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

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Period: 2017/04/01-2017/06/30

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Summary

Under the GAGE Facility Data Analysis subaward, 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 2016/03/15 to 2017/06/10, time series velocity field analyses for the GAGE reprocessing analyses (1996-2017). Several earthquakes were investigated this quarter but none generated coseismic displacements > 1mm. There were some earthquakes that could not be assessed due to no available post-earthquake data although the expected magnitudes for an coseismic displacements were small. For this quarter, the last finals results were for June 10, 2017. Associated with the report are the ASCII text files that are linked into this document.

Our monthly reports now contain the estimates of the offsets in the time series due to equipment changes and earthquakes and we generate events files for coseismic offsets and postseismic log terms (when needed) using a Kalman filter time series analysis.

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

GPS Analysis of Level 2a and 2b products

ITRF2014 transition

The GAGE analyses are in a transition between the ITRF2008 and ITRF2014 systems. For GPS analyses, the realizations of these systems are IGb08 and IGS14. The critical elements of the realizations are the coordinates and motions of reference frame sites (ITRF2014 has parameterized postseismic motions, where needed, in addition to linear motions) and the antenna phase center patterns and offsets. For IGS14 there is a small 0.3 ppb scale change embedded in the patterns that results from a systematic orbit radial changes associated with Earth albedo and antenna thrust forces, and there are several antennas with updated phase center patterns based on robotic arm calibrations. The details of this transition are discussed in https://www.unavco.org/data/gps-gnss/derived-products/docs/GAGE_IGS14_transition_plan_20170327.pdf

Level 2a products: Rapid products

Final and rapid level 2a products have been in general 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. The rapid products are generated in IGS14 by CWU. NMT uses IGS08 to be consistent with the methods used for the final products.

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 remains about the same. In this quarter 1833 stations were processed which is 6 fewer than last quarter. The CWU finals and other products are generated with IGb08 consistent orbits and clocks generated by JPL. NMT results are generated using the IGS14 orbits but still retaining the IGb08 antenna model file to be consistent with the CWU analyses.

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.

Analysis of Final products: March 15, 2017 and June 10, 2017

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 1996 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 March 15, 2017 and June 10, 2017. 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 station 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 or equal 1.02 mm for all centers and as low as 0.79-0.81 mm for NMT north and PBO east components. The up-RMS scatters are less than or equal 4.55 mm for all analyses and as low as 3.86 mm for the PBO solution. These statistics are a little less than last quarter. Seasonal changes in atmospheric delay properties will introduce small variations in these values quarter to quarter. 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 1833, 1832 and 1831 stations for PBO, NMT and CWU analyzed in the finals analysis between March 15, 2017and June 10, 2017. Histograms of the RMS scatters are shown in Figure 1-3.

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
PBO	0.82	0.81	3.86
NMT	0.79	0.83	3.89

CWU	1.02	0.95	4.55
70%			
PBO	1.00	1.00	4.39
NMT	0.98	1.01	4.47
CWU	1.21	1.15	5.16
95%			
PBO	1.86	1.85	6.15
NMT	1.84	1.89	6.44
CWU	2.13	2.11	7.57

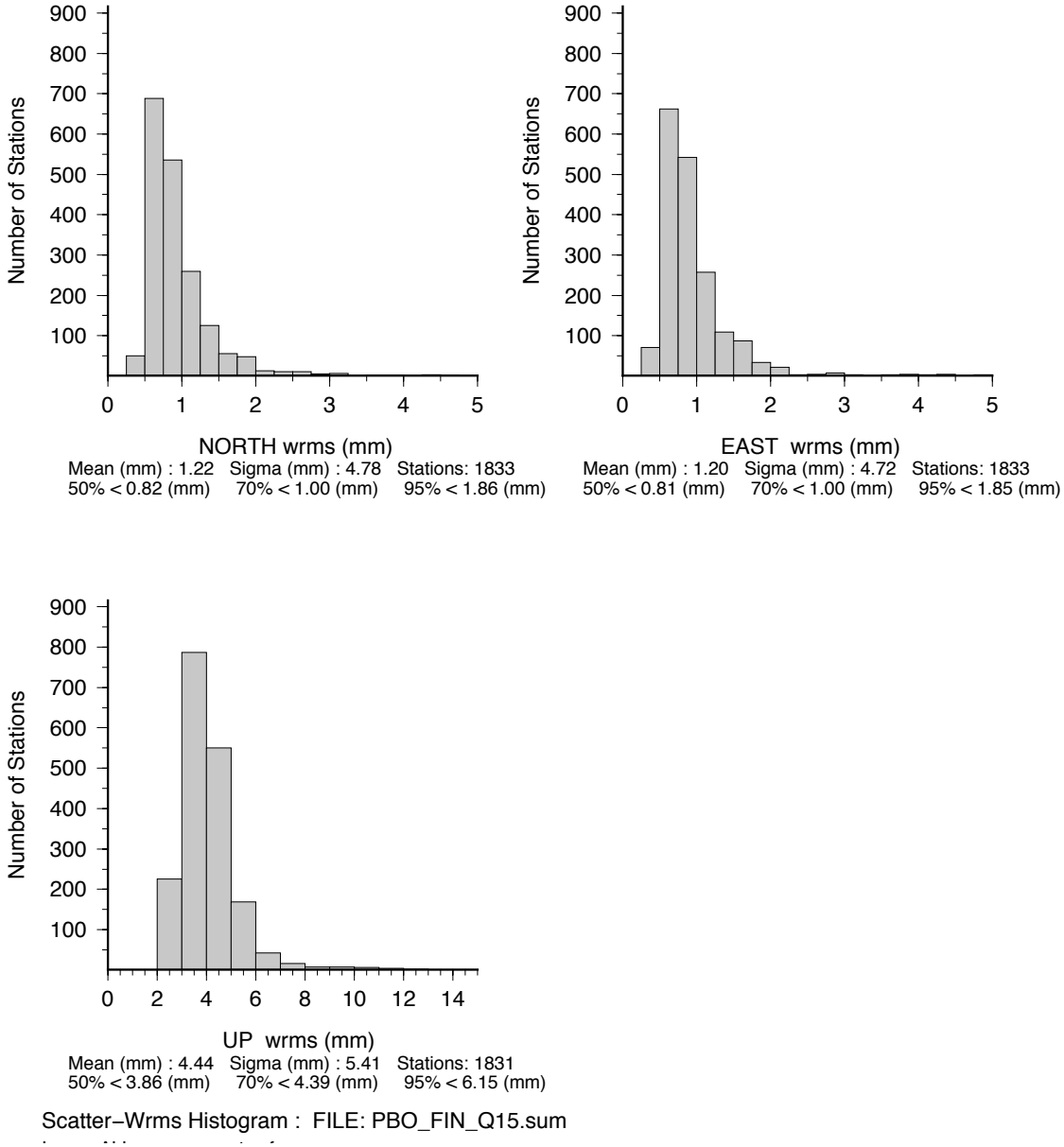

Figure 1: PBO combined solution histograms of the North, East and Up RMS scatters of the position residuals for 1833 stations analyzed between March 15, 2017 and June 10, 2017. Linear trends and annual signals were estimated from the time series.

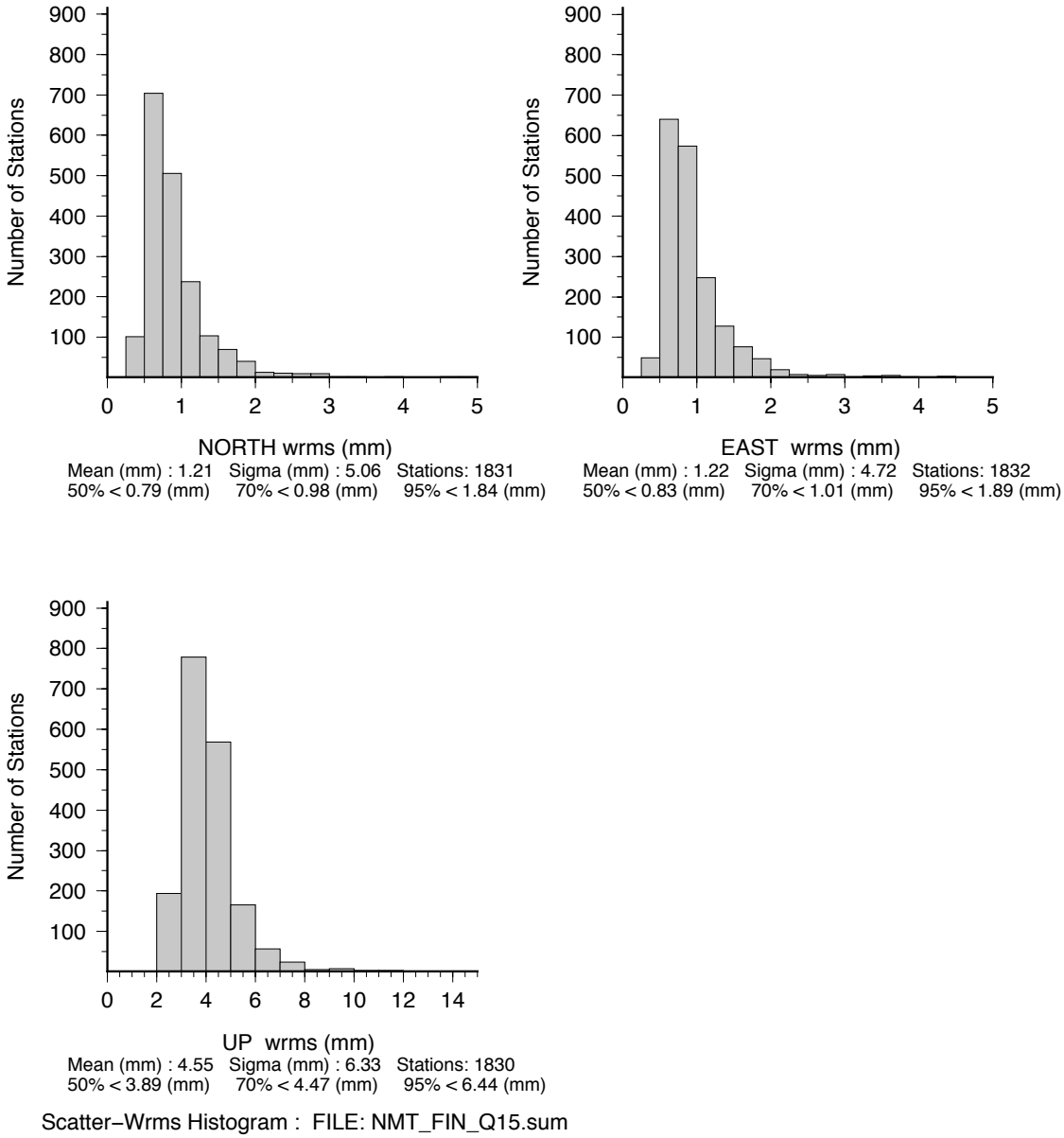

Figure 2: NMT combined solution histograms of the North, East and Up RMS scatters of the position residuals for 1832 stations analyzed between March 15, 2017 and June 10, 2017. Linear trends and annual signals were estimated from the time series.

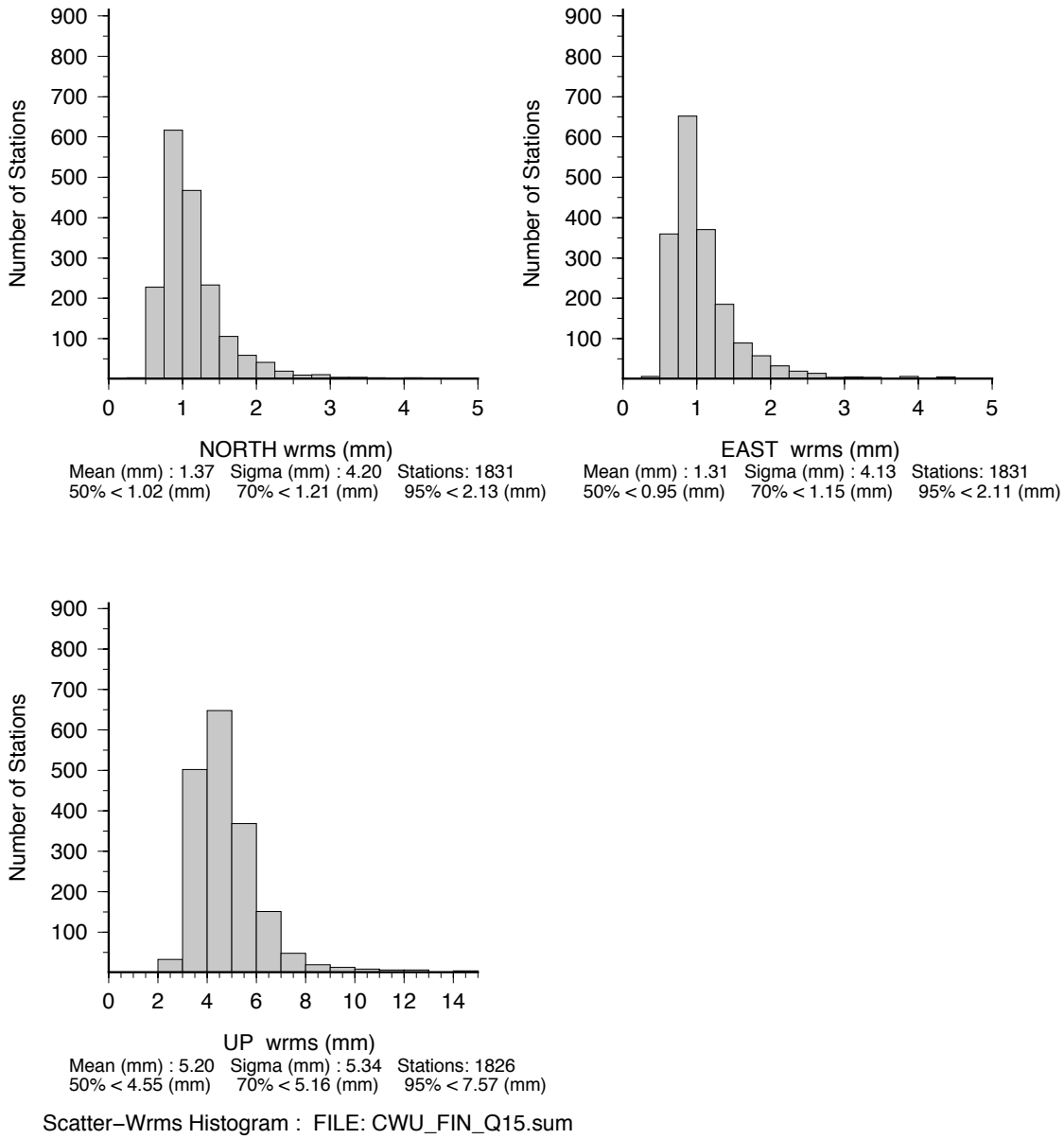

Figure 3: CWU combined solution histograms of the North, East and Up RMS scatters of the position residuals for 1831 stations analyzed between March 15, 2017 and June 10, 2017. Editing removes two stations for North and Up. Linear trends and annual signals were estimated from the time series.

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 nominally 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_Q15.tab. There are 1831 stations in the file for sites that have at least 2 measurements during the month. The contents of the files are of this form:

```
Tabular Position RMS scatters created from PBO_FIN_Q15.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    79      1.1   0.51      1.1   0.50     6.0   0.59     14.13
 1NSU    88      0.8   0.47      0.9   0.55     4.6   0.62     13.40
 1ULM    82      0.9   0.51      1.1   0.70     3.9   0.56     13.99
 7ODM    78      1.0   0.68      0.7   0.53     3.2   0.59     16.14
…
 ZBW1    88      0.7   0.36      0.9   0.54     4.0   0.57     14.02
 ZDC1    88      0.8   0.40      0.8   0.51     4.3   0.62     14.02
 ZDV1    88      0.8   0.41      0.9   0.54     5.2   0.75     14.02
 ZKC1    88      0.8   0.40      0.6   0.40     4.8   0.71     14.02
 ZLA1    87      1.3   0.66      1.1   0.59     3.9   0.53     14.02
 ZME1    88      1.1   0.58      0.8   0.49     4.8   0.65     14.25
 ZMP1    87      0.7   0.34      0.6   0.38     4.4   0.67     14.49
 ZNY1    88      0.8   0.38      0.7   0.45     3.5   0.51     14.40
 ZSE1    88      0.7   0.32      0.7   0.42     3.8   0.56     14.40
 ZTL4    88      0.9   0.48      0.8   0.49     4.4   0.60     14.60
```

Table 2: RMS scatter of the position residuals for the PBO combined solution between March 15, 2017 and June 10, 2017 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	0.77	0.77	3.64	869
NUCLEUS	0.76	0.74	3.45	204
GAMA	0.73	0.72	4.64	15
COCONet	1.24	1.22	5.11	107
USGS SCIGN	0.83	0.79	3.41	132
Expanded	0.84	0.83	4.23	506
70%				
PBO	0.96	0.95	4.13	
NUCLEUS	0.90	0.86	3.82	
GAMA	0.79	0.77	4.69	
COCONet	1.38	1.44	5.73	
USGS SCIGN	1.03	1.02	3.86	
Expanded	0.98	1.01	4.58	
95%				
PBO	1.84	1.83	5.75	
NUCLEUS	1.54	1.40	5.41	
GAMA	0.86	0.87	5.41	
COCONet	2.11	2.88	9.49	
USGS SCIGN	1.96	1.69	5.76	
Expanded	1.76	1.83	6.21	

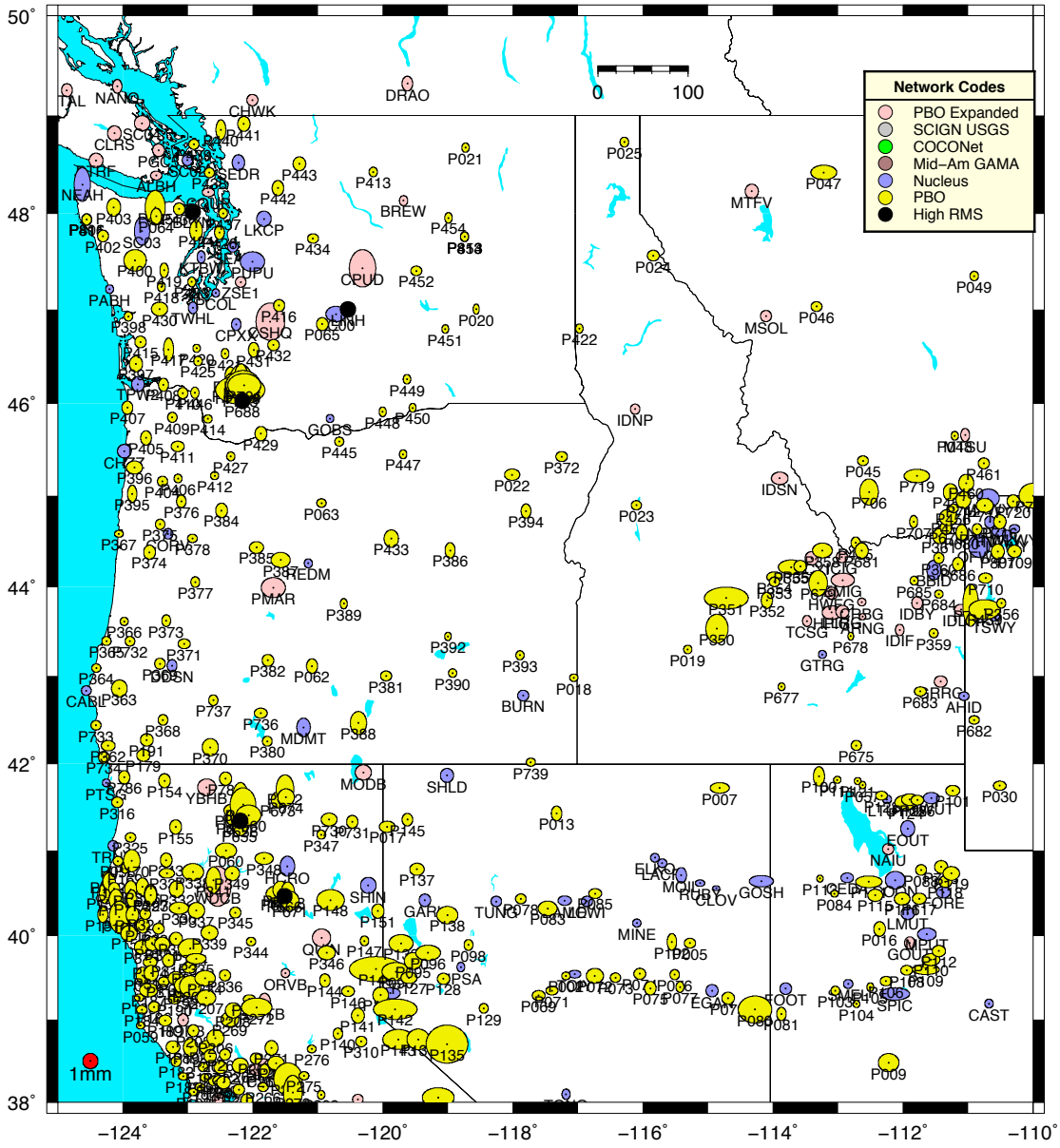

Figure 4: Distribution of the RMS scatters of horizontal position estimates from the PBO combined analysis for the Northern Western United States. The color of the ellipses that give the north and east RMS scatters denotes the network given by the legend in the figure. The small red circle shows the 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 that have no data during this 3-month interval.

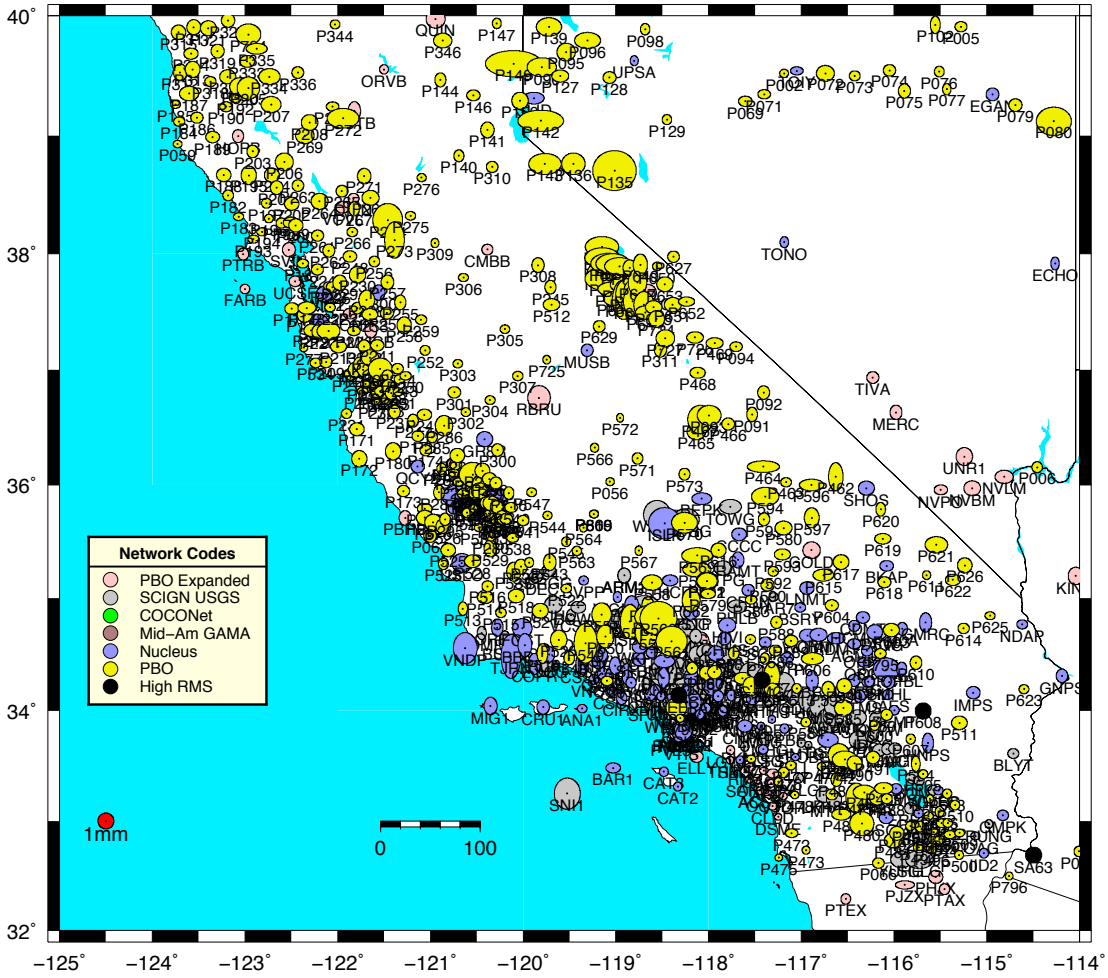

Figure 5: Same as Figure 4 except for the Southern Western United States. Black circles in the Yucca mountain region have no data during this 3-month period.

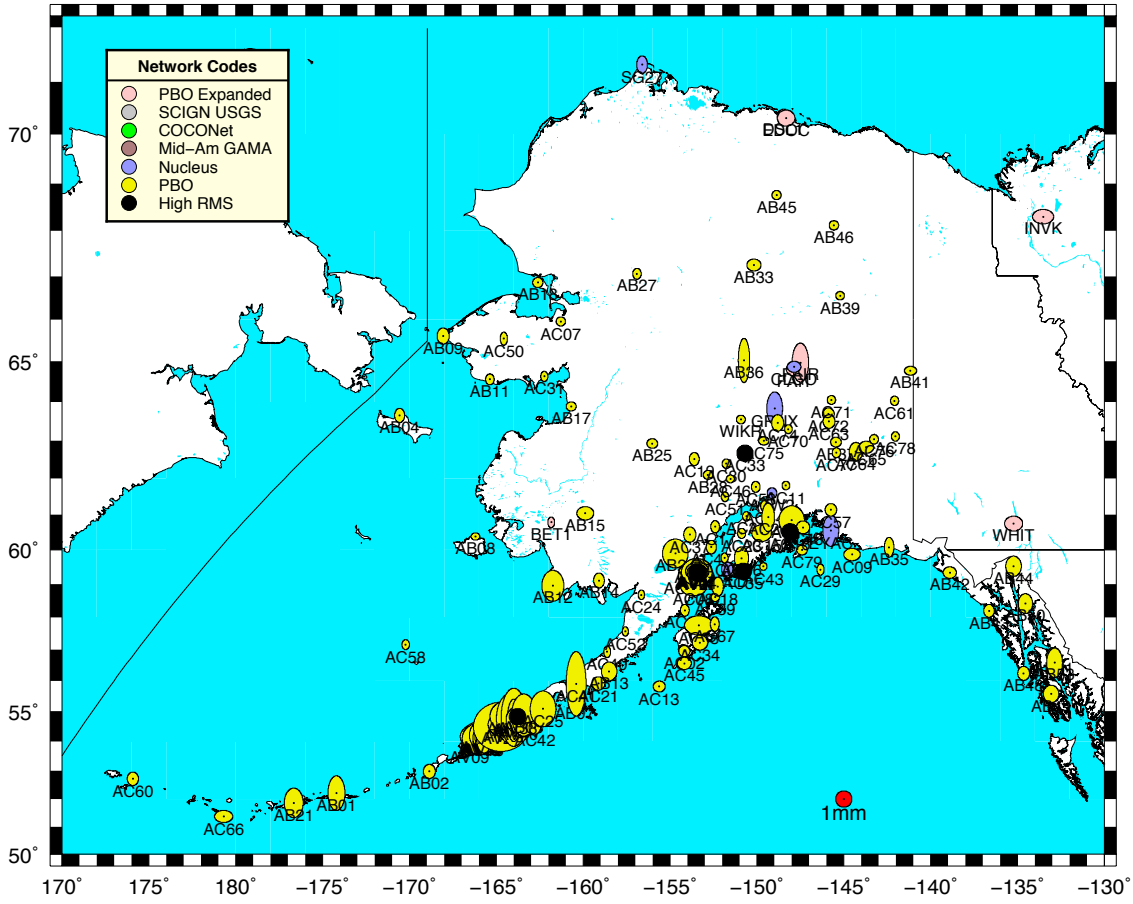

Figure 6: Same as Figure 4 except for the Alaskan region.

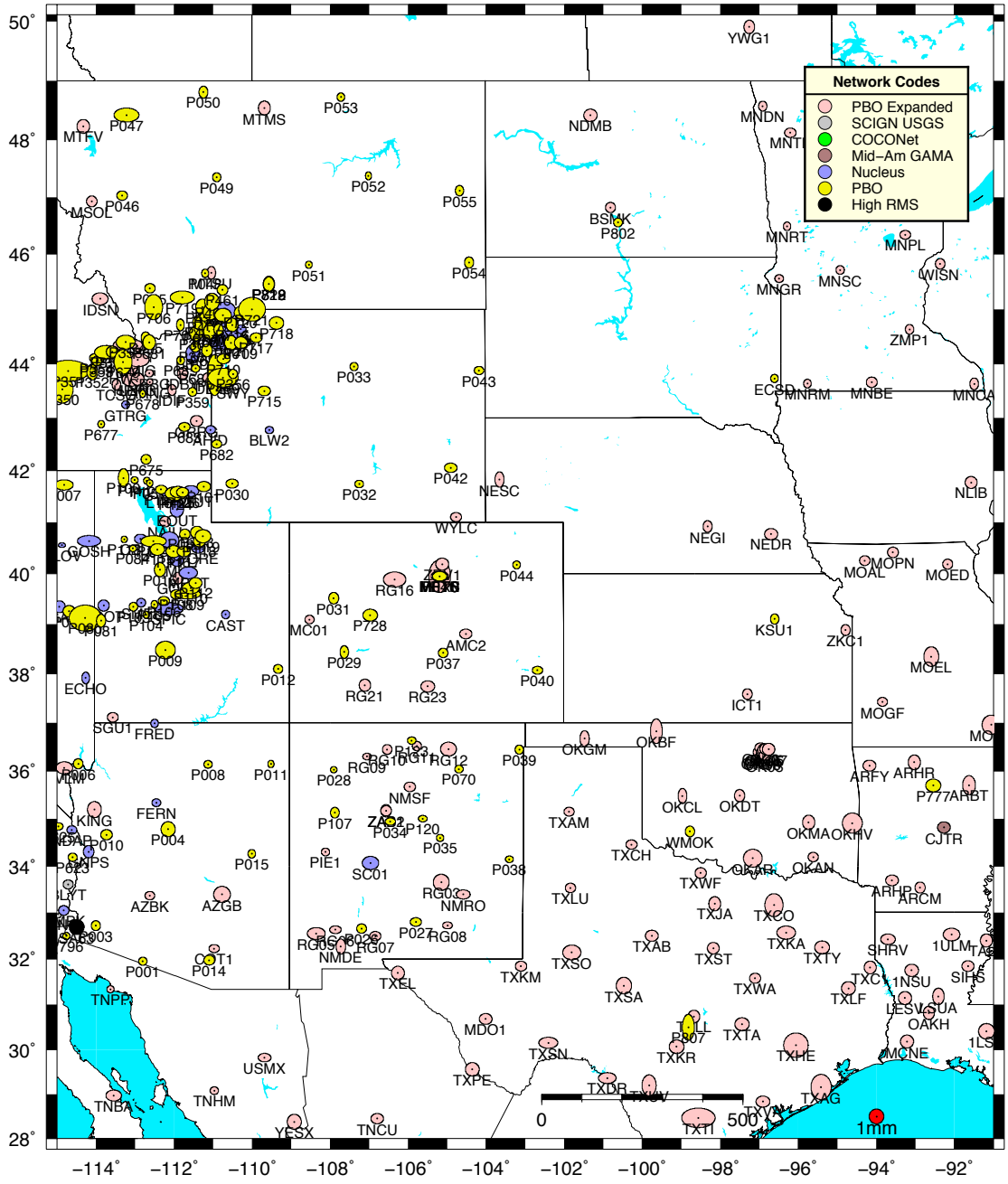

Figure 7: Same as Figure 4 except for the Central United States

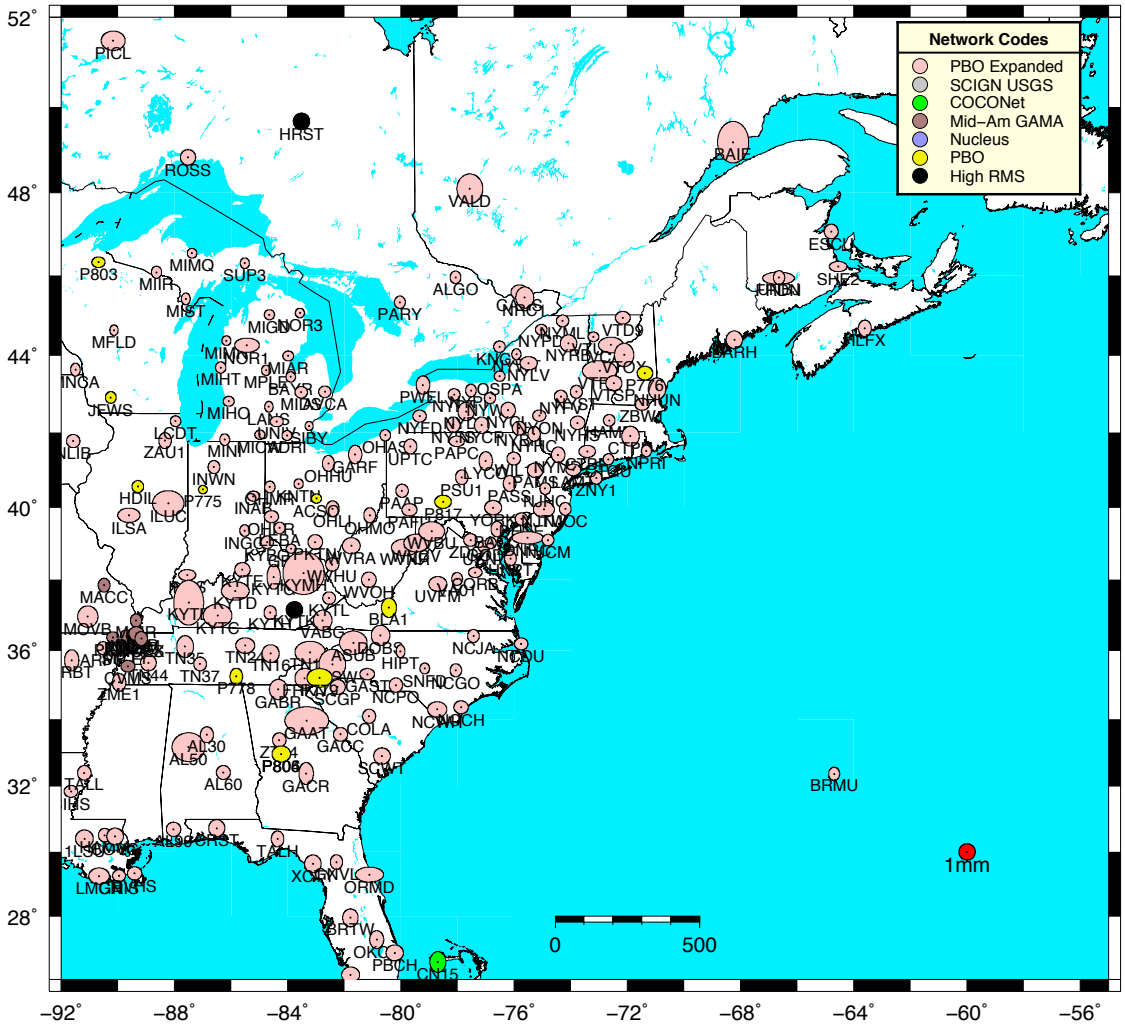

Figure 8: Same as Figure 4 except for the Eastern United States

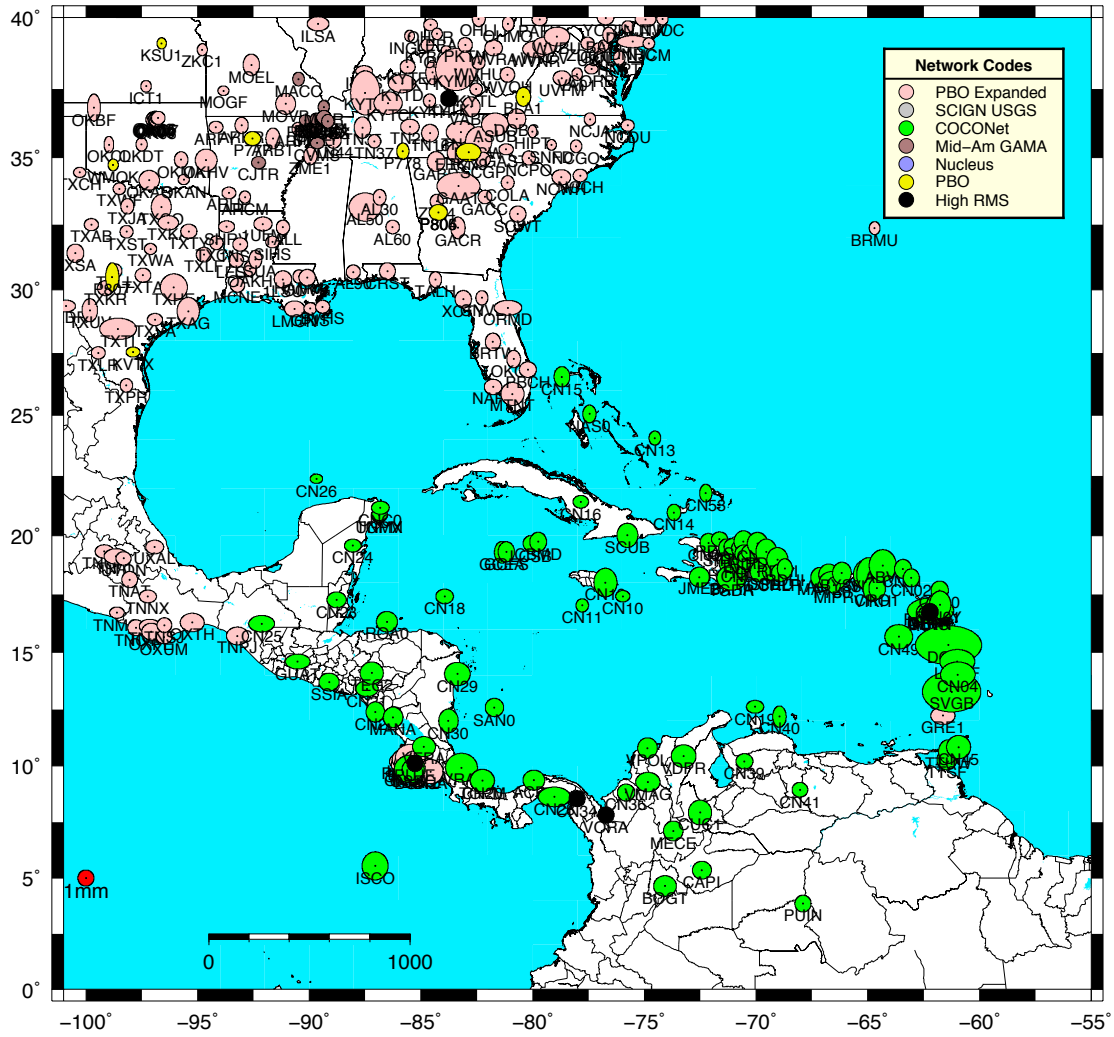

Figure 9: Same as Figure 4 except for the Caribbean region.

GLOBK Apriori coordinate file and earthquake files

As part of the quarterly analysis we run complete analysis of the time series files and generate position, velocity and other parameter estimates from these time series. These files can be directly used in the GLOBK analysis files sent with the GAGE analysis documentation. These links point to the current earthquake and discontinuity files used in the GAGE ACC analyses: All_PBO_eqs.eq All_PBO_ants.eq All_PBO_unkn.eq. The GLOBK apriori coordinate file All_PBO_nam08.apr is the current estimates based on data analysis in this quarterly report. Starting in Q06, we added a GLOBK apriori coordinate file based on the latest SNIPS PBO velocity file that are generated monthly. The SNIPS file updates the coordinates and velocities of stations that have changed in some significant fashion since the generation of the primary apriori coordinate file. The current file is All_PBO_nam08_snips.apr. Both of these apriori files are read with the –PER option in GLOBK (i.e., no periodic terms are applied). In these files, comments have a non-blank character in the first column and text after a ! in lines is treated as a

comment. The apriori file contains Cartesian XYZ positions and velocities in meters with the epoch of the position in decimal years (day of year divided by days in the specific year). The comments contain the standard deviations of the estimates and are not specifically used in GLOBK (yet). The GEOD lines give geodetic coordinates and not directly used (information only). The EXTENDED lines give the extended parts of the model parameters. Specifically, OFFSETS are NEU position and velocity offsets at the times of discontinuities. The velocity changes are all zero in the PBO analyses. The Type in the comment at the end of line indicates the type of offset. If a name is given, then this is an antenna or unknown origin offset. For earthquakes, EQ is the type and two characters after is the code for the earthquake. If postseismic motion is model, then LOG or EXP EXTENDED lines will appear. The time constant of the function is given after the date (days) and the amplitudes in meters in NEU frame is given after that. The comment contains the standard deviations in mm. PERIODIC terms give the period (days) after the date and then cosine and sine terms in NEU. The periodic terms are not used in the standard GLOBK analyses. The comment contains the standard deviations. The GLOBK apriori coordinate file contains annual periodic terms but these are not used in the daily reference frame realization.
When interpreting the offsets in the apriori file, it is important to note that these are obtained for a simultaneous analysis of all data from a site. If the residuals to the fit are systematic, the offsets often will not be the same as an offset computed from analysis of shot spans of data on either side of the offset. We are considering adding such an analysis type in the future.
The Kalman filter estimated offsets are now supplied monthly as part of the monthly reports.

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. We have now started to distribute the snapshot fields (SNAPS) and the significant updates to the standard PBO velocity file (SNIPS file) in standard PBO velocity field format. These files are distributed in the monthly reports. For this quarterly report, we generate these velocity estimates for the reprocessed results and the current GAGE analyses that are in the NAM08 reference frame. There are 2224 stations in the combined PBO solution which is slightly larger than the 2207 stations reported in the last quarter. 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 fit along with the duration of the data used are given in the following linked files: pbo_nam08_170610.tab, nmt_nam08_170610.tab and cwu_nam08_170610.tab. The velocity estimates are shown by region and network type in Figures 10-16. The color scheme used is the same as Figures 4-9. The snapshot velocity field files are linked as: pbo_nam08_170610.snpvel, nmt_nam08_170610.snpvel and cwu_nam08_170610.snpvel.

Table 3: Statistics of the fits of 2224, 2223 and 2216 stations analyzed by PBO, NMT and CWU in the reprocessed analysis for data collected between Jan 1, 1996 and June 10, 2017.

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
NMT	1.12	1.22	5.80
CWU	1.34	1.32	6.03
PBO	1.13	1.18	5.36
70%			
NMT	1.48	1.57	6.53
CWU	1.66	1.63	6.81
PBO	1.45	1.49	6.03
95%			
NMT	3.22	3.21	9.26
CWU	3.45	3.31	10.30
PBO	3.26	3.16	8.96

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 that 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 0.07 mm/yr horizontal and 0.70 mm/yr vertical from differences of all stations in the two solutions that have velocity sigmas that sum to less than 100 mm/yr. This is a small change from previous reports and now only common stations are now compared and nearby stations have been removed. The χ^2/f of the difference is $(1.03)^2$ for the horizontal and $(1.96)^2$ for the vertical component. These comparisons are summarized in Table 4. As noted in previous reports, adding small minimum sigmas (added in a root-sum-squared sense), computed such that χ^2/f is near unity changes the statistic slightly (Table 4). With the FOGMEX correlated noise model used to compute the velocity sigmas, the comparison statistics are close but still 3-96% optimistic over expectations. The 10-worst stations, in the order they are removed, are P797, P497, P502, MTA1, DSME, P483, P509, P599, P556, MYT2 when the added sigmas are not applied and P562, P797, P497, P502, DSME, P556, P599, P483, P509, MYT2 when the values given in Table 4 are sum-squared into the velocity sigma estimates. This list is similar to the list in the previous quarter although this time we have split the list into two parts. Some stations have been added and others removed.

Table 4: Statistics of the differences between the CWU and NMT velocity solutions with no transformation between them. The stations common to the CWU and NMT solutions are used which is a slightly smaller number than in either solution. The PBO, NMT and CWU solutions themselves have 2224, 2223 and 2216 stations whose velocities can be determined to better than 100 mm/yr. WRMS is weighted-root-mean-scatter and NRMS is $\sqrt{(\chi^2/f)}$ where f is the number of comparisons.

Solution	#	NE WRMS (mm/yr)	U WRMS (mm/yr)	NE NRMS	U NRMS
All	2206	0.08	0.76	1.10	1.86
Edited-10_worst	2196	0.07	0.74	1.03	1.83
Less than median (0.15 0.53 mm/yr)	1204	0.06	0.67	1.06	1.98
Added minimum sigma NE 0.01 U 0.50 mm/yr					
All	2206	0.08	1.00	1.07	1.07
Edited-10_worst	2196	0.08	0.98	1.00	1.04
Less than median (0.15 0.73 mm/yr)	1204	0.06	0.77	1.02	0.91

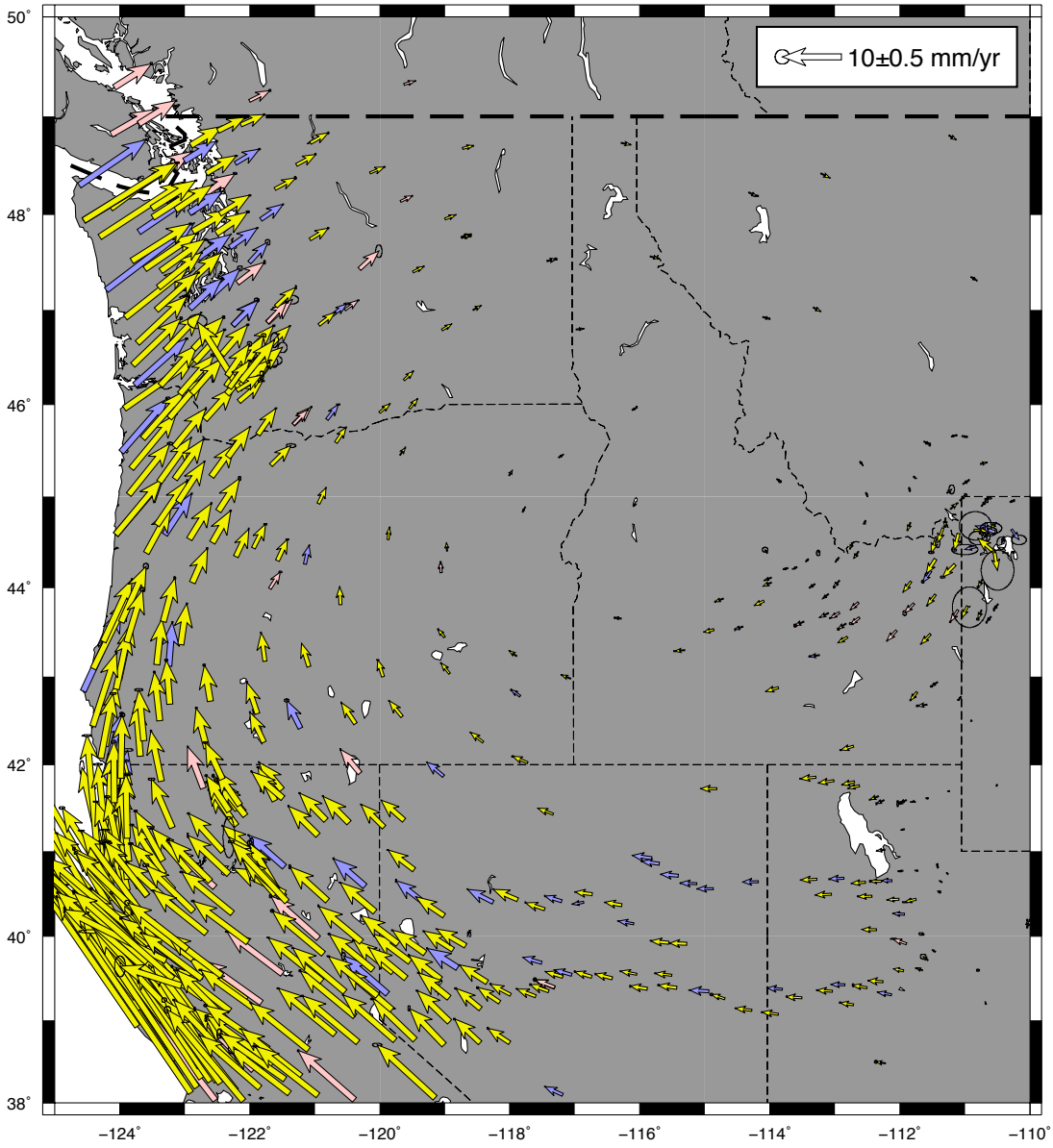

Figure 10: Velocity field estimates from the combined PBO solutions generated using time series analysis and the FOGMEX error model. 95% confidence interval error ellipses are shown. The color scheme of the vectors matches the network type legend in Figure 4. Only velocities with horizontal standard deviations less than 2 mm/yr are shown (this value is reduced from previous reports due the improved velocity sigmas).

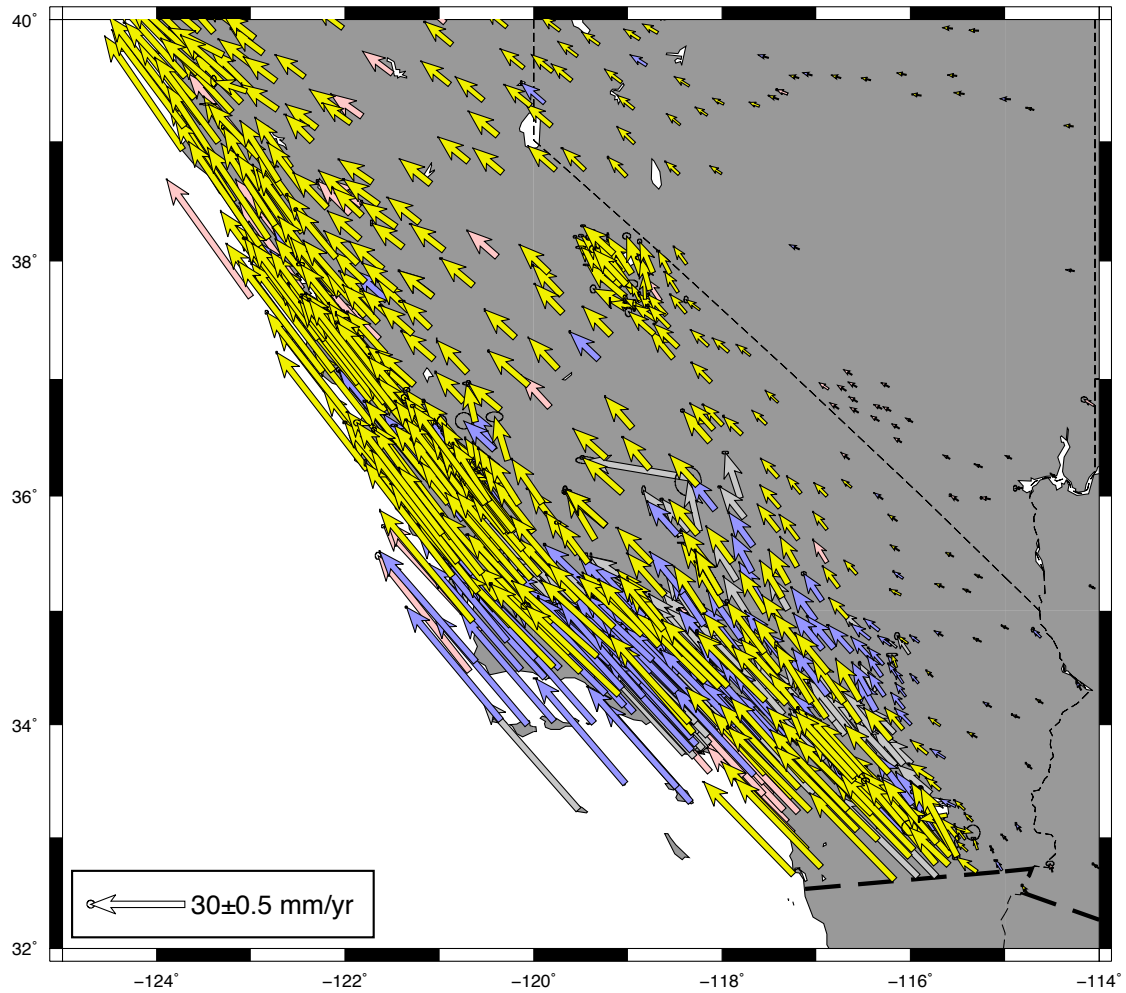

Figure 11: Same as Figure 10 except for South Western United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown.

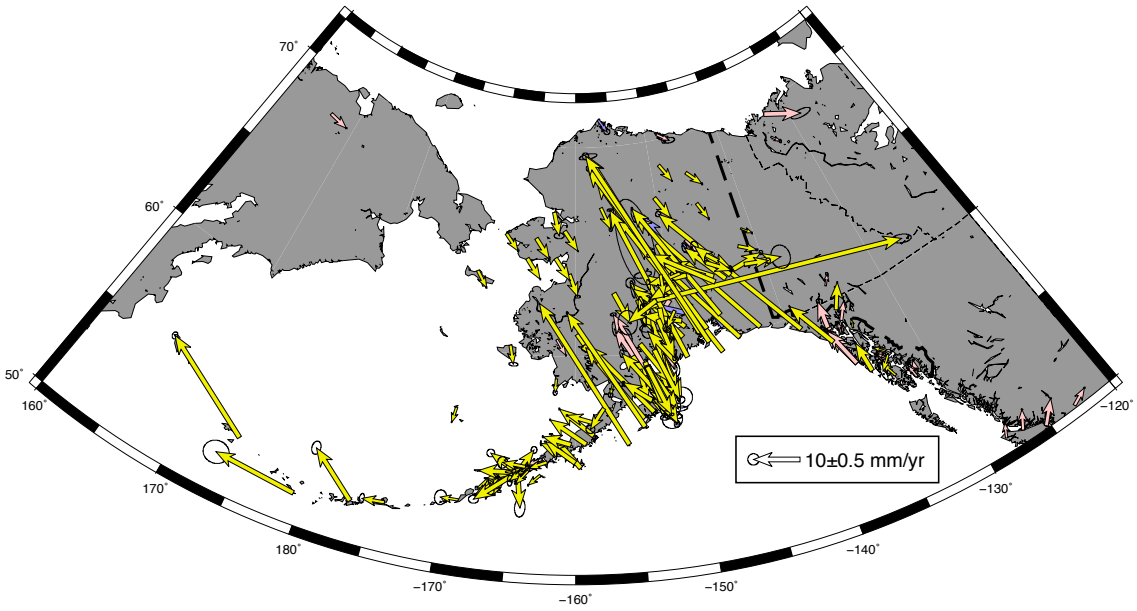

Figure 12: Same as Figure 10 except for Alaska. Only velocities with horizontal standard deviations less than 5 mm/yr are shown

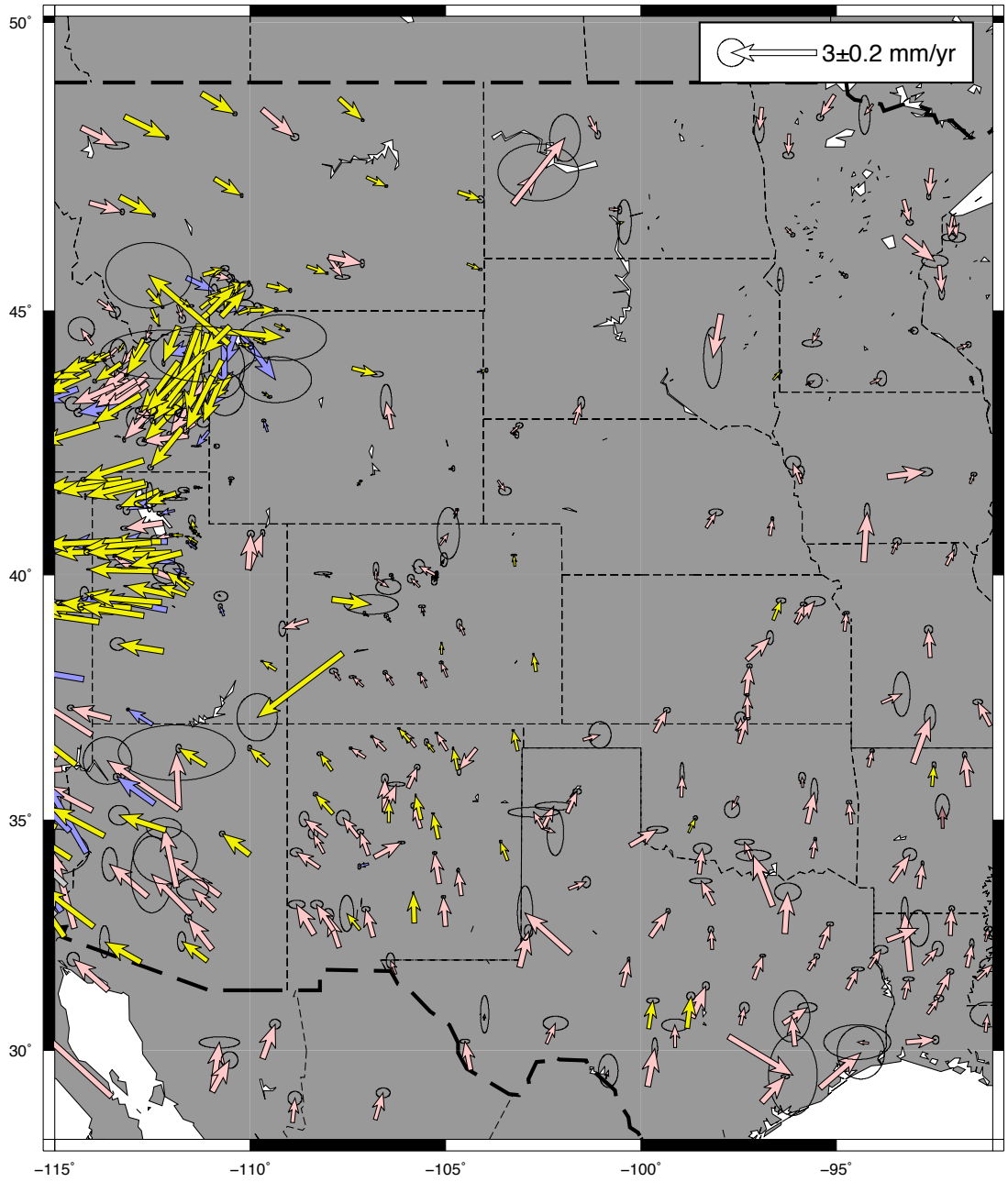

Figure 13: Same as Figure 10 except for Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown.

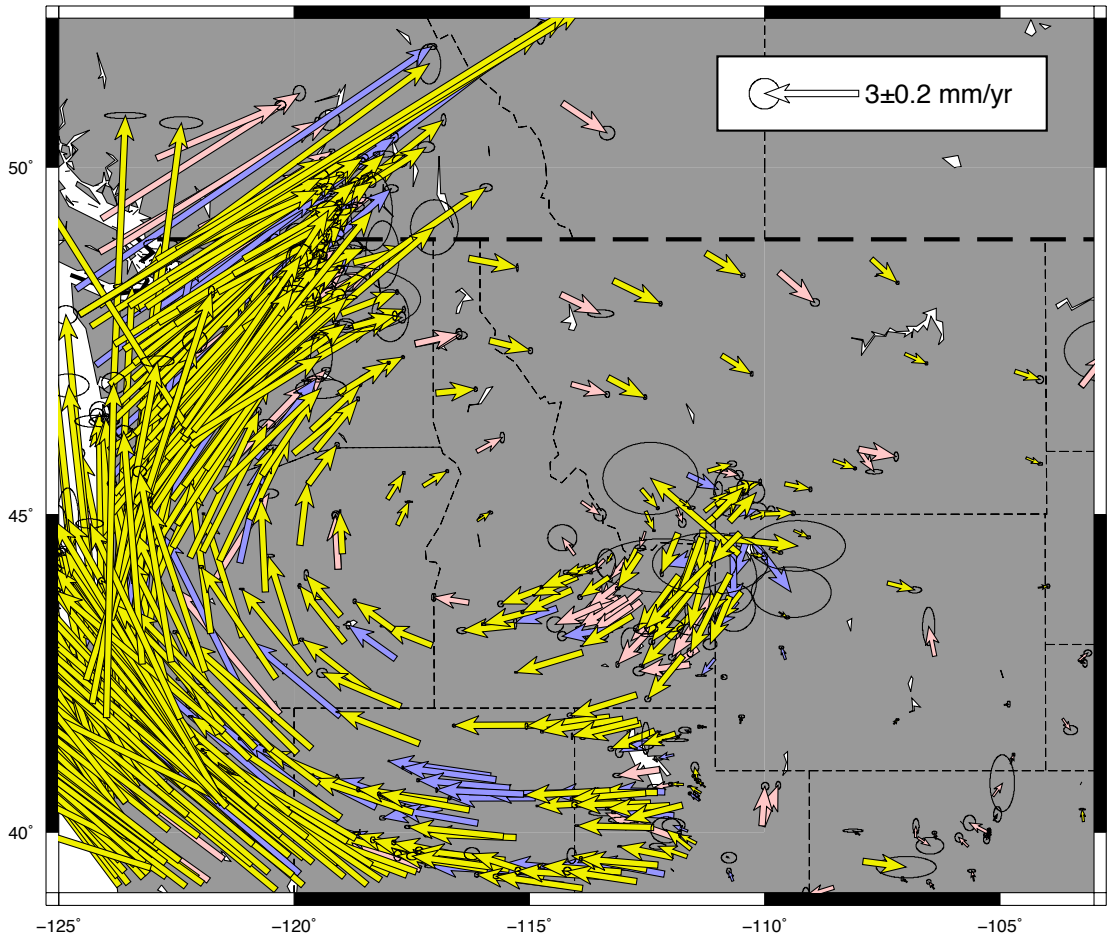

Figure 14: Same as Figure 10 except for Western Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown. Anomalous vectors at longitude 250^{o} are in the Yellowstone National Park and most likely are showing volcanic processes.

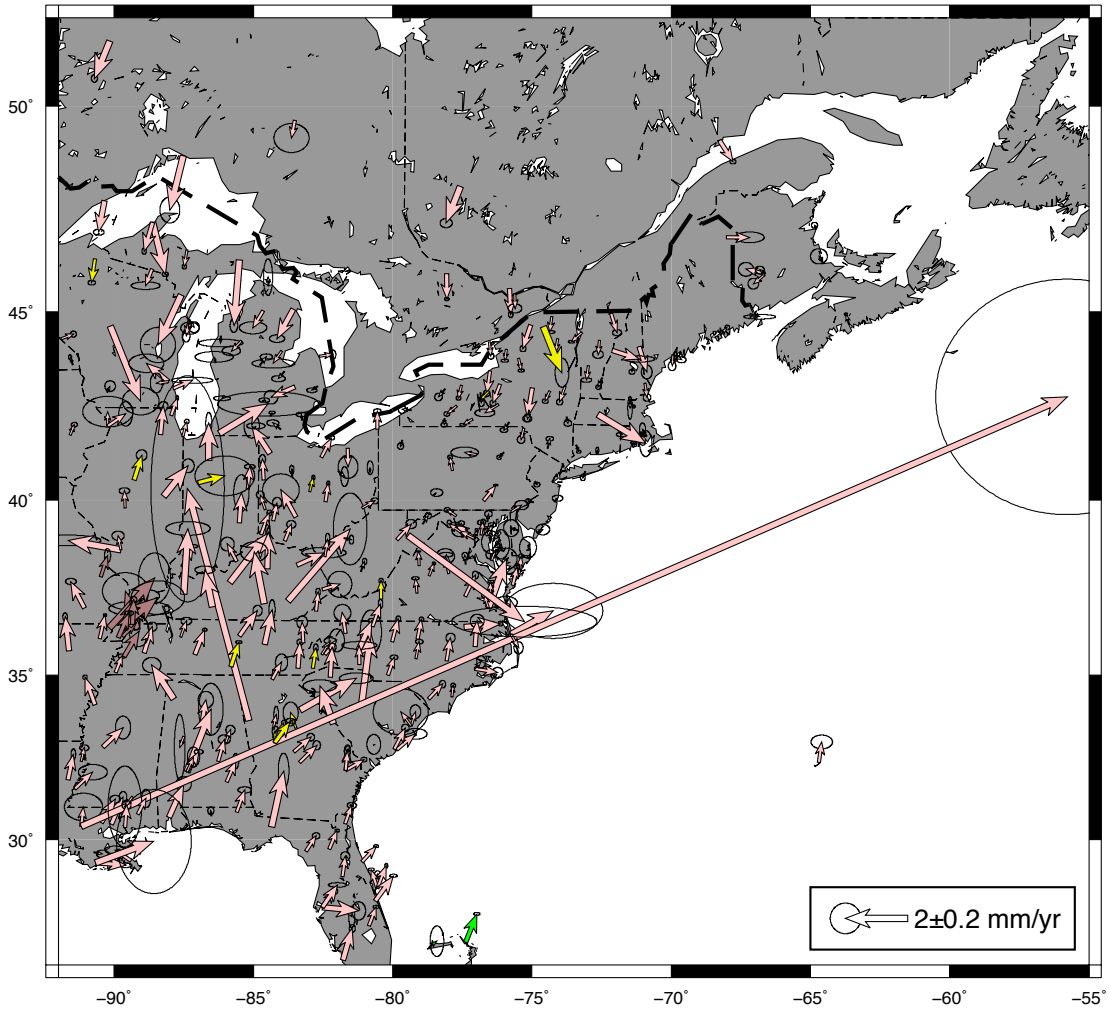

Figure 15: Same as Figure 10 except for the Eastern United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown. The systematic velocity of sites in the Northeast and central US show deviations for current GIA models in the horizontal velocities. The large outlier is LST1 which has only a short amount of data (less than 1 year). The vertical motions match quite well but geodetic vertical motions are already included in the development of the models. Horizontal GIA motions will affect the North America Euler pole from ITRF2008.

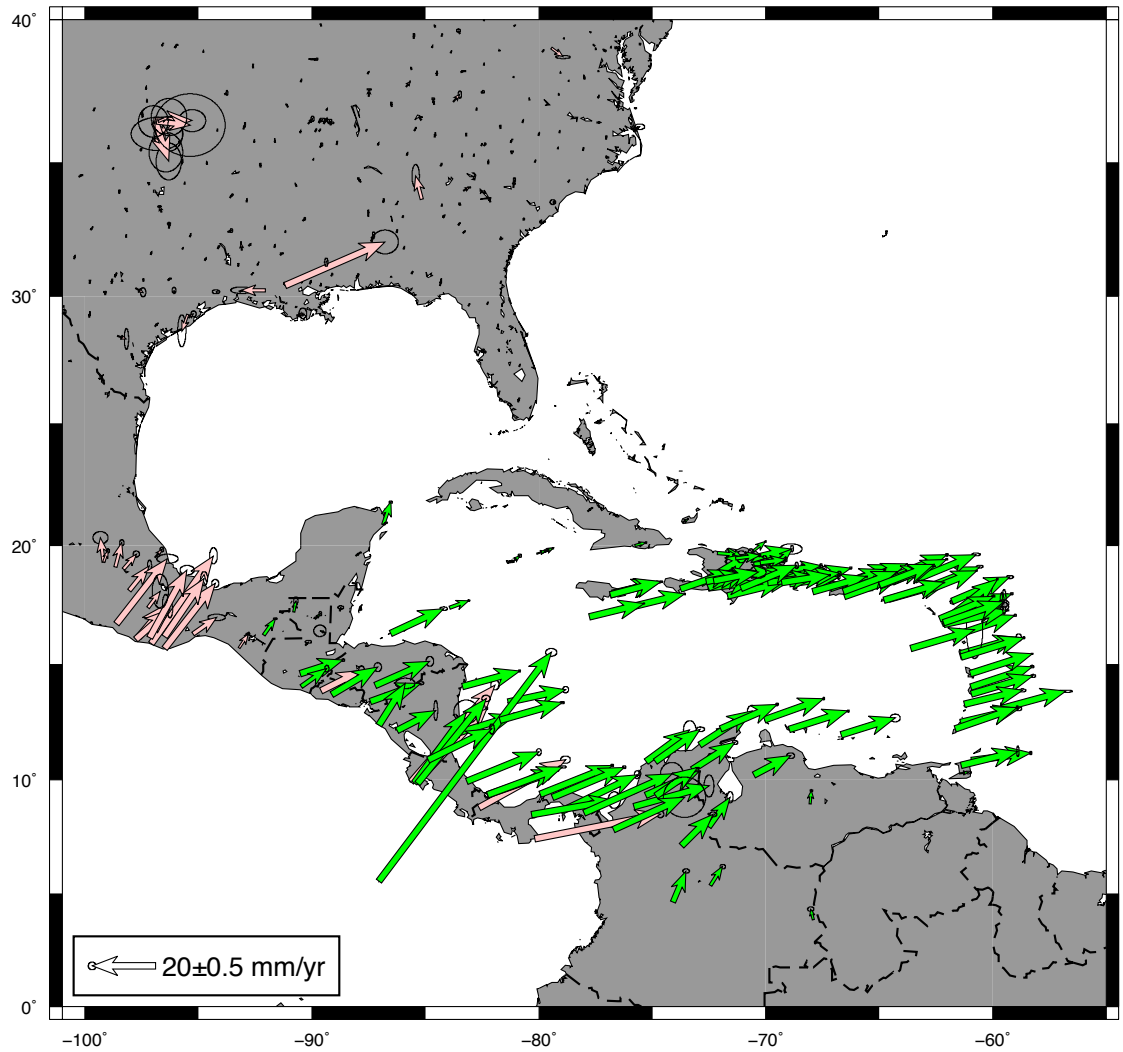

Figure 16: Same as Figure 10 except for the Caribbean region. Only velocities with horizontal standard deviations less than 5 mm/yr are shown.

Earthquake Analyses: 2016/03/15-2017/03/15.

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. In these output, each earthquake that might have generated coseismic displacements is numbered and the "SEQ Earthquake # n" starts the block of information about the earthquake. The EQ MM lines, give station name, distance from hypocenter (km), maximum distance that could cause coseismic offsets > 1 mm, and the "CoS" (coseismic offset) value is the possible offset in the mm. The eq_def lines give the event number, latitude, longitude, radius of influence, and depth of event followed by the date and time of the event. If an event is found to be significant, the event number is modified to reflect the total number of events so far included in the PBO analyses. Large events are often given a two-character code to reflect their location (e.g., PA is Parkfield).

In March/April 2017, we investigated the following events.

```
* EQDEFS for 2017 03 14 to 2017 04 15 Generated Sun Apr 16 11:31:20 EDT 2017
* Proximity based on Week_All.Pos file
* ----------------------------------
* SEQ Earthquake # 1
* EQ 26 P488_GPS       4.91       8.80 CoS        0.8 mm
* EQ 26 P489_GPS       8.44       8.80 CoS        0.3 mm
* EQ_DEF M3.6 11km SW of Salton City
 eq_def 01   33.2390 -116.0535      8.8  8  2017 03 14 17 15    0.0003
 eq_rename 01
 eq_coseis 01  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ----------------------------------
* SEQ Earthquake # 2
* EQ 52 OK03_GPS       8.23       8.70 CoS        0.2 mm
* EQ 52 OK04_GPS       2.67       8.70 CoS        1.8 mm
* EQ 52 OK05_GPS       3.64       8.70 CoS        1.0 mm
* EQ 52 OK06_GPS       7.08       8.70 CoS        0.3 mm
* EQ 52 OK08_GPS       5.81       8.70 CoS        0.4 mm
* EQ_DEF M3.5 10km NW of Pawnee
 eq_def 02   36.4008  -96.8841      8.7  8  2017 03 15 15 17    0.0002
 eq_rename 02
 eq_coseis 02  0.0010 0.0010 0.0010      0.0002     0.0002     0.0002
* ----------------------------------
* SEQ Earthquake # 3
* EQ 54 CRLR_GPS       3.36       8.80 CoS        1.7 mm
* EQ_DEF M3.6 14km SE of Miches
 eq_def 03   18.4454  -68.9284      8.8  8  2017 03 15 15 24    0.0003
 eq_rename 03
 eq_coseis 03  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ----------------------------------
* SEQ Earthquake # 4
* EQ 76 AC02_GPS       7.40      11.00 CoS        2.8 mm
* EQ_DEF M4.4 59km SSW of Larsen Bay
 eq_def 04   57.0168 -154.1732     11.0  8  2017 03 16 07 56    0.0024
 eq_rename 04
 eq_coseis 04  0.0010 0.0010 0.0010      0.0024     0.0024     0.0024
* ----------------------------------
* SEQ Earthquake # 5
* EQ 379 P488_GPS       2.04       8.70 CoS        4.6 mm
* EQ_DEF M3.5 10km NNE of Ocotillo Wells
 eq_def 05   33.2192 -116.0825      8.7  8  2017 03 26 08 26    0.0003
 eq_rename 05
 eq_coseis 05  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ----------------------------------
* SEQ Earthquake # 6
```

```
* EQ 407 P571_GPS       8.35       8.80 CoS        0.3 mm
* EQ_DEF M3.6 29km ENE of Porterville
 eq_def 06   36.1658 -118.7230      8.8  8  2017 03 27 01 46    0.0003
 eq_rename 06
 eq_coseis 06  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ---------------------------------
* SEQ Earthquake # 7
* EQ 546 P211_GPS       7.59       9.60 CoS        1.0 mm
* EQ 546 P234_GPS       2.87       9.60 CoS        7.0 mm
* EQ 546 P235_GPS       9.50       9.60 CoS        0.6 mm
* EQ 546 P236_GPS       5.94       9.60 CoS        1.6 mm
* EQ 546 P787_GPS       9.16       9.60 CoS        0.7 mm
* EQ_DEF M4.0 2km ESE of Aromas
 eq_def 07   36.8777 -121.6142      9.6  8  2017 03 31 10 56    0.0009
 eq_rename 07
 eq_coseis 07  0.0010 0.0010 0.0010      0.0009     0.0009     0.0009
* ---------------------------------
* SEQ Earthquake # 8
* EQ 574 AV29_GPS       8.13       9.00 CoS        0.4 mm
* EQ_DEF M3.7 79km ENE of Akutan
 eq_def 08   54.4098 -164.6525      9.0  8  2017 04 01 20 15    0.0004
 eq_rename 08
 eq_coseis 08  0.0010 0.0010 0.0010      0.0004     0.0004     0.0004
* ---------------------------------
* SEQ Earthquake # 9
* EQ 777 SSIA_GPS       7.61      13.70 CoS        7.4 mm
* EQ_DEF M4.8 2km NW of Soyapango
 eq_def 09   13.7494  -89.1633     13.7  8  2017 04 10 23 54    0.0067
 eq_rename 09
 eq_coseis 09  0.0010 0.0010 0.0010      0.0067     0.0067     0.0067
* ---------------------------------
* SEQ Earthquake # 10
* EQ 828 P285_GPS       6.30       8.70 CoS        0.5 mm
* EQ_DEF M3.5 27km NE of Greenfield
 eq_def 10   36.4725 -120.9975      8.7  8  2017 04 13 22 22    0.0003
 eq_rename 10
 eq_coseis 10  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ---------------------------------
* SEQ Earthquake # 11
* EQ 849 MOPR_GPS       7.82       8.70 CoS        0.2 mm
* EQ_DEF M3.5 70km WSW of Stella
 eq_def 11   18.1221  -67.8760      8.7  8  2017 04 14 22 45    0.0002
 eq_rename 11
 eq_coseis 11  0.0010 0.0010 0.0010      0.0002     0.0002     0.0002
```

EQ01 No data are available (P488 and P489). Co-seismic offsets are unlikely.

EQ02 is in Oklahoma but no offset above 1 mm can be seen. Since these
sites are new we do not have a good calibration of their noise characteristics yet.
EQ03 No obvious >1 mm offset.
EQ04 No data are available (AC02).
EQ04 Aftershock to EQ01 (see EQ01 comment).
EQ05 No obvious >1 mm offset.
EQ07 No obvious >1 mm offsets even at P234.
EQ08 No data are available (AV29). Co-seismic offsets is unlikely.
EQ09 Some gaps in data before event (SSIA) but no obvious >1 mm offsets.
EQ10 No obvious >1 mm offset at P285 (antenna offset 2016/10/12).
EQ11 Nor data since July 2016. Co-seismic offsets is unlikely.

No offsets can be seen for any of the earthquakes in the list.

In April/May 2017 the following events were investigated

```
* EQDEFS for 2017 04 14 to 2017 05 15 Generated Fri May 19 15:47:50 EDT 2017
* Proximity based on Week_All.Pos file
* ---------------------------------
* SEQ Earthquake # 1
* EQ 39 MOPR_GPS       7.82       8.70 CoS        0.2 mm
* EQ_DEF M3.5 70km WSW of Stella
 eq_def    01   18.1221  -67.8760      8.7  8  2017 04 14 22 45    0.0002
 eq_rename 01
 eq_coseis 01  0.0010 0.0010 0.0010      0.0002     0.0002     0.0002
* ---------------------------------
* SEQ Earthquake # 2
* EQ 581 P230_GPS       1.75       9.10 CoS       10.5 mm
* EQ_DEF M3.8 8km E of Blackhawk
 eq_def    02   37.8252 -121.8060      9.1  8  2017 04 30 01 30    0.0005
 eq_rename 02
 eq_coseis 02  0.0010 0.0010 0.0010      0.0005     0.0005     0.0005
* ---------------------------------
* SEQ Earthquake # 3
* EQ 990 AV26_GPS      13.73      14.70 CoS        2.9 mm
* EQ_DEF M4.9 75km WSW of False Pass
 eq_def    03   54.6939 -164.5535     14.7  8  2017 05 12 22 54    0.0086
 eq_rename 03
 eq_coseis 03  0.0010 0.0010 0.0010      0.0086     0.0086     0.0086
* ---------------------------------
* SEQ Earthquake # 4
* EQ 1045 P598_GPS       4.83       8.80 CoS        0.8 mm
* EQ_DEF M3.6 10km ESE of Big Bear City
 eq_def    04   34.2272 -116.7430      8.8  8  2017 05 15 18 44    0.0003
 eq_rename 04
 eq_coseis 04  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
```

EQ01: No data at MOPR but unlikely to be affected.
EQ02: Maybe displaced P230 but looks more systematic data noise (any offset <2mm)
EQ03: No offsets
EQ04: No offsets

No offsets can be seen for any of the earthquakes in the list.

In May/Jun 2017, the following events were investigated.

```
* EQDEFS for 2017 05 14 to 2017 06 15 Generated Thu Jun 15 10:43:26 EDT 2017
* Proximity based on Week_All.Pos file
* SEQ Earthquake # 1
* EQ 54 P598_GPS       4.83       8.80 CoS        0.8 mm
* EQ_DEF M3.6 10km ESE of Big Bear City
 eq_def    01   34.2272 -116.7430      8.8  8  2017 05 15 18 44    0.0003
 eq_rename 01
 eq_coseis 01  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ----------------------------------
* SEQ Earthquake # 2
* EQ 175 CN05_GPS       7.55       8.80 CoS        0.3 mm
* EQ_DEF M3.6 13km S of Punta Cana
 eq_def    02   18.5026  -68.3913      8.8  8  2017 05 20 02 41    0.0003
 eq_rename 02
 eq_coseis 02  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ----------------------------------
* SEQ Earthquake # 3
* EQ 534 RAMT_GPS       7.02       8.90 CoS        0.4 mm
* EQ_DEF M3.6 8km WNW of Johannesburg
 eq_def    03   35.3975 -117.7128      8.9  8  2017 06 04 00 07    0.0003
 eq_rename 03
 eq_coseis 03  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ----------------------------------
* SEQ Earthquake # 4
* EQ 632 ABVI_GPS       4.04       8.70 CoS        0.8 mm
* EQ_DEF M3.5 49km NE of Road Town
 eq_def    04   18.7608  -64.3141      8.7  8  2017 06 11 03 38    0.0002
 eq_rename 04
 eq_coseis 04  0.0010 0.0010 0.0010      0.0002     0.0002     0.0002
* ----------------------------------
* SEQ Earthquake # 5
* EQ 640 TRND_GPS       3.66       8.70 CoS        1.4 mm
* EQ_DEF M3.5 0km WSW of Westhaven-Moonstone
 eq_def    05   41.0418 -124.1117      8.7  8  2017 06 11 12 20    0.0003
 eq_rename 05
 eq_coseis 05  0.0010 0.0010 0.0010      0.0003     0.0003     0.0003
* ----------------------------------
* SEQ Earthquake # 6
```

```
* EQ 688 CN25_GPS     140.03     174.30 CoS        4.8 mm
* EQ 688 GUAT_GPS     163.77     174.30 CoS        3.5 mm
* EQ 688 TNPJ_GPS     154.79     174.30 CoS        3.9 mm
* EQ_DEF M6.9 5km NNE of San Pablo
 eq_def    06   14.9823  -91.9882    174.3  8  2017 06 14 07 30    1.4566
 eq_rename 06
 eq_coseis 06  0.0010 0.0010 0.0010      1.4566     1.4566     1.4566
```

EQ01: No offset seen
EQ02: No results from CN05 since 2016/10/21. Results were of poor quality up to time of data loss.
EQ03: No offset
EQ04: No results after 2017/03/19. CWU results have large standard deviations up to time of failure. The error bars on the NMT results stays the same as earlier results
EQ05: No offset at time of earthquake but there is ~2 mm North offset 2017/03/19 but there have been similar events before. Site has been affected by three prior earthquakes (EQ 06, 18 and 29). â□œSlow looking event before EQ29 2014 03 10 .
EQ06: Too close to end of rapids at the moment. (No processing after earthquake). This event will be considered next month.

No offsets can be seen for any of the earthquakes in the list.

Antenna Change Offsets: 2016/03/01-2017/05/31

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

```
Station      Date      From          To
EGAN 2017   3 16   0   0 TRM29659.00 TRM59800.80
PICL 2017   3  1   0   0 AOAD/M_T    TPSCR.G3
AB49 2017   4 13  19  17 TRM29659.00 TRM59800.80
OKHV 2017   4 27  18  40 ASH700718B  LEIAT502
P531 2017   4 27  22  36 TRM29659.00 TRM59800.80
AC11 2017   5 10  20  56 TRM29659.00 TRM59800.00
ATW2 2017   5 21   0   0 TRM29659.00 TRM59800.80
CORB 2017   5  2  15   0 ASH700936E  JAVRINGANT_DM
KYBO 2017   5 11  13  31 TRM57971.00 TRM115000.00
OHAS 2017   5  3   7   0 TRM57971.00 TRM115000.00
P046 2017   5  6   0   0 TRM29659.00 TRM59800.80
P621 2017   5 30   0  50 TRM29659.00 TRM59800.80
P623 2017   5 29  20  39 TRM29659.00 TRM59800.80


Analysis
EGAN WLS dNEU   -1.10 +- 1.68,   5.60 +- 4.53,  -0.95 +- 8.86 mm,
      KF dNEU   -1.04 +- 0.31,   5.26 +- 0.30,  -1.74 +- 1.04 mm
Offset in east and north is clear in the time series.
PICL WLS dNEU    1.17 +- 2.09,  -4.00 +- 3.00,   2.76 +- 5.90 mm,
```

```
      KF dNEU    2.24 +- 0.29,  -4.44 +- 0.25,   5.17 +- 0.85 mm
Data has outliers and systematic deviations (51 deg Lat in Ontario
so could be snow).
Gap just before antenna change although offset look significant.
AB49:WLS dNEU    1.64 +- 2.20,   3.35 +- 3.02,  -7.62 +- 9.37 mm,
      KF dNEU    1.48 +- 0.46,   1.17 +- 0.37,  -2.34 +- 1.44 mm
Antenna change on 2017  4 13 19 17, caused small offset.  There is
however a
much larger break and change in residuals on 2015  7 15 00 00.
Offset estimates are
WLS dNEU    3.90 +- 0.99,   9.56 +- 1.28, -13.60 +- 4.42 mm,
 KF dNEU    3.51 +- 0.35,   8.47 +- 0.32,  -6.86 +- 1.21 mm .
2-3 mm amplitude NE and 10 mm vertical goes away at this time.

OKHV:WLS dNEU    1.25 +- 2.97,  -2.47 +- 2.82,  14.53 +- 15.09 mm,
      KF dNEU    2.28 +- 0.65,  -2.58 +- 0.59,  14.50 +- 2.54 mm
4-days where ACs used wrong antenna type were removed.
P531: WLS dNEU    1.14 +- 1.90,   2.55 +- 2.49,  -6.38 +- 15.31 mm,
       KF dNEU    0.96 +- 0.32,   2.04 +- 0.31,  -1.80 +- 1.25 mm
Estimates made with annual estimated at the same time.
AC11: WLS dNEU    4.07 +- 16.02,  -4.89 +- 45.57,   0.09 +- 21.41 mm,
       KF dNEU   -0.82 +- 0.57,  -4.47 +- 0.87,   5.34 +- 1.50 mm
Gap in data for 2-3 weeks before results from new antenna.  There
are very long period
deviations in east.  Decade time scale amplitude almost +-10 mm.
ATW2: WLS dNEU    4.46 +- 60.39,  -2.27 +- 35.20,  -3.08 +- 59.24 mm,
       KF dNEU   -2.68 +- 0.94,   1.88 +- 0.62,   8.09 +- 2.09 mm
North offset looks clear.  Again decadal variations with amplitude
+-10-15 mm.
CORB: WLS dNEU   -0.97 +- 4.58,   1.64 +- 1.33,   2.04 +- 3.97 mm,
       KF dNEU   -1.61 +- 0.35,   1.05 +- 0.27,   3.08 +- 1.02 mm
Gap in data prior to new antenna being installed.  Offset looks
small.
KYBO: WLS dNEU   -0.58 +- 1.18,  -2.28 +- 1.06,   4.38 +- 12.38 mm,
       KF dNEU   -0.91 +- 0.35,  -1.60 +- 0.31,   7.71 +- 1.33 mm
Small offset. Its not clear the time is correct.  No data gap at
time of break but there
is a gap a few days before.
OHAS: WLS dNEU    1.39 +- 3.79,  -0.75 +- 1.30,   1.46 +- 12.17 mm,
       KF dNEU    0.49 +- 0.36,  -1.05 +- 0.27,   7.66 +- 1.19 mm
Small gap and not clearly seen.
P046: WLS dNEU    2.48 +- 0.75,  -1.98 +- 0.73,  -4.18 +- 5.96 mm,
       KF dNEU    2.54 +- 0.32,  -1.90 +- 0.26,  -0.66 +- 1.04 mm
NE offsets are clear in the time series.
P621: WLS dNEU    3.01 +- 1.17,   2.06 +- 0.76,   4.38 +- 6.71 mm,
       KF dNEU    2.48 +- 0.42,   1.99 +- 0.38,  10.54 +- 1.58 mm
Gap before change of antenna so offsets are not so clear.
P623: WLS dNEU   -1.38 +- 3.24,  -2.52 +- 1.43,   8.60 +- 14.69 mm,
       KF dNEU   -1.77 +- 0.99,  -2.55 +- 0.92,  12.34 +- 3.71 mm
Only a few days of rapid solutions and so offsets may not be that
reliable.
```

New offsets of unknown origin and data anomalies

CJMG 2016 10 3 0 0 Data is bad after this time and show be removed.

AC11 Long period (decade wavelength) variation in east. Amplitude almost +-10 mm.
ATW2 Long period (decade wavelength) variation in east. Amplitude almost +-15 mm.
There seems to be a phase lag with AC11

GAMIT/GLOBK Community Support

During this quarter we have completed the coding and testing of most of the models necessary to process in GAMIT and combine in GLOBK two-frequency observations of Galileo and Beidou satellites. We discuss below the models, test results, and the current limitations of these systems for high-precision geodesy. We continue to spend 5-10 hours per week in email support of users. During the quarter we issued 23 (thru 7/1) royalty-free licenses to educational and research institutions.

GNSS orbits.

The IGS distributes orbit products in the form of sp3 files for GPS through a combination of results submitted by nine analysis centers, (http://acc.igs.org) and for Glonass, Beidou, and Galileo through a combinations from six analysis centers participating in the Multi-GNSS Experiment (MGEX) (http://mgex.igs.org/analysis) . Comparison of the orbits among the analysis centers using software, data sets, and estimation strategies that have commonalities but are in aggregate somewhat independent provides a basis for assessing the ability of the orbits to produce consistent estimates of station positions and velocities. These comparisons suggest a consistency at the level of 10-20 mm (0.5-1 ppb) for GPS and 40-60 mm (2-3 ppb) for the other three systems. SLR range residuals for the Glonass, Beidou, and Galileo satellites that have retro-reflectors also suggest GNSS errors at the level of 40-60 mm. In our analysis of the GNSS data, we generate numerically integrated orbits by estimating initial positions and velocities and nine solar radiation-pressure parameters to the positions on the IGS sp3 files. The quality of the fit indicates the consistency of our orbital model with the model used by the IGS to generate the combined orbits. The rms of our fits for a 24-hour arc are typically 5 mm for GPS and Beidou, 15 mm for Glonass, and 35 mm for Galileo. Based on the IGS comparisons of results from different analysis centers and with SLR residuals, we infer that the low rms values for GPS, Glonass, and Beidou are a reflection of the use of common models rather than the inherent accuracy of the orbits, but they do give us confidence that we can reproduce in our processing the accuracy of the IGS orbits. In most respects, Galileo orbits should behave in ways similar to the other systems, but we are aware that the 9-parameter empirical radiation pressure model we use may need to be enhanced to account for sub-daily variations at low Sun angles due to the elongated shape of the Galileo spacecraft body (*Montenbruck et al*., 2015).

Yaw models

The rotation of the GNSS satellites to maintain exposure of their solar panels to the Sun ("yaw") causes the phase centers of the transmitter antennas to vary throughout an orbit. If not modeled correctly these rotations can cause decimeter-level errors due to the physical offsets of the spacecraft antennas and phase changes due to the relative

alignment of the spacecraft and ground antennas. The effects are particularly acute, and the models most complicated, when during satellite-Earth-Sun alignment ("low beta angle") the spacecraft has to execute rapid turns at two points in the orbit. An effective yaw model for GPS was developed by Bar-Sever (1996), enhanced by Kouba (2009) and implemented in GAMIT in 2014. Recently Montenbruck et al. (2015) and Kouba (http://acc.igs.org/orbits/eclips_May2017.tar) have described models for Beidou and Galileo, which we have implemented and checked by comparison with values provided by Kouba (personal communication, 2017). (We have also coded Kouba's model for Glonass but it is untested.)

Positioning tests

To test GAMIT and GLOBK for positioning with Galileo and Beidou we processed data available in the CDDS archive from each of these systems and GPS over 5 days (2017 121-125) for a 15-station network spanning ~5000 km and centered on Europe, which has the greatest density of stations producing RINEX 3 data for all three systems (Figure 17). For each system we used phase and pseudorange data from the two primary frequencies: GPS G1 (1575.42 MHz) and G2 (1227.6 MHz); Galileo E1 (same as G1) and E5 (1176.45 MHz); Beidou C2 (1561.098 MHz) and C7 (1207.14 MHz) . Since models for phase-center variations (PCVs) for the ground antennas are available only for G1 and G2, we used these for the higher and lower frequencies of the other systems. For the Galileo and Beidou satellite antennas, only mean offsets (PCOs), not nadir-angle-dependent values (PCVs) are currently available. From our processing the phase residuals for GPS and Galileo were similar for all stations (6-13 mm except18-20 mm for KOUR). Plots of phase versus elevation angle for Galileo show little evidence of poorly modeled PCVs. Beidou's phase residuals were within the same range but less consistent with GPS and Galileo for a given station because of a much-different tracking geometry due to the current availability of only three medium-Earth-orbit (MEO) satellites.

We used GLOBK, separately for each GNSS, to generate position estimates for each of the five days, defining the reference frame on each day by minimizing the coordinate adjustments of 10 of the stations to their ITRF2008 values while estimating a translation and rotation. For GPS the weighted rms scatters in N, E and U for the 15 station were 0.3-2.9, 0.2-2.4, 2-10 mm with median values of 0.8, 0.6, 2.5 mm; for Galileo 0.3-2.8, 0.3-2.4, 6-20 mm with median values 1.9, 2.1, 8,1 mm; for Beidou 3-72, 5-66, 6-120 mm with median values 9, 7, 21 mm. The Beidou results were sufficiently weak due to the limited satellite geometry that we did not carry out any further comparisons for this system.

Our final test was to combine the five days into a single solution, first with GPS and Galileo alone, then with the two together. Over the five days, the GPS combination produced a chi2 of 0.18 (chi 0.4) with N E U wrms values of the 10 reference frame stations with respect to ITRF2008 of 1.2, 1.3, 7.0 mm. The Galileo combination produced a chi2 of 0.66 (chi 0.8) with N E U wrms values with respect to ITRF2008 of 2.4, 1.0, 12.7 mm. In Figure 17 we plot the differences between the GPS and Galileo position estimates from the 5-day solutions. The wrms differences are 2.0 mm in N and 1.2 mm

in E, consistent with the suggestion from the repeatabilities and reference frame consistency that Galileo is better in E than in N. Our overall conclusion is that the current Galileo orbits limit the accuracy of the system to about two or three times worse than GPS.

Future prospects

Although we cannot rule out a contribution of GAMIT model deficiencies to our position estimates from Galileo and Beidou observations, results from these systems are currently limited primarily by the number of satellites and the number and extent of the tracking network. Over the next few months we will continue tests with Galileo, including with GAGE networks in North America available through the UNAVCO data archive.

References

Kouba, J., 2009. A simplified yaw-attitude model for eclipsing GPS satellites. *GPS solutions, 13(1*), pp.1-12.

Montenbruck, O., Schmid, R., Mercier, F., Steigenberger, P., Noll, C., Fatkulin, R., Kogure, S. and Ganeshan, A.S., 2015. GNSS satellite geometry and attitude models. *Advances in Space Research, 56(6*), pp.1015-1029.

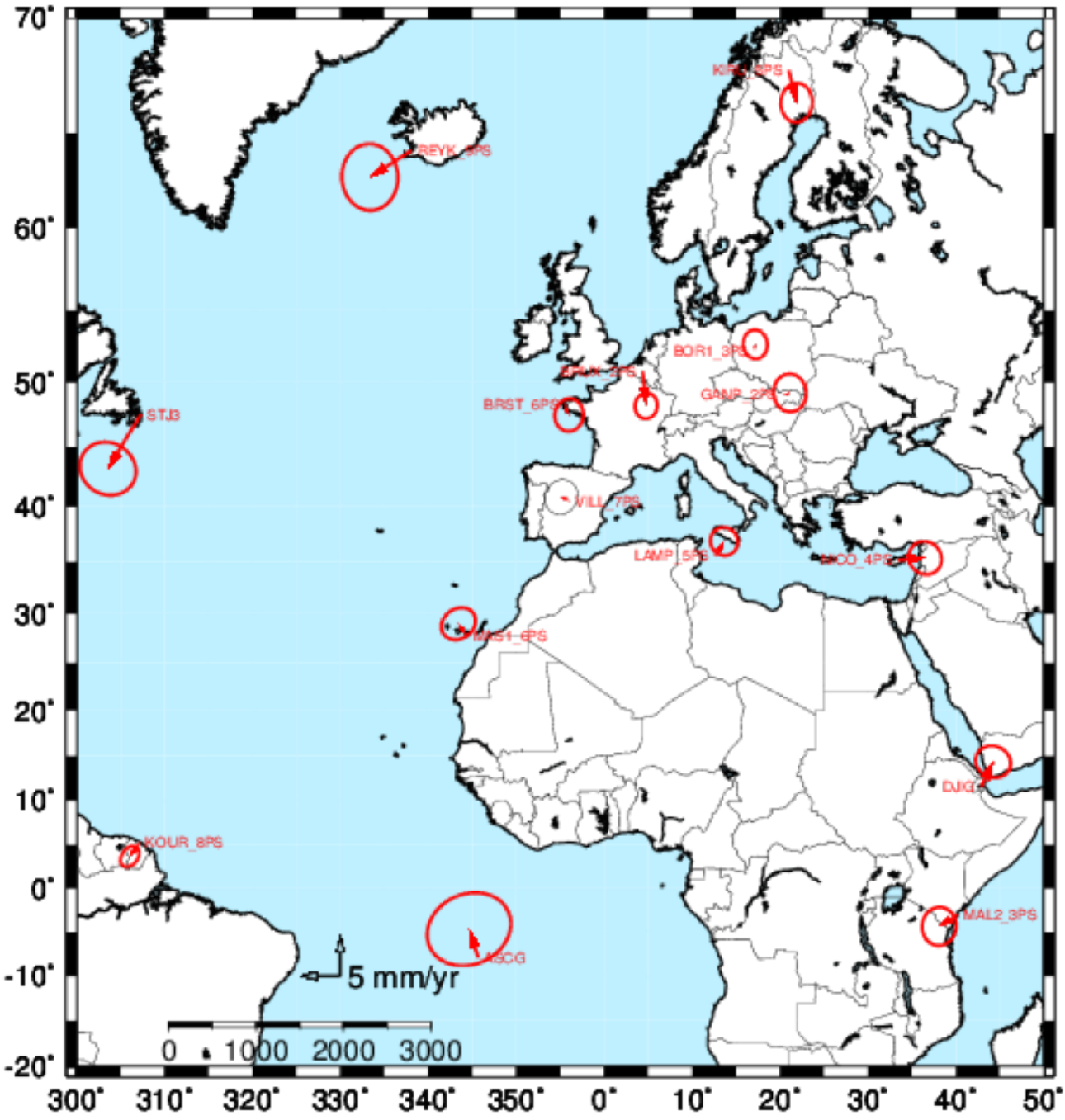

Figure 17. Horizontal position differences Galileo-GPS from 5-day solutions, 2017 days 121-125. Error ellipses are 70% confidence.