClaw can be found in [1] and [5], and its performance on the 2011 NTHMP problems in [4] and [6]. For a description of the MOST model see [7]. Here, we give a quick summary of our progress on such comparisons for the Japan 2011, Samoa 2009, Kuril 2007, Chile 2010 and HaidiGwaii 2012 tsunamis at tide gauge destinations at Crescent City, Arena Cove, Port Orford, Hilo, Midway Island and Pago Pago. In the next sections, we provide more details.

1.1 Source deformation (dtopo) files

The source deformation files that were provided to us by PMEL were not on a uniform latitude-longitude grid. Initially, we erroneously assumed they were (much in the spirit of topo files that one downloads from the websites) and needless to say the GeoClaw results were not good at all! We had to take some care to convert them to a uniform grid as required by GeoClaw. Indeed, we formed our own from the unit sources and compared to the converted ones to make sure we had achieved the conversion in an accurate way. The reason we mention this is that often people ask us for dtopo files to use with GeoClaw, and these sometimes come through PMEL. As a result of this discovery, we have examined several of the dtopo files we have used in the past and verified they were handled correctly. Likewise, PMEL should be aware of giving dtopo files for use with GeoClaw to indicate that they might have to be converted to a uniform grid.

1.2 De-Tiding gauges

PMEL provided us with around 50 tide gauge files and a plot of the detided tsunami, along with the maximum detided amplitude and the time this maximum occurred. We did not receive a file of the time series of the detided tsunami, so instead of pursuing this with PMEL, we took it as an opportunity to compare our own detiding to the maximum values we were provided. Happily, we compare extremely well at almost all of these gauges with the time of the maximum amplitude being identical as seen in Appendix A.2. There is one main difference. The Japan 2011 tsunami at the Midway Island tide gauge had a detided maximum amplitude of 1.5607 (PMEL) and 1.709 (UW). These maximums were at the same time. We feel the detided maximum could even be a bit higher than 1.709. This might be one tide gauge for PMEL to re-examine.

1.3 GeoClaw refinement

The wave tolerance was set to 0.005m to flag refinement in a variable refinement region when the wave height reached this tolerance. We used this tolerance to use up to 4 minute (or in some cases 1 minute) resolution across the ocean in pre-determined regions. For some of our job runs, we used the new adjoint-GeoClaw method [3] in an automatic way to refine up to 4 minute (or 1 minute) resolution across the ocean instead of setting regions a priori and using the tolerance of 0.005m. We were anxious to use this project to also refine and learn about the performance of this new adjoint-GeoClaw feature. The timing information provided in Appendix B shows that we still have work to do to make the adjoint-GeoClaw method more efficient.

1.4 Maximum amplitudes summary

The maximum values in meters of the tsunami amplitudes for the tide gauge, MOST, and GeoClaw tsunamis rounded to the nearest centimeter are given in Figures 1 and 2. The resolution of the C-grid (called C-res) for the computation is also included. The resolution across the ocean (called O-res) is included for the GeoClaw runs, and varies during the computation depending on the adjoint flagging or region control. For the MOST runs, the O-res was constant at 4min resolution. Around the source region for one hour, GeoClaw computed with a resolution called S-res. MOST used 4 minute resolution at all times around the source. Details including plots of the tide gauge, MOST, and GeoClaw tsunamis can be found in Section 2 for Japan 2011, Section 3 for Samoa 2009, Section 4 for Chile 2010, Section 5 for Kuril 2007, and Section 6 for Haida Gwaii 2012 tsunamis.

SOURCE-DESTINATION	TG	TG	MOST		GeoClaw			
	(max) (m)	(res)	(max) (m)	(C-res)	(max) (m)	(C-res)	(O-res)	(S-res)
Japan11-Hilo	1.27	15s	1.80	2s	1.50	1s	2deg-1min**	1min
Japan11-ArenaCove	1.70	60s	1.58	2s*	1.29	1s	2deg-1min**	1min
					1.28	1/3s	2deg-1min**	1min
					1.31++	1/3s	2deg-1min**	1min
Japan11-CrescentCity	2.46	15s	2.43	2s	2.15	2s	2deg-4min	4min
					2.29	1s	2deg-4min	4min
					2.41	1/3s	2deg-4min	4min
Japan11-PortOrford	1.88	15s	1.95	2s	1.84	2s	2deg-4min	4min
					1.90	1s	2deg-4min	4min
					1.93	1/3s	2deg-4min	4min
Japan11-Midway	1.71+	15s	1.47	2s	1.65	2s	2deg-4min	4min
					1.91	1s	2deg-4min	4min
					2.13	1/3s	2deg-4min	4min
					2.17	1/3s	2deg-1min	1min
Samoa09-Hilo	0.18	60s	0.29	2s	0.26	1s	2deg-1min**	1min
Samoa09-ArenaCove	0.47	60s	0.23	2s*	0.44	1s	2deg-1min**	1min
Samoa09-CrescentCity	0.33	60s	0.38	2s	0.16	1s	2deg-1min**	1min
					0.17	1/3s	2deg-1min**	1min
					0.18++	1/3s	2deg-1min**	1min
					0.15	0.5s	2deg-4min	1min
Samoa09-PortOrford	0.20	60s	0.22	2s	0.15	1s	2deg-1min**	1min
					0.15	1/3s	2deg-1min**	1min
Samoa09-Midway Island	0.20	60s	0.23	2s	0.31	1s	2deg-1min**	1min
Samoa09-PagoPago	2.74	15s	2.37	0.7s	2.26	1/3s	2deg-1min	1min
					2.28++	1/3s	2deg-1min	1min

* -- MOST used 2sec (long.) and 1.5sec (lat.)
++ -- Used extended regions at the destination
\+ -- PMEL had 1.56
** -- GeoClaw used the GeoClaw-adjoint method

Figure 1: Japan 2011 and Samoa 2009 tsunami maximum amplitudes

SOURCE-DESTINATION	TG (max) (m)	TG (res)	MOST (max) (m)	MOST (C-res)	GeoClaw (max) (m)	GeoClaw (C-res)	GeoClaw (O-res)	GeoClaw (S-res)
Chile10-Hilo	0.74	15s	1.01	2s	0.92	1s	2deg-4min**	1min
Chile10-ArenaCove	0.47+	15s	0.16	2s*	0.19	1s	2deg-4min**	1min
					0.19	1/3s	2deg-4min**	1min
Chile10-CrescentCity	0.69	15s	0.64	2s	0.33	1s	2deg-4min**	1min
					0.54++	1/3s	2deg-4min**	1min
Chile10-PortOrford	0.46	15s	0.15	2s	0.13	1s	2deg-4min**	1min
Kuril07-Hilo	0.10	60s	0.24	2s	0.15	1s	2deg-4min**	1min
Kuril07-Arena Cove	0.19	60s	0.18	2s*	0.39	1s	2deg-1min**	1min
Kuril07-CrescentCity	0.24	60s	0.33	2s	0.16	1s	2deg-4min**	1min
					0.16	1/3s	2deg-4min**	1min
					0.25++	1/3s	2deg-4min**	1min
					0.30++	1/3s	2deg-1min**	1min
Kuril07-PortOrford	0.20	60s	0.21	2s	0.07	1s	2deg-4min**	4min
					0.23	1/3s	2deg-1min**	1min
HG12-Hilo	0.27	60s	0.43	2s	0.31	1s	2deg-1min**	1min
HG12-ArenaCove	0.36	60s	0.14	2s*	0.12	1s	2deg-1min**	1min
					0.12	1/3s	2deg-1min**	1min
HG12-CrescentCity	0.47	15s	0.30	2s	0.15	1s	2deg-1min**	1min
					0.15	1/3s	2deg-1min**	1min
					0.22++	1/3s	2deg-1min**	1min
HG12-PortOrford	0.21	60s	0.14	2s	0.07	1s	2deg-1min**	1min
					0.07	1/3s	2deg-1min**	1min

++ -- Used extended regions at the destination
\+ -- Tide Gauge at 0.47 at 14.5 hrs. postquake. 0.69 was at 85.65 hrs. post quake
* -- MOST used 2sec (long.) and 1.5sec (lat.)
** -- GeoClaw used the GeoClaw-adjoint method

Figure 2: Chile 2010, Kuril 2007, and HG 2012 tsunami maximum amplitudes

1.5 Maximum amplitude differences summary

In Figure 3, in the first three columns, we repeat the maximum amplitudes of the detided tide gauge (TG), the MOST, and the GeoClaw tsunamis in meters as given in Figures 1 and 2 for our finest resolution calculations. Some of these calculations were finer resolution and on larger regions than those used by the MOST example we included. Then in the last two columns, we give the differences of MOST and GeoClaw maximums to that of the tide gauge, denoted (MOST-TG) and (GeoClaw-TG), respectively. The final four rows in the table give the maximum overshoot, the maximum undershoot, the mean difference, and the mean absolute difference seen over all 23 of these tsunamis.

	TG (m)	MOST (m)	GeoClaw (m)	MOST-TG (m)	GeoClaw-TG (m)
Japan11-Hilo	1.27	1.80	1.50	+0.53	+0.23
Japan11-ArenaCove	1.70	1.58	1.31	-0.12	-0.39
Japan11-CrescentCity	2.46	2.43	2.41	-0.03	-0.05
Japan11-PortOrford	1.88	1.95	1.93	+0.07	+0.05
Japan11-Midway	1.71	1.47	2.17	-0.24	+0.46
Samoa09-Hilo	0.18	0.29	0.26	+0.11	+0.08
Samoa09-ArenaCove	0.47	0.23	0.44	-0.24	-0.03
Samoa09-CrescentCity	0.33	0.38	0.18	+0.05	-0.15
Samoa09-PortOrford	0.20	0.22	0.15	+0.02	-0.05
Samoa09-Midway Island	0.20	0.23	0.31	+0.03	+0.11
Samoa09-PagoPago	2.74	2.37	2.28	-0.37	-0.46
Chile10-Hilo	0.74	1.01	0.92	+0.27	+0.18
Chile10-ArenaCove	0.47	0.16	0.19	-0.31	-0.28
Chile10-CrescentCity	0.69	0.64	0.54	-0.05	-0.15
Chile10-PortOrford	0.46	0.15	0.13	-0.31	-0.33
Kuril07-Hilo	0.10	0.24	0.15	+0.13	+0.05
Kuril07-Arena Cove	0.19	0.18	0.39	-0.01	+0.20
Kuril07-CrescentCity	0.24	0.33	0.30	+0.09	+0.06
Kuril07-PortOrford	0.20	0.21	0.23	+0.01	+0.03
HG12-Hilo	0.27	0.43	0.31	+0.16	+0.04
HG12-ArenaCove	0.36	0.14	0.12	-0.22	-0.24
HG12-CrescentCity	0.47	0.30	0.22	-0.17	-0.25
HG12-PortOrford	0.21	0.14	0.07	-0.07	-0.14
Max absolute difference (overshoot)				0.53	0.46
Max absolute difference (undershoot)				0.37	0.46
Mean difference				-0.03	-0.04
Mean absolute difference				0.16	0.17

Figure 3: Maximum amplitudes and differences to 23 detided gauge tsunamis

In Figures 4 and 5, we give scatter plots for all 23 tsunamis in this study, and for just the 15 where the maximum detided gauge amplitude was less that 0.5 meters, respectively. We use the values in Figure 3. On the x-axis, we plot the maximum detided tide gauge tsunami, and on the y-axis, the corresponding maximum amplitude of the MOST tsunami as a blue dot and that of the GeoClaw tsunami as a red dot. The line where these tsunamis have equal maximum amplitudes is plotted as the solid black line. Lines of plus or minus 10%, 20%, 30%, and 40% differences to the solid black line are plotted as the dashed black, green, magenta, and yellow lines, respectively.

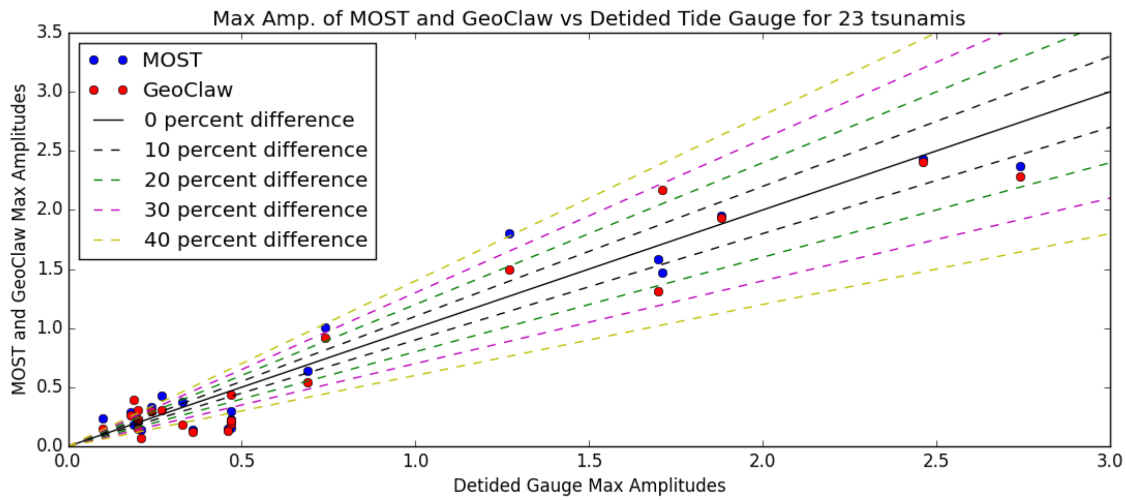

Figure 4: Maximum Amplitudes for 23 Tsunamis

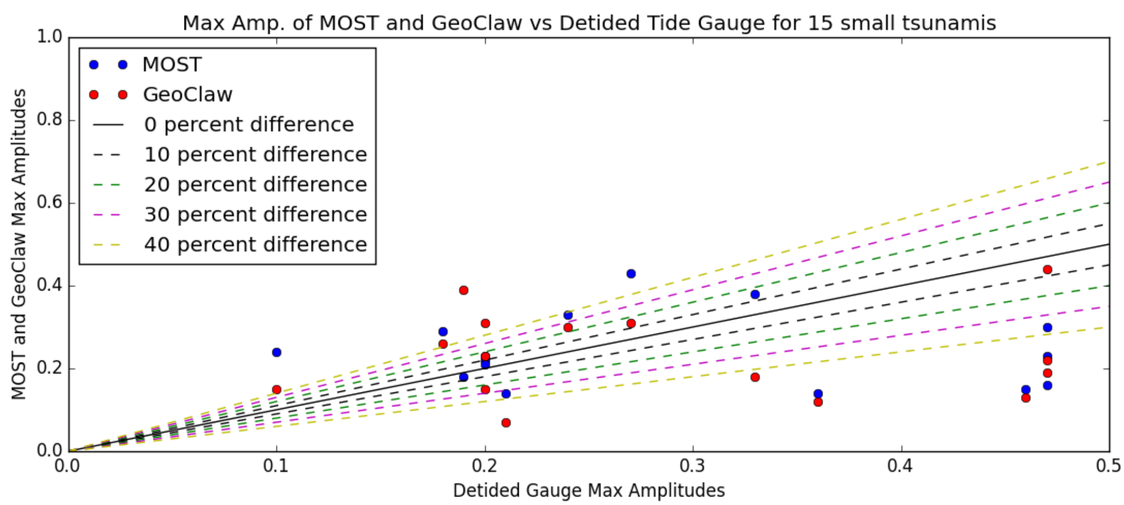

Figure 5: Maximum Amplitudes for 15 Small Tsunamis

1.6 Wave train summary

In the Figures that follow we give thumbnail plots of the tide gauge, MOST, and GeoClaw tsunamis. Figure 6 shows the Samoa 2009 and Japan 2011 tsunamis and Figure 7 shows the Chile 2010, Kuril 2007, and Haida Gwaii 2012 tsunamis.

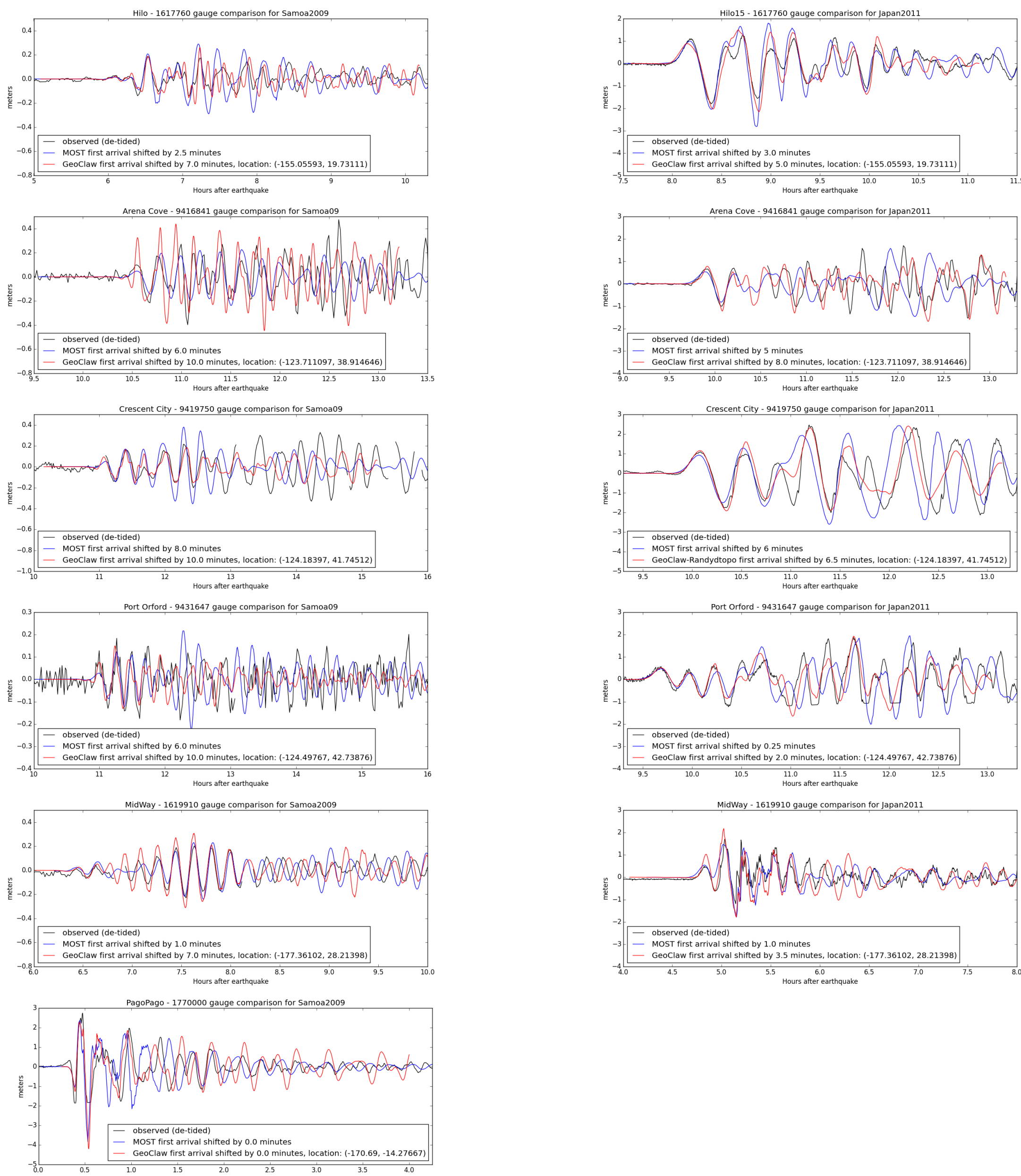

Figure 6: Samoa 2009 and Japan 2011 tide gauge, MOST, and GeoClaw tsunamis

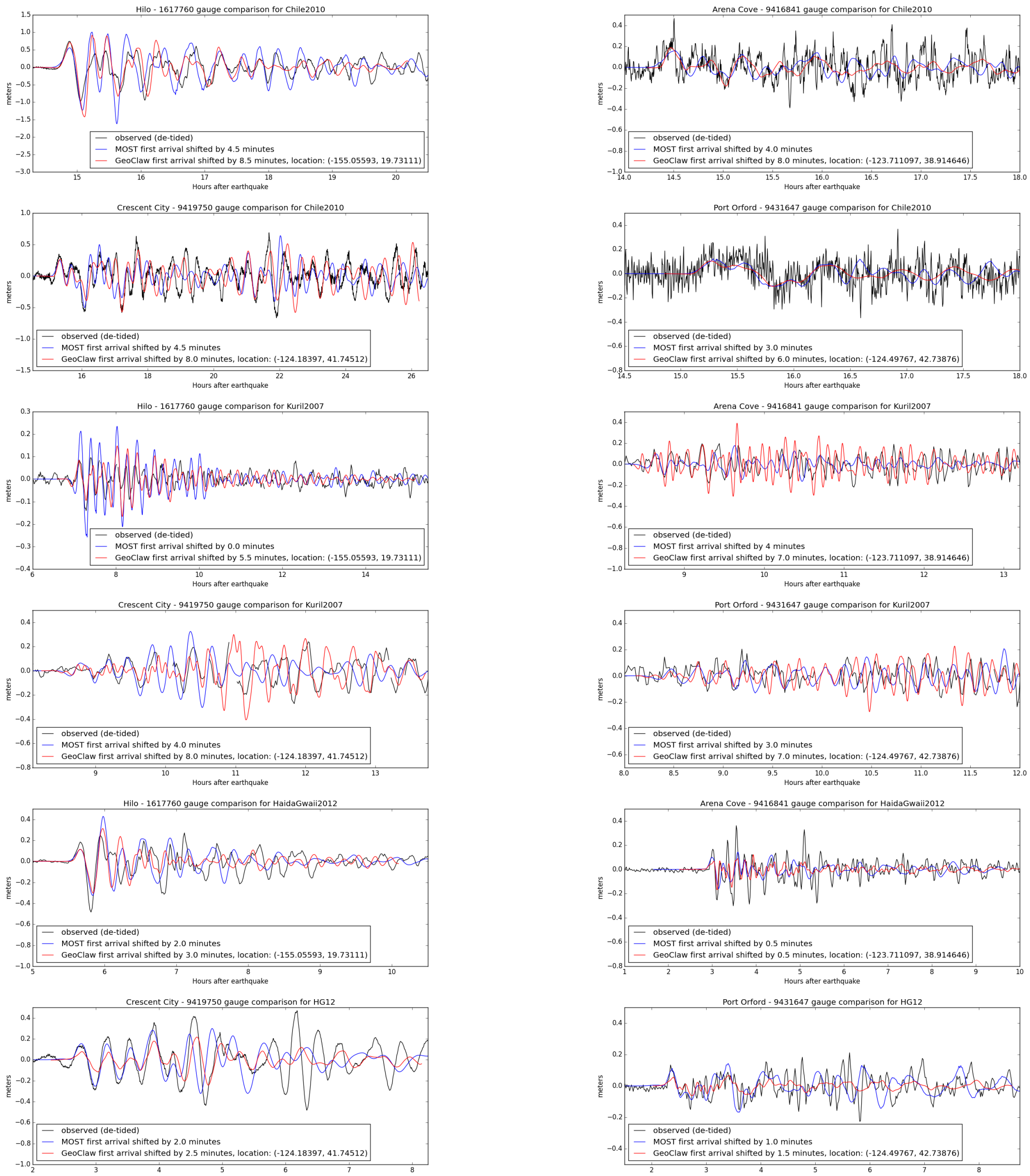

Figure 7: Chile 2010, Kuril 2007, and HG 2012 tide gauge, MOST, and GeoClaw tsunamis

1.7 Executive summary

The plots in Section 1.5 show that plotting the percentage difference from the tide gauge maximum makes sense for the larger tsunamis, but can be misleading for smaller tsunamis. For smaller tsunamis, reporting just the difference to the tide gauge, not the percentage difference is more reasonable given the noise remaining in the tide gauge tsunami and possible errors in detiding and omissions due to the sampling rate (60sec or 15sec) of the gauge. For larger tsunamis, however, the percentage difference is a more reasonable measure than just the difference from the gauge.

Comparing GeoClaw and tide gauge results based on just one parameter such as the maximum amplitude achieved throughout the entire tsunami wave train can not possibly give the complete story as shown in the thumbnail plots of Section 1.6. In the next sections, we examine each of the 23 tsunamis in more detail by plotting their wave trains computed by GeoClaw and MOST to show a more complete comparison to the detided tide gauge tsunami. In these plots, the following features are seen:

- The first three to five waves are usually captured by both MOST and GeoClaw.
- Waves that occur much later in the wave train that travel along the coast are often not resolved well by either GeoClaw or MOST, since for this study neither used topography refined along enough of the coast that impacts the destination. These are perhaps "edge waves" and we should not expect them to be resolved well.
- Sometimes, GeoClaw and/or MOST obtain the same or lower value for the wave amplitude that corresponds to the tide gauge's detided maximum, but then have an even higher wave at a different time than does the tide gauge. Looking at the time history gives a more complete story.
- Some of the tide gauges only had 60sec resolution, so wave amplitudes higher than that reported at the gauge should be viewed as a difference rather than an error (the gauge value could be higher with a more refined sampling rate). This is clearly seen in the Japan - Midway Island 15sec gauge data rather than the Japan - Midway Island 60sec data that is on the NOAA website.
- GeoClaw and MOST have different amounts of dispersion, which makes the wave trains arrive at slightly different times. This is accounted for in the plots in the next sections.
- GeoClaw's wave trains for the same tsunami with different resolutions, but the same underlying topography, were similar with slightly varying amplitudes. This was encouraging to see. What still needs more attention is knowing where to place appropriate topography to cover the right regions that impact the destination. Sometimes, GeoClaw needs slightly more refined topography/computation than does MOST to achieve a similar maximum amplitude or to match the tide gauge's maximum amplitude.

Theoretically, GeoClaw can be made fast for across the ocean computations. In this study, we focussed on the new adjoint-GeoClaw method which has not yet been optimized, as we were interested in accuracy. Section B addresses more fully the timing information for 11 of the source-destination pairs. We show that the wave tolerance flagging method for refinement in GeoClaw is already efficient, but regridding using adjoint flagging is the main impediment to efficiency of the adjoint-GeoClaw method, especially for 1 minute calculations across the ocean.

The human setup time for a GeoClaw run is substantially reduced with the adjoint-GeoClaw method. Once optimized, we view this method as a huge advance, since it reduces the need for human intervention to specify where refinement is needed. Of course the user is still required to place appropriate refinement regions based on available topography around the destination.

2 Japan 2011 Tsunami

2.1 Comparisons with Detided DART Locations

We began the study by investigating the level of refinement we needed around the source region (Japan) up to the Hawaiian Islands. The MOST tsunami code used 4 minute calculations to propagate the tsunami across the ocean to where the more refined grids near the destination were used.

GeoClaw has the ability to change refinement regions automatically. We experimented with 3 levels of refinement (2 degree, 24 minute, 4 minute) crossing the ocean and around the source region (before getting close to the destination). GeoClaw also has a refinement tolerance parameter. The smaller this parameter is set, the more likely GeoClaw will refine to the smallest grid allowed in a particular region. For example, if a region is allowed to use any of the choices above (2 degree, 24 minute, 4 minute), the region will be refined when the amplitude of a wave achieves this refinement tolerance. Our goal was to show that this choice of grid resolutions, together with an appropriate refinement criterion, is sufficient to match the detided DART data well.

We first allowed the three choices above, up to 4 minute resolution with quite a large refinement tolerance (0.2). As expected, the amplitudes were only 1/2 of what they should be at the DART locations below. We then essentially enforced refinement with a tolerance of 0.005. With this, we successfully matched the DART data. To further ensure a calculation as similar to MOST as possible, we enforced 4 minute computation in the rectangular region longitude -231 to -170 and latitude 18 to 62 for 7 hours, reverting to the choices of 2 degrees or 24 minutes in this region after 7 hours when the amplitudes were below tolerance. Then moving onward toward the destination, we again enforced 4 minute computation in the rectangular region longitude -170 to -120 and latitude 18 to 62 starting at 7 hours till the end of the 13 hour computation. This enforcement is seen in the region statements below where Level 1 means 2 degrees, Level 2 means 24 minutes, and Level 3 means 4 minute calculations. The range 1, 3 in the second region statement below thus means a minimum refinement of 2 degrees and a maximum refinement of 4 minutes.

```
rundata.regiondata.regions.append([1, 1, 0., 1e9, -360,0,-90,90])
rundata.regiondata.regions.append([1, 3, 0., 13.0*3600., -360,0,0,90])
rundata.regiondata.regions.append([3, 3, 0*3600., 7*3600, -231.0,-170.0,18,62.0])
rundata.regiondata.regions.append([3, 3, 7.0*3600., 1e9, -170.0,-120.0,18,62.0])
```

The locations of the DART gauges are plotted in Figure 8 and given below. In Figure 8 the pink rectangle shows the extent of the Japan2011 source. However, in much of this region, the deformation is nearly zero. The green rectangular region shows where most of the source is concentrated. Here, we imposed one minute topo to make sure we had it well resolved, but computed only on a 4 minute grid. The gauge numbered 51407 is near the Big Island of Hawaii and is plotted in Figure 9.

```
rundata.gaugedata.gauges.append([21401, 152.583-360., 42.617, 1800., 1.e10])
rundata.gaugedata.gauges.append([21413, 152.1167-360., 30.5153, 1800., 1.e10])
rundata.gaugedata.gauges.append([21418, 148.694-360., 38.711, 0., 1.e10])
rundata.gaugedata.gauges.append([21419, 155.736-360., 44.455, 1800., 1.e10])
rundata.gaugedata.gauges.append([51407, -156.546, 19.553, 1800., 1.e10])
```

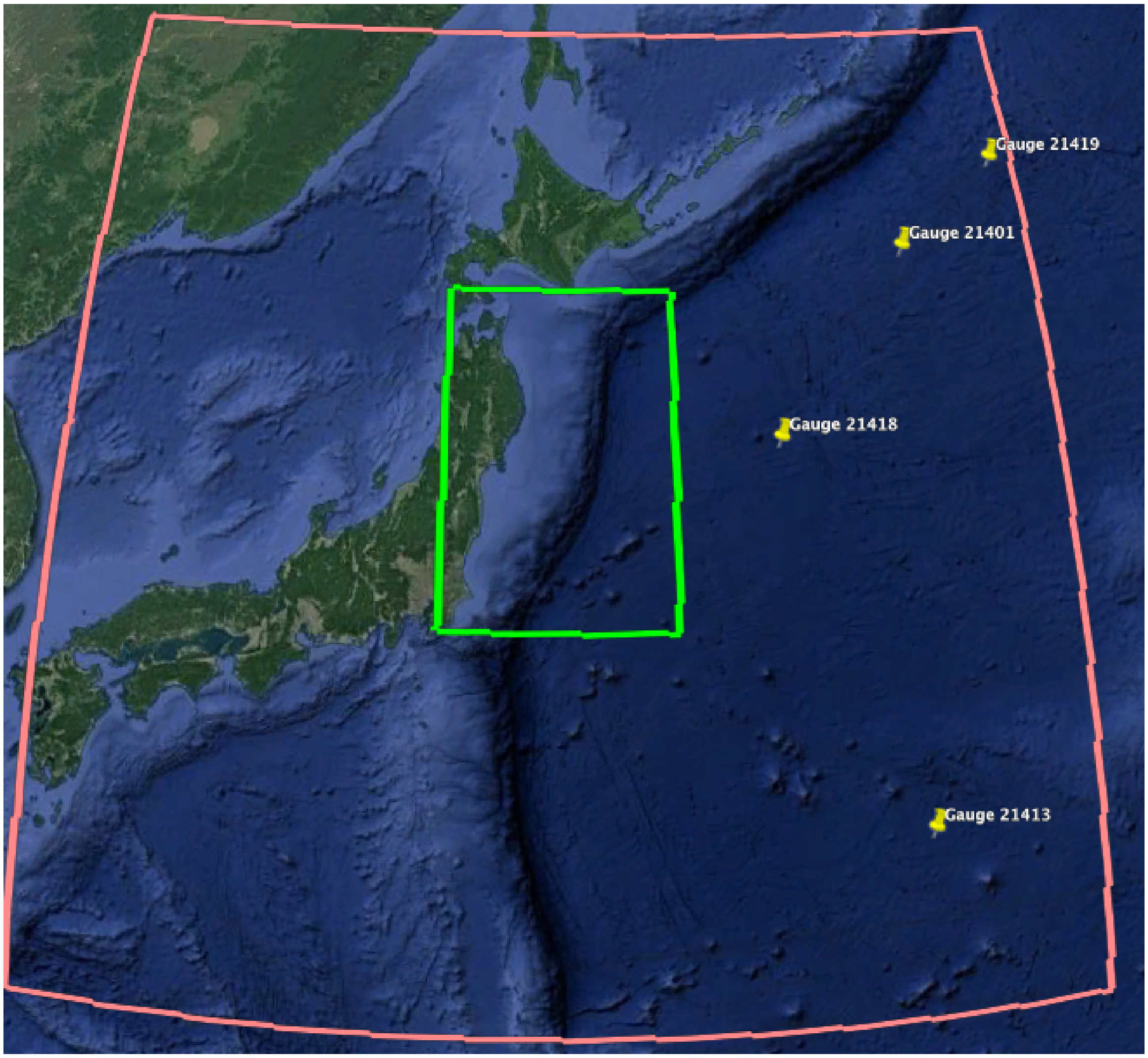

Figure 8: Japan2011 Source and Dart Locations, extent=-230.05, -203.383, 26.635, 47.636

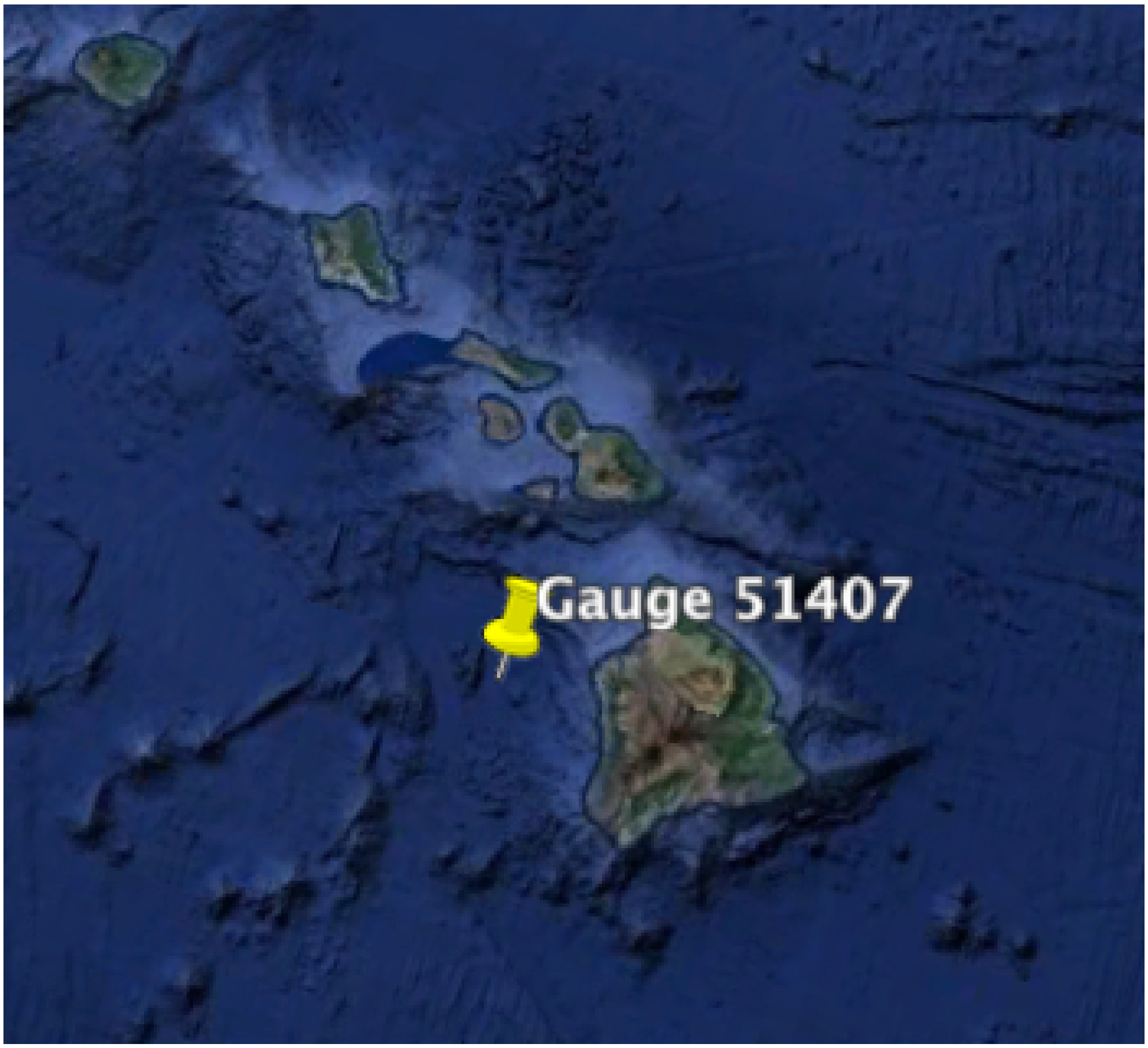

Figure 9: Japan2011, Gauge 51407 Location

The results below show we compare quite well to the first four DART locations. The one near Hawaii has not yet been detided, but ensuring 4 minute resolution increased the amplitude at this gauge by a factor of 2.

```
Geoclaw gauge_number (DART):  21401
max_geoclaw:  0.5848713
max_detided:  0.664344266018

Geoclaw gauge_number (DART):  21413
max_geoclaw:  0.7312096
max_detided:  0.773620541449

Geoclaw gauge_number (DART):  21418
max_geoclaw:  1.421522
max_detided:  1.87315953213

Geoclaw gauge_number (DART):  21419
max_geoclaw:  0.4811033
max_detided:  0.540306271859

Geoclaw gauge_number (DART):  51407
max_geoclaw:  0.2792238
```

Time series at the DART locations are given in Figures 10, 11, 12, 13, and 14.

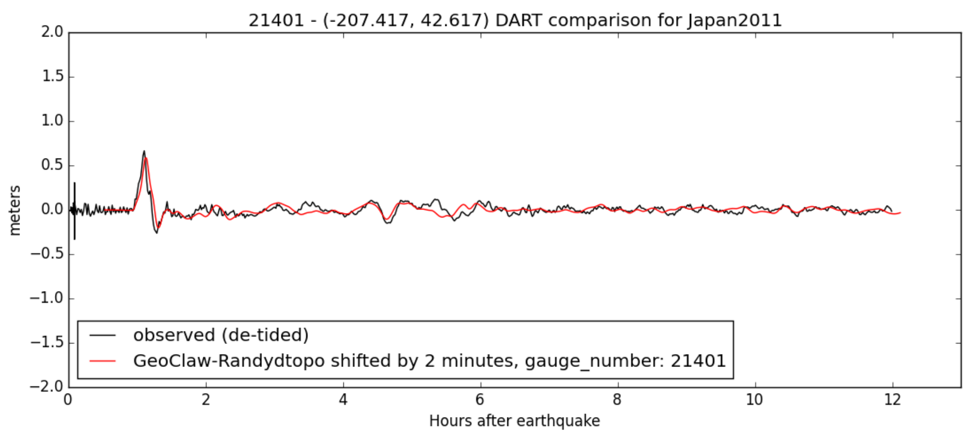

Figure 10: Japan2011, DART 21401 Comparisons

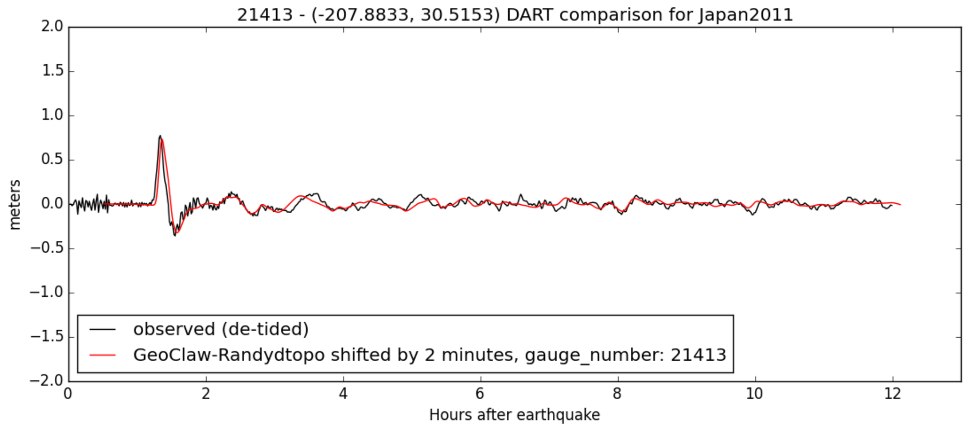

Figure 11: Japan2011, DART 21413 Comparisons

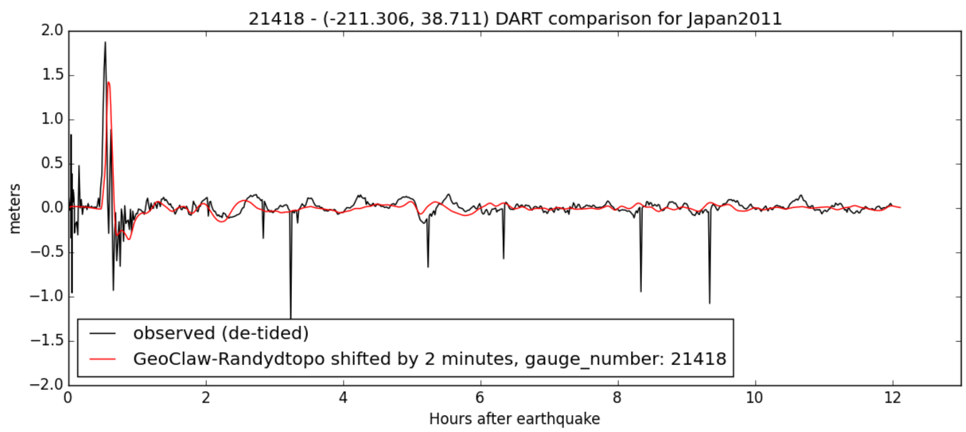

Figure 12: Japan2011, DART 21418 Comparisons

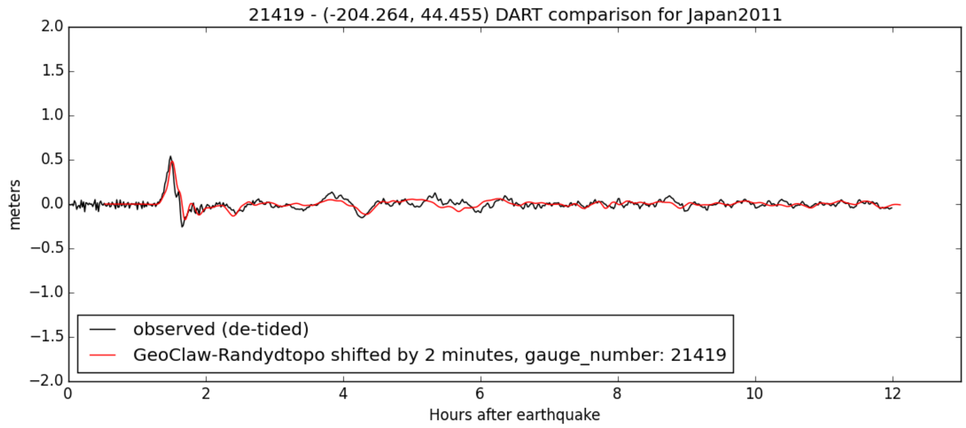

Figure 13: Japan2011, DART 21419 Comparisons

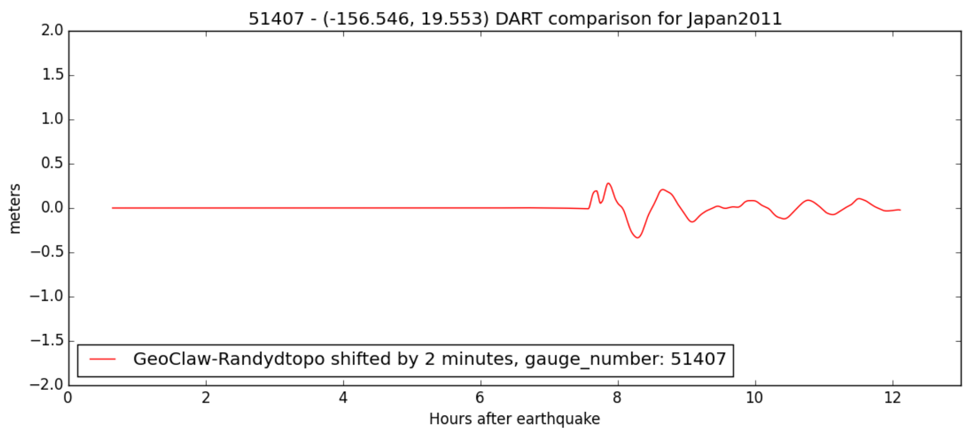

Figure 14: Japan2011, Gauge 51407 Comparisons

In the next sections, we compare GeoClaw and MOST results at Hilo, Crescent City, Arena Cove, Port Orford, and Midway Island to the detided tide gauge results. At some of these locations, we put several computational gauges near the tide gauge to see how sensitive the results would be. For each computational gauge used, we provide the maximum GeoClaw amplitude, and for the computational gauge closest to the one MOST used, we provide a plot of the MOST, the detided tide gauge, and the GeoClaw tsunamis.

2.2 Hilo

Gauge detiding

We began by detiding the Hilo station 1617760 15 second data that was provided by PMEL in the file **20110311-hilo-hi-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 15 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 16 shows a blowup from 6.5 to 11.5 hours post quake.

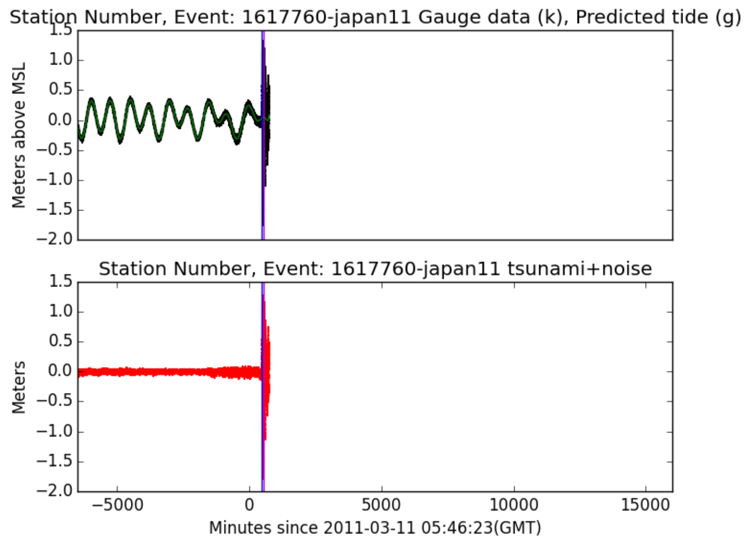

Figure 15: Japan 2011, Hilo, DeTided Tsunami

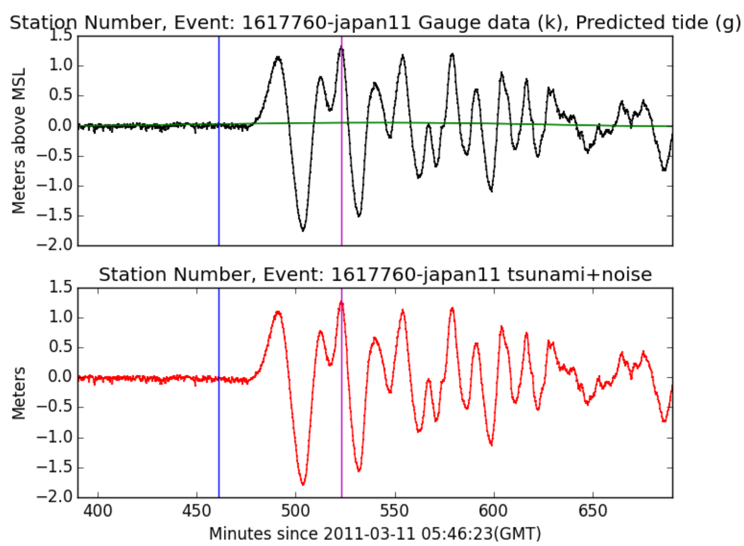

Figure 16: Japan 2011, Hilo, DeTided Tsunami, 6.5-11.5 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -220 to -214 longitude and 35 to 42 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Hilo between 7.5 and 11 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Hilo, we used 1min (Level 4), 6sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -220  -214  35  42
4  4  25200  1e+09  -161  -154.033  18.0317  22.9983
5  5  25200  1e+09  -156.262  -154.597  18.685  20.415
6  6  25200  1e+09  -155.101  -155.01  19.7  19.79
```

The topo files we used that supported this computation were:

```
etopo1_-240_-180_-41_65_1min.tt3
etopo1_-180_-100_-41_65_1min.tt3
hawaii_36s.asc
hawaii_6s_20070806.asc
hilo_hi_Port_onethird.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 0 below and depicted in Figure 17. The MOST computational gauge as recorded in the file **hilo2timeseriesC.txt** was the same as Gauge 0. Gauge 0 was turned on at 7.5 hours post-quake. Its location as specified in GeoClaw is given below:

```
rundata.gaugedata.gauges.append([0, -155.05593, 19.73111, 7.5*3600.,1.e10])
```

Figure 17: Hilo gauge location

In Figure 18 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 1.80m and came from a C grid of 2 second resolution. The detided max amplitude was 1.27m based on the 15sec gauge data. The maximum for GeoClaw was 1.50m. The Bathymetry used at the gauge for the GeoClaw computation was B=-9.42m.

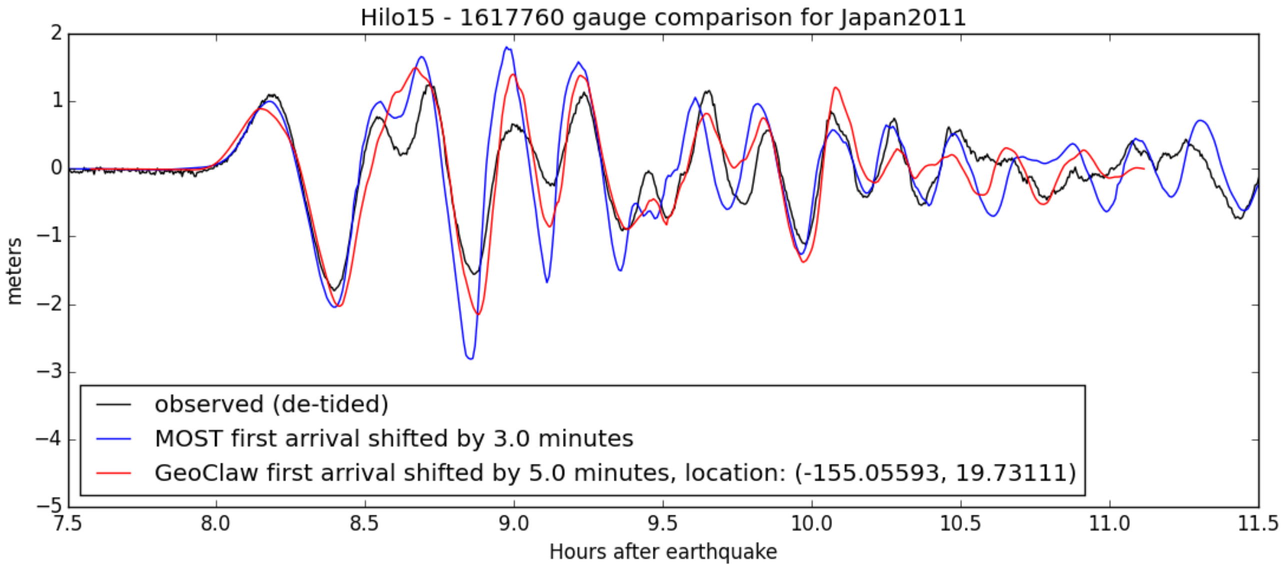

Figure 18: Japan2011, Hilo, 1sec

Discussion:

Both MOST and GeoClaw tsunamis have excellent agreement with the 15sec tide gauge tsunami, with both overshooting the wave around 9 hours post-quake. GeoClaw and the tide gauge achieve the maximum amplitude on the second wave, and MOST's overshoot around 9 hours gives its maximum on the third wave.

2.3 Crescent City

Gauge detiding

We began by detiding the Crescent City station 9419750 15 second data that was provided by PMEL in the file **20110311-crescent-city-ca-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 19 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 20 shows a blowup from 9 to 13 hours post quake.

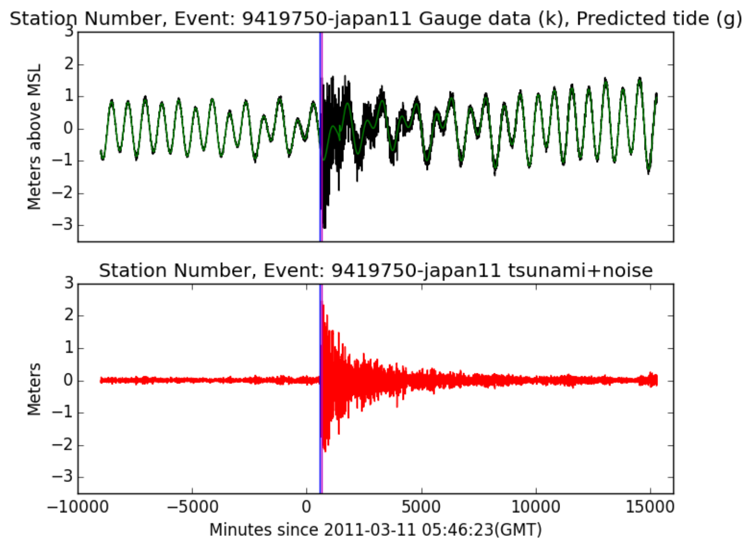

Figure 19: Japan2011, Crescent City, DeTided Tsunami

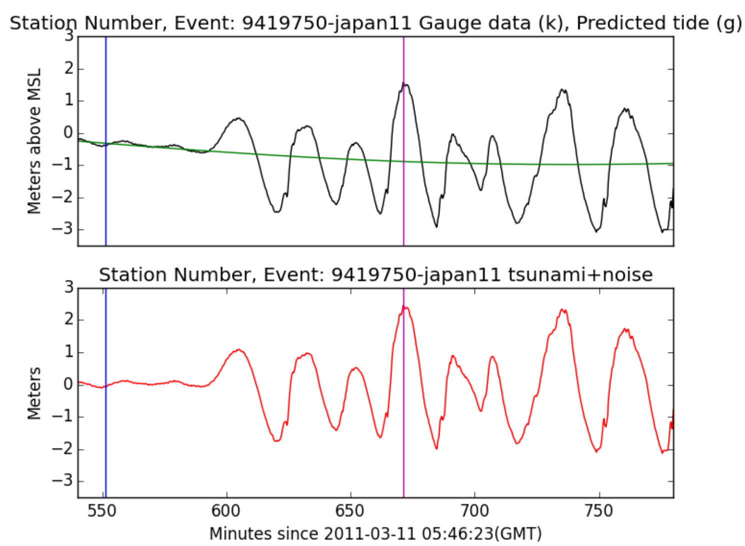

Figure 20: Japan2011, Crescent City, DeTided Tsunami, 9-13 hrs post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -31 to 65 latitude.

Around the source, we used one minute topo but computed with four minute resolution (level 3) since the source region -220 to -214 longitude, 35 to 42 latitude is inside the region -231 to -170 longitude, 18 to 62 latitude which used four minute computation (level 3) for 25200 sec (7 hrs) as seen in the region specifications below.

Across the ocean, we used 4 minute resolution in the relevant parts of the ocean and either 24 minute or 2 degree resolution elsewhere. This is specified apriori (see the first four regions specifications below). A refinement tolerance of 0.005 was used for the variable 1,3 region, which means if a wave height exceeds this tolerance the resolution in the region is increased up to a maximum of level 3.

Around Crescent City, the finest grid mimicked PMEL's C grid for the 2sec and 1sec runs (level 6 below is either 2sec resolution or 1sec resolution). For the one third arc sec run, we used our Crescent City 1/3sec topo (which had the pier removed). For this run, our 1/3sec topo supported PMEL's C grid (1sec computational resolution) and our finest 1/3sec grid which was inside PMEL's C grid just around the Harbor. All three of these runs used regions that mimicked PMEL's A and B grids, with 1 minute and 12 second resolution, respectively. The specifics of the 7 regions we used are given below for the 2sec or 1sec runs. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
7                    =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  3  0  46800  -360  0  0  90
3  3  0  25200  -231  -170  18  62
3  3  25200  1e+09  -170  -120  18  62
4  4  28800  1e+09  -126.995  -123.535  40.515  44.495
5  5  28800  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  30600  1e+09  -124.234  -124.143  41.7168  41.7829
```

The topo files we used that supported the 2sec or 1sec computations were:

```
etopo1_-180_-60_-65_65_4min.tt3
etopo1_-240_-180_-65_65_4min.tt3
etopo1_-220_-214_35_42_1min.asc
etopo1_-130_-120_37_51_1min.tt3
etopo1_-126_-114_29_37_1min.tt3
cresc1sec.asc
```

For the one third arc sec run, we used 8 regions. The first 6 above were unchanged, level 6 became a 1sec region matching our 1/3sec data and level 7 was added as the one third arc sec region around Crescent City Harbor also covered by 1/3sec data. The specifics are:

```
8                    =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  3  0  46800  -360  0  0  90
3  3  0  25200  -231  -170  18  62
3  3  25200  1e+09  -170  -120  18  62
4  4  28800  1e+09  -126.995  -123.535  40.515  44.495
5  5  28800  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  30600  1e+09  -124.234  -124.159  41.7168  41.7695
7  7  31500  1e+09  -124.202  -124.18  41.733  41.752
```

The topo files we used that supported the one third sec computation were:

```
etopo1_-180_-60_-65_65_4min.tt3
etopo1_-240_-180_-65_65_4min.tt3
etopo1_-220_-214_35_42_1min.asc
etopo1_-130_-120_37_51_1min.tt3
etopo1_-126_-114_29_37_1min.tt3
cc-1_3sec-c_pierless.asc
```

We considered 5 GeoClaw computational gauges. Gauges 0, 2, 19750, and 19751 were near the tide gauge and Gauge 1 was in deeper water at the mouth of the harbor. The MOST gauge as recorded in the file **crescenttimeseriesC.txt** was the same as our Gauge 2. The locations of these gauges are given below and plotted in Figure 21. They were turned on at 9 hours post-quake.

```
rundata.gaugedata.gauges.append([0, -124.1839, 41.74512, 9*3600, 1.e10])
rundata.gaugedata.gauges.append([2, -124.18397, 41.74512, 9*3600, 1.e10])
rundata.gaugedata.gauges.append([19750, -124.1838, 41.745616, 9*3600, 1.e10])
rundata.gaugedata.gauges.append([19751, -124.1844, 41.745604, 9*3600, 1.e10])
rundata.gaugedata.gauges.append([1, -124.184291, 41.734929, 9*3600, 1.e10])
```

Figure 21: Crescent City gauge locations

The first four gauges gave very similar results, so we only give comparison plots for Gauge 2 in Figures 22, 23, and 24 for the 2sec, 1sec, and 1/3sec runs.

The MOST max amplitude was 2.4323 and came from a C grid of 2 second resolution. The detided max amplitude was 2.463. Maximums for GeoClaw, and Bathymetry used at the gauge for the computations are given below. Note that GeoClaw uses cell averaged Bathymetry, so a coarser grid calculation might well have a different bathymetry from a finer one.

```
Gauge 0:                Gauge 2:
2sec: 2.15,  B=-4.65    2sec: 2.15,  B=-4.65
1sec: 2.29,  B=-4.75    1sec: 2.29,  B=-4.75
1/3:  2.41,  B=-5.90    1/3:  2.41,  B=-5.90

Gauge 19750:            Gauge 19751:            Gauge 1:
2sec: 2.10,  B=1.29     2 sec: 2.17, B=-2.98    2sec: 1.71, B=-10.74
1sec: 2.29,  B=-0.24    1 sec: 2.30, B=-4.71    1sec: 1.68, B=-10.65
1/3:  2.41,  B=-3.46    1/3:   2.38, B=-4.84    1/3:  1.59, B=-10.35
```

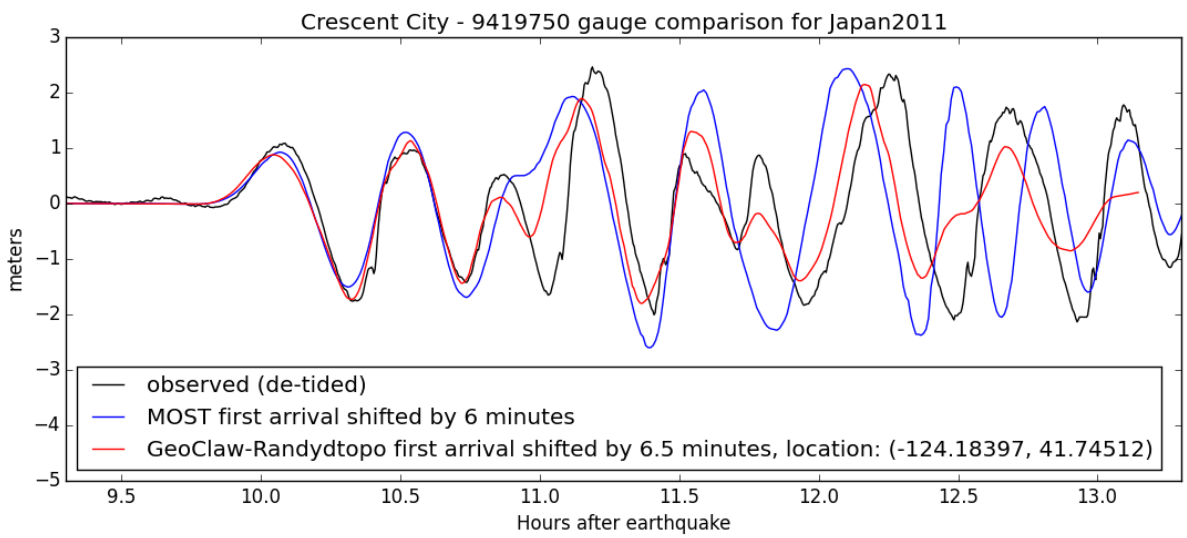

Figure 22: Japan2011, Crescent City, 2sec, Gauge 2

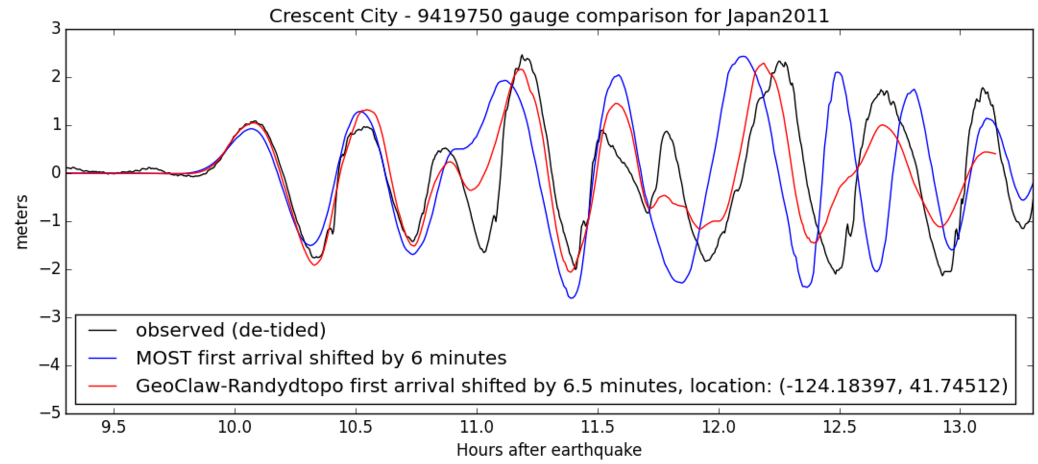

Figure 23: Japan2011, Crescent City, 1sec, Gauge 2

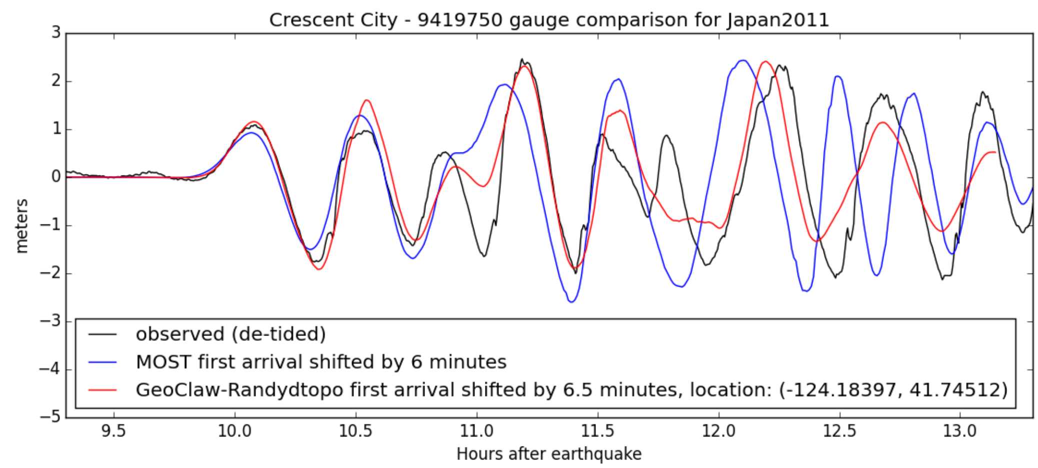

Figure 24: Japan2011, Crescent City, 1/3 sec, Gauge 2

Timing information for this 1/3sec run is given in Appendix B.1.

Discussion:

The MOST and GeoClaw tsunamis were very similar and compared well to detided gauge results. The GeoClaw tsunami more closely matches the detided gauge tsunami in time – note from Figure 22 that MOST's maximum (2.43m) did not occur at the time of the detided maximum (11.19hr), and at 11.19 hr both MOST and GeoClaw waves had a maximum amplitude around 2.0m only.

2.4 Arena Cove

Gauge detiding

We began by detiding the Arena Cove station 9416841 60 second data that was provided by PMEL in the file **20110311-arena-cove-ca-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 25 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the detided maximum amplitude in magenta. Figure 26 shows a blowup from 9 to 13 hours post quake where missing data is clearly seen in the black curve.

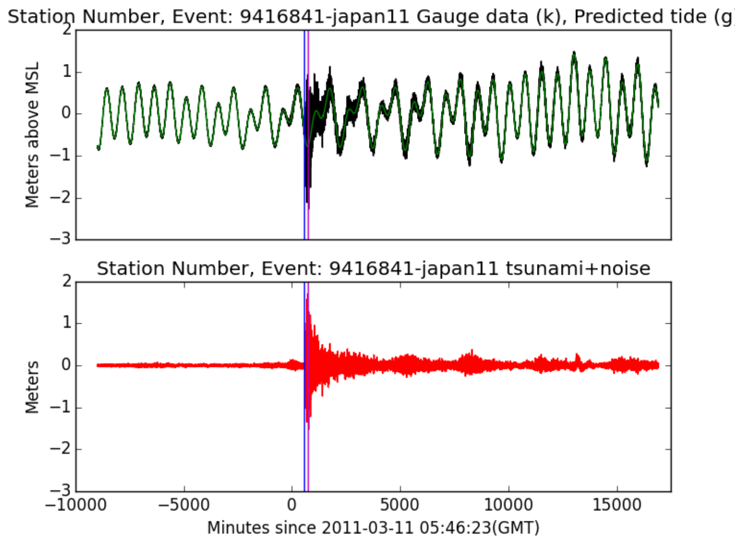

Figure 25: Japan2011, Arena Cove, DeTided Tsunami

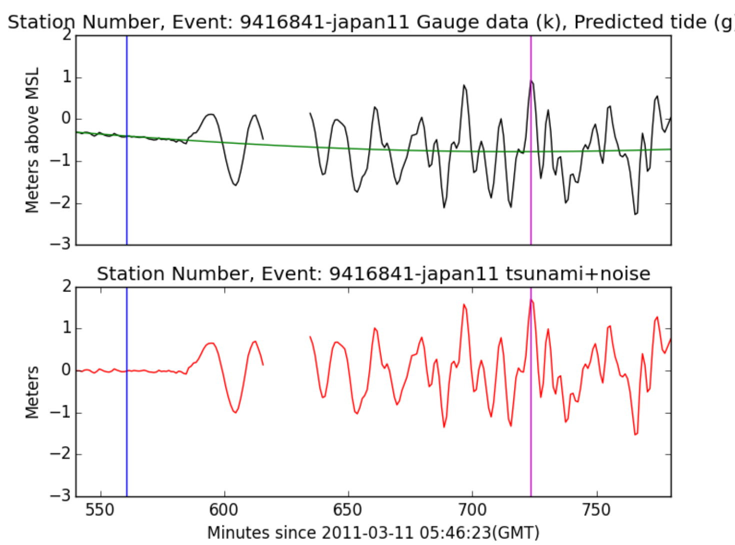

Figure 26: Japan2011, Arena Cove, DeTided Tsunami, 9-13 hrs post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we put a one minute topo grid and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -220 to -214 longitude and 35 to 42 latitude. Across the ocean, we used the adjoint method to automatically flag cells for refinement, only flagging the waves that would arrive at Arena Cove Harbor between 8.75 and 13.0 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed 24 minute (Level 2), 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Arena Cove, we used 1min (Level 4), 12sec (Level 5), 6sec (Level 6), 2sec (Level 7), and 1sec (Level 8) grids. The 1sec grid was the same as PMEL's C grid. The 1 min grid was an extension of PMEL's A grid, the 12 sec grids were extensions of PMEL's B grid, the 6sec grid was inside PMEL's B grid, and the 2sec grid was somewhat larger than PMEL's C grid. The specifics of the 8 regions used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
8                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -220  -214  35  42
4  4  28800  1e+09  -135  -120  32  46
5  5  30600  1e+09  -124.65  -123.065  38.35  39.8
5  5  28800  1e+09  -124.65  -123.835  39.8  46
6  6  30600  1e+09  -124.43  -123.43  38.4  39.4
7  7  30600  1e+09  -123.85  -123.651  38.845  39.0445
8  8  30600  1e+09  -123.78  -123.685  38.89  39.02
```

The topo files we used that supported this computation were:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
arena_cove_6sec.asc
arena_cove_1sec.asc
arena_cove_2sec.asc
arena_cove_Port_onethird.asc
cca_12s_mhw_v2.asc
```

We considered 1 GeoClaw computational gauge called Gauge 0. Gauge 0 was close to the MOST gauge, given in the file **arenacovetimeseriesC.txt** as having location (-123.71111, 38.91458). In a picture, it wouldn't be distinguished from Gauge 0. Gauge 0 was turned on at 9 hours post-quake. Its location as described to Geoclaw is given below and it can be seen in Figure 27.

```
rundata.gaugedata.gauges.append([0, -123.711097, 38.914646, 9*3600.,1.e10])
```

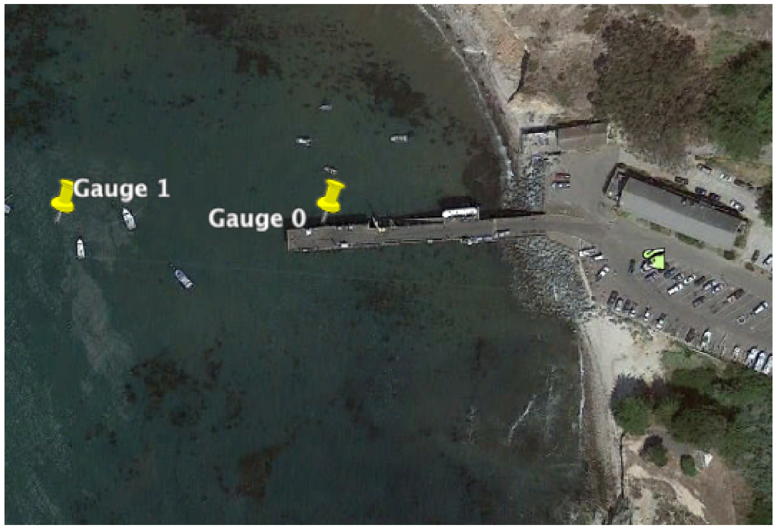

Figure 27: Arena Cove gauge Locations

We give a comparison plot for Gauge 0 in Figure 28. The MOST max amplitude was 1.5793m and came from a C grid of 2 second resolution in longitude and 1.5 second resolution in latitude. The detided max amplitude was 1.7036m. The maximum for GeoClaw was 1.2891m. The bathymetry used by GeoClaw at the gauge was -3.496m.

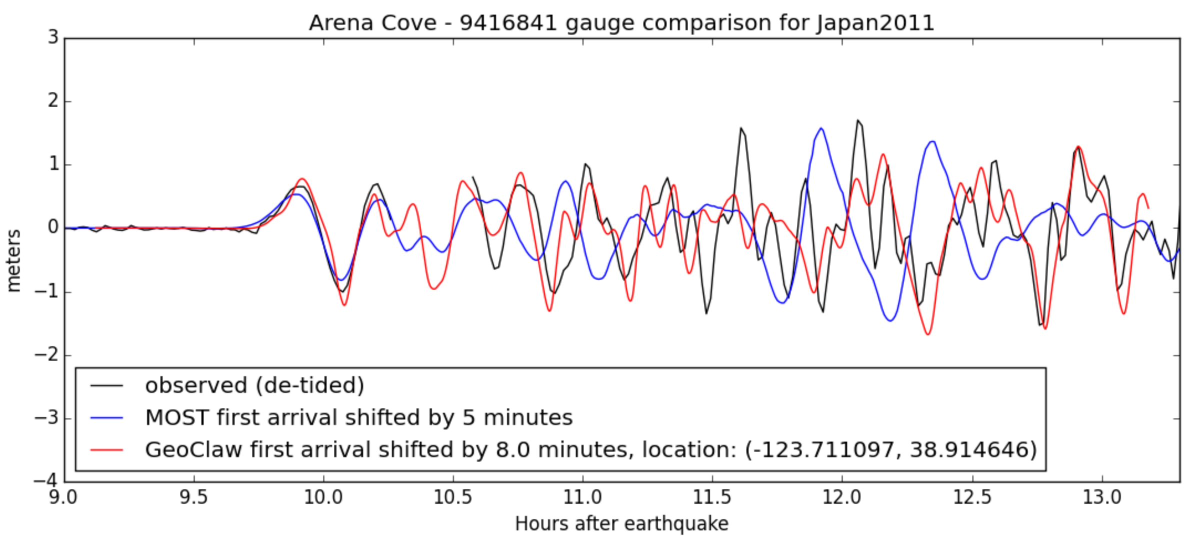

Figure 28: Japan2011, Arena Cove, 1sec

We also did a GeoClaw 1/3sec run around a region inside the C grid, and got an almost identical wave train. We then did another 1/3sec run with expanded regions for the 12sec computations (Level 5). This last run increased the maximum amplitude only 2cm from 1.29m to 1.31m and produced essentially the same wave train as seen in Figure 28. The same topography and gauge were used for this run, and the regions used are given below where Level 1 through Level 9 means 2 degree, 24min, 4min, 1min, 12sec, 6sec, 2sec, 1sec, and 1/3sec computation, respectively. The bathymetry used by GeoClaw for these 1/3sec runs was -3.61m.

```
10                   =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  4  0  1e+09  -240  -100  0  65
4  4  0  3600  -231  -203  26  48
4  4  28800  1e+09  -135  -120  32  46
5  5  30600  1e+09  -126.065  -123.065  37.9601  39.8
5  5  28800  1e+09  -126.065  -123.835  39.8  46
6  6  30600  1e+09  -124.43  -123.43  38.4  39.4
7  7  30600  1e+09  -123.85  -123.651  38.845  39.0445
8  8  30600  1e+09  -123.78  -123.685  38.89  39.02
9  9  31500  1e+09  -123.73  -123.71  38.91  38.92
```

Discussion:

Both MOST and GeoClaw tsunamis match the tide gauge tsunami fairly well until about 11.5 hrs post-quake with a gap in tide gauge data between 10.25 to 10.6 hrs post-quake. They both miss one of the tide gauge's biggest waves around 11.75 hrs post-quake. MOST's two largest waves appear at slightly wrong times between 11.75 and 12.5 hours post-quake. Increasing the finest grid to 1/3sec and expanding the size of the 12sec computational regions did nothing to help GeoClaw capture this big wave around 11.75 hrs post-quake.

2.5 Port Orford

Gauge detiding

We began by detiding the Port Orford station 9431647 15 second data that was provided by PMEL in the file **20110311-port-orford-or-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 29 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red and the location of the maximum detided amplitude in magenta. Figure 30 shows a blowup from 9 to 13 hours post quake.

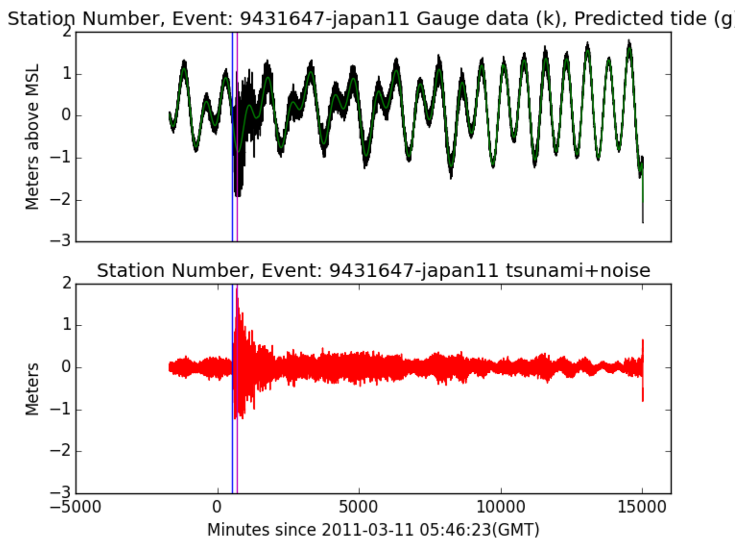

Figure 29: Japan2011, Port Orford, DeTided Tsunami

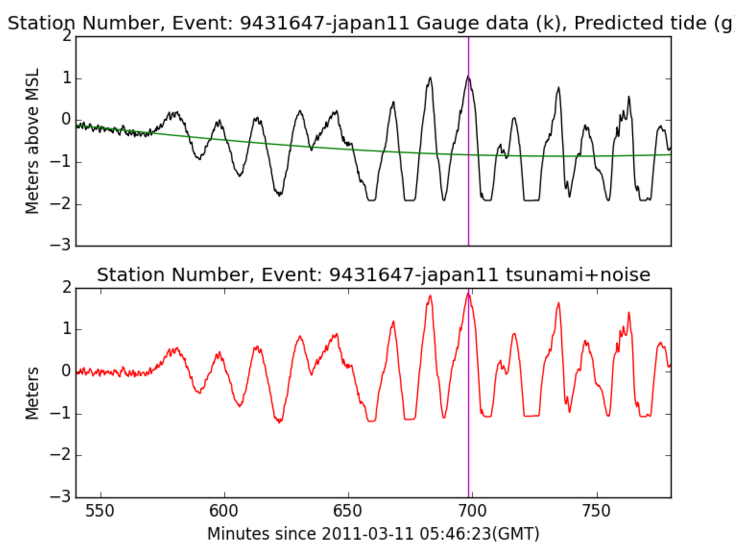

Figure 30: Japan2011, Port Orford, DeTided Tsunami, 9-13 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -31 to 65 latitude.

Across the ocean, we used 4 minute resolution in the relevant parts of the ocean and either 24 minute or 2 degree resolution elsewhere. This is specified apriori (see the first four regions specifications below). A refinement tolerance of 0.005 was used for the variable 1,3 region, which means if a wave height exceeds this tolerance the resolution in the region is increased up to a maximum of level 3.

Around Port Orford, the finest grid mimicked PMEL's C grid for the 2sec and 1sec runs (level 6 below is either 2sec resolution or 1sec resolution). The 1/3sec resolution run used 1sec resolution calculation around PMEL's C grid with 1/3sec resolution around the smaller region around the harbor. For the one third sec run, we used the 1/3sec topo that PMEL provided to make 1sec and 1/3sec topo for our purposes. The 1sec topo supported our (2sec or 1sec) regions. The 1/3sec topo was only used around a small part of PMEL's C region that surrounded the harbor where the tide gauge was located for the 1/3sec finest resolution run. All three of these runs used regions that mimicked PMEL's A and B grids, with 1 minute and 12 second resolution, respectively. The B grid (12 second resolution) was supported by one minute data and 1 second data closer to the destination.

The specifics of the 7 regions we used are given below for the 2sec or 1sec runs. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
7                    =: num_regions
1  1  0  1e+09  -300  -60  -80  80
1  3  0  46800  -360  0  0  90
3  3  0  25200  -231  -170  18  62
3  3  25200  1e+09  -170  -120  18  62
4  4  27000  1e+09  -127.5  -123.5  39.01  47.19
5  5  28800  1e+09  -124.933  -124.27  42.0683  43.265
6  6  30600  1e+09  -124.551  -124.44  42.6715  42.7732
```

The topo files we used that supported the 2sec or 1sec computations were:

```
etopo1_-180_-60_-65_65_4min.tt3
etopo1_-240_-180_-65_65_4min.tt3
etopo1_-130_-120_37_51_1min.tt3
PortOrford_1sec.asc
etopo1_-220_-214_35_42_1min.asc
```

For the one third arc sec run, the following region was added:

```
7  7  30600  1e+09  -124.516  -124.48  42.73  42.7439
```

The following topography file was also added to support this Level 7 region:

```
PortOrfordHarbor.asc
```

We considered the GeoClaw computational gauge labelled Gauges 0. The MOST gauge as recorded in the file **porfordtimeseriesC.txt** was the same as our Gauge 0. The location of this gauge is given below and plotted in Figure 31. It was turned on at 9 hours post-quake.

```
rundata.gaugedata.gauges.append([0, -124.49767, 42.73876, 9*3600, 1.e10])
```

Figure 31: Port Orford gauge locations

We give comparison plots for Gauge 0 in Figures 32, 33, and 34 for the 2sec, 1sec, and 1/3sec runs. The MOST max amplitude was 1.9478 and came from a C grid of 2 second resolution. The detided max amplitude was 1.884. Maximums for GeoClaw, and Bathymetry used at the gauge for the computation are given below. Recall, a coarser grid calculation might well have a different bathymetry from a finer one.

```
Gauge 0:
2sec: 1.84,  B=-4.798
1sec: 1.90,  B=-4.043
1/3:  1.93,  B=-3.906
```

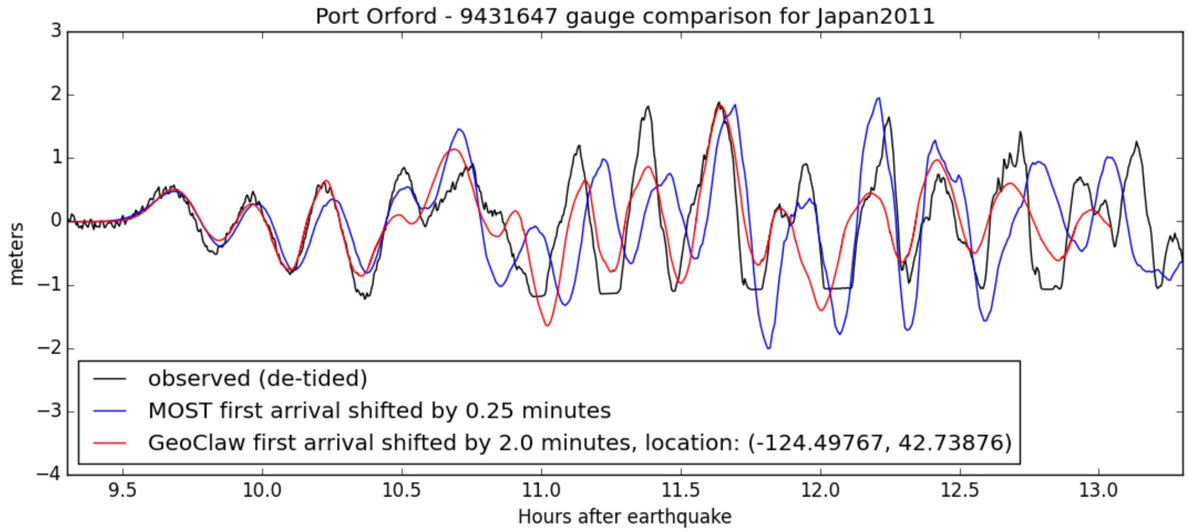

Figure 32: Japan2011, Port Orford, 2sec, Gauge 0

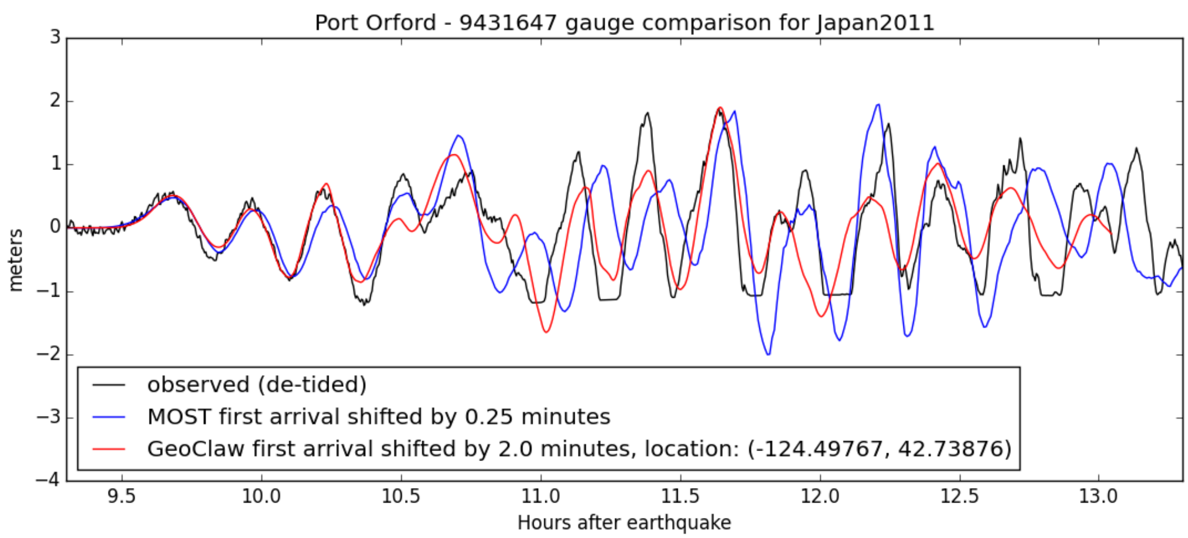

Figure 33: Japan2011, Port Orford, 1sec, Gauge 0

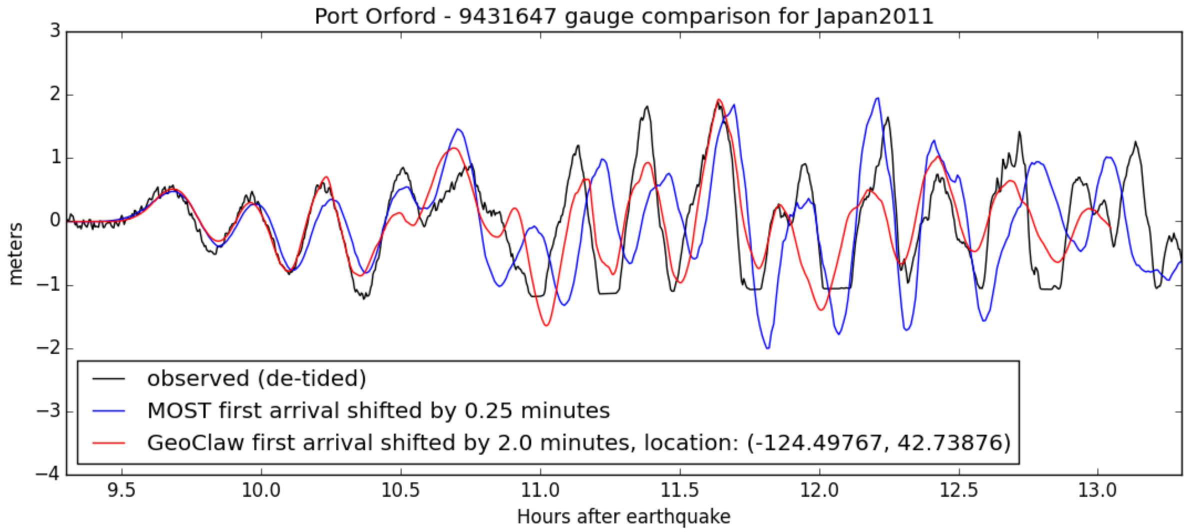

Figure 34: Japan2011, Port Orford, 1/3 sec, Gauge 0

Timing information is given in Appendix B.3 for the 2sec run.

Discussion:

The MOST and GeoClaw tsunamis were very similar and compared well to detided gauge results for the first 5 or 6 waves. The tide gauge wave ending around 11.5 hrs post-quake was not captured well by either MOST or GeoClaw, but both captured the following wave starting shortly thereafter. MOST also captures the wave that peaks around 12.25 hrs post-quake and reports it as its highest wave. GeoClaw and the tide gauge have their maximums at the same time.

Note from the plots that the actual tide gauge tsunami bottomed out around −1 meters; whereas, both the MOST and GeoClaw tsunamis do not. This is because Gauge 0 is not actually in the correct location (near the dock) as can also be seen in Figure 31.

2.6 Midway Island

Gauge detiding

We began by detiding the Midway station 1619910 15 second data that was provided by PMEL in the file **20110311-sand-island-midway-islands-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 35 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red and the location of the maximum detided amplitude in magenta. Figure 36 shows a blowup from 4 to 13 hours post quake. These figures clearly show oscillations in the caldera that form Midway Atoll many hours after the arrival of the first wave.

The detided max amplitude was 1.709 (1.56 was obtained by PMEL at the same time post-quake). This 1.709 could even be higher by at most 0.1m as seen from the blowup from 0 to 7 hours post-quake in Figure 36 where the approximated tide in green is more positive than perhaps it should be near the first waves.

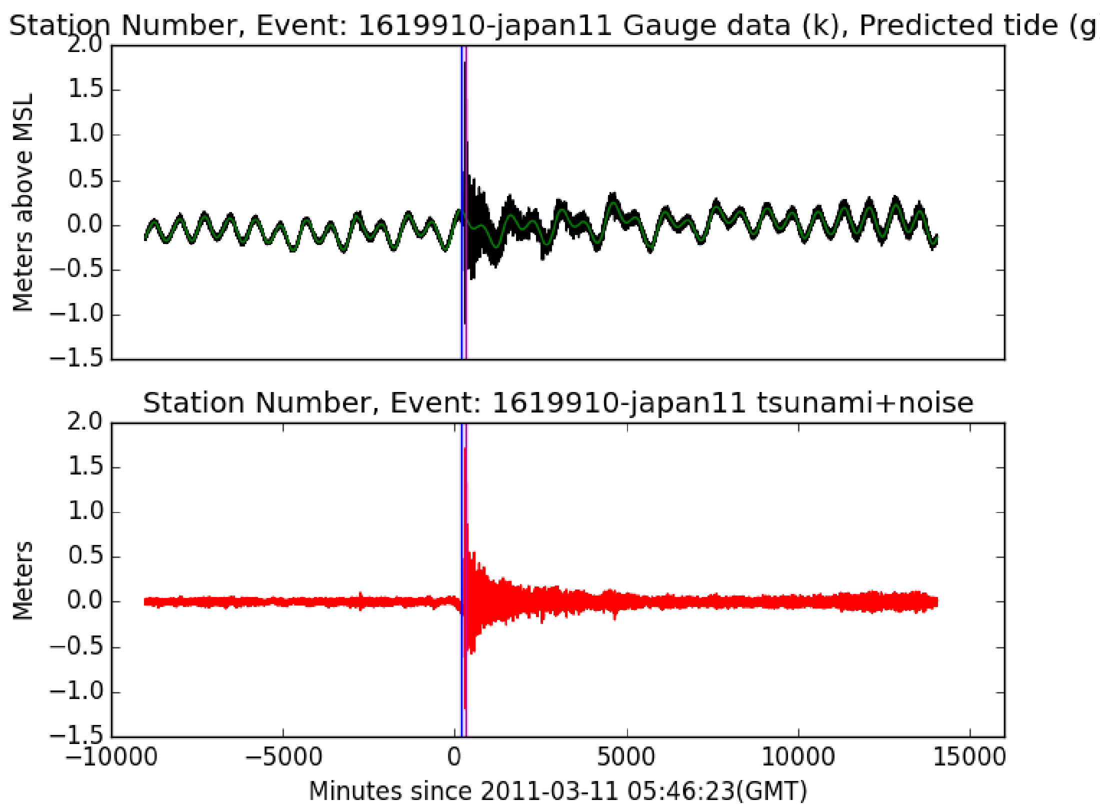

Figure 35: Japan2011, Midway, DeTided Tsunami

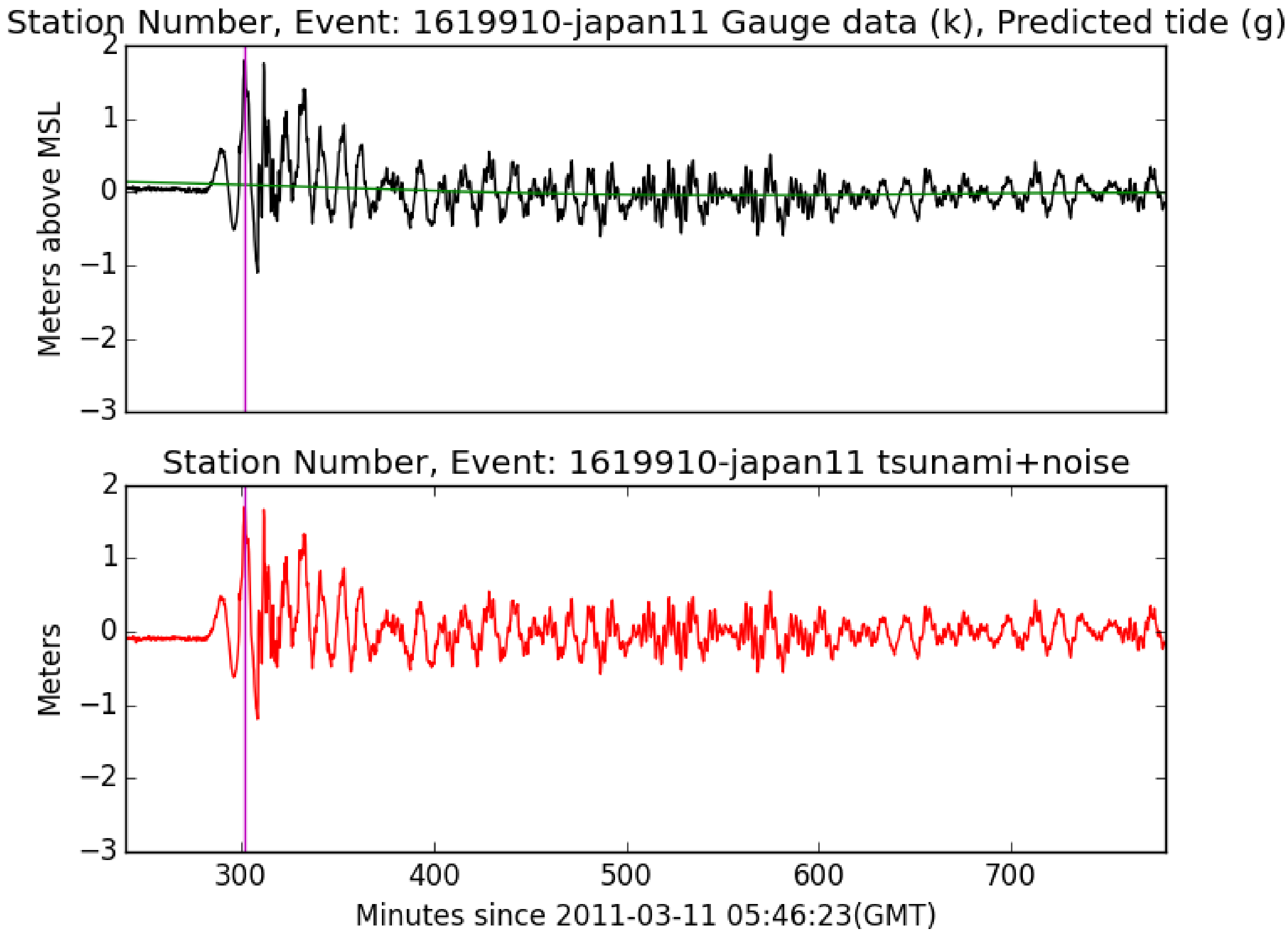

Figure 36: Japan2011, Midway, DeTided Tsunami, 4 to 13 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -31 to 65 latitude.

Around the source, we used one minute topo but computed with four minute resolution (level 3) for 1 hour (3600 sec) from -231 to -203 longitude and 26 to 48 latitude.

Across the ocean, we used 4 minute resolution in the relevant parts of the ocean and either 24 minute or 2 degree resolution elsewhere as described in the first 4 region specifications below. A refinement tolerance of 0.005 was used for the variable 1,3 region to enforce refinement up to a maximum of level 3 (4 minute) where this tolerance was exceeded.

Around Midway Island, we used the 1/3 sec topo that PMEL provided, and cropped and coarsened it to get 6 sec, 1sec, and 1/3 sec topo for our use. For the 2sec and 1sec finest runs, the finest computational resolution was around PMEL's C grid. The 1/3 arc sec run used 1sec computational resolution around PMEL's C grid with 1/3 arc sec around the region inside the C grid where the harbor with the tide gauge is located. All three of these runs used regions that mimicked PMEL's A and B grids, with 1 minute and 6 second resolution, respectively. The specifics of the 7 regions we used for the 2sec and 1sec runs are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
7                   =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  3  0  46800  -360  0  0  90
3  3  0  3600  -231  -203  26  48
3  3  10800  1e+09  -185  -175  26  36
4  4  12600  1e+09  -178.4  -176.4  27.2  29.2
5  5  14400  1e+09  -177.57  -177.16  28.09  28.42
6  6  14400  1e+09  -177.436  -177.309  28.1895  28.289
```

The one third arc second run used 8 regions, the 7 above plus the one below around the Midway Harbor.

```
7  7  14440  1e+09  -177.369  -177.354  28.1995  28.2205
```

The following topo was used for all three of these runs. Since the topography changes rapidly around Midway Island, we included the one third arc sec topo for all three runs.

```
etopo1_-180_-60_-65_65_4min.tt3
etopo1_-240_-180_-65_65_4min.tt3
etopo1_-220_-214_35_42_1min.asc
etopo1_-179_-176_27_30_1min.tt3
Midway_Smaller_1s_v2.asc
midway_6s_v2.asc
MidwayHarbor_1-3s.asc
```

We also ran one last enhanced 1/3sec run, by allowing for up to one minute computation across the ocean in a larger region around Midway Island with the 1,4 region specification below. In particular, the regions we used for this computation are given below.

```
1  1  0  1e+09  -240  -100  -31  65
1  3  0  1e+09  -240  -140  0  65
1  4  0  1e+09  -190  -170  20  40
4  4  0  3600  -231  -203  26  48
4  4  12600  1e+09  -178.4  -176.4  27.2  29.2
5  5  14400  1e+09  -177.57  -177.16  28.09  28.42
6  6  14400  1e+09  -177.436  -177.309  28.1895  28.289
7  7  14400  1e+09  -177.369  -177.354  28.1995  28.2205
```

These regions were supported by one minute topo files. In particular, the topo we used for this last 1/3sec computation are given below.

```
etopo1_-180_-100_-41_65_1min.tt3    Midway_Smaller_1s_v2.asc
etopo1_-240_-180_-41_65_1min.tt3    midway_6s_v2.asc
MidwayHarbor_1-3s.asc
```

We used one GeoClaw computational gauge, called Gauge 0 shown in Figure 37. It was at the same location (-177.36103,28.21398) as the MOST gauge, given in the file **midwaytimeseriesC.txt**, and was turned on 4 hours and one minute post quake.

```
rundata.gaugedata.gauges.append([0, -177.36102, 28.21398, 4.0*3600.+60.,1.e10])
```

Figure 37: Midway gauge location

The MOST max amplitude was 1.4654 and came from a C grid of 2 second resolution, and the detided max amplitude was 1.709. Maximums for GeoClaw, and Bathymetry used at the gauge for the computation are given below. Note that GeoClaw uses cell averaged Bathymetry, so a coarser grid calculation might well have a different bathymetry from a finer one. It is interesting that the 1/3sec results below are around 0.5m higher than the 2sec ones, and that the bathymetry on the grids has not yet converged to a similar B value.

```
Gauge 0:
2sec:             1.646,  B=-7.315
1sec:             1.914   B=-11.367
1/3:              2.127   B=-13.401
1/3 (enhanced):   2.174   B=-13.401
```

In Figures 38, 39, 40, and 41 we compare the MOST, GeoClaw, and tide gauge tsunamis from 4 to 8 hours post-quake.

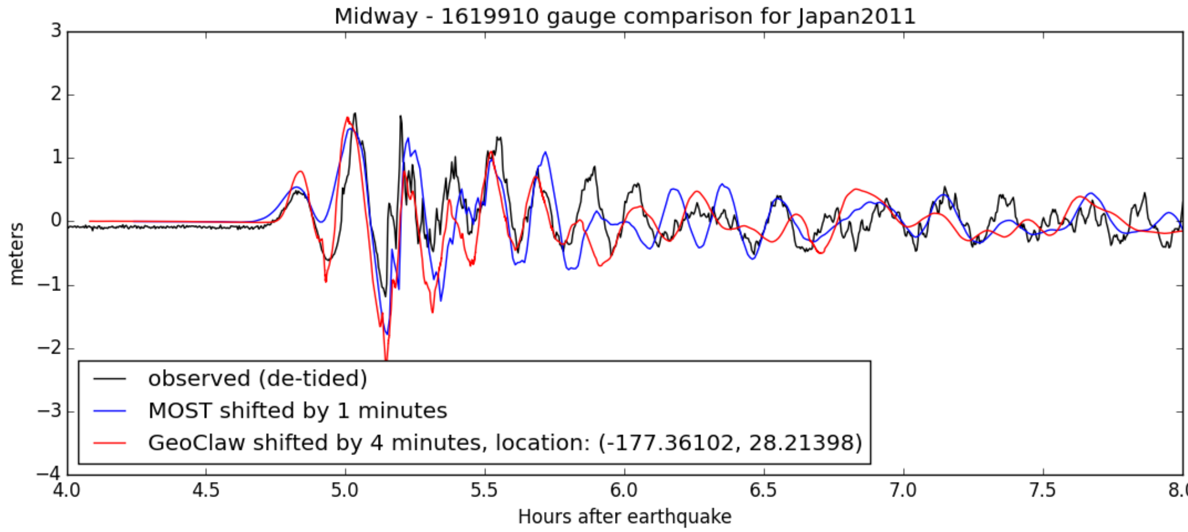

Figure 38: Japan2011, MidWay, 2sec, Gauge 0

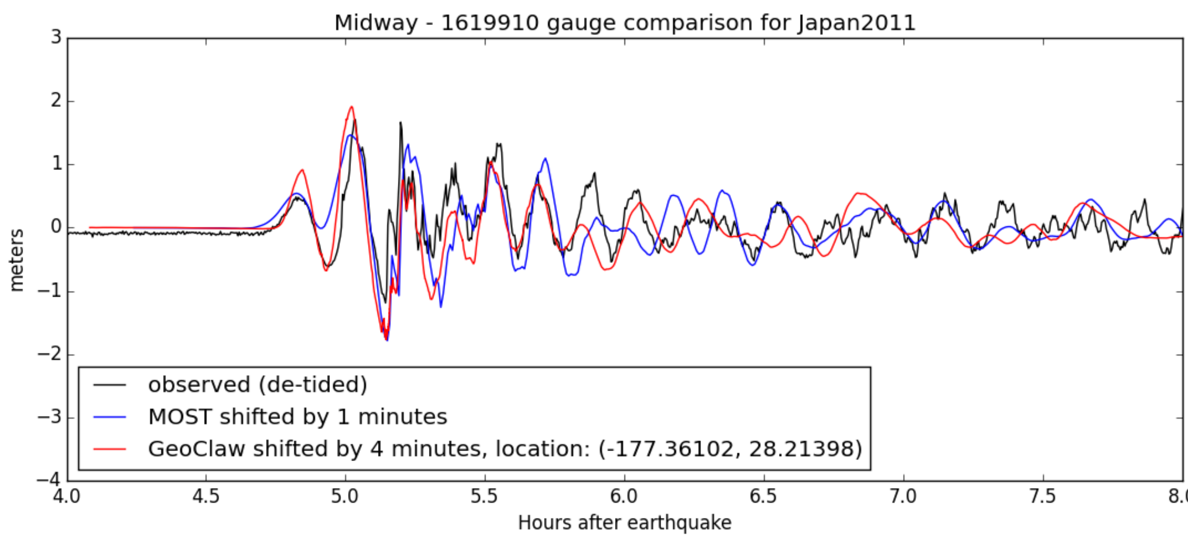

Figure 39: Japan2011, Midway, 1sec, Gauge 0

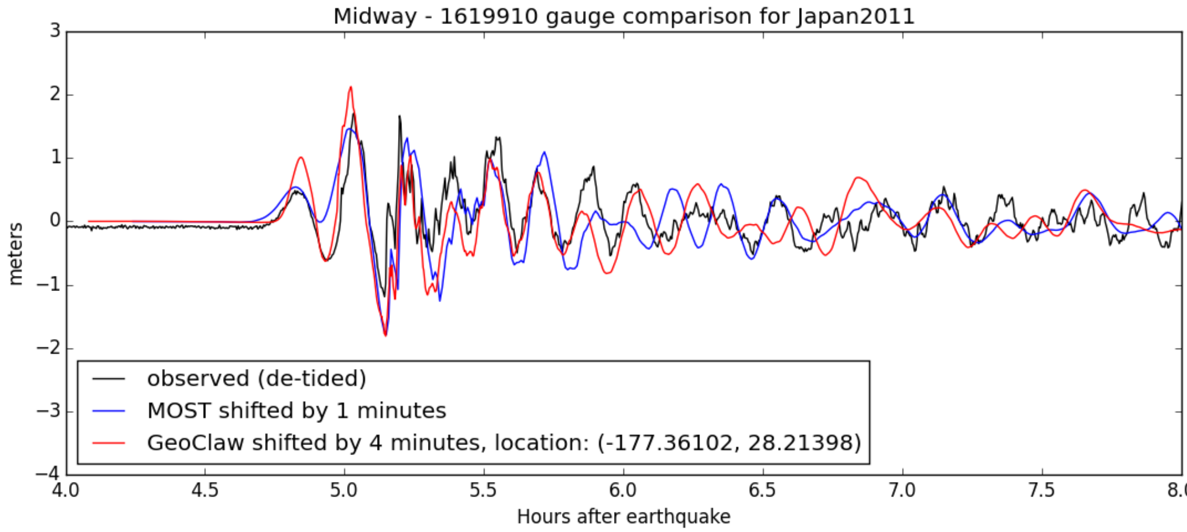

Figure 40: Japan2011, Midway, 1/3 sec, Gauge 0

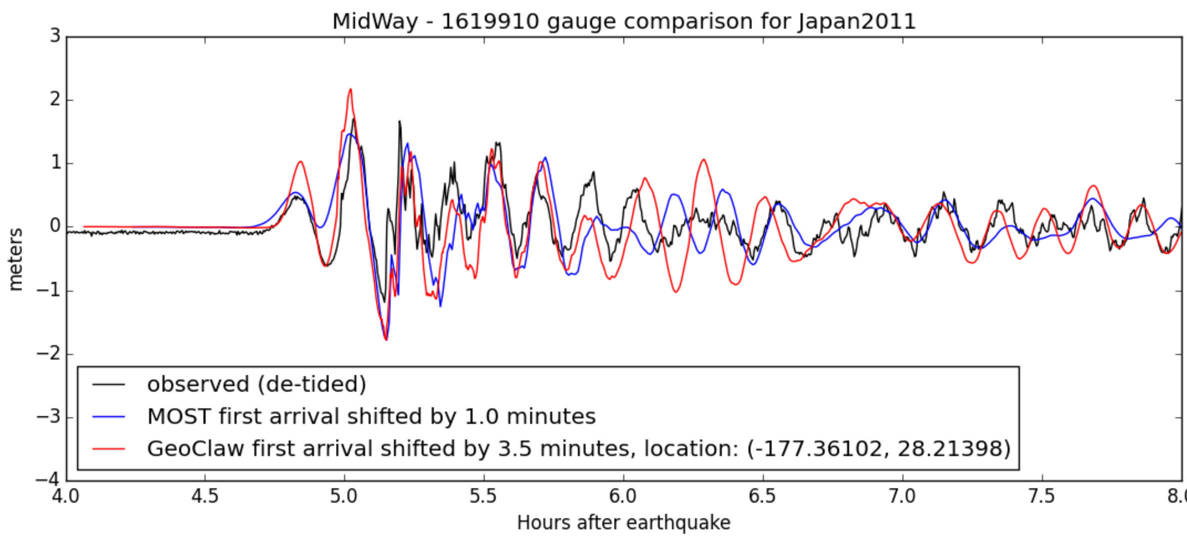

Figure 41: Japan2011, Midway, 1/3 sec, Gauge 0, enhanced regions

Timing information for this last 1/3 enhanced computation is given in Appendix B.2.

Discussion:

The GeoClaw maximum was 1.65 (2sec run), 1.91 (1sec run), and 2.13 and 2.17 (1/3 sec runs) while MOST had a maximum of 1.47 (2sec run). The raw (un-detided) tide gauge data at this maximum was 1.805 relative to MSL. We believe the tide was between 0.0 and 0.1m relative to MSL at the maximum which would put the maximum between 1.705 and 1.805 meters, higher than the MOST value and somewhat lower than that produced by GeoClaw's 1 and 1/3 sec runs. Both the GeoClaw and MOST maximums matched the time of the detided maximum and the first five or six waves very well. We also note Midway Island is a caldera and waves bouncing around in this bounded region account for many of the later waves at the tide gauge.

3 Samoa 2009 Tsunami

In the next sections, we compare GeoClaw and MOST results at Hilo, Crescent City, Arena Cove, Port Orford, Midway Island, and Pago Pago to the detided tide gauge results. At these locations, we put a computational gauge near the tide gauge at the location of the MOST computational gauge. We provide the maximum GeoClaw, MOST, and detided tide gauge amplitudes and give a plot showing these three tsunamis.

Figure 42 shows the extent of the Samoa2009 source used by GeoClaw (and MOST) as the pink rectangle.

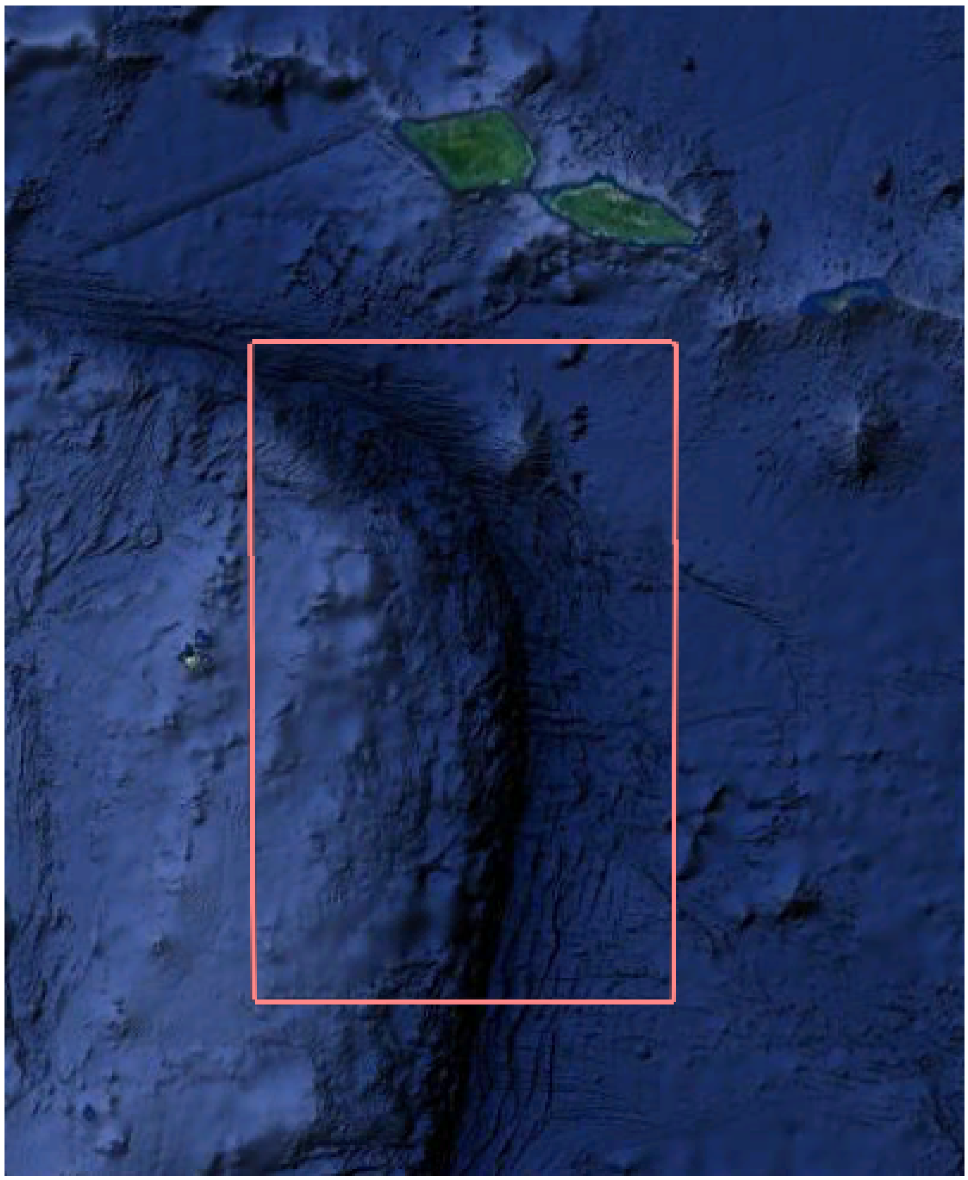

Figure 42: Samoa2009 source region, extent=-173.5, -171.5, -17.5, -14.5

3.1 Hilo

Gauge detiding

We began by detiding the Hilo station 1617760 60 second data that was provided by PMEL in the file **20090929-hilo-hi-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 43 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 44 shows a blowup from 5 to 10 hours post quake.

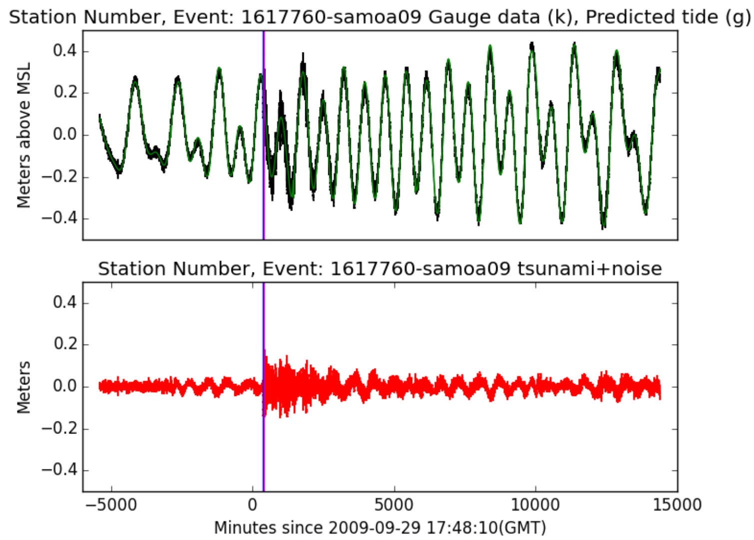

Figure 43: Samoa2009, Hilo, DeTided Tsunami

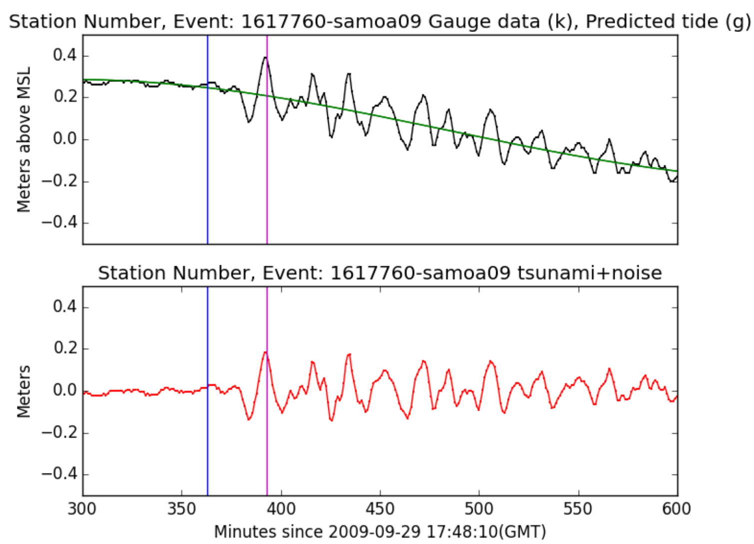

Figure 44: Samoa2009, Hilo, DeTided Tsunami, 5-10 hrs post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -178 to -163 longitude and -19 to -5 latitude. This was because the Samoa2009 quake produced shorter wavelengths than that of Japan2011 and we felt this was necessary.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Hilo Harbor between 5 and 10 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Hilo, we used 1min (Level 4), 6sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -178  -163  -19  -5
4  4  14400  1e+09  -161  -154.033  18.0317  22.9983
5  5  14400  1e+09  -156.262  -154.597  18.685  20.415
6  6  16200  1e+09  -155.101  -155.01  19.7  19.79
```

The topo files we used that supported this computation were:

```
etopo1_-240_-180_-41_65_1min.tt3
etopo1_-180_-100_-41_65_1min.tt3
hawaii_36s.asc
hawaii_6s_20070806.asc
hilo_hi_Port_onethird.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 0 below and depicted in Figure 17. The MOST computational gauge as recorded in the file **hilo2timeseriesC.txt** was the same as Gauge 0. Gauge 0 was turned on at 5 hours post-quake. Its location as specified in GeoClaw is given below:

```
rundata.gaugedata.gauges.append([0, -155.05593, 19.73111, 5.0*3600.,1.e10])
```

In Figure 45 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.29 and came from a C grid of 2 second resolution. The detided max amplitude was 0.18 based on the 60sec gauge data. The maximum for GeoClaw was 0.26m. The Bathymetry used at the gauge for the GeoClaw computation was B=-9.42m.

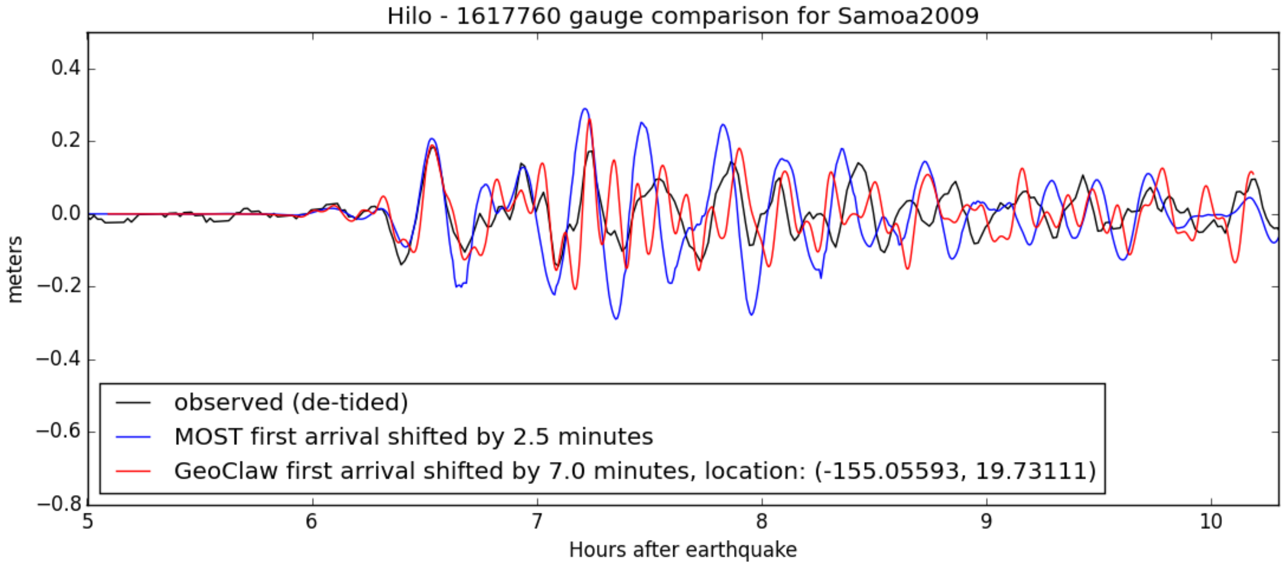

Figure 45: Samoa2009, Hilo, 1sec

Discussion:

Both MOST and GeoClaw match the tide gauge tsunami well up to about 7 hours post-quake. This includes an excellent match for the gauge's maximum of 0.18m. Then, around 7.25 hours post-quake, both MOST and GeoClaw overshoot the gauge data and obtain their maximums of 0.29 and 0.26m, respectively at the same time. The gauge data was only at the 60sec resolution and could be missing the true peaks.

3.2 Crescent City

Gauge detiding

We began by detiding the Crescent City station 9419750 60 second data that was provided by PMEL in the file **20090929-crescent-city-ca-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 46 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 47 shows a blowup from 9 to 15 hours post quake.

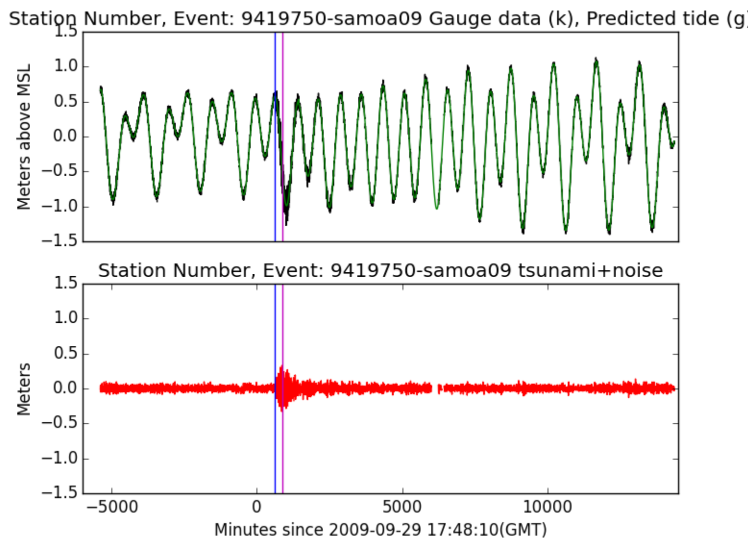

Figure 46: Samoa2009, Crescent City, DeTided Tsunami

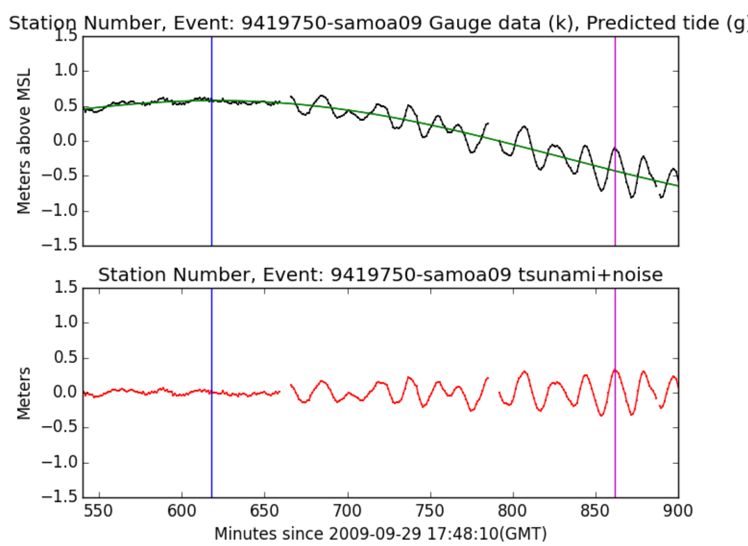

Figure 47: Samoa2009, Crescent City, DeTided Tsunami, 9-15 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -178 to -163 longitude and -19 to -5 latitude. This was because the Samoa2009 quake produced shorter wavelengths than that of Japan2011 and we felt this was necessary.

Across the ocean, we used the the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Crescent City between 9.5 and 15 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

We ran GeoClaw for 1 arc sec finest computation run around PMEL's C grid and used the 1 sec topo that PMEL provided. Then we ran GeoClaw for 1/3 arc sec finest computation around a region inside PMEL's C grid and used 1 sec and 1/3 sec topo (pier removed) that we had used for other projects. Both runs gave basically the same results. We include both here as it demonstrates that to achieve the amplitude of later waves, perhaps more refined computation needs to be done along the coastal area both north and south of Crescent City.

In particular, around Crescent City, for the 1sec run we used 1min (Level 4), 12sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used for the 1sec run are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -178  -163  -19  -5
4  4  34200  1e+09  -126.995  -123.535  40.515  44.495
5  5  34200  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  34200  1e+09  -124.234  -124.143  41.7168  41.7829
```

The topography files that supported the 1sec run are given below:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
cresc1sec.asc
```

For the 1/3sec run, the regions used were

```
6                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -178  -163  -19  -5
4  4  34200  1e+09  -126.995  -123.535  40.515  44.495
5  5  34200  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  34200  1e+09  -124.234  -124.159  41.7168  41.7695
7  7  36000  1e+09  -124.202  -124.18  41.733  41.752
```

and the topography files that supported this 1/3 run are given below:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
cc-1_3sec-c_pierless.asc
cc-1sec-c.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 2 below and depicted in Figure 21. The MOST computational gauge as recorded in the file **crescenttimeseriesC.txt** was the same as Gauge 2. The location of Gauge 2 as specified in GeoClaw was turned on at 10 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([2, -124.18397, 41.74512, 10.*3600, 1.e10])
```

In Figure 48 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.38 and came from a C grid of 2 second resolution. The detided max amplitude was 0.33. The maximum for GeoClaw was 0.16m. The Bathymetry used at the gauge for the GeoClaw computation was B=-4.75m.

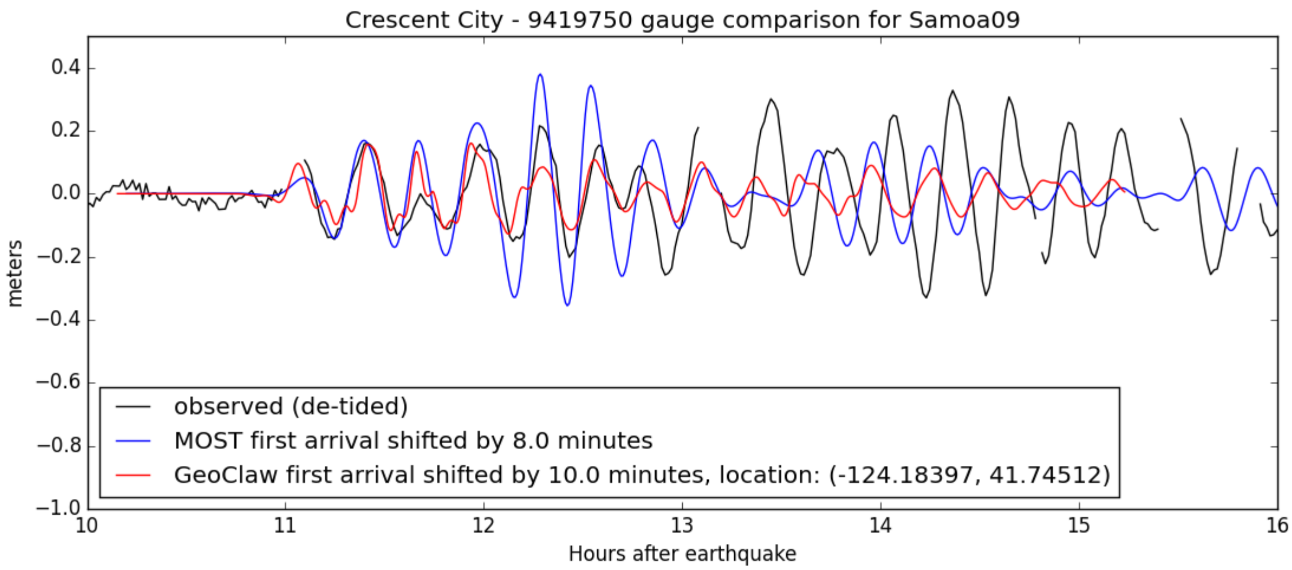

Figure 48: Samoa2009, Crescent City, 1sec

Timing information about this 1sec run is given in Appendix B.4

In Figure 49 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.38 and came from a C grid of 2 second resolution. The detided max amplitude was 0.33. The maximum for GeoClaw was 0.17m. The bathymetry used at the gauge for the GeoClaw computation was B=-5.90m.

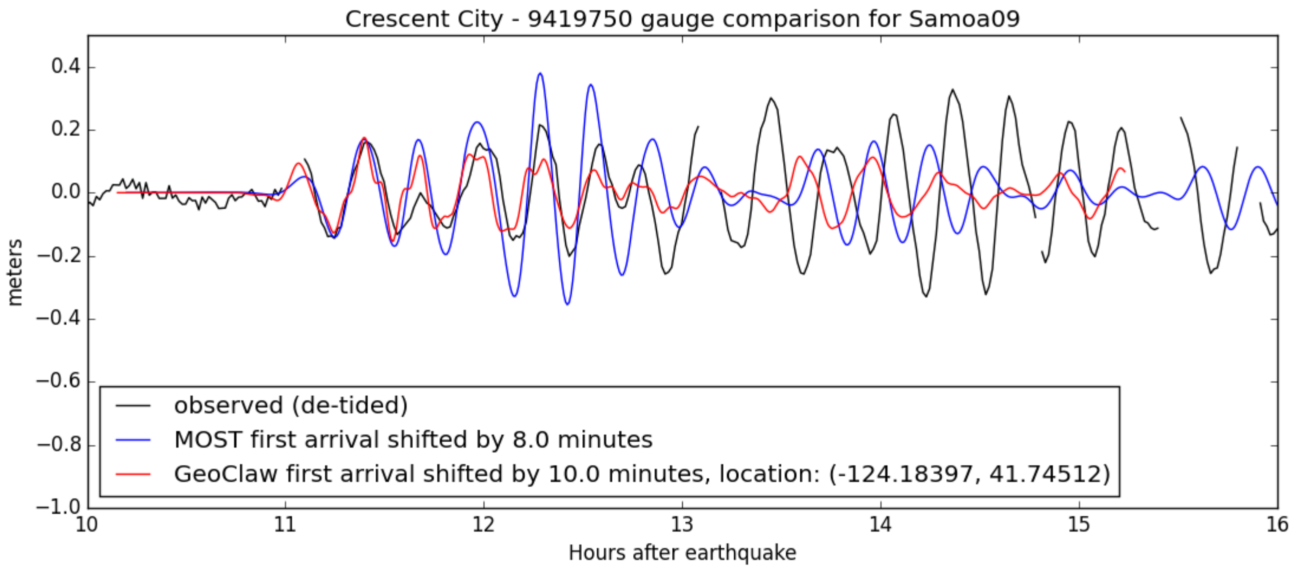

Figure 49: Samoa2009, Crescent City, 1/3sec

In an attempt to understand why the GeoClaw maximum amplitude was low compared to that of both the gauge and the MOST value, we decided to put extended regions around Crescent City and try the 1/3sec run again. We made a larger A grid (1min), made the old A grid become a 12sec grid, made the 12sec grid become a 6sec grid, and kept the 1sec and 1/3sec grids the same. We used the same topography and gauge location. In particular, the new regions are given below where the Levels 1 to 8 are now 2 degrees, 24min, 4min, 1min, 12sec, 6sec, 1sec, and 1/3sec, respectively.

```
7                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -178  -163  -19  -5
4  4  30600  1e+09  -129  -123  38  46
5  5  34200  1e+09  -126.995  -123.535  40.515  44.495
6  6  34200  1e+09  -124.6  -124.05  41.5017  41.9983
7  7  34200  1e+09  -124.234  -124.159  41.7168  41.7695
8  8  36000  1e+09  -124.202  -124.18  41.733  41.752
```

These changes really made a difference in the wave train even though the maximum amplitude changed very little. In Figure 50 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.38 and came from a C grid of 2 second resolution. The detided max amplitude was 0.33. The maximum amplitude for GeoClaw increased from 0.17m to 0.18m, but many of the waves in the wave train increased their amplitudes much more from the previous 1/3sec run depicted in Figure 49. The bathymetry used at the gauge for the GeoClaw computation was still B=-5.90m.

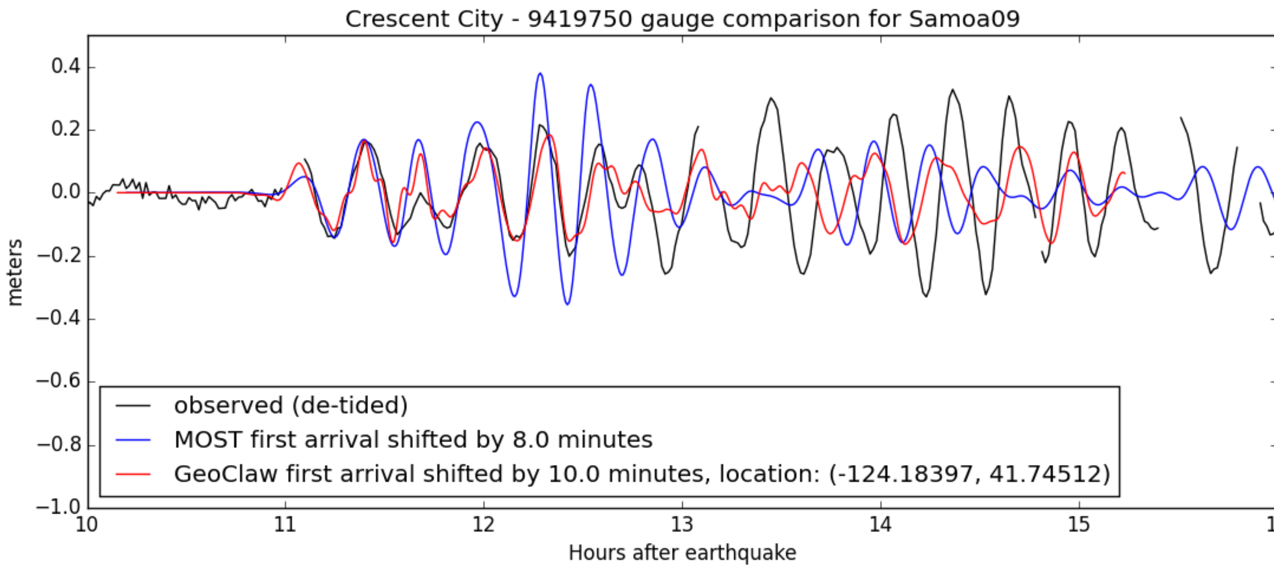

Figure 50: Samoa2009, Crescent City, 1/3sec, extended regions

Discussion:

From Figure 50, we see that both MOST and GeoClaw compare well to the detided tide gauge tsunami for the early waves (say first 4) and achieve their maximums at the same time during the 4th wave (around 12.5 hours post quake). MOST's maximum overshot this 4th wave, but this might be valid as the gauge data was only 60sec resolution. Neither GeoClaw nor MOST capture the largest wave which occurs post quake between 14 and 15 hours at Crescent City though GeoClaw (with the extended regions in the last 1/3sec run) does a better job.

It is interesting that the first 1/3sec run did not change the results in any significant way. This run used the UW topography around Crescent City, but the 1sec run used the 1sec topography provided by PMEL. Also, although not detailed here, we did a run using pre-determined regions with the GeoClaw method (not the adjoint-GeoClaw method) with wave tolerance 0.005, 1 minute calculation around the source, and 2deg-4min across the ocean with finest resolution of 0.5sec and obtained a maximum of only 0.15m with an almost identical wave train.

The second 1/3sec GeoClaw run, however, matched the gauge's wave train much better. So we learned that more resolution around Crescent City was necessary for this tsunami. But to resolve the later waves around 14 to 15 hours, we feel we still need better topography around the coastal areas. At the moment, GeoClaw only used 12 second resolution (B grid) and at most 1 minute resolution outside this B grid along the coast.

3.3 Arena Cove

Gauge detiding

We began by detiding the Arena Cove station 9416841 60 second data that was provided by PMEL in the file **20090929-arena-cove-ca-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 51 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the detided maximum amplitude in magenta. Figure 52 shows a blowup from 9 to 14 hours post quake.

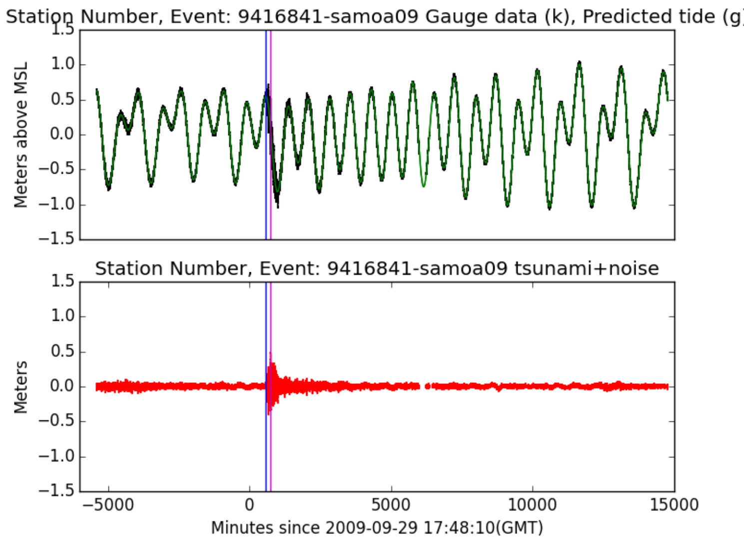

Figure 51: Samoa2009, Arena Cove, DeTided Tsunami

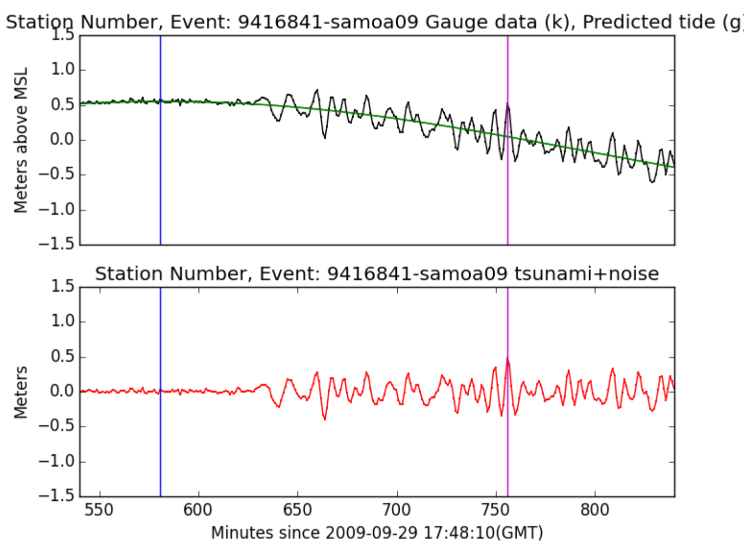

Figure 52: Samoa2009, Arena Cove, DeTided Tsunami, 9-14 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we put a one minute topo grid and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -178 to -163 longitude and -19 to -5 latitude. Across the ocean, we used the adjoint method to automatically flag cells for refinement, only flagging the waves that would arrive at Arena Cove Harbor between 9.5 and 13.0 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed 24 minute (Level 2), 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Arena Cove, we used 1min (Level 4), 12sec (Level 5), 6sec (Level 6), 2sec (Level 7), and 1sec (Level 8) grids. The 1sec grid was the same as PMEL's C grid. The 1 min grid was an extension of PMEL's A grid, the 12 sec grids were extensions of PMEL's B grid, the 6sec grid was inside PMEL's B grid, and the 2sec grid was somewhat larger than PMEL's C grid. The specifics of the 8 regions used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
8                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -178  -163  -19  -5
4  4  28800  1e+09  -135  -120  32  46
5  5  32400  1e+09  -124.65  -123.065  38.35  39.8
5  5  32400  1e+09  -124.65  -123.835  39.8  46
6  6  32400  1e+09  -124.43  -123.43  38.4  39.4
7  7  34200  1e+09  -123.85  -123.651  38.845  39.0445
8  8  34200  1e+09  -123.78  -123.685  38.89  39.02
```

The topo files we used that supported this computation were:

```
etopo1_-180_-60_-65_65_4min.tt3
etopo1_-240_-180_-65_65_4min.tt3
etopo1_-180_-110_-20_60_1min.tt3
arena_cove_6sec.asc
arena_cove_1sec.asc
arena_cove_2sec.asc
arena_cove_Port_onethird.asc
cca_12s_mhw_v2.asc
```

We used one GeoClaw computational gauge, called Gauge 0, as depicted in Figure 27. Gauge 0 was close to the MOST gauge, given in the file **arenacovetimeseriesC.txt** as having location (-123.71111, 38.91458). In a picture, it wouldn't be distinguished from Gauge 0. Gauge 0 was turned on at 9.5 hours post-quake and has location given below:

```
rundata.gaugedata.gauges.append([0, -123.711097, 38.914646, 9.5*3600.,1.e10])
```

In Figure 53 we give comparison plots when GeoClaw used a 1sec resolution around the finest grid. The MOST max amplitude was 0.227m and came from a C grid of 2 second resolution in longitude and 1.5 second resolution in latitude. The detided max amplitude was 0.475m. The GeoClaw maximum was 0.438m. The bathymetry used by GeoClaw at Gauge 0 was -3.495m. We note that the tide gauge data was only 60sec, so it is totally reasonable that these higher wave amplitudes were missed by the tide gauge but resolved with a 1sec calculation.

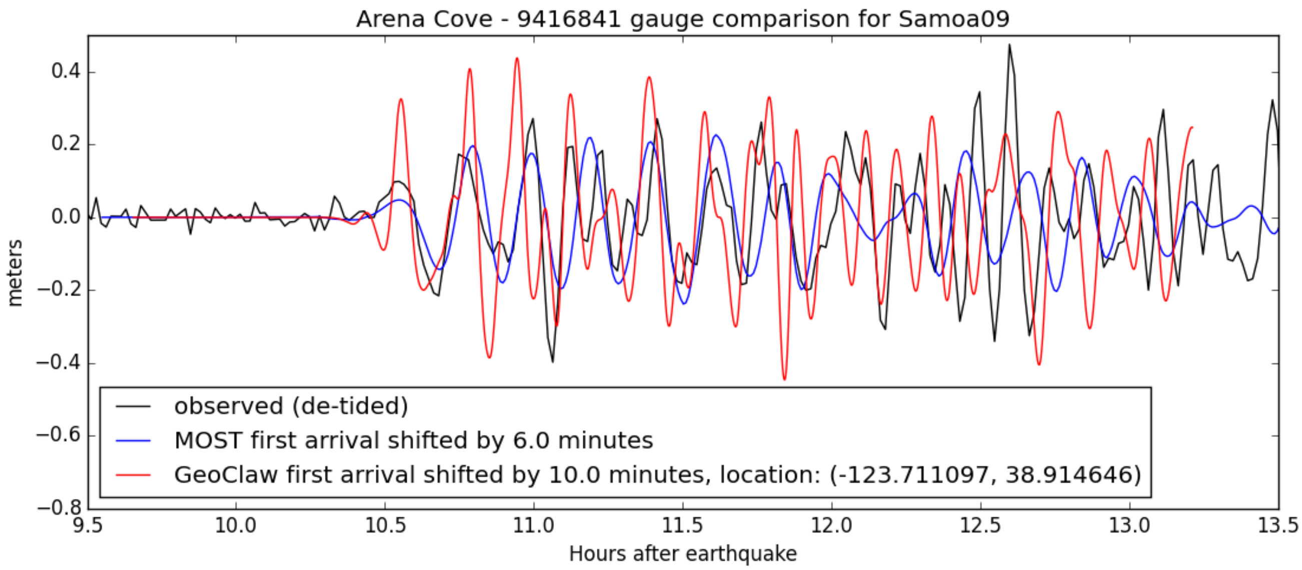

Figure 53: Samoa2009, Arena Cove, 1sec, Gauge 0

Discussion:

For 2 sec (1sec) resolution around PMEL's C grid by MOST (GeoClaw), both GeoClaw and MOST capture the times of the detided tide gauge tsunami for the early waves (say first 4) with GeoClaw's 1sec resolution giving higher amplitudes for these waves. Note, again, the gauge data was only 60 sec resolution, and higher amplitudes might have been present. It would be interesting to have 15sec data for this tide gauge. Neither GeoClaw nor MOST capture the largest wave which occurs post quake between 12.5 and 13 hours. More resolution along the coastal area would be necessary to capture these later "edge waves". At the moment, GeoClaw only used 12 second resolution (B grid) and at most 1 minute resolution outside the Level 5 grids along the coast. We did extend the B grid to some coastal areas with 12 second resolution, but probably need finer resolution on the coast near the gauge.

Timing information about this run is given in Appendix B.5

3.4 Port Orford

Gauge detiding

We began by detiding the Port Orford station 9431647 60 second data that was provided by PMEL in the file **20090929-port-orford-or-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 54 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red and the location of the maximum detided amplitude in magenta. Figure 55 shows a blowup from 10 to 16 hours post quake.

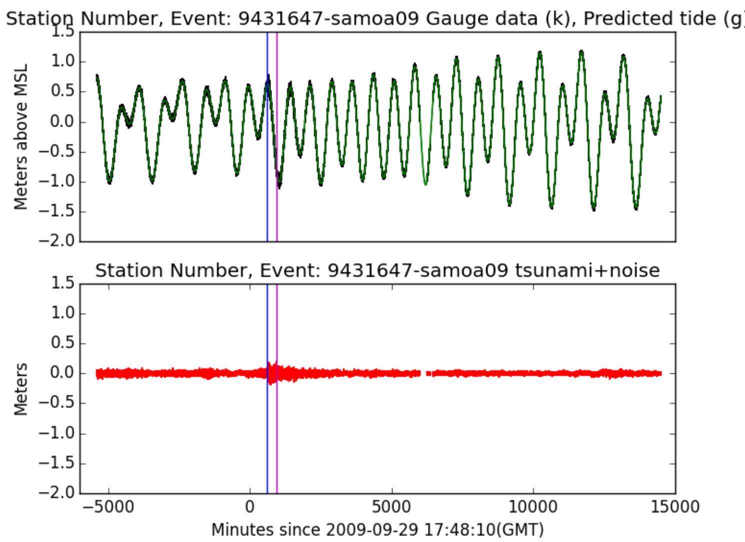

Figure 54: Samoa2009, Port Orford, DeTided Tsunami

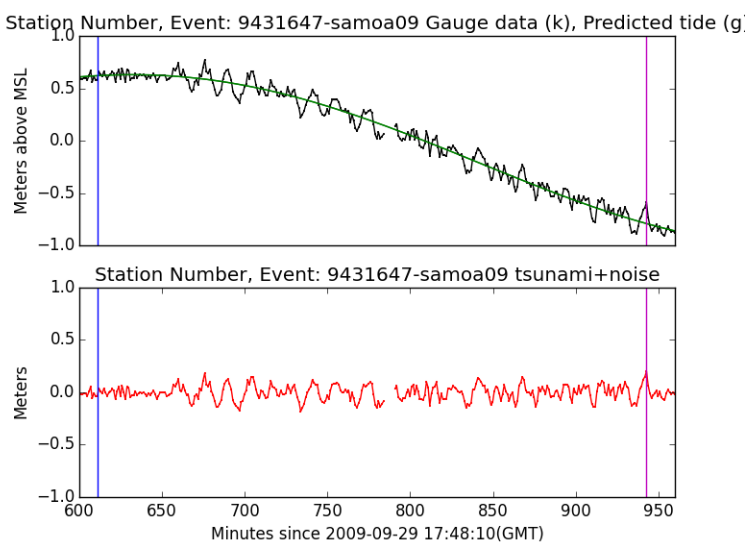

Figure 55: Samoa2009, Port Orford, DeTided Tsunami, 10-16 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -178 to -163 longitude and -19 to -5 latitude. This was because the Samoa2009 quake produced shorter wavelengths than that of Japan2011 and we felt this was necessary.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Port Orford between 10 and 16 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Port Orford, we required 1 minute (Level 4), 12 second (Level 5), and 1sec (Level 6) resolution on the A, B, and C grids, respectively. The region specifics for the 5 regions we used for this run are given below. The first two numbers are the minimum and maximum levels allowed. The third and fourth numbers are are the times in seconds post-quake when the region is turned on and off. The last four numbers are the longitude and latitude limits of the rectangular region.

```
5                     =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -178  -163  -19  -5
4  4  32400  1e+09  -127.5  -123.5  39.01  47.19
5  5  34200  1e+09  -124.933  -124.27  42.0683  43.265
6  6  36000  1e+09  -124.551  -124.44  42.6715  42.7732
```

The topography files that supported the 1sec run are given below:

```
etopo1_-180_-60_-65_65_4min.tt3
etopo1_-240_-180_-65_65_4min.tt3
etopo1_-180_-110_-20_60_1min.tt3
PortOrford_1sec.asc
PortOrfordHarbor.asc
```

We used one GeoClaw computational gauge called Gauge 0. This gauge was the same as the MOST computational gauge reported in the file **porfordtimeseriesC.txt** and depicted in Figure 31. Gauge 0 was turned on at 10 hours post-quake and had location as given below:

```
rundata.gaugedata.gauges.append([0, -124.49767, 42.73876, 10.0*3600, 1.e10])
```

The comparison plots for Gauge 0 are in Figure 56 for this 1sec run. The MOST max amplitude was 0.217m and came from a C grid of 2 second resolution. The detided max amplitude was 0.202m. The GeoClaw max amplitude was 0.150m. The bathymetry at the gauge used by GeoClaw was -3.879m.

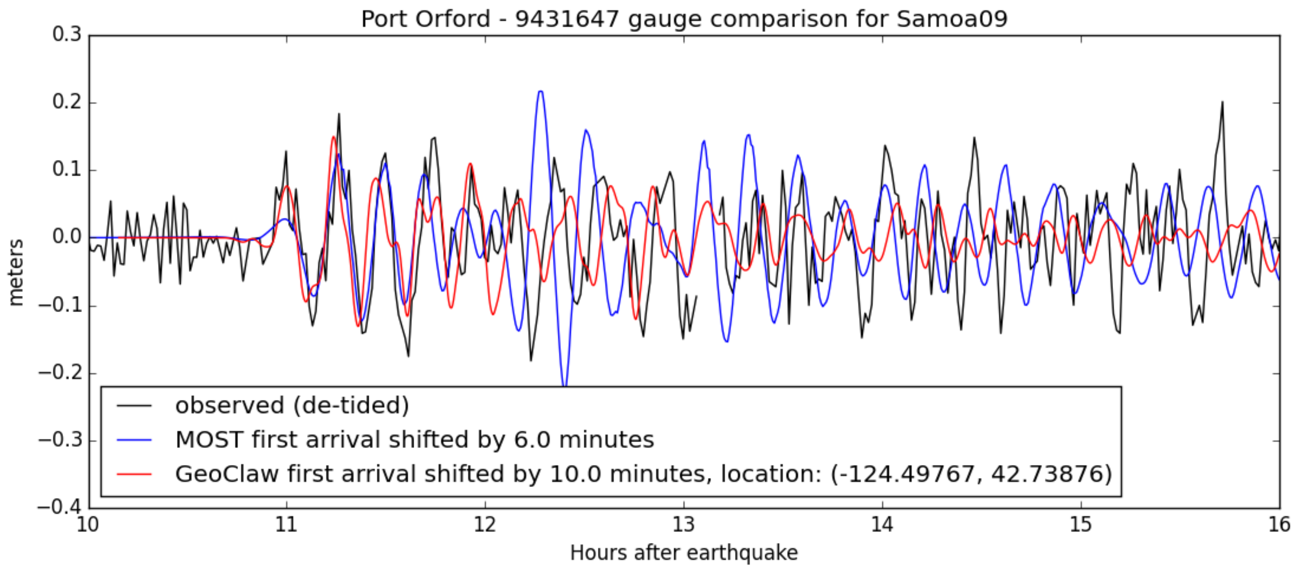

Figure 56: Samoa2009, Port Orford, 1sec

Discussion:

The earlier waves are captured fairly well by both MOST and GeoClaw. MOST used 2 sec around the C grid, and GeoClaw used 1 sec resolution. This tsunami was a very small one, so it is not clear how reliable conclusions are here given that the noise before the quake in the detided results could be significant in this case. The detided max amplitude was only 0.202 m. GeoClaw's max was 0.150m (1 sec run) and MOST's was in the wrong place and was 0.212m (MOST had an amplitude of less than 0.1m at the time of the detided maximum). We did a 1/3sec GeoClaw run and the wave train was unchanged from the 1sec run and the maximum was still the same. We believe the detided max between 15 and 16 hours post quake probably can't be resolved well without better bathymetry resolution along the coastal area between the source and destination that would support refined calculation in this region.

Timing information about this run is given in Appendix B.6

3.5 Midway Island

Gauge detiding

We began by detiding the Midway station 1619910 60 second data that was provided by PMEL in the file **20090929-sand-island-midway-islands-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 57 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the detided maximum amplitude in magenta. Figure 58 shows a blowup from 5 to 10 hours post quake.

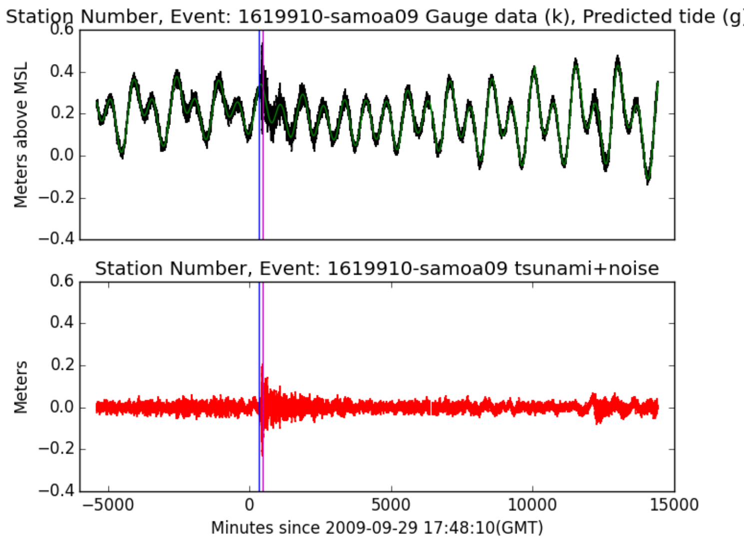

Figure 57: Samoa2009, Midway, DeTided Tsunami

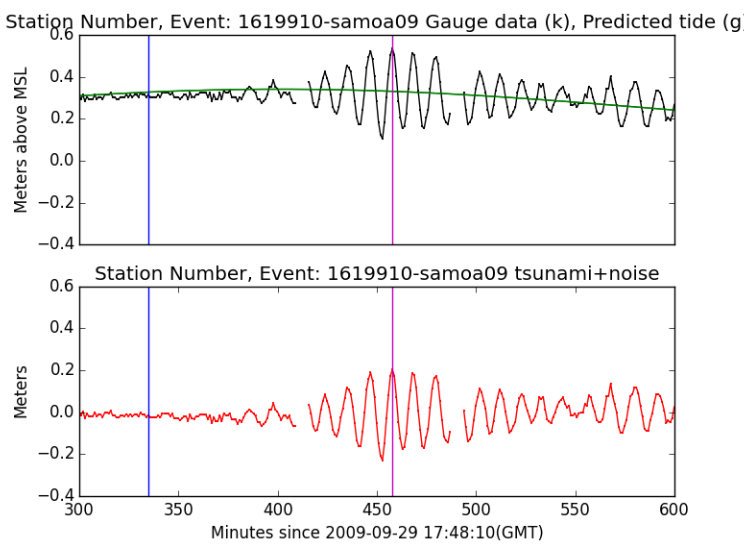

Figure 58: Samoa2009, Midway, DeTided Tsunami, 5-10 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -178 to -163 longitude and -19 to -5 latitude. Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Midway Harbor between 5.0 and 10.0 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Midway Island, we used 1min (Level 4), 6sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -178  -163  -19  -5
4  4  14400  1e+09  -178.4  -176.4  27.2  29.2
5  5  14400  1e+09  -177.57  -177.16  28.09  28.42
6  6  16200  1e+09  -177.436  -177.309  28.1895  28.289
```

The following topo was used to support this computation. Since the topography changes rapidly around Midway Island, we included the one third arc sec topo.

```
etopo1_-180_-60_-65_65_4min.tt3
etopo1_-240_-180_-65_65_4min.tt3
etopo1_-180_-110_-20_60_1min.tt3
Midway_Smaller_1s_v2.asc
midway_6s_v2.asc
MidwayHarbor_1-3s.asc
```

We used one GeoClaw computational gauge, called Gauge 0, as depicted in Figure 37. Gauge 0 was turned on at 5 hours post-quake and has location given below:

```
rundata.gaugedata.gauges.append([0, -177.36102, 28.21398, 5.0*3600.,1.e10])
```

In Figure 59 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.23m. The detided max amplitude was 0.20m. The GeoClaw maximum was 0.31m. We note that the gauge data was at 60 sec resolution, so it is reasonable that waves higher than that recorded at this resolution were present. The bathymetry used by GeoClaw at Gauge 0 was -11.37m.

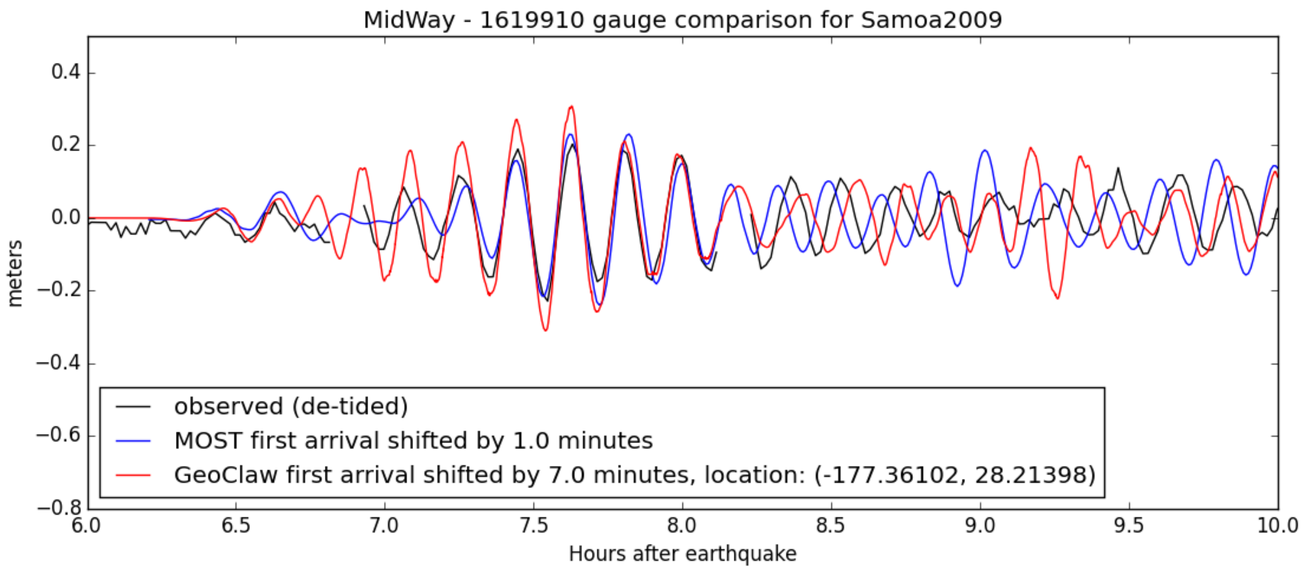

Figure 59: Samoa2009, Midway, 1sec, Gauge 0

Discussion:

MOST (using 2sec) and GeoClaw (using 1sec) finest resolution matched the detided gauge results well, even up to the 10th wave.

Timing information about this run is given in Appendix B.7

3.6 PagoPago

Gauge detiding

We began by detiding the Pago Pago station 1770000 15 second data that was provided by PMEL in the file **20090929-pago-pago-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 60 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 61 shows a blowup from 0 to 5 hours post quake.

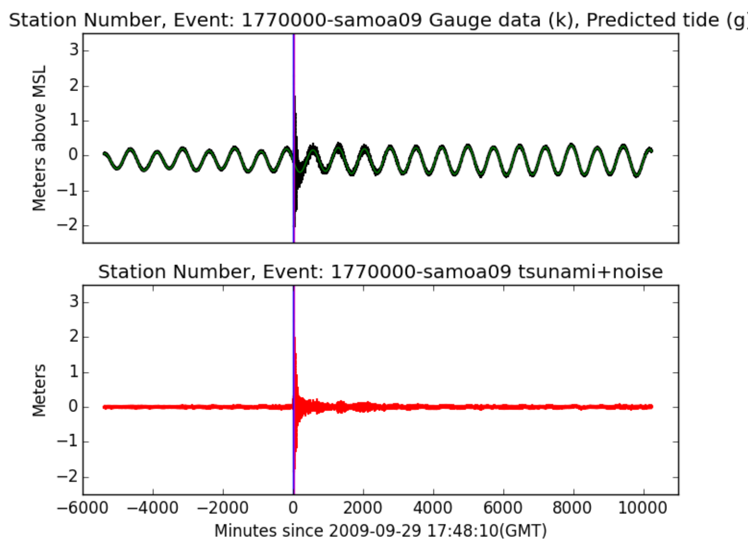

Figure 60: Samoa2009, Pago Pago, DeTided Tsunami

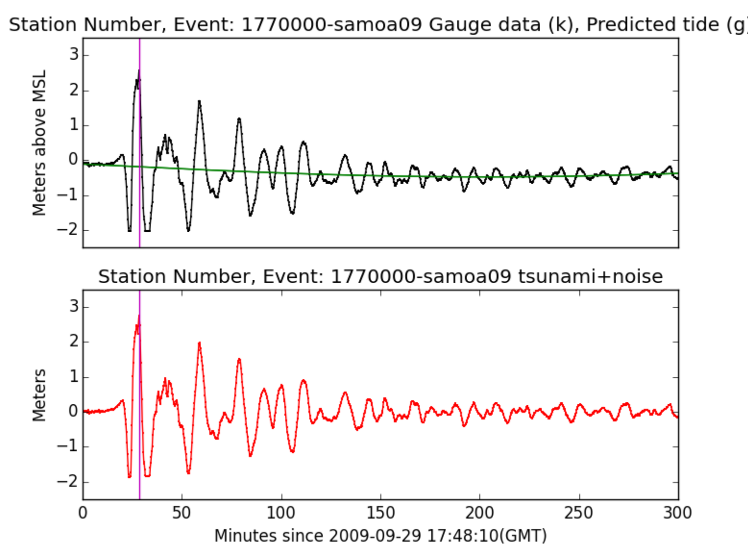

Figure 61: Samoa2009, Pago Pago, DeTided Tsunami, 0-5 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -200 to -140 longitude, -32 to 0 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -176 to -165 longitude and -19 to -10 latitude.

Across the ocean, we used the first three region specifications below to enforce 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation. (We also did a run using up to only 4 minute (Level 3) computation across the ocean and got the same results. So in retrospect, the Level 4 was not needed across the ocean, but we did use it around the source for 1 hour as described above.)

Around Pago Pago, we used 1min (Level 4), 15sec (Level 5), 1sec (Level 6) and 1/3sec (Level 7) grids, mimicking PMEL's A, B, C, and a region inside the C grid, respectively. The specifics of the 6 regions we used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
6                    =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  4  0  14400  -200  -120  -30  60
4  4  0  3600  -176  -165  -19  -10
5  5  600  1e+09  -172  -170  -14.6  -14
6  6  900  1e+09  -170.73  -170.6  -14.35  -14.26
7  7  900  1e+09  -170.71  -170.66  -14.3  -14.265
```

The topo files we used that supported this computation were:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
pago_pago_3s.asc
pago_pago_1-3s.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 0 below and depicted in Figure 62. The MOST computational gauge as recorded in the file **pagopagotimeseriesC.txt** was the same as Gauge 0. The location of Gauge 0 as specified in GeoClaw was turned on at 1000 sec post-quake and given below:

```
rundata.gaugedata.gauges.append([0,-170.69,-14.27667, 1000, 1.e10])
```

Figure 62: Pago Pago gauge location

In Figure 63 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 2.37m and came from a C grid of 0.7 second resolution. The detided max amplitude was 2.74m at the 15sec gauge. The maximum for GeoClaw was 2.26m. The Bathymetry used at the gauge for the GeoClaw computation was B=-17.745m.

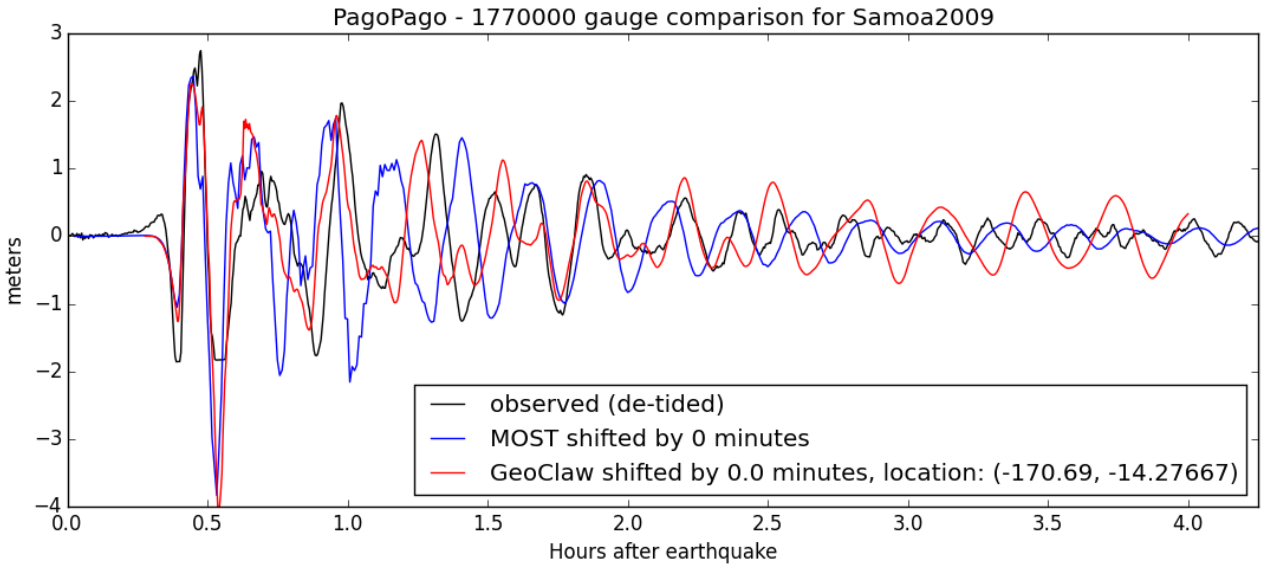

Figure 63: Samoa2009, Pago Pago, 1/3sec

Since Pago Pago was so close to the Samoa source, we felt that the 1/3 run above did not use large enough computational grids around Pago Pago, and did not compute long enough with the 1 minute grid around the source area. So, we did one more run that used the 8 regions given below for a 4 hour run. Level 4 was still 1 minute, Level 5 was 12 sec, Level 6 was 6sec, Level 7 was 1sec, and Level 8 was 1/3sec resolution. We used the same Gauge 0 and the same topography as given above.

```
8                    =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  4  0  1e+09  -200  -140  -32  0
4  4  0  1e+09  -178  -163  -19  -10
5  5  0  1e+09  -174  -170  -15  -13
6  6  0  1e+09  -171.14  -170  -14.6  -14
7  7  600  1e+09  -170.95  -170.45  -14.4  -14.18
8  8  600  1e+09  -170.73  -170.6  -14.35  -14.26
9  9  600  1e+09  -170.71  -170.66  -14.3  -14.265
```

In Figure 64 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 2.37m and came from a C grid of 0.7 second resolution. The detided max amplitude was 2.74m at the 15sec gauge. The maximum for GeoClaw increased to 2.28m, but as the plot shows more waves in the wave train increased in amplitude. The Bathymetry used at the gauge for this run was was also B= −17.745m.

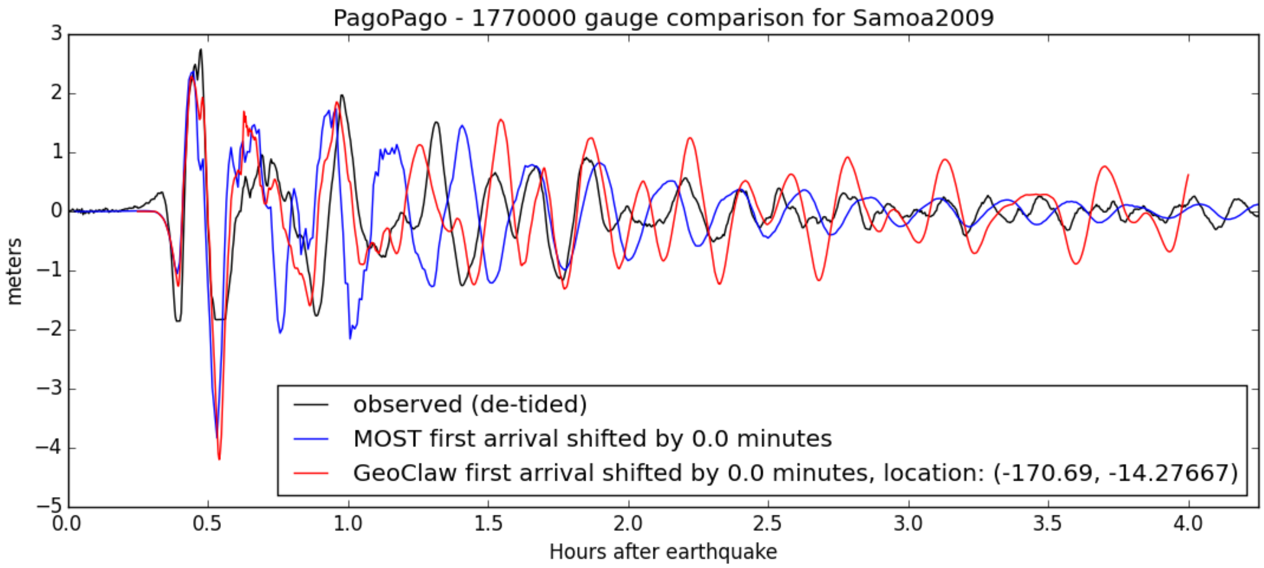

Figure 64: Samoa2009, Pago Pago, 1/3sec expanded regions

Discussion:

Both MOST and GeoClaw tsunamis match the 15sec tide gauge tsunami well over the 4 hour period post-quake. Expanding the regions used around Pago Pago for the 1/3sec GeoClaw run increased the maximum amplitude by 2cm, but increased quite a few other wave amplitudes by more as shown in the plots.

It is interesting to note that the minimum captured by both MOST and GeoClaw was around −4 meters; whereas, the tide gauge minimum bottomed out at about −2m.

Timing information about this run is given in Appendix B.8 for the first 1/3sec run and is for the maximum of 1 minute (rather than 4 minute) computation across the ocean.

4 Chile 2010 Tsunami

In the next sections, we compare GeoClaw and MOST results at Hilo, Crescent City, Arena Cove, and Port Orford to the detided tide gauge results. At each of these destinations, we put a computational gauge near the tide gauge at the same location of the MOST computational gauge. We provide the maximum GeoClaw, MOST, and tide gauge amplitudes and a plot of the associated tsunamis there.

Figure 65 shows the extent of the Chile 2010 source used by GeoClaw (and MOST) as the pink rectangle.

Figure 65: Chile 2010 source region,extent=-94.65, -67.98, -46.29, -24.86

4.1 Hilo

Gauge detiding

We began by detiding the Hilo station 1617760 15 second data that was provided by PMEL in the file **20100227-hilo-hi-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 66 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 67 shows a blowup from 14 to 20 hours post quake.

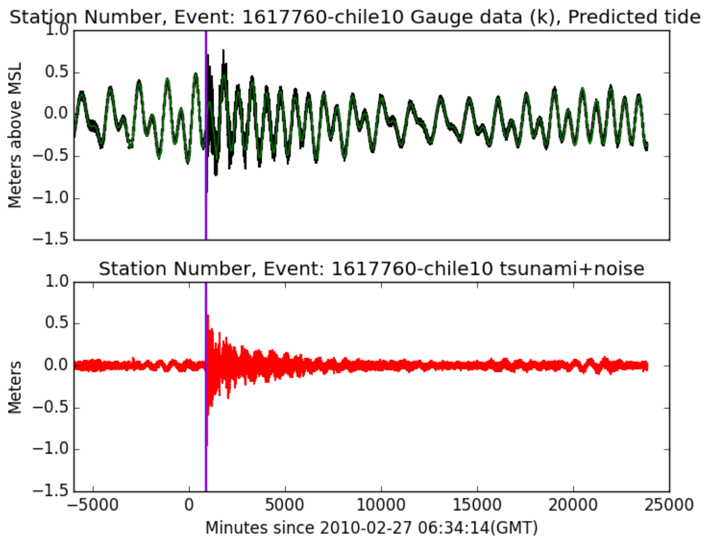

Figure 66: Chile 2010, Hilo, DeTided Tsunami

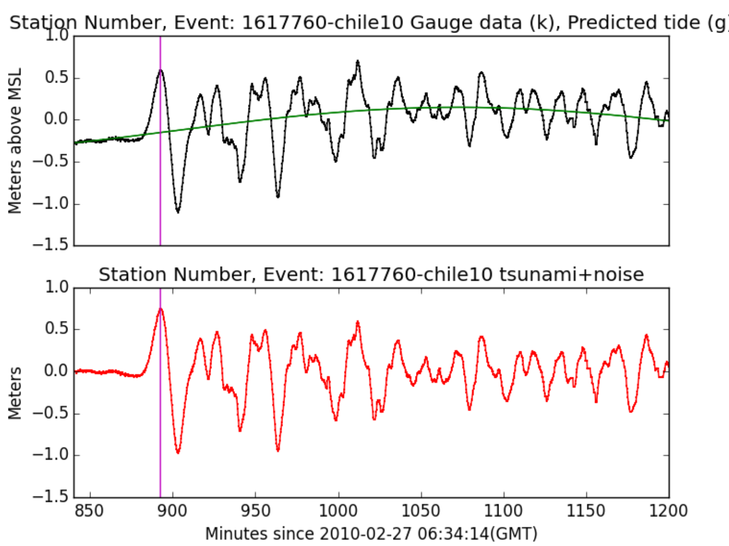

Figure 67: Chile 2010, Hilo, DeTided Tsunami, 14-20 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -66 longitude, -47 to 65 latitude.

Around the source, we did use one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -96 to -68 longitude and -47 to -24 latitude.

Across the ocean, we used the the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Hilo between 14 and 20 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) up to a maximum of 4 minute (Level 3) resolution everywhere in our computational grid for the entire computation.

Around Hilo, we used 1min (Level 4), 6sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                    =: num_regions
1  3  0  1e+09  -360  0  -90  90
4  4  0  3600  -96  -68  -47  -24
4  4  48600  1e+09  -161  -154.033  18.0317  22.9983
5  5  50400  1e+09  -156.262  -154.597  18.685  20.415
6  6  50400  1e+09  -155.101  -155.01  19.7  19.79
```

The topo files we used that supported this computation were:

```
etopo1_-240_-180_-47_65_1min.tt3
etopo1_-180_-66_-47_65_1min.tt3
hawaii_36s.asc
hawaii_6s_20070806.asc
hilo_hi_Port_onethird.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 0 below and depicted in Figure 17. The MOST computational gauge as recorded in the file **hilo2timeseriesC.txt** was the same as Gauge 0. The location of Gauge 0 as specified in GeoClaw was turned on at 14 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([0, -155.05593, 19.73111, 14.0*3600.,1.e10])
```

In Figure 68 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 1.01 and came from a C grid of 2 second resolution. The detided max amplitude was 0.74 for the 15sec gauge data. The maximum for GeoClaw was 0.92m. The Bathymetry used at the gauge for the GeoClaw computation was B=-9.42m.

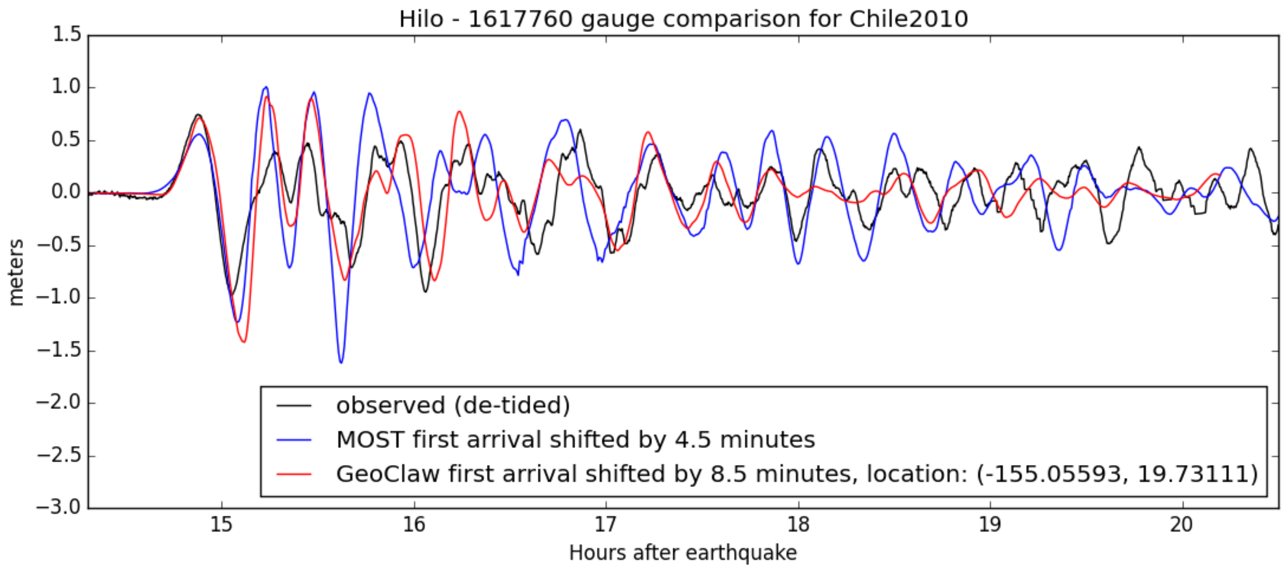

Figure 68: Chile 2010, Hilo, 1sec

Discussion:

The MOST and GeoClaw tsunamis agree well on the first 7 or 8 waves at this gauge. In particular, they agree on a higher value for the 2nd and 3rd waves than is recorded by the 15sec tide data, with both achieving their maximum on the 2nd wave.

4.2 Crescent City

Gauge detiding

We began by detiding the Crescent City station 9419750 15 second data that was provided by PMEL in the file **20100227-crescent-city-ca-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 69 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 70 shows a blowup from 14.0 to 26.25 hours post quake.

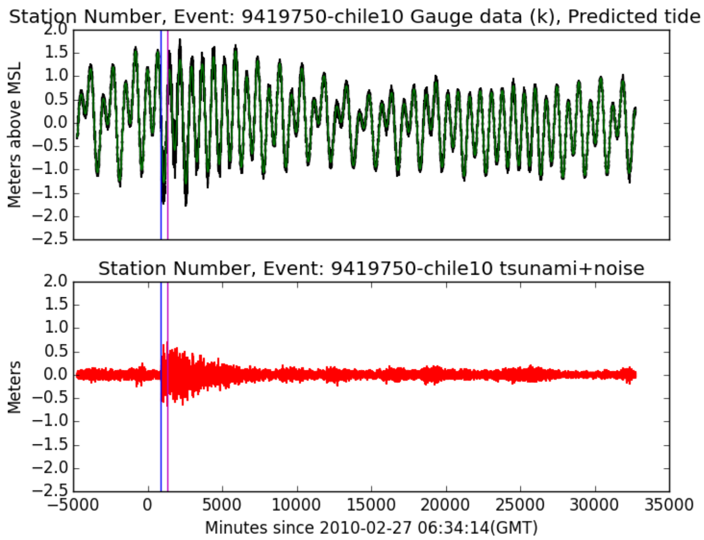

Figure 69: Chile2010, Crescent City, DeTided Tsunami

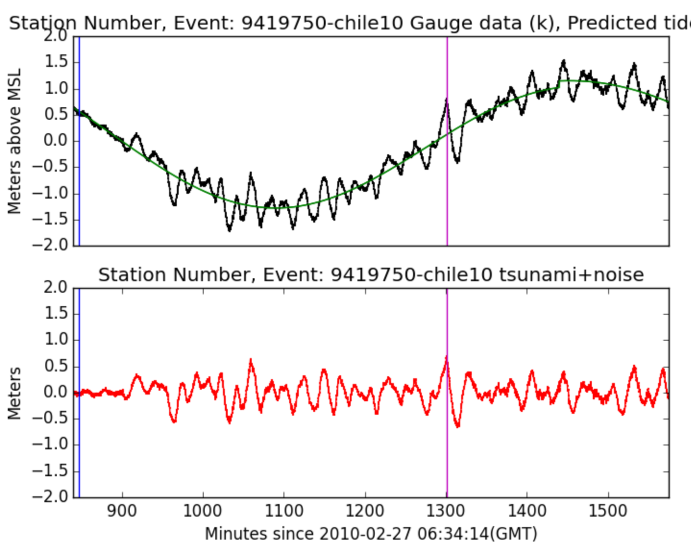

Figure 70: Chile2010, Crescent City, DeTided Tsunami, 14.0-26.25 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -66 longitude, -47 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -96 to -68 longitude and -47 to -24 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Crescent City between 14.5 and 26 hours post-quake for a 1sec run and between 14 and 26 hours for a 1/3sec run. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) up to a maximum of 4 minute (Level 3) resolution everywhere in our computational grid for the entire computation.

We ran GeoClaw for 1 arc sec finest computation run around PMEL's C grid and used the 1 sec topo that PMEL provided. Then we ran GeoClaw for 1/3 arc sec finest computation around a region inside PMEL's C grid and used 1 sec and 1/3 sec topo (pier removed) that we had used for other projects. The 1/3 run gave slightly higher amplitudes for some waves, but did not resolve some of the other tide gauge waves. This demonstrates that to achieve the amplitude of later waves, perhaps more refined computation needs to be done along the coastal area both north and south of Crescent City.

In particular, around Crescent City, for the 1sec run we used 1min (Level 4), 12sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used for the 1sec run are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                    =: num_regions
1  3  0  1e+09  -360  0  -90  90
4  4  0  3600  -96  -68  -47  -24
4  4  50400  1e+09  -126.995  -123.535  40.515  44.495
5  5  52200  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  52200  1e+09  -124.234  -124.143  41.7168  41.7829
```

The topography files that supported the 1sec run are given below:

```
etopo1_-180_-66_-47_65_1min.tt3
etopo1_-240_-180_-47_65_1min.tt3
cresc1sec.asc
```

For the 1/3sec run, the regions used were

```
6                    =: num_regions
1  3  0  1e+09  -360  0  -90  90
4  4  0  3600  -96  -68  -47  -24
4  4  50400  1e+09  -126.995  -123.535  40.515  44.495
5  5  52200  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  52200  1e+09  -124.234  -124.159  41.7168  41.7695
7  7  54000  1e+09  -124.202  -124.18  41.733  41.752
```

and the topography files that supported this 1/3 run are given below:

```
etopo1_-180_-66_-47_65_1min.tt3
etopo1_-240_-180_-47_65_1min.tt3
cc-1_3sec-c_pierless.asc
cc-1sec-c.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 2 below and depicted in Figure 21. The MOST computational gauge as recorded in the file **crescenttimeseriesC.txt** was the same as Gauge 2. The location of Gauge 2 as specified in GeoClaw was turned on at 15 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([2, -124.18397, 41.74512, 15*3600., 1.e10])
```

In Figure 71 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.64 and came from a C grid of 2 second resolution. The detided max amplitude was 0.69. The maximum for GeoClaw was 0.33m. The Bathymetry used at the gauge for the GeoClaw computation was B=-4.75m.

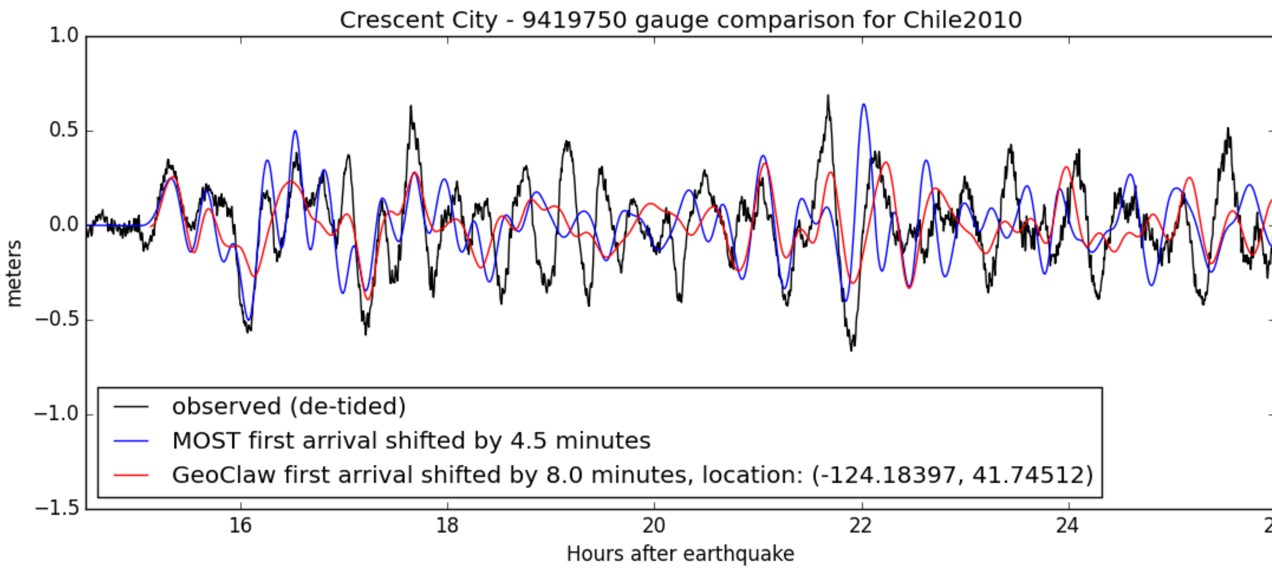

Figure 71: Chile2010, Crescent City, 1sec

In Figure 72 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.64 and came from a C grid of 2 second resolution. The detided max amplitude was 0.69. The maximum for GeoClaw was 0.41m. The bathymetry used at the gauge for the GeoClaw computation was B=-5.90m.

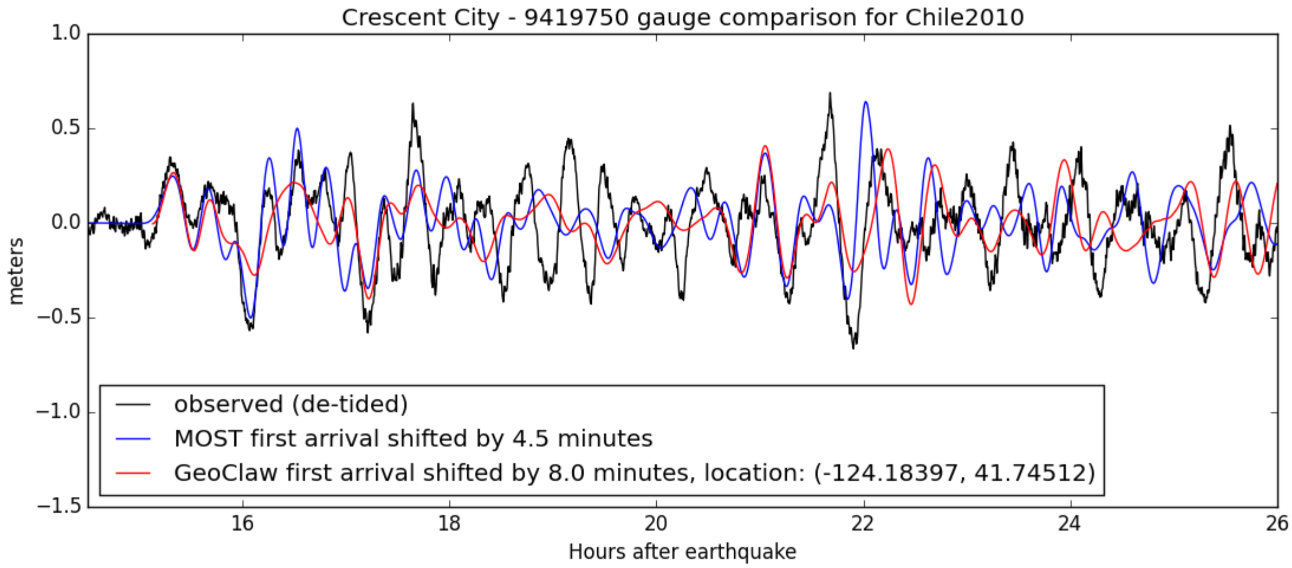

Figure 72: Chile2010, Crescent City, 1/3sec

In an attempt to understand why the GeoClaw maximum amplitude was low compared to that of both the gauge and the MOST value, we decided to put extended regions around Crescent City and try the 1/3sec run again. We made a larger A grid (1min), made the old A grid become a 12sec grid, made the 12sec grid become a 6sec grid, and kept the 1sec and 1/3sec grids the same. We used the same topography and gauge location but turned the gauge on at 14.5 hours post quake. In particular, the new regions are given below where the Levels 1 to 8 are now 2 degrees, 24min, 4min, 1min, 12sec, 6sec, 1sec, and 1/3sec, respectively. Inside the 1,3 region (up to 4 min calculation) across the ocean, we added two 1,4 (up to 1 min calculation) regions – one to include waves bouncing off the Hawaii Islands and one further north near the coast of Alaska.

```
9                     =: num_regions
1  3  0   1e+09  -240  -66  -47  65
1  4  46800  1e+09  -160  -120  34  62
1  4  37800  1e+09  -160  -110  18  34
4  4  0  14400  -96  -68  -47  -24
4  4  46800  1e+09  -129  -123  38  46
5  5  50400  1e+09  -126.995  -123.535  40.515  44.495
6  6  52200  1e+09  -124.6  -124.05  41.5017  41.9983
7  7  52200  1e+09  -124.234  -124.159  41.7168  41.7695
8  8  52200  1e+09  -124.202  -124.18  41.733  41.752
```

These changes really made a difference. In particular, the extra computation around Crescent City contributed largely to this difference. In Figure 73 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.64 and came from a C grid of 2 second resolution. The detided max amplitude was 0.69. The maximum for GeoClaw increased from the 0.41m described previously to 0.54m. The bathymetry used at the gauge for the GeoClaw computation was still B=-5.90m.

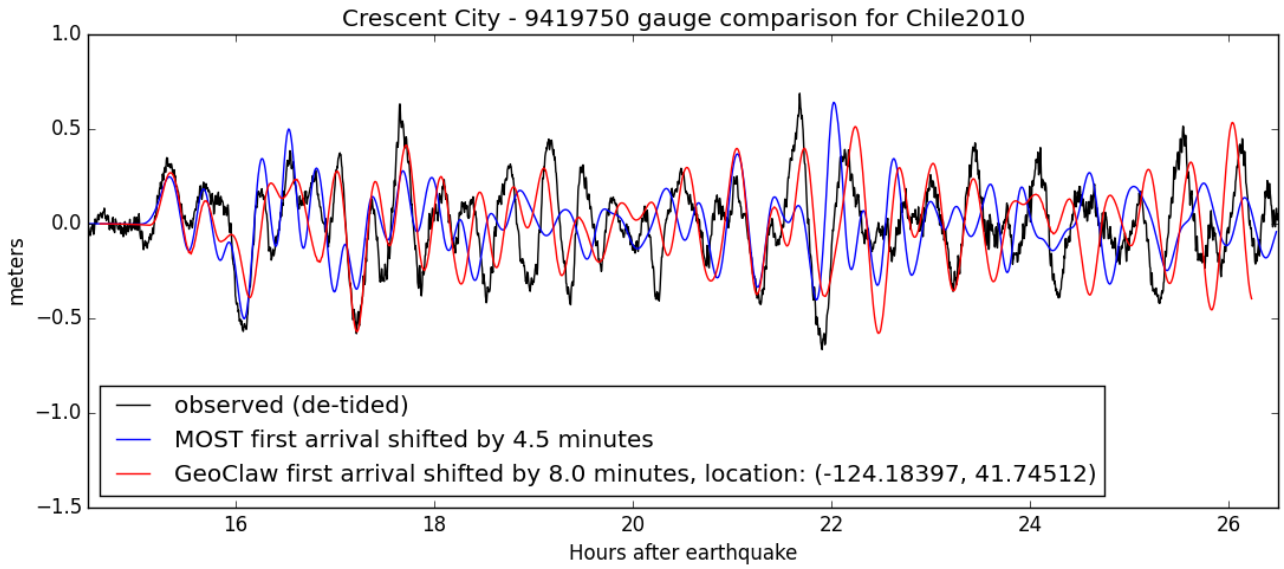

Figure 73: Chile2010, Crescent City, 1/3sec, extended regions

Discussion:

From Figure 73, the MOST and GeoClaw tsunamis look quite similar with a few notable differences. MOST better captures the 2nd and 3rd in the series of three waves between 16 and 17 hours post quake, and overshoots the wave that begins at 22 hours post quake to achieve its maximum amplitude and misses somewhat the large wave around 26 hours post quake. GeoClaw does a pretty good job capturing the high waves, even the one at 22 hours, and achieves its maximum with the wave at 26 hours post quake.

It is interesting that the last 1/3sec run had a maximum amplitude 0.13m higher than that of the first 1/3sec run with both maximums occurring at the same time. The reason is that more computation needed to be done around Crescent City to capture the waves that were hugging the coast coming north from Chile and those bouncing off Hawaii. We could potentially increase the GeoClaw amplitude more with even larger regions with finer computation around Crescent City. The topo files we had that were 1sec and 1/3sec did not cover a very large region. We are however very encouraged that we were able to do as well as we did in capturing the large waves around 22 to 26 hours post quake with the topo we had at our disposal knowing that some of these “edge waves” were only supported with 1 minute topography.

4.3 Arena Cove

Gauge detiding

We began by detiding the Arena Cove station 9416841 15 second data that was provided by PMEL in the file **20100227-arena-cove-ca-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 74 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 75 shows a blowup from 13.5 to 21.5 hours post quake.

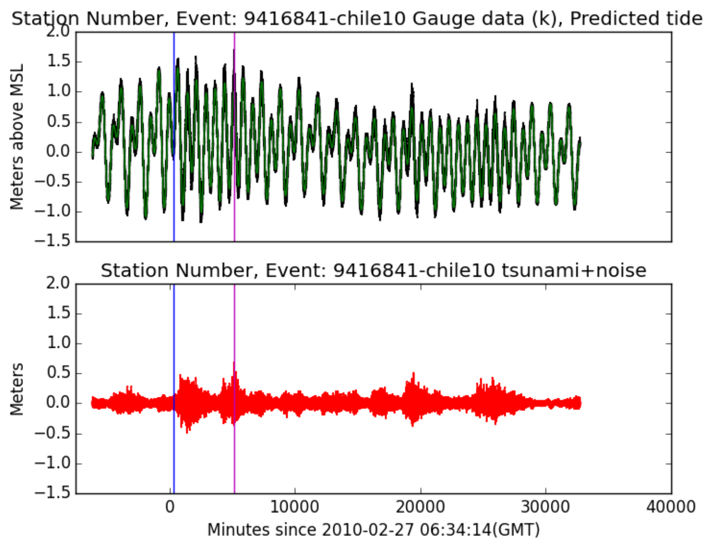

Figure 74: Chile 2010, Arena Cove, DeTided Tsunami

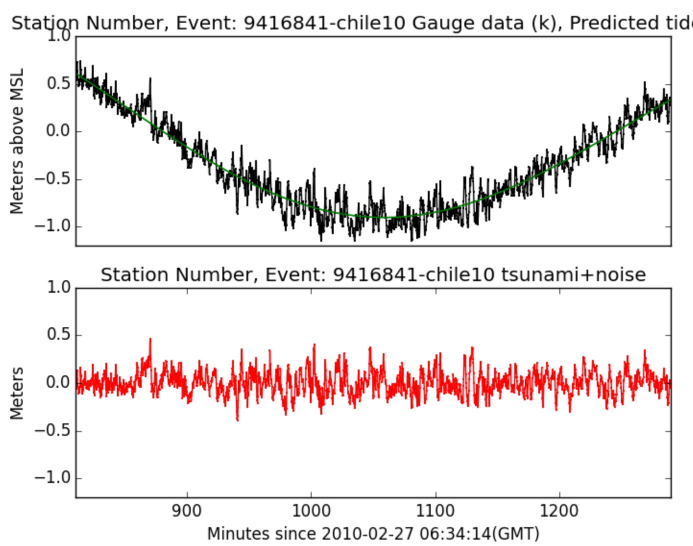

Figure 75: Chile 2010, Arena Cove, DeTided Tsunami, 13.5-21.5 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -66 longitude, -47 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -96 to -68 longitude and -47 to -24 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Arena Cove between 13.5 and 21 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) up to a maximum of 4 minute (Level 3) resolution everywhere in our computational grid for the entire computation.

Around Arena Cove, we used 1min (Level 4), 12sec (Level 5), 6sec (Level 6), 2sec (Level 7), and 1sec (Level 8) grids. The 1sec grid was the same as PMEL's C grid. The 1 min grid was an extension of PMEL's A grid, the 12 sec grids were extensions of PMEL's B grid, the 6sec grid was inside PMEL's B grid, and the 2sec grid was somewhat larger than PMEL's C grid. The specifics of the 8 regions used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
8                    =: num_regions
1  3  0  1e+09  -360  0  -90  90
4  4  0  3600  -96  -68  -47  -24
4  4  48600  1e+09  -135  -120  32  46
5  5  50400  1e+09  -124.65  -123.065  38.35  39.8
5  5  50400  1e+09  -124.65  -123.835  39.8  46
6  6  50400  1e+09  -124.43  -123.43  38.4  39.4
7  7  50400  1e+09  -123.85  -123.651  38.845  39.0445
8  8  50400  1e+09  -123.78  -123.685  38.89  39.02
```

The topo files we used that supported this computation were:

```
etopo1_-180_-66_-47_65_1min.tt3
etopo1_-240_-180_-47_65_1min.tt3
arena_cove_6sec.asc
arena_cove_1sec.asc
arena_cove_2sec.asc
arena_cove_Port_onethird.asc
```

We considered 1 GeoClaw computational gauge called Gauge 0. Gauge 0 was close to the MOST gauge, given in the file **arenacovetimeseriesC.txt** as having location (-123.71111, 38.91458). In a picture, it wouldn't be distinguished from Gauge 0. Gauge 0 was turned on at 14.1 hours post-quake. Its location as described to Geoclaw is given below and it can be seen in Figure 27.

```
rundata.gaugedata.gauges.append([0, -123.711097, 38.914646, 14.1*3600.,1.e10])
```

In Figure 76 we give comparison plots for this 1sec (GeoClaw) and 2sec longitude, 1.5sec latitude (MOST) resolution around the finest grid. The MOST max amplitude was 0.16 and came from a C grid of 2 second resolution. The detided max amplitude was 0.47 for the 15sec gauge data. (There was a detided wave of amplitude 0.69 was at 85.65 hrs. post quake.) The maximum for GeoClaw was 0.19m. The Bathymetry used at the gauge for the GeoClaw computation was B=-3.49m.

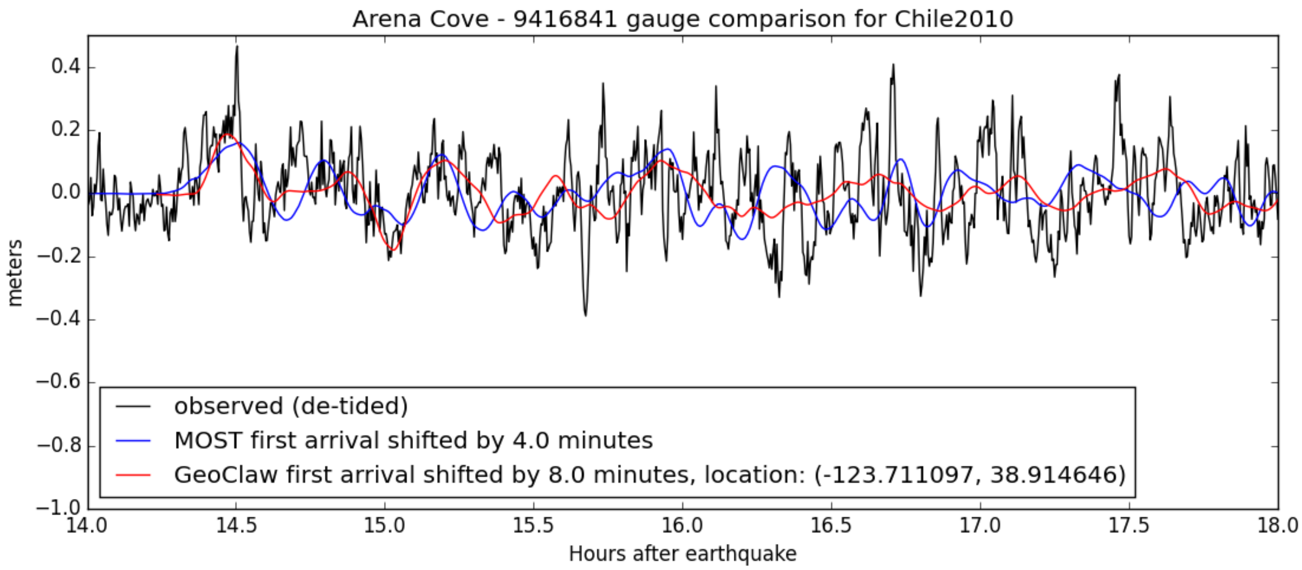

Figure 76: Chile 2010, Arena Cove, 1sec

Discussion:

This was a small tsunami with noisy 15sec tide gauge data. It is interesting that the MOST and GeoClaw tsunamis look very similar with neither capturing the gauge's highest peaks (which look rather suspect, especially the earlier one around 14.5 hours post quake). We also did a 1/3sec GeoClaw run that used 4 hours of 1 minute computation around the Chile source region which only increased the maximum amplitude by a few millimeters and did not change the wave train significantly from the 1sec run shown here. Doing a better job modelling this Chile 2010 tsunami, especially for the later waves, would require more coastal resolution since the tsunami hugs the coast all the way to Arena Cove.

Timing information for this run can be found in Appendix B.11.

4.4 Port Orford

Gauge detiding

We began by detiding the Port Orford station 9431647 15 second data that was provided by PMEL in the file **20100227-port-orford-or-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 77 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 78 shows a blowup from 14.5 to 24.5 hours post quake.

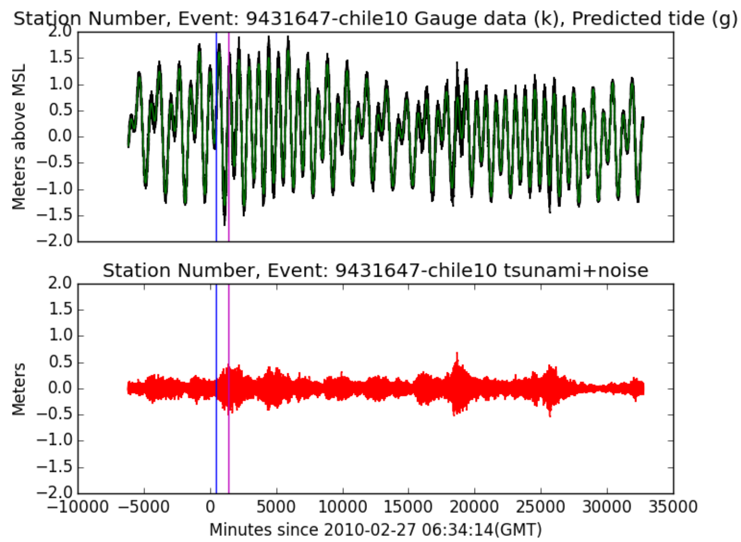

Figure 77: Chile 2010, Port Orford, DeTided Tsunami

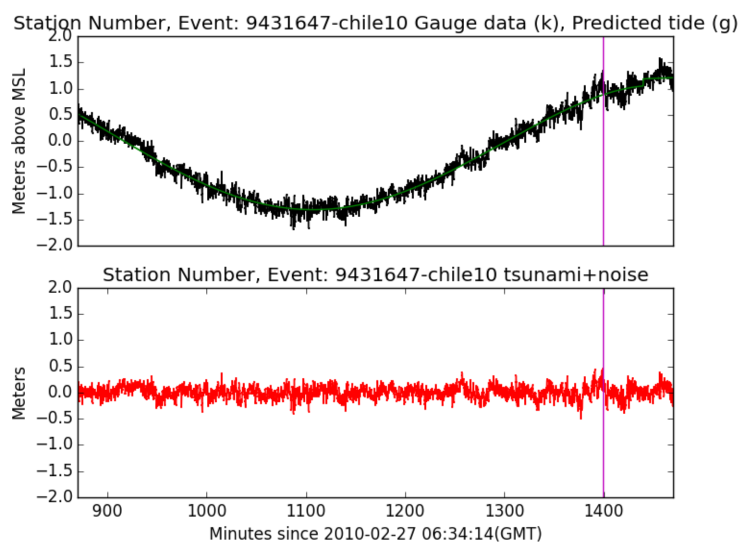

Figure 78: Chile 2010, Port Orford, DeTided Tsunami, 14.5-24.5 hrs. post-quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -66 longitude, -47 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -96 to -68 longitude and -47 to -24 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Port Orford between 14.5 and 24 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) up to a maximum of 4 minute (Level 3) resolution everywhere in our computational grid for the entire computation.

Around Port Orford, we required 1 minute (Level 4), 12 second (Level 5), and 1sec (Level 6) resolution on the A, B, and C grids, respectively. The region specifics for the 5 regions we used for this run are given below. The first two numbers are the minimum and maximum levels allowed. The third and fourth numbers are are the times in seconds post-quake when the region is turned on and off. The last four numbers are the longitude and latitude limits of the rectangular region.

```
5                    =: num_regions
1  3  0  1e+09  -360  0  -90  90
4  4  0  3600  -96  -68  -47  -24
4  4  50400  1e+09  -127.5  -123.5  39.01  47.19
5  5  52200  1e+09  -124.933  -124.27  42.0683  43.265
6  6  52200  1e+09  -124.551  -124.44  42.6715  42.7732
```

The topo files we used that supported this computation were:

```
etopo1_-240_-180_-47_65_1min.tt3
etopo1_-180_-66_-47_65_1min.tt3
PortOrford_1sec.asc
PortOrfordHarbor.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 0 below and depicted in Figure 31. The MOST computational gauge as recorded in the file **porfordtimeseriesC.txt** was the same as Gauge 0. The location of Gauge 0 as specified in GeoClaw was turned on at 14.75 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([0, -124.49767, 42.73876, 14.75*3600, 1.e10])
```

In Figure 79 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.15 and came from a C grid of 2 second resolution. The detided max amplitude was 0.46 for the 15sec gauge data. The maximum for GeoClaw was 0.13m. The Bathymetry used at the gauge for the GeoClaw computation was B=-3.96m.

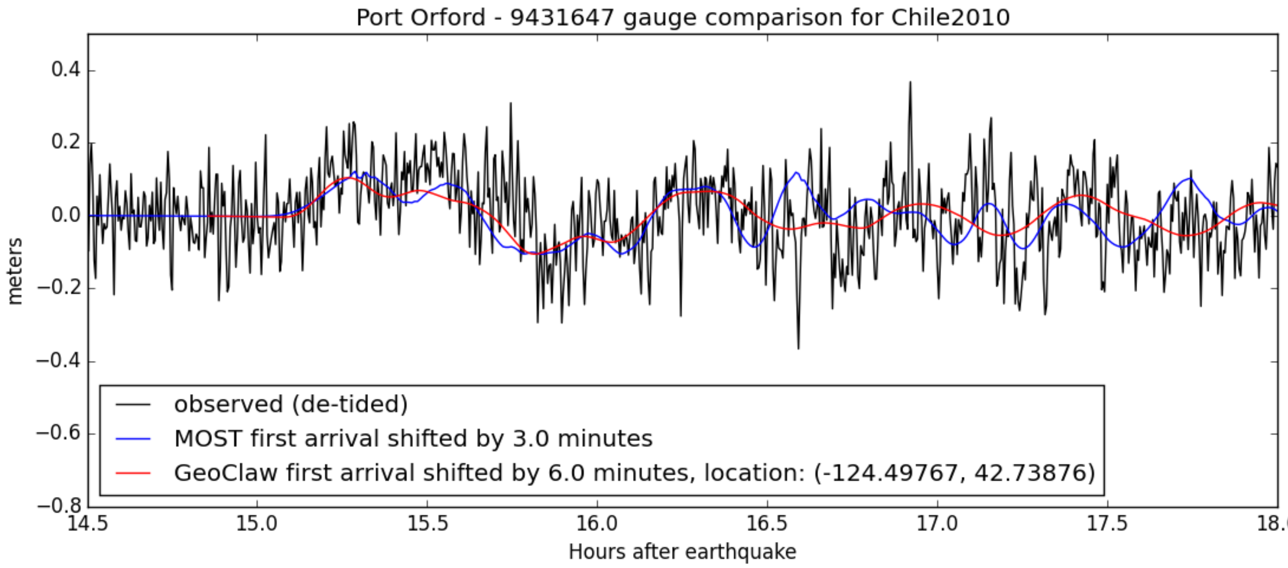

Figure 79: Chile 2010, Port Orford, 1sec

Discussion:

This was a small tsunami with noisy 15sec tide gauge data. It is interesting that the MOST and GeoClaw tsunamis look very similar with neither capturing the gauge's highest peaks (which are suspect, especially the one right before 17 hours post quake). We did a 1/3sec GeoClaw run, and the wavetrain was identical to that described above. Doing a better job modelling this Chile 2010 tsunami, especially for the later waves, would require more coastal resolution since the tsunami hugs the coast from source to destination.

5 Kuril 2007 Tsunami

In the next sections, we compare GeoClaw and MOST results at Hilo, Crescent City, Arena Cove, and Port Orford to the detided tide gauge results. For these destinations, we put a computational gauge near the tide gauge at the location of the MOST computational gauge. We provide the maximum GeoClaw, MOST, and tide gauge amplitudes at this gauge and a plot of the associated tsunamis there.

Figure 80 shows the extent of the Kuril 2007 source used by GeoClaw (and MOST) as the pink rectangle.

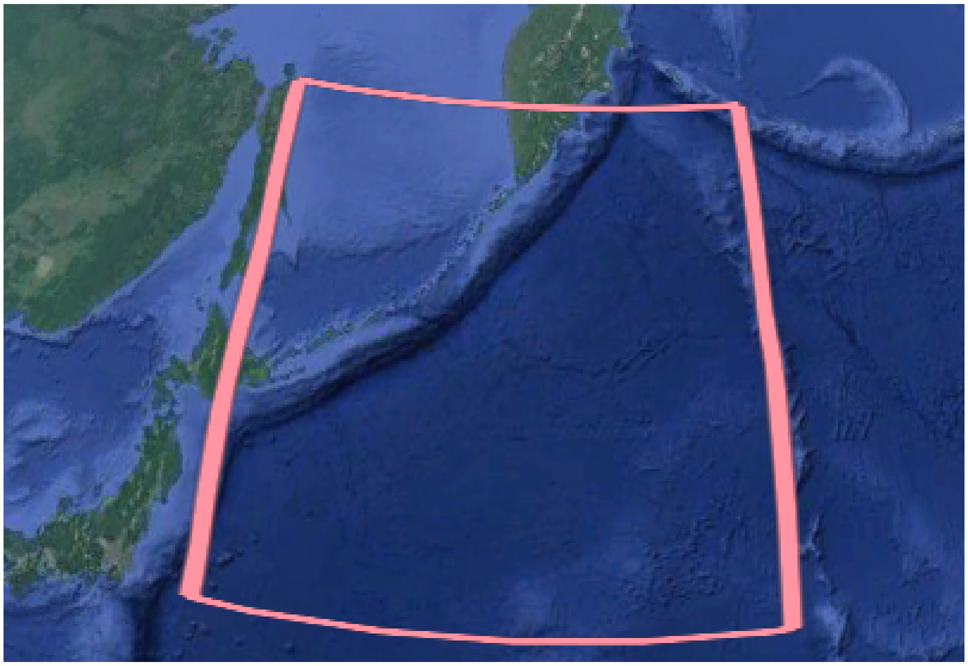

Figure 80: Kuril 2007 source region, extent=-216.717, -190.05, 35.20, 53.94

5.1 Hilo

Gauge detiding

We began by detiding the Hilo station 1617760 60 second data that was provided by PMEL in the file **20070113-hilo-hi-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 81 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 82 shows a blowup from 6 to 15 hours post quake.

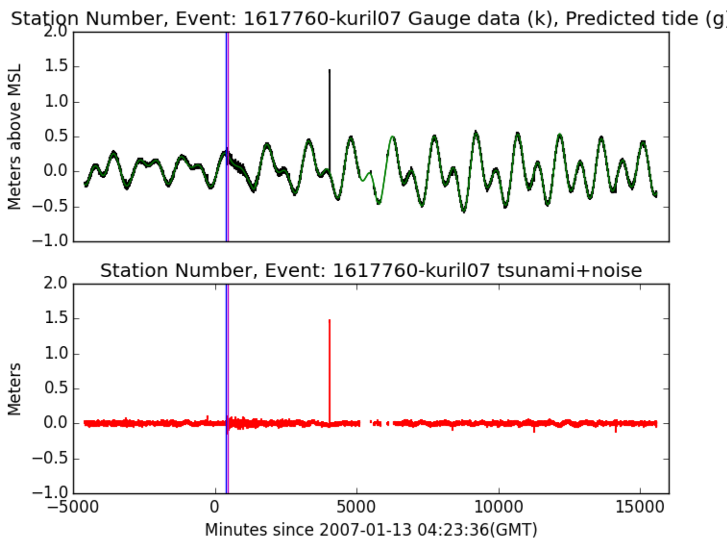

Figure 81: Kuril 2007, Hilo, DeTided Tsunami

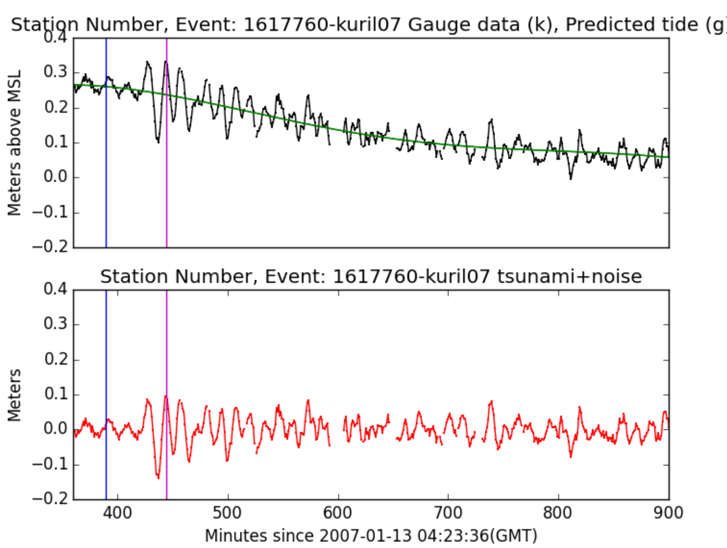

Figure 82: Kuril 2007, Hilo, DeTided Tsunami, 6-15 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -218 to -188 longitude and 34 to 54 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Hilo between 6 and 15 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and up to a maximum of 4 minute (Level 3) resolution everywhere in our computational grid for the entire computation.

Around Hilo, we used 1min (Level 4), 6sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                  =: num_regions
1  3  0  1e+09  -360  0  -90  90
4  4  0  3600  -218  -188  34  54
4  4  19800  1e+09  -161  -154.033  18.0317  22.9983
5  5  21600  1e+09  -156.262  -154.597  18.685  20.415
6  6  21600  1e+09  -155.101  -155.01  19.7  19.79
```

The topo files we used that supported this computation were:

```
etopo1_-240_-180_-41_65_1min.tt3
etopo1_-180_-100_-41_65_1min.tt3
hawaii_36s.asc
hawaii_6s_20070806.asc
hilo_hi_Port_onethird.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 0 below and depicted in Figure 17. The MOST computational gauge as recorded in the file **hilo2timeseriesC.txt** was the same as Gauge 0. The location of Gauge 0 as specified in GeoClaw was turned on at 6.5 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([0, -155.05593, 19.73111, 6.5*3600.,1.e10])
```

In Figure 83 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.24m and came from a C grid of 2 second resolution. The detided max amplitude was 0.095m for this 60sec tide gauge. The maximum for GeoClaw was 0.15m. The Bathymetry used at the gauge for the GeoClaw computation was B=-9.42m.

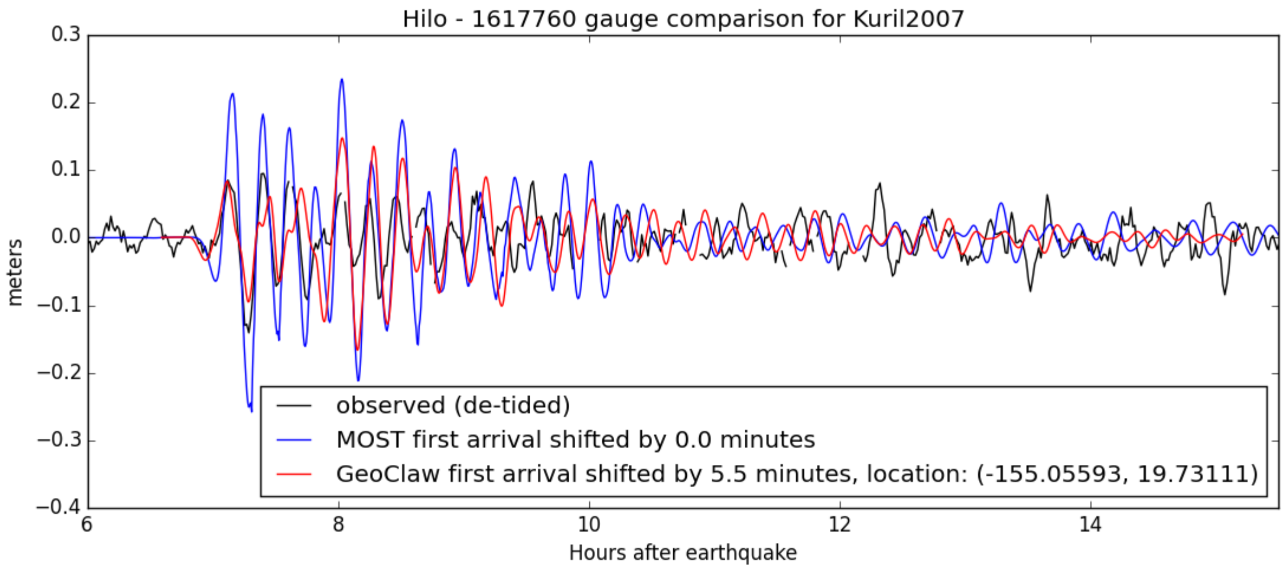

Figure 83: Kuril 2007, Hilo, 1sec

Discussion:

Both MOST and GeoClaw did an excellent job matching the timing of the tide gauge waves. This gauge only had 60 second resolution, and indeed both MOST and GeoClaw report higher amplitude waves than the gauge, especially around 8 to 9 hours post-quake, with MOST overshooting the most.

5.2 Crescent City

Gauge detiding

We began by detiding the Crescent City station 9419750 60 second data that was provided by PMEL in the file **20070113-crescent-city-ca-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 84 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 85 shows a blowup from 7.5 to 14 hours post quake.

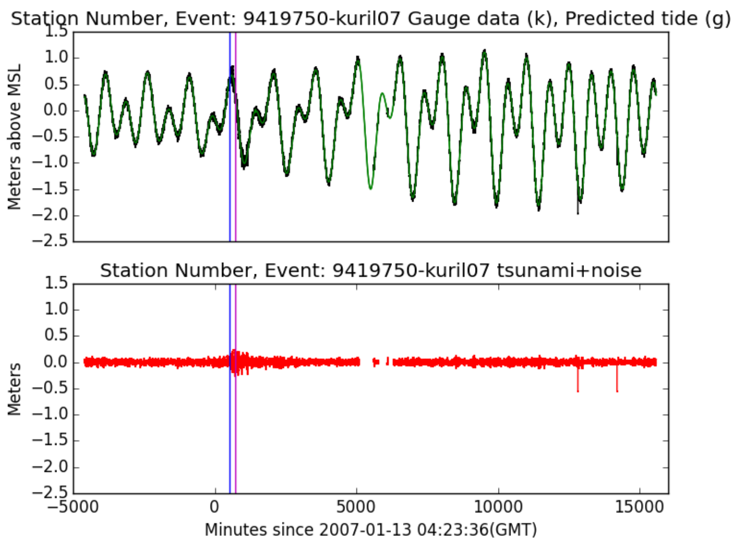

Figure 84: Kuril 2007, Crescent City, DeTided Tsunami

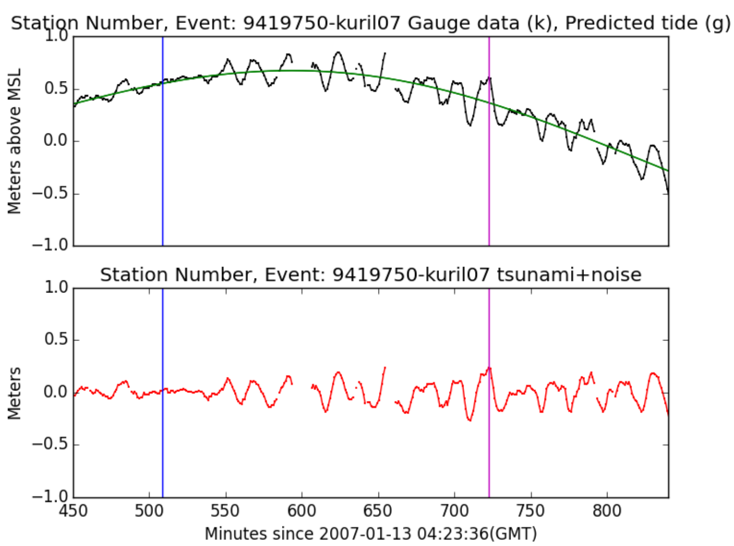

Figure 85: Kuril 2007, Crescent City, DeTided Tsunami, 7.5-14 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -218 to -188 longitude and 34 to 54 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Crescent City between 7.5 and 13.5 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and up to a maximum of 4 minute (Level 3) resolution everywhere in our computational grid for the entire computation.

Around Crescent City, we used 1min (Level 4), 12sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used for the 1sec run are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                    =: num_regions
1  3  0  1e+09  -360  0  -90  90
4  4  0  3600  -218  -188  34  54
4  4  27000  1e+09  -126.995  -123.535  40.515  44.495
5  5  28800  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  28800  1e+09  -124.234  -124.143  41.7168  41.7829
```

The topography files that supported the 1sec run are given below:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
cresc1sec.asc
```

We also did a 1/3sec run. The regions we used were:

```
1  1  0  1e+09  -360  0  -90  90
1  3  0  1e+09  -220  -122  5  60
4  4  0  3600  -218  -188  34  54
4  4  27000  1e+09  -126.995  -123.535  40.515  44.495
5  5  28800  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  28800  1e+09  -124.234  -124.143  41.7168  41.7829
7  7  28800  1e+09  -124.202  -124.18  41.733  41.752
```

These regions for the 1/3sec run were supported by the topo below:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
cc-1_3sec-c_pierless.asc
cc-1sec-c.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 2 below and depicted in Figure 21. The MOST computational gauge as recorded in the file **crescenttimeseriesC.txt** was the same as Gauge 2. The location of Gauge 2 as specified in GeoClaw was turned on at 8.1 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([2, -124.18397, 41.74512, 8.1*3600., 1.e10])
```

In Figure 86 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. In Figure 87 we compare the 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. For both runs, the MOST max amplitude was 0.33 and came from a C grid of 2 second resolution. The detided max amplitude was 0.24. The maximum for GeoClaw was 0.16m for both runs. The Bathymetry used at the gauge for the GeoClaw computation was B=-4.75m for the 1sec run and B=-5.90m for the 1/3sec run.

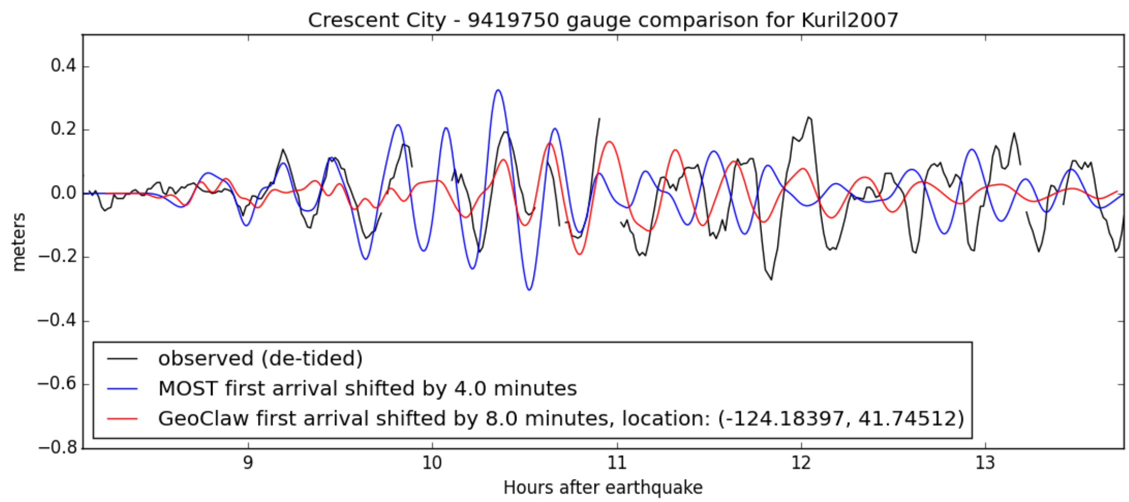

Figure 86: Kuril2007, Crescent City, 1sec

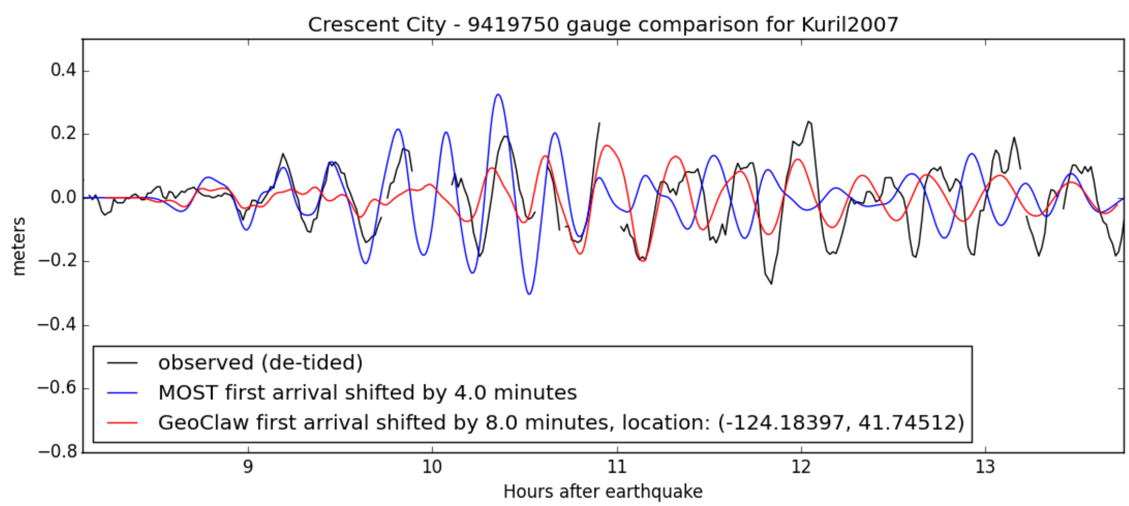

Figure 87: Kuril2007, Crescent City, 1/3sec

In an attempt to understand why the GeoClaw maximum amplitude was low compared to that of both the gauge and the MOST value, we decided to put extended regions around Crescent City and try the 1/3sec run again. We made a larger A grid (1min), made the old A grid become a 12sec grid, made the 12sec grid become a 6sec grid, and kept the 1sec and 1/3sec grids the same. We used the same topography and gauge location. In particular, the new regions are given below where the Levels 1 to 8 are now 2 degrees, 24min, 4min, 1min, 12sec, 6sec, 1sec, and 1/3sec, respectively.

```
8                        =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  3  0  1e+09  -220  -122  5  60
4  4  0  3600  -218  -188  34  54
4  4  23400  1e+09  -129  -123  38  46
5  5  27000  1e+09  -126.995  -123.535  40.515  44.495
6  6  28800  1e+09  -124.6  -124.05  41.5017  41.9983
7  7  28800  1e+09  -124.234  -124.159  41.7168  41.7695
8  8  28800  1e+09  -124.202  -124.18  41.733  41.752
```

These changes really made a difference. In particular, the extra computation around Crescent City was the reason for this difference. In Figure 88 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.33 and came from a C grid of 2 second resolution. The detided max amplitude was 0.24. The maximum for GeoClaw increased from the 0.16m described previously to 0.25m, and many of the other waves increased in amplitude. The bathymetry used at the gauge for this second 1/3sec run with extended regions for the GeoClaw computation was still B=-5.90m.

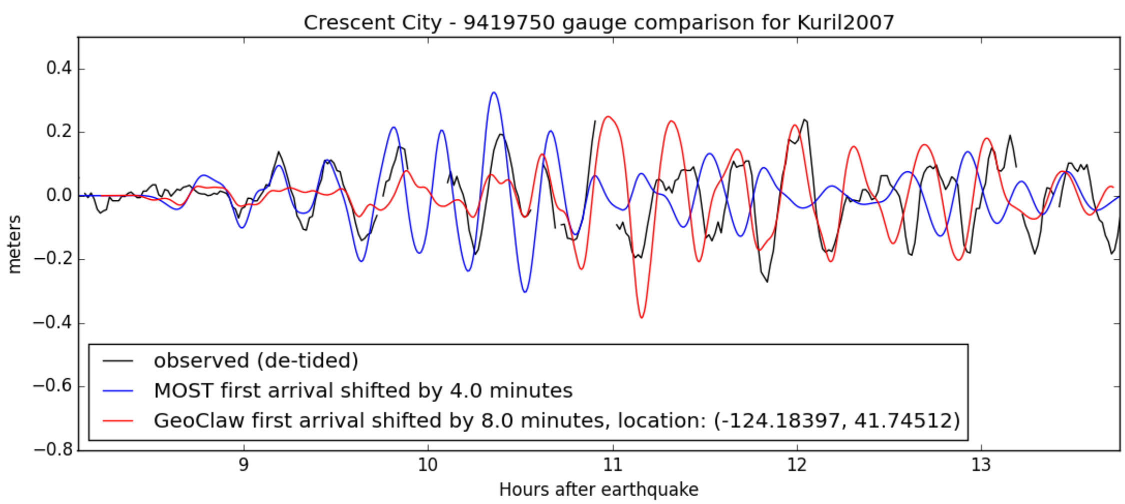

Figure 88: Kuril2007, Crescent City, 1/3sec, extended regions, 4min ocean max

The 1sec run and the two 1/3sec runs described above all used a maximum of 4 minute computation across the ocean. We thought it would be interesting to complete the story with a run that used up a maximum of 1 minute computation across the ocean to see how the wave train would change. For this last 1/3sec run we used the regions given below, keeping the same topography and gauge location. Again, Levels 1 to 8 were still 2 degree, 24min, 4min, 1min, 12sec, 6sec, 1sec, and 1/3sec, respectively. Notice that only the second region statement has changed from allowing Levels 1 to 3 of refinement to allowing for Levels 1 to 4.

```
8                    =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  4  0  1e+09  -220  -122  5  60
4  4  0  3600  -218  -188  34  54
4  4  23400  1e+09  -129  -123  38  46
5  5  27000  1e+09  -126.995  -123.535  40.515  44.495
6  6  28800  1e+09  -124.6  -124.05  41.5017  41.9983
7  7  28800  1e+09  -124.234  -124.159  41.7168  41.7695
8  8  28800  1e+09  -124.202  -124.18  41.733  41.752
```

Using up to 1min computation across the ocean gave more detailed patterns in the wave train, and increased the maximum amplitude from 0.25m to 0.30m. In Figure 89 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.33 and came from a C grid of 2 second resolution. The detided max amplitude was 0.24. The maximum for GeoClaw increased from the last 1/3sec run of 0.25 to 0.30 meters. The bathymetry used at the gauge for this second 1/3sec run with extended regions for the GeoClaw computation was still B=-5.90m.

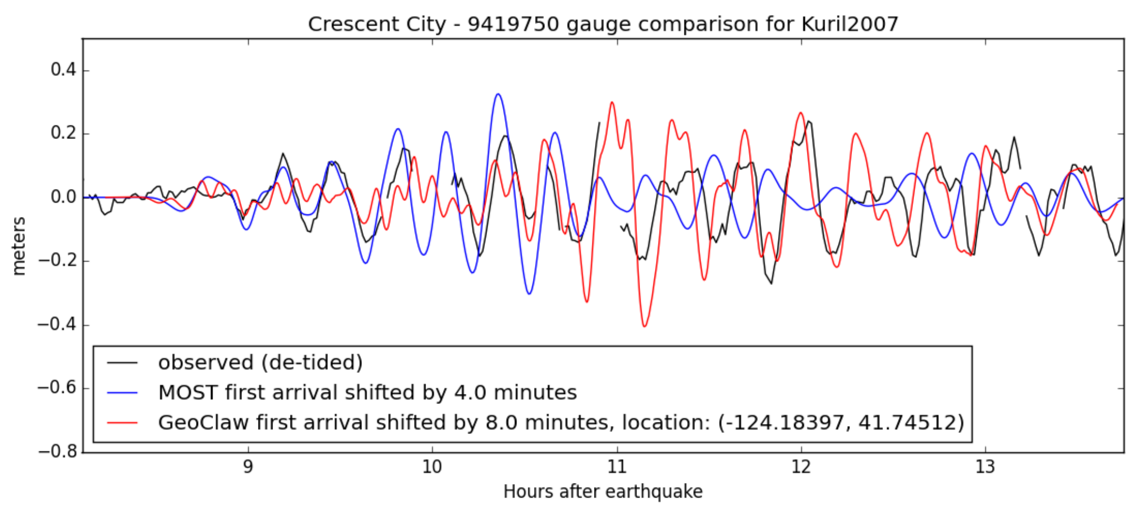

Figure 89: Kuril2007, Crescent City, 1/3sec, extended regions, 1min ocean max

Discussion:

This was a small tsunami. MOST does a better job matching the gauge's first few earlier waves than GeoClaw's 1sec and first two 1/3sec runs, while GeoClaw's last 1/3sec run gave more pattern in the early part of the wave train than either the gauge or the MOST results. GeoClaw does better for the waves after 10.5 hours post quake. In particular, GeoClaw's second and third 1/3sec runs capture really well two of the gauge's biggest waves, including the maximum amplitude waves around 11 and 12 hours post quake. MOST overshoots the wave at about 10.5 hours post quake to achieve its maximum amplitude. We note that the gauge data was only 60sec resolution, the overshoots seen in the model results might be valid.

Increasing the resolution to 1/3sec around the Crescent City harbor did not substantially change the wave train when the same regions as the 1sec run were used for the Levels up through 1sec. When we extended these regions as described for the second 1/3sec run, the wave train changed substantially to look more like the gauge's wave train. So for this tsunami the 1sec and first 1/3sec GeoClaw computation were not sufficient – more refined computation was necessary in larger regions around Crescent City. Finally, when we allowed for up to 1 minute resolution across the ocean, more detailed patterns appear in the earlier waves, and wave heights increased (to possibly fill in the 60sec gauge data).

Timing information about this 1sec run is given in Appendix B.10

5.3 Arena Cove

Gauge detiding

We began by detiding the Arena Cove station 9416841 60 second data that was provided by PMEL in the file **20070113-arena-cove-ca-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 90 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 91 shows a blowup from 7 to 14 hours post quake.

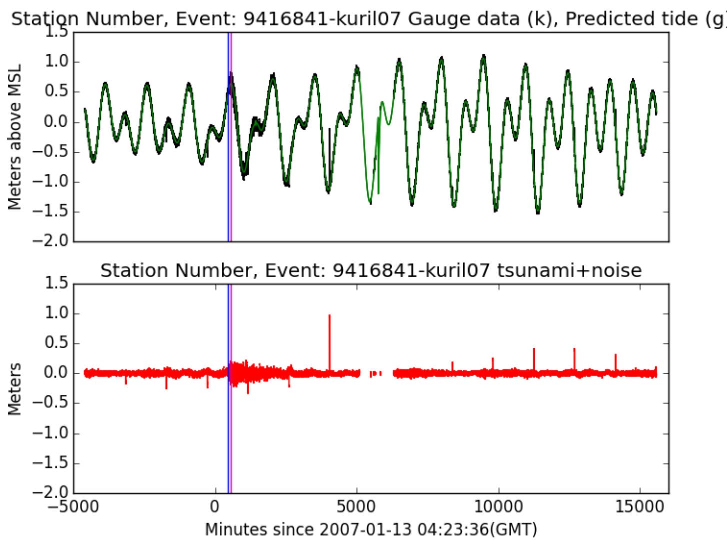

Figure 90: Kuril 2007, Arena Cove, DeTided Tsunami

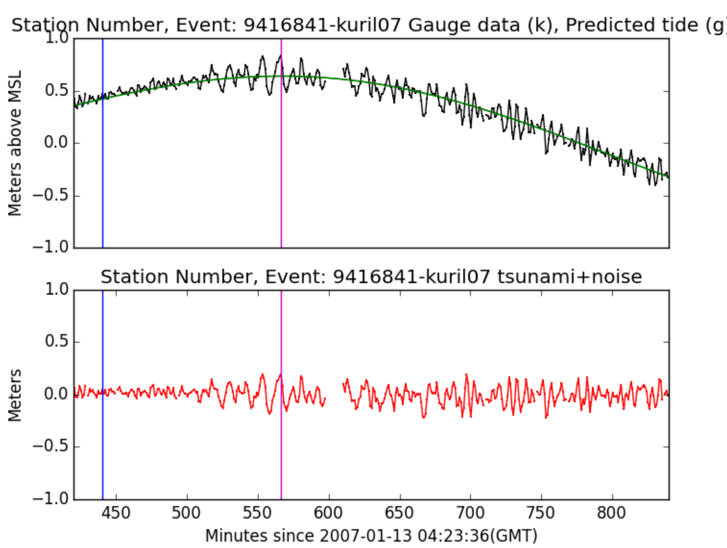

Figure 91: Kuril 2007, Arena Cove, DeTided Tsunami, 7-14 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -218 to -188 longitude and 34 to 54 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Arena Cove between 7.5 and 13.0 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Arena Cove, we used 1min (Level 4), 12sec (Level 5), 6sec (Level 6), 2sec (Level 7), and 1sec (Level 8) grids. The 1sec grid was the same as PMEL's C grid. The 1 min grid was an extension of PMEL's A grid, the 12 sec grids were extensions of PMEL's B grid, the 6sec grid was inside PMEL's B grid, and the 2sec grid was somewhat larger than PMEL's C grid. The specifics of the 8 regions used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
8                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -218  -188  34  54
4  4  27000  1e+09  -135  -120  32  46
5  5  28800  1e+09  -124.65  -123.065  38.35  39.8
5  5  28800  1e+09  -124.65  -123.835  39.8  46
6  6  28800  1e+09  -124.43  -123.43  38.4  39.4
7  7  28800  1e+09  -123.85  -123.651  38.845  39.0445
8  8  28800  1e+09  -123.78  -123.685  38.89  39.02
```

The topo files we used that supported this computation were:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
arena_cove_6sec.asc
arena_cove_1sec.asc
arena_cove_2sec.asc
arena_cove_Port_onethird.asc
cca_12s_mhw_v2.asc
```

We considered 1 GeoClaw computational gauge called Gauge 0. Gauge 0 was close to the MOST gauge, given in the file **arenacovetimeseriesC.txt** as having location (-123.71111, 38.91458). In a picture, it wouldn't be distinguished from Gauge 0. Gauge 0 was turned on at 8.25 hours post-quake. Its location as described to Geoclaw is given below and it can be seen in Figure 27.

```
rundata.gaugedata.gauges.append([0, -123.711097, 38.914646, 8.25*3600.,1.e10])
```

In Figure 92 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.18 and came from a C grid of 2 second in longitude and 1.5 second in latitude resolution. The detided max amplitude was 0.19m. The maximum for GeoClaw was 0.39m. The Bathymetry used at the gauge for the GeoClaw computation was B=-3.49m.

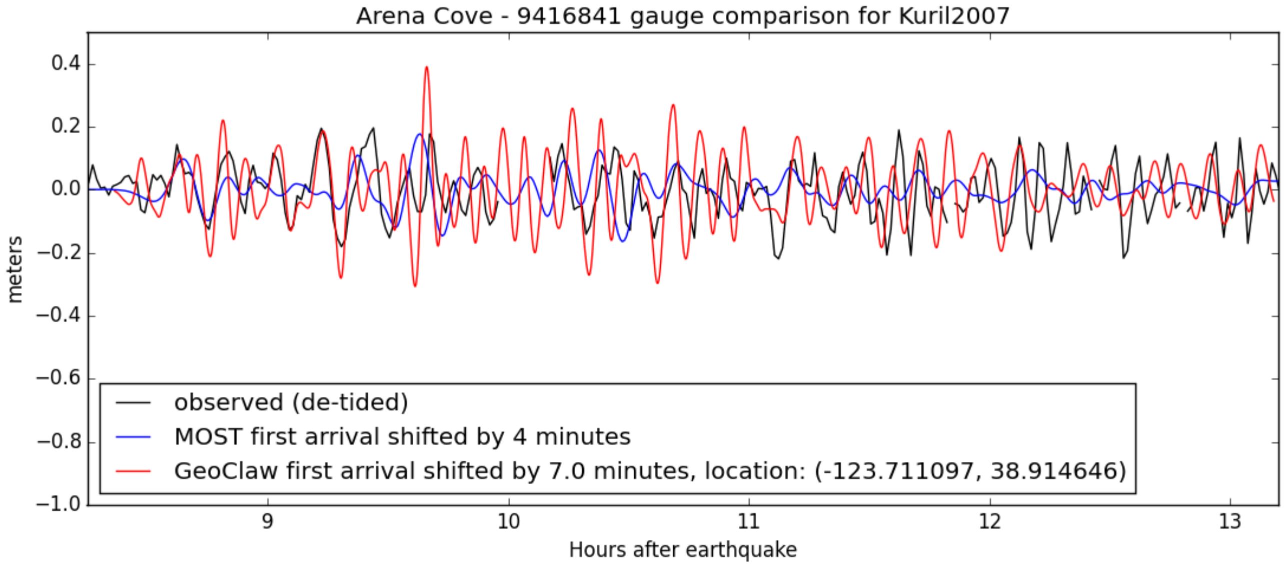

Figure 92: Kuril 2007, Arena Cove, 1sec

Discussion:

This was a small tsunami and only a 60sec resolution tide gauge. GeoClaw used 1sec computation and 1 minute refinement across the ocean and gets larger amplitudes than does MOST or the tide gauge, especially for the waves 9.5 to 11.0 hours post quake. MOST underestimates the tide gauge amplitudes occurring around 9 to 9.5 hours post quake. Our experience shows that Arena Cove needs a little more resolution, so it is not surprising that MOST with the resolution used underestimates the gauge tsunami.

5.4 Port Orford

Gauge detiding

We began by detiding the Port Orford station 9431647 60 second data that was provided by PMEL in the file **20070113-port-orford-or-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 93 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red and the location of the maximum detided amplitude in magenta. Figure 94 shows a blowup from 7.5 to 14 hours post quake.

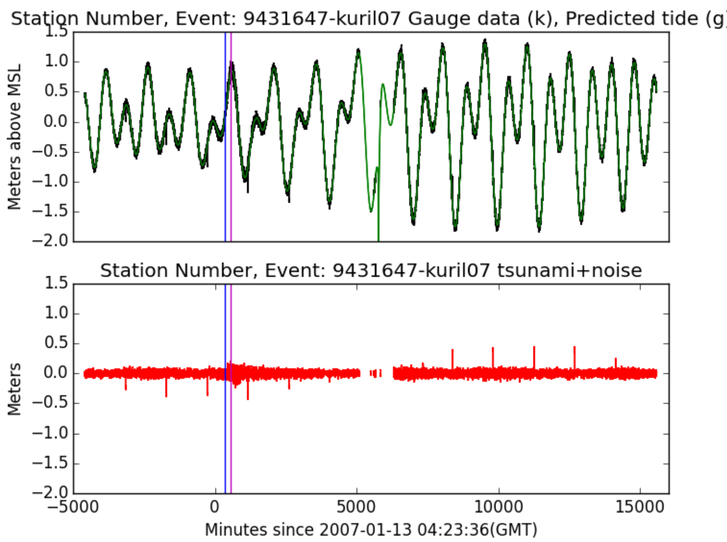

Figure 93: Kuril 2007, Port Orford, DeTided Tsunami

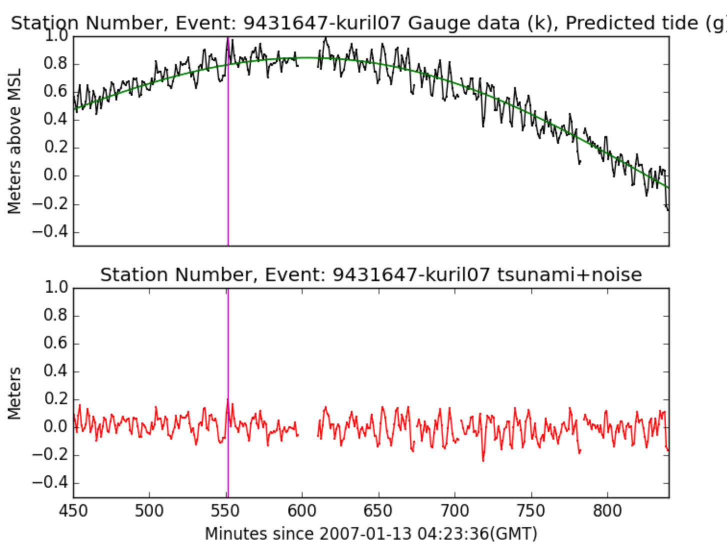

Figure 94: Kuril 2007, Port Orford, DeTided Tsunami, 7.5-14 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -218 to -188 longitude and 34 to 54 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Port Orford between 7.5 and 14 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Port Orford, we required 1 minute (Level 4), 12 second (Level 5), and 1sec (Level 6) resolution on the A, B, and C grids, respectively, and 1/3sec (Level 7) resolution on a small grid inside the C grid around Port Orford Harbor. The region specifics for the 6 regions we used for this run are given below. The first two numbers are the minimum and maximum levels allowed. The third and fourth numbers are the times in seconds post-quake when the region is turned on and off. The last four numbers are the longitude and latitude limits of the rectangular region.

```
6                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -218  -188  34  54
4  4  27000  1e+09  -127.5  -123.5  39.01  47.19
5  5  28800  1e+09  -124.933  -124.27  42.0683  43.265
6  6  28800  1e+09  -124.551  -124.44  42.6715  42.7732
7  7  28800  1e+09  -124.516  -124.48  42.73  42.7439
```

The topography files that supported this 1/3sec run are given below:

```
etopo1_-240_-180_-41_65_1min.tt3
etopo1_-180_-100_-41_65_1min.tt3
PortOrford_1sec.asc
PortOrfordHarbor.asc
```

We used one GeoClaw computational gauge called Gauge 0. This gauge was the same as the MOST computational gauge reported in the file **porfordtimeseriesC.txt** and depicted in Figure 31. Gauge 0 was turned on at 8 hours post-quake and had location as given below:

```
rundata.gaugedata.gauges.append([0, -124.49767, 42.73876, 8.0*3600, 1.e10])
```

The comparison plots for Gauge 0 are in Figure 95 for this 1/3sec run. The MOST max amplitude was 0.207m and came from a C grid of 2 second resolution. The detided max amplitude was 0.204m. The GeoClaw max amplitude was 0.227m. The bathymetry at the gauge used by GeoClaw was -3.916m.

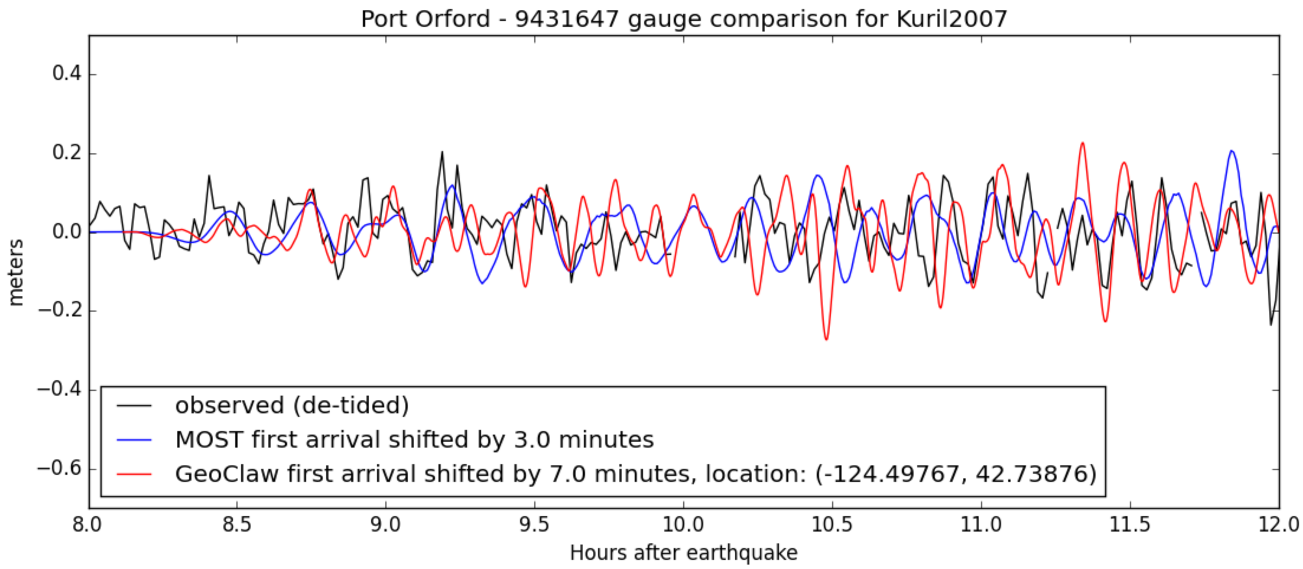

Figure 95: Kuril 2007, Port Orford, 1/3sec

Discussion:

This was a very small tsunami with many detided-gauge waves of similar amplitude. The gauge data was only 60sec resolution, so it is hard to make many conclusions about model code performance. However, both MOST and GeoClaw achieved waves with amplitudes the same as the detided-gauge. Both GeoClaw and MOST achieve their maximum values much later than that of the detided-gauge, but do have waves around 0.2 meters. We also note that a GeoClaw run that used only 4min resolution (a 1,3 region) across the ocean in conjunction with only 1sec resolution, not 1/3sec, around Port Orford Harbor (inside the C grid) did not capture the waves as well as this calculation. MOST only used 4min resolution across the ocean, and it can be seen in Figure 95 that the GeoClaw waves are higher than those of MOST at many locations, but again this is a small tsunami and noise remains in the detided-gauge tsunami.

6 Haidi Gwaii 2012 Tsunami

In the next sections, we compare GeoClaw and MOST results at Hilo, Crescent City, Arena Cove, and Port Orford to the detided tide gauge results. At these destinations, we put a computational gauge near the tide gauge at the location used by MOST. We provide the maximum GeoClaw, MOST, and tide gauge amplitudes and and provide plots of the respective tsunamis at this gauge.

Figure 96 shows the extent of the Haida Gwaii 2012 source used by GeoClaw (and MOST) as the pink rectangle.

Figure 96: Haida Gwaii 2012 source region, extent=-136, -129, 50, 55

6.1 Hilo

Gauge detiding

We began by detiding the Hilo station 1617760 60 second data that was provided by PMEL in the file **20121028-hilo-hi-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 97 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 98 shows a blowup from 4.5 to 10.0 hours post quake.

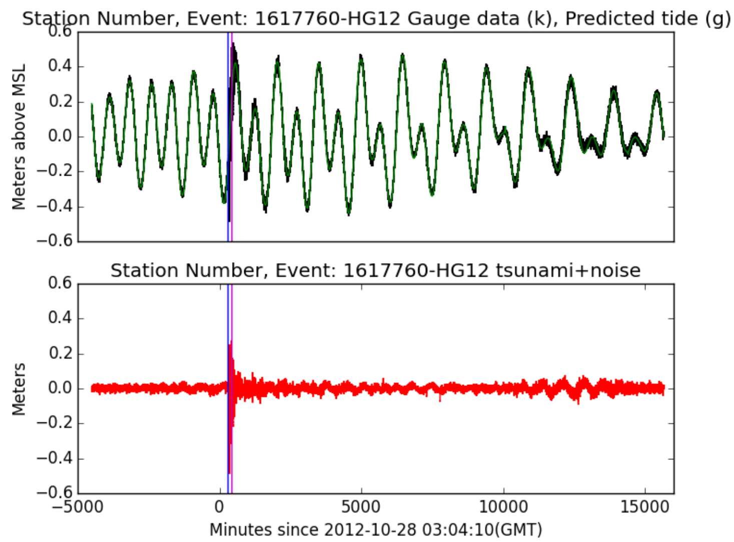

Figure 97: HG 2012, Hilo, DeTided Tsunami

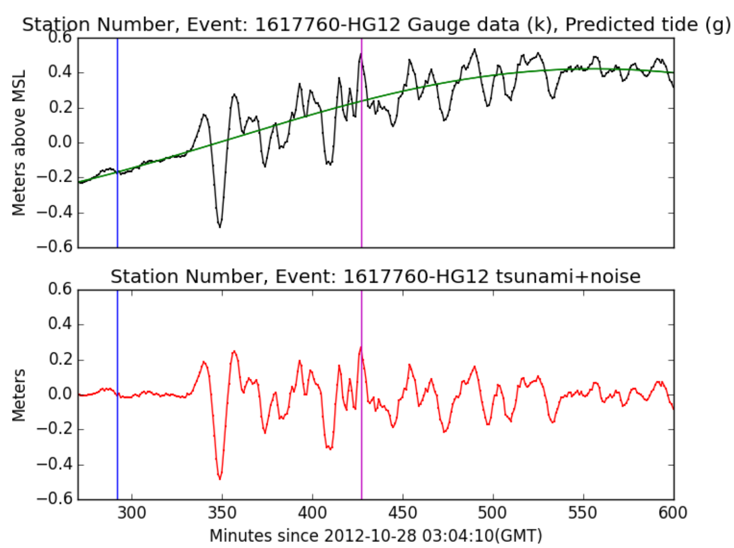

Figure 98: HG12, Hilo, DeTided Tsunami, 4.5-10.0 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -136 to -129 longitude and 50 to 55 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Hilo between 4.5 and 10.0 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2), 4 minute (Level 3), up to 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Hilo, we used 1min (Level 4), 6sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
5                   =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -136  -129  50  55
4  4  14400  1e+09  -161  -154.033  18.0317  22.9983
5  5  16200  1e+09  -156.262  -154.597  18.685  20.415
6  6  16200  1e+09  -155.101  -155.01  19.7  19.79
```

The topo files we used that supported this computation were:

```
etopo1_-240_-180_-41_65_1min.tt3
etopo1_-180_-100_-41_65_1min.tt3
hawaii_36s.asc
hawaii_6s_20070806.asc
hilo_hi_Port_onethird.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 0 below and depicted in Figure 17. The MOST computational gauge as recorded in the file **hilo2timeseriesC.txt** was the same as Gauge 0. The location of Gauge 0 as specified in GeoClaw was turned on at 4.5 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([0, -155.05593, 19.73111, 4.5*3600.,1.e10])
```

In Figure 99 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.43m and came from a C grid of 2 second resolution. The detided max amplitude was 0.27m for this 60sec tide gauge. The maximum for GeoClaw was 0.31m. The Bathymetry used at the gauge for the GeoClaw computation was B=-9.42m.

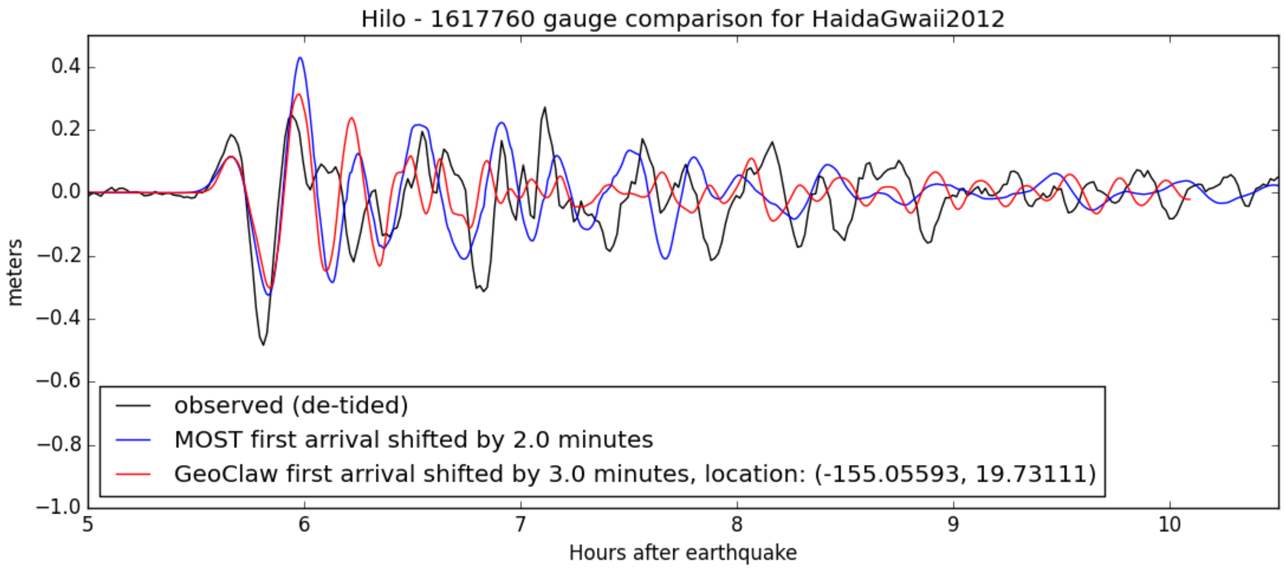

Figure 99: HG12, Hilo, 1sec

Discussion:

This was a small tsunami. Both MOST and GeoClaw overshoot the 2nd and 3rd waves but get the location of those waves correct. The gauge was only 60sec resolution, so it can be expected that some overshoot is valid. On the flip side, both MOST and GeoClaw undershoot the tide gauge's highest wave which begins after 7 hrs. post-quake. It would be interesting to see 15sec data for this gauge.

Timing information about this run is given in Appendix B.9

6.2 Crescent City

Gauge detiding

We began by detiding the Crescent City station 9419750 15 second data that was provided by PMEL in the file **20121028-crescent-city-ca-15.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 100 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the maximum detided amplitude in magenta. Figure 101 shows a blowup from 1.5 to 8.5 hours post quake.

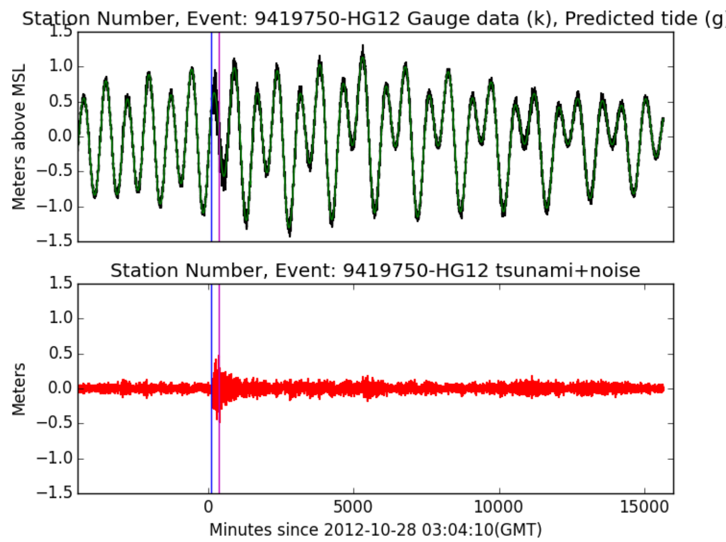

Figure 100: HG 2012, Crescent City, DeTided Tsunami

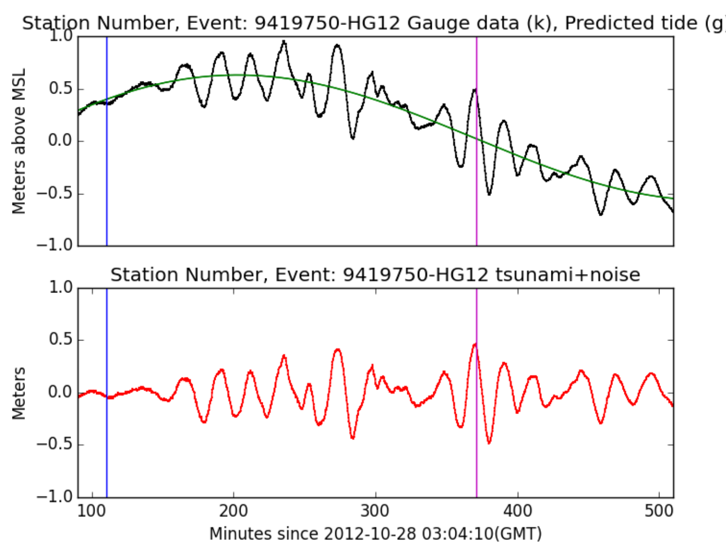

Figure 101: HG 2012, Crescent City, DeTided Tsunami, 1.5-8.5 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -136 to -129 longitude and 50 to 55 latitude.

Across the ocean, we used the the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Crescent City between 1.5 and 8 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

We ran GeoClaw for 1 arc sec finest computation run around PMEL's C grid and used the 1 sec topo that PMEL provided. Then we ran GeoClaw for 1/3 arc sec finest computation around a region inside PMEL's C grid and used 1 sec and 1/3 sec topo (pier removed) that we had used for other projects. Both runs gave basically the same results. We include both here as it demonstrates that to achieve the amplitude of later waves, perhaps more refined computation needs to be done along the coastal area both north and south of Crescent City.

In particular, around Crescent City, for the 1sec run we used 1min (Level 4), 12sec (Level 5), and 1sec (Level 6) grids, mimicking PMEL's A, B, and C grids, respectively. The specifics of the 5 regions we used for the 1sec run are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
 5                   =: num_regions
 1  4  0  1e+09  -360  0  -90  90
 4  4  0  3600  -136  -129  50  55
 4  4  5400  1e+09  -126.995  -123.535  40.515  44.495
 5  5  7200  1e+09  -124.6  -124.05  41.5017  41.9983
 6  6  7200  1e+09  -124.234  -124.143  41.7168  41.7829
```

The topography files that supported the 1sec run are given below:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
cresc1sec.asc
```

For the 1/3sec run, the regions used were

```
7                   =: num_regions
1  4  0  1e+09  -240  -100  0  65
1  1  0  1e+09  -240  -100  -41  0
4  4  0  3600  -136  -129  50  55
4  4  5400  1e+09  -126.995  -123.535  40.515  44.495
5  5  7200  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  7200  1e+09  -124.234  -124.159  41.7168  41.7695
7  7  7200  1e+09  -124.202  -124.18  41.733  41.752
```

and the topography files that supported this 1/3 run are given below:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
cc-1_3sec-c_pierless.asc
cc-1sec-c.asc
```

We considered one GeoClaw computational gauge, labelled Gauge 2 below and depicted in Figure 21. The MOST computational gauge as recorded in the file **crescenttimeseriesC.txt** was the same as Gauge 2. The location of Gauge 2 as specified in GeoClaw was turned on at 2.25 hours post-quake and given below:

```
rundata.gaugedata.gauges.append([2, -124.18397, 41.74512, 2.25*3600., 1.e10])
```

In Figure 102 we give comparison plots for this 1sec (GeoClaw) and 2sec (MOST) resolution run around the finest grid. The MOST max amplitude was 0.30 and came from a C grid of 2 second resolution. The detided max amplitude was 0.47. The maximum for GeoClaw was 0.15m. The Bathymetry used at the gauge for the GeoClaw computation was B=-4.75m.

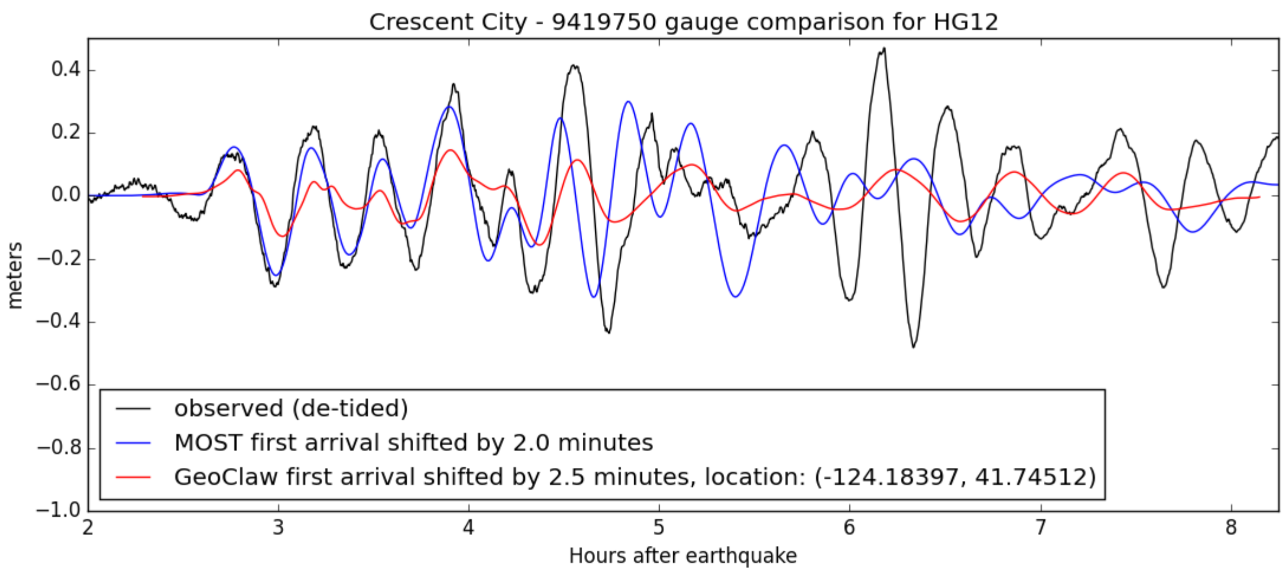

Figure 102: HG 2012, Crescent City, 1sec

In Figure 103 we give comparison plots for the 1/3sec (GeoClaw) and 2sec (MOST) resolution run around the finest grid. The MOST max amplitude was 0.30 and came from a C grid of 2 second resolution. The detided max amplitude was 0.47. The maximum for GeoClaw was 0.15m. The Bathymetry used at the gauge for the GeoClaw computation was B=-5.90m.

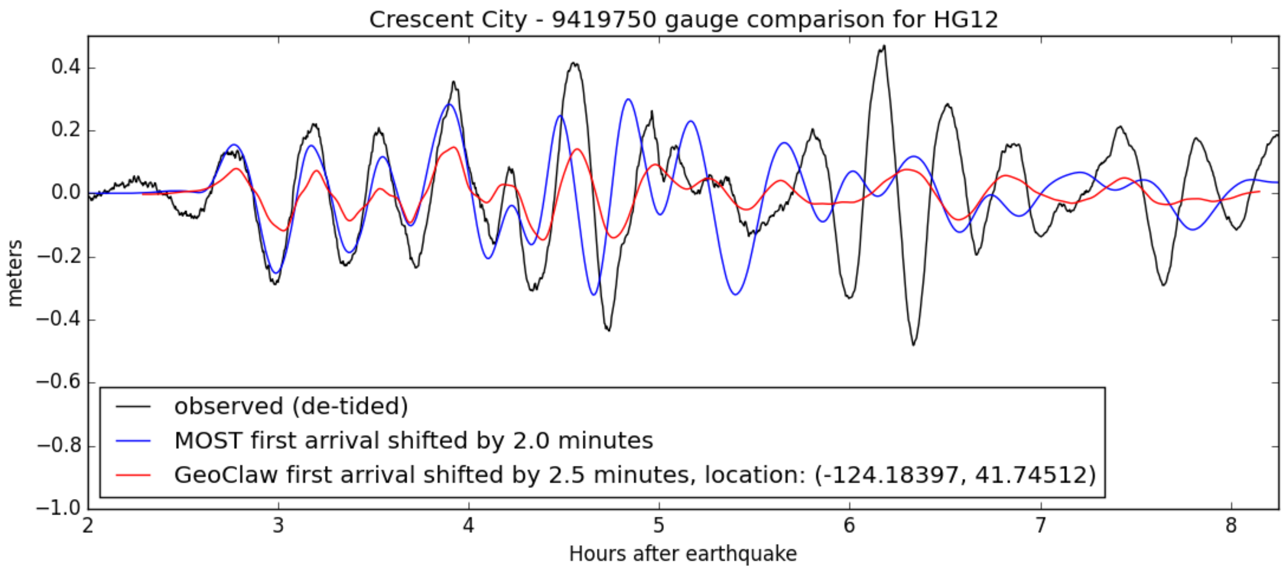

Figure 103: HG 2012, Crescent City, 1/3sec

In an attempt to understand why the GeoClaw maximum amplitude was low compared to that of both the gauge and the MOST value, we decided to put extended regions around Crescent City and try the 1/3sec run again. We made a larger A grid (1min), made the old A grid become a 12sec grid, made the 12sec grid become a 6sec grid, and kept the 1sec and 1/3sec grids the same. We used the same topography and gauge location. In particular, the new regions are given below where the Levels 1 to 8 are now 2 degrees, 24min, 4min, 1min, 12sec, 6sec, 1sec, and 1/3sec, respectively.

```
8                    =: num_regions
1  4  0  1e+09  -240  -100  0  65
1  1  0  1e+09  -240  -100  -41  0
4  4  0  3600  -136  -129  50  55
4  4  1800  1e+09  -129  -123  38  46
5  5  5400  1e+09  -126.995  -123.535  40.515  44.495
6  6  7200  1e+09  -124.6  -124.05  41.5017  41.9983
7  7  7200  1e+09  -124.234  -124.159  41.7168  41.7695
8  8  7200  1e+09  -124.202  -124.18  41.733  41.752
```

These changes really made a difference. In particular, the extra computation around Crescent City contributed largely to this difference. In Figure 104 we give comparison plots for this 1/3sec (GeoClaw) and 2sec (MOST) resolution around the finest grid. The MOST max amplitude was 0.30 and came from a C grid of 2 second resolution. The detided max amplitude was 0.47. The maximum for GeoClaw increased from the 0.15m described previously to 0.22m, and many of the other waves increased in amplitude. The bathymetry used at the gauge for the GeoClaw computation was still B=-5.90m.

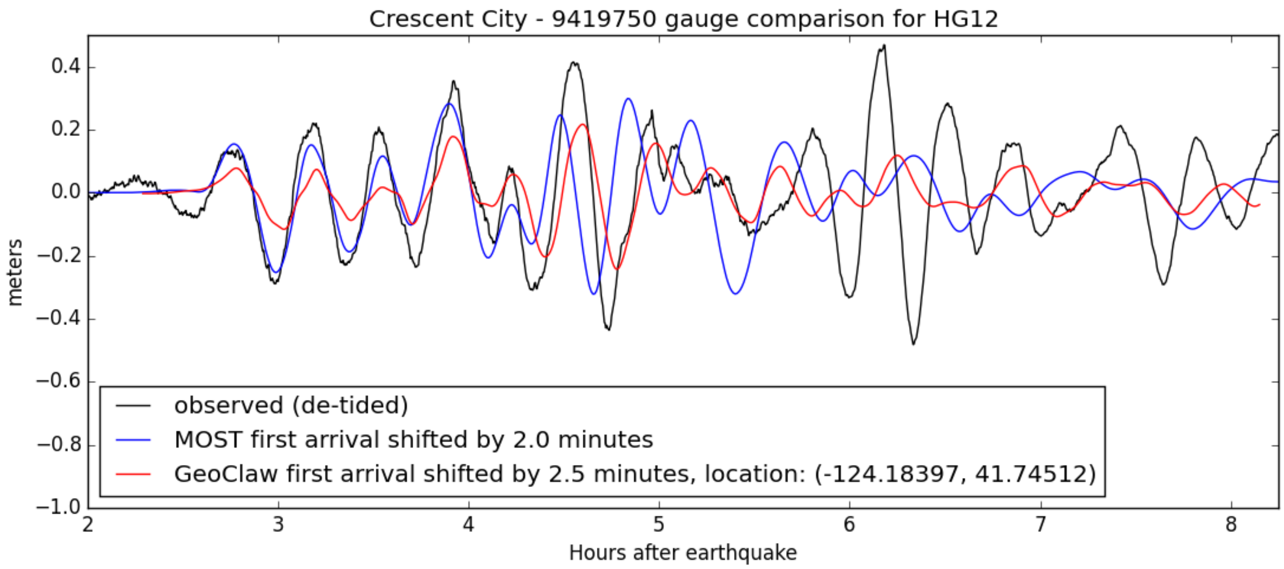

Figure 104: HG 2012, Crescent City, 1/3sec, extended regions

Discussion:

This is a small tsunami. Both MOST and GeoClaw capture the times of the first six waves very well, with MOST doing a better job of matching the amplitudes of the first four. Neither MOST nor GeoClaw capture the gauge's two large waves between 6 and 7 hours post quake.

It is interesting that the first 1/3sec run did not change the results in any significant way from the 1sec run as can be seen from the plots in Figures 102 and 103. This 1/3sec run used the UW topography around Crescent City, but the 1sec run used the 1sec topography provided by PMEL. However, the second 1/3sec got a better wave train simply by increasing the computation around Crescent City as described above in the new region specifications. Still, as Figure 104 shows, more resolved computation along the coastal area would be necessary to capture the later waves as the HG 2012 tsunami hugs the coast from the source to the destination. At the moment, GeoClaw only used 12 second resolution (B grid) and at most 1 minute resolution outside this B grid along the coast.

6.3 Arena Cove

Gauge detiding

We began by detiding the Arena Cove station 9416841 60 second data that was provided by PMEL in the file **20121028-arena-cove-ca-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 105 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red, and the location of the detided maximum amplitude in magenta. Figure 106 shows a blowup from 2 to 10 hours post quake.

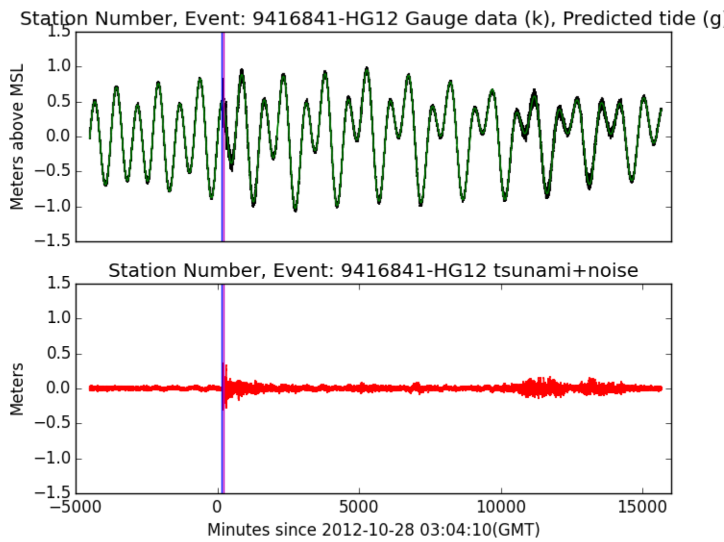

Figure 105: HG 2012, Arena Cove, DeTided Tsunami

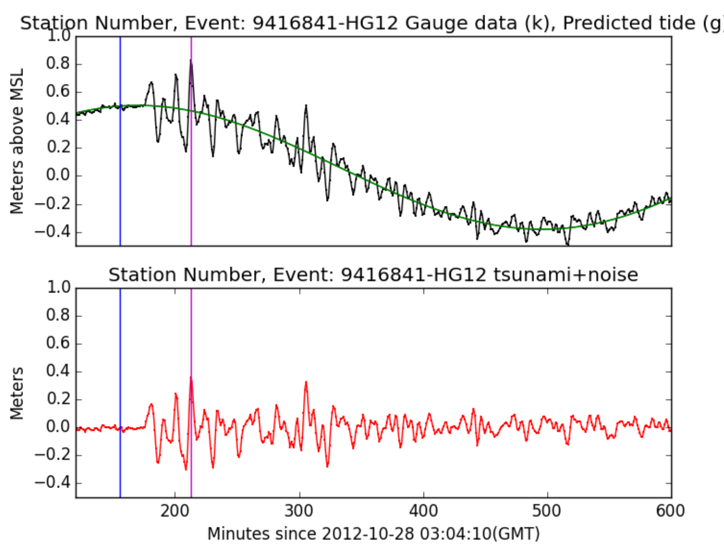

Figure 106: HG 2012, Arena Cove, DeTided Tsunami, 2-10 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -100 longitude, -41 to 65 latitude.

Around the source, we put a one minute topo grid and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -136 to -129 longitude and 50 to 55 latitude. Across the ocean, we used the adjoint method to automatically flag cells for refinement, only flagging the waves that would arrive at Arena Cove Harbor between 2 and 10 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed 24 minute (Level 2), 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Arena Cove, we used 1min (Level 4), 12sec (Level 5), 6sec (Level 6), 2sec (Level 7), and 1sec (Level 8) grids. The 1sec grid was the same as PMEL's C grid. The 1 min grid was an extension of PMEL's A grid, the 12 sec grids were extensions of PMEL's B grid, the 6sec grid was inside PMEL's B grid, and the 2sec grid was somewhat larger than PMEL's C grid. The specifics of the 8 regions used are given below. The first two numbers are the minimum and maximum levels allowed, the next two numbers are the start and ending time in seconds for the region, and the last four numbers are the longitude and latitudes that describe the rectangular region.

```
8                    =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -136  -129  50  55
4  4  3600  1e+09  -135  -120  32  46
5  5  5400  1e+09  -124.65  -123.065  38.35  39.8
5  5  5400  1e+09  -124.65  -123.835  39.8  46
6  6  7200  1e+09  -124.43  -123.43  38.4  39.4
7  7  7200  1e+09  -123.85  -123.651  38.845  39.0445
8  8  7200  1e+09  -123.78  -123.685  38.89  39.02
```

The topo files we used that supported this computation were:

```
etopo1_-180_-100_-41_65_1min.tt3
etopo1_-240_-180_-41_65_1min.tt3
arena_cove_6sec.asc
arena_cove_1sec.asc
arena_cove_2sec.asc
arena_cove_Port_onethird.asc
cca_12s_mhw_v2.asc
```

We used one GeoClaw computational gauge, called Gauge 0, as depicted in Figure 27. Gauge 0 was close to the MOST gauge, given in the file **arenacovetimeseriesC.txt** as having location (-123.71111, 38.91458). In a picture, it wouldn't be distinguished from Gauge 0. Gauge 0 was turned on at 2.25 hours post-quake and has location given below:

```
rundata.gaugedata.gauges.append([0, -123.711097, 38.914646, 2.25*3600.,1.e10])
```

In Figure 107 we give comparison plots when GeoClaw used a 1sec resolution around the finest grid. The MOST max amplitude was 0.144m and came from a C grid of 2 second resolution in longitude and 1.5 second resolution in latitude. The detided max amplitude was 0.362m. The GeoClaw maximum was 0.122m. The Bathymetry used by GeoClaw at Gauge 0 was -3.495m.

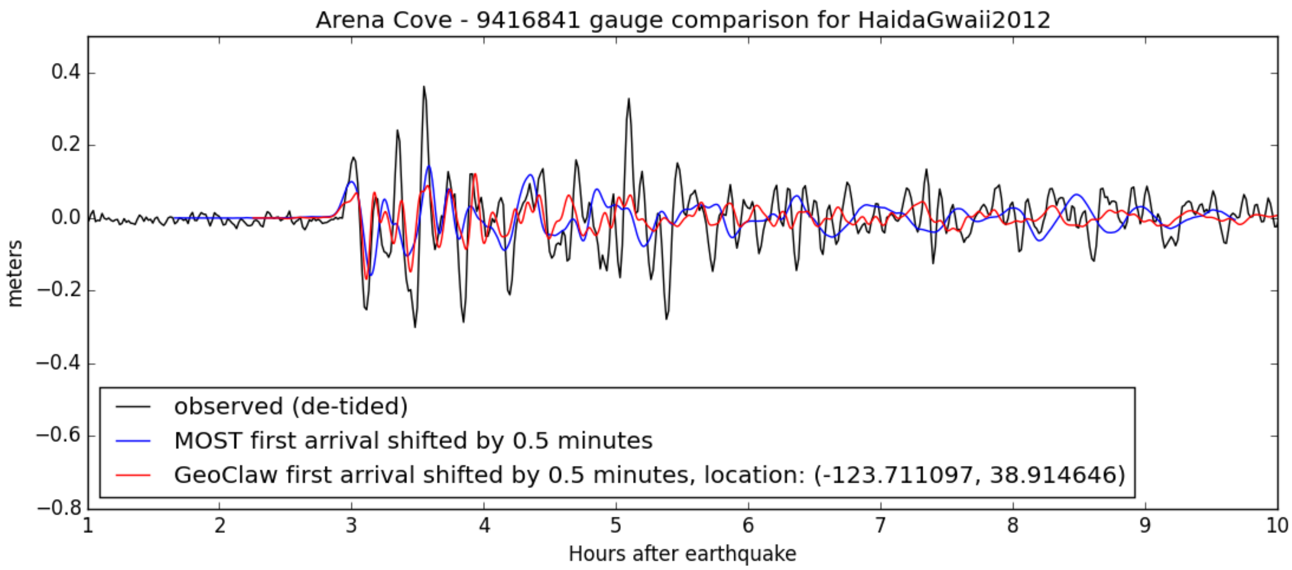

Figure 107: HG 2012, Arena Cove, 1sec, Gauge 0

Discussion:

This was a small tsunami. The GeoClaw and MOST tsunamis compare fairly well. Neither capture the gauge's waves of amplitude around 0.4 meters. We actually did an additional GeoClaw run with 1/3sec resolution around the Harbor and extended the region of 12 minute and 1 minute refinements, but this made no difference in the wave train and the GeoClaw maximum amplitude. This tells us that more resolution along the coastal area would be necessary to determine the actual amplitude of these waves since the Haidi Gwaii tsuanmi hugs the coastal area from source to destination and at the moment we only used at most 12 second resolution in the extended Level 5 grids, and at most 1 minute resolution outside these Level 5 grids along the coast.

6.4 Port Orford

Gauge detiding

We began by detiding the Port Orford station 9431647 60 second data that was provided by PMEL in the file **20121028-port-orford-or-60.csv**. The process we used is described in detail in Appendix A. Here we simply give two plots showing the result of this process. Figure 108 shows the original data in black, the part to be subtracted off in green (tidal component plus a slow adjustment), the tsunami in red and the location of the maximum detided amplitude in magenta. Figure 109 shows a blowup from 1.5 to 8.5 hours post quake.

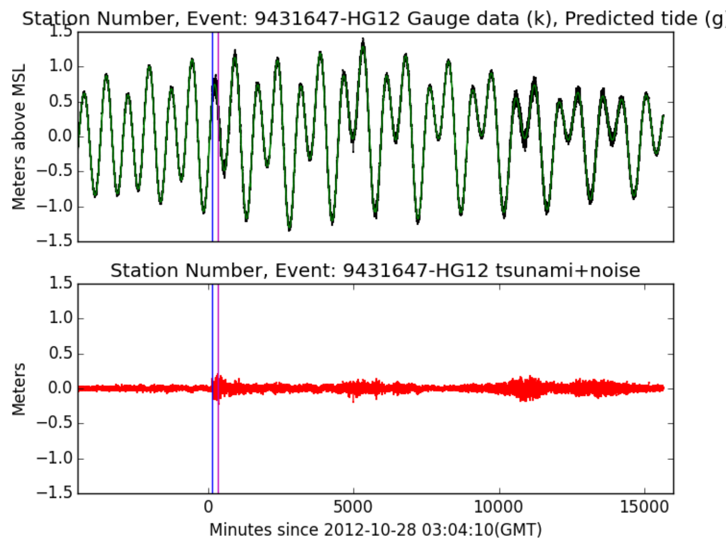

Figure 108: HG 2012, Port Orford, DeTided Tsunami

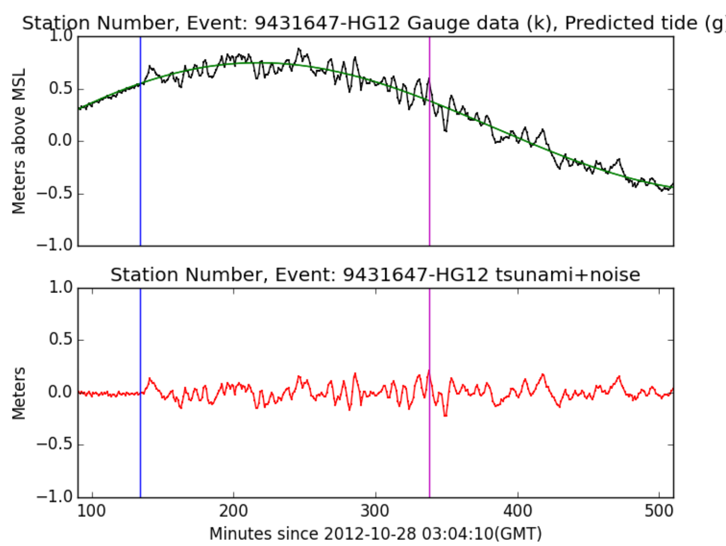

Figure 109: HG 2012, Port Orford, DeTided Tsunami, 1.5-8.5 hrs. post quake

Tsunami comparisons

GeoClaw's computational domain was the rectangle -240 to -66 longitude, -47 to 65 latitude. This is definitely larger than necessary, but the adjoint method will only allow refinement as described below.

Around the source, we used one minute topo and computed with one minute resolution (level 4) for 1 hour (3600 sec) from -136 to -129 longitude and 50 to 55 latitude.

Across the ocean, we used the adjoint-GeoClaw method to automatically flag cells for refinement, only flagging the waves that would arrive at Port Orford between 1.5 and 8.5 hours post-quake. We required a minimum of 2 degree resolution (Level 1), but allowed for 24 minute (Level 2) and 4 minute (Level 3) up to a maximum of 1 minute (Level 4) resolution everywhere in our computational grid for the entire computation.

Around Port Orford, we required 1 minute (Level 4), 12 second (Level 5), and 1sec (Level 6) resolution on the A, B, and C grids, respectively. The region specifics for the 5 regions we used for this run are given below. The first two numbers are the minimum and maximum levels allowed. The third and fourth numbers are are the times in seconds post-quake when the region is turned on and off. The last four numbers are the longitude and latitude limits of the rectangular region.

```
5                   =: num_regions
1  4  0  1e+09  -360  0  -90  90
4  4  0  3600  -136  -129  50  55
4  4  3600  1e+09  -127.5  -123.5  39.01  47.19
5  5  5400  1e+09  -124.933  -124.27  42.0683  43.265
6  6  7200  1e+09  -124.551  -124.44  42.6715  42.7732
```

The topography files that supported the 1sec run are given below:

```
etopo1_-240_-180_-47_65_1min.tt3
etopo1_-180_-66_-47_65_1min.tt3
PortOrford_1sec.asc
PortOrfordHarbor.asc
```

We used one GeoClaw computational gauge called Gauge 0. This gauge was the same as the MOST computational gauge reported in the file **porfordtimeseriesC.txt** and depicted in Figure 31. Gauge 0 was turned on at 2 hours post-quake and had location as given below:

```
rundata.gaugedata.gauges.append([0, -124.49767, 42.73876, 2.0*3600, 1.e10])
```

The comparison plots for Gauge 0 are in Figure 110 for this 1sec run. The MOST max amplitude was 0.14m and came from a C grid of 2 second resolution. The detided max amplitude was 0.21m. The GeoClaw max amplitude was 0.07m. The bathymetry at the gauge used by GeoClaw was -3.96m.

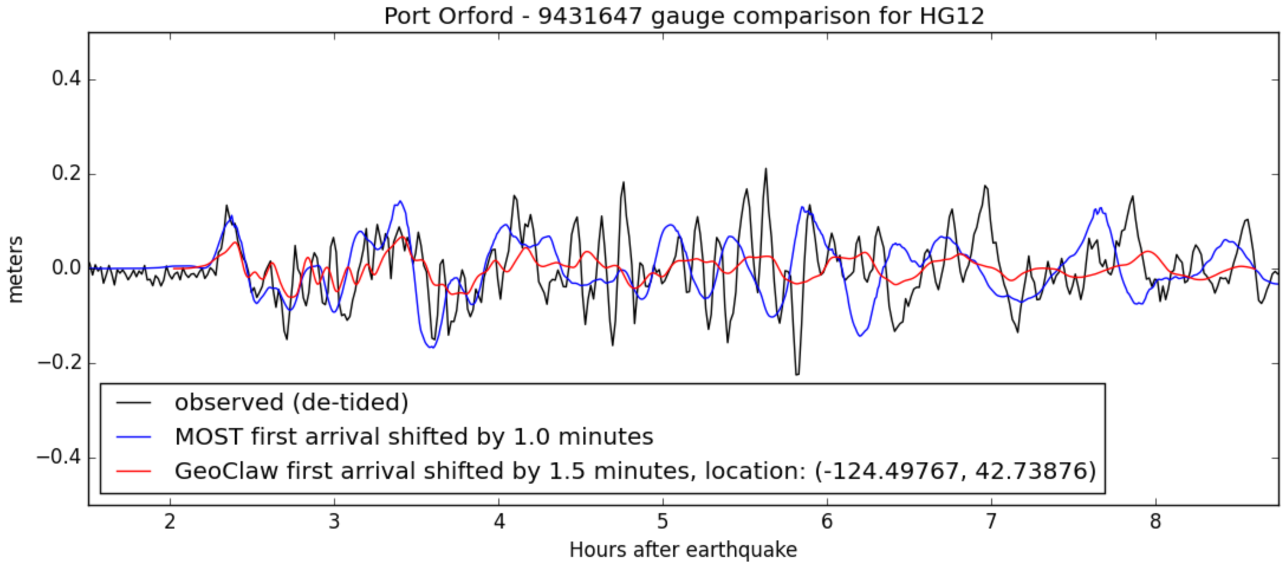

Figure 110: HG 2012, Port Orford, 1sec

Discussion:

The first few waves are captured fairly well by both MOST and GeoClaw, but later waves are not. This tsunami was a very small one, so it is not clear how reliable any conclusions about model results would be in this case. We note that MOST used 2sec and GeoClaw 1sec calculation around Port Orford's C grid. We also ran GeoClaw using 1/3sec around the Port Orford harbor with larger computational regions for the 1min and 12sec calculations and an additional 6sec region with the results of a nearly identical wave train as the GeoClaw 1sec result plotted above. Since the HG12 tsunami hugs the coast, it might be necessary to use more accurate topography and calculations around the coast from the source to the destination. At the moment, only 12sec calculation is used around the B grid in the vicinity of Port Orford.

References

[1] M. J. Berger, D. L. George, R. J. LeVeque, and K. T. Mandli. The geoclaw software for depth-averaged flows with adaptive refinement. Preprint and simulations: `www.clawpack.org/links/papers/awr10`, 2010.

[2] S. Cox. Pytides. http://github.com/sam-cox/pytides, 2013.

[3] B. N. Davis and R. J. LeVeque. Adjoint methods for guiding adaptive mesh refinement in tsunami modeling. *Pure Appl. Geophys.*, 173:4055–4074, 2016.

[4] F. González, R. J. LeVeque, J. Varkovitzky, P. Chamberlain, B. Hirai, and D. L. George. GeoClaw Results for the NTHMP Tsunami Benchmark Problems. http://depts.washington.edu/clawpack/links/nthmp-benchmarks/geoclaw-results.pdf, 2011.

[5] R. J. LeVeque, D. L. George, and M. J. Berger. Tsunami modeling with adaptively refined finite volume methods. *Acta Numerica*, pages 211–289, 2011.

[6] Proceedings and results of the 2011 NTHMP Model Benchmarking Workshop. U.S. Department of Commerce/ NOAA/NTHMP; (NOAA Special Report). 436 p., http://nthmp.tsunami.gov/documents/nthmpWorkshopProcMerged.pdf, 2011.

[7] V. V. Titov and F. Gonzales. Implementation and testing of the method of splitting tsunamis (MOST) model. NOAA Tech. Memo. ERL PMEL-112, 1997.

A De-Tiding

For each tide gauge, we were given the gauge data and a .png file that shows the de-tided tsunami that PMEL produced, including the date and time of the maximum amplitude, but were not given the time series of the detided tsunami that was plotted; hence, we detided the gauges ourselves. We carefully compared the time and maximum amplitude we obtained to that produced by PMEL. In most cases, we agree with the date-time of the maximum amplitude, and with the maximum amplitude PMEL produced and for the tide gauges used in this report, we give these numbers in Section A.2. In Section A.1 below, we describe the method we used to detide the gauges.

A.1 De-Tiding Method

The given gauge data (often referenced to MLLW or to some other datum) was referenced to MSL and plotted and compared to that given on the NOAA website to make sure we were dealing with the correct gauge. Once this checked out, a two-step detiding process was implemented using the MSL-referenced gauge data.

Step 1: Use the harmonic constituents

All the gauges in this report were harmonic gauges; hence, we could easily use the harmonic constituents as published on NOAA's website for each gauge. We used the **Pytides** python code [2] to evaluate the tide for the times in the gauge data. We also used **Pytides** to evaluate the tide for equally spaced times that spanned the gauge data, since often data times would be missing. The constituents used were the 37 NOAA constituents. The tide produced was then compared to the "predicted" tide seen on the NOAA website for reasonableness, especially in cases were it missed the observed data somewhat. This pytides "predicted" tide was then subtracted from the MSL-referenced gauge data to produce the pytides-noaa tsunami plus a remainder. We now proceeded to Step 2.

Step 2: Fit the remainder with a piecewise slow component

Since the predicted tide will often miss fitting the slowly varying observed data even in regions where there is no tsunami, it is necessary to correct for these effects. So, the remainder from Step 1 was fit with a piecewise 15-degree polynominal. Each 15-degree polynominal spanned 72 hours (a degree of 15 was sufficient for the max and min that could happen in this time frame for the slowly varying part of the remainder). The region (-48hr, 24hr] (0hr is the time of the quake) always used the same polynominal. Then (-120hr, 48hr] and (24hr, 96hr] used separate polynominals, etc. until the time span of the data was covered. This piecewise polynominal fit (slow) was then subtracted from the pytides-noaa tsunami that resulted from Step 1, and was added to the "predicted" tide from Step 1 to get the final tidal component that is plotted in green in Figures 115 and 116 and the final tsunami that is plotted in red.

The process is illustrated in pictures below for the Japan2011 - Port Orford 9431647 tide gauge. Figure 111 shows the original tide gauge data. Figure 112 shows the tide gauge data referenced to MSL.

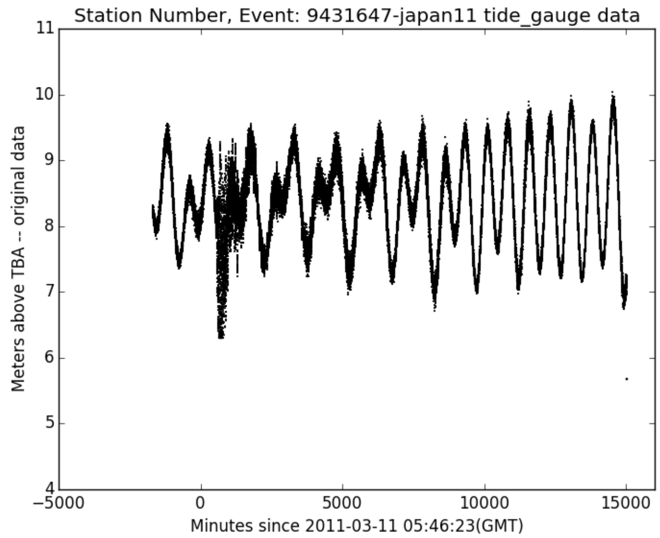

Figure 111: Japan2011, Port Orford, Gauge 9431647 data

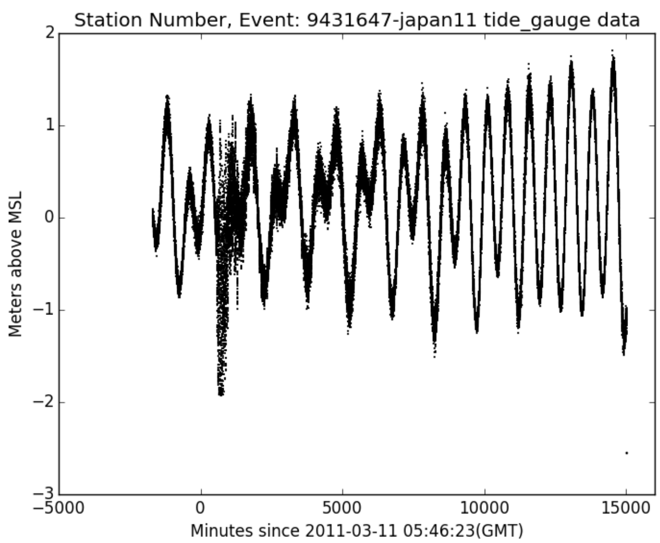

Figure 112: Japan2011, Port Orford, Gauge 9431647 MSL data

Figures 113 and 114 show the Pytides "predicted" tide from the harmonic constituents and the pytides-noaa tsunami that would result if we stopped after Step 1.

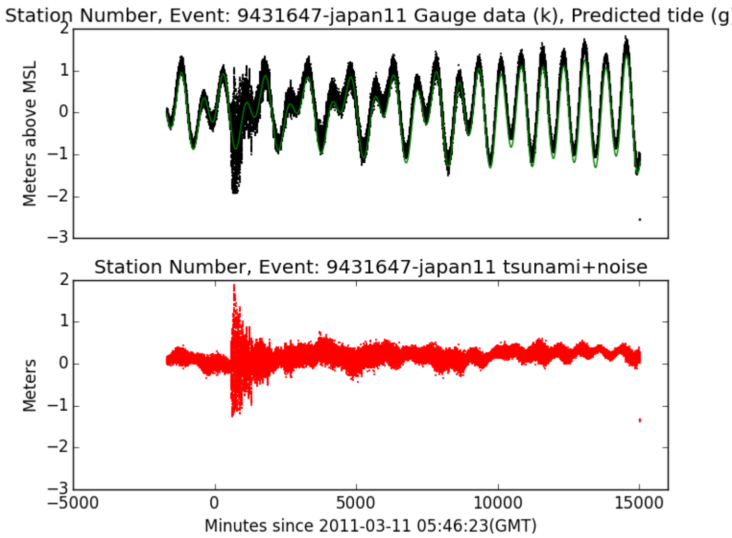

Figure 113: Japan2011, Port Orford, Pytide Predicted Tsunami

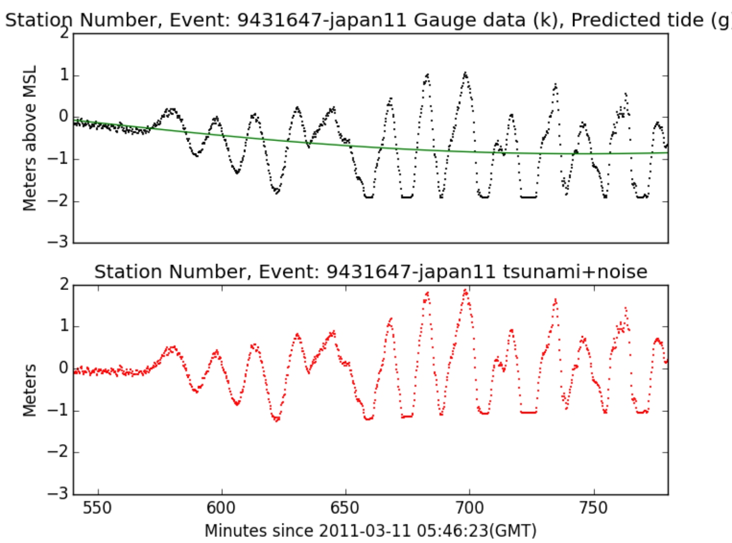

Figure 114: Japan2011, Port Orford, Pytide Predicted Tsunami

Figures 115 and 116 show the final accepted tsunami and final accepted tide after the slow component has been subtracted and are identical to Figures 29 and 30. We note that no attempt was made to subtract out any faster varying noise from the pre-tsunami region, nor any faster varying noise from the tsunami region. We note that noise that is present can be amplified by the tsunami and would not be captured by either MOST or GeoClaw.

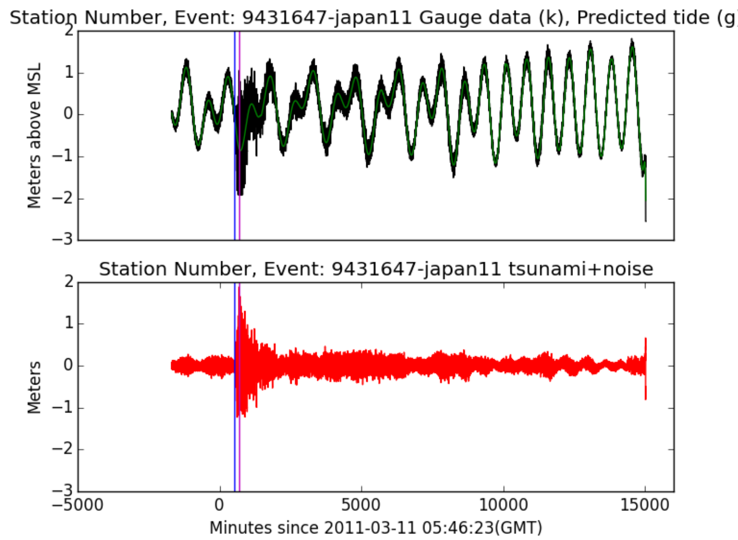

Figure 115: Japan2011, Port Orford, Final DeTided Tsunami

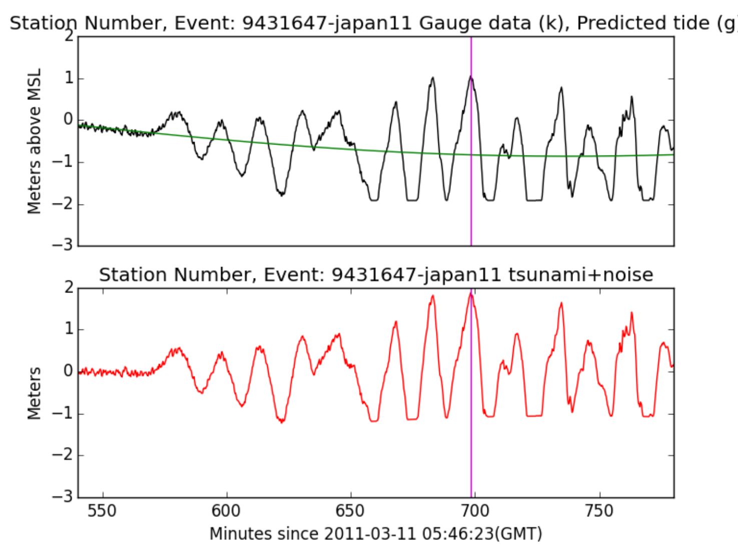

Figure 116: Japan2011, Port Orford, Final DeTided Tsunami

A.2 De-Tiding comparisons

In the sections below, we give the maximum de-tided tsunami amplitude and its time obtained by our detiding method and that found by PMEL for the indicated event and tide gauge.

A.2.1 Japan 2011 De-Tiding comparisons

Japan 2011 - Hilo

```
station_number:  1617760
tidegaugecsv:  20110311_hilo-hi_15.csv
event_datetime:  2011-03-11 05:46:23
prediction_t0:  2011-03-05 00:00:14
prediction_end:  2011-03-11 18:16:44
PMEL used arrival_datetime:  2011-03-11 13:27:44
Max_Amplitude_datetime:  2011-03-11 14:29:29
Max_Amp occurred post quake in sec=  31386, min=  523.10, hr=    8.72
Max Amplitude (PMEL) : 1.2728 m
Max Amplitude (UW): 1.2691 m
```

Japan 2011 - Crescent City

```
station_number=9419750
tidegaugecsv='20110311_crescent-city-ca_15.csv'
event_datetime=datetime(2011,3,11,5,46,23)
prediction_t0 = datetime(2011,3,5,0,0,0)
prediction_end= datetime(2011,3,21,20,32,15)
arrival_datetime=datetime(2011,3,11,14,57,45)
Max_Amplitude_datetime=datetime(2011,3,11,16,57,45)
Max Amplitude post event: 40282 sec = 671.36 min = 11.19 hr
Max Amplitude (PMEL) : 2.536   m
Max Amplitude (UW): 2.463   m
```

Japan 2011 - Port Orford

```
station_number=9431647
tidegaugecsv='20110311_port-orford-or_15.csv'
event_datetime=datetime(2011,3,11,5,46,23)
prediction_t0 = datetime(2011,3,10,1,48,15)
prediction_end= datetime(2011,3,21,16,5,30)
arrival_datetime=datetime(2011,3,11,14,35,30)
Max_Amplitude_datetime=datetime(2011,3,11,17,24,45)
Max Amplitude post event: 41902 sec = 698.36 min = 11.64 hr
Max Amplitude (PMEL) : 1.8486 m
Max Amplitude (UW): 1.884  m
```

Japan 2011 - Arena Cove

```
station_number=9416841
tidegaugecsv='20110311_arena-cove-ca_60.csv'
event_datetime=datetime(2011,3,11,5,46,23)
prediction_t0 = datetime(2011,3,5,0,0,0)
prediction_end= datetime(2011,3,22,23,59,0)
arrival_datetime=datetime(2011,3,11,15,7,0)
Max_Amplitude_datetime=datetime(2011,3,11,17,50,0)
Max Amplitude post event: 43417 sec = 723.62 min = 12.06 hr
Max Amplitude (PMEL) : 1.728  m
Max Amplitude (UW): 1.704  m
```

Japan 2011 - Midway

```
station_number=1619910
tidegaugecsv='20110311_sand-island-midway-islands_15.csv'
event_datetime=datetime(2011,3,11,5,46,23)
prediction_t0 = datetime(2011,3,5,0,0,0)
prediction_end= datetime(2011,3,20,23,54,0)
arrival_datetime=datetime(2011,3,11,9,5,30)
Max_Amplitude_datetime=datetime(2011,3,11,10,48,30)
Max Amplitude post event: 18127 sec = 302.11 min = 5.03 hr
Max Amplitude (PMEL) : 1.5607 m
Max Amplitude (UW): 1.709 m
```

A.2.2 Samoa 2009 De-Tiding comparisons

Samoa2009 - Hilo

```
station_number=1617760
tidegaugecsv='20090929_hilo-hi_60.csv'
event_datetime=datetime(2009,9,29,17,48,10)
prediction_t0 = datetime(2009,9,26,0,0,0)
prediction_end= datetime(2009,10,9,17,33,0)
arrival_datetime=datetime(2009,9,29,23,51,0)
Max_Amplitude_datetime=datetime(2009,9,30,0,21,0)
Max Amplitude post event: 23570 sec = 392.83 min = 6.54 hr
Max Amplitude (PMEL) : 0.1797    m
Max Amplitude (UW): 0.182     m
```

Samoa2009 - Crescent City

```
station_number=9419750
tidegaugecsv='20090929_crescent-city-ca_60.csv'
event_datetime=datetime(2009,9,29,17,48,10)
prediction_t0 = datetime(2009,9,26,0,1,0)
prediction_end= datetime(2009,10,9,17,17,0)
arrival_datetime=datetime(2009,9,30,4,6,0)
Max_Amplitude_datetime=datetime(2009,9,30,8,10,0)
Max Amplitude post event: 51710 sec = 861.83 min = 14.36 hr
Max Amplitude (PMEL) : 0.3192  m
Max Amplitude (UW): 0.3277  m
```

Samoa2009 - Port Orford

```
station_number=9431647
tidegaugecsv='20090929_port-orford-or_60.csv'
event_datetime=datetime(2009,9,29,17,48,10)
prediction_t0 = datetime(2009,9,26,0,0,0)
prediction_end= datetime(2009,10,9,19,22,0)
arrival_datetime=datetime(2009,9,30,3,59,0)
Max_Amplitude_datetime=datetime(2009,9,30,9,31,0)
Max Amplitude post event: 56570 sec = 942.83 min = 15.71 hr
Max Amplitude (PMEL) : 0.19691 m
Max Amplitude (UW): 0.20156 m
```

Samoa2009 - Arena Cove

```
station_number=9416841
tidegaugecsv='20090929_arena-cove-ca_60.csv'
event_datetime=datetime(2009,9,29,17,48,10)
prediction_t0 = datetime(2009,9,26,0,0,0)
prediction_end= datetime(2009,10,9,23,59,0)
arrival_datetime=datetime(2009,9,30,3,29,0)
Max_Amplitude_datetime=datetime(2009,9,30,6,24,0)
Max Amplitude post event: 45350 sec = 755.83 min = 12.60 hr
Max Amplitude (PMEL) : 0.4784  m
Max Amplitude (UW): 0.475   m
```

Samoa2009 - Midway Island

```
station_number=1619910
tidegaugecsv='20090929_sand-island-midway-islands_60.csv'
event_datetime=datetime(2009,9,29,17,48,10)
prediction_t0 = datetime(2009,9,26,0,0,0)
prediction_end= datetime(2009,10,9,18,1,0)
arrival_datetime=datetime(2009,9,29,23,23,0)
Max_Amplitude_datetime=datetime(2009,9,30,1,26,0)
Max Amplitude post event: 27470 sec = 457.83 min = 7.63 hr
Max Amplitude (PMEL) : 0.213 m
Max Amplitude (UW): 0.203 m
```

Samoa2009 - Pago Pago

```
station_number=1770000
tidegaugecsv='20090929_pago-pago_15.csv'
event_datetime=datetime(2009,9,29,17,48,10)
prediction_t0 = datetime(2009,9,26,0,0,0)
prediction_end= datetime(2009,10,6,20,35,45)
arrival_datetime=datetime(2009,9,29,17,44,45)
Max_Amplitude_datetime=datetime(2009,9,29,18,16,45)
Max Amplitude post event: 1715 sec =28.6 min = .476 hr
Max Amplitude (PMEL) : 2.7315 m
Max Amplitude (UW): 2.7436 m
```

A.2.3 Chile 2010 De-Tiding comparisons

Chile 2010 - Hilo

```
tidegaugecsv='20100227_hilo-hi_15.csv'
event_datetime=datetime(2010,2,27,6,34,14)
prediction_t0 = datetime(2010,2,23,0,0,0)
prediction_end= datetime(2010,3,15,20,1,0)
arrival_datetime=datetime(2010,2,27,20,19,15)
Max_Amplitude_datetime=datetime(2010,2,27,21,26,45)
Max Amplitude post event: 53551 sec = 892.52 min = 14.88 hr
Max Amplitude (PMEL) : 0.74    m
Max Amplitude (UW): 0.744   m
```

Chile 2010 - Crescent City

```
station_number=9419750
tidegaugecsv='20100227_crescent-city-ca_15.csv'
event_datetime=datetime(2010,2,27,6,34,14)
prediction_t0 = datetime(2010,2,24,0,0,0)
prediction_end= datetime(2010,3,22,0,0,0)
arrival_datetime=datetime(2010,2,27,20,41,45)
Max_Amplitude_datetime=datetime(2010,2,28,4,15,0)
Max Amplitude post event:  78046 sec = 1300.76 min = 21.68 hr
Max Amplitude (PMEL) : 0.740    m
Max Amplitude (UW): 0.6883   m
```

Chile 2010 - Arena Cove

```
station_number=9416841
tidegaugecsv='20100227_arena-cove-ca_15.csv'
event_datetime=datetime(2010,2,27,6,34,14)
prediction_t0 = datetime(2010,2,23,0,0,0)
prediction_end= datetime(2010,3,22,0,0,0)
arrival_datetime=datetime(2010,2,27,11,53,0)
Max_Amplitude_datetime=datetime(2010,3,2,20,13,0)
Max Amplitude post event: 308326 sec = 5138.76 min = 85.65 hr
Max Amplitude (PMEL) : 0.6914   m
Max Amplitude (UW): 0.688    m
Note: UW also gets amp=.4658 m at datetime(2010,2,27,21,4,30)
      which is 52216 sec = 870.26 min = 14.5 hrs post quake
```

Chile 2010 - Port Orford

```
station_number=9431647
tidegaugecsv='20100227_port-orford-or_15.csv'
event_datetime=datetime(2010,2,27,6,34,14)
prediction_t0 = datetime(2010,2,23,0,0,0)
prediction_end= datetime(2010,3,22,0,0,0)
arrival_datetime=datetime(2010,2,27,14,3,45)
Max_Amplitude_datetime=datetime(2010,2,28,5,53,15)
Max Amplitude post event: 83941 sec = 1399.02 min = 23.32 hr
Max Amplitude (PMEL) : 0.45185 m
Max Amplitude (UW): 0.45537 m
```

A.2.4 Kuril 2007 De-Tiding comparisons

Kuril 2007 - Crescent City

```
station_number=1617760
tidegaugecsv='20070113_hilo-hi_60.csv'
event_datetime=datetime(2007,1,13,4,23,36)
prediction_t0 = datetime(2007,1,10,0,0,0)
prediction_end= datetime(2007,1,23,23,59,0)
arrival_datetime=datetime(2007,1,13,10,53,0)
Max_Amplitude_datetime=datetime(2007,1,13,11,48,0)
Max Amplitude post event: 26664 sec = 444.4 min = 7.41 hr
Max Amplitude (PMEL) : 0.096      m
Max Amplitude (UW): 0.095      m
```

Kuril 2007 - Crescent City

```
station_number=9419750
tidegaugecsv='20070113_crescent-city-ca_60.csv'
event_datetime=datetime(2007,1,13,4,23,36)
prediction_t0 = datetime(2007,1,10,0,0,0)
prediction_end= datetime(2007,1,23,23,59,0)
arrival_datetime=datetime(2007,1,13,12,52,0)
Max_Amplitude_datetime=datetime(2007,1,13,16,26,0)
Max Amplitude post event: 43344 sec = 722.4 min = 12.04 hr
Max Amplitude (PMEL) : 0.2522 m
Max Amplitude (UW): 0.24   m
```

Kuril 2007 - Arena Cove

```
station_number=9416841
tidegaugecsv='20070113_arena-cove-ca_60.csv'
event_datetime=datetime(2007,1,13,4,23,36)
prediction_t0 = datetime(2007,1,10,0,0,0)
prediction_end= datetime(2007,1,23,23,59,0)
arrival_datetime=datetime(2007,1,13,11,44,0)
Max_Amplitude_datetime=datetime(2007,1,13,16,1,0)
Max Amplitude post event: 41844 sec = 697.4 min = 11.62 hr
Max Amplitude (PMEL) : 0.2126 m
Max Amplitude (UW): 0.1895   m
Note:  UW gets amp=.2142 at datetime(2007,1,13,22,49,0) which is
       66324 sec = 1105.4 min = 18.42 hr post quake.  There are a lot
       of similar sized waves. UW also gets amp=.196 at
       datetime(2007,1,13,13,50,0) which is post  33984 sec = 566.4 min = 9.44 hr
```

Kuril 2007 - Port Orford

```
station_number=9431647
tidegaugecsv='20070113_port-orford-or_60.csv'
event_datetime=datetime(2007,1,13,4,23,36)
prediction_t0 = datetime(2007,1,10,0,0,0)
prediction_end= datetime(2007,1,23,23,59,0)
arrival_datetime=datetime(2007,1,13,10,31,0)
Max_Amplitude_datetime=datetime(2007,1,13,13,35,0)
Max Amplitude post event: 33084 sec = 551.4 min = 9.19 hr
Max Amplitude (PMEL) : 0.19257 m
Max Amplitude (UW): 0.20424 m
```

A.2.5 Haida Gwaii 2012 De-Tiding comparisons

HG12 - Hilo

```
station_number=1617760
tidegaugecsv='20121028_hilo-hi_60.csv'
event_datetime=datetime(2012,10,28,3,4,10)
prediction_t0 = datetime(2012,10,25,0,0,0)
prediction_end= datetime(2012,11,7,23,59,0)
arrival_datetime=datetime(2012,10,28,7,56,0)
Max_Amplitude_datetime=datetime(2012,10,28,10,11,0)
Max Amplitude post event: 25610 sec = 426.83 min = 7.113 hr
Max Amplitude (PMEL) : 0.29    m
Max Amplitude (UW): 0.271   m
```

HG12 - Crescent City

```
station_number=9419750
tidegaugecsv='20121028_crescent-city-ca_15.csv
event_datetime=datetime(2012,10,28,3,4,10)
prediction_t0 = datetime(2012,10,25,0,0,0)
prediction_end= datetime(2012,11,7,23,59,45)
arrival_datetime=datetime(2012,10,28,4,54,45)
Max_Amplitude_datetime=datetime(2012,10,28,9,15,0)
Max Amplitude post event:  22250 sec = 370 min = 6.18 hr
Max Amplitude (PMEL) : 0.465   m
Max Amplitude (UW): 0.469   m
```

HG12 - Arena Cove

```
station_number=9416841
tidegaugecsv='20121028_arena-cove-ca_60.csv'
event_datetime=datetime(2012,10,28,3,4,10)
prediction_t0 = datetime(2012,10,25,0,0,0)
prediction_end= datetime(2012,11,7,23,59,0)
arrival_datetime=datetime(2012,10,28,5,40,0)
Max_Amplitude_datetime=datetime(2012,10,28,6,37,0)
Max Amplitude post event: 12770 sec = 212.83 min = 3.55 hr
Max Amplitude (PMEL) : 0.3737 m
Max Amplitude (UW): 0.3618 m
```

HG12 - Port Orford

```
station_number=9431647
tidegaugecsv='20121028_port-orford-or_60.csv'
event_datetime=datetime(2012,10,28,3,4,10)
prediction_t0 = datetime(2012,10,25,0,0,0)
prediction_end= datetime(2012,11,7,23,59,0)
arrival_datetime=datetime(2012,10,28,5,18,0)
Max_Amplitude_datetime=datetime(2012,10,28,8,42,0)
Max Amplitude post event: 20270 sec = 337.83 min = 5.63 hr
Max Amplitude (PMEL) : 0.20898 m
Max Amplitude (UW): 0.21169 m
```

B Timing

In this section we give information about 11 sample GeoClaw run times for various source-destination pairs. In particular, the 11 runs we chose are given in Figure 117 below.

SOURCE-DESTINATION	GeoClaw (max,m.)	(C-res)	(O-res)	(S-res)
Japan11-CrescentCity	2.41	1/3s	2deg-4min	4min
Japan11-Midway	2.17	1/3s	2deg-1min	1min
Japan11-PortOrford	1.84	2s	2deg-4min	4min
Samoa09-CrescentCity	0.16	1s	2deg-1min**	1min
Samoa09-ArenaCove	0.44	1s	2deg-1min**	1min
Samoa09-PortOrford	0.15	1s	2deg-1min**	1min
Samoa09-Midway Island	0.31	1s	2deg-1min**	1min
Samoa09-PagoPago	2.26	1/3s	2deg-1min	1min
HG12-Hilo	0.31	1s	2deg-1min**	1min
Kuril07-CrescentCity	0.16	1s	2deg-4min**	1min
Chile10-ArenaCove	0.19	1s	2deg-4min**	1min

** -- GeoClaw used the GeoClaw-adjoint method

Figure 117: 11 sample source-destinations for timing results

The Japan 2011 runs in Sections B.1, B.2 and B.3 were done on a laptop with 4 threads as the sole job running on the machine. Hence, the Wall Clock time has some meaning (unless the laptop was sleeping for some time), and statements can be made about the parallelism seen and the job time required in addition to statements about the amount of serial work (across all threads) for each of the GeoClaw levels of refinement. In the remaining Sections B.4 to B.11, the runs were done on a University of Washington larger computer using 6 threads, but shared with other users. In these cases, the Wall Clock time has no meaning (sometimes it is more than the total serial time across the 6 threads when other users have more access to the machine), and we can only make statements about the amount of serial work that is required in various parts of GeoClaw refinement and regridding overhead. This is still useful, as it points to areas for improvement.

B.1 Japan2011 - Crescent City

In this section we give the timing results for the two methods of flagging for region refinement using the Japan 2011 tsunami with destination Crescent City. In Section B.1.1 we give results for the 1/3sec run reported in Section 2.3. This run gave a maximum amplitude of 2.41m, only used a 1/3sec topography file around the destination, and used the wave tolerance flagging method.

In Section B.1.2, we give timing results for another 1/3sec run that also used wave tolerance flagging. This run used the same topography files as those in Section B.1.1 with the addition of a 1sec topography file that supported a larger 1sec computational region. The maximum amplitude for this job run was 2.32m.

In Section B.1.3, we give timing results for the same 1/3 run of Section B.1.2 with the only change being adjoint flagging instead of wave tolerance flagging. The maximum amplitude for this job run was also 2.32m.

B.1.1 Wave tolerance flagging: 1/3sec run

The following is for the 1/3sec GeoClaw run reported in Section 2.3 that used up to 4 minute resolution across the ocean. Adjoint flagging was not used. Instead a wave tolerance of 0.005 was used to flag cells for refinement. This run was for 0-13 hours post quake. The A-grid around Crescent City that used 1 minute calculations was turned on at 8 hours post quake. This run was done on a laptop with this being the only job running.

These results show the percentage of the cpu work (over all threads) for each of the 7 levels. About 41% of the work was for Level 3 which was for the 4 minute calculation across the ocean. About 58.5% of the work was for the Level 4 (1 minute), Level 5 (12 sec), and Level 6 (1sec), and Level 7 (1/3sec) grids around Crescent City.

Also note that the amount of regridding work was only 2.7% of the work needed for step-grid (accounting for 0.12 hours of Wall Clock time using 4 threads), showing that the regridding based on the wave tolerance is efficient.

Finally, note that the speedup of the Wall Clock time over the CPU time by using 4 threads on the laptop was very good at 3.82. This is a fair comparison since only one user and only one job was running on the laptop for this timing. This job took 4.40 hours on the laptop using 4 threads.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level         Wall Time (sec)  CPU Time (sec) %CPU   Total Cell Updates
  1             5.494             9.113    0.02       0.444E+06
  2            65.731           235.651    0.40       0.358E+08
  3          6157.160         24129.574   40.99       0.612E+10
  4           299.670          1108.245    1.88       0.300E+09
  5           309.188          1104.833    1.88       0.333E+09
  6          3785.867         14400.539   24.46       0.474E+10
  7          4719.924         17874.652   30.37       0.479E+10
total        15343.034         58862.607              0.163E+11

All levels:
stepgrid            14874.853              57215.693
BC/ghost cells        448.352               1625.824
Regridding            437.323               1523.911
Output (valout)         7.220                  0.000

Total time:         15857.777              60566.757
Using  4 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above
=========================================================================

for level   1 average num. grids =       2.00 over          1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =      25.45 over         44 regridding steps
for level   2  current num. grids =      32
for level   3 average num. grids =    1238.74 over        254 regridding steps
for level   3  current num. grids =    2048
for level   4 average num. grids =      12.66 over       1514 regridding steps
```

```
for level   4  current num. grids =      32
for level   5 average num. grids =      10.44 over       2631 regridding steps
for level   5  current num. grids =      16
for level   6 average num. grids =      45.58 over       4347 regridding steps
for level   6  current num. grids =      64
for level   7 average num. grids =      43.99 over      21141 regridding steps
for level   7  current num. grids =      48


current  space usage =     48417860
maximum  space usage =     51968052
need space dimension =     51987796

number of cells advanced for time integration =   16317136956.000000
   # cells advanced on level    1 =           443520.00
   # cells advanced on level    2 =         35811000.00
   # cells advanced on level    3 =       6124561956.00
   # cells advanced on level    4 =        299994240.00
   # cells advanced on level    5 =        332560800.00
   # cells advanced on level    6 =       4737196800.00
   # cells advanced on level    7 =       4786568640.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =      3.14


 ------  end of AMRCLAW integration --------
```

B.1.2 Wave tolerance flagging: Additional 1/3sec run

The following is for an additional 1/3sec GeoClaw run (not described in 2.3) that used up to 4 minute resolution across the ocean, the same topography files as in Section 2.3 with the addition of a 1sec topography file that supported a larger 1sec computational region. In particular, the region specifications and the additional topography are given below.

```
8                    =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  3  0  46800  -360  0  0  90
3  3  0  25200  -231  -170  18  62
3  3  25200  1e+09  -170  -120  18  62
4  4  28800  1e+09  -126.995  -123.535  40.515  44.495
5  5  28800  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  30600  1e+09  -124.234  -124.143  41.7168  41.7829
7  7  31500  1e+09  -124.202  -124.18  41.733  41.752
cc-1sec-c.asc
```

Adjoint flagging was not used. Instead a wave tolerance of 0.005 was used to flag cells for refinement. This run was for 0-13 hours post quake. The A-grid around Crescent City that used 1 minute calculations was turned on at 8 hours post quake. This run was done on a laptop with this being the only job running.

These results show the percentage of the cpu work (over all threads) for each of the 7 levels. About 33.7% of the work was for Level 3 which was for the 4 minute calculation across the ocean. About 66% of the work was for the Level 4 (1 minute), Level 5 (12 sec), and Level 6 (1sec), and Level 7 (1/3sec) grids around Crescent City.

Also note that the amount of regridding work was only 6.5% of the work needed for step-grid (accounting for 0.34 hours of Wall Clock time using 4 threads), showing that the regridding based on the wave tolerance is pretty efficient.

Finally, note that the speedup of the Wall Clock time over the CPU time by using 4 threads on the laptop was very good at 3.74. This is a fair comparison since only one user and only one job was running on the laptop for this timing. This job took 5.77 hours on the laptop using 4 threads.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level        Wall Time (sec)  CPU Time (sec) %CPU   Total Cell Updates
  1             13.452          16.282     0.02       0.444E+06
  2             60.502         214.525     0.29       0.358E+08
  3           6371.659       24695.293    33.67       0.612E+10
  4            306.993        1129.909     1.54       0.300E+09
  5           1795.997        5856.090     7.99       0.333E+09
  6           5628.104       21473.107    29.28       0.724E+10
  7           5268.185       19951.964    27.21       0.516E+10
total        19444.892       73337.170                0.192E+11

All levels:
stepgrid            16896.299             64762.812
BC/ghost cells       2526.483              8550.664
Regridding           1237.473              4202.470
Output (valout)         6.850                 0.000

Total time:         20795.166             77711.281
Using  4 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================



for level   1 average num. grids =       2.00 over         1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =      25.45 over        44 regridding steps
for level   2  current num. grids =      32
for level   3 average num. grids =    1238.74 over       254 regridding steps
for level   3  current num. grids =    2048
for level   4 average num. grids =      12.66 over      1514 regridding steps
for level   4  current num. grids =      32
for level   5 average num. grids =      10.44 over      2631 regridding steps
for level   5  current num. grids =      16
for level   6 average num. grids =      51.28 over      4347 regridding steps
for level   6  current num. grids =      72
for level   7 average num. grids =      44.27 over     22710 regridding steps
```

```
for level   7  current num. grids =      48

current  space usage =     48874780
maximum  space usage =     52424972
need space dimension =     52446105

number of cells advanced for time integration =   19187058774.000000
   # cells advanced on level    1 =           443520.00
   # cells advanced on level    2 =         35811000.00
   # cells advanced on level    3 =       6124561956.00
   # cells advanced on level    4 =        299994240.00
   # cells advanced on level    5 =        332560800.00
   # cells advanced on level    6 =       7236459648.00
   # cells advanced on level    7 =       5157227610.00
number of cells advanced for error estimation =            0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =      3.23

 ------  end of AMRCLAW integration --------
```

B.1.3 Adjoint flagging: Additional 1/3sec run

The following is for the same 1/3sec GeoClaw run reported in B.1.2 that used up to 4 minute resolution across the ocean except that adjoint flagging was used to flag cells for refinement across the ocean that would impact the destination at Crescent City from 8 to 13 hours post-quake. The region statements were changed to the following:

```
7                    =: num_regions
1  1  0  1e+09  -360  0  -90  90
1  3  0  46800  -360  0  0  90
3  3  0  3600  -220  -214  35  42
4  4  28800  1e+09  -126.995  -123.535  40.515  44.495
5  5  28800  1e+09  -124.6  -124.05  41.5017  41.9983
6  6  30600  1e+09  -124.234  -124.143  41.7168  41.7829
7  7  31500  1e+09  -124.202  -124.18  41.733  41.752
```

This run was still for 0-13 hours post quake, and the A-grid around Crescent City that used 1 minute calculations was still turned on at 8 hours post quake. This run was done on a laptop with this being the only job running.

These results show the percentage of the cpu work (over all threads) for each of the 7 levels. About 9.98% of the work was for Level 3 which was for the 4 minute calculation across the ocean. This should be compared to the 33.7% that was used in the refinement regions (determined manually) to bring the waves properly to the Crescent City area. This shows a huge savings of the ocean calculations using the adjoint method – which only refines for the waves that will impact the destination during the 8 to 13 hours post-quake. About 89.7% of the work was for the Level 4 (1 minute), Level 5 (12 sec), and Level 6 (1sec), and Level 7 (1/3sec) grids around Crescent City, as compared to the 66% needed when wave tolerance flagging was used.

Also note that the amount of regridding work was 11.34% of the work needed for step-grid (accounting for 0.41 hours of Wall Clock time using 4 threads), showing that the regridding based on the adjoint method is more expensive than that based on the wave tolerance (which needed only 0.34 hours of Wall Clock time using 4 threads). This points to an area that needs improvement, especially when job runs require one minute calculation across the ocean which uses even more regridding.

Finally, note that the speedup of the Wall Clock time over the CPU time by using 4 threads on the laptop was very good at 3.67. This is a fair comparison since only one user and only one job was running on the laptop for this timing. This job took 4.315 hours on the laptop using 4 threads; whereas, the job that used wave tolerance flagging in Section B.1.2 took 5.77 hours. Once the regridding time for the adjoint method is fixed, the job time will decrease further.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level        Wall Time (sec)  CPU Time (sec) %CPU   Total Cell Updates
  1            13.345           16.179       0.03       0.444E+06
  2            65.327          152.836       0.30       0.120E+08
  3          1411.840         5121.841       9.98       0.115E+10
  4           259.845          950.234       1.85       0.263E+09
  5          1736.408         5632.220      10.97       0.323E+09
  6          5346.858        20215.984      39.38       0.691E+10
  7          5137.446        19247.423      37.49       0.505E+10
total        13971.069        51336.718                  0.137E+11

All levels:
stepgrid            11349.148              42898.220
BC/ghost cells       2602.523               8417.658
Regridding           1464.064               4865.459
Output (valout)         2.703                  0.000

Total time:         15534.968              56345.042
Using  4 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================


for level   1 average num. grids =      2.00 over         1 regridding steps
for level   1  current num. grids =      2
for level   2 average num. grids =     11.20 over        44 regridding steps
for level   2  current num. grids =      1
for level   3 average num. grids =    194.30 over       249 regridding steps
for level   3  current num. grids =      4
for level   4 average num. grids =     11.49 over      1317 regridding steps
for level   4  current num. grids =     32
for level   5 average num. grids =     10.26 over      2352 regridding steps
for level   5  current num. grids =     16
for level   6 average num. grids =     52.48 over      4175 regridding steps
for level   6  current num. grids =     72
for level   7 average num. grids =     44.51 over     21642 regridding steps
for level   7  current num. grids =     48
```

```
current  space usage =      4201784
maximum  space usage =     12466766
need space dimension =     12480594

number of cells advanced for time integration =   13710726216.000000
   # cells advanced on level    1 =           443520.00
   # cells advanced on level    2 =         11994600.00
   # cells advanced on level    3 =       1146552948.00
   # cells advanced on level    4 =        263381040.00
   # cells advanced on level    5 =        322773900.00
   # cells advanced on level    6 =       6913703808.00
   # cells advanced on level    7 =       5051876400.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       7.02


 ------  end of AMRCLAW integration --------
```

B.2 Japan2011 - Midway Island

The following is for the 1/3sec enhanced GeoClaw run reported in Section 2.6 that used up to 4 minute resolution across most of the ocean and 1 minute resolution in an enhanced region around Midway Island. This run was for 0-10 hours post quake. The adjoint method was not used. Instead, the wave tolerance of 0.005 was used to decide cell flagging for refinement in the variable regions. The A-grid around Midway Island was turned on at 3.5 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 7 levels. Only 7.47% of the work was in Level 3 (4 minute) for ocean calculation. Level 4 which was for the enhanced 1 minute region around Midway Island and the 1 minute A-grid around Midway required 27.82% of the work. Level 5 (6sec), Level 6 (1sec) and Level 7 (1/3 sec) together required about 64% of the work.

Also note that the amount of regridding work was only 3% of that required for the step-grid work. This points out that the wave tolerance flagging is very efficient.

Finally, note that the speedup of the Wall Clock time over the CPU time by using 4 threads on the laptop was very good at 3.84. This is a fair comparison since only one user and only one job was running on the laptop for this timing. This job took 13.43 hours on the laptop using 4 threads.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level     Wall Time (sec)    CPU Time (sec) %CPU     Total Cell Updates
  1         35.078              68.490     0.04          0.353E+06
  2        235.799             819.839     0.46          0.187E+08
  3       3457.158           13423.196     7.47          0.318E+10
  4      12753.410           50009.576    27.82          0.122E+11
  5       3028.901           11674.636     6.49          0.276E+10
  6      22016.043           85326.100    47.46          0.210E+11
  7       4912.123           18443.129    10.26          0.470E+10
total    46438.512          179764.966                   0.438E+11
```

```
All levels:
stepgrid           45260.344           175661.691
BC/ghost cells      1102.739             4025.367
Regridding          1629.678             5325.236
Output (valout)       12.806                0.000

Total time:        48349.465           185614.354
Using  4 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above
=========================================================================

for level   1 average num. grids =       2.00 over          1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =      19.94 over         35 regridding steps
for level   2  current num. grids =      32
for level   3 average num. grids =     658.86 over        194 regridding steps
for level   3  current num. grids =    1024
for level   4 average num. grids =     748.65 over       1121 regridding steps
for level   4  current num. grids =    1024
for level   5 average num. grids =      42.58 over       3096 regridding steps
for level   5  current num. grids =      64
for level   6 average num. grids =     118.04 over      13319 regridding steps
for level   6  current num. grids =     128
for level   7 average num. grids =      31.12 over      37885 regridding steps
for level   7  current num. grids =      32


current  space usage =    247236364
maximum  space usage =    249955724
need space dimension =    250001829

number of cells advanced for time integration =   43770266258.000000
   # cells advanced on level    1 =           352800.00
   # cells advanced on level    2 =         18689150.00
   # cells advanced on level    3 =       3175059096.00
   # cells advanced on level    4 =      12163277712.00
   # cells advanced on level    5 =       2763900000.00
   # cells advanced on level    6 =      20953078380.00
   # cells advanced on level    7 =       4695909120.00
number of cells advanced for error estimation =            0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       0.75

 ------  end of AMRCLAW integration --------
```

B.3 Japan2011 - Port Orford

The following is for the 2 sec GeoClaw run reported in Section 2.5 that used up to 4 minute resolution across most of the ocean. This run was for 0-13 hours post quake. The adjoint method was not used. Instead, the wave tolerance of 0.005 was used to decide cell flagging for refinement in the variable regions. The A-grid around Port Orford was turned on at 7.5 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 6 levels. About 67% of the work was in Level 3 (4 minute) for ocean calculation. This amount was high because we insisted on a large part of the ocean to have required 4 minute computation, including around the source, because we did not use the adjoint method to select just what needed to be refined. Level 4 (1 minute), Level 5 (12sec) and Level 6 (2sec) together required about 32.5% of the work for the regions around Port Orford.

Also note that the amount of regridding work was only 2.7% of that required for the step-grid work. This points out that the wave tolerance flagging is very efficient.

Finally, note that the speedup of the Wall Clock time over the CPU time by using 4 threads on the laptop was pretty good at 2.94 given that virtually no parallelism was happening on the Level 5 grid (probably due to laptop sleeping that was noticed). Otherwise, this is a fair comparison since only one user and only one job was running on the laptop for this timing. This job took 3.53 hours on the laptop using 4 threads.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level    Wall Time (sec)    CPU Time (sec)  %CPU   Total Cell Updates
  1          3.836              6.650      0.02     0.444E+06
  2         59.973            212.275      0.59     0.358E+08
  3       6259.192          24258.531     66.97     0.612E+10
  4        784.623           3008.869      8.31     0.749E+09
  5       4013.224           4198.579     11.59     0.128E+10
  6       1237.028           4535.467     12.52     0.136E+10
total    12357.876          36220.370               0.955E+10

All levels:
stepgrid           12065.964             35197.928
BC/ghost cells       281.604              1011.651
Regridding           292.367               975.488
Output (valout)        7.618                 0.000

Total time:        12690.402             37274.567
Using  4 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================

for level   1 average num. grids =      2.00 over         1 regridding steps
for level   1  current num. grids =      2
for level   2 average num. grids =     25.45 over        44 regridding steps
for level   2  current num. grids =     32
for level   3 average num. grids =   1238.74 over       254 regridding steps
for level   3  current num. grids =   2048
for level   4 average num. grids =     55.63 over      1514 regridding steps
for level   4  current num. grids =    128
for level   5 average num. grids =     20.04 over      2745 regridding steps
for level   5  current num. grids =     32
for level   6 average num. grids =     21.00 over      6143 regridding steps
```

```
for level   6  current num. grids =      28


current  space usage =     76587290
maximum  space usage =     80149016
need space dimension =     80174744

number of cells advanced for time integration =    9551676396.000000
   # cells advanced on level    1 =           443520.00
   # cells advanced on level    2 =         35811000.00
   # cells advanced on level    3 =       6124561956.00
   # cells advanced on level    4 =        748893600.00
   # cells advanced on level    5 =       1283343600.00
   # cells advanced on level    6 =       1358622720.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       0.75

 ------  end of AMRCLAW integration --------
```

B.4 Samoa2009 - Crescent City

The following is for the 1sec GeoClaw run reported in Section 3.2 that used up to 1 minute resolution across the ocean with adjoint flagging. This run was for 0-15 hours post quake with the adjoint method flagging waves that would arrive between 9.5 and 15 hours post quake. The A-grid around Crescent City was turned on at 8.5 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 6 levels. About 94% of the work was for level 4, which included 1 minute calculation around the source for 1 hour, moving the tsunami across the ocean with 1 minute calculation and the 1 minute A-grid around the destination. About 3.2% of the work was for the Level 5 (12 sec) and Level 6 (1sec) grids around Crescent City.

Also note that the amount of regridding work was more than the amount of step-grid work. This points out that the adjoint method has inefficiencies in the regridding that need to be addressed.

```
============================== Timing Data ==============================
Integration Time (stepgrid + BC + overhead)
Level     Wall Time (seconds)    CPU Time (sec)  %CPU   Total Cell Updates
  1             12.334                 17.460   0.01     0.575E+06
  2            121.836                370.512   0.21     0.172E+08
  3           1110.853               5145.740   2.97     0.194E+10
  4          28409.469             162771.860  93.63     0.784E+11
  5            198.061                907.240   0.52     0.406E+09
  6            925.022               4628.280   2.66     0.313E+10
total        30777.575             173841.092            0.838E+11

All levels:
stepgrid            29913.608            170642.644
BC/ghost cells        709.153              2976.992
Regridding          32879.869            180342.288
Output (valout)        11.281                 0.000

Total time:         63901.258            355084.364
```

```
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above
=========================================================================

for level   1 average num. grids =       2.00 over          1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =      12.44 over         52 regridding steps
for level   2  current num. grids =       1
for level   3 average num. grids =     295.81 over        261 regridding steps
for level   3  current num. grids =       4
for level   4 average num. grids =    3245.03 over       1326 regridding steps
for level   4  current num. grids =      32
for level   5 average num. grids =       6.02 over       5116 regridding steps
for level   5  current num. grids =      16
for level   6 average num. grids =      40.93 over       7398 regridding steps
for level   6  current num. grids =      72


current  space usage =      2481270
maximum  space usage =    804597632
need space dimension =    804598779

number of cells advanced for time integration =   83844615684.000000
   # cells advanced on level    1 =            575050.00
   # cells advanced on level    2 =          17187550.00
   # cells advanced on level    3 =        1936473012.00
   # cells advanced on level    4 =       78353048928.00
   # cells advanced on level    5 =         406371400.00
   # cells advanced on level    6 =        3130959744.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       0.75

 ------  end of AMRCLAW integration --------
```

B.5 Samoa2009 - Arena Cove

The following is for the 1sec GeoClaw run reported in Section 3.3 that used up to 1 minute computation across the ocean and adjoint flagging. This run was for 0-13 hours post quake with the adjoint method flagging waves that would arrive between 9.5 and 13 hours post quake. The A-grid around Arena Cove was turned on at 8.0 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 6 levels. About 63% of the work was for level 4, which included 1 minute calculation around the source for 1 hour, moving the tsunami across the ocean with 1 minute calculation and the 1 minute A-grid around the destination. About 34% of the cpu work was in the 12sec, 6sec, 2sec, and 1sec grids (Levels 5 to 8) around Arena Cove.

Also note that the amount of regridding work was more than half the amount of the step-grid work, indicating that the adjoint method has inefficiencies in the regridding that need to be addressed.

```
============================== Timing Data ==============================
```

```
Integration Time (stepgrid + BC + overhead)
Level      Wall Time (sec)    CPU Time (sec)  %CPU   Total Cell Updates
  1           10.868             15.912    0.01    0.501E+06
  2           73.267            294.696    0.26    0.109E+08
  3          430.389           2386.668    2.12    0.968E+09
  4        11928.387          71182.584   63.17    0.391E+11
  5         2303.690          13628.880   12.10    0.107E+11
  6         2506.512          15021.492   13.33    0.109E+11
  7          789.612           4686.416    4.16    0.352E+10
  8          911.461           5463.252    4.85    0.428E+10
total       18954.186         112679.900            0.695E+11

All levels:
stepgrid           18300.158            109644.272
BC/ghost cells       413.475              2332.092
Regridding         11375.975             61753.604
Output (valout)        5.274                 0.000

Total time:        30550.067            175519.832
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

==========================================================================

for level   1 average num. grids =      2.00 over          1 regridding steps
for level   1  current num. grids =      2
for level   2 average num. grids =     11.69 over         45 regridding steps
for level   2  current num. grids =      4
for level   3 average num. grids =    199.47 over        220 regridding steps
for level   3  current num. grids =     64
for level   4 average num. grids =   2110.36 over       1059 regridding steps
for level   4  current num. grids =    336
for level   5 average num. grids =    179.83 over       4065 regridding steps
for level   5  current num. grids =    589
for level   6 average num. grids =    162.26 over       7729 regridding steps
for level   6  current num. grids =    256
for level   7 average num. grids =     43.04 over      12610 regridding steps
for level   7  current num. grids =     64
for level   8 average num. grids =     86.07 over      12610 regridding steps
for level   8  current num. grids =    128


current  space usage =    126687866
maximum  space usage =    700568070
need space dimension =    700580089

number of cells advanced for time integration =   69530864563.000000
   # cells advanced on level    1 =            500850.00
   # cells advanced on level    2 =          10874100.00
   # cells advanced on level    3 =         968327748.00
```

```
   # cells advanced on level    4 =       39069034608.00
   # cells advanced on level    5 =       10735301225.00
   # cells advanced on level    6 =       10949475600.00
   # cells advanced on level    7 =        3519105120.00
   # cells advanced on level    8 =        4278245312.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       0.75

 ------  end of AMRCLAW integration --------
```

B.6 Samoa2009 - Port Orford

The following is for the 1sec GeoClaw run reported in Section 3.4 that used up to 1 minute calculation across the ocean and adjoint flagging. This run was for 0-16 hours post quake with the adjoint method flagging waves that would arrive between 10 and 16 hours post quake. The A-grid around Port Orford was turned on at 9 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 6 levels. About 89.4% of the work was for level 4, which included calculation around the source for 1 hour, moving the tsunami across the ocean with 1 minute calculation and the 1 minute A-grid around the destination. About 7.6% of the cpu work was in the 12sec and 1sec grids (Levels 5 and 6) around Port Orford.

Also note that the amount of regridding work was more than the amount of the step-grid work, indicating that the adjoint method has inefficiencies in the regridding that need to be addressed.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level    Wall Time (sec)      CPU Time (sec)  %CPU  Total Cell Updates
  1            11.685             17.204     0.01   0.612E+06
  2           103.727            375.204     0.18   0.214E+08
  3          1183.582           5932.736     2.86   0.253E+10
  4         31355.389         185158.832    89.38   0.986E+11
  5           475.563           2244.960     1.08   0.135E+10
  6          2549.140          13421.796     6.48   0.882E+10
total       35679.086         207150.732            0.111E+12

All levels:
stepgrid            34601.531             202737.480
BC/ghost cells        878.387               4104.076
Regridding          45394.321             258729.380
Output (valout)        12.072                  0.000

Total time:         81345.353             466948.516
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================

for level   1 average num. grids =       2.00 over          1 regridding steps
```

```
for level   1  current num. grids =       2
for level   2 average num. grids =      15.16 over         55 regridding steps
for level   2  current num. grids =       2
for level   3 average num. grids =     319.31 over        282 regridding steps
for level   3  current num. grids =       8
for level   4 average num. grids =    3732.89 over       1435 regridding steps
for level   4  current num. grids =     128
for level   5 average num. grids =      13.44 over       5557 regridding steps
for level   5  current num. grids =      32
for level   6 average num. grids =      95.76 over       8612 regridding steps
for level   6  current num. grids =     165


current  space usage =      6044764
maximum  space usage =   1058599094
need space dimension =   1058599408

number of cells advanced for time integration =  111379305472.000000
   # cells advanced on level    1 =           612150.00
   # cells advanced on level    2 =         21350950.00
   # cells advanced on level    3 =       2533570596.00
   # cells advanced on level    4 =      98649334816.00
   # cells advanced on level    5 =       1351644800.00
   # cells advanced on level    6 =       8822792160.00
number of cells advanced for error estimation =            0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =      0.75

 ------  end of AMRCLAW integration --------
```

B.7 Samoa2009 - Midway Island

The following is for the 1sec GeoClaw run reported in Section 3.5 that used up to 1 minute computation across the ocean and adjoint flagging. This run was for 0-10 hours post quake with the adjoint method flagging waves that would arrive between 5 and 10 hours post quake. The A-grid around Midway Island was turned on at 4 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 6 levels. About 51.9% of the work was for level 4, which included 1 minute calculation around the source for 1 hour, moving the tsunami across the ocean with 1 minute calculation and the 1 minute A-grid around the destination. About 46.4% of the cpu work was in the 6sec and 1sec grids (Levels 5 and 6) around Midway Island.

Also note that the amount of regridding work was about half the amount of the step-grid work, indicating that the adjoint method has inefficiencies in the regridding that need to be addressed.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level     Wall Time (sec)     CPU Time (sec)  %CPU  Total Cell Updates
  1            14.270             18.876    0.02    0.352E+06
  2            61.923            179.000    0.17    0.684E+07
  3           351.691           1657.808    1.55    0.619E+09
  4          9745.617          55239.576   51.89    0.271E+11
```

```
  5          1371.988          6352.124    5.97    0.290E+10
  6          8529.093         43007.636   40.40    0.207E+11
total       20074.582        106455.020            0.513E+11

All levels:
stepgrid           19306.871             104261.768
BC/ghost cells       702.959               2008.256
Regridding          9372.642              51096.624
Output (valout)        4.525                  0.000

Total time:        29693.264             158217.628
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================



for level   1 average num. grids =       2.00 over          1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =       9.97 over         32 regridding steps
for level   2  current num. grids =       1
for level   3 average num. grids =     170.94 over        155 regridding steps
for level   3  current num. grids =       4
for level   4 average num. grids =    1764.96 over        790 regridding steps
for level   4  current num. grids =      16
for level   5 average num. grids =      35.74 over       3082 regridding steps
for level   5  current num. grids =      64
for level   6 average num. grids =     109.30 over      14241 regridding steps
for level   6  current num. grids =     128


current  space usage =      4170050
maximum  space usage =    297782984
need space dimension =    297786333

number of cells advanced for time integration =   51339096189.000000
   # cells advanced on level    1 =            352450.00
   # cells advanced on level    2 =           6841675.00
   # cells advanced on level    3 =         618742800.00
   # cells advanced on level    4 =       27092509744.00
   # cells advanced on level    5 =        2896725000.00
   # cells advanced on level    6 =       20723924520.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       0.75


 ------  end of AMRCLAW integration --------
```

B.8 Samoa2009 - Pago Pago

The following is for the 1/3 sec GeoClaw run reported in Section 3.6 that used up to 1 minute computation around the ocean from source to destination (this was a near field tsunami). Fixed aprior grids (no adjoint flagging) were used with a wave tolerance of 0.03 for flagging. This run was for 0-4 hours post quake. The A-grid around Pago Pago was turned on for the entire four hours allowing up to 1 minute computation. A 15sec grid around Pago Pago was turned on at 600 sec post-quake and remained throughout the computation.

These results show the percentage of the cpu work (over all threads) for each of the 7 levels. Only 5.6% of the work was for level 4, which included one minute calculation around the source for 1 hour, moving the tsunami across the ocean with 1 minute calculation and the 1 minute A-grid around the destination. This is because Pago Pago was so close to the source and very little ocean had to be crossed in the four hours post-quake for this computation. About 93.7% of the cpu work was in the 15sec, 1sec, and 1/3sec grids (Levels 5, 6, and 7) around Pago Pago as one would expect for a near field tsunami.

Also note that the amount of regridding work was 18% of the amount of the step-grid work, indicating that regridding using wave tolerance (instead of adjoint) flagging was fairly efficient.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level       Wall Time (sec)   CPU Time (sec) %CPU   Total Cell Updates
  1              39.681          20.316     0.02     0.259E+05
  2             160.251         102.924     0.08     0.201E+07
  3             711.625         619.268     0.51     0.159E+09
  4            6617.693        6852.800     5.61     0.267E+10
  5            2970.938        2918.528     2.39     0.870E+09
  6           73387.671       74703.056    61.12     0.216E+11
  7           36723.667       36997.336    30.27     0.219E+11
total        120611.526      122214.228              0.471E+11

All levels:
stepgrid              83981.194              85719.288
BC/ghost cells        36460.492              36234.340
Regridding            16735.540              15704.132
Output (valout)          16.759                  0.000

Total time:          140581.311             140895.008
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================

for level   1 average num. grids =       1.00 over          1 regridding steps
for level   1  current num. grids =       1
for level   2 average num. grids =       5.28 over         18 regridding steps
for level   2  current num. grids =       8
for level   3 average num. grids =      92.27 over         82 regridding steps
for level   3  current num. grids =     100
for level   4 average num. grids =     539.73 over        358 regridding steps
for level   4  current num. grids =     461
for level   5 average num. grids =      61.29 over       1204 regridding steps
```

```
for level   5  current num. grids =      64
for level   6 average num. grids =     156.90 over       3599 regridding steps
for level   6  current num. grids =     160
for level   7 average num. grids =     127.53 over      33146 regridding steps
for level   7  current num. grids =     128


current  space usage =     32452786
maximum  space usage =     65582885
need space dimension =     65594487

number of cells advanced for time integration =   47149415007.000000
   # cells advanced on level    1 =            25920.00
   # cells advanced on level    2 =          2013525.00
   # cells advanced on level    3 =        158722092.00
   # cells advanced on level    4 =       2666057488.00
   # cells advanced on level    5 =        869986736.00
   # cells advanced on level    6 =      21560867550.00
   # cells advanced on level    7 =      21891741696.00
number of cells advanced for error estimation =            0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       0.76


 ------  end of AMRCLAW integration --------
```

B.9 HG12 - Hilo

The following is for the 1sec GeoClaw run reported in Section 6.1 that used up to 1 minute computation across the ocean and adjoint flagging. This run was for 0-10 hours post quake with the adjoint method flagging waves that would arrive between 4.5 and 10 hours post quake. The A-grid around Hilo was turned on at 4 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 6 levels. About 28.5% of the work was for level 4, which included 1 minute calculation around the source for 1 hour, moving the tsunami across the ocean with 1 minute calculation and the 1 minute A-grid around the destination. About 69.8% of the work was for the Level 5 (6 sec) and Level 6 (1sec) grids around Hilo.

Also note that the amount of regridding work was 36.1% the amount of step-grid work. This points out that the adjoint regridding still needs to be addressed even though less regridding was necessary in this job run than that needed when the source and destination are farther apart and more hours of interest post-quake are specified for the adjoint method flagging.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level       Wall Time (sec)    CPU Time (sec) %CPU   Total Cell Updates
  1           120.781             69.456      0.04     0.390E+06
  2           787.179            559.720      0.34     0.823E+07
  3          1820.189           2224.192      1.35     0.652E+09
  4          2417.935          46995.688     28.46     0.178E+11
```

```
  5        72151.637         94902.060     57.47     0.426E+11
  6        18147.421         20377.032     12.34     0.956E+10
total     125445.142        165128.148               0.706E+11

All levels:
stepgrid          116973.679            156676.152
BC/ghost cells      7954.344              8198.272
Regridding         37341.585             56624.832
Output (valout)       14.318                 0.000

Total time:       164574.038            223352.284
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================



for level   1 average num. grids =       2.00 over          1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =       8.94 over         35 regridding steps
for level   2  current num. grids =       2
for level   3 average num. grids =     157.94 over        181 regridding steps
for level   3  current num. grids =      16
for level   4 average num. grids =    1187.84 over        876 regridding steps
for level   4  current num. grids =      64
for level   5 average num. grids =     521.73 over       3421 regridding steps
for level   5  current num. grids =    1024
for level   6 average num. grids =      56.43 over      14192 regridding steps
for level   6  current num. grids =      64


current  space usage =     31779744
maximum  space usage =    443755366
need space dimension =    443767718

number of cells advanced for time integration =   70559890468.000000
   # cells advanced on level    1 =           389550.00
   # cells advanced on level    2 =          8226450.00
   # cells advanced on level    3 =        651805236.00
   # cells advanced on level    4 =      17783341312.00
   # cells advanced on level    5 =      42559020000.00
   # cells advanced on level    6 =       9557107920.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =      0.76


 ------  end of AMRCLAW integration --------
```

B.10 Kuril 2007 - Crescent City

The following is for the 1 sec GeoClaw run reported in Section 5.2 that used up to 4 minute computation across the ocean and adjoint flagging. This run was for 0-13.5 hours post quake with the adjoint method flagging waves that would arrive between 7.5 and 13.5 hours post quake. The A-grid around Crescent City was turned on at 7.5 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 6 levels. About 12.62% of the work was for Level 3, which was for moving the tsunami across the ocean with 4 minute calculation. About 84% of the work was for the Level 4 (1 min), Level 5 (12 sec) and Level 6 (1sec) grids around Crescent City with some of the Level 4 work being for 1 hour calculation around the source.

Also note that the amount of regridding work was only 14.5% the amount of step-grid work. This points out that adjoint flagging for 4 minute ocean calculations is more efficient than for 1 minute ocean calculations, but is still not as efficient as the wave tolerance flagging of around 3% reported in Sections B.1 and B.2 for example.

```
============================== Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level     Wall Time (secs)  CPU Time (secs)  %CPU   Total Cell Updates
  1           110.766           57.456        0.28      0.519E+06
  2           908.589          689.788        3.32      0.114E+08
  3          2510.980         2625.580       12.62      0.681E+09
  4          7357.670         9309.448       44.76      0.335E+10
  5          1461.608         1322.832        6.36      0.391E+09
  6          7165.672         6792.844       32.66      0.330E+10
total       19515.285        20797.948                  0.773E+10

All levels:
stepgrid            16627.827              18247.924
BC/ghost cells       2872.747               2540.092
Regridding           2874.251               2639.904
Output (valout)         3.182                  0.000

Total time:         22875.335              23885.784
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================



for level   1 average num. grids =       2.00 over          1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =      10.02 over         47 regridding steps
for level   2  current num. grids =       1
for level   3 average num. grids =     122.36 over        253 regridding steps
for level   3  current num. grids =       4
for level   4 average num. grids =     126.81 over       1265 regridding steps
for level   4  current num. grids =      32
```

```
for level   5 average num. grids =       9.02 over       2891 regridding steps
for level   5  current num. grids =      16
for level   6 average num. grids =      54.84 over       5295 regridding steps
for level   6  current num. grids =      72


current  space usage =      2481270
maximum  space usage =     67096888
need space dimension =     74590126

number of cells advanced for time integration =    7729088802.000000
   # cells advanced on level    1 =           519400.00
   # cells advanced on level    2 =         11386850.00
   # cells advanced on level    3 =        680786208.00
   # cells advanced on level    4 =       3346579600.00
   # cells advanced on level    5 =        390636200.00
   # cells advanced on level    6 =       3299180544.00
number of cells advanced for error estimation =             0.000000

 percentage of cells advanced in time  =     100.00
 maximum Courant number seen =       0.75


 ------  end of AMRCLAW integration --------
```

B.11 Chile 2010 - Arena Cove

The following is for the 1 sec GeoClaw run reported in Section 4.3 that used up to 4 minute computation across the ocean and adjoint flagging.

This run was for 0-21 hours post quake with the adjoint method flagging waves that would arrive between 13.5 and 21 hours post quake. The A-grid around Arena Cove was turned on at 13.5 hours post quake.

These results show the percentage of the cpu work (over all threads) for each of the 8 levels. Only 5.44% of the time was spent in Level 3 (4 minute computation), which was for moving the tsunami across the ocean. Level 4 through Level 8 represented the bulk of the calculation (about 93.8%) and were the grids around Arena Cove. Level 4 was for the 1 minute computation around Arena Cove's A grid and 1 minute computation around the source for 1 hour. Levels 5 through 8 were 12, 6, 2, and 1 second computation, respectively.

Note that the regridding work was about 10.2% that of the step-grid work. Using at most 4 minute calculation across the ocean, as is done in this run, results in cheaper regridding compared to that for the Samoa results which used at most 1 minute calculation across the ocean.

```
============================= Timing Data ==============================

Integration Time (stepgrid + BC + overhead)
Level       Wall Time (sec)    CPU Time (sec)  %CPU  Total Cell Updates
  1           123.571            76.248       0.05     0.105E+07
  2          1386.101           991.768       0.70     0.266E+08
  3          8140.127          7705.312       5.44     0.250E+10
  4         16974.059         17642.388      12.46     0.779E+10
  5         38074.822         36620.904      25.85     0.189E+11
  6         45427.758         42797.612      30.22     0.192E+11
```

```
  7        18290.843         16246.524      11.47     0.712E+10
  8        22014.021         19558.240      13.81     0.866E+10
total     150431.302        141638.996                0.642E+11

All levels:
stepgrid          140347.762            133408.644
BC/ghost cells      9509.893              7699.020
Regridding         20700.009             13646.656
Output (valout)       18.046                 0.000

Total time:       176235.504            159335.060
Using  6 thread(s)

Note: The CPU times are summed over all threads.
      Total time includes more than the subroutines listed above

=========================================================================



for level   1 average num. grids =       2.00 over          1 regridding steps
for level   1  current num. grids =       2
for level   2 average num. grids =      15.14 over         72 regridding steps
for level   2  current num. grids =       4
for level   3 average num. grids =     304.64 over        355 regridding steps
for level   3  current num. grids =      64
for level   4 average num. grids =     178.00 over       1747 regridding steps
for level   4  current num. grids =     336
for level   5 average num. grids =     350.12 over       3643 regridding steps
for level   5  current num. grids =     589
for level   6 average num. grids =     218.15 over      10077 regridding steps
for level   6  current num. grids =     256
for level   7 average num. grids =      58.88 over      18652 regridding steps
for level   7  current num. grids =      64
for level   8 average num. grids =     117.76 over      18652 regridding steps
for level   8  current num. grids =     128


current  space usage =    126700406
maximum  space usage =    169389992
need space dimension =    169404835

number of cells advanced for time integration =   64208829981.000000
   # cells advanced on level    1 =          1047480.00
   # cells advanced on level    2 =         26573300.00
   # cells advanced on level    3 =       2497298796.00
   # cells advanced on level    4 =       7787534688.00
   # cells advanced on level    5 =      18897232725.00
   # cells advanced on level    6 =      19216273680.00
   # cells advanced on level    7 =       7122901248.00
   # cells advanced on level    8 =       8659968064.00
number of cells advanced for error estimation =             0.000000
```

```
percentage of cells advanced in time  =      100.00
maximum Courant number seen =       0.81

------  end of AMRCLAW integration --------
```