Quarterly Report
Massachusetts Institute of Technology
GAGE Facility GPS Data Analysis Center Coordinator

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Period: 2023/10/01-2023/12/31

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Summary

Under the GAGE2 Facility Data Analysis sub-award, MIT has been processing SINEX files from Central Washington University (CWU) and aligning them to the GAGE NAM14 reference frame. In this report, we show analyses of the data processing for the period 2023/10/01 to 2023/12/31, as well as time series velocity field analyses for the GAGE reprocessing analyses (1996-2023). Several earthquakes were investigated this quarter up to 12/15/2023, and none of them generated any detectable co-seismic offsets.

Analysis files (pbo format velocity files and offset files) are generated monthly and sent via LDM in the middle of each month.

We continue to process ANET data. These solutions are in the ANT14 frame as defined in the ITRF2014 plate motion model [*Altamimi et al.,* 2017].

GPS Analysis of Level 2a and 2b products

Level 2a products: Rapid products

Final and rapid level 2a products have been, in general, generated routinely during this quarter for the CWU solutions. 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 JPL orbits and clocks. Finals and rapid solutions are now being generated in the IGS14 system. In this quarter, 1978 stations were processed. In addition, up to 36 sites were processed in the ANET solutions, 8 more than last quarter. The number of stations processed fluctuated as data systems were updated at EarthScope.

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 CWU for the main GAGE2 Networks of the Americas stations (NOTA). The delivery schedule for these products is also unchanged.

Analysis of Final products: September 15, 2023– January 20, 2024

For this report, we generated the statistics using the ~3 months of CWU results between September 15, 2023, and January 20, 2024. These results are summarized in Table 1 and Figure 1.

For the three months of the final position time series generated, 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. Table 1 shows the median (50%), 70%, and 95% limits for the RMS scatters CWU. The detailed histograms of the RMS scatters are shown in Figure 1 CWU.

Table 1: Statistics of the fits of 1978 stations for CWU analyzed in the finals analysis between September 15, 2023, and January 20, 2024. Figure 1 shows histograms of the RMS scatters.

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
CWU	0.89	0.85	4.96
70%			
CWU	1.17	1.07	5.59
95%			
CWU	2.31	2.36	9.00

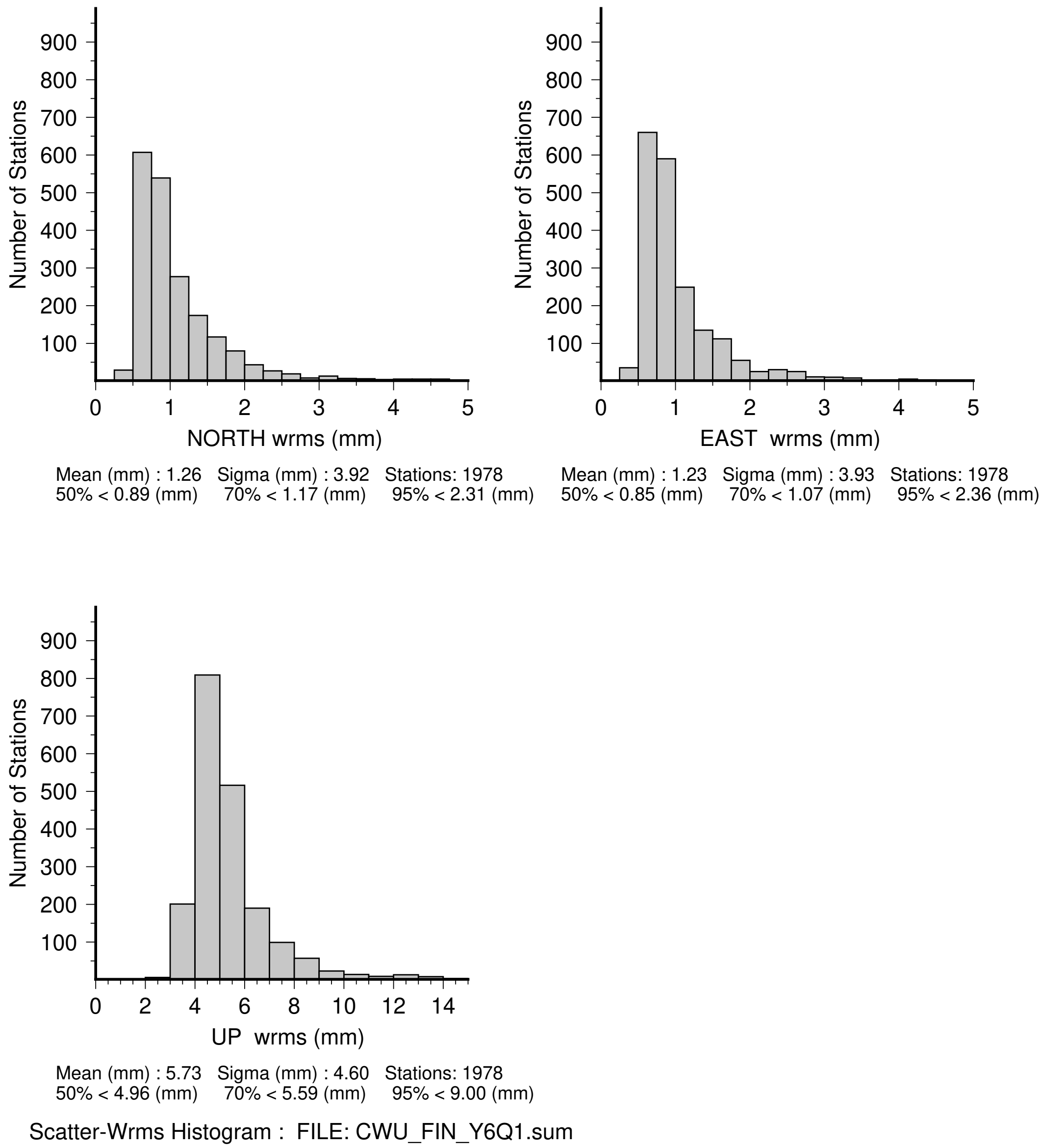

Figure 1: CWU solution histograms of the North, East, and Up RMS scatters of the position residuals for 1978 stations analyzed between September 15, 2023 and January 20, 2024. Linear trends and annual signals were estimated from the time series.

For the CWU 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 three 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 2-7. The values plotted are given in

CWU_FIN_Y6Q1.tab. There are 1974 stations in the file for sites with at least two measurements during the month.

Table 1: Head and tail of WRMS scatter summary file CWU_FIN_Y6Q1.tab.

```
Tabular Position RMS scatters created from CWU_FIN_Y6Q1.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   106     1.2   0.66      1.2   0.62     6.7   0.76     20.74
 1NSU   107     0.8   0.51      1.2   0.73     4.9   0.67     20.00
 1ULM   107     0.8   0.47      1.1   0.67     5.0   0.68     20.60
 7ODM   107     0.9   0.48      0.9   0.59     4.7   0.62     22.75
…
 ZDV1   107     0.9   0.46      0.9   0.56     5.0   0.67     20.63
 ZKC1   100     0.9   0.47      0.8   0.49     6.0   0.78     20.63
 ZLA1   107     0.9   0.49      0.9   0.59     5.0   0.66     20.63
 ZLC1   107     0.8   0.43      0.8   0.56     5.1   0.68     20.86
 ZME1   107     0.9   0.51      0.7   0.44     4.9   0.67     20.86
 ZMP1   107     0.9   0.48      0.8   0.49     5.6   0.75     21.10
 ZNY1   107     0.9   0.46      0.8   0.56     5.3   0.71     21.02
 ZOA1   106     0.8   0.43      0.8   0.50     4.9   0.64     21.55
 ZSE1   107     1.0   0.45      0.8   0.53     5.8   0.78     21.02
 ZTL4   107     0.9   0.56      0.9   0.57     7.3   1.00     21.21
```

Table 2: RMS scatter of the position residuals for the CWU solution between September 15, 2023, and January 20, 2024, 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, COCONet and Expanded PBO

Network	North (mm)	East (mm)	Up (mm)	#Sites
Median (50%)				
PBO	0.80	0.77	4.72	822
NUCLEUS	0.70	0.70	4.37	183
GAMA	0.70	0.74	4.55	10
COCONet	1.64	1.78	7.36	69
USGS_SCIGN	0.78	0.75	4.20	119
Expanded	1.01	0.96	5.35	775
70%				
PBO	1.03	0.96	5.18	
NUCLEUS	0.84	0.80	4.84	
GAMA	0.78	0.79	4.89	

COCONet	1.88	2.05	8.59
USGS_SCIGN	1.03	0.87	4.61
Expanded 95%	1.28	1.18	5.99
PBO	2.19	1.91	7.89
NUCLEUS	1.74	1.35	6.44
GAMA	0.81	0.91	5.22
COCONet	3.18	5.60	15.67
USGS_SCIGN	1.84	1.53	6.91

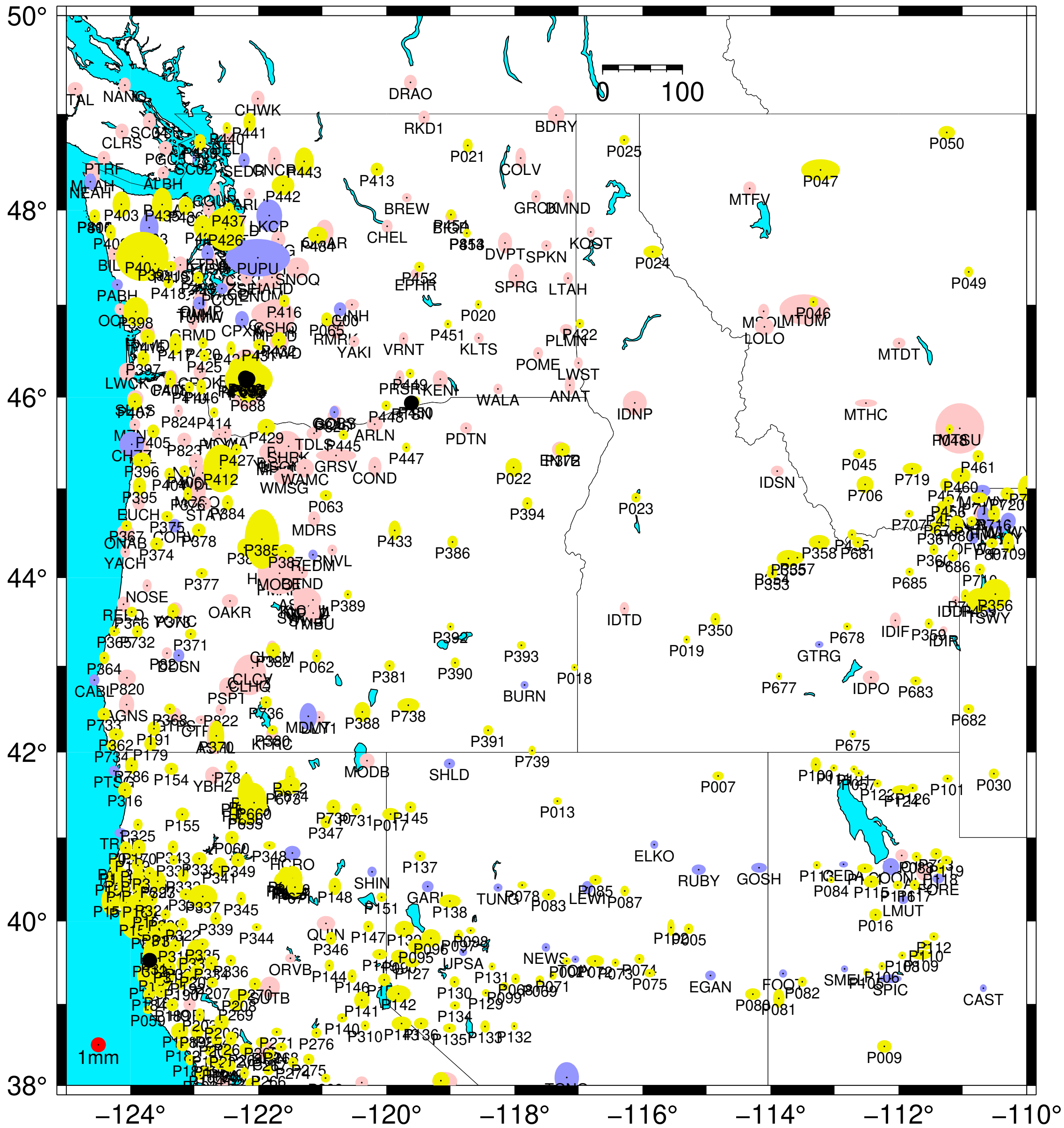

Figure 2: Distribution of the RMS scatters of horizontal position estimates from the CWU analysis for the Northern Western United States. The color of the ellipses that give the north and east RMS scatters denotes the network given by the legend in the figure. The small red circle shows the size of 1 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.

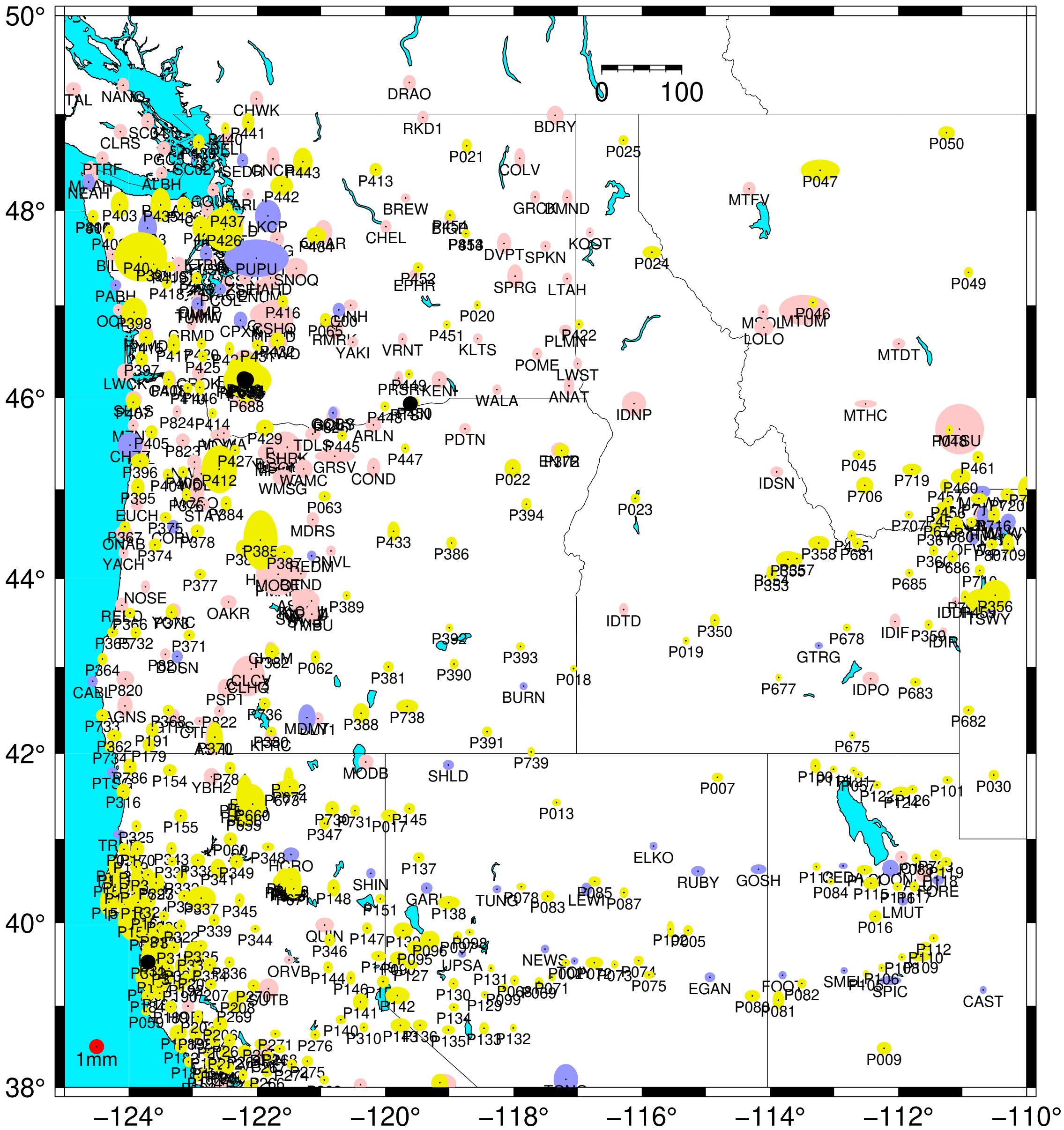

Figure 3: Same as Figure 4 except for the Southern Western United States. Black circles show large RMS scatter sites.

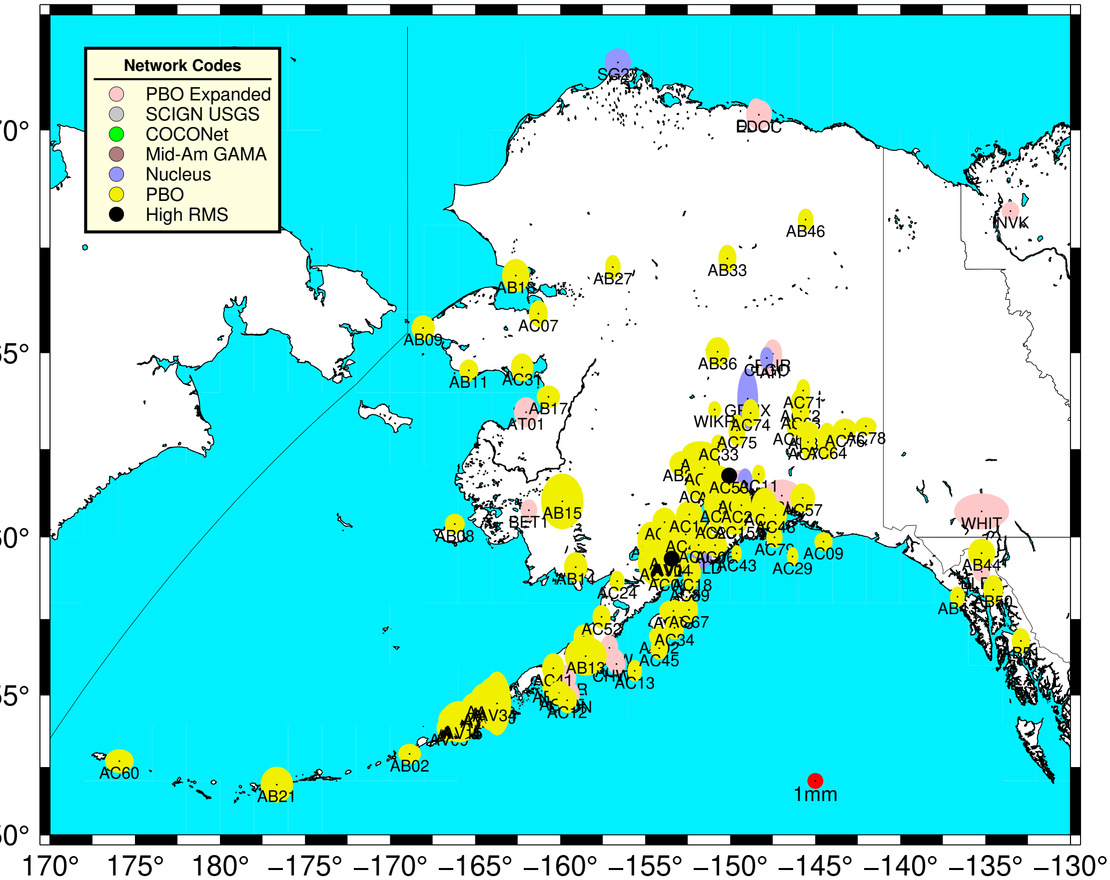

Figure 4: Same as Figure 4 except for the Alaskan region.

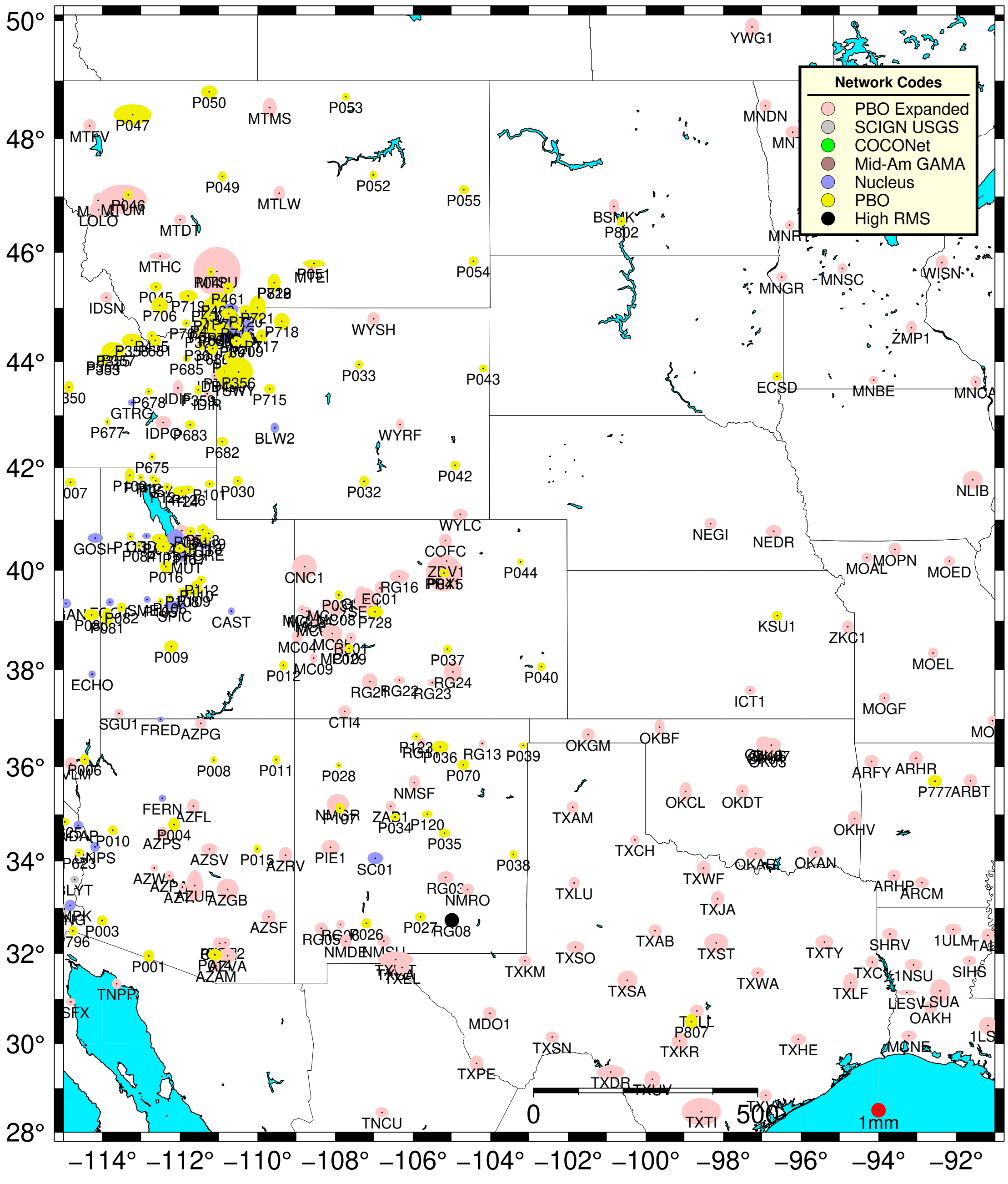

Figure 5: Same as Figure 4 except for the Central United States

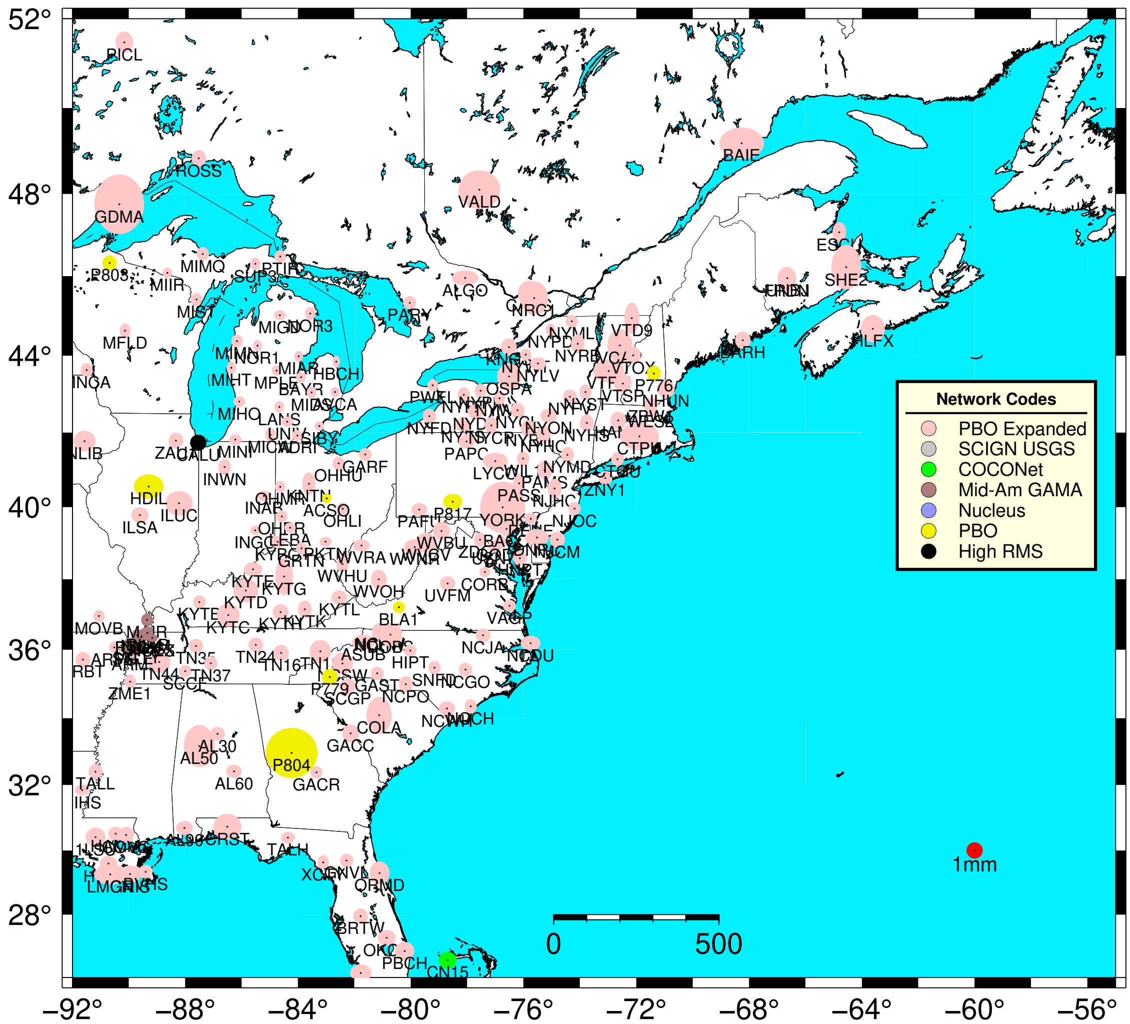

Figure 6: Same as Figure 4 except for the Eastern United States

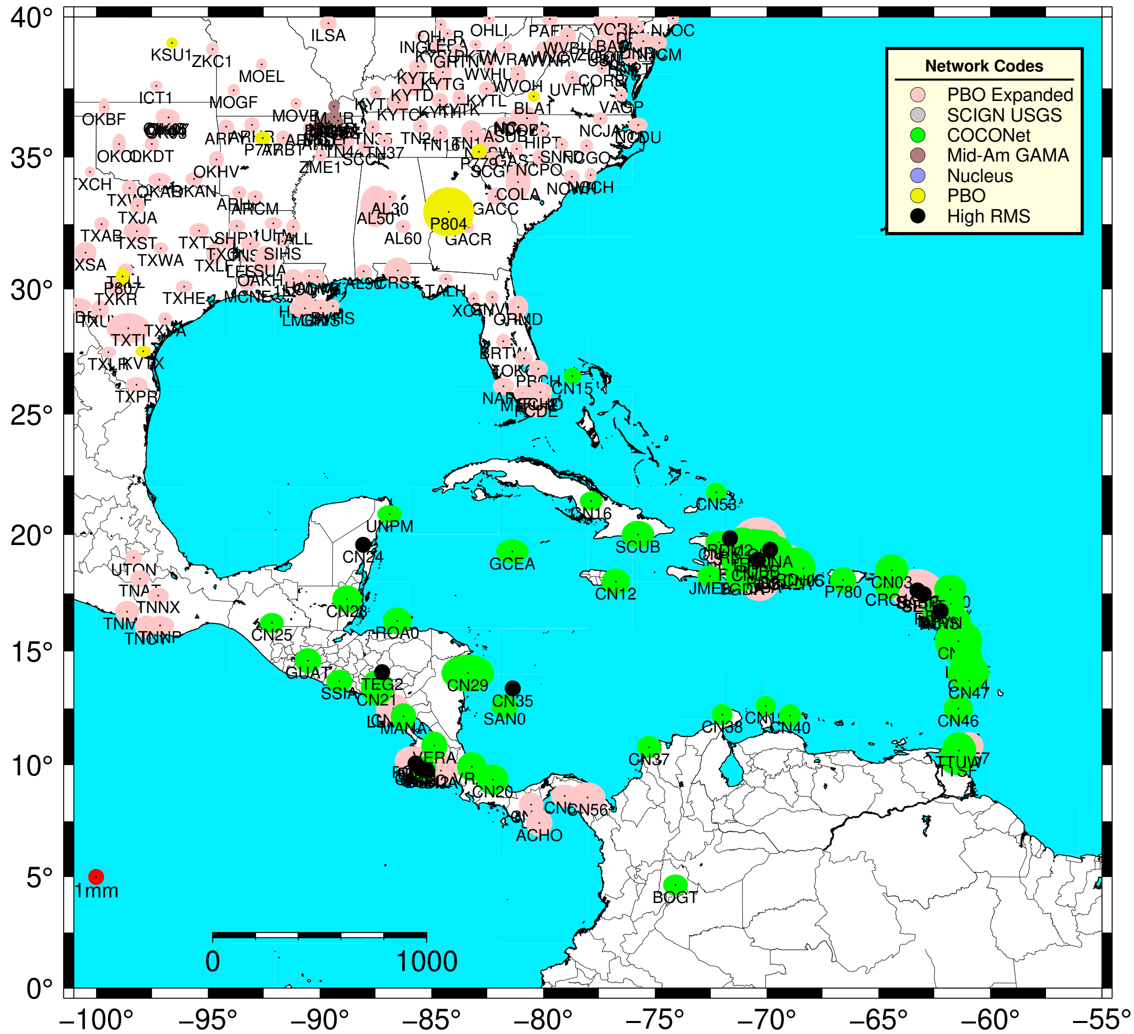

Figure 7: Same as Figure 4 except for the Caribbean region.

GLOBK Apriori coordinate file and earthquake files

As part of the quarterly analysis, we run a 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. The current earthquake and discontinuity files used in the GAGE ACC analyses are All_NOTA_eqs.eq All_NOTA_ants.eq All_NOTA_unkn.eq. These names have been changed to reflect that they now refer to the Network of America and no longer just the plate boundary observatory. The GLOBK apriori coordinate file All_CWU_nam14.apr is the current estimate based on data analysis in this quarterly report.

Snapshot velocity field analysis from the reprocessed PBO analysis.

For this quarterly report, we generate velocity estimates for the reprocessed results and the current GAGE analyses that are in the NAM14 reference frame using the CWU analysis. There are 2719 stations in the CWU solution (2 more than last quarter). The statistics of the fits to results are shown in Table 3. Because these are cumulative statistics, they are little changed from last quarter. 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 cwu_nam14_240120.tab. The velocity estimates are shown by region and network type in Figures 8-14. The color scheme used is the same as Figures 2-7. The snapshot velocity field file for CWU is cwu_nam14_240120.snpvel.

Table 3: Statistics of the fits of 2729 stations analyzed CWU in the reprocessed analysis for data collected between Jan 1, 1996 and January 20, 2024.

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
CWU	1.41	1.37	6.25
70%			
CWU	1.79	1.74	7.12
95%			
CWU	3.99	3.67	11.48

In Figures 8-14, different tolerances are used for maximum standard deviation in each figure 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.

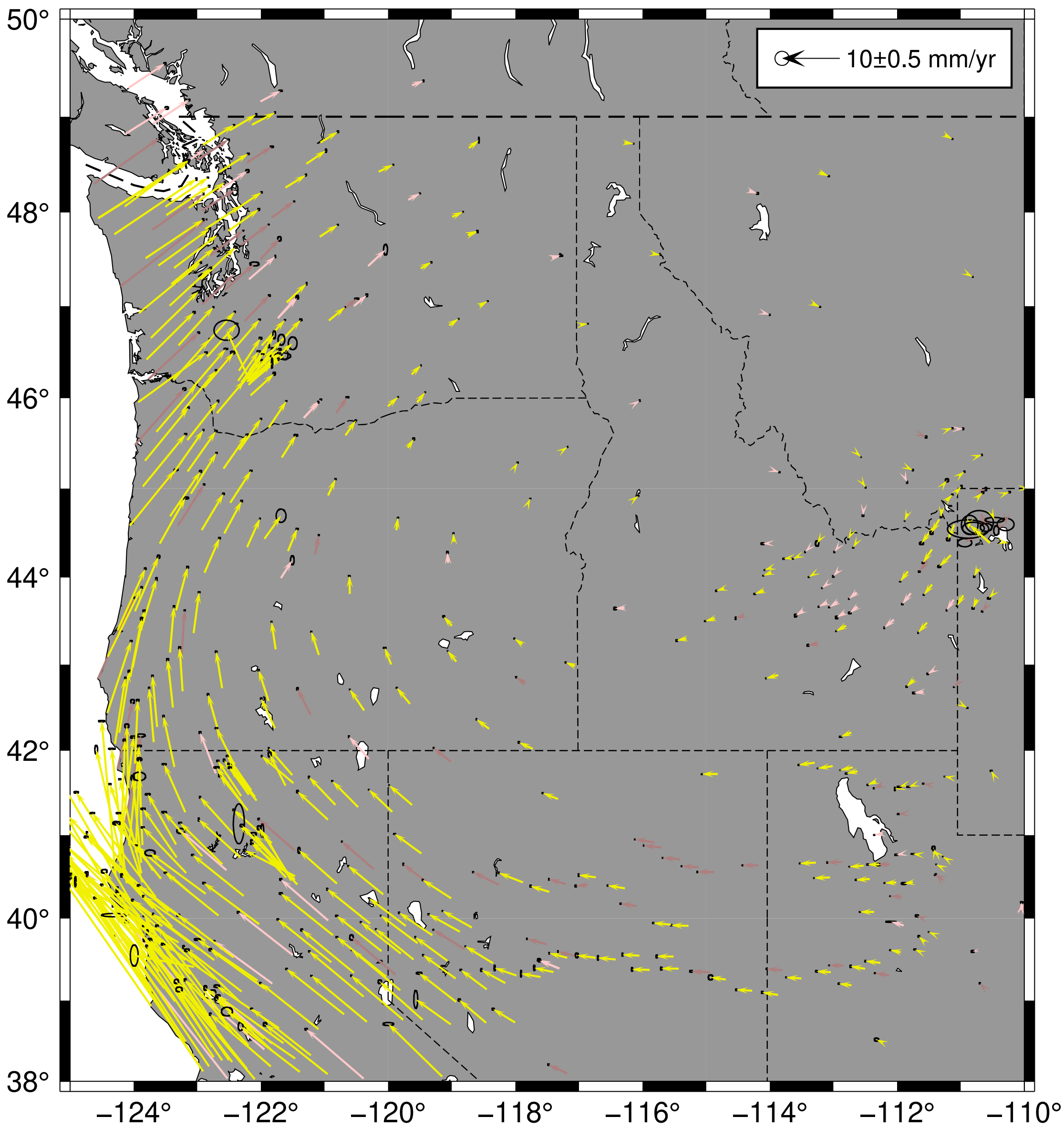

Figure 8: Velocity field estimates for the Pacific northwest from the CWU solution generated using time series analysis and the FOGMEX error model. 95% confidence interval error ellipses are shown. The color scheme of the vectors matches the network type legend in Figure 4. Only velocities with horizontal standard deviations less than 2 mm/yr are shown (this value is reduced from previous reports due to the improved velocity sigmas).

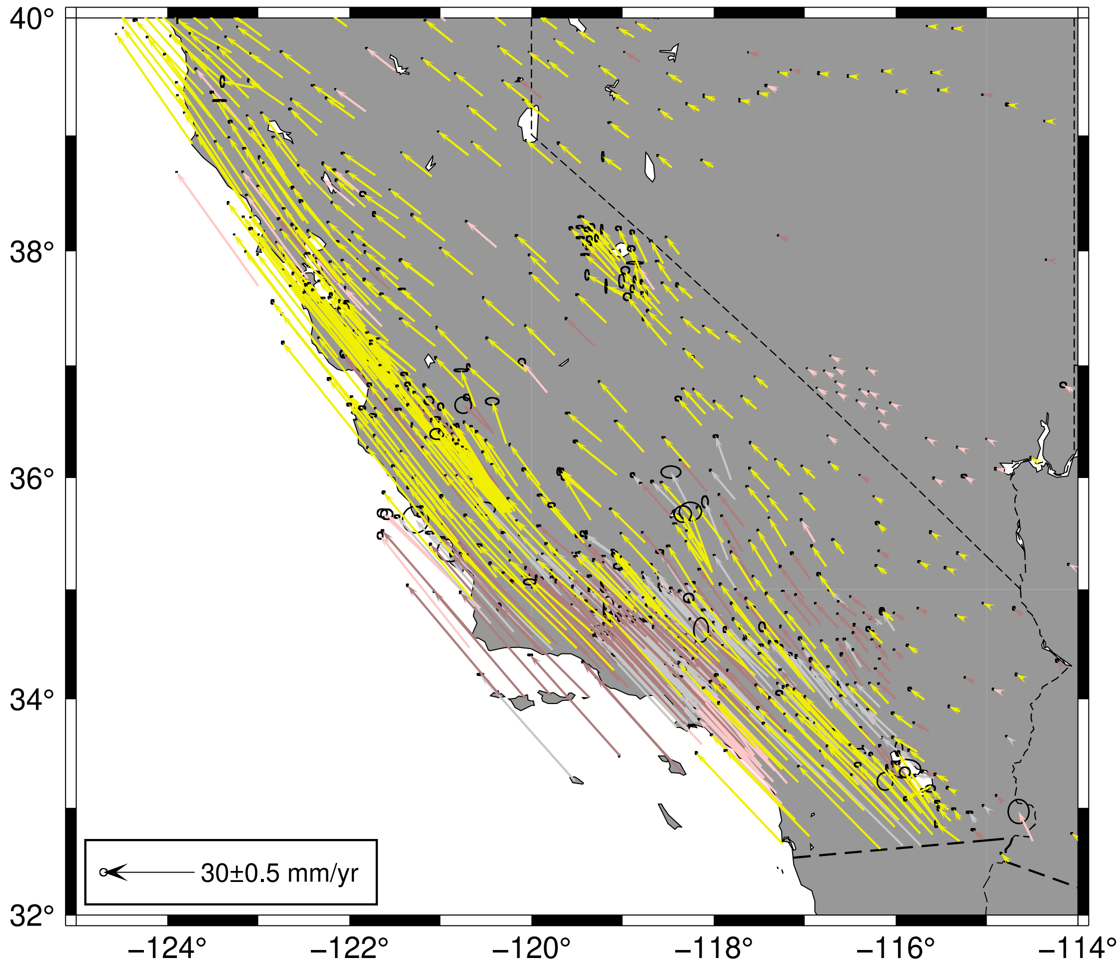

Figure 9: Same as Figure 8 except for South Western United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown.

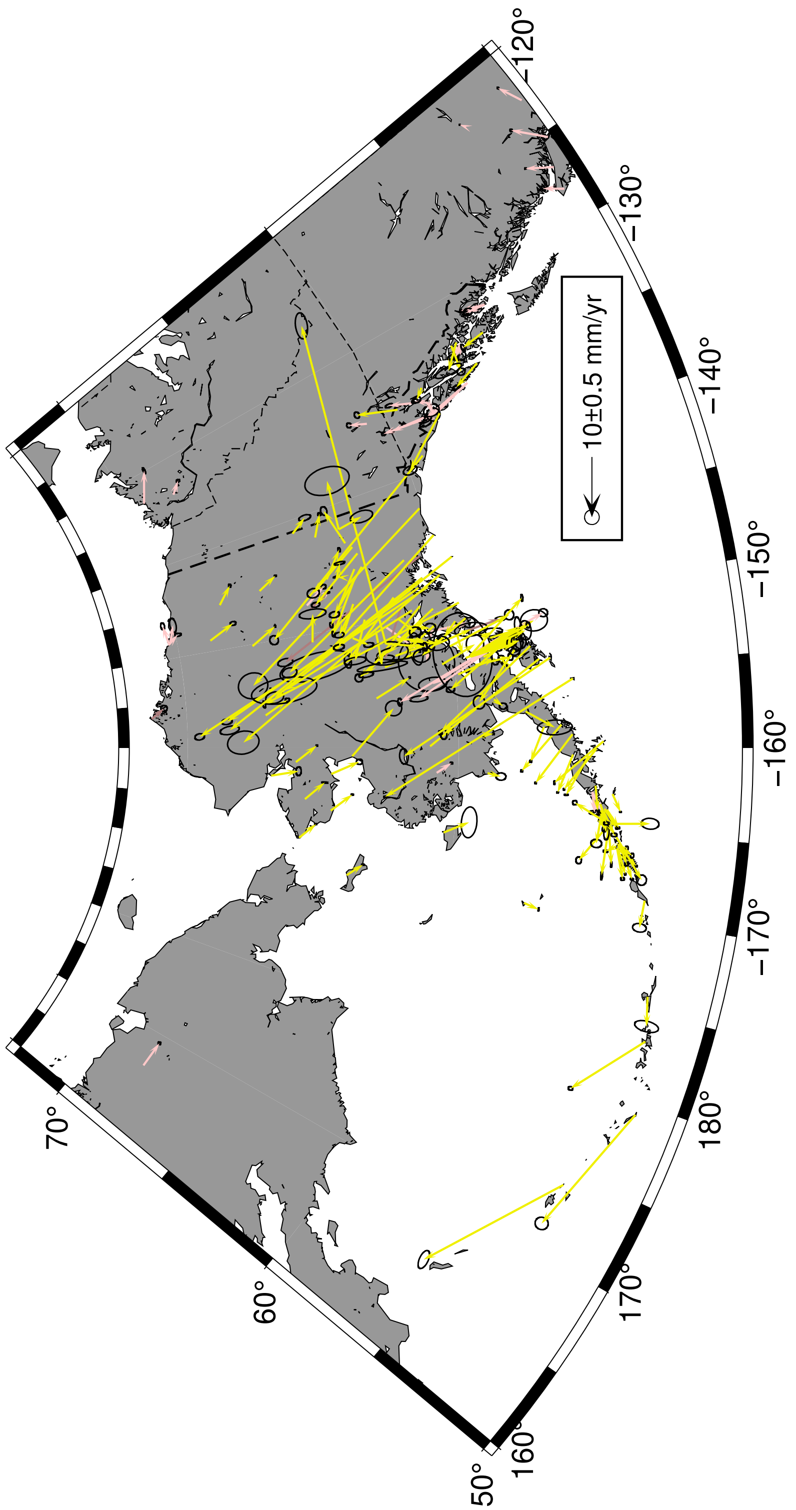

Figure 10: Same as Figure 8 except for Alaska. Only velocities with horizontal standard deviations less than 5 mm/yr are shown

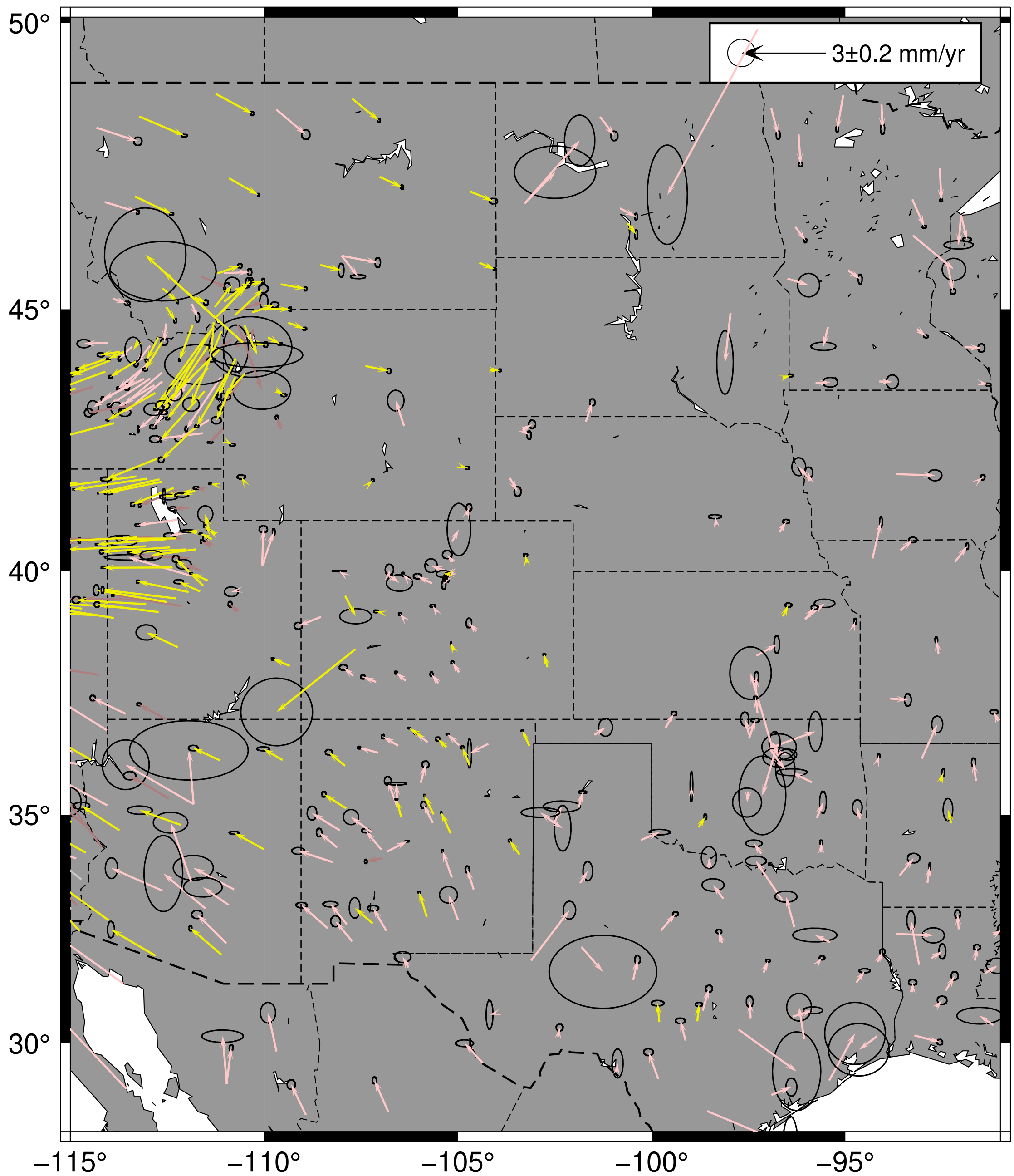

Figure 11: Same as Figure 8 except for Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown.

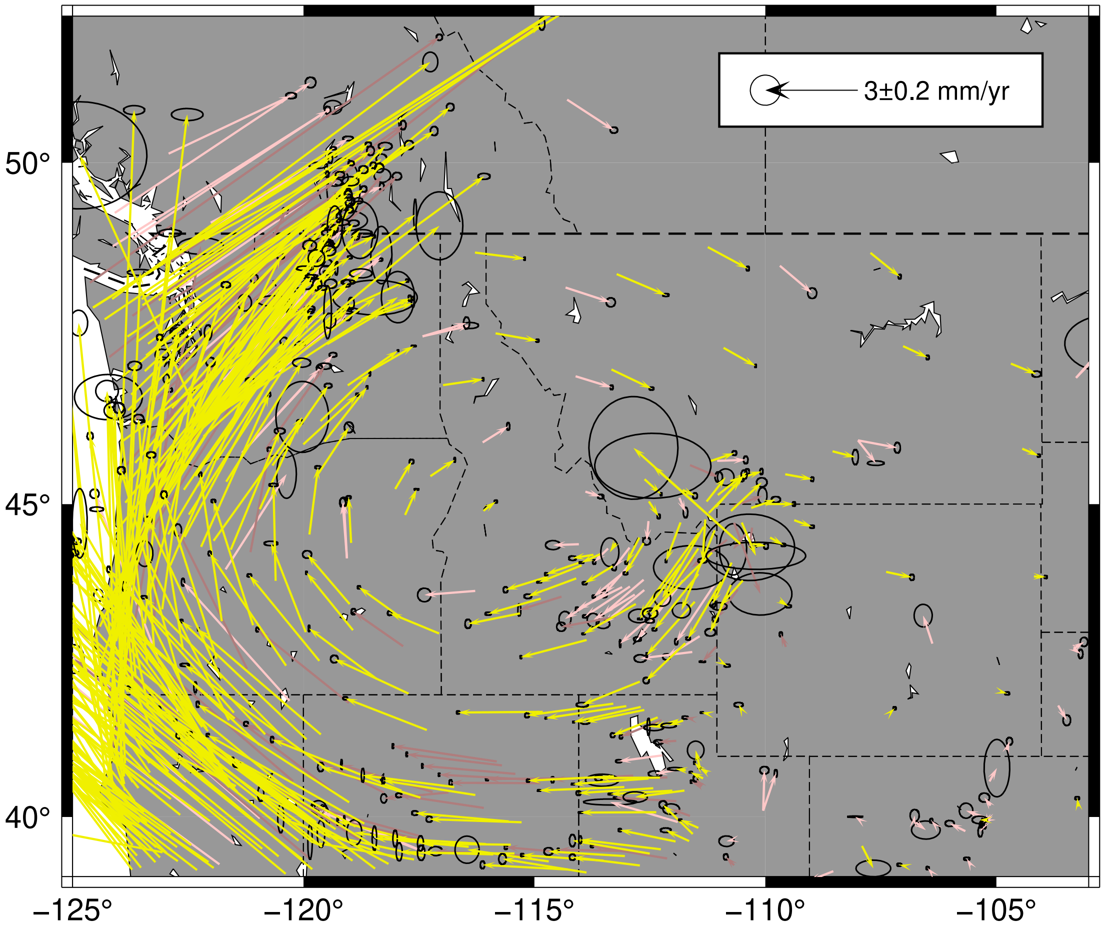

Figure 12: Same as Figure 8 except for Western Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown. Anomalous vectors at longitude 250° are in the Yellowstone National Park and most likely are showing volcanic processes.

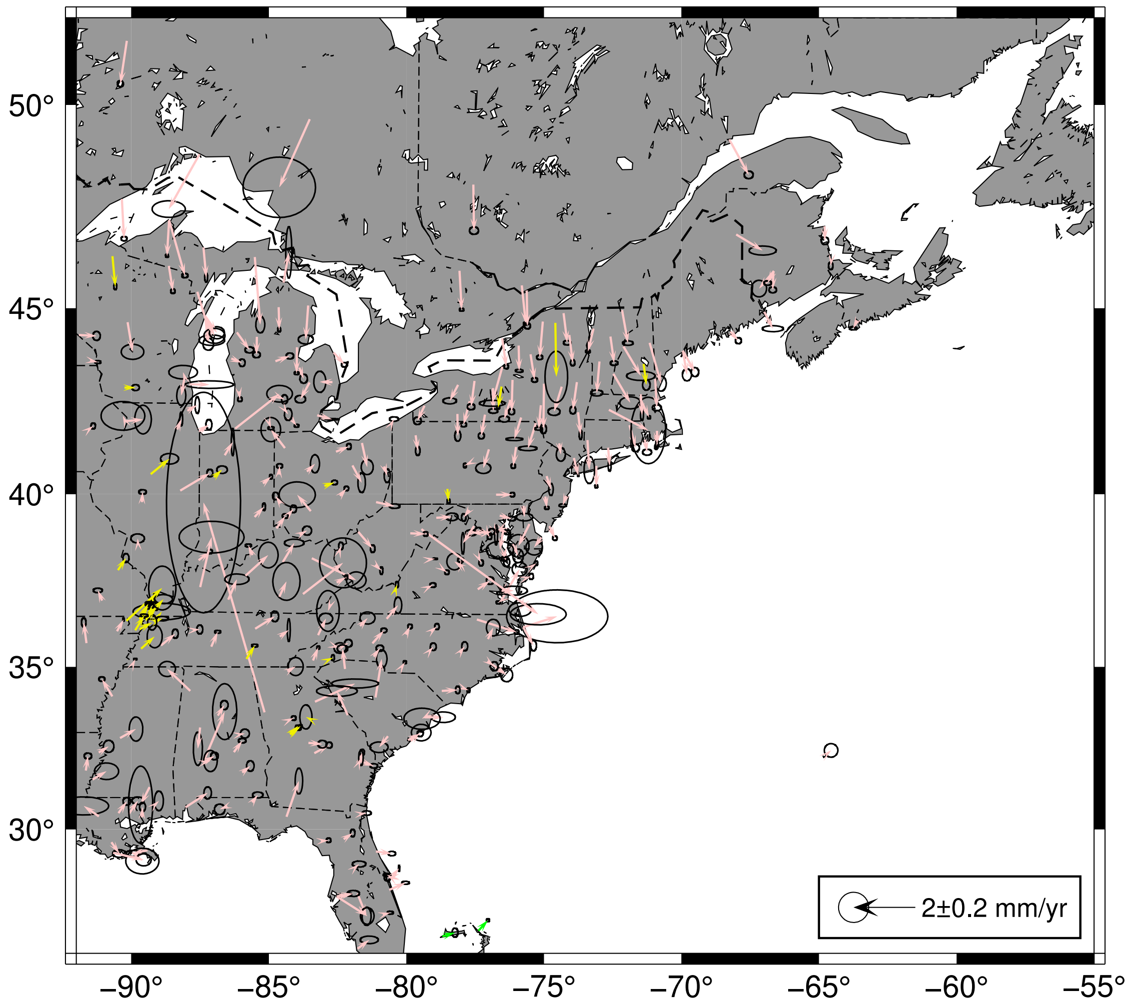

Figure 13: Same as Figure 8 except for the Eastern United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown. The systematic velocity of sites in the Northeast and central US show deviations for current GIA models in the horizontal velocities.

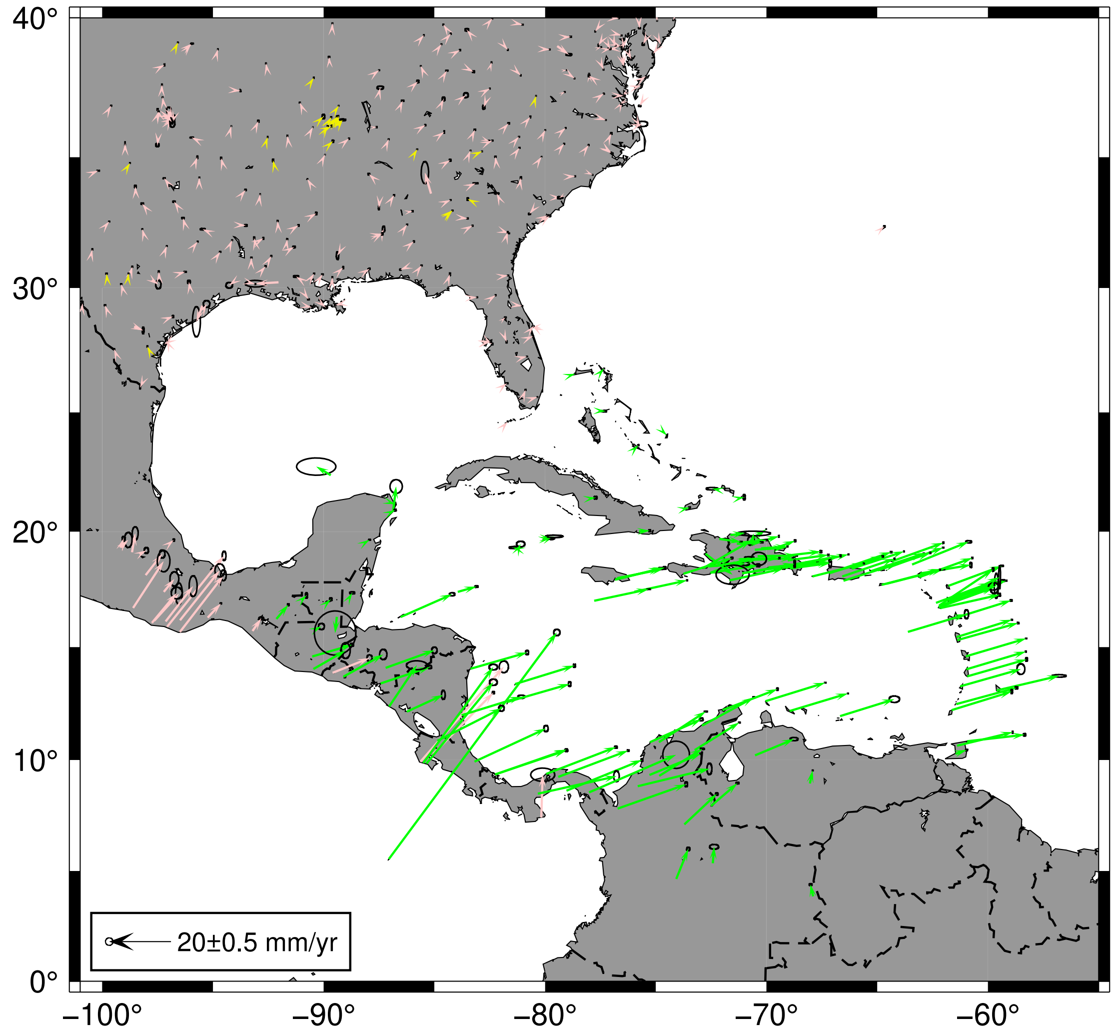

Figure 14: Same as Figure 8 except for the Caribbean region. Only velocities with horizontal standard deviations less than 5 mm/yr are shown.

Earthquake Analyses: 2023/09/15-2023/12/15

We use the NEIC catalog to search for earthquakes that could cause coseismic offsets at the sites analyzed by the GAGE analysis centers. Of the 47 earthquakes examined during this quarter, none generated co-seismic offsets greater than 1 mm.

Antenna and other discontinuity events.

Antenna swaps at 31 sites have been added to the list of offsets that are estimated when fitting velocities and other parameters to the CWU time series. These offsets were spread throughout the quarter.

Anomalous sites

The following sites have been noted as having anomalous motions during this quarter. We updated the ACC_GAGE website to show times of earthquakes, antenna changes, and offsets for unknown reasons. Plots for CWU are now generated with and without offsets (computed from the Kalman filter time series analysis) removed. The landing page for http://geoweb.mit.edu/~tah/ACC_GAGE/ now has the following explanation.

NOTA RAPID Solution Outlier sites for PROD ID 20230120183013

Analyses from Central Washington University (CWU). Series are:
  NMT -- Old plots from New Mexico Tech Analyses (Ends 9/15/2018).
  PBO -- Old plots from Combined NMT+CWU analyses (Ends 9/15/2108).
  CWURAW -- Raw time series with linear trend removed
  CWUOFF -- Time series with linear trend and offsets from cwu.kalts_nam14.off removed
Vertical lines denote times of offsets in time series:
  Purple, solid: Earthquakes (OffEq ! EQ)
  Blue, dotted: Antenna changes (Break ! AN)
  Cyan, dashed: Breaks for unkown reasons (Break ! UN)

N after site name means NOTA operated site, U means UNAVCO/Earthscope log file.
The table below includes new and old style plots (update was made that the end of the quarter).

Site	N	Issues related to site
		2023-10-06
GRSV		PANGA site. Jump in height looks like an antenna change but no log file update. http://geoweb.mit.edu/~tah/ACC_PBO/GRSV.CWUOFF.png
P711	N	Yellowstone site showing decadal systematics. http://geoweb.mit.edu/~tah/ACC_PBO/P711.CWUOFF.png
		2023-10-20 Not in monthly
P412	N	Oregon site. Previously noted but deviations have now grown to over 20 mm in North and East and 60 mm in height. http://geoweb.mit.edu/~tah/ACC_PBO/P412.CWUOFF.png
RG08		Previously reported. Clearly has failed DM element. http://geoweb.mit.edu/~tah/ACC_PBO/RG08.CWUOFF.png
		2023-10-27
P577	N	Site near Silverwood Lake west of LA. Seems to have large numbers of outliers. Not clear why. Nearby P612 also has outliers (maybe skewed but not near heigh mountains). http://geoweb.mit.edu/~tah/ACC_PBO/P577.CWUOFF.png
		2023-11-13
CARH	U	Just came back online after gap since July 2021. 100 mm height change suggests new antenna but no update to meta data in EarthScope log. http://geoweb.mit.edu/~tah/ACC_PBO/CARH.CWUOFF.png
HUNT	U	Same as CARH. http://geoweb.mit.edu/~tah/ACC_PBO/HUNT.CWUOFF.png

P249	N	Strange systematics. Site in Northern Central Valley inland of Monterey Bay. http://geoweb.mit.edu/~tah/ACC_PBO/P249.CWUOFF.png
		2023-11-17
AC53	N	10-40 mm NE offset. No apparent earthquake associated with offset. Site well inland from Anchorage, AK. Monument has been damaged. http://geoweb.mit.edu/~tah/ACC_GAGE/AC53.CWUOFF.png
		2023-12-01
RDBN	U	Dominican Republic site. Jump in east by 15 mm for unknown reason. http://geoweb.mit.edu/~tah/ACC_GAGE/RDBN.CWUOFF.png
VCAP		Site in Vermont: May be snow. http://geoweb.mit.edu/~tah/ACC_GAGE/VCAP.CWUOFF.png
VTDP		Also in Vermont: May be snow http://geoweb.mit.edu/~tah/ACC_GAGE/VTD9.CWUOFF.png
VTRU		Outlier but also strong annual signals in north and east. On building on Rutland. http://geoweb.mit.edu/~tah/ACC_GAGE/VTRU.CWUOFF.png
		2023-12-08
GRSV		PANGA site with new antenna but no meta-data update. http://geoweb.mit.edu/~tah/ACC_GAGE/GRSV.CWUOFF.png
KYTD		New antenna 2023-333. Offset in rapids. CORS site. http://geoweb.mit.edu/~tah/ACC_GAGE/KYTD.CWUOFF.png
		2023-12-29 Not in monthly
COND		PANGA site with new antenna but no log file update. http://geoweb.mit.edu/~tah/ACC_GAGE/COND.CWUOFF.png
P802	N	East changes by 10 and then 20 mm in rapids. Site in North Dakota, could be snow? http://geoweb.mit.edu/~tah/ACC_GAGE/P802.CWUOFF.png
PIMA		CORS site, jump of -25 mm in height on 2023/09/24. No log update for site. Site in Tucson AZ. Added to UNKN offset file.
		2024-01-16
P802	N	Two outliers in East; recovered so not clear what happened. Did something similar last year. http://geoweb.mit.edu/~tah/ACC_GAGE/P802.CWUOFF.png
PMAR	U	Height jump pf 50 mm, no meta-data update. Similar 2 and 3 years ago. http://geoweb.mit.edu/~tah/ACC_GAGE/PMAR.CWUOFF.png
YOCR	U	Large outliers; on Mt. Hood so could be snow. http://geoweb.mit.edu/~tah/ACC_GAGE/YOCR.CWUOFF.png
YORK		CORS site; antenna seems to have failed again. Site In York, PA. Rapids being removed from plot. http://geoweb.mit.edu/~tah/ACC_GAGE/YORK.CWUOFF.png
		2024-01-19 Not in monthly
KYTL		CORS station in Kentucky. Seems to be 25 mm height offset between rapids and finals processing (most sites don't show this.) http://geoweb.mit.edu/~tah/ACC_GAGE/KYTL.CWUOFF.png
MTUM		University of Montana site (in CWUPANGA logs but not PANGA). Seems to have tree growing but seems to be in open field In satellite image. Could be bad antenna. http://geoweb.mit.edu/~tah/ACC_GAGE/MTUM.CWUOFF.png

P302	N	In Great Valley with large East systematics. http://geoweb.mit.edu/~tah/ACC_GAGE/P302.CWUOFF.png
P375	N	Oregon, inland of Newport; slow slip site but rapid change in east coordinate. Could be big slow slip event. http://geoweb.mit.edu/~tah/ACC_GAGE/P375.CWUOFF.png
P377	N	East of Eugene, OR. Large east offsets, could be ice on the antenna. http://geoweb.mit.edu/~tah/ACC_GAGE/P377.CWUOFF.png
		2024-01-26
CARH	U	Unknown break added 2023 8 13 after a long gap in data. 100 mm in height but no log update at Earthscope. http://geoweb.mit.edu/~tah/ACC_GAGE/CARH.CWUOFF.png
		2024-02-02
PAPC		Site in Pennsylvania, new unknown break in 2018/10/09 added. Break mostly in east. http://geoweb.mit.edu/~tah/ACC_GAGE/PAPC.CWUOFF.png
RDOE		Newer Dominican Republic site. Check later but rapid after 2 month gaps seems off by 15 mm in N and E. http://geoweb.mit.edu/~tah/ACC_GAGE/RDPE.CWUOFF.png

ANET Processing

The ANET additional sites are being processed as a separate network and the frame resolved SINEX files will be given in the Antarctica 2014 reference frame (Altamimi *et al.*, 2016, 2017). We label this frame ant14. Time series and SINEX files are generated only for final orbit solutions and are labeled as fanet (instead of final to avoid name conflicts with loose solutions). The IGS14 loose submission files are labeled with "lse14" to differentiate them for the IGS08 loose submissions which were simply label as loose. The statistics of the time series fits from the CWU solution for this quarter are given in Table 4.

Table 4: Statistics of the fits of 36 stations in the ANET region for CWU analyzed in the final orbit analysis between September 15, 2023 and January 20, 2024.

CWU	North (mm)	East (mm)	Up (mm)
Median ANET	1.33	1.17	6.07
70% ANET	1.45	1.37	7.64
95% ANET	2.14	2.14	8.94

The histogram to the RMS scatter of the results for this quarter are shown in Figure A.1

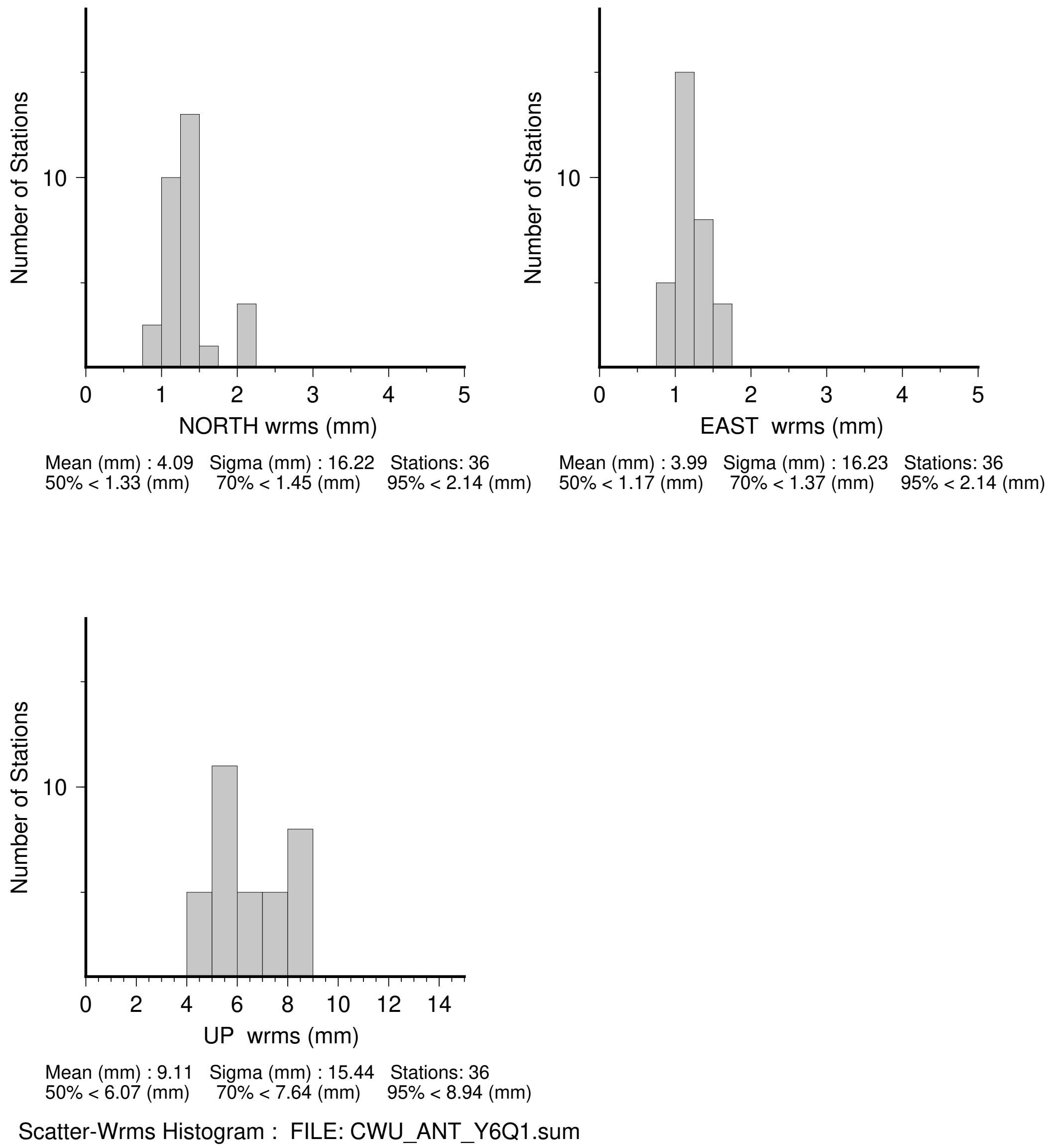

Figure A.1: CWU solution histograms of the North, East and Up RMS scatters of the position residuals for 50 stations in Antarctica analyzed between September 15, 2023 and January 20, 2024. Linear trends and annual signals were estimated from the time series.

References

Altamimi, Z., P. Rebischung, L. Metivier, and X. Collilieux (2016), ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, *J. Geophys. Res. Solid Earth*, 121, 6109-6131, doi: 10.1002/2016JB013098.

Altamimi, Z., L. Metivier, P. Rebischung, H. Rouby, X. Collilieux; ITRF2014 plate motion model, *Geophysical Journal International, Volume 209*, Issue 3, 1 June 2017, Pages 1906-1912, https://doi.org/10.1093/gji/ggx136