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

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Period: 2023/01/01-2023/03/30

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Summary

Under the GAGE2 Facility Data Analysis subaward, MIT has been processing SINEX files 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 2022/13/15 to 2023/03/30, time series velocity field analyses for the GAGE reprocessing analyses (1996-2023). Several earthquakes were investigated this quarter up to 03/15/2023 and one of them, mw6.4 15km WSW of Ferndale latitude/longitude 40.5250 -124.4230 Date 2022/12/20 Time 10:35 UTC generated coseismic offsets. This event has been designated EQ 69.

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. Starting GPS Week 2021 (2018/09/30) only CWU solutions are included. These solutions are in then 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 1997 stations were processed. In addition up to 50 sites were processed in the ANET solutions, 3 more than last quarter.

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

Each week we also process the Supplemental (12-week latency) and six months 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: December 15, 2022– March 30, 2023

For this report, we generated the statistics using the ~3 months of CWU results between December 15, 2022 and March 30, 2023. These results are summarized in Table 1 and figures 1.

For the three months of the final position time series generated by, 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 1977 stations for CWU analyzed in the finals analysis between December 15, 2022 and March 30, 2023. Histograms of the RMS scatters are shown in Figure 1.

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
CWU	1.01	0.95	5.61
70%			
CWU	1.31	1.21	6.46
95%			
CWU	3.38	3.16	13.44

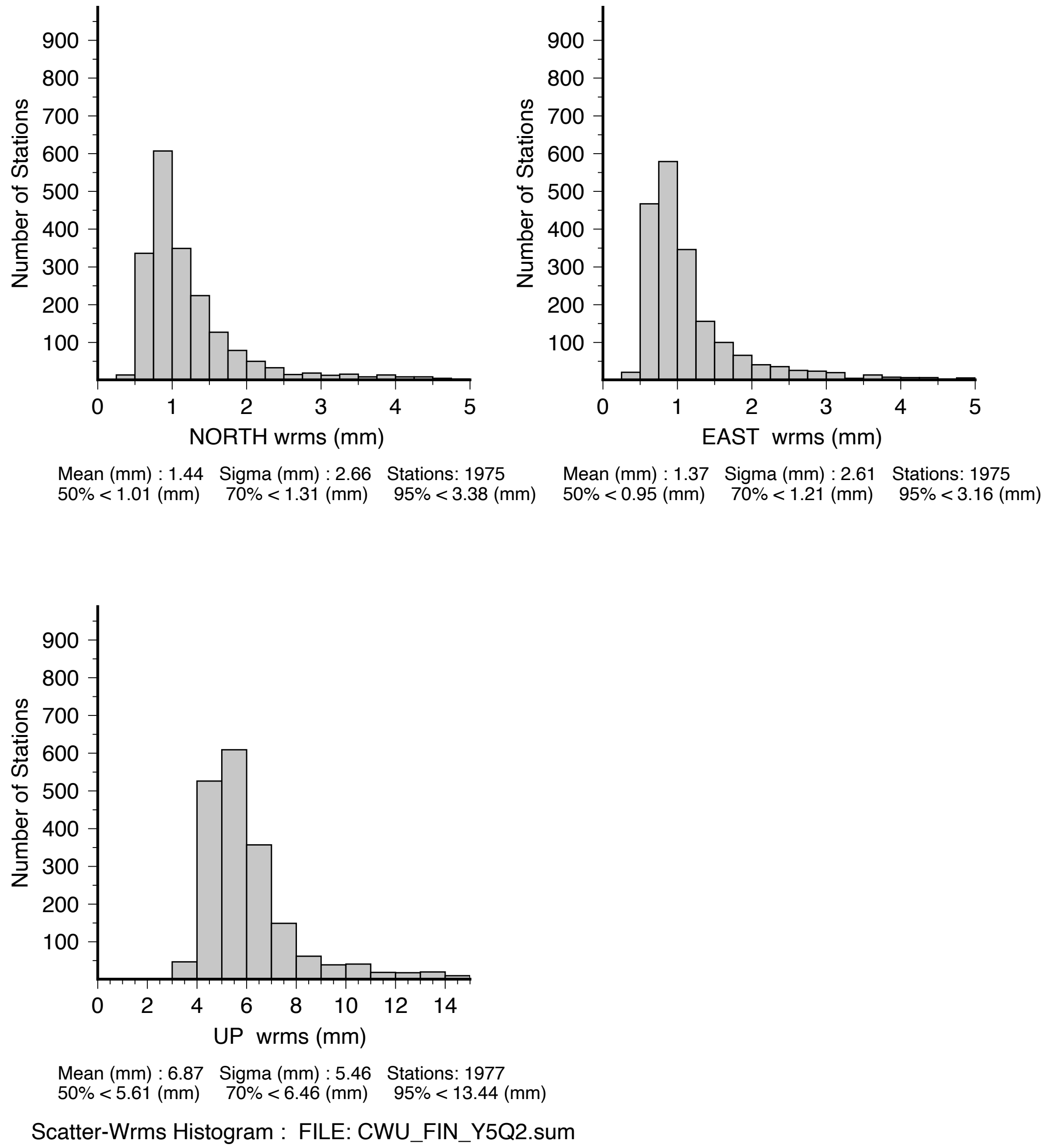

Figure 1: CWU solution histograms of the North, East and Up RMS scatters of the position residuals for 1997 stations analyzed between December 15, 2022 and March 30, 2023. Linear trends and annual signals were estimated from the time series.

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 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 2-7. The values plotted are given in CWU_FIN_Y5Q2.tab.

There are 1984 stations in the file for sites that have at least 2 measurements during the month.

Table 1: Head and tail of WRMS scatter summary file CWU_FIN_Y5Q1.tab.

```
Tabular Position RMS scatters created from CWU_FIN_Y5Q2.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     1.1   0.62      1.4   0.72     7.0   0.76     19.96
 1NSU   106     1.0   0.61      0.9   0.57     6.9   0.92     19.21
 1ULM   105     0.8   0.45      0.8   0.51     6.6   0.88     19.82
 AB02   106     1.4   0.65      1.5   1.03     4.2   0.61     15.88
…
 ZDV1   103     0.8   0.41      0.8   0.55     6.4   0.86     19.85
 ZKC1   102     0.7   0.39      0.8   0.49     6.3   0.84     19.85
 ZLA1   103     1.6   0.89      1.1   0.75     6.6   0.86     19.85
 ZLC1   102     0.8   0.43      0.7   0.46     6.2   0.81     20.07
 ZME1   101     1.0   0.56      1.0   0.65     6.7   0.89     20.07
 ZMP1   102     0.8   0.42      0.7   0.44     7.7   1.05     20.32
 ZNY1   103     0.9   0.46      0.9   0.56     5.5   0.73     20.23
 ZOA1    94     0.8   0.42      0.8   0.55     5.5   0.73     20.76
 ZSE1   103     0.9   0.40      0.8   0.53     6.1   0.83     20.23
 ZTL4   102     0.9   0.55      1.1   0.71     7.3   0.98     20.42
```

Table 2: RMS scatter of the position residuals for the CWU solution between December 15, 2022 and March 30, 2023 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	0.95	0.91	5.31	821
NUCLEUS	0.89	0.78	4.93	182
GAMA	0.82	0.77	5.94	14
COCONet	1.33	1.44	6.51	76
USGS_SCIGN	1.02	0.86	4.81	111
Expanded	1.07	1.01	6.14	773
70%				
PBO	1.26	1.16	6.04	
NUCLEUS	1.03	0.93	5.39	
GAMA	0.82	0.79	6.08	

COCONet	1.56	1.78	7.85
USGS_SCIGN	1.29	1.13	5.32
Expanded	1.39	1.29	6.86
95%			
PBO	3.49	3.82	13.59
NUCLEUS	1.77	1.66	8.44
GAMA	0.92	1.02	6.91
COCONet	2.42	2.90	13.23
USGS_SCIGN	1.91	1.78	9.08

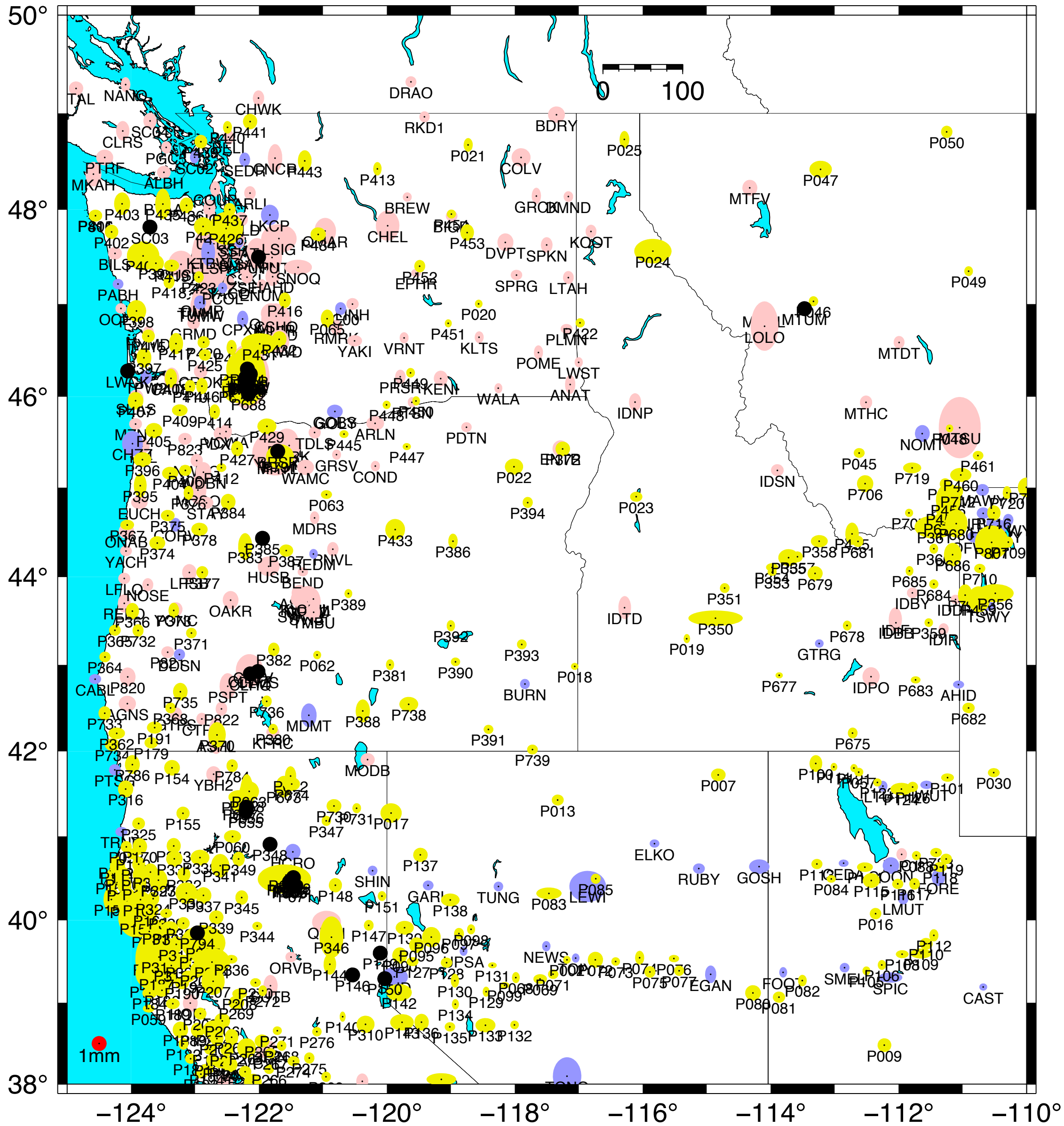

Figure 2: Distribution of the RMS scatters of horizontal position estimates from the CWU analysis for the Northern Western United States. The color of the ellipses that give the north and east RMS scatters denotes the network given by the legend in the figure. The small red circle shows the size of 1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

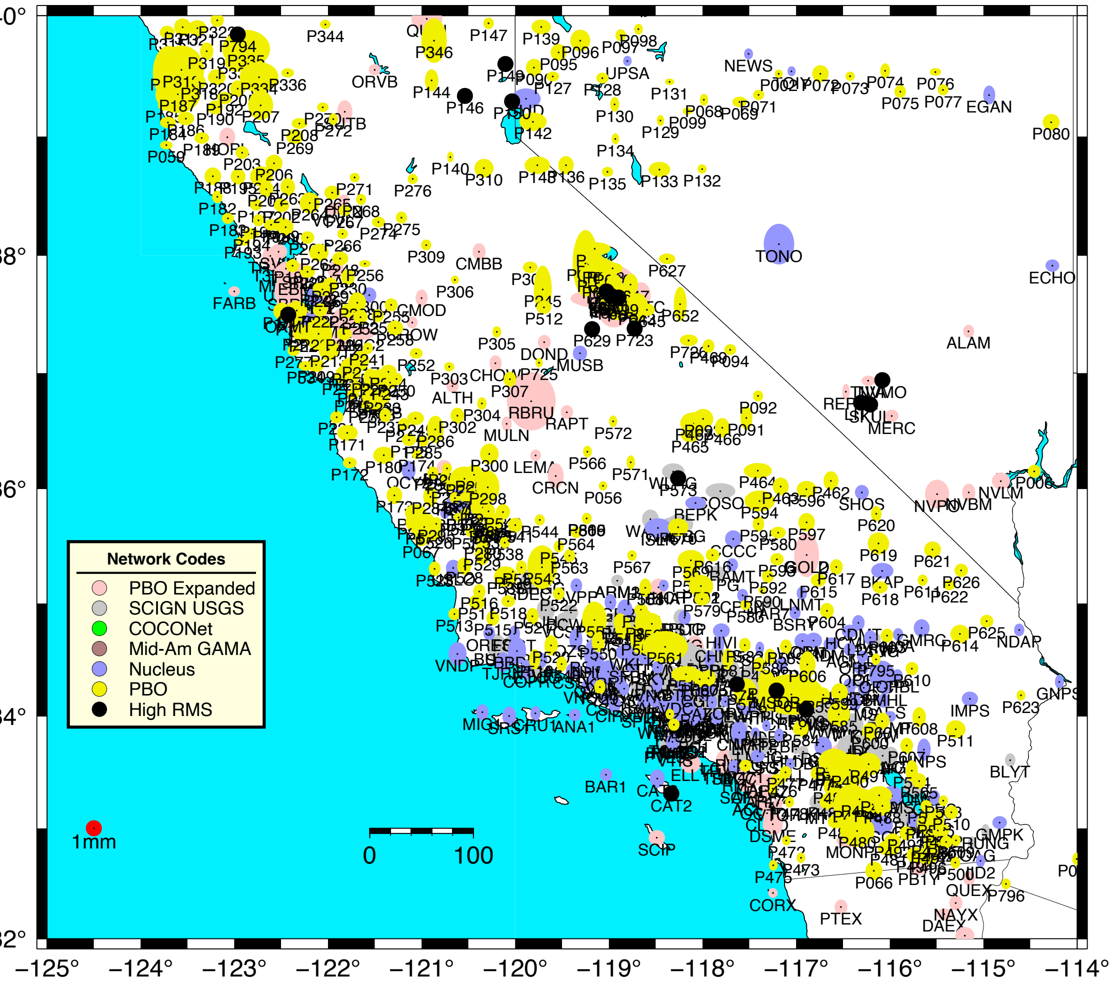

Figure 3: Same as Figure 4 except for the Southern Western United States. Black circles show large RMS scatter sites.

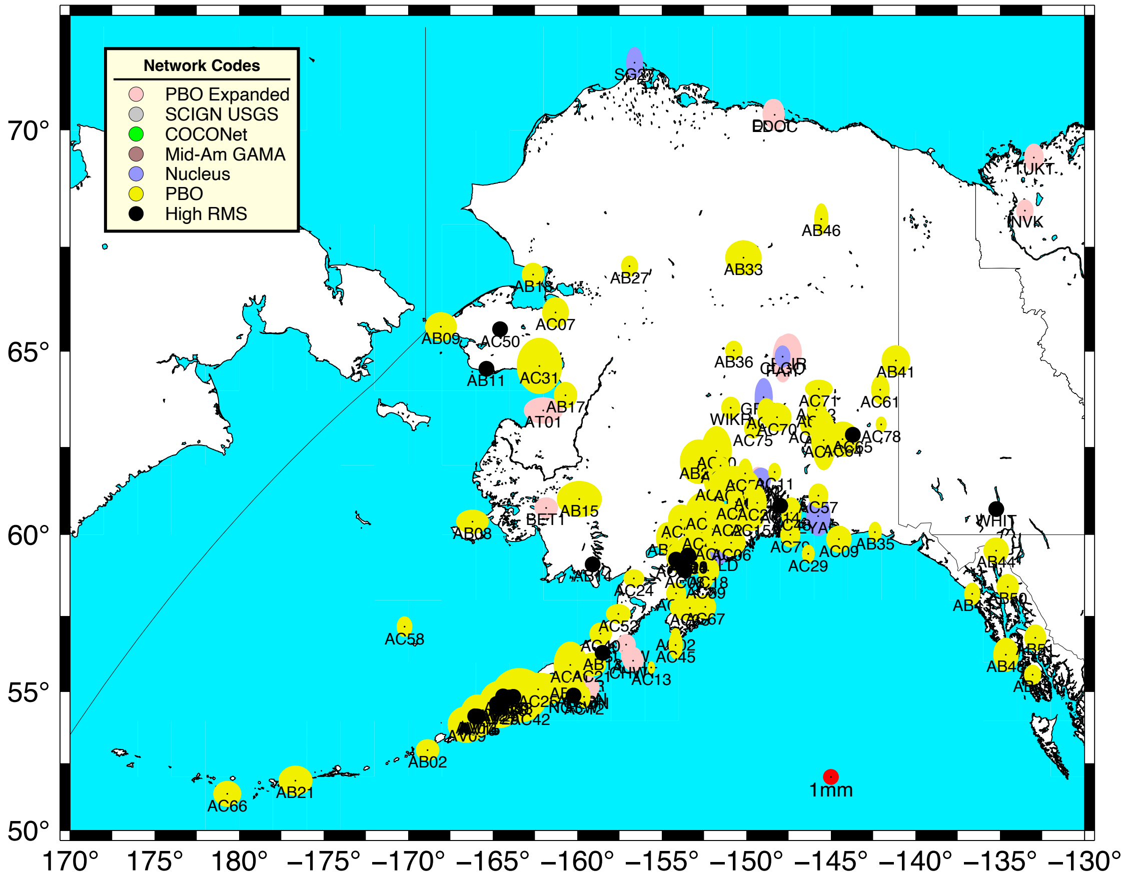

Figure 4: Same as Figure 4 except for the Alaskan region.

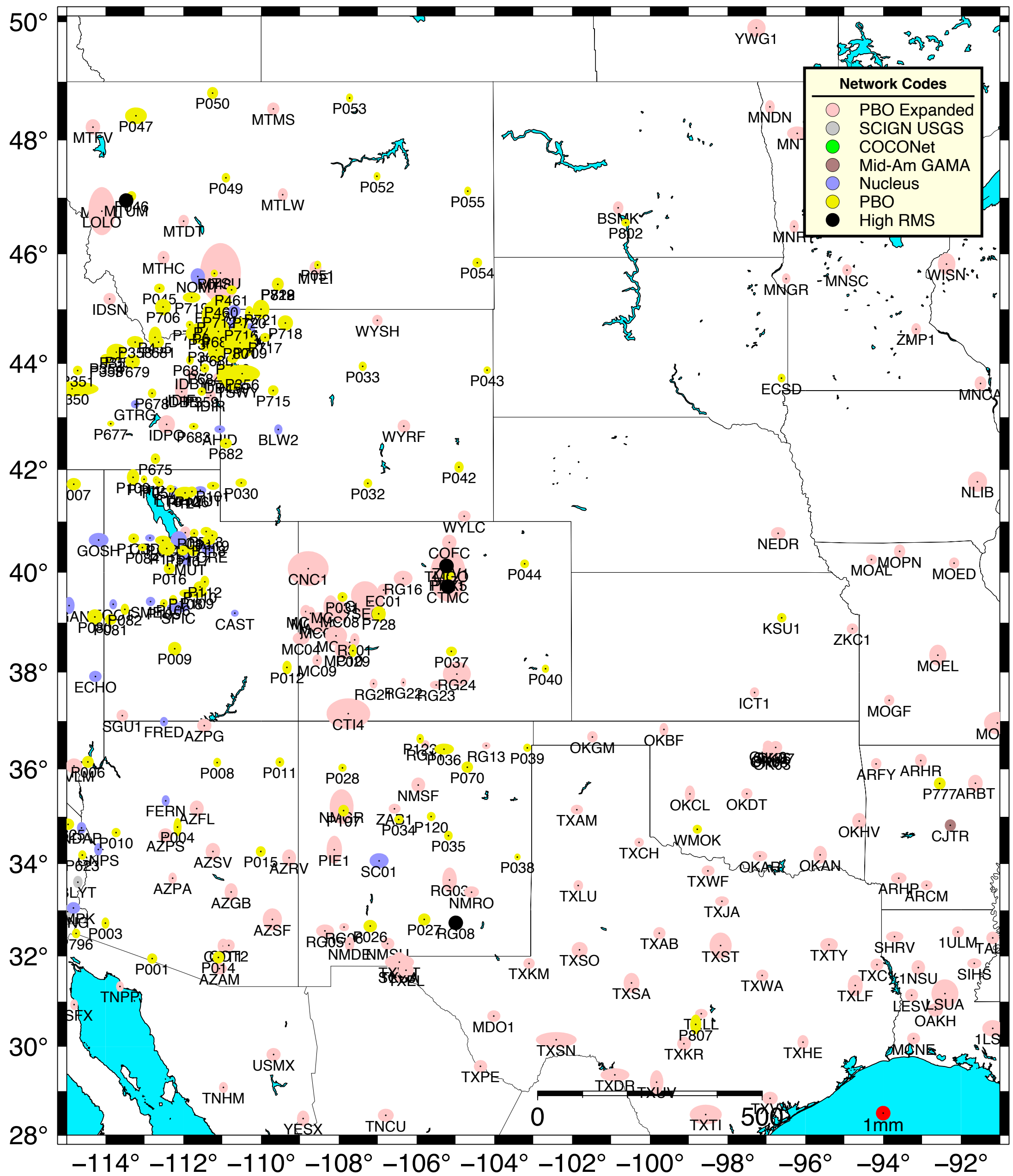

Figure 5: Same as Figure 4 except for the Central United States

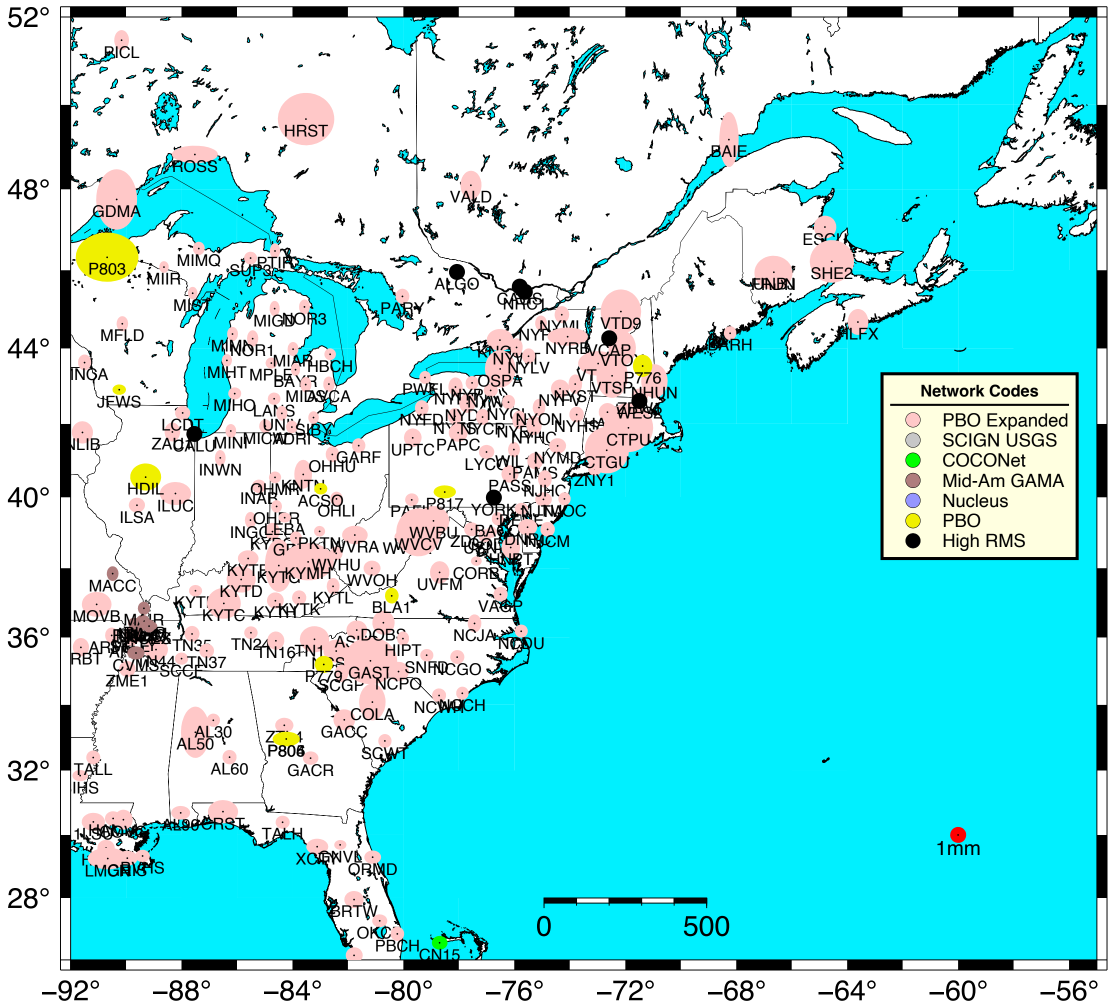

Figure 6: Same as Figure 4 except for the Eastern United States

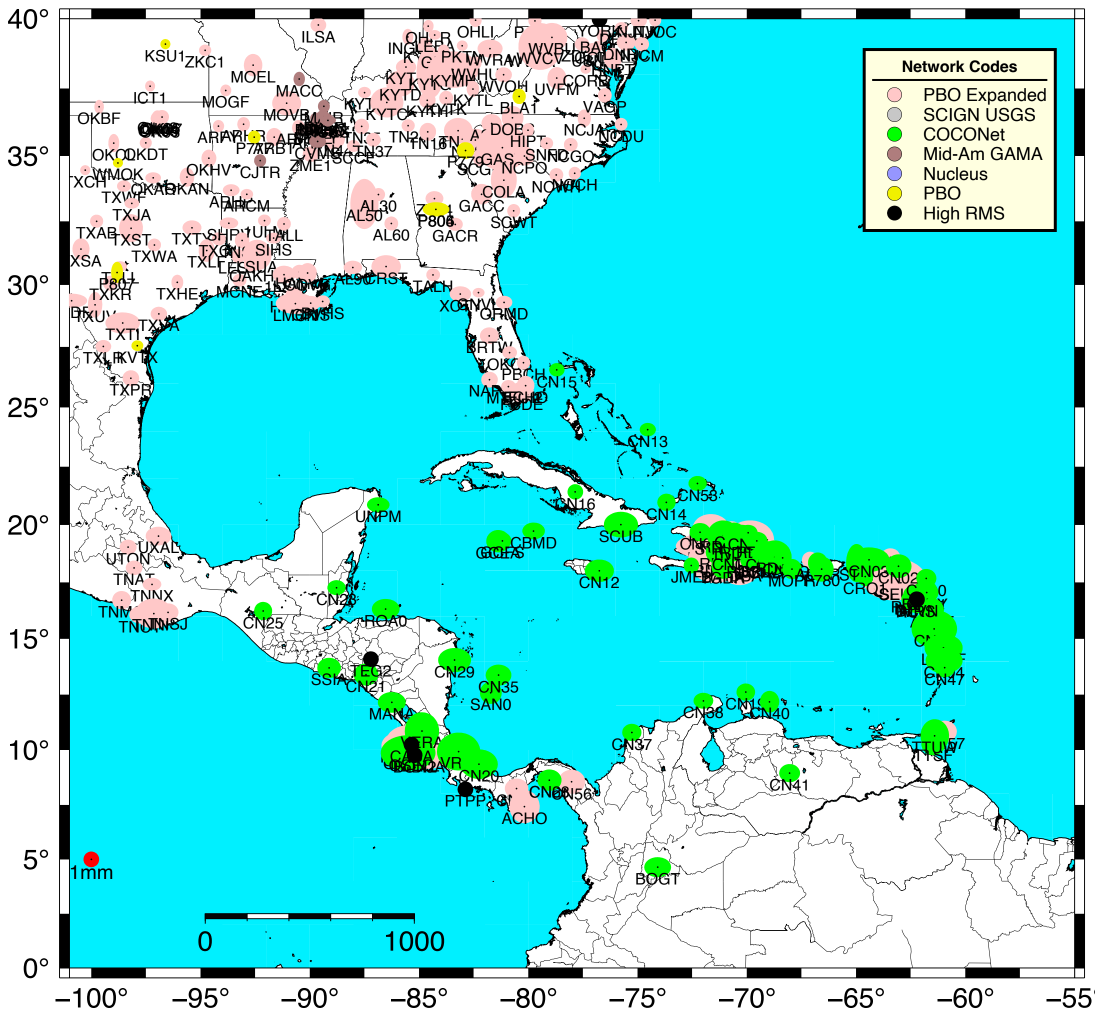

Figure 7: Same as Figure 4 except for the Caribbean region.

GLOBK Apriori coordinate file and earthquake files

As part of the quarterly analysis we run 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 estimates 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 2717 stations in the CWU solution (8 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_220408.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_220408.snpvel.

Table 3: Statistics of the fits of 2717 stations analyzed CWU in the reprocessed analysis for data collected between Jan 1, 1996 and April 04, 2023.

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
CWU	1.41	1.36	6.22
70%			
CWU	1.77	1.74	7.07
95%			
CWU	3.93	3.67	11.65

In Figures 8-14, 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.

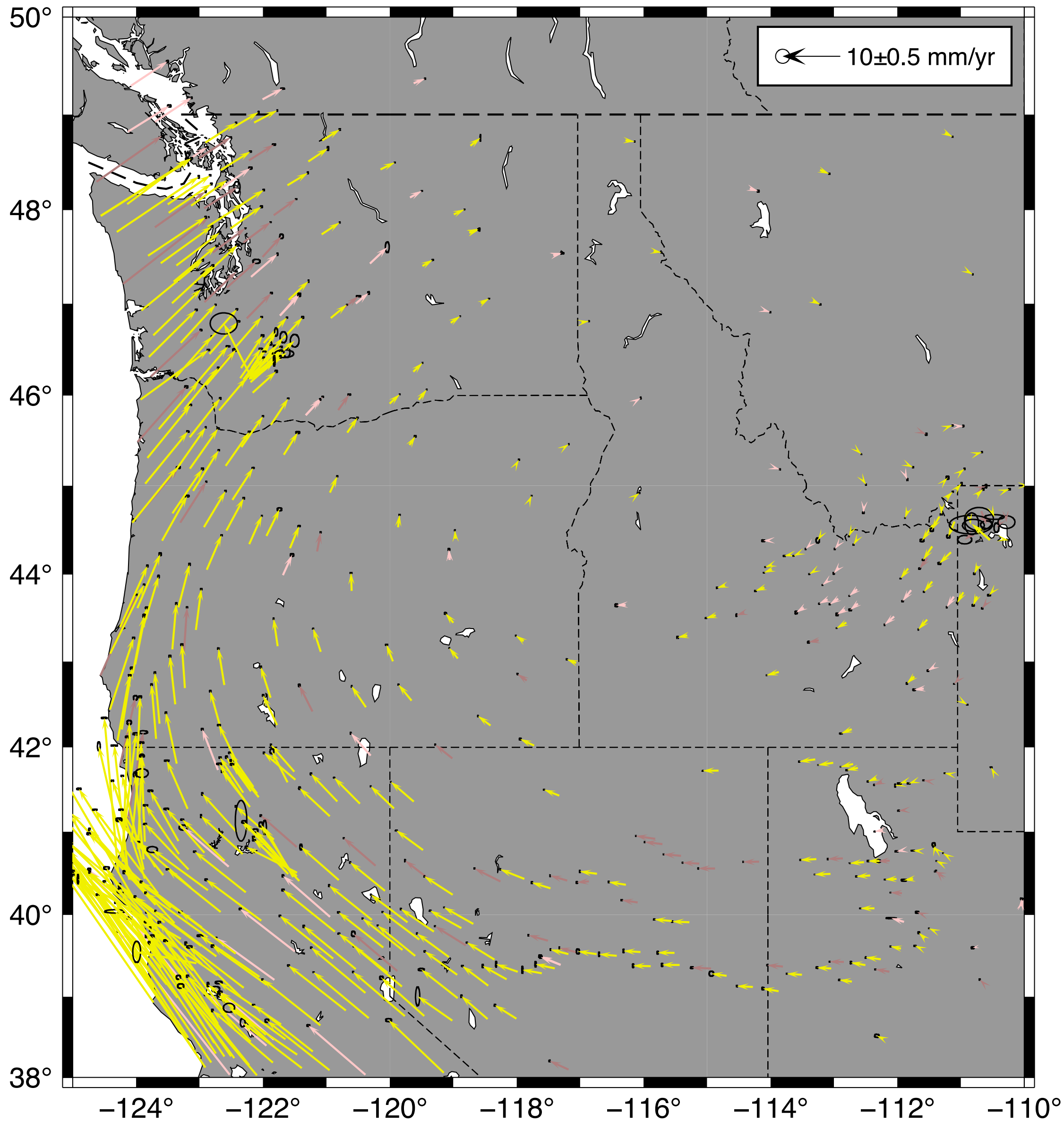

Figure 8: Velocity field estimates for the Pacific north-west from the CWU solution generated using time series analysis and the FOGMEX error model. 95% confidence interval error ellipses are shown. The color scheme of the vectors matches the network type legend in Figure 4. Only velocities with horizontal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

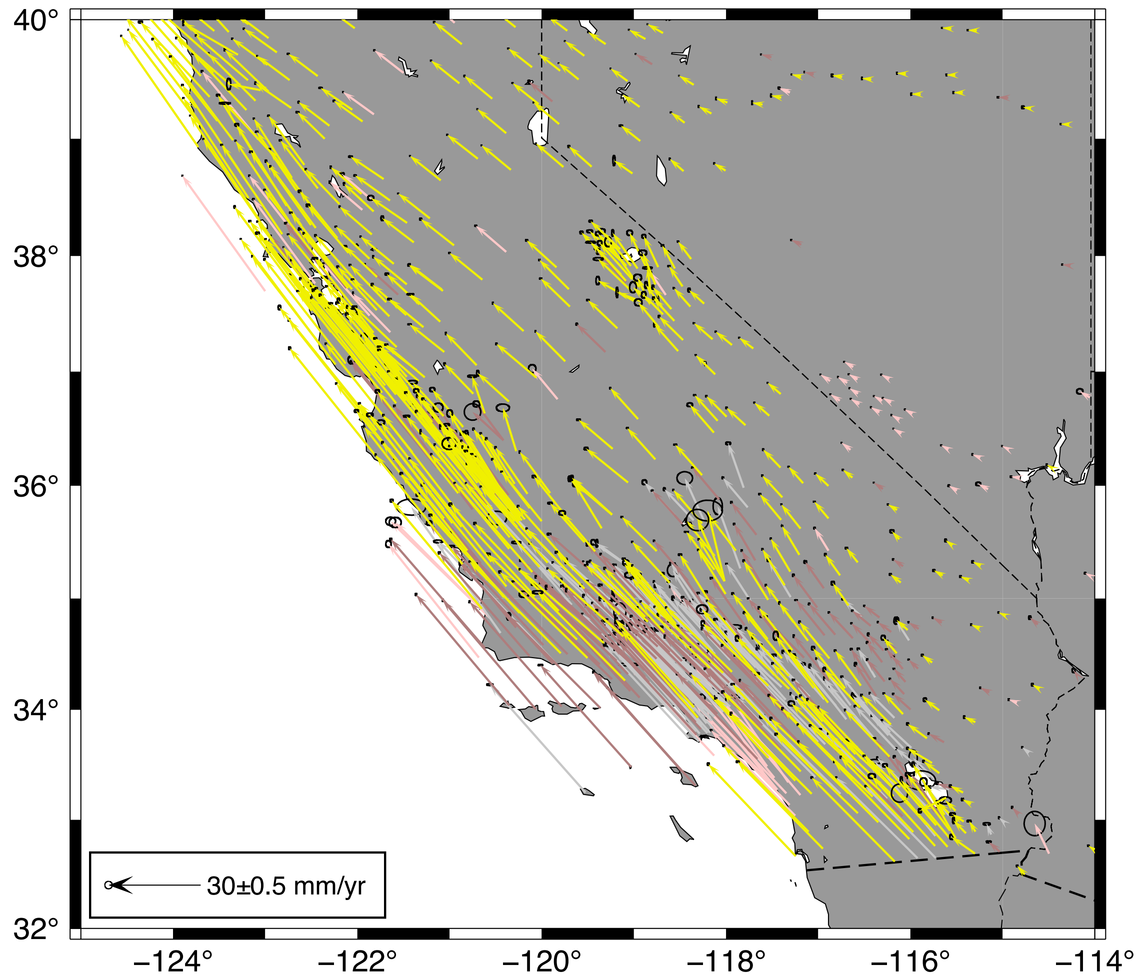

Figure 9: Same as Figure 8 except for South Western United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown.

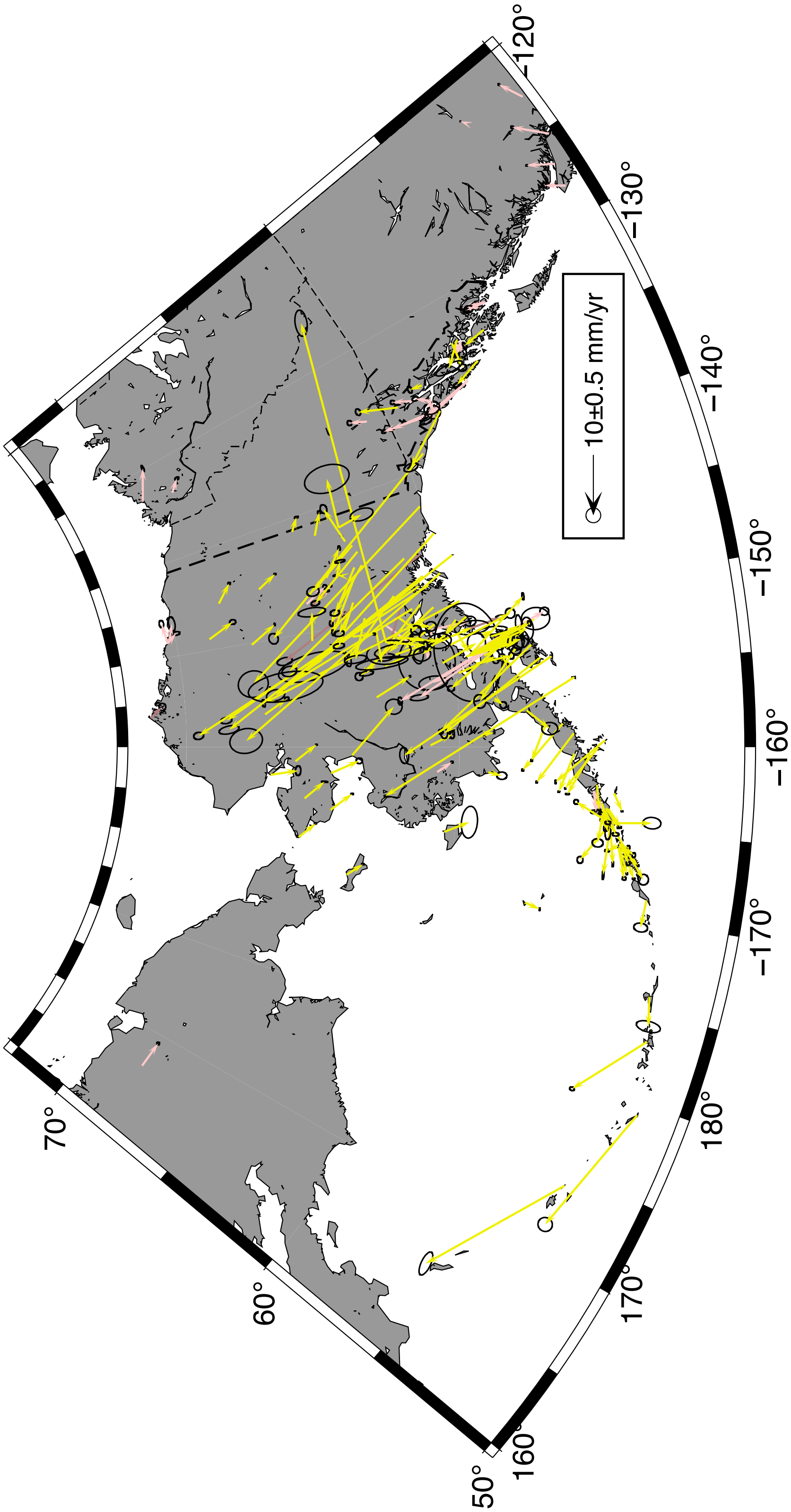

Figure 10: Same as Figure 8 except for Alaska. Only velocities with horizontal standard deviations less than 5 mm/yr are shown

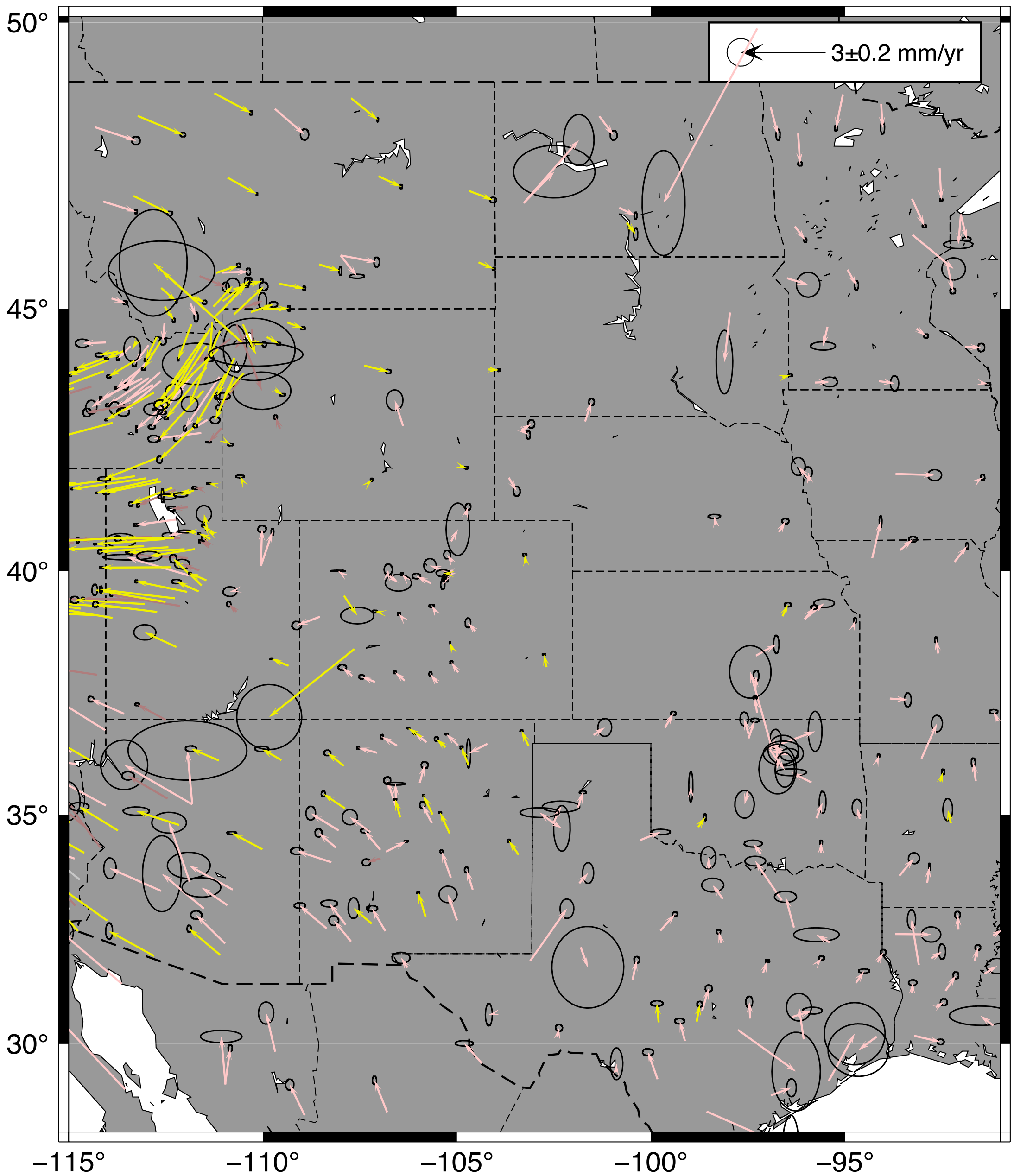

Figure 11: Same as Figure 8 except for Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown.

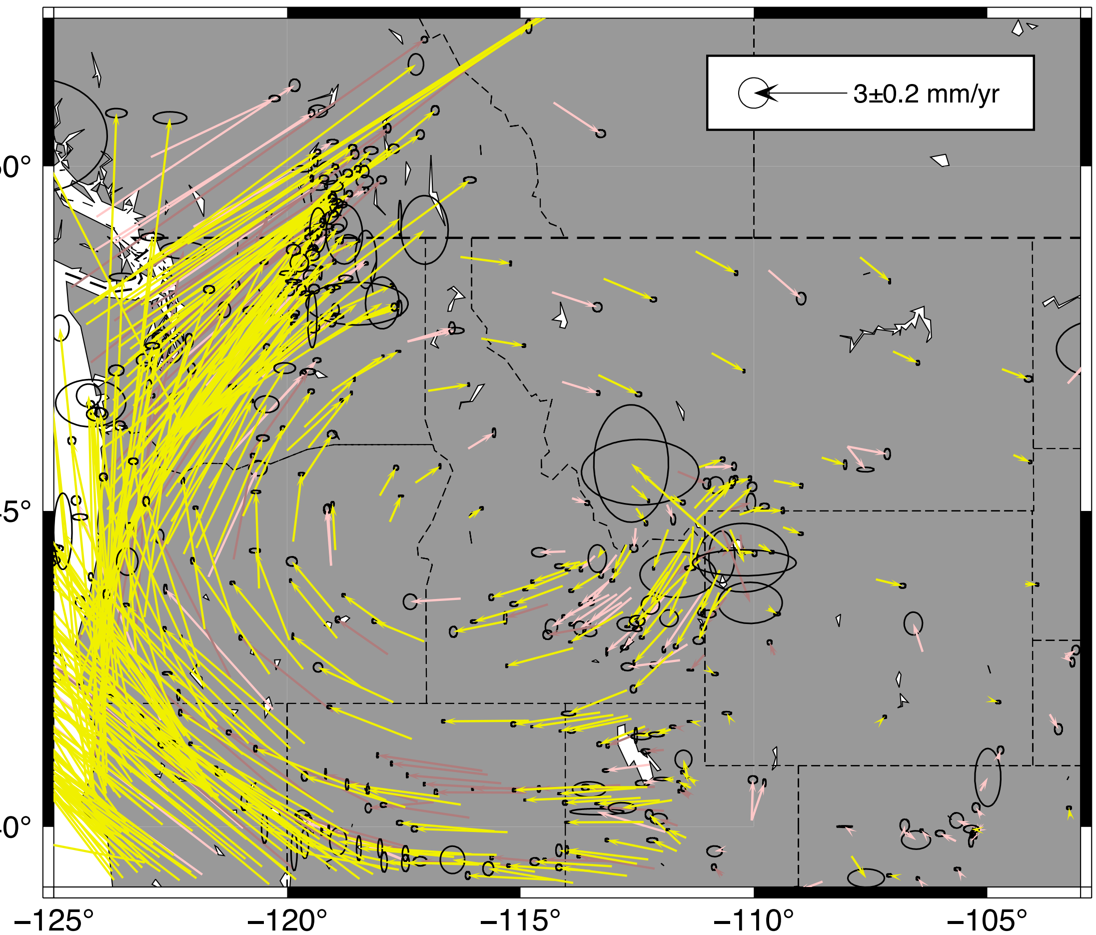

Figure 12: Same as Figure 8 except for Western Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown. Anomalous vectors at longitude 250° are in the Yellowstone National Park and most likely are showing volcanic processes.

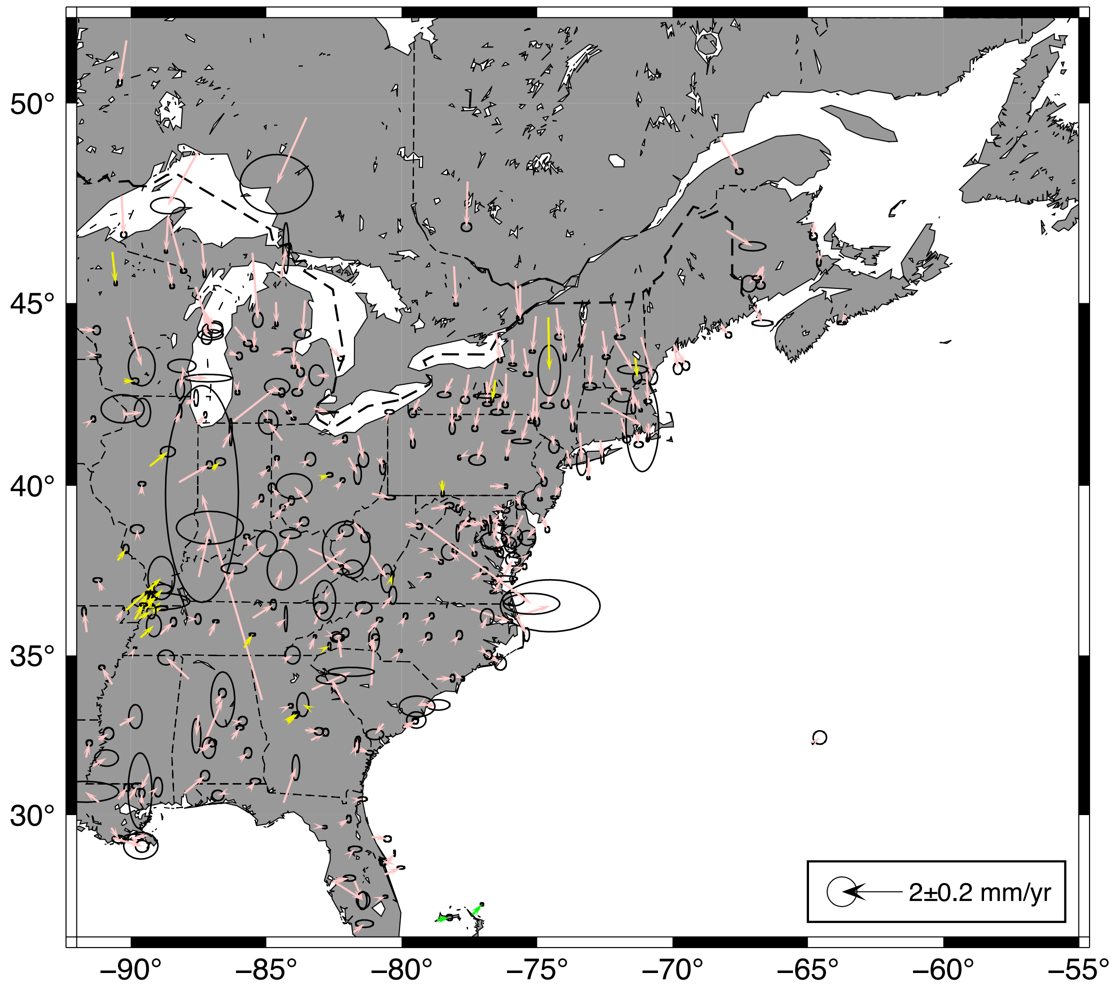

Figure 13: Same as Figure 8 except for the Eastern United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown. The systematic velocity of sites in the Northeast and central US show deviations for current GIA models in the horizontal velocities.

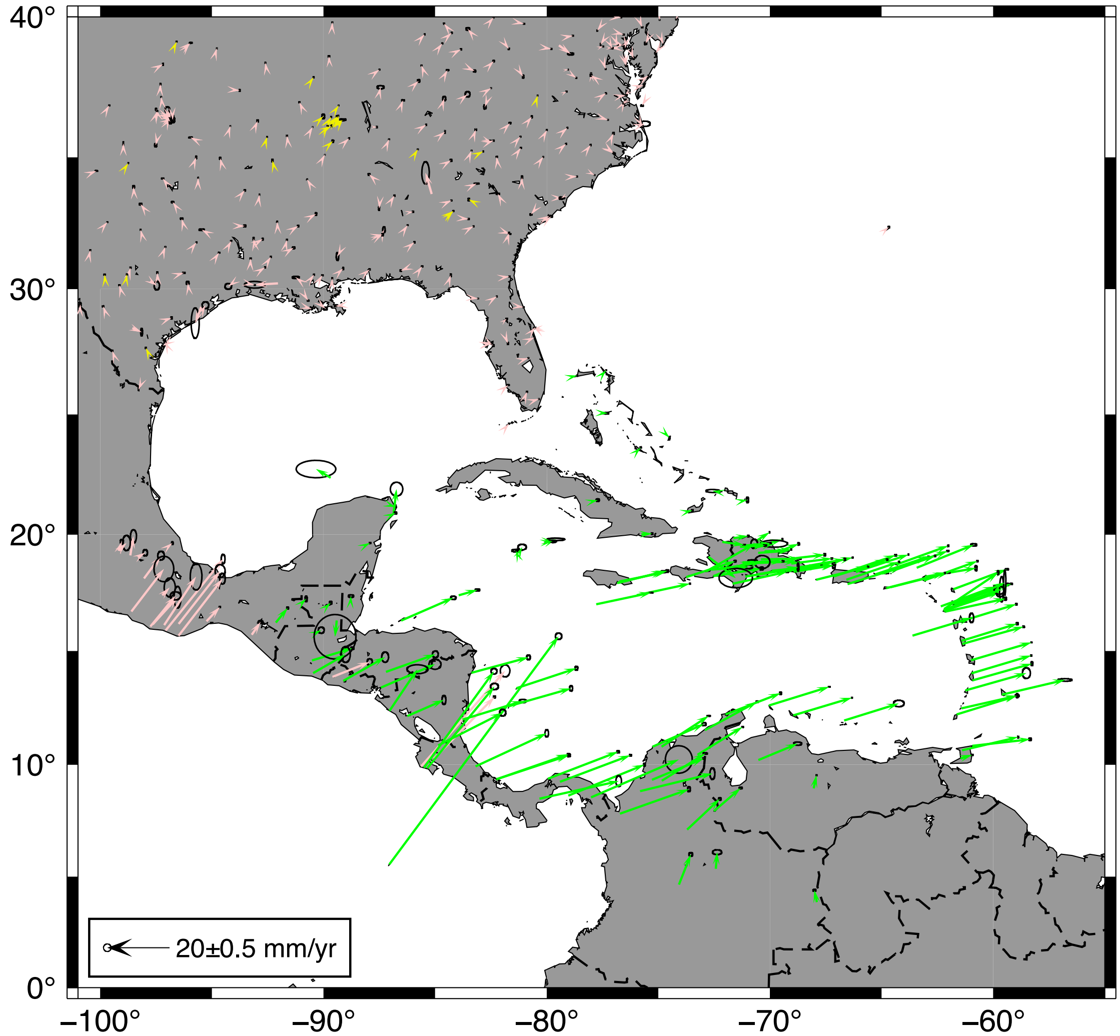

Figure 14: Same as Figure 8 except for the Caribbean region. Only velocities with horizontal standard deviations less than 5 mm/yr are shown.

Earthquake Analyses: 2022/12/15-2023/03/15

We use the NEIC catalog to search for earthquakes that could cause coseismic offsets at the sites analyzed by the GAGE analysis centers. Of the 24 earthquakes examined during this quarter, only 1 generated co-seismic offsets greater than 1 mm. This event, a mw6.4 15km WSW of Ferndale latitude/longitude 40.5250 -124.4230 Date 2022/12/20 Time 10:35 UTC has been designated EQ 69. Co-seismic offsets have been sent to UNAVCO via LDM.

Antenna and other discontinuity events.

Antenna swaps at 9 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 web site 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) remove. 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
The table below includes new and old style plots (update was made that the end of the quarter).

Site/s	**Issues related to site**
MC03	Very systematic, Fruita CO (near Utah border). http://geoweb.mit.edu/~tah/ACC_GAGE/MC03.CWUOFF.png
MC04	Similar region. Large North annual. http://geoweb.mit.edu/~tah/ACC_GAGE/MC04.CWUOFF.png
MC07	Systematic but different to MC03. http://geoweb.mit.edu/~tah/ACC_GAGE/MC07.CWUOFF.png

https://data.unavco.org/archive/gnss/pickup/analysis_centers/nota_core_sites.txt NOTA Earthscope core sites.
N is network or log source: N – NOTA in list above, C – CORS, U – UNAVCO log, P – PANGA, W – WCDA, I – IGS

Site	N	Notes
		2023-01-27
ARBT	C	Height jump: Looks like antenna change that is not in logs. Site in Arkansas. Recovered after 1-day. (all same day below). http://geoweb.mit.edu/~tah/ACC_PBO/ARBT.CWUOFF.png

ARFY	C	Same as above. Recovered after 1-day. http://geoweb.mit.edu/~tah/ACC_PBO/ARFY.CWUOFF.png
MOPN	C	Looks like antenna change with no meta data update. N and E offsets in this case. Site in Missouri. . Recovered after 1-day. http://geoweb.mit.edu/~tah/ACC_PBO/MOPN.CWUOFF.png
OK07	U	North offset of 15 mm. UNAVCO log file but no update. Site in Oklahoma. . Recovered after 1-day. http://geoweb.mit.edu/~tah/ACC_PBO/OK07.CWUOFF.png
TXWF	C	Large 200 mm height jump, no log update. Site in Texas. Recovered after 1-day. http://geoweb.mit.edu/~tah/ACC_PBO/TXWF.CWUOFF.png
		2023-02-03
P807	N	30 mm drop in height. Seen once before. West of Austin, TX 420 m altitude. Recovered after two days. Snow likely. http://geoweb.mit.edu/~tah/ACC_PBO/P807.CWUOFF.png
		2023-02-17 Not in monthly
AB06	N	Jump in east during missing data in 2021. Not apparent antenna change after gap. Gap from 20200630-20210418. http://geoweb.mit.edu/~tah/ACC_PBO/AB06.CWUOFF.png
PSPT		Jump on 20220109 most likely due to last update of meta data from an earlier antenna change. Added to UNKN list (remove when reprocessing done). http://geoweb.mit.edu/~tah/ACC_PBO/PSPT.CWUOFF.png
POME		Added unknown break 20110202 (3 months before antenna change on 20110519). http://geoweb.mit.edu/~tah/ACC_PBO/POME.CWUOFF.png
WALA		Added unknown breaks at 20100401 (month before antenna change) 20140610 (large height jump seen at POME and ANAT as well around same time), 20191006 (smaller but clear). http://geoweb.mit.edu/~tah/ACC_PBO/WALA.CWUOFF.png
		2023-02-24
AV38		Strongly skewed with lots of small sigma outliers. Unimak Island. http://geoweb.mit.edu/~tah/ACC_PBO/AV38.CWUOFF.png
MC05		Clear break 2014/11/16 after gap but no meta data change. Site in western Colorado. Added to UNKN list. http://geoweb.mit.edu/~tah/ACC_PBO/MC05.CWUOFF.png
MC10		Same region; systematics n East. 35 mm height jump on 2023/01/26 (finals and rapids). http://geoweb.mit.edu/~tah/ACC_PBO/MC10.CWUOFF.png
NVMO	U	Receiver goes bad 2022/05/06. Clear increase in noise level. UNAVCO hosts log file. Site in Nevada. http://geoweb.mit.edu/~tah/ACC_PBO/NVMO.CWUOFF.png
OAKR	C	Jump in height in rapids. No metadata change. South/West of Eugene OR. Check later to see if persistent. A couple of day outlier. Likely snow. http://geoweb.mit.edu/~tah/ACC_PBO/OAKR.CWUOFF.png
ROSS	C	On Lake Superior with large east systematics becoming larger after 2016. http://geoweb.mit.edu/~tah/ACC_PBO/ROSS.CWUOFF.png
		2023-03-03

CNCR		Northern Washington State. Snow outliers? http://geoweb.mit.edu/~tah/ACC_PBO/CNCR.CWUOFF.png
FAI1		Systematic annuals in all components. Unknown break 2016/07/12. Added to list. Site near Fairbanks AK. http://geoweb.mit.edu/~tah/ACC_PBO/FAI1.CWUOFF.png
P609	N	Snow. Very extreme compared to outliers in earlier year. Near San Bernardino. http://geoweb.mit.edu/~tah/ACC_PBO/P609.CWUOFF.png
P613	N	Similar region to P609, likely snow but sites also shows systematic horizontal motion (but not vertical). http://geoweb.mit.edu/~tah/ACC_PBO/P613.CWUOFF.png
TEHA		Unknown offset 2016/04/20. Site between Bakersfield and Lancaster, CA. http://geoweb.mit.edu/~tah/ACC_PBO/TEHA.CWUOFF.png
VTRU		Offset in North (check later to see if snow). Strong NE annual signals. Site in Vermont. http://geoweb.mit.edu/~tah/ACC_PBO/VTRU.CWUOFF.png
		2023-03-10
P573	N	Nice Ridgecrest postseismic. Recent deviations are likely snow. Death Valley; 2440 m height. http://geoweb.mit.edu/~tah/ACC_PBO/P573.CWUOFF.png
PTSN		Unknown height jump 2014/06/10. Added to UNKN eq file. http://geoweb.mit.edu/~tah/ACC_PBO/PTSN.CWUOFF.png
		2023-03-17 Not included in Monthly
P146	N	Snow most likely. Near Lake Tahoe. http://geoweb.mit.edu/~tah/ACC_PBO/P146.CWUOFF.png
P359	N	Snow mostly likely. 100 mm height error with small error bar. 20 mm East error. Site in Idaho. http://geoweb.mit.edu/~tah/ACC_PBO/P350.CWUOFF.png
P776	N	50 mm height error. Could be snow for recent storm. Unique in height but has had North outliers in the past. http://geoweb.mit.edu/~tah/ACC_PBO/P776.CWUOFF.png
		2023-03-24
ELVI		Nothing too strange. Data has gaps but seems OK. Large Ridgecrest post-seismic. http://geoweb.mit.edu/~tah/ACC_PBO/ELVI.CWUOFF.png
QSEC		Gaps in data with large Ridgecrest post-seismic plus annual in East but not same amplitude year-to-year. http://geoweb.mit.edu/~tah/ACC_PBO/QSEC.CWUOFF.png
		2023-03-31
P383	N	Some outliers in East rapids. Has been seen occasional in the past. See if this persists. http://geoweb.mit.edu/~tah/ACC_PBO/P383.CWUOFF.png
P735	N	Outliers in NEU in rapids. This has happened in the past. http://geoweb.mit.edu/~tah/ACC_PBO/P735.CWUOFF.png
PKDL		Outliers. Could be snow. Site near Mt. Hood OR. http://geoweb.mit.edu/~tah/ACC_PBO/PKDL.CWUOFF.png
		2023-04-07
AC09	N	Rapid North change similar to 2016 and 2011. Geophysical. On Alaska

		coast. http://geoweb.mit.edu/~tah/ACC_PBO/AC09.CWUOFF.png
CPCO	U	Interior Oregon (east of Eugene). Starting deviate in all components. Maybe offsets in E and U. http://geoweb.mit.edu/~tah/ACC_PBO/CPCO.CWUOFF.png
P249	N	Long term systematics in horizontals (height has annual and long term curvature). Site south of San Jose, west of Fresno, CA. Nearby P247 (12.50km), P175 (15.61km) have very different rates so must be creeping section? P286 on same side, not systematic. http://geoweb.mit.edu/~tah/ACC_PBO/P249.CWUOFF.png
P455	N	In Yellowstone National Park Idaho. Jump in East and Up in rapids. See what happens. High so could be snow. http://geoweb.mit.edu/~tah/ACC_PBO/P455.CWUOFF.png
P458	N	Similar height and location as P458 so could be snow. http://geoweb.mit.edu/~tah/ACC_PBO/P458.CWUOFF.png
		2023-04-14
AB07	N	Changed trend after recent earthquake. http://geoweb.mit.edu/~tah/ACC_PBO/AB07.CWUOFF.png
P576	N	Post-seismic but strong annual in East. P276 seems to something similar but smaller. Site near San Simeon, CA. P526 in this region also interesting but no annual. http://geoweb.mit.edu/~tah/ACC_PBO/P576.CWUOFF.png
		2023-04-21 Not in monthly.
LJRN	U	Jump in east in rapids. Seen previously so may be just outlier. http://geoweb.mit.edu/~tah/ACC_PBO/LJRN.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 50 stations in the ANET region for CWU analyzed in the final orbit analysis between December 15, 2022 and March 30, 2023.

CWU	North (mm)	East (mm)	Up (mm)
Median			
ANET	1.26	1.06	6.22
70%			
ANET	1.33	1.24	6.74

95%			
ANET	1.93	2.21	8.66

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

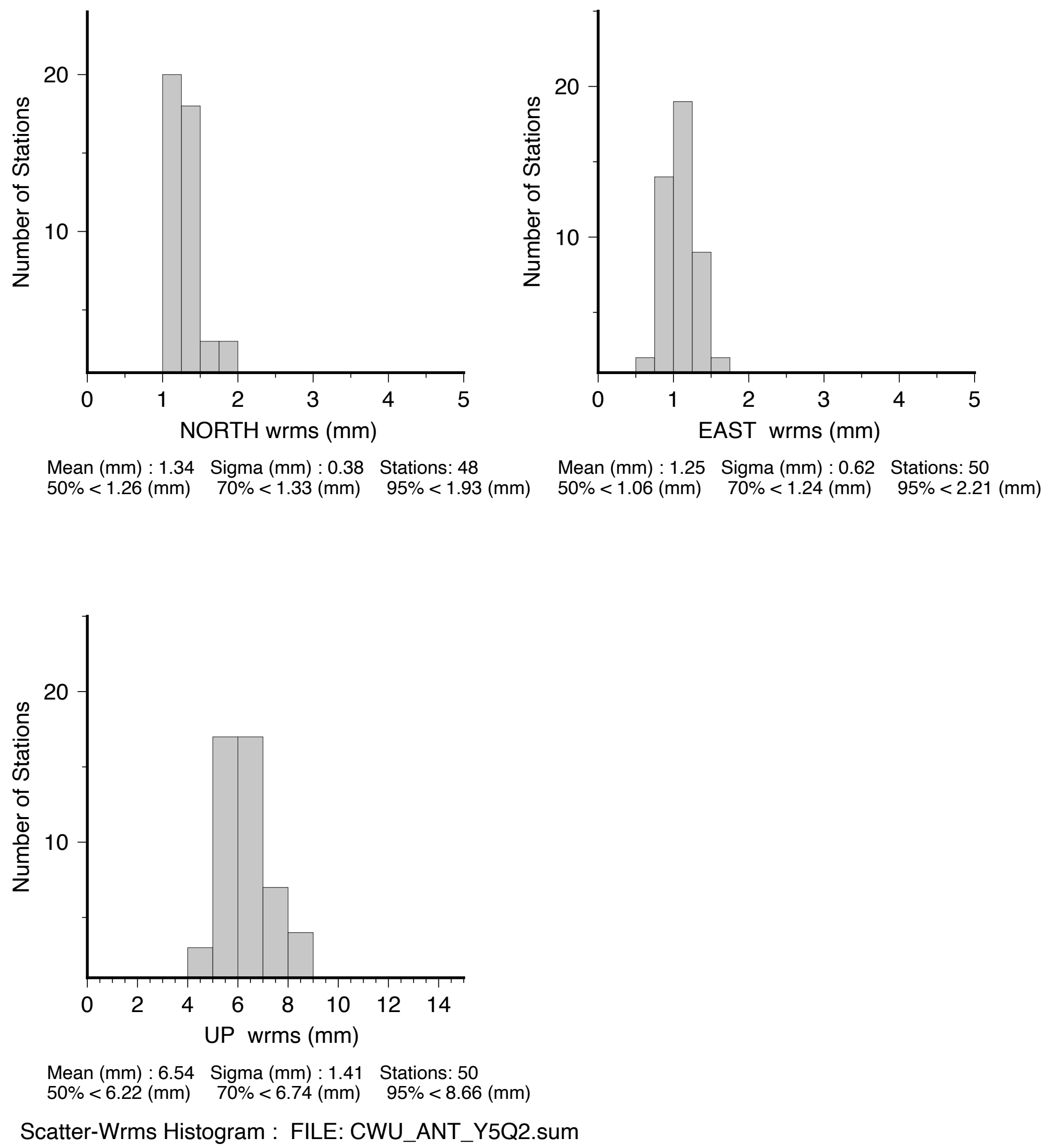

Figure A.1: CWU solution histograms of the North, East and Up RMS scatters of the position residuals for 50 stations in Antarctica analyzed between December 15, 2022 and March 30, 2023. Linear trends and annual signals were estimated from the time series.

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