# Quarterly Report
# Massachusetts Institute of Technology
# GAGE Facility GPS Data Analysis Center Coordinator
# And
# GAGE Facility GAMIT/GLOBK Community Support

**Thomas Herring, Robert King and Mike Floyd**

**Period: 2014/01/01-2014/03/31**

## Table of Contents

Summary....2
GPS Analysis of Level 2a and 2b products....2
  Level 2a products: Rapid products....2
  Level 2a products: Final products....2
  Level 2a products: 12-week, 26-week supplement products....2
  Analysis of Final products: Jan 1, 2014 and Mar 22, 2014....2
  Snapshot velocity field analysis from the reprocessed PBO analysis.....13
  Earthquake Analyses: 2014/01/01-2014/03/31.....21
  Antenna Change Offsets: 2014/01/01-2014/03/31....22
  Anomalous height results in the CWU time-series....23
  Script updates....26
GAMIT/GLOBK Community Support....27

## Summary

Under the GAGE Facility Data Analysis subcontract, MIT has been combining results from the New Mexico Tech (NMT) and Central Washington University (CWU). In this report, we show analyses of the data processing for the period 01/01/2014 to 03/31/2014, time series velocity field analyses for the GAGE reprocessing analyses (1996-2014), earthquake effects during the interval (2 detectable events), comparison between results from the previous quarter, and an analysis of the ambiguity resolution issue in the Central Washington reprocessing results. Associated with the report are ASCII text files that are linked into this document.

Under the GAGE Facility GAMIT/GLOBK Community Support we report on activities during this quarter.

## GPS Analysis of Level 2a and 2b products

*Level 2a products: Rapid products*

Final and rapid level 2a products have been generated routinely during this quarter. The description of these products, the delivery schedule and the delivery list remain unchanged from the previous quarter and will not be reported here.

*Level 2a products: Final products*

The final products are generated weekly and are based on the final IGS orbits. The description of these products, the delivery schedule and the delivery list remain unchanged from the previous quarter and will not be reported here. Data volumes being transferred also remains the same since the average number of sites is about the same. In this quarter 1837 sites were processed compared to 1847 for the previous quarter.

*Level 2a products: 12-week, 26-week supplement products*

Each week we also process the Supplemental (12-week latency) and six month supplemental (26-week latency) analyses from the ACs. The delivery schedule for these products is also unchanged. All supplement products are now up to date and have been transmitted to the UNAVCO GAGE archive. The 12-week and 26-week supplemental time series are included with the finals time series since the orbit used for these solutions is the IGS final orbit. (The rapid solution uses the IGS rapid orbit solution and these are replaced with final orbit solutions when the final orbits become available.)

*Analysis of Final products: Jan 1, 2014 and Mar 22, 2014*

Each month, we submit reports of the statistics of the PBO combined analyses and estimates of the latest velocity fields in the NAM08 reference frame based on the time series analysis of data between 2004 and month preceding the report (we need to allow 2-3 weeks for the generation of the final products). For this report, we generated the statistics using the ~3 months of results generated between Jan 1, 2014 and Mar 22, 2014. These results are summarized in table 1 and figures 1-3.

For the three months of the final position time series generated by NMT, CWU and combination of the two (PBO), we fit linear trends and annual signals and compute the RMS scatters of the position residuals in north, east and up for each site in the analysis. Our first analysis of the distribution of these RMS scatters by analysis center and the combination. Table 1 shows the median (50%), 70% and 95% limits for the RMS scatters for PBO, NMT and CWU. The median horizontal RMS scatters are less than 1.2 mm for all centers and as low as 0.7 mm for NMT north component. The up RMS scatters are less than 6.0 mm and as low as 4.4 mm. In the NAM08 frame realization, scale changes are not estimated. If scale changes were estimated, the up scatter would be reduced but the sum of scale change RMS and the lower height scatter would equal the values shown in Table 1. The detailed histograms of the RMS scatters are shown in Figures 1-3 for PBO, NMT and CWU.

**Table 1:** Statistics of the fits of 1837 sites for PBO and 1834 each for NMT and CWU analyzed in the finals analysis between Jan 1, 2014 and Mar 22, 2014. (Finals are run 1-2 weeks behind current date and at the beginning of the month not all all data from the previous month have been processed. PBO is the combined solution. Histograms of the RMS scatters are shown in Figure 1-3.

| Center | North (mm) | East (mm) | Up (mm) |
|---|---|---|---|
| *Median (50%)* | | | |
| PBO | 0.9 | 1.0 | 5.0 |
| NMT | 0.7 | 0.8 | 4.4 |
| CWU | 1.2 | 1.2 | 6.0 |
| *70%* | | | |
| PBO | 1.1 | 1.4 | 6.0 |
| NMT | 0.9 | 1.1 | 5.4 |
| CWU | 1.4 | 1.7 | 7.7 |
| *95%* | | | |
| PBO | 2.3 | 2.5 | 8.7 |
| NMT | 1.9 | 2.2 | 8.0 |
| CWU | 3.2 | 3.2 | 11.4 |

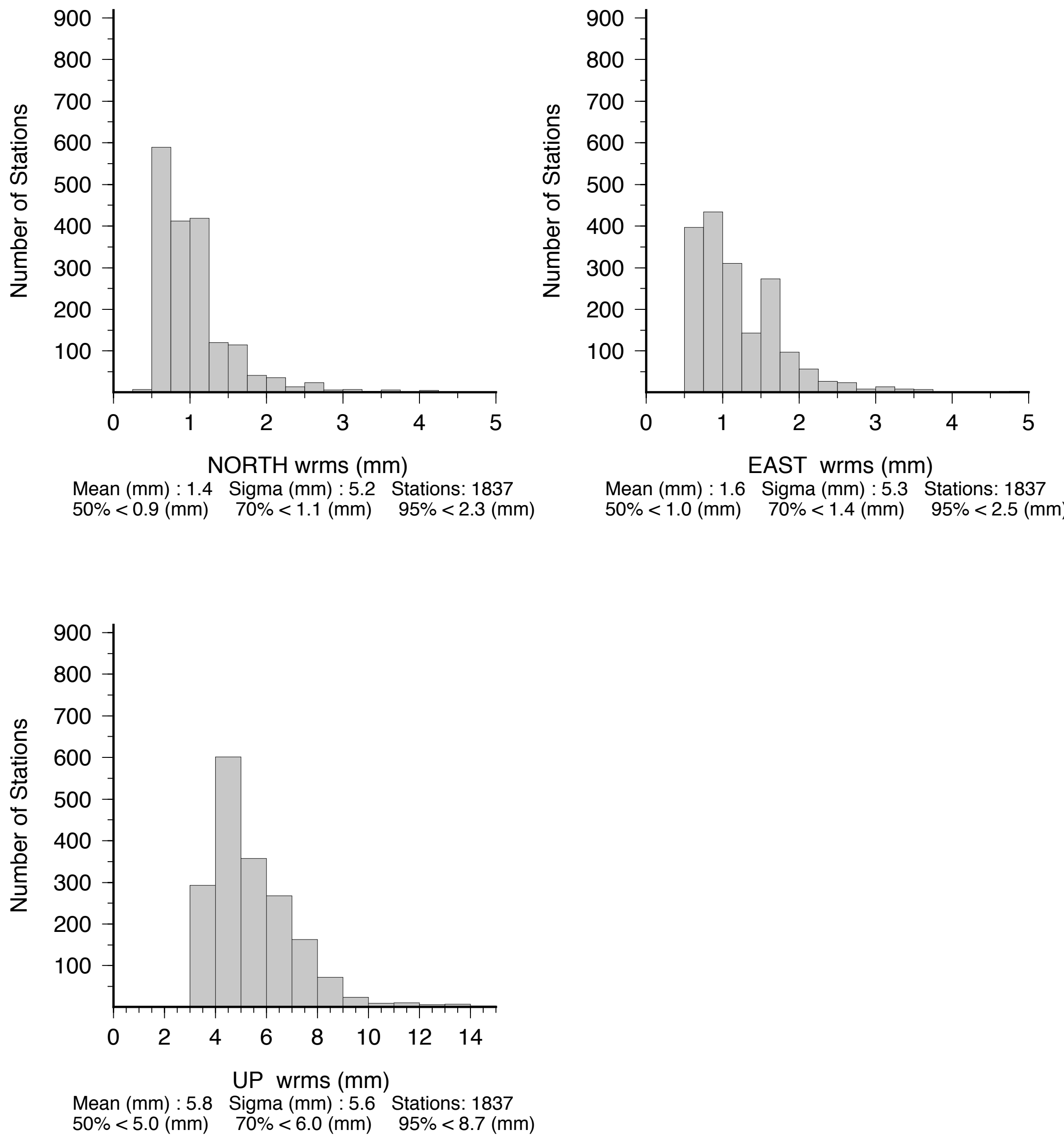



**Figure 1:** PBO combined solution histograms of the North, East and Up RMS scatters of the position residuals for 1837 sites analyzed between Jan 1, 2014 and Mar 22,2014. Linear trends and annual signals were estimated from the time series.

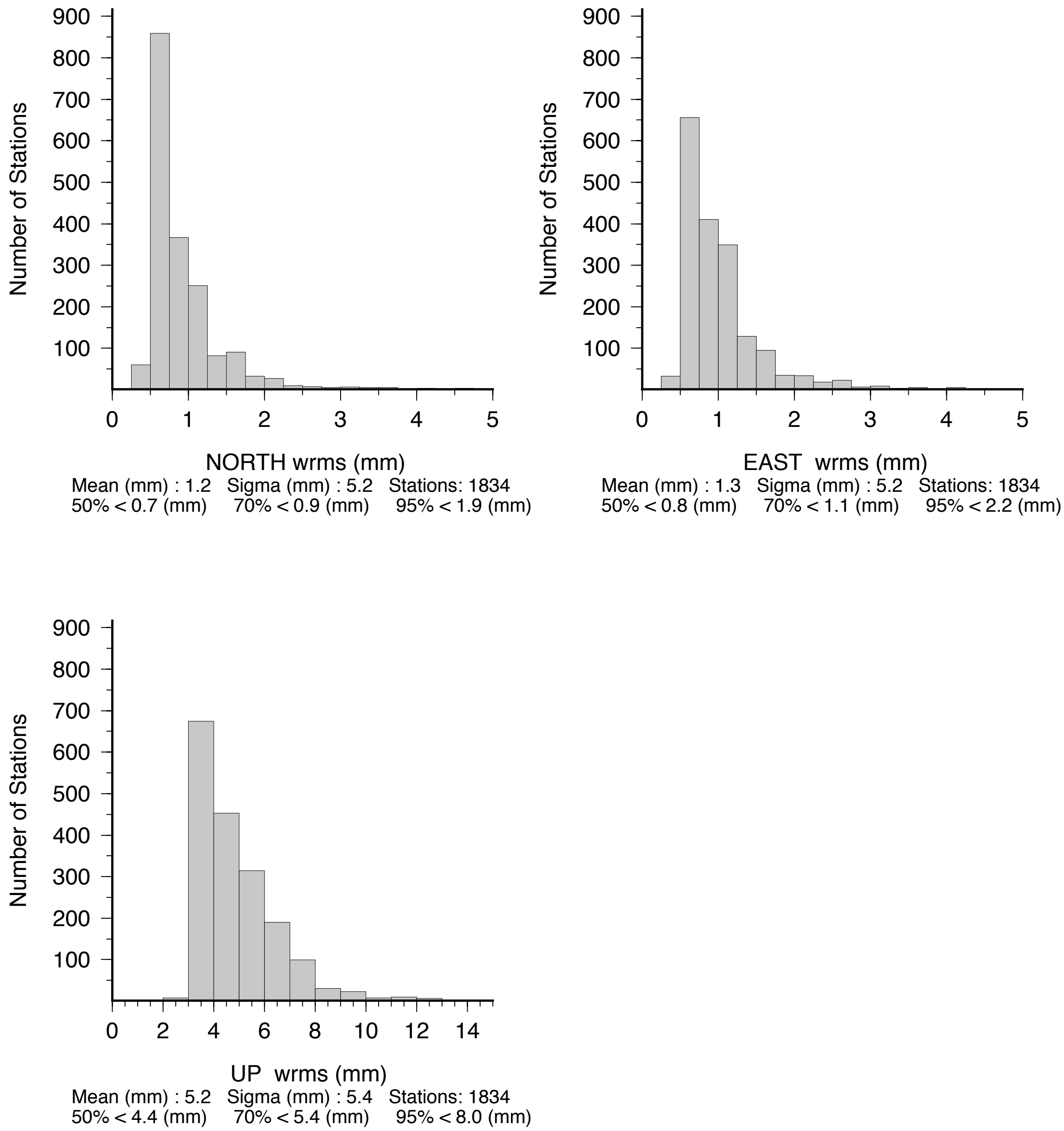



**Figure 2:** NMT combined solution histograms of the North, East and Up RMS scatters of the position residuals for 1834 sites analyzed between Jan 1, 2014 and Mar 22,2014. Linear trends and annual signals were estimated from the time series.

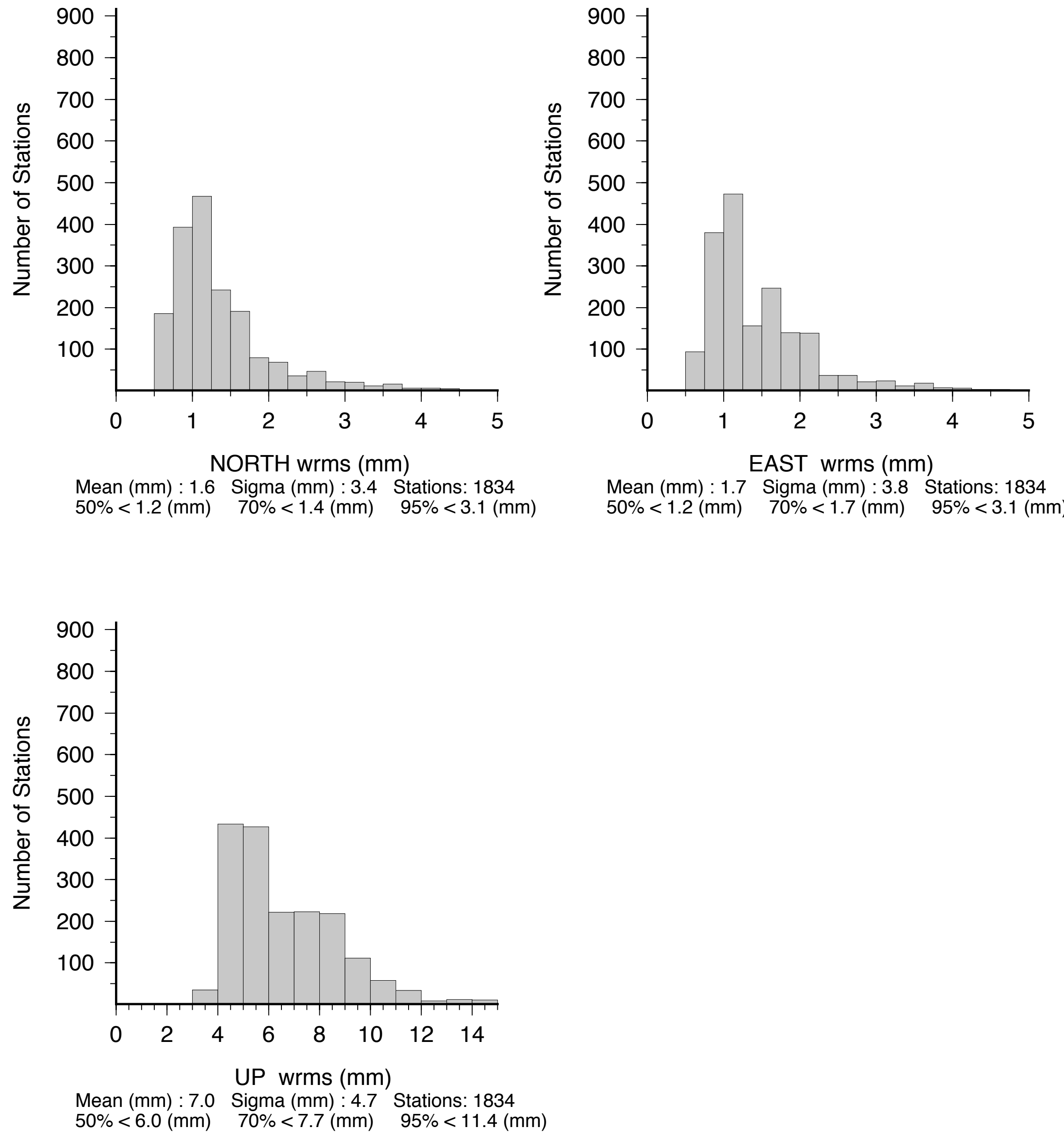



**Figure 3:** CWU combined solution histograms of the North, East and Up RMS scatters of the position residuals for 1834 sites analyzed between Jan 1, 2014 and Mar 22,2014. Linear trends and annual signals were estimated from the time series.

For the PBO combined analysis, we also evaluate the RMS scatters of the position estimates by network type. The figures below are based on our monthly submissions but here we use 3 months of data to evaluate the RMS scatters. In Table 2, we give the median, 70 and 95 percentile limits on the RMS scatters. The geographical distributions of the RMS scatters by network type are shown in Figures 4-9. The values plotted are given in PBO_FIN_Q02.tab. There are 1838 sites in the file. The contents of the files is of this form:

```
Tabular Position RMS scatters created from PBO_FIN_Q02.sum
ChiN/E/U are square root of chisquared degree of freedom of the fits.
Values of ChiN/E/U near unity indicate that the estimated error
bars are consistent the scatter of the position estimates

.Site     #    N (mm)  ChiN     E (mm) ChiE   U (mm)  ChiU     Years
 1LSU    81     1.0   0.62      1.8   1.08     5.7   0.92     10.91
 1NSU    81     0.9   0.60      1.7   1.03     6.2   0.98     10.18
 1ULM    81     0.9   0.59      1.6   1.04     6.3   1.09     10.77
…
 ZDC1    80     1.5   0.84      1.9   1.09     7.0   1.04     10.80
 ZDV1    81     1.3   0.61      1.2   0.66     7.2   0.97     10.80
 ZKC1    81     1.5   0.76      1.6   0.88     7.2   1.03     10.80
 ZLA1    81     1.2   0.54      1.3   0.67     5.2   0.66     10.80
 ZME1    56     1.3   0.64      1.5   0.76     6.8   0.86     11.03
 ZNY1    81     2.0   1.04      1.8   1.03     7.9   1.15     11.18
 ZSE1    81     1.7   0.71      1.2   0.67     7.1   0.93     11.18
 ZTL4    81     1.3   0.72      1.6   0.88     5.6   0.76     11.38
```

Table 2: RMS scatter of the position residuals for the PBO combined solution between Jan 1, 2014 and Mar 22, 2014 divided by network type. The division of networks is based on the JAVA script unavcoMetdata.jar with network codes PBO, Nucleus, Mid-SCIGN_USGS , America_GAMA, Expanded_PBO, COCONet and Expanded_PBO

| Network | North (mm) | East (mm) | Up (mm) | #Sites |
|---|---|---|---|---|
| *Median (50%)* | | | | |
| PBO | 0.8 | 0.9 | 4.4 | 893 |
| NUCLEUS | 0.7 | 0.8 | 4.4 | 206 |
| USGS SCIGN | 0.9 | 0.9 | 4.4 | 100 |
| Expanded | 1.1 | 1.5 | 6.1 | 546 |
| GAMA | 0.8 | 2.0 | 6.3 | 13 |
| COCO Net | 1.5 | 1.8 | 7.4 | 79 |
| *70 %* | | | | |
| PBO | 1.0 | 1.1 | 5.2 | |
| NUCLEUS | 0.9 | 0.9 | 4.9 | |
| USGS SCIGN | 1.1 | 1.1 | 4.7 | |
| Expanded | 1.3 | 1.7 | 6.9 | |
| GAMA | 0.9 | 2.6 | 6.6 | |
| COCO Net | 1.8 | 2.1 | 8.2 | |
| *95%* | | | | |
| PBO | 2.0 | 2.3 | 8.5 | |
| NUCLEUS | 1.3 | 1.4 | 6.7 | |
| USGS SCIGN | 1.6 | 2.0 | 6.6 | |
| Expanded | 2.5 | 2.5 | 9.0 | |
| GAMA | 1.6 | 3.7 | 7.4 | |
| COCO Net | 8.8 | 35.8 | 38.7* | |

* This large scatter in COCO Net is from site CN20 which generates very poor repeatability in the CWU solution and in the PBO combined solutions when combined with the standard RMS scatter results from NMT.

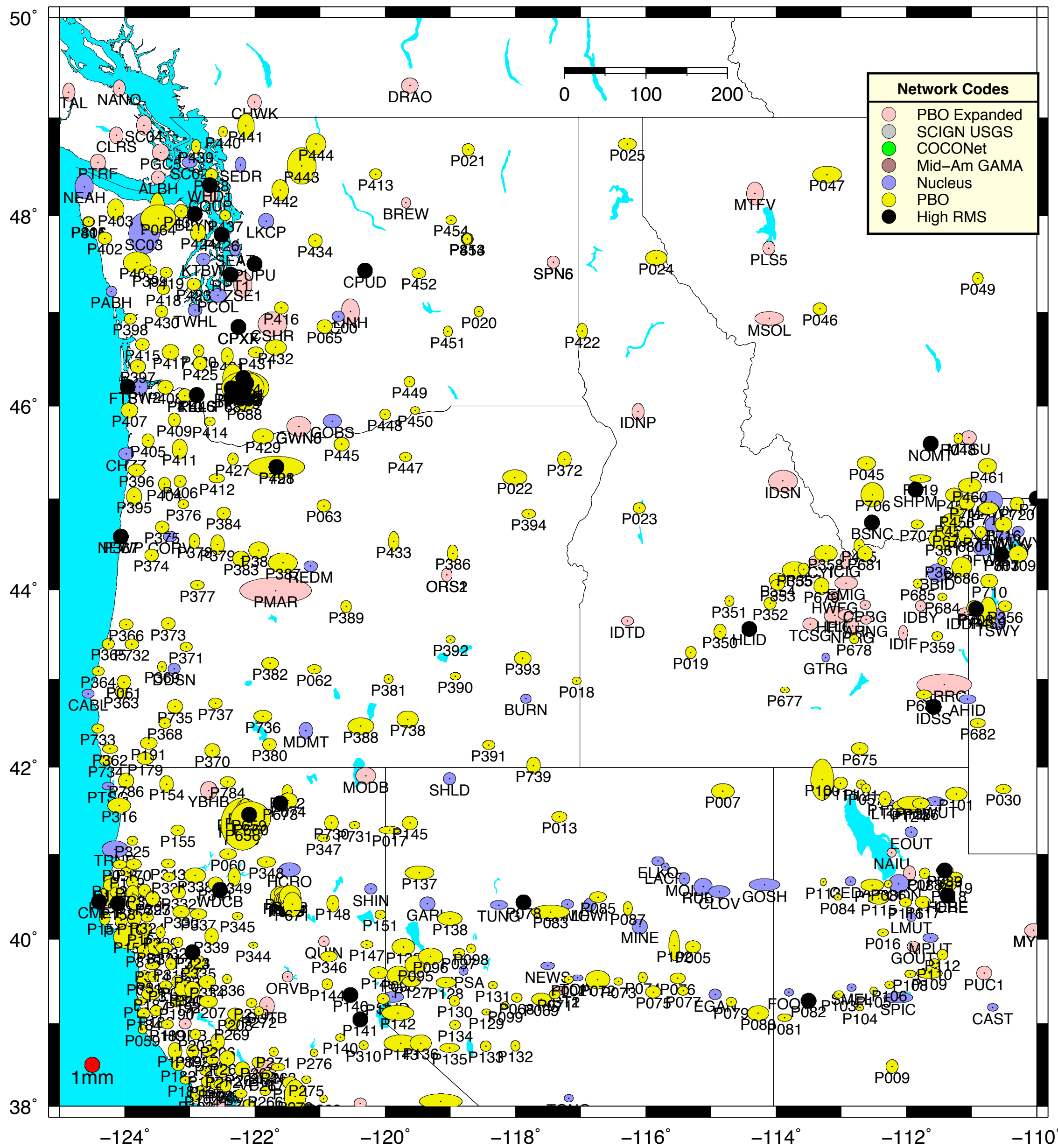



**Figure 4:** Distribution of the RMS scatters of horizontal position estimates from the PBO combined analysis for the Northern Western United States. The color of the ellipses that give the north and east RMS scatters denotes the network given by the legend in the figure. The small red circle shows the size of 1 mm scatters. Sites shown with black circles have combined RMS scatters in north and east greater than 5 mm or are sites which have no data during this 3-month interval.

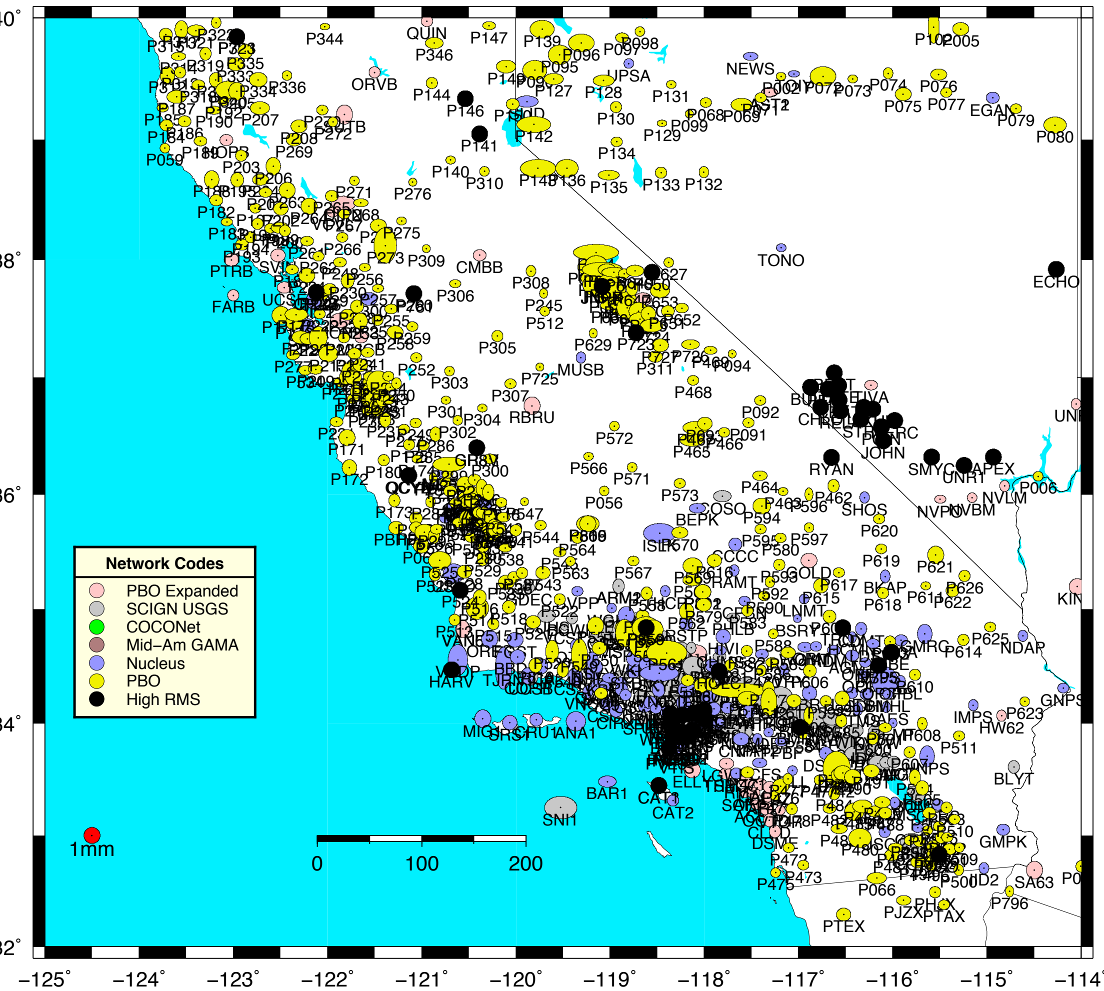



**Figure 5**: Same as Figure 4 except for the Southern Western United States. Black circles in the Yucca mountain region have no data during this 3-month period.

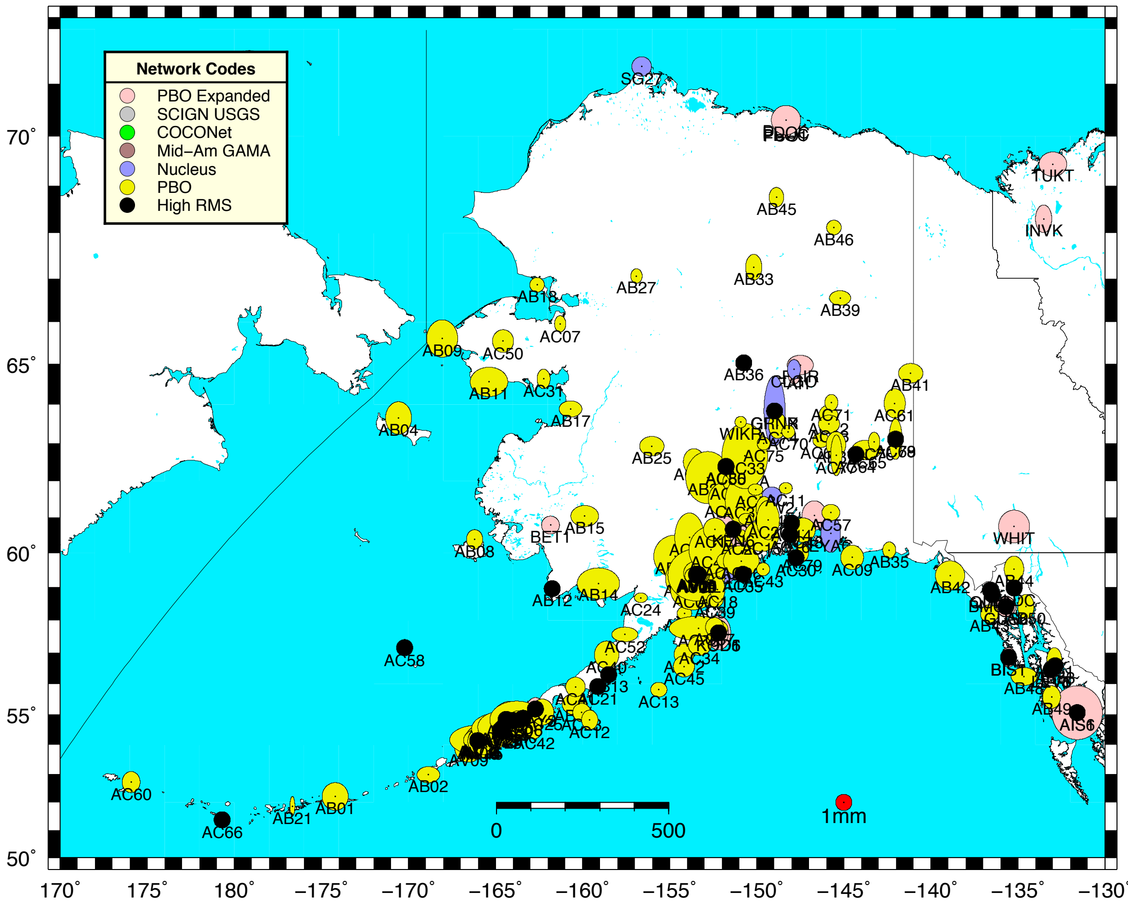


**Figure 6**: Same as Figure 4 except for the Alaskan region.

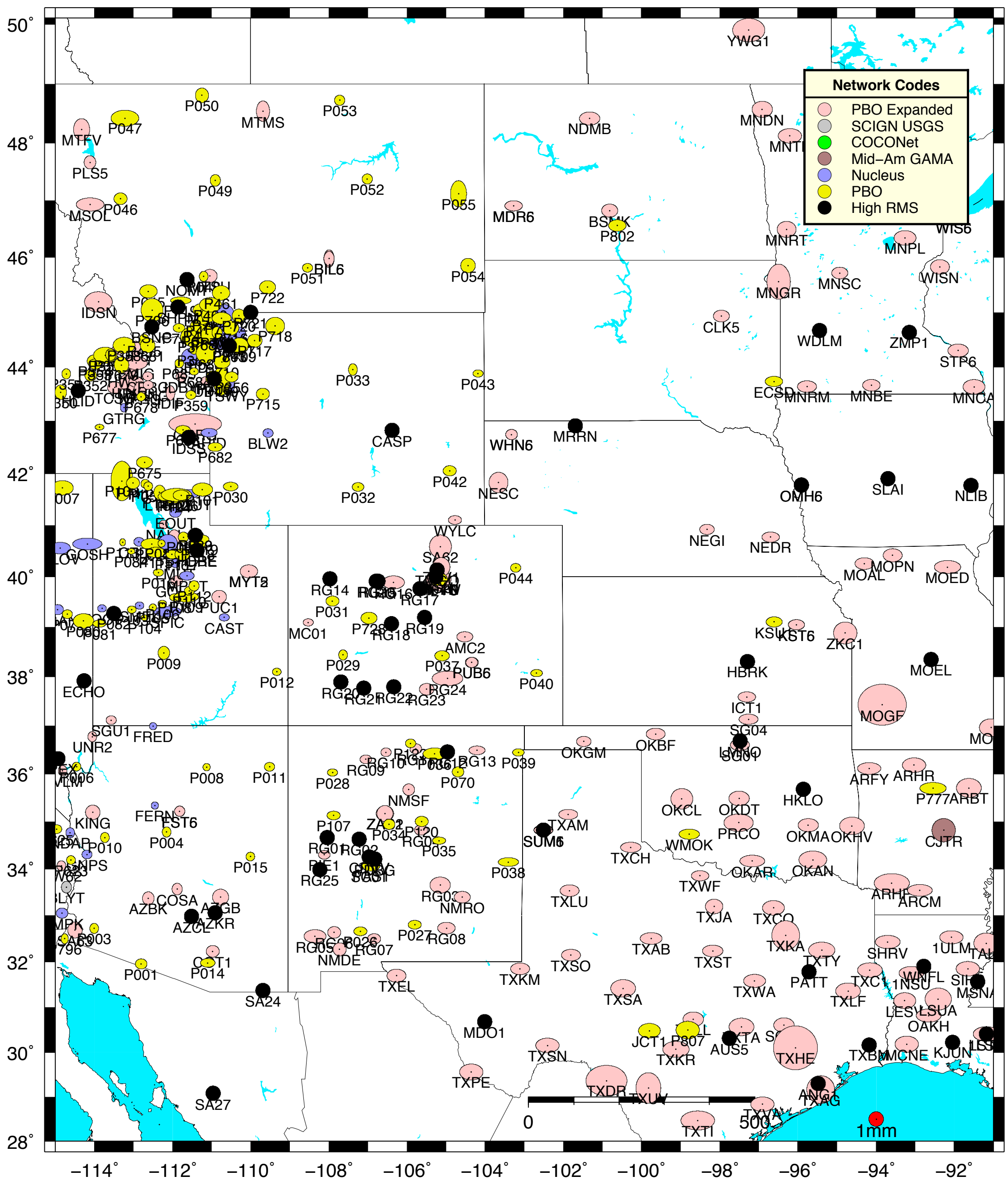



**Figure 7:** Same as Figure 4 except for the Central United States

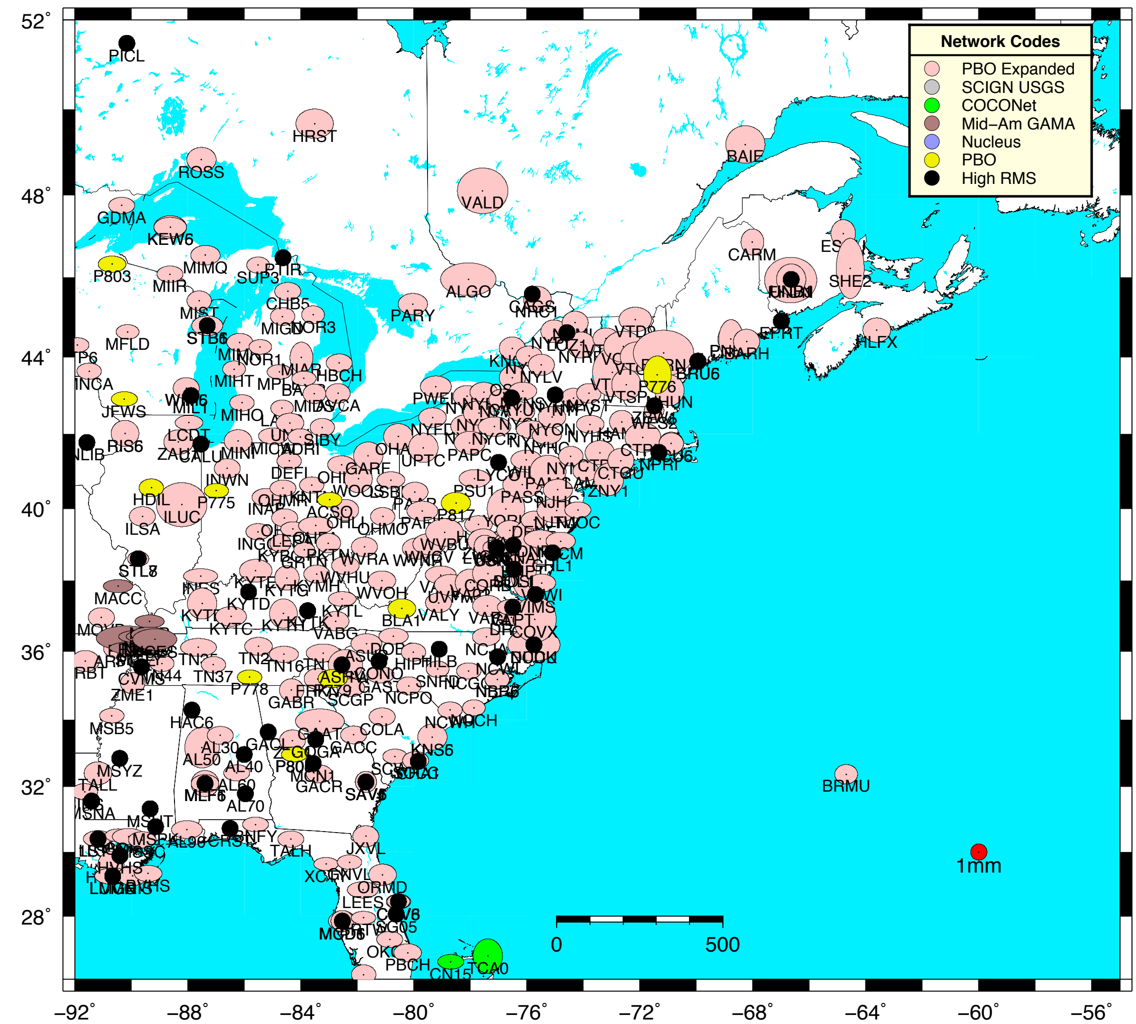



**Figure 8:** Same as Figure 4 except for the Eastern United States

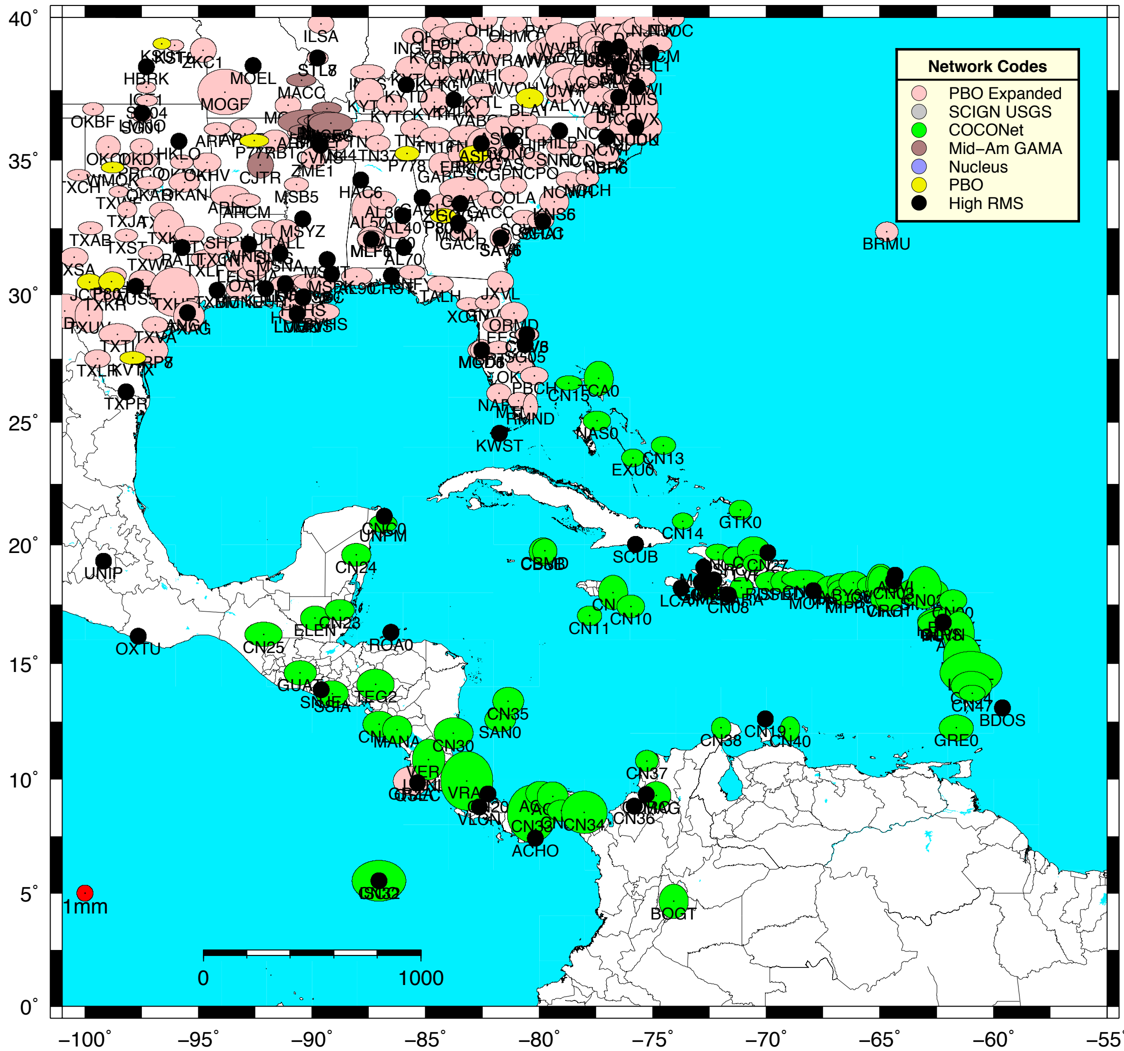



**Figure 9:** Same as Figure 4 except for the Caribbean region.

*Snapshot velocity field analysis from the reprocessed PBO analysis.*

In our monthly reports, we generate "snapshot" velocity fields in the NAM08 reference frame based on the time series analysis of all data processed to that time. For this quarterly report, we generate these velocity estimates for the reprocessed results and the current GAGE analyses (starting 2012/09/23) that are in the NAM08 reference frame. There 2052 sites, 8 more than last quarter, in the analyses and the statistics of the fits to results are shown in Table 3. In this analysis, offsets are estimated for antenna changes and earthquakes. Annual signals are estimated and for some earthquakes, logarithmic post-seismic signals are also estimated. The full tables of RMS fits along with the duration of the data used are given in the following linked files: pbo_nam08_140322.tab, nmt_nam08_140322.tab and cwu_nam08_140322.tab. The velocity estimates are shown by region and network type in Figures 10-15. The color scheme used is the same as Figures 4-9. The snapshot velocity field files are linked as: pbo_nam08_140322.snpvel, nmt_nam08_140322.snpvel and cwu_nam08_140322.snpvel.

**Table 3:** Statistics of the fits of 2052 sites analyzed in the reprocessed analysis for data collected between Jan 1, 1996 and Mar 22, 2014.

| Center | North (mm) | East (mm) | Up (mm) |
|---|---|---|---|
| *Median (50%)* | | | |
| PBO | 1.4 | 1.6 | 8.3 |
| NMT | 1.2 | 1.3 | 5.5 |
| CWU | 1.8 | 2.5 | 9.3 |
| *70%* | | | |
| PBO | 2.0 | 2.6 | 8.8 |
| NMT | 1.5 | 1.7 | 6.4 |
| CWU | 2.4 | 3.5 | 10.2 |
| *95%* | | | |
| PBO | 4.0 | 4.2 | 11.7 |
| NMT | 3.4 | 3.2 | 8.9 |
| CWU | 4.5 | 5.9 | 14.0 |

Different tolerances are used for maximum standard deviation in each of the figures so that regions with small velocity vectors can be displayed at large scales without the plots being dominated by large error bar points. The standard deviations of the velocity estimated are computed using the GLOBK First-order-Gauss-Markov Extrapolation (FOGMEX) model which aims to account for temporal correlations in the time series residuals. This algorithm is also called the "Realistic Sigma" model.

A direct comparison of the NMT and CWU solutions shows the weighted root-mean-square (WRMS) difference between the two velocity fields is 0.18 mm/yr horizontal and 0.71 mm/yr vertical in direct difference of all sites in both solutions (2021 sites). The $\chi/f^2$ of the difference is $(1.56)^2$. Since the RMS is weighted, sites with small standard deviations with tend to dominate the WRMS. Establishing a lower bound on the standard deviation of the velocity estimates 0.21 mm/yr (summed squared into the horizontal velocity standard deviations) and 0.45 mm/yr in heights generates and RMS difference of 0.36 mm/yr with a $\chi/f^2$ of unity horizontal only and 0.43 mm/yr weighted 3-D

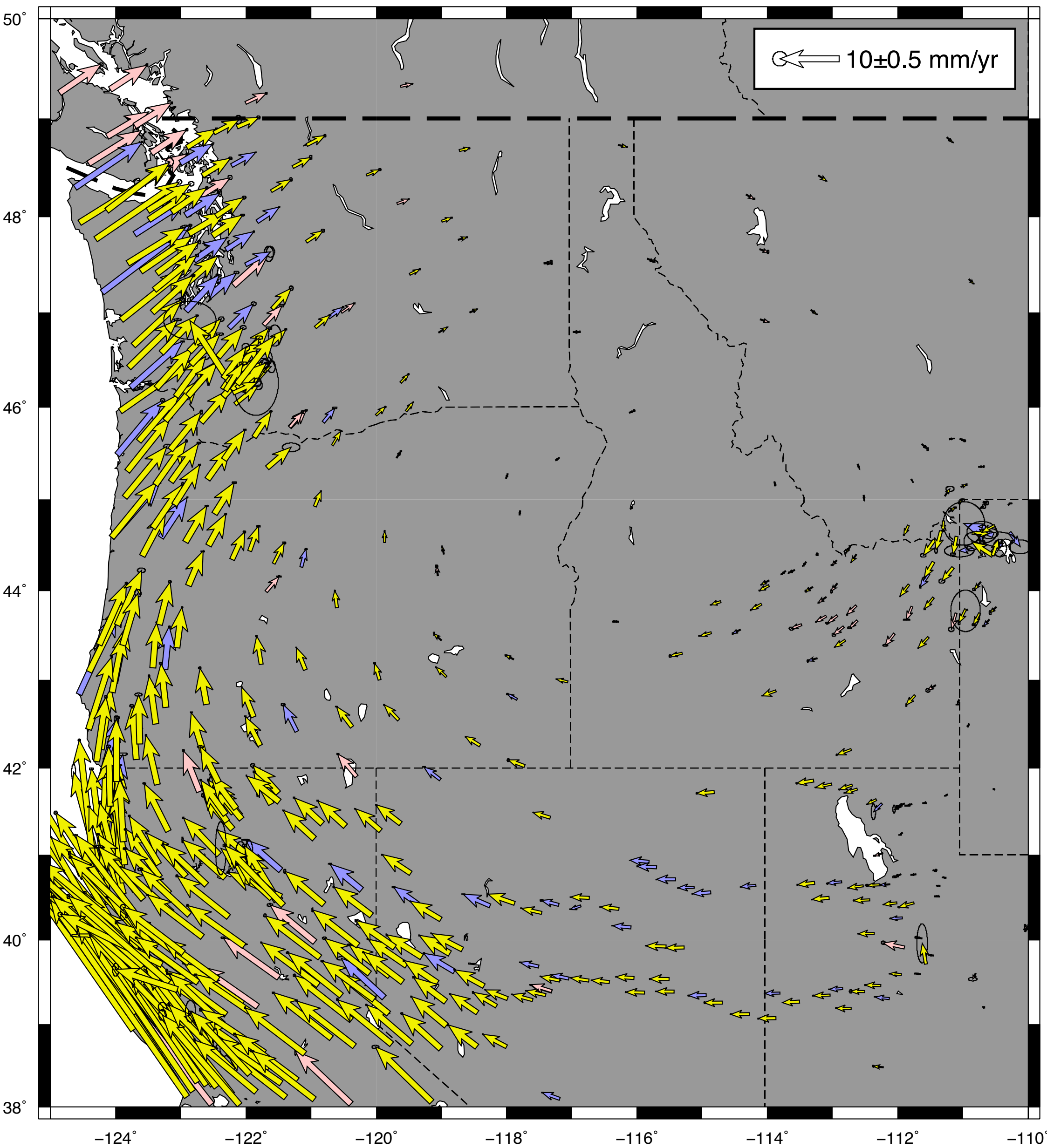
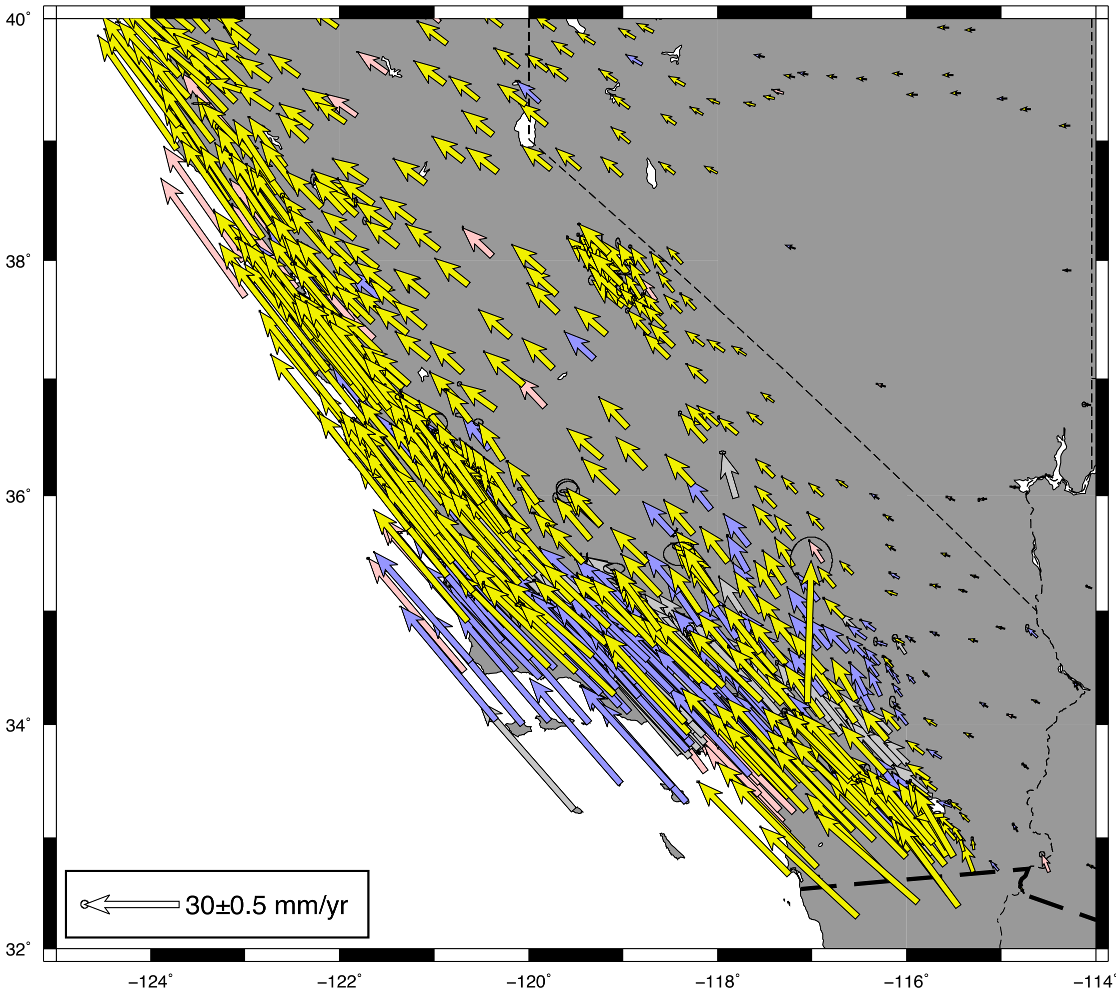



**Figure 10**: Velocity field estimates from the combined PBO solutions generated using time series analysis and the FOGMEX error model. 95% confidence interval error ellipses are shown. The color scheme of the vectors matches the network type legend in Figure 4. Only velocities with horizontal standard deviations less than 3 mm/yr are shown.


40°
38°
36°
34°
32°
−124°
−122°
−120°
−118°
−116°
−114°
30±0.5 mm/yr

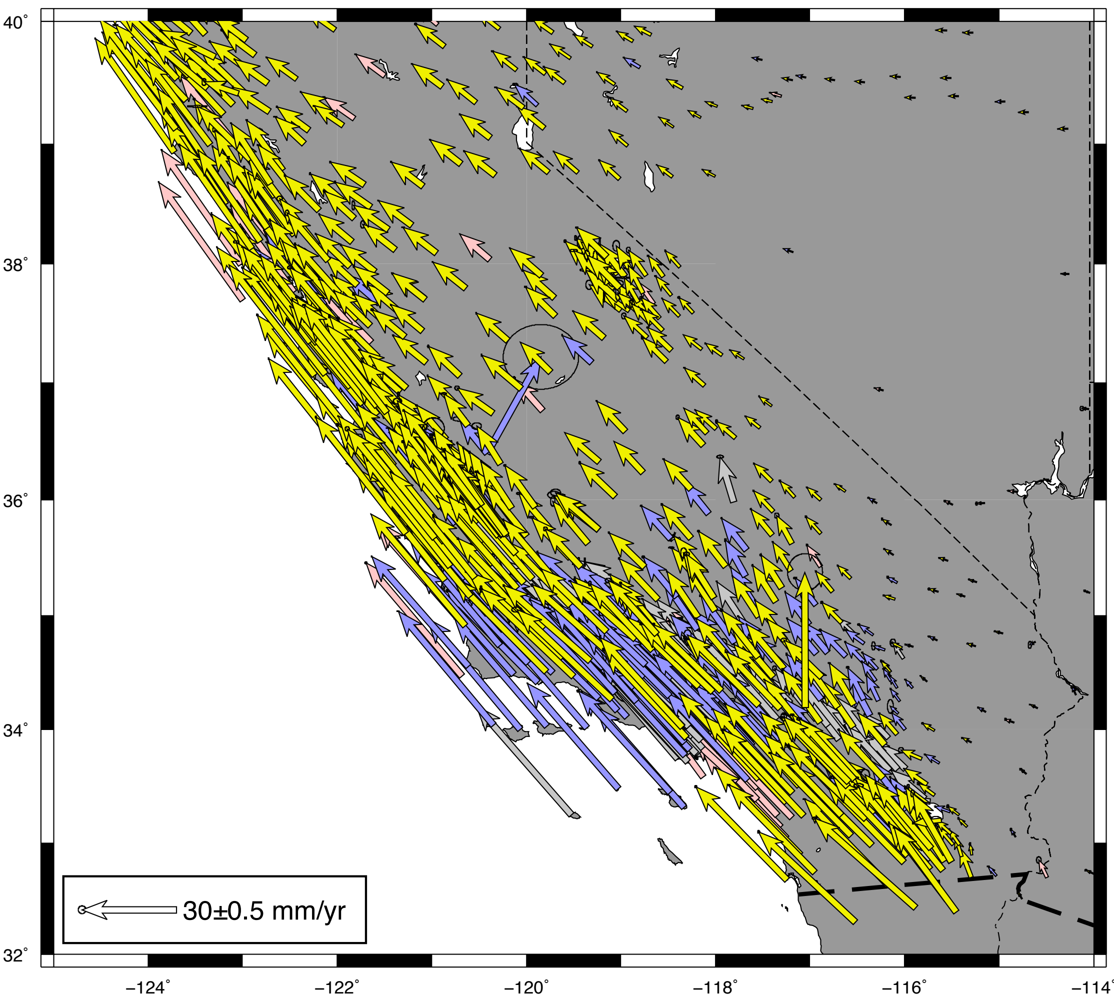



**Figure 11:** Same as Figure 10 except for South Western United States. Only velocities with horizontal standard deviations less than 5 mm/yr are shown. The anomalous site at latitude 34, longitude -117 is P613 and is effected by the estimation of post-seismic motion after the 2010 Apr 4 El Major Cucupah earthquake.

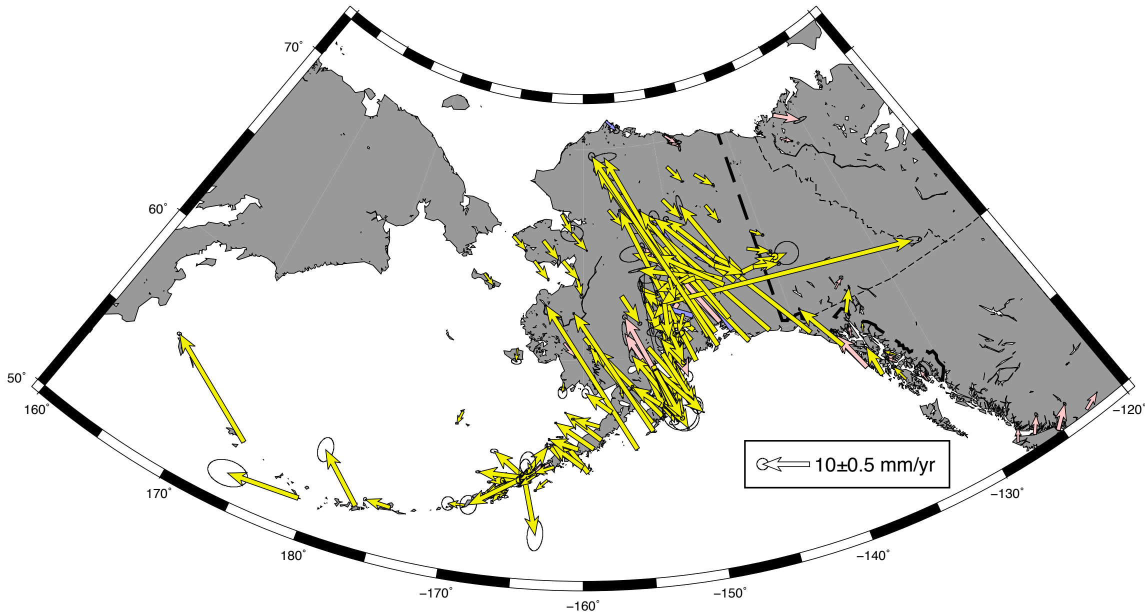



**Figure 12:** Same as Figure 10 except for Alaska. Only velocities with horizontal standard deviations less than 5 mm/yr are shown. The anomalous vector in Central Alaska is AC55 as the sites does move with anomalous motion. The site was discontinued in mid-2010.

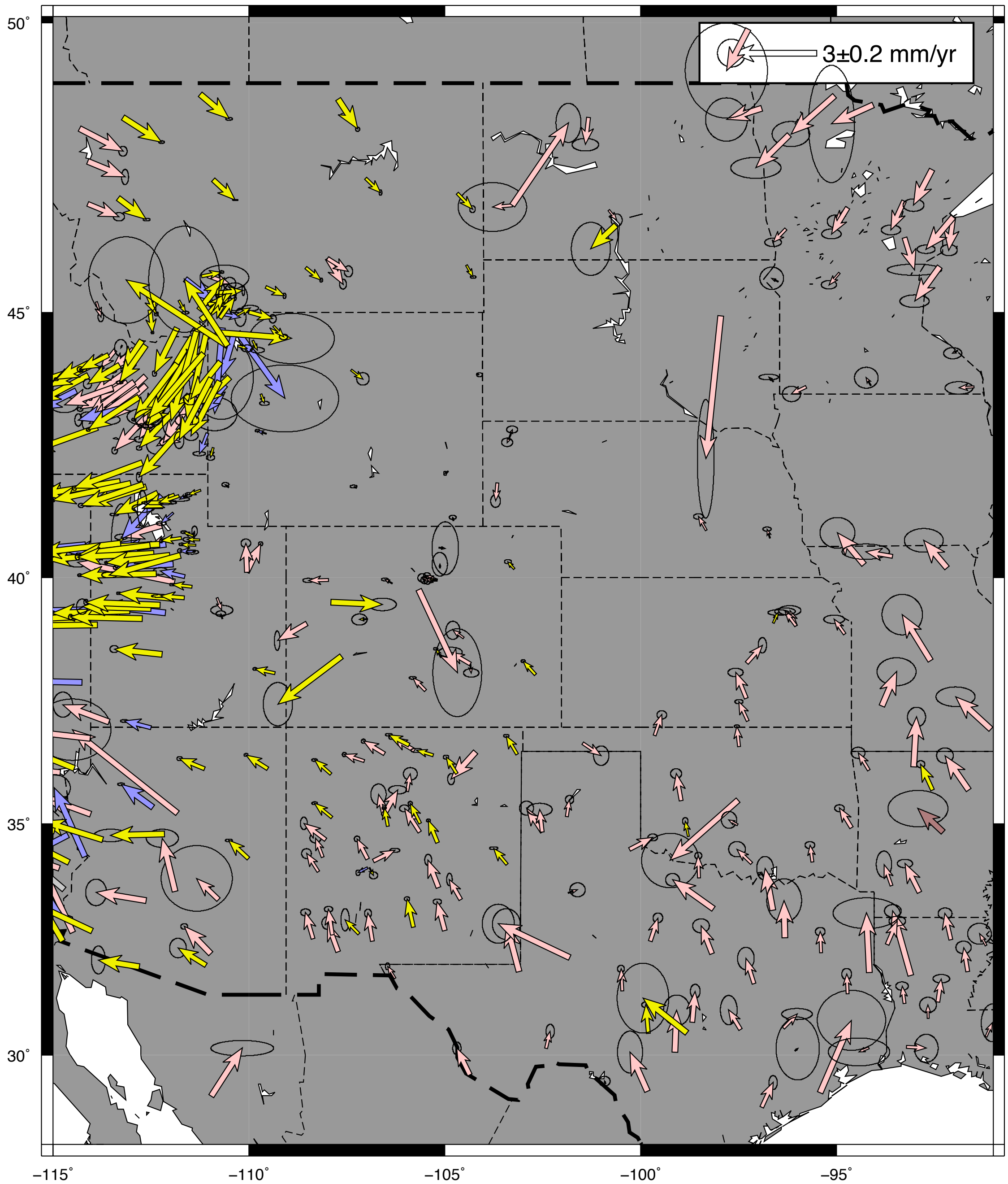



**Figure 13:** Same as Figure 10 except for Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown.

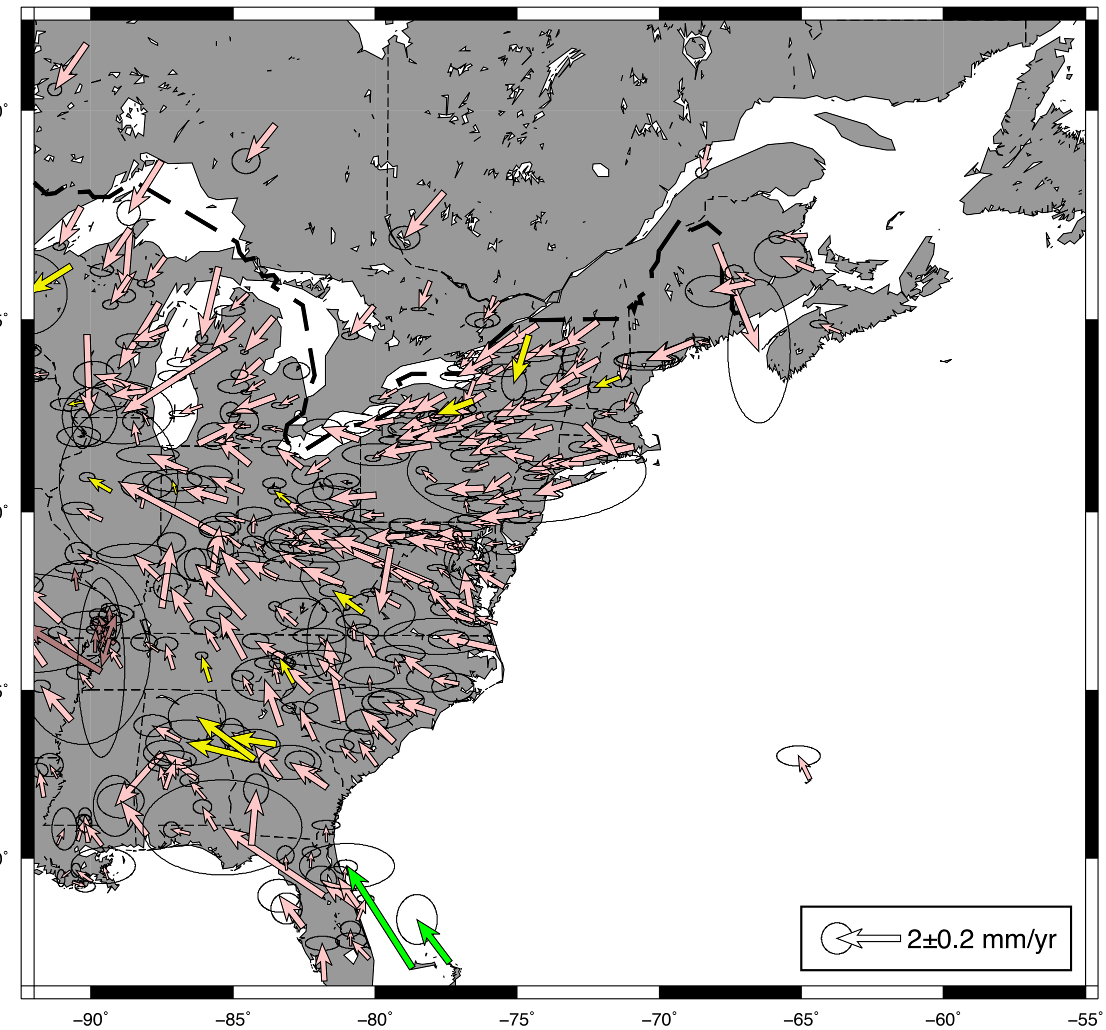



**Figure 14:** Same as Figure 10 except for the Eastern United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown. The systematic western velocity of sites in the North east is being investigated.

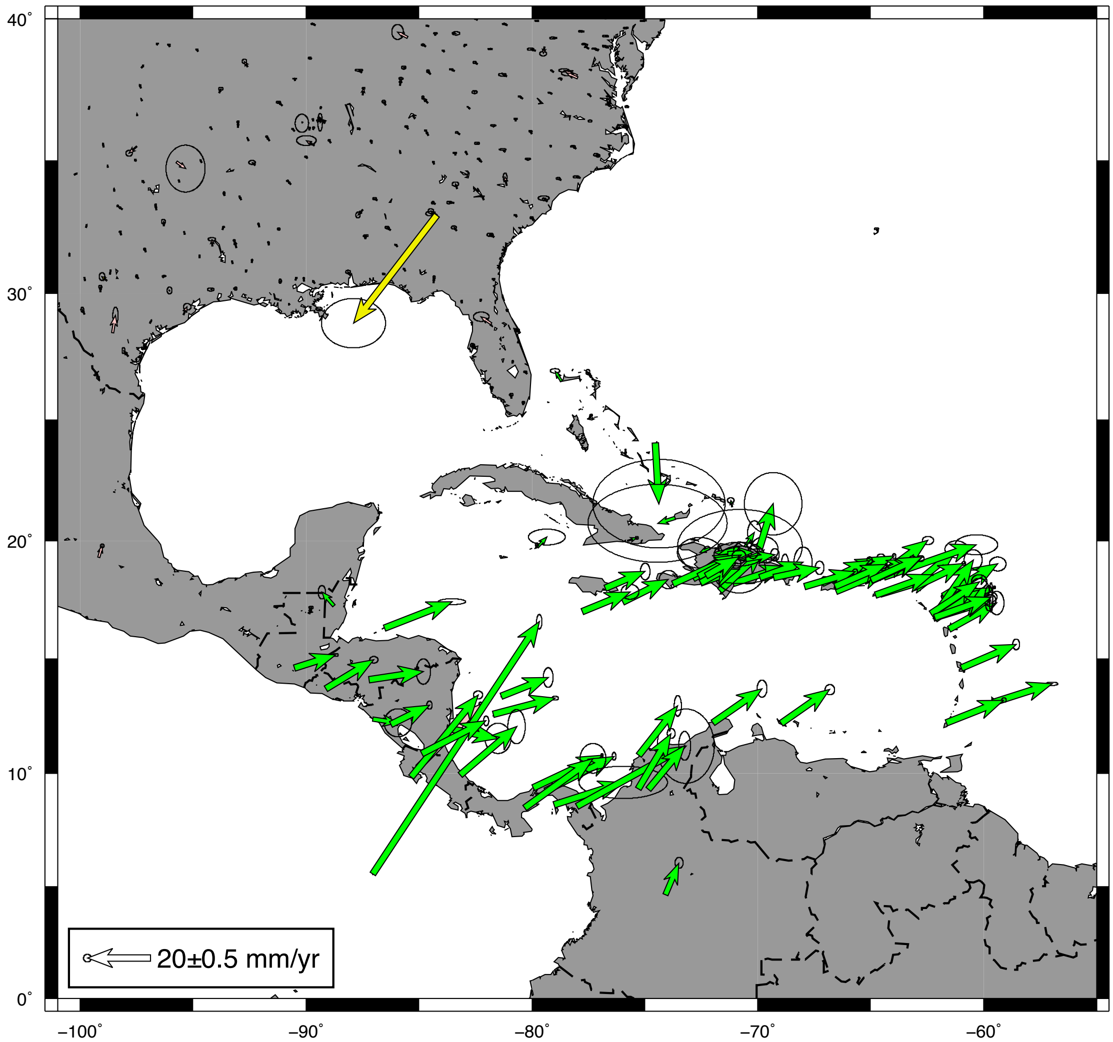



**Figure 15:** Same as Figure 10 except for the Caribbean region. Only velocities with horizontal standard deviations less than 10 mm/yr are shown. The anomalous yellow vector in the southeastern United states is P806 which has a failed antenna that was not accounted for in this analysis.

*Earthquake Analyses: 2014/01/01-2014/03/31.*

We use the NEIC catalog to search for earthquakes that could cause coseismic offsets at the sites analyzed by the GAGE analysis centers. We examined the following earthquakes:

```
* EQ_DEF M4.5 6km NW of The Geysers
 eq_def   38.8135 -122.8162     11.5 8 2014 01 12 20 25    0.003
* EQ_DEF M6.4 61km N of Hatillo
 eq_def  19.0408  -66.8054     82.4 8 2014 01 13 04 02    0.404
* EQ_DEF M4.4 5km N of Fontana
 eq_def   34.1430 -117.4425     11.1 8 2014 01 15 09 36    0.003
```

* EQ_DEF M3.7 47km WSW of Anchorage
eq_def 61.0262 -150.6881 9.0 8 2014 03 09 16 12 0.000
and found no offsets in the time series of the GAGE sites likely to be affected by these events. However the 2014/03/01 M6.8 8.8 km WNW of Ferndale did generate observed coseismic offsets and event files
pbo_140310_0519_EQ29_coseis_rapid.evt.20140317114927
pbo_140310_0519_EQ29_coseis_rapid.ps.20140317114927
were sent to UNAVCO. This event was numbered 29.

*Antenna Change Offsets: 2014/01/01-2014/03/31*

The follow antenna changes were investigated and reported on in the MIT ACC monthly reports.

```
Site      Date            From           To
1LSU 2014  1 14 18 31   TRM41249.00     TRM57971.00
BRTW 2014  1 31  0  0   ASH701933A_M    LEIAR20
COVG 2014  1  7 18 57   ASH701945E_M    TRM57971.00
FZHS 2014  1 10  0  0   ASH701945B_M    TRM57971.00
MSCG 2014  1 22 21 48   TPSCR.G3        TRM57971.00
NYPF 2014  1 22 15  0   LEIAT504        LEIAR10
OKCB 2014  1 31 14  0   ASH701945C_M    LEIAR20
OLVN 2014  1  2 18 32   ASH701945B_M    TRM59800.00
P122 2014  2  4  0  0   TRM29659.00     TRM59800.00
P130 2014  1 29 21 58   TRM29659.00     TRM59800.80
P392 2014  1 15 20 42   TRM29659.00     TRM59800.80
P412 2014  2  5  0  0   TRM29659.00     TRM59800.00
P423 2014  1 28 19 45   TRM29659.00     TRM59800.80
P816 2014  1 30 20 22   TRM59800.00     TRM59800.00
PBCH 2014  1 29 14  0   ASH701933A_M    LEIAR20
THMG 2014  1 23 21  8   TPSCR.G3        TRM57971.00
MTNT 2014  2 26 17  0   ASH701933C_M    LEIAR20
NAPL 2014  2 26 14  0   ASH701933C_M    LEIAR20
P122 2014  2  4  0  0   TRM29659.00     TRM59800.00
P132 2014  2 23 20 38   TRM29659.00     TRM59800.00
P235 2014  2 25 21 12   TRM29659.00     TRM59800.00
P412 2014  2  5  0  0   TRM29659.00     TRM59800.00
SC01 2014  2 25 17 55   TRM29659.00     TRM59800.80
```

The MTNT antenna change results ultimately in ~+10-15 mm height change when processed correctly. If the meta data is not corrected, the height error is ~+90 mm.

```
The NAPL site behaved the same as MTNT:
P122: Offsets NEU -10.47 +- 0.13,   3.15 +- 0.16,   9.93 +- 1.45 mm
P132: Offsets NEU   3.99 +- 0.26,  -0.03 +- 0.23,   1.54 +- 1.83 mm
P235: Offsets NEU   3.12 +- 0.23,  -4.44 +- 0.21,   5.77 +- 1.51 mm
P412: Offsets NEU   3.85 +- 0.10,  -1.73 +- 0.14,   6.82 +- 0.76 mm
ETS site
SC01: Offsets NEU   5.49 +- 0.20,   5.72 +- 0.22,  -0.40 +- 1.11 mm
Large gap between 2013 08 03 and 2014 02 25
```

We noted in our reports that the changes to TRM57971.00 antennas are often (but not always) show +3-4 mm East shifts.

*Anomalous height results in the CWU time-series*

Anomalous height estimates in the CWU solutions have been reported and the problem seems to have arisen from bad widelane ambiguity (L1-L2 number of cycles) resolution by the JPL analysis center for the Goldstone site. For much of the reprocessing results, CWU was using these anomalous results which affected their solutions. We show an example of the effect of this problem in Figures 16- .

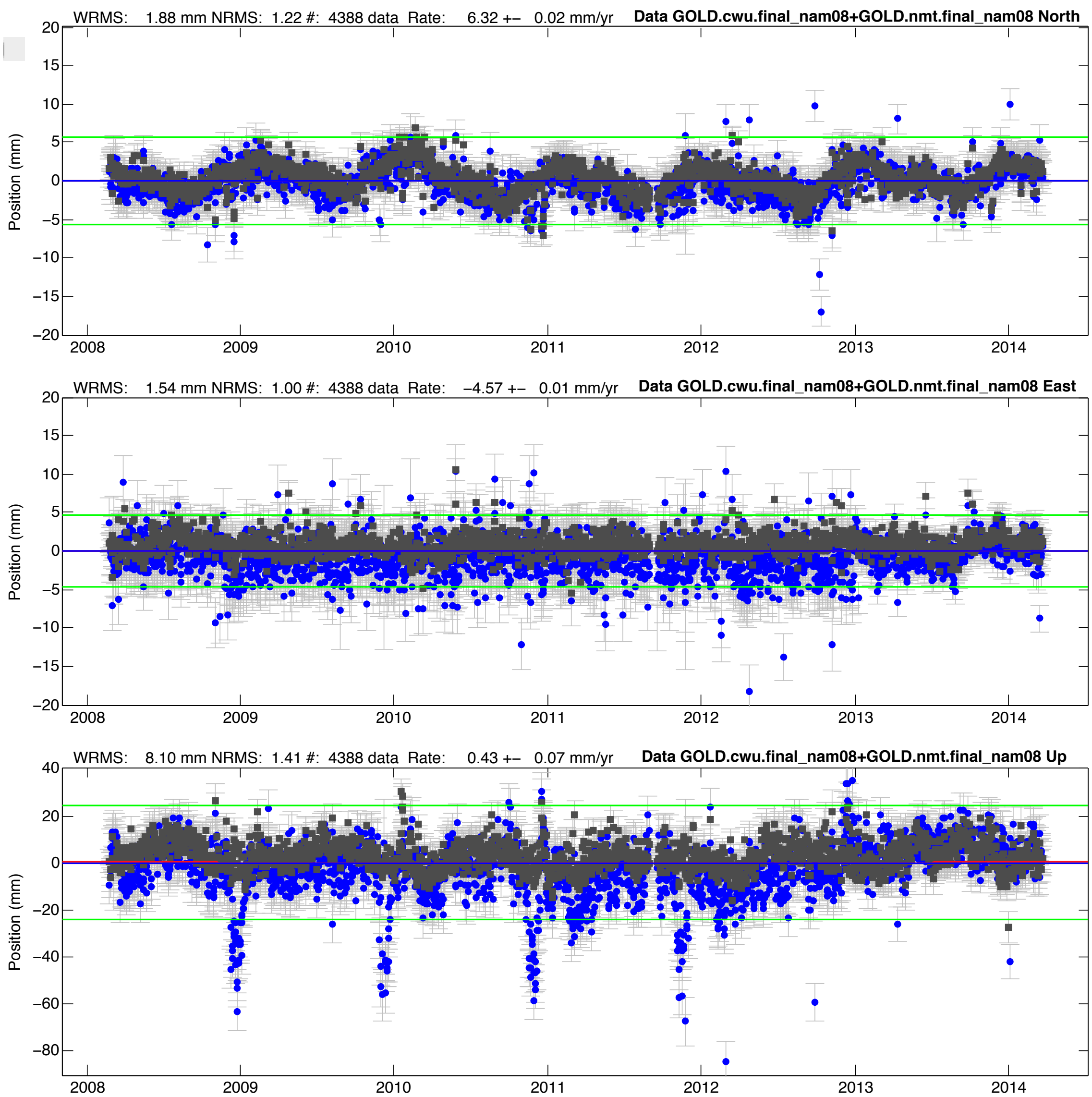



**Figure 16**: Ambiguity resolution anomaly in the CWU reprocessing results. The blue symbols show CWU detrended results in North, East and Up for the post 2008 Goldstone data. The black symbols show the NMT solution which does not show the anomalous height deviation in late 2009-2012. The east scatter in general is higher the CWU solution. During the interval the WRMS scatters of the CWU analysis in NEU are 2.1, 2.4 and 11.8 mm compared to the NMT analysis with scatters of 1.7, 1.1 and 5.6 mm.

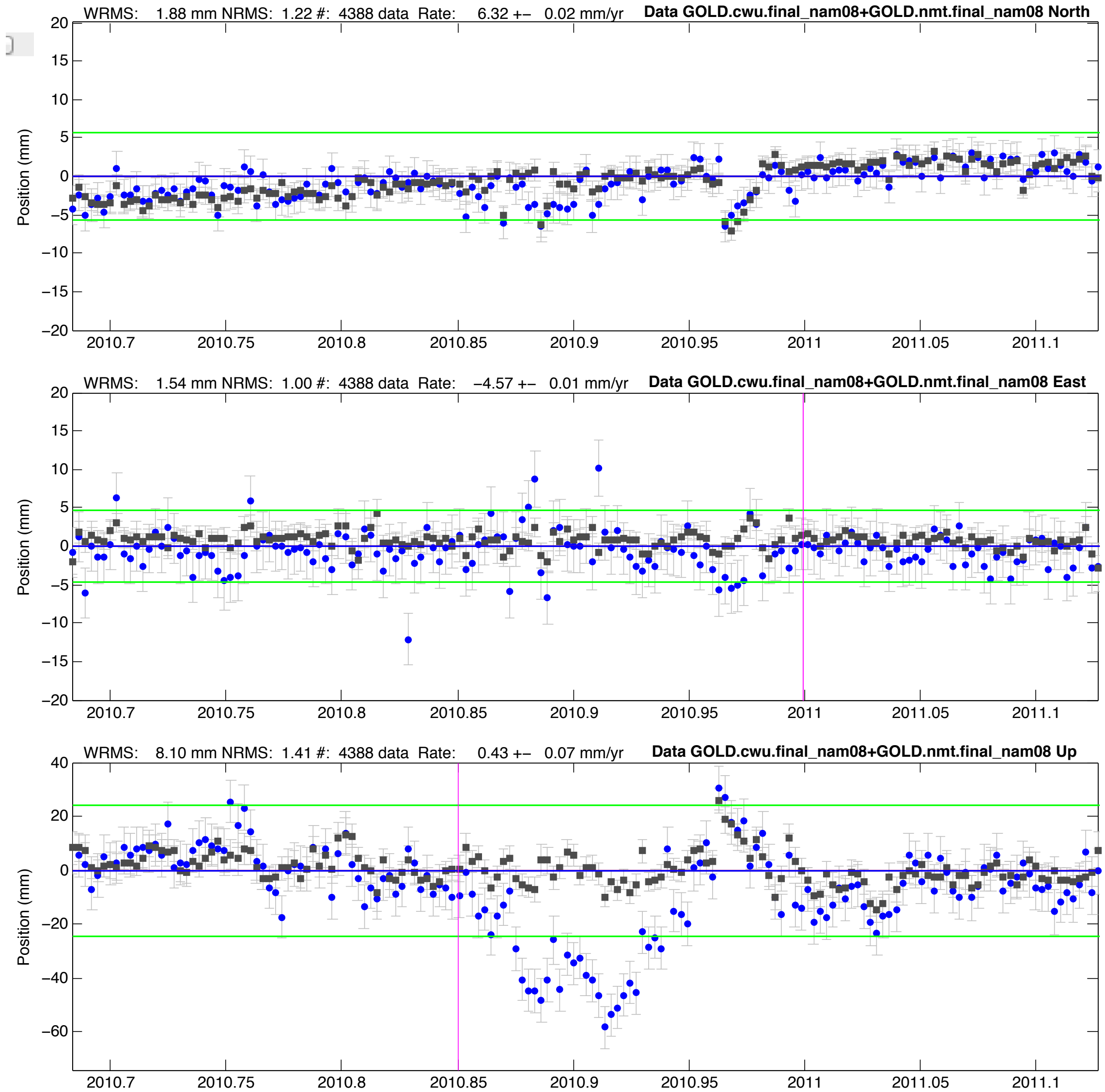



**Figure 17:** Zoom of the 2010 anomaly showing the excursion is largest between Nov 1, 2010 and mid-December.

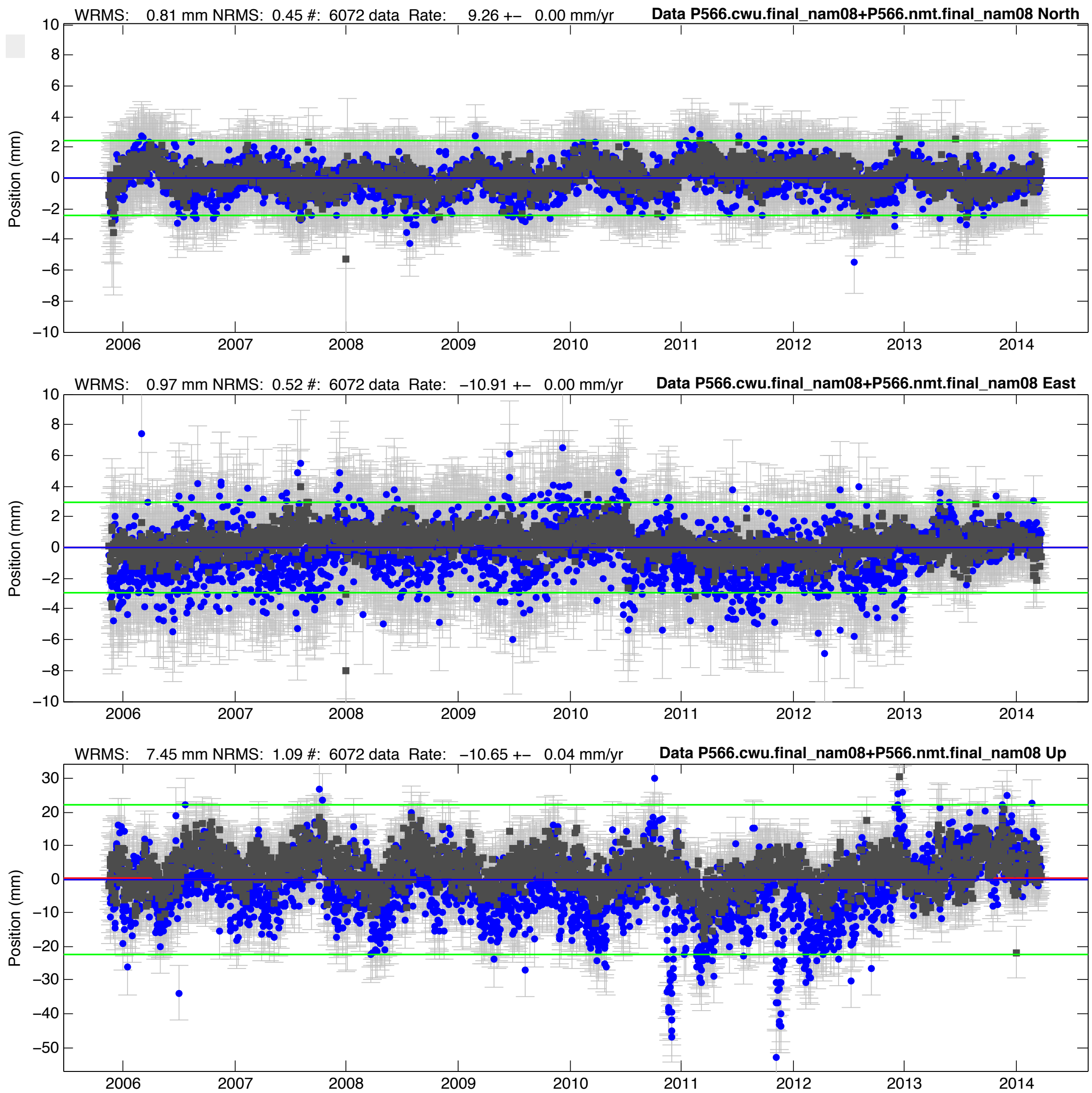



**Figure 18:** Central Valley site P566 also affected by the anomaly shown on Figure 16. For most sites, the effect seems largest at the ends of 2010 and 2011 and generally starts around Nov 1 of each year.

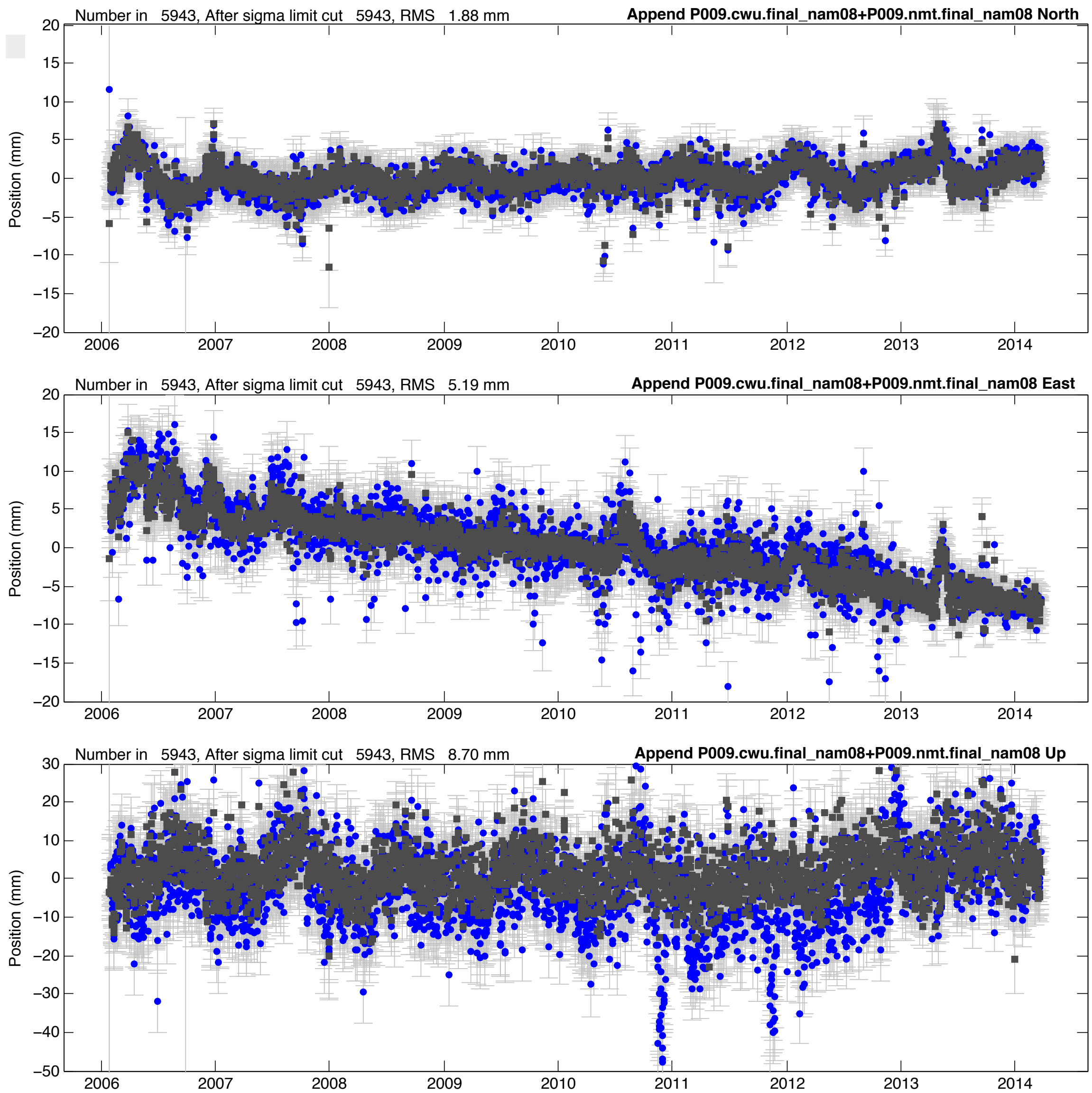



**Figure 19:** More distant sites P009, 500 km from Goldstone still showing anomaly.

*Script updates*

Despite our efforts to develop scripts which would not overflows the LMD queues before the UNAVCO archive was able to transfer SINEX files to the community accessible areas, analysis of the contents of the archives shows that there are occasional missing files. We are limited at 50 Gbytes per day in our transfer of reprocessed SINEX files which means that no more than 10-weeks of solutions per day can be transferred to UNAVCO. We expect that the reprocessed SINEX files should be all transferred to UNAVCO by April 20, 2014. When the transfer is complete, we will develop new scripts that make a comprehensive comparison of our products directory with the products available at UNAVCO and which will re-queue the missing products in batches not to exceed 50 Gbytes per day. When this script completes and the data have been thought to be transferred we will repeat the process. Hopefully it will converge.

**GAMIT/GLOBK Community Support**

During this period we carried out routine development of the GAMIT/GLOBK software: minor enhancement of 6 features, table updates of PRN reassignments for 5 satellites, and support for 3 new receivers and 12 new antennas. We began in late March major enhancements of the software to incorporate models to be consistent with IGS standards for the second reprocessing of the global data and an eventual reprocessing of PBO: Kouba model for satellite yaw, general relativity effects in satellite orbits, updated coefficients for the solid-Earth pole tide, and implementation of the ocean pole tide.

There were no workshops, but we spent 5-10 hours per week in email support for users. During this period, we issued royalty-free licenses to 18 new users from universities and government laboratories.