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

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Period: 2019/04/01-2019/06/30

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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 NAM08 reference frame. In this report, we show analyses of the data processing for the period 2019/03/16 to 2019/06/30, time series velocity field analyses for the GAGE reprocessing analyses (1996-2019). Several earthquakes were investigated this quarter but none generated coseismic displacements > 1mm.

Associated with report, event files, pbovel files and offset files have been queued to LDM with time tag 20190710161317.

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

ITRF2014 transition

The ITRF2014 re-processing analysis has been completed and the transition from the NAM08 system to NAM14 will happen shortly. Appendix A of this report contains the draft velocity solution documentation that will be posted when the transition to NAM14 takes place.

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 2089 stations were processed which is 1 more than last quarter. In addition up to 61 sites were processed in the ANET solutions.

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: March 17, 2019– June 22, 2019

For this report, we generated the statistics using the ~3 months of CWU results between March 17, 2019 and June 22, 2019. 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 2088 stations for CWU analyzed in the finals analysis between March 17, 2019 and June 22, 2019. Histograms of the RMS scatters are shown in Figure 1.

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
CWU	1.04	0.98	4.65
70%			
CWU	1.29	1.20	5.36
95%			
CWU	2.36	2.57	8.52

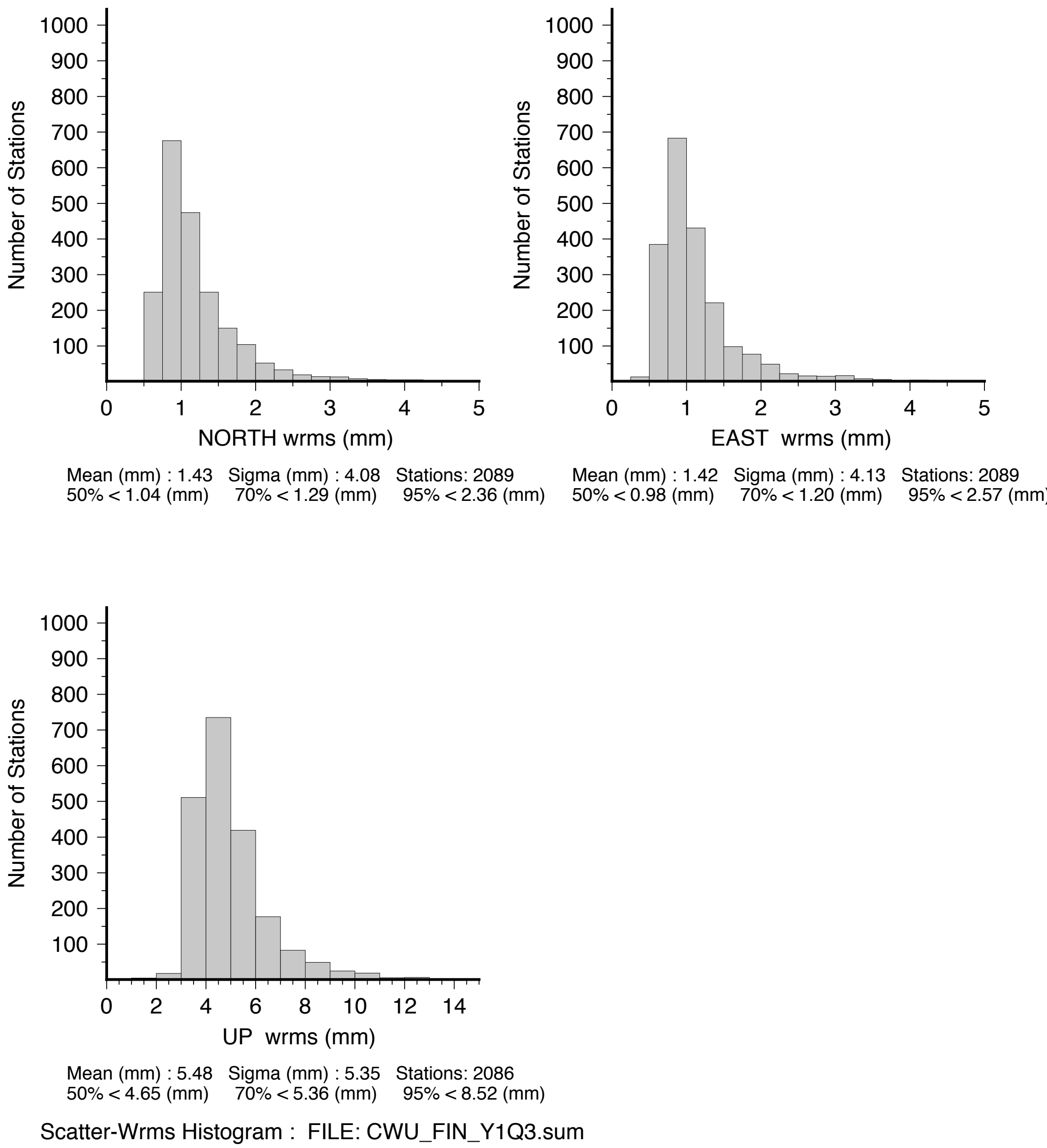

Figure 1: CWU solution histograms of the North, East and Up RMS scatters of the position residuals for 2089 stations analyzed between March 17, 2019 and June 22, 2019. Linear trends and annual signals were estimated from the time series.

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_Y1Q3.tab.

There are 2089 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 CWU_FIN_Y1Q3.sum
ChiN/E/U are square root of chisquared degree of freedom of the fits.
Values of ChiN/E/U near unity indicate that the estimated error
bars are consistent the scatter of the position estimates

.Site      #     N (mm)  ChiN     E (mm)  ChiE   U (mm)  ChiU     Years
 1LSU     81       1.1   0.58      1.6    0.78     6.5   0.69     16.16
 1NSU     81       1.0   0.53      1.0    0.60     5.7   0.76     15.42
 1ULM     81       0.9   0.49      0.9    0.54     4.9   0.66     16.02
 7ODM     62       0.8   0.40      0.9    0.56     5.4   0.69     18.17
…
 ZDV1     81       1.2   0.56      1.1    0.69     5.8   0.81     16.05
 ZKC1     81       1.2   0.60      0.8    0.52     5.5   0.74     16.05
 ZLA1     81       1.3   0.67      1.1    0.69     5.4   0.73     16.05
 ZLC1     80       1.2   0.59      1.0    0.63     4.8   0.68      1.43
 ZME1     81       1.2   0.61      0.7    0.44     5.8   0.77     16.28
 ZMP1     81       1.1   0.53      0.7    0.42     5.1   0.71     16.52
 ZNY1     80       1.0   0.51      1.2    0.74     6.3   0.87     16.44
 ZOA1     81       0.9   0.47      1.0    0.62     3.7   0.52      1.43
 ZSE1     80       1.1   0.48      1.0    0.60     5.0   0.71     16.44
 ZTL4     81       1.1   0.60      0.9    0.58     6.9   0.91     16.63
```

Table 2: RMS scatter of the position residuals for the CWU solution between March 17, 2019 and June 22, 2019 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	0.97	0.91	4.29	857
NUCLEUS	0.90	0.88	4.14	201
GAMA	0.89	0.93	5.60	15
COCONet	1.65	1.48	6.41	79
USGS_SCIGN	0.94	0.88	4.37	121
Expanded	1.12	1.07	5.04	816
70%				
PBO	1.18	1.10	4.88	
NUCLEUS	1.06	1.02	4.59	
GAMA	1.25	1.04	5.99	
COCONet	1.86	1.75	7.20	
USGS_SCIGN	1.19	1.07	4.83	
Expanded	1.35	1.30	5.66	

95%			
PBO	2.22	1.99	7.51
NUCLEUS	1.84	1.65	7.17
GAMA	1.46	2.19	7.59
COCONet	2.48	3.82	11.51
USGS_SCIGN	2.24	2.37	9.19

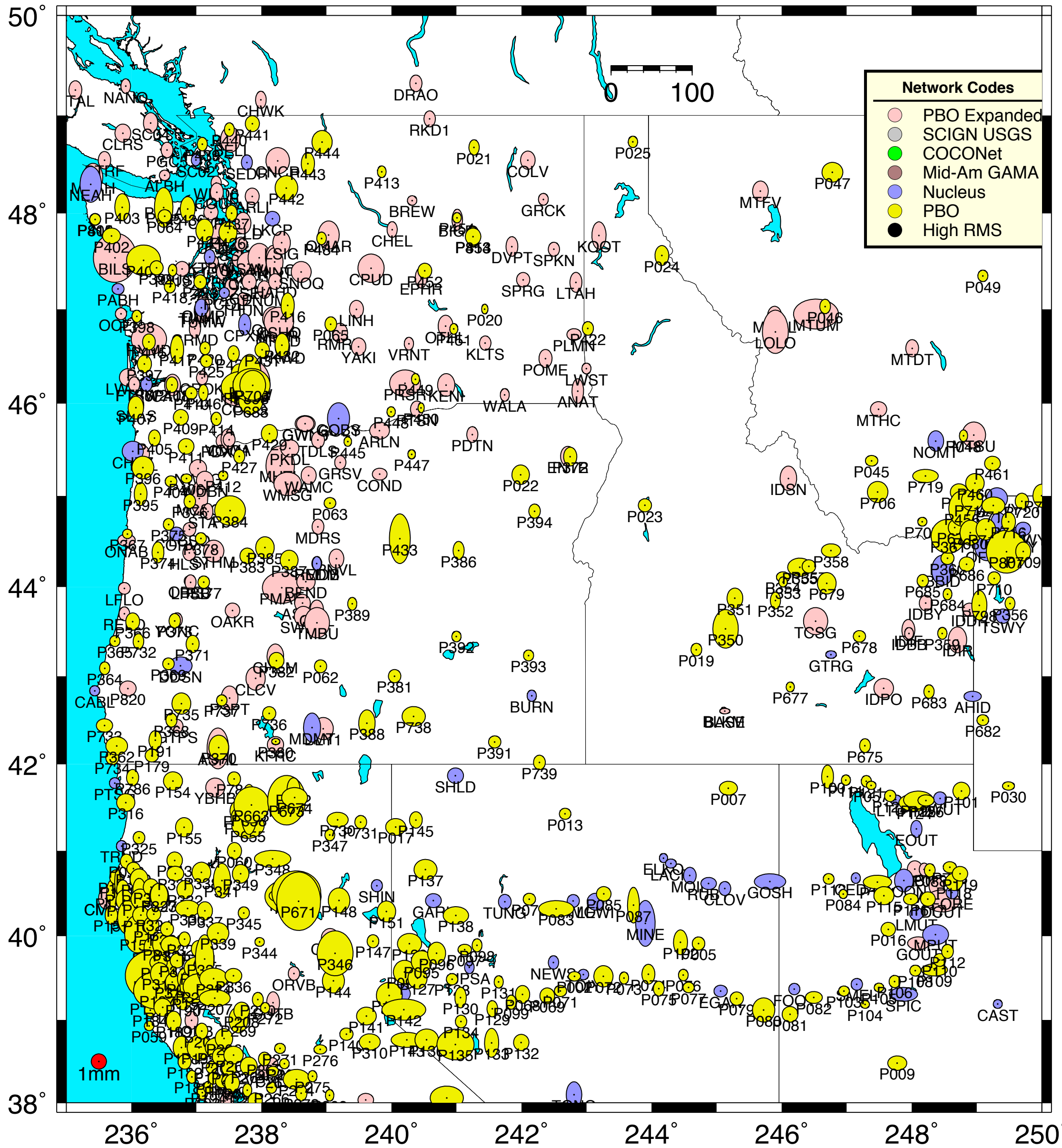

Figure 2: Distribution of the RMS scatters of horizontal position estimates from the CWU analysis for the Northern Western United States. The color of the ellipses that give the north and east RMS scatters denotes the network given by the legend in the figure. The small red circle shows the size of 1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

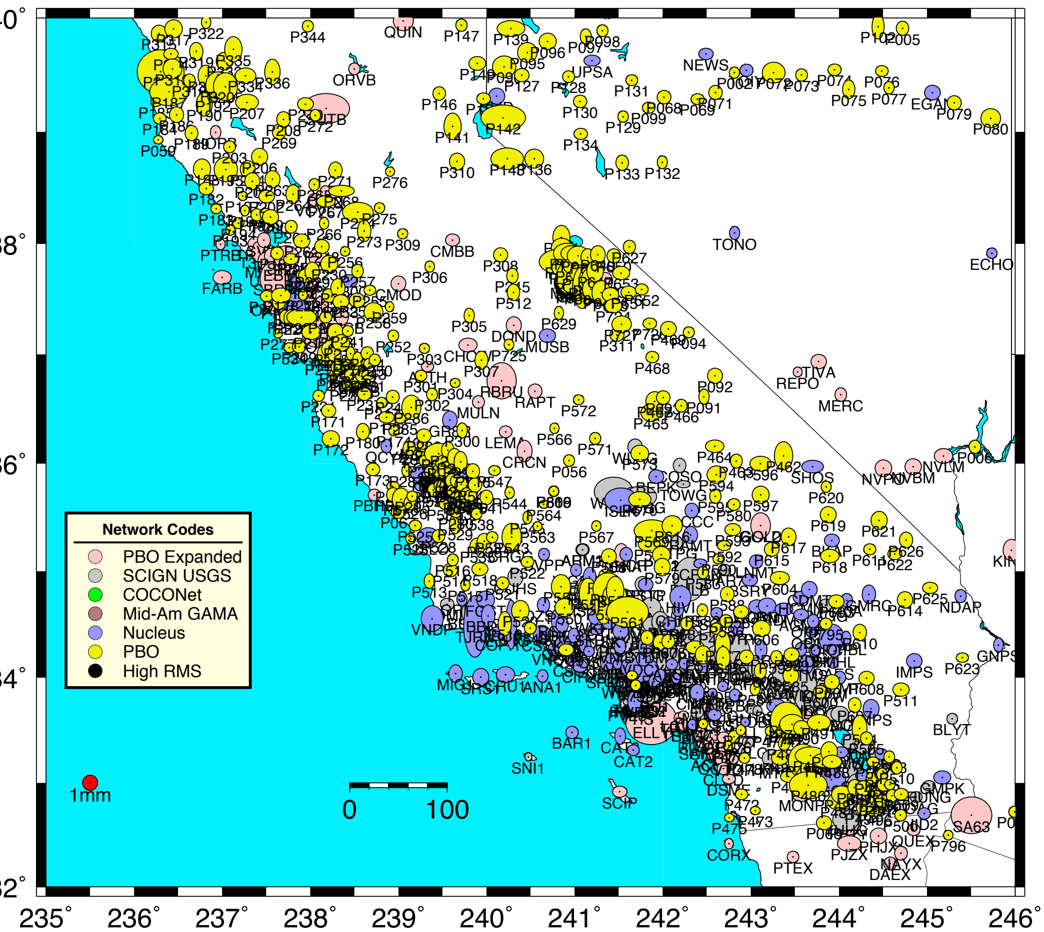

Figure 3: Same as Figure 4 except for the Southern Western United States. Black circles show large RMS scatter sites.

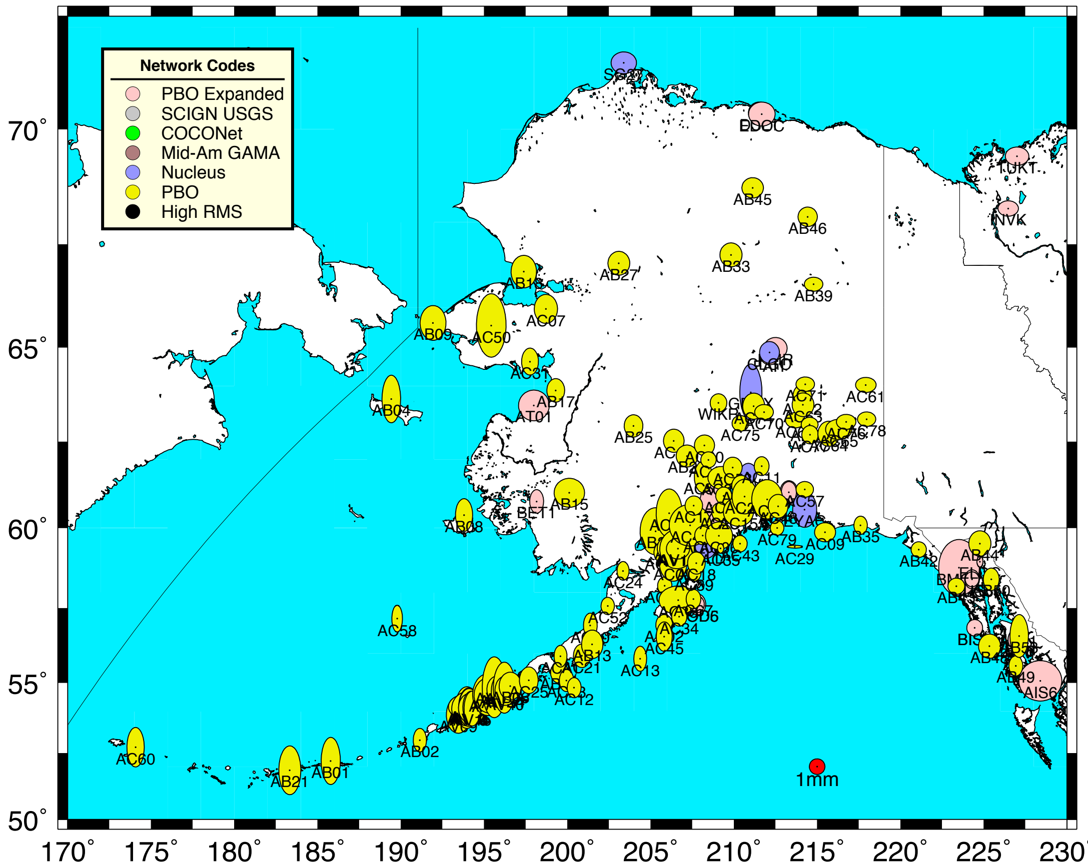

Figure 4: Same as Figure 4 except for the Alaskan region.

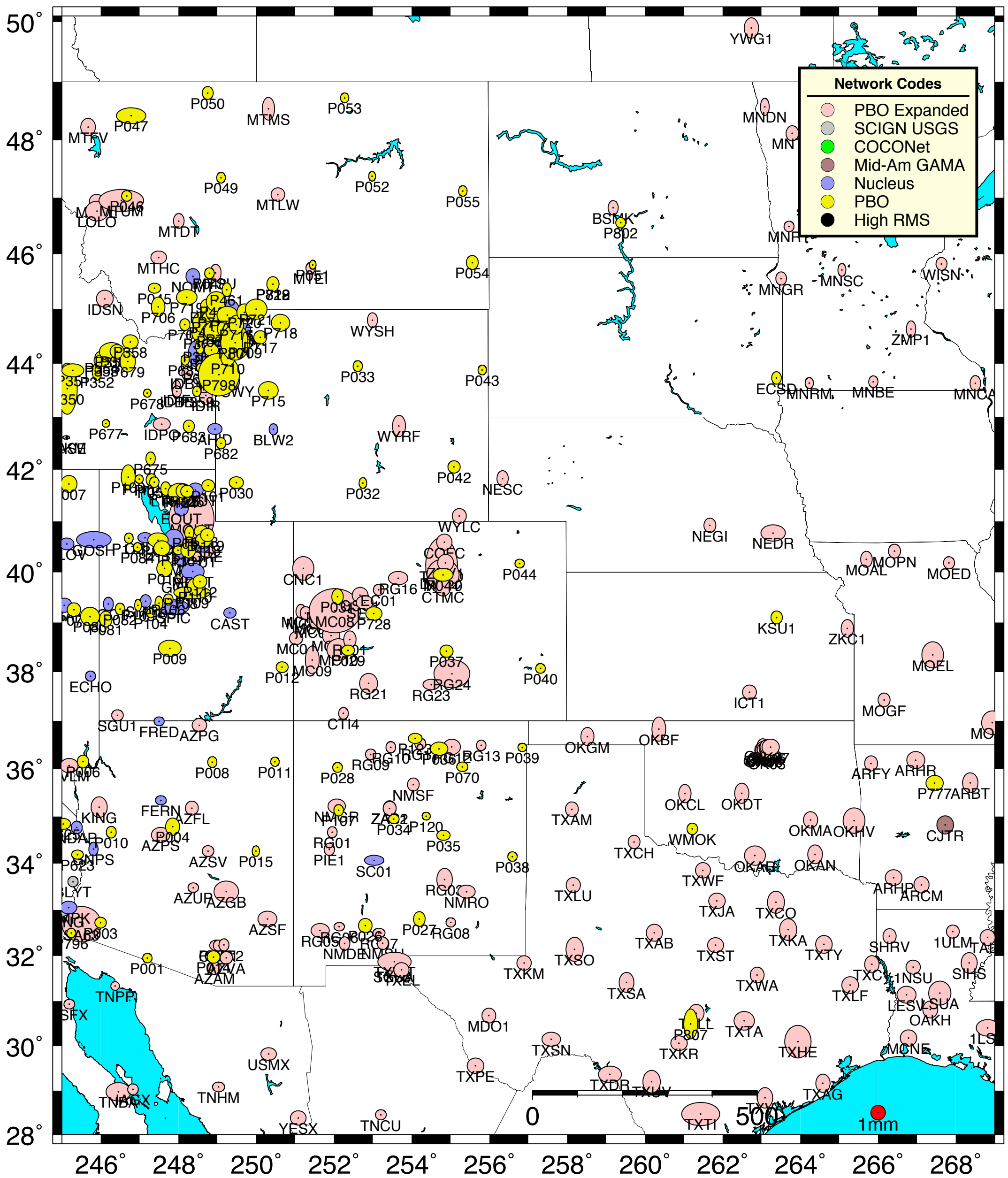

Figure 5: Same as Figure 4 except for the Central United States

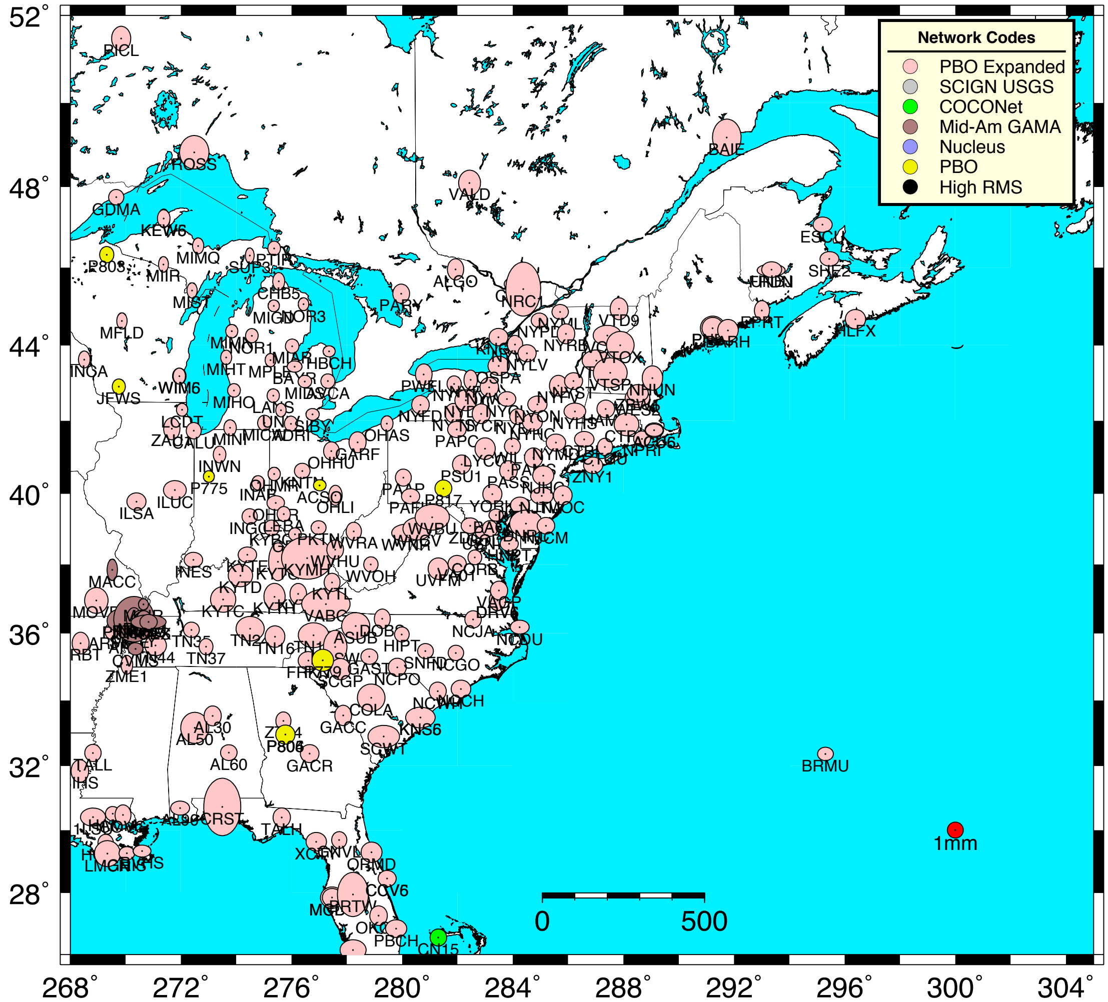

Figure 6: Same as Figure 4 except for the Eastern United States

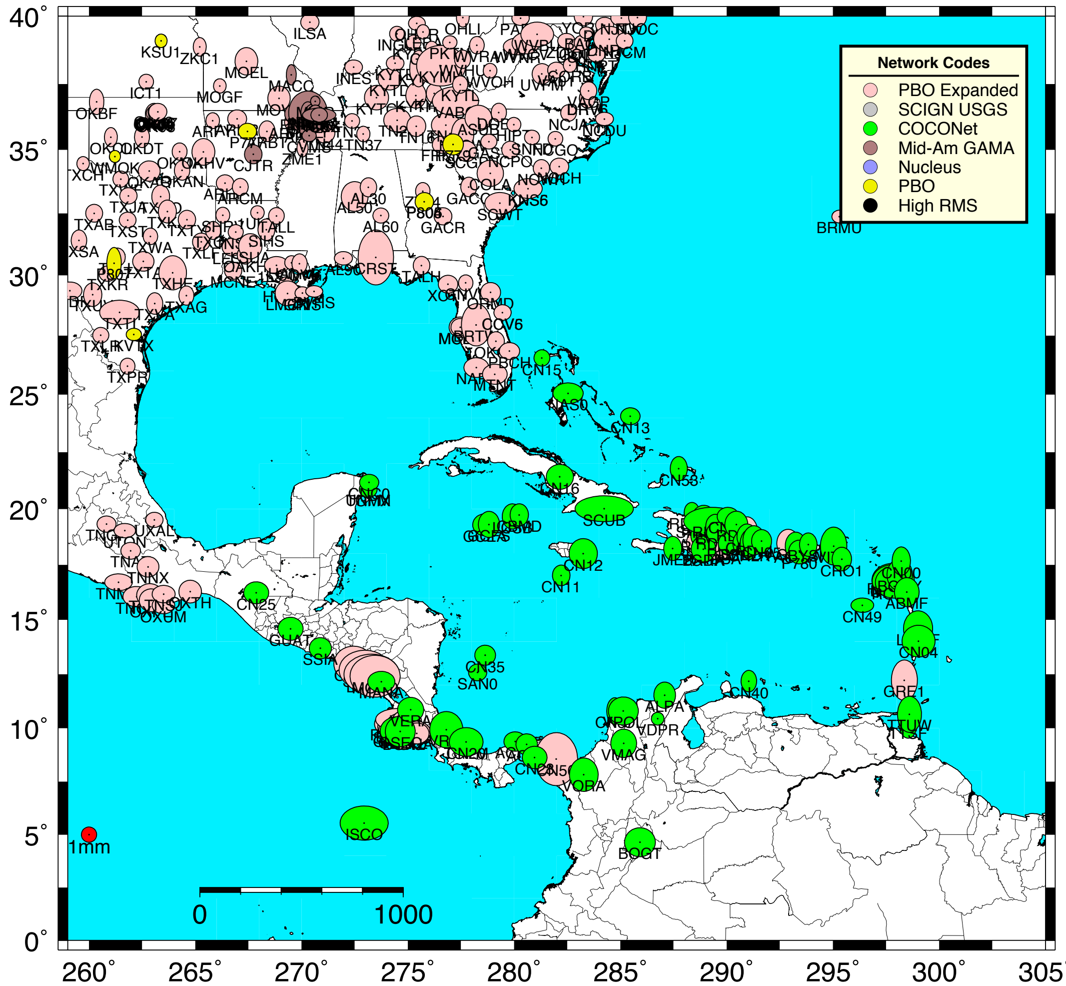

Figure 7: Same as Figure 4 except for the Caribbean region.

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_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. Currently this file defines the definitive coordinates and velocities of the NAM08 system. We now also include All_CWU_nam08.apr which includes recently added sites that do not appear in the PBO apriori file based on the combination of NMT and CWU analyses.

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 NAM08 reference frame using the CWU analysis. There are 2587 stations in the CWU solution. 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 cwu_nam08_190622.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_nam08_190622.snpvel.

Table 3: Statistics of the fits of 2587 stations analyzed CWU in the reprocessed analysis for data collected between Jan 1, 1996 and June 22, 2019

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
CWU	1.36	1.34	6.09
70%			
CWU	1.71	1.67	6.91
95%			
CWU	3.46	3.56	10.80

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.

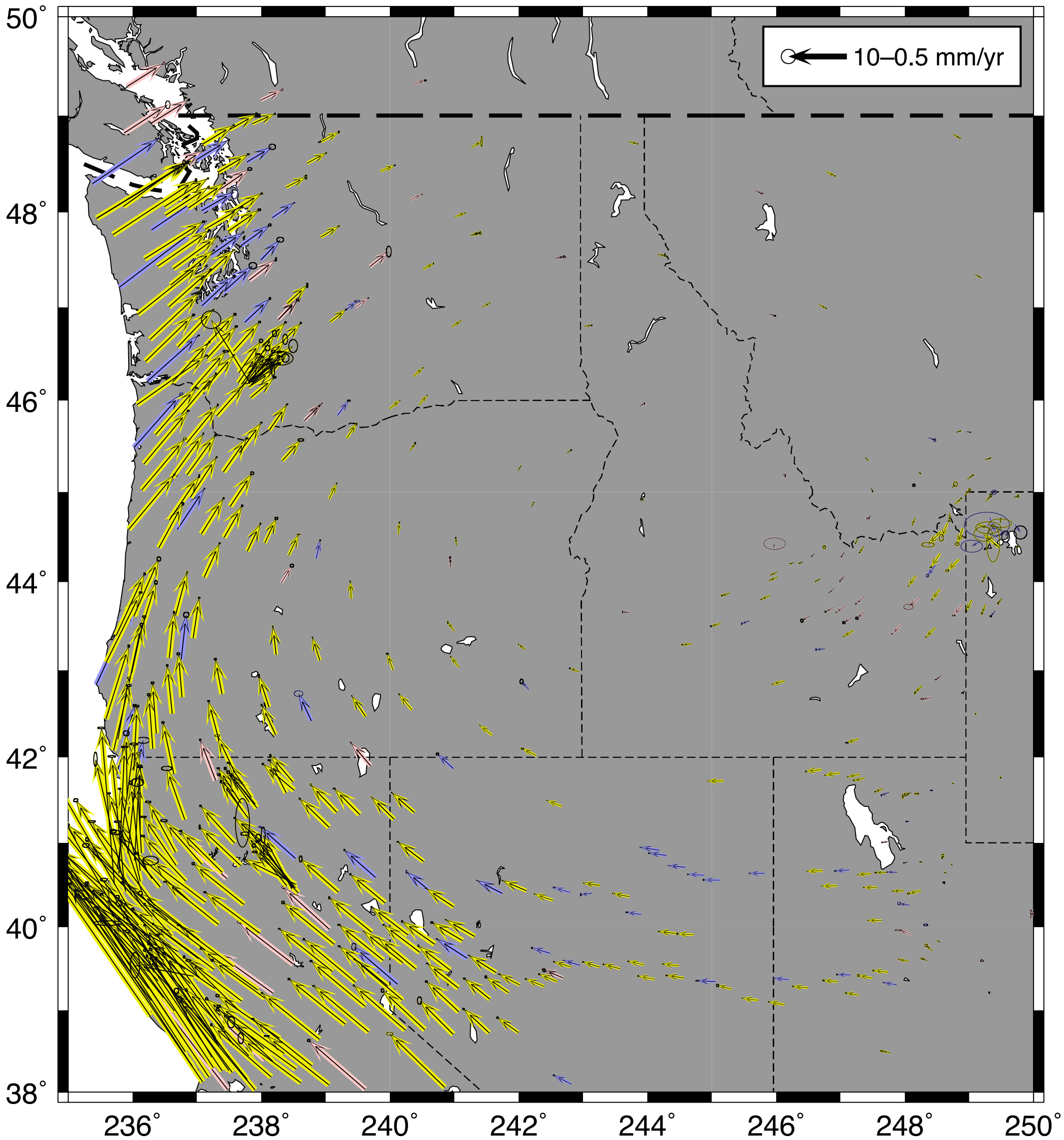

Figure 8: Velocity field estimates for the Pacific north-west from the CWU solution generated using time series analysis and the FOGMEX error model. 95% confidence interval error ellipses are shown. The color scheme of the vectors matches the network type legend in Figure 4. Only velocities with horizontal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

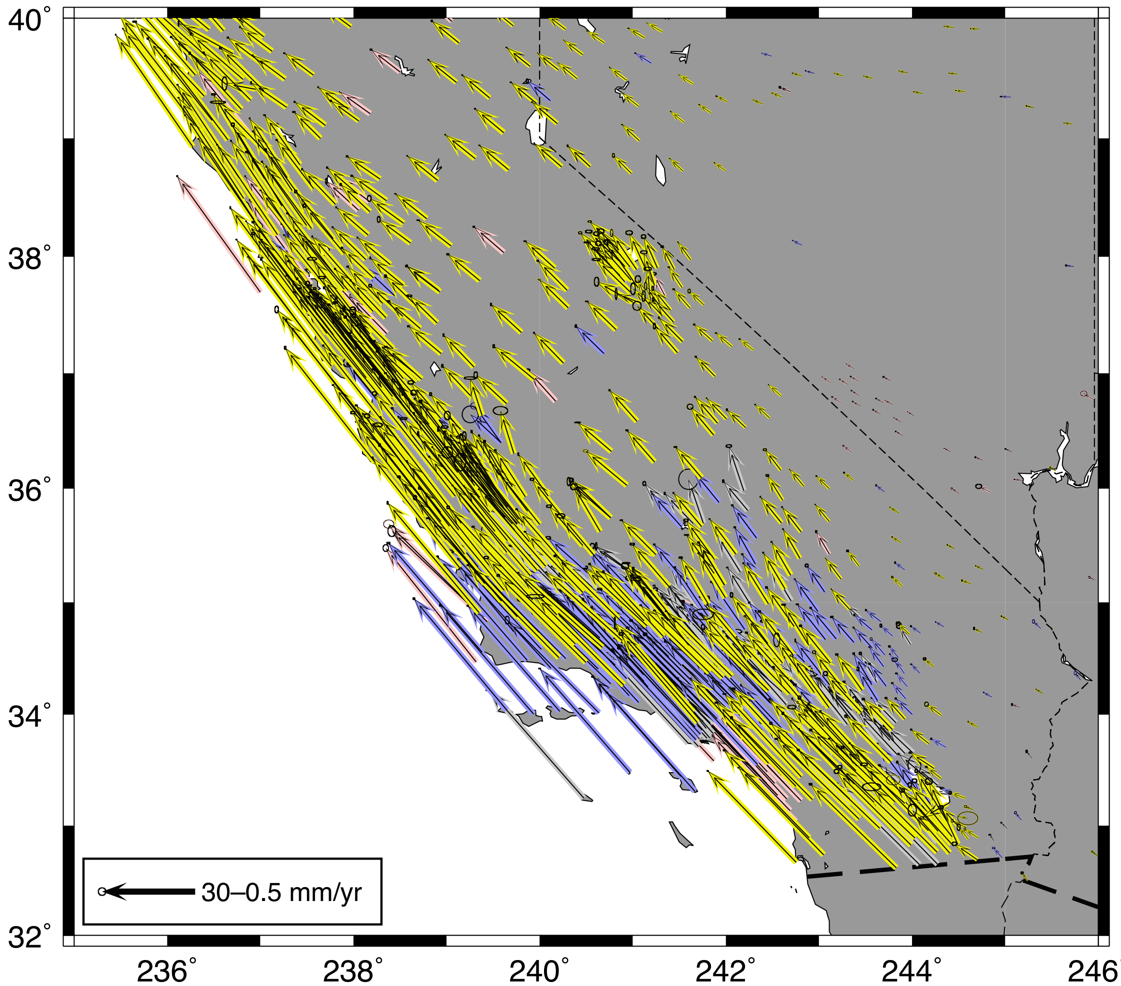

Figure 9: Same as Figure 10 except for South Western United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown.

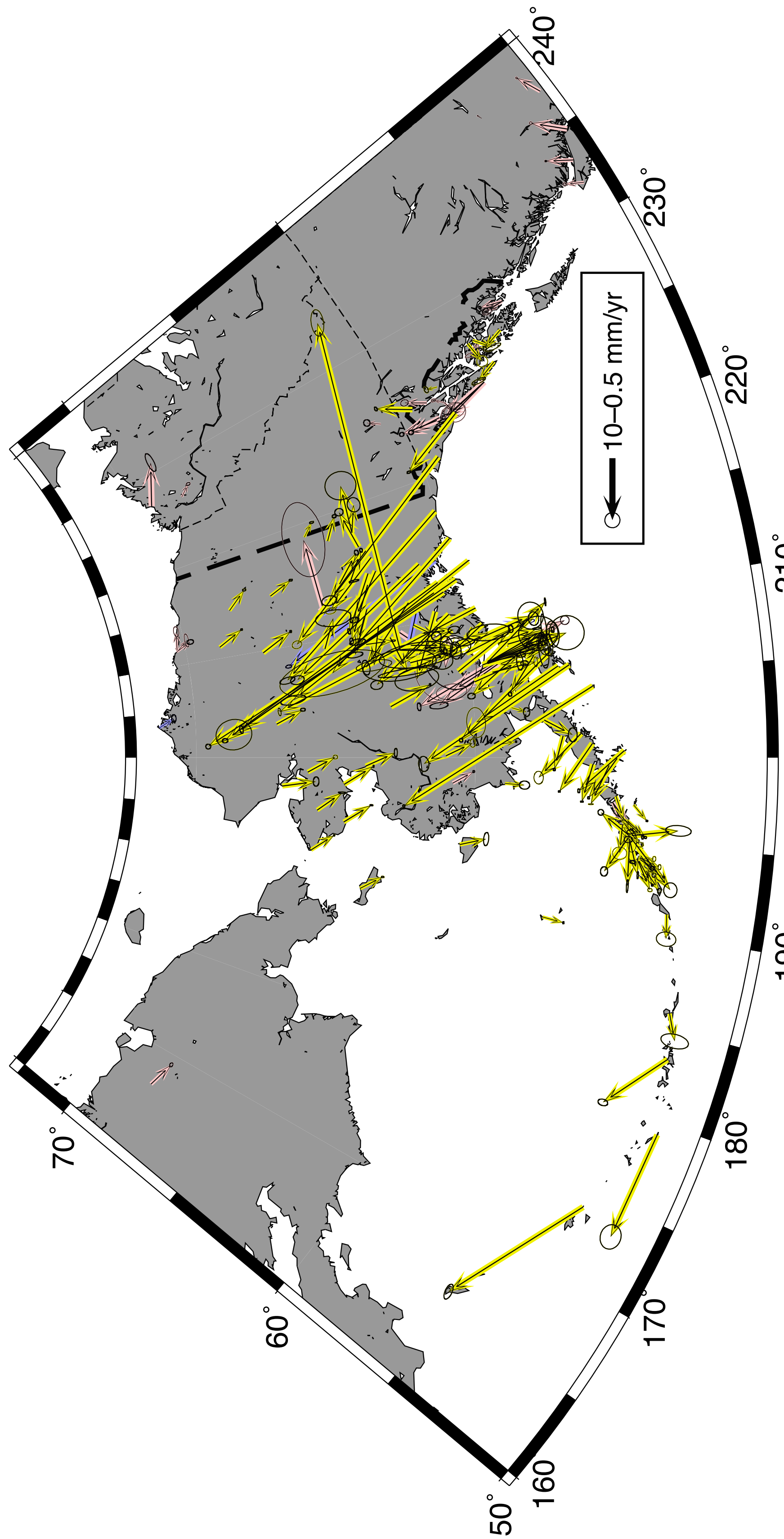

Figure 10:

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

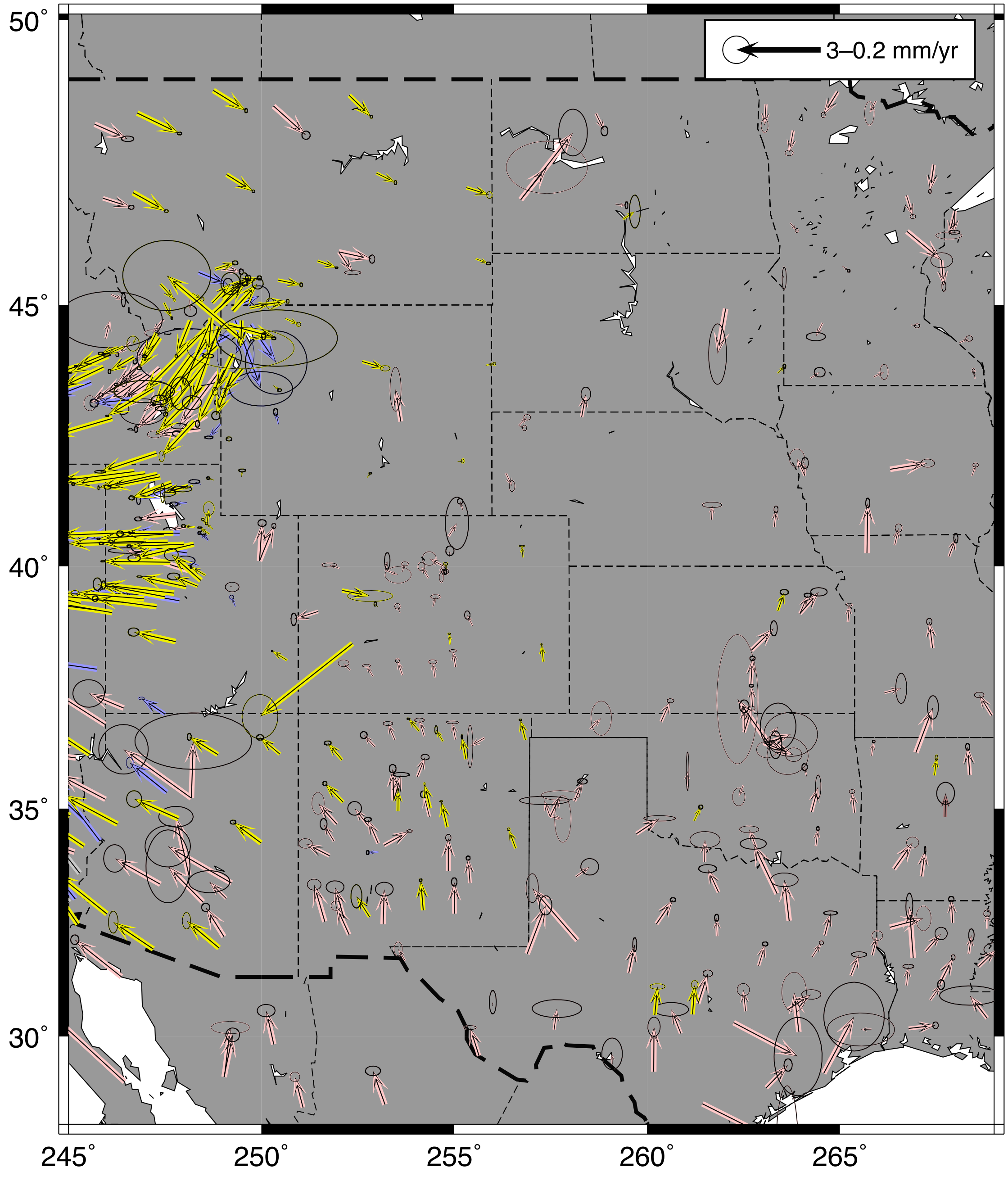

Figure 11: Same as Figure 10 except for Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown.

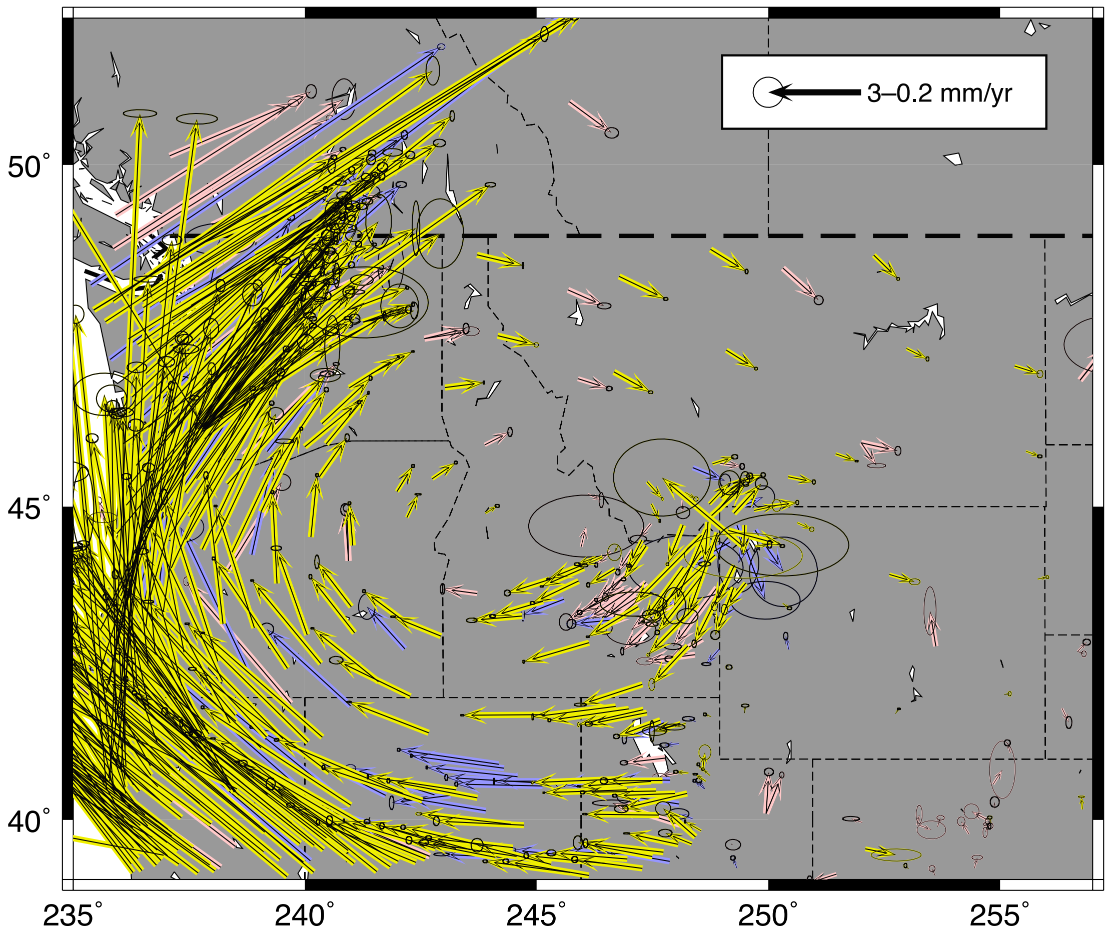

Figure 12: Same as Figure 10 except for Western Central United States. Only velocities with horizontal standard deviations less than 1 mm/yr are shown. Anomalous vectors at longitude 250° are in the Yellowstone National Park and most likely are showing volcanic processes.

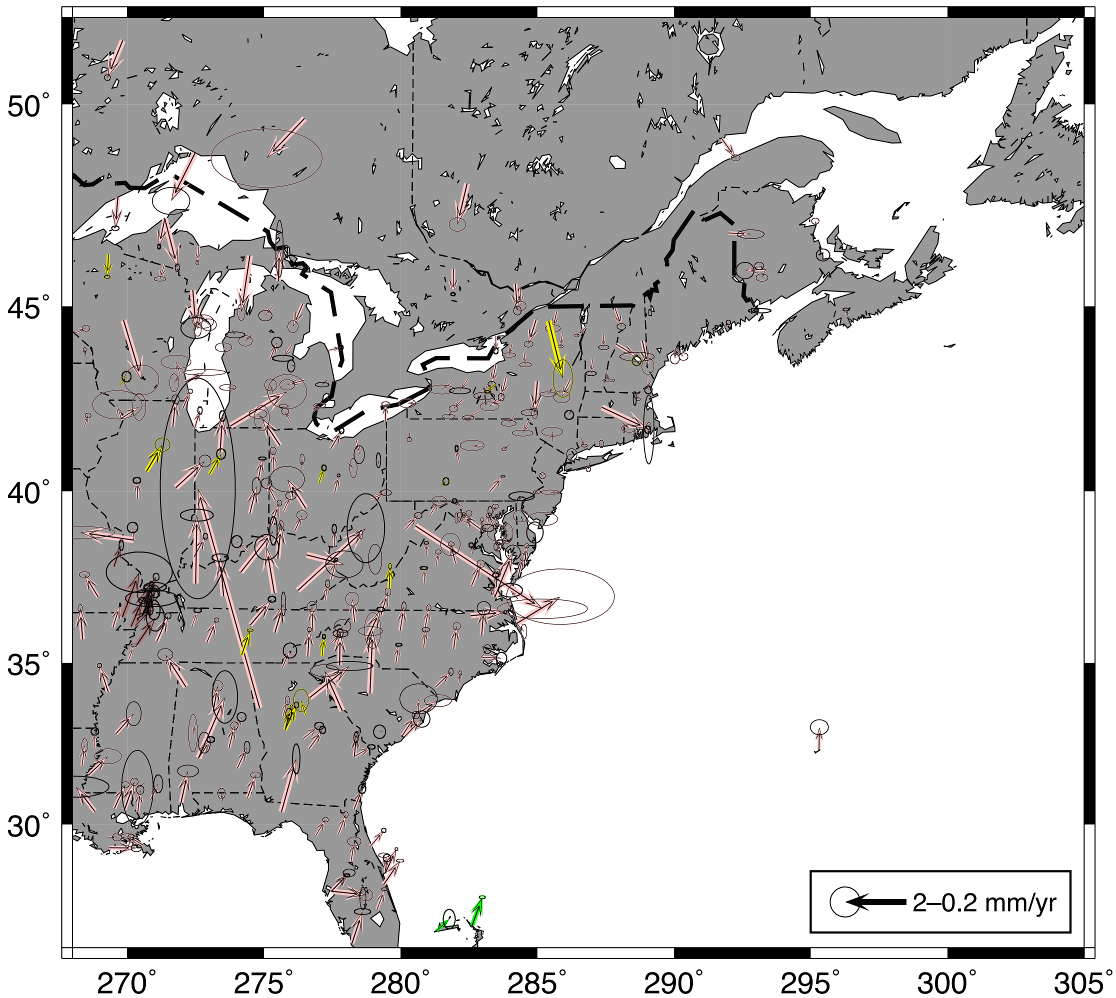

Figure 13: Same as Figure 10 except for the Eastern United States. Only velocities with horizontal standard deviations less than 2 mm/yr are shown. The systematic velocity of sites in the Northeast and central US show deviations for current GIA models in the horizontal velocities.

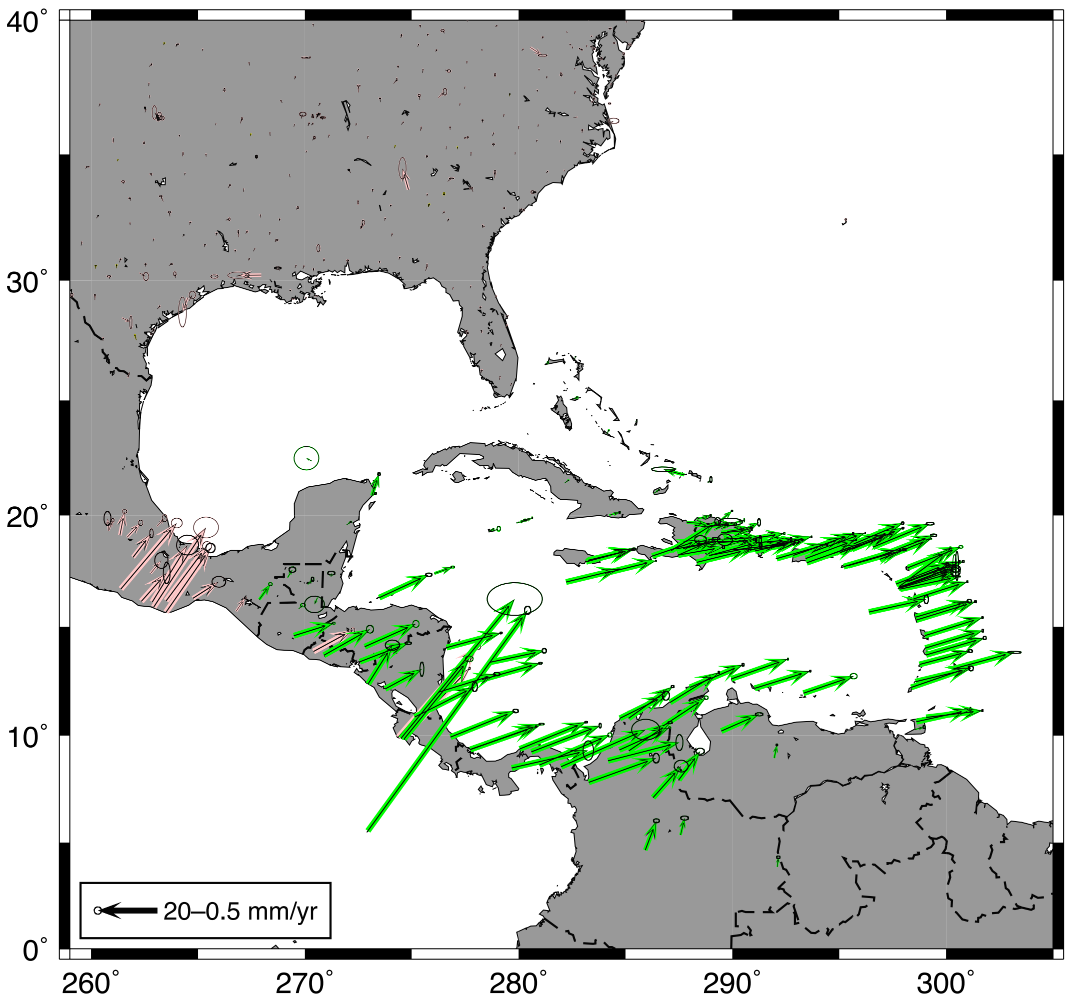

Figure 14: Same as Figure 10 except for the Caribbean region. Only velocities with horizontal standard deviations less than 5 mm/yr are shown.

Earthquake Analyses: 2019/03/16-2019/06/15

We use the NEIC catalog to search for earthquakes that could cause coseismic offsets at the sites analyzed by the GAGE analysis centers. During this quarter no new earthquakes which would display sites by more than 1 mm were detected. We did examine the following earthquakes:

```
ANSS(ComCat) us600032fs mwr4.4 9km NE of Lima (15.62 km depth)
Location and date   44.6965 -112.5040  2019 04 09 18 09
ANSS(ComCat) uw61523381 ml3.6 3km ESE of Rose Lodge (44.02 km depth)
Location and date   44.9975 -123.8413  2019 05 19 16 24
ANSS(ComCat) nc73184841 mw3.8 16km ESE of Pine Hills (21.45 km)
Location and date   40.6948 -123.9637  2019 05 21 17 20
ANSS(ComCat) us70003t7p ml3.5 5km WSW of Akutan (6.2 km depth)
Location and date   54.1150 -165.8578  2019 05 27 00 08
```

```
ANSS(ComCat) ak0196r9o3rq ml5.8 89km SSW of Homer (64 km depth)
Location and date   58.8565 -152.3581 2019 05 27 09 53
ANSS(ComCat) us70003t2n mww6.6 27km SSE of La Libertad (65.08 km)
Location and date   13.2428  -89.2719 2019 05 30 09 04
ANSS(ComCat) ci38624056 mw4.3 13km W of San Clemente Is. (SE tip)
(8.38 km depth)
Location and date   32.8228 -118.4828 2019 06 05 10 48
ANSS(ComCat) ci38624424 mw4.3 15km W of San Clemente Is. (SE tip)
(8.4 km depth)
Location and date   32.8377 -118.5032 2019 06 05 14 33
```

Some of these events could have displaced sites that have been used in the past but there is not recent data for these sites e.g., us70003t2n likely displaced SSIA and SNJE (up to 15 mm offset predicted) but there is not data from these sites since 2018.

All event files and plots have been queued to LDM with time-tag 20190710161317.

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 61 stations in the ANET region for CWU analyzed in the final orbit analysis between March 17, 2019 and June 22, 2019.

CWU	North (mm)	East (mm)	Up (mm)
Median (50%)	1.05	0.92	5.62
70%	1.37	1.05	6.52
95%	2.47	2.41	10.25

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

Appendix A: NAM14 Reprocessing release notes (DRAFT)

Notes on the 2019 GAGE NAM14 Combined Velocity field to GPS Week 2018 2019-09-15

These notes add supplemental information to "Notes on the 2017 GAGE Velocity field to GPS Week 1977 2017-12-02" https://www.unavco.org/data/gps-gnss/derived-products/docs/GAGE_GPS_Velocity_Release_Notes_20171202.pdf, "Notes on the 2016 PBO Velocity field to Week 1925 2016-12-30", https://www.unavco.org/data/gps-gnss/derived-products/docs/GAGE_GPS_Velocity_Release_Notes_20161230.pdf, and "Notes on the 2015 PBO Velocity field to Week 1870 2015-11-14" https://www.unavco.org/data/gps-gnss/derived-products/docs/GAGE_GPS_Velocity_Release_Notes_20151223.pdf

The 2019 GAGE full velocity solution includes GPS data from GPS week 0834 (Jan-01-1996) to week 2018 (Sep-15-2018) and contains all reprocessed data from NMT, CWU and the combined PBO solution in the ITRF2014 system realization of the North America fixed reference frame. Time tag on LMD queue is 20190608084204. There is a DOI folder DIO_180915 associated with this release. The data in release represents the final combined solutions using NMT and CWU solutions. The reference frame for this release is NAM14 based on the ITRF2014 system [*Altamimi et al.*, 2016] and the North America plate Euler pole in the ITRF2014 system [*Altamimi, et al.*, 2017].

The complete analysis of the full GAGE velocity field generated from SINEX files (i.e., incorporating full variance covariance matrices and allowing re-alignment of the reference frame for the velocity field) is now released. The 2015 release documents the methods being used to generate these velocity fields using combinations of sub-networks. These methods remain unchanged and here we update the tables derived from those methods.

The process noise models, in the form of random walk time-step variances or process noise (RWPN) are given in All_PBO.rw. These values are generated by analysis of the position residuals from fitting the time series for each station. Stations that have process noise values greater than 100.0 mm^2/yr are not included in this velocity solution so that they do not contaminate nearby stations. Twenty six stations are excluded based on this criterion (AC09, AC30, ARGI, AV05, BLKM, BLOK, CASA, EISL, ELMA, EOCG, FCTF, GUAX, KOD1, LUMC, MARC, MIDB, NTOE, P323, P656, SATS, SMM1, SMM2, SMM3, STOE, and

WLHG). Most of these stations have a combination of large systematics and/or short durations of valid data (see explanations in Table 5). We also impose a minimum random walk process noise (RWPN) of 0.05 mm^2/yr. 589 stations have computed RWPN values less than this value. The process noise statistics are generated from the time series using the GAMIT/GLOBK script sh_gen_stats based on tsfit fits to the time series with the realistic sigma algorithm used to account for correlated noise. [*Herring et al*., 2016; *Floyd and Herring*, 2019]. The tsfit solution also generates a list of station position estimates not to be used in the velocity solution because they are outliers (either due to bad analyses, antenna failures or snow on antennas). The current list of edited station position estimates is given in All_PBO_edits.eq. These edits can by AC or for both ACs. The total GAGE time series contain 10818003 station-days. The outlier criteria remove 18904 (0.02%) of NMT and 3697 (0.00%) of CWU station-days of solutions.

The processing divides the 2619 stations analyzed into 34 networks each with approximately 80 station locations. (The final number of estimated parameters for each network depends on the number of breaks needed at each station. The networks need from 86 to 287 individual station names to accommodate the discontinuities, with a median number of stations of 170. Over all, each station has one break over the 22 year duration of data). There is no overlap between the stations in the first 33 networks. A 34th network is created to tie all the other 33 networks into a single solution. To form the stations in the 34th network, three stations for each network are chosen so as to minimize the trace of the covariance matrix of the estimates of rotation and translation using these stations. Weights assigned to each station in accord with the expected variance of the velocity estimate for the station (i.e., combination of the RWPN and duration of data at the station). If equal weights are given to each station, this algorithm is the same as choosing the three stations that cover the largest area. The details of the stations in each network are given in All_PBO_netsel.use. The analyses of the 34 networks can be run in parallel and takes a few hours to run. The combination of the 34 networks uses ~11 Gbytes of memory and the NMT and CWU combination, along the equating of velocities (with a constraint of ±0.01 mm/yr) at stations with discontinuities takes about three days of CPU time. The NMT and CWU velocity solutions are then merged to form the PBO solution combined solution. This combination uses ~40 Gb of memory and also takes just over 3 days to complete. The velocity combinations use loose constraints and we align the reference frame as we wish at the end of the combination. We generate four reference frame realizations: (1) A North America frame aligned to our current NAM14 frame using 1311 stations in our hierarchical list of reference frame stations; (2) A North America frame aligned to IGS14 rotated into the North America frame using the 86 stations original used in ITRF2014 to define the North America plate and (3) and (4) are the same as (1) and (2) except the reference velocities are in a NNR reference frame.

The full GLOBK SINEX velocity solution allows us to re-align the reference frames based on the combination of all of the data collected between 1996 and current day (2018-09-15 GPS Week 2108 for this analysis). The time series analyses for velocities is much faster but the daily solutions need to be aligned the reference frame each day based on an earlier realization of the frames. Tables 1 and 2 compare the WRMS and NRMS scatters of the differences between the velocity estimates obtained by the two GAGE ACs and the combination of the two ACs using different analysis methods. Table 1's caption explains the naming scheme used to describe the solutions. There are the three analysis centers, NMT, CWU and their combination PBO. The velocity estimates are generated with three different methods (1) GLOBK SINEX combinations, GK (2) time series analyses using weighted least squares (LS) and (3) time series analyses using a Kalman filter of the time series (KF). The time series LS analysis is the one that generates the quarterly GAGE SNAPSHOT fields. The GK analysis can be aligned to the current NAM14 frame (NA) or be realigned to the IGS14 frame (IG). In all analyses, the same process noise models, discontinuities and post-seismic non-linear models (based on time series analyses) are used. The comparisons do not re-align the velocity fields in any way. The RMS values are based on the simple differences between the estimates. The numbers of stations do not match between the analyses because the GK analyses exclude stations with large process noise values. Tables 3 and 4 show the same type of comparison when we restrict the stations to the best 925 stations in the solution. (These stations have velocity standards less than the median standard deviations in north, east and up in all three components, 0.16, 0.16 and 0.55 mm/yr, respectively). The number of stations is less than half the number of stations because the standard deviation condition must be met in all components). The NRMS values are very consistent with those in Tables 1 and 2, and in many cases smaller, suggesting that even the stations with the smallest sigma match in accordance with their sigmas.

Over all the agreement between the different methods of estimating the velocities are very good with the WRMS difference in the NE components typically <0.4 mm/yr with the comparison to the PBO 2017, PBO 2016, and PBO 2015 velocity all being about 0.4 mm/yr. This difference is due to change from NAM08 to NAM14. The height WRMS differences are less than 1.0 mm/yr with the comparisons to the earlier solutions being less than 1.2 mm/yr. The CWU and NMT full solutions (GKNA) have WRMS differences of 0.09 and 0.64 mm/yr in horizontal and vertical components. The NRMS scatter of the differences is typically less than unity for the current solutions showing that the error bars are of the somewhat larger than the differences. There are correlations between these solutions so the NRMS scatter being less than unity should be expected. Comparisons with earlier solution, with no re-alignment of the reference frame have NRMS scatter between 1.5 and 2.0.

In tables 2 and 4, we see the average height rates in the CWU and NMT solutions are in good agreement with mean differences of only 0.05 and 0.04 mm/yr for the comparison of all stations and the stations with standard deviations less than the median velocity uncertainties. We do see a 0.73-0.89 mm/yr mean vertical rate difference between the NAM14 solutions and the older NAM08 solutions. There is also a +0.45 ± 0.12 mm/yr average height rate difference between vertical rates of the 86 stations used to define the North America plate in ITRF2014 and our estimates. The NAM14 system changes the alignment with the ITRF from that used in NAM08 (i.e., effectively at different date is used to align the NAM frame with the ITRF frame is used. For NAM14 the alignment data is 2010.0, i.e., at 2010.0 the NAM14 coordinates are the same as the ITRF2014 coordinates of the stations.) The difference in alignment results in the NAM08 station coordinates differing from the NAM14 coordinate by 30-40 mm north and east and about 20 mm in height depending on the geographic location of the station.

As noted above, stations have been removed from the GLOBK Kalman filter estimation if the Horizonal Random Walk (HRW) value with >100 mm2/yr. Velocity estimates for these stations only appear in the time series based analyses. The nature the time series for this stations is documented in Table 5. In addition, in generating the statistics of the comparisons of all stations in Tables 1 and 2, we removed stations that had large differences between the CWU and NMT solutions. Only 17 of 2579 stations were removed. Velocities for these stations appear in all the velocity field files.

To show most of the distribution of the stations in the velocity field estimates, we show in Figure 1, the vertical rates of the 2540 stations which have vertical rates with standard deviations less than 5 mm/yr. Figure 2 shows the rates in California.

Along with this release of the velocity field we also release a folder with ancillary files and results similar to the files released for the Reviews of Geophysics paper. The contents of the DOI_180915 folder are described in Table 6.

Table 1: Comparison of North and East velocities between different velocity field determination methods. No transformation parameters between the fields have been estimated. The codes for the solutions are: CCC_TTYY where CCC is the center NMT, CWU or the combined PBO analysis; TT is the type of analysis: GK – GLOBK Kalman filter; TS – time series fit; and YY is combination of method and reference frame: LS – least squares, KF – Kalman filter; NA – NAM14, IG – IGS14 rotated to NA. The final entries PBO_2017, PBO_2016, and PBO_2015 are the earlier 2017, 2016 and 2015 PBO full solution generated in December 2017, December 2016 and November 2015. These fields are in the NAM08 reference frame, # is the number of common stations in the solutions.

Soln1 -	Soln2	#	N mean (mm/yr)	N WRMS (mm/yr)	N NRMS	E mean (mm/yr)	E WRMS (mm/yr)	E NRMS
PBO_GKNA-	CWU_GKNA	2566	0.00	0.05	0.249	0.01	0.05	0.256
PBO_GKNA-	NMT_GKNA	2572	0.00	0.06	0.297	0.01	0.07	0.318
CWU_GKNA-	NMT_GKNA	2562	0.00	0.09	0.451	-0.00	0.09	0.423
PBO_GKNA-	PBO_TSLS	2576	0.00	0.14	0.878	0.01	0.24	1.486
PBO_GKNA-	PBO_TSKF	2576	-0.02	0.20	1.078	-0.02	0.30	1.595
PBO_GKNA-	CWU_TSLS	2565	-0.01	0.23	1.452	0.01	0.28	1.744
PBO_GKNA-	CWU_TSKF	2565	-0.03	0.33	1.795	-0.01	0.40	2.131
PBO_GKNA-	NMT_TSLS	2572	0.01	0.16	0.985	0.01	0.25	1.538
PBO_GKNA-	NMT_TSKF	2570	-0.01	0.19	1.011	-0.02	0.29	1.563
PBO_GKNA-	PBO_GKIG	2576	-0.05	0.07	0.308	0.07	0.11	0.488
PBO_GKNA-	CWU_GKIG	2566	-0.04	0.08	0.350	0.09	0.14	0.621
PBO_GKNA-	NMT_GKIG	2572	-0.09	0.12	0.503	0.13	0.19	0.807
PBO_GKNA-	PBO_2017	2191	0.09	0.36	1.753	0.16	0.43	2.073
PBO_GKNA-	PBO_2016	2156	0.07	0.39	1.859	0.16	0.45	2.103
PBO_GKNA-	PBO_2015	2119	0.05	0.41	1.883	0.13	0.44	2.030

Table 2: Similar to Table 1 except here the mean horizontal velocity (HzMean, HzWRMS, HzNRMS) and vertical velocity (U columns) are compared.

Soln1 - Soln2	#	HzMean (mm/yr)	HzWRMS (mm/yr)	HzNRMS	U Mean (mm/yr)	U WRMS (mm/yr)	U NRMS
PBO_GKNA- CWU_GKNA	2566	0.00	0.05	0.252	-0.05	0.34	0.519
PBO_GKNA- NMT_GKNA	2572	0.00	0.06	0.308	-0.00	0.31	0.472
CWU_GKNA- NMT_GKNA	2562	0.00	0.09	0.437	0.05	0.64	0.968
PBO_GKNA- PBO_TSLS	2576	0.00	0.19	1.220	-0.01	0.54	1.011
PBO_GKNA- PBO_TSKF	2576	-0.02	0.25	1.361	0.01	0.62	1.102
PBO_GKNA- CWU_TSLS	2565	-0.00	0.26	1.605	0.13	0.67	1.197
PBO_GKNA- CWU_TSKF	2565	-0.02	0.37	1.970	0.40	0.96	1.634
PBO_GKNA- NMT_TSLS	2572	0.01	0.21	1.291	0.15	0.67	1.228
PBO_GKNA- NMT_TSKF	2570	-0.02	0.25	1.316	0.22	0.73	1.285
PBO_GKNA- PBO_GKIG	2576	0.01	0.10	0.408	0.23	0.29	0.423
PBO_GKNA- CWU_GKIG	2566	0.03	0.12	0.504	0.15	0.42	0.604
PBO_GKNA- NMT_GKIG	2572	0.03	0.16	0.672	0.31	0.50	0.731
PBO_GKNA- PBO_2017	2191	0.13	0.40	1.920	0.73	0.94	1.525
PBO_GKNA- PBO_2016	2156	0.11	0.42	1.985	0.88	1.13	1.838
PBO_GKNA- PBO_2015	2119	0.09	0.42	1.958	0.89	1.17	1.673

Table 3: Comparison of North and East velocities similar to Table 1 except we limit the stations to those that have horizontal and vertical velocities sigmas both less than the median horizontal and vertical velocity sigmas. (Reason there are less than 1283 stations is because both horizontal and vertical sigma conditions must be satisfied.) To be included in this table the north and east velocity sigmas must be less than 0.16 and 0.16 mm/yr and the height velocity sigma less than 0.55 mm/yr.

Soln1 - Soln2	#	N mean (mm/yr)	N WRMS (mm/yr)	N NRMS	E mean (mm/yr)	E WRMS (mm/yr)	E NRMS
PBO_GKNA- CWU_GKNA	925	0.00	0.04	0.250	0.01	0.05	0.342
PBO_GKNA- NMT_GKNA	925	0.01	0.04	0.257	0.01	0.05	0.322
CWU_GKNA- NMT_GKNA	925	0.01	0.07	0.458	-0.00	0.09	0.600
PBO_GKNA- PBO_TSLS	925	-0.00	0.08	0.716	0.01	0.09	0.747
PBO_GKNA- PBO_TSKF	925	-0.01	0.09	0.681	-0.01	0.11	0.807
PBO_GKNA- CWU_TSLS	925	-0.01	0.12	1.012	0.01	0.11	0.916
PBO_GKNA- CWU_TSKF	925	-0.02	0.15	1.062	-0.00	0.16	1.133
PBO_GKNA- NMT_TSLS	925	0.00	0.09	0.799	0.01	0.10	0.819
PBO_GKNA- NMT_TSKF	925	-0.01	0.10	0.718	-0.01	0.11	0.810
PBO_GKNA- PBO_GKIG	925	-0.06	0.07	0.371	0.06	0.10	0.544
PBO_GKNA- CWU_GKIG	925	-0.05	0.07	0.385	0.09	0.13	0.739
PBO_GKNA- NMT_GKIG	925	-0.09	0.11	0.577	0.12	0.17	0.935
PBO_GKNA- PBO_2017	818	0.10	0.28	1.742	0.11	0.25	1.588
PBO_GKNA- PBO_2016	818	0.08	0.28	1.742	0.12	0.26	1.585
PBO_GKNA- PBO_2015	818	0.07	0.28	1.645	0.10	0.24	1.381

Table 4: Same as Table 3 except for the combined horizontal and vertical comparison.

Soln1 - Soln2	#	HzMean (mm/yr)	HzWRMS (mm/yr)	HzNRMS	U Mean (mm/yr)	U WRMS (mm/yr)	U NRMS
PBO_GKNA- CWU_GKNA	925	0.01	0.05	0.300	-0.05	0.15	0.300
PBO_GKNA- NMT_GKNA	925	0.01	0.04	0.292	-0.01	0.13	0.271
CWU_GKNA- NMT_GKNA	925	0.00	0.08	0.534	0.04	0.26	0.528
PBO_GKNA- PBO_TSLS	925	0.00	0.09	0.732	0.01	0.36	0.906
PBO_GKNA- PBO_TSKF	925	-0.01	0.10	0.746	-0.00	0.42	1.012
PBO_GKNA- CWU_TSLS	925	0.00	0.11	0.965	0.11	0.42	1.019
PBO_GKNA- CWU_TSKF	925	-0.01	0.15	1.098	0.34	0.64	1.473
PBO_GKNA- NMT_TSLS	925	0.01	0.09	0.809	0.11	0.46	1.162
PBO_GKNA- NMT_TSKF	925	-0.01	0.11	0.765	0.18	0.54	1.289
PBO_GKNA- PBO_GKIG	925	0.00	0.08	0.466	0.22	0.27	0.510
PBO_GKNA- CWU_GKIG	925	0.02	0.11	0.589	0.15	0.24	0.452
PBO_GKNA- NMT_GKIG	925	0.02	0.14	0.777	0.29	0.37	0.727
PBO_GKNA- PBO_2017	818	0.10	0.27	1.667	0.74	0.88	1.885
PBO_GKNA- PBO_2016	818	0.10	0.27	1.665	0.88	1.04	2.214
PBO_GKNA- PBO_2015	818	0.09	0.26	1.519	0.87	1.04	1.903

Table 5: Notes on the nature of the time series of stations that were (a) not included in the full Kalman filter GLOBK analysis; and (b) excluded from Table 1 and 2 analyses due to >10σ differences between the CWU and NMT horizontal velocity estimates and (c) excluded from Table 1 and 2 analyses due to 3-5σ differences between CWU and NMT solutions.

Station	Explanation
(a) Stations that were excluded based large HRW(> 100 mm^2/yr)	
AC09	Large horizontal smooth non secular deviations. Amplitude north -20 to 40 mm.
AC30	Limited data between 2007-2009 with large gaps and snow effects.
ARGI	Small amount of data in 2013 and one point in 2018
AV05	Limited data between 2003-2006 with large gap and snow effects.
BLKM	Only data between 2017-2018 with non-seasonal oscillation in East.
BLOK	Patchy data in 2017, end early 2018. Oscillation seems related to BLKM.
CASA	Bimodal north coordinates in 1996-1997, then large 100 mm change in north until 2000. Multiyear systematics until end of data in 2006.
EISL	Large systematics between 1996-2000. Data ends in 2005. Only marginally similar to CASA between 1996-2000.
ELMA	Small amount of data between 2016.4 and 2018.7. Break and systematic motion around 2018-09-16.
EOCG	Systematic variations and “breaks” around 2014-12-13. 2016-01-04 and 2016-12-23.
FCTF	Small amount of data in 2017 and 2018. Data early in 2017 very noisy.
GUAX	Data looks OK except only in 2002-2004 and then large gap to 2017.
KOD1	Data between 1996-2002 very systematic with slope that is different to the post 2002 data. Data ends in July 2007.
LUMC	Only processed by NMT. Small amount of data between 2001 and 2003.
MARC	Some in 2010 and then gap to 2012, end at end of 2012. Offset on 2012 that appears and then disappears.
MIDB	Small amount of data in 2017 and 2018. Systematic in East, maybe related to BLKM and BLOK.
NTOE	Very similar to MIDB with systematics and only data in 2018 and 2018.
P323	Small amount of data in 2007 to early 2008. Affected by snow.
P656	Very severe snow events with 400 mm North and 1000 mm vertical excursions.
SATS	Limited data between 1996-2003. Excursions until 2000 similar to EISL and CASA.
SMM[1-3]	Greenland summit stations with large height offsets (4 meters) and non secular motions.
STOE	Data only between 2017 and 2018. East systematics similar to MIDB
WLHG	Limit data between 2015 and 2018 with systematic excursions. Gap in early 2017.
(b) > 10σ differences	

LINC	CWU has a large number of outliers and large 2 meters errors at start of data in 1999.
P669	Nearly all data affected by snow resulting in 200 mm/yr differences between NMT and CWU solution.
AC33	Lots of snow events .
GTRG	Offsets in 1997 between CWU and NMT. Probably an antenna change that was not processed consistently.
AHID	Data before 2000/12/19 very erratic – deviations of 50 mm.
P664	Snow events
(c) 3-5σ differences	
P135	Data quality degrades after 2015/06/06. NMT stops processing 2017/04/30.
AC16	Snow events. Large sigmas in CWU solution after 2018/06/17. No NMT solution.
PVE3	Poor data quality between mid 2002 and 2003/04/04. Looks like failing antenna.
RBRU	Bad CWU results in September 2006; very few data in CWU solution at this time.
WMAP	Bad antenna between 1999 and 2005/05/28
LOZI	Only data between 2006 and 2013. CWU solution is very noisy compared to NMT solution.
MOMI	Only data between 2016 and 2017. Noisy and NMT has only half the span of CWU
P791	Snow events prior to 2012. Large offset in April 2012 with 100 mm offset in East coordinate.
BLYN	Station becomes noisy after 2014. Could be due to vegetation growth or failing antenna.
NARA	Data only between 2012-2016. NMT has offset 2014/06/14 possible due to incorrect meta data.
MAWY	Strange slow shift in position in late 1999. Likely volcanic activity in Yellowstone.

Table 6: Ancillary and velocity fields supplied with this solution (folder DOI_180915)

File	Description
All_PBO.rw	Random walk parameters by station for use in GLOBK Kalman filter
All_PBO_ants.eq	List of epochs of discontinuities due to antenna and radome changes in GLOBK EQ-format. There are 1994 entries.
All_PBO_edits.eq	List of stations and times of position estimates removed from the final velocity solution combination either because they are outliers (e.g., snow/ice on antenna) or have large standard deviations (22601 entries).
All_PBO_eqs.eq	List of 51 earthquakes included for co-seismic offset discontinuities. 15 of these earthquakes include parameterized logarithmic post-seismic terms.
All_PBO_unkn.eq	List of stations and epochs of discontinuities in position time series that occur for unknown reasons (or unknown times when an antenna partially fails). There are 157 entries
All_PBO_netsel.use	List of sub-networks used to create the combined velocity solution.
All_PBO.stab	Hierarchical list of reference frame stations used to define the NAM14 reference frame
All_PBO_nam14.apr	GLOBK apriori position, velocity and extended entry format file defined in NAM14 frame
All_PBO_igs14.apr	GLOBK apriori position, velocity and extended entry format file defined in IGS14 frame
pbo.final_nam14.20180915.vel	Combined velocity field based on GLOBK SINEX file analysis in the NAM14 reference frame. PBO velocity field file format.
cwu.final_nam14.20180915.vel	CWU velocity field based on GLOBK SINEX file analysis in the NAM14 reference frame.

	PBO velocity field file format.
nmt.final_nam14.20180915.vel	NMT velocity field based on GLOBK SINEX file analysis in the NAM14 reference frame. PBO velocity field file format.
pbo.snaps_nam14.20180915.vel	Combined velocity field based on time series analysis in the NAM14 reference frame. PBO velocity field file format.
pbo.snaps_igs14.20180915.vel	Combined velocity field based on time series analysis in the IGS14 reference frame. PBO velocity field file format.
cwu.snaps_nam14.20180915.vel	CWU velocity field based on time series analysis in the NAM14 reference frame. PBO velocity field file format.
nmt.snaps_nam14.20180915.vel	NMT velocity field based on time series analysis in the NAM14 reference frame. PBO velocity field file format.
pbo.final_igs14.20180915.vel	Combined velocity field based on GLOBK SINEX file analysis in the IGS14 reference frame. PBO velocity field file format.
pbo.tswls_nam14.20180915.gvl	Combined velocity field based on time series weighted least squares (WLS) analysis in the NAM14 reference frame. GLOBK velocity field file format.
pbo.tskfa_nam14.20180915.gvl	Combined velocity field based on time series Kalman filter (KF) analysis in the NAM14 reference frame. GLOBK velocity field file format.
pbo.gkiga_nam14.20180915.gvl	Combined velocity field based on GLOBK SINEX file analysis in a North America reference frame directly realized from the IGS14 reference frame stations. GLOBK velocity field file format.
pbo.gknam_nam14.20180915.gvl	This is the pbo.final_nam14.20180915.vel file in GAMIT/GLOBK velocity field format. This format can be used with the GAMIT/GLOBK tools for analysis of the velocity field.
cwu.gknam_nam14.20180915.gvl	cwu.final_nam14.20180915.vel in

	GAMIT/GLOBK format.
nm.gknam_nam14.20180915.gvl	nmt.final_nam14.20180915.vel in GAMIT/GLOBK format.
cwu.tswls_nam14.20180915.gvl	CWU velocity field based on time series weighted least squares (WLS) analysis in the NAM14 reference frame. GLOBK velocity field file format.
cwu.tskfa_nam14.20180915.gvl	CWU velocity field based on time series Kalman filter (KF) analysis in the NAM14 reference frame. GLOBK velocity field file format.
cwu.gkiga_nam14.20180915.gvl	CWU velocity field based on GLOBK SINEX file analysis in a North America reference frame directly realized from the IGS14 reference frame stations. GLOBK velocity field file format.
nmt.tswls_nam14.20180915.gvl	NMT velocity field based on time series weighted least squares (WLS) analysis in the NAM14 reference frame. GLOBK velocity field file format.
nmt.tskfa_nam14.20180915.gvl	NMT velocity field based on time series Kalman filter (KF) analysis in the NAM14 reference frame. GLOBK velocity field file format.
nmt.gkiga_nam14.20180915.gvl	NMT velocity field based on GLOBK SINEX file analysis in a North America reference frame directly realized from the IGS14 reference frame stations. GLOBK velocity field file format.

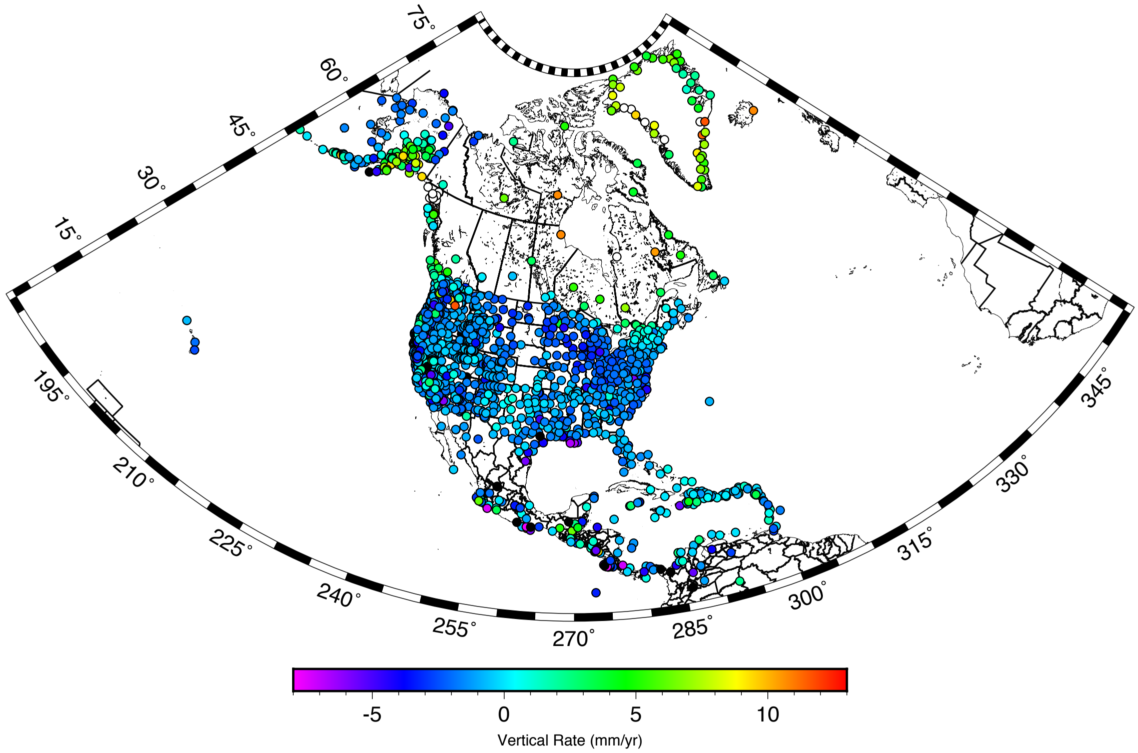

Figure 1: Vertical rate estimates for the 2540 stations in the PBO NAM14 solution with vertical velocity standard deviations of less than 5 mm/yr.

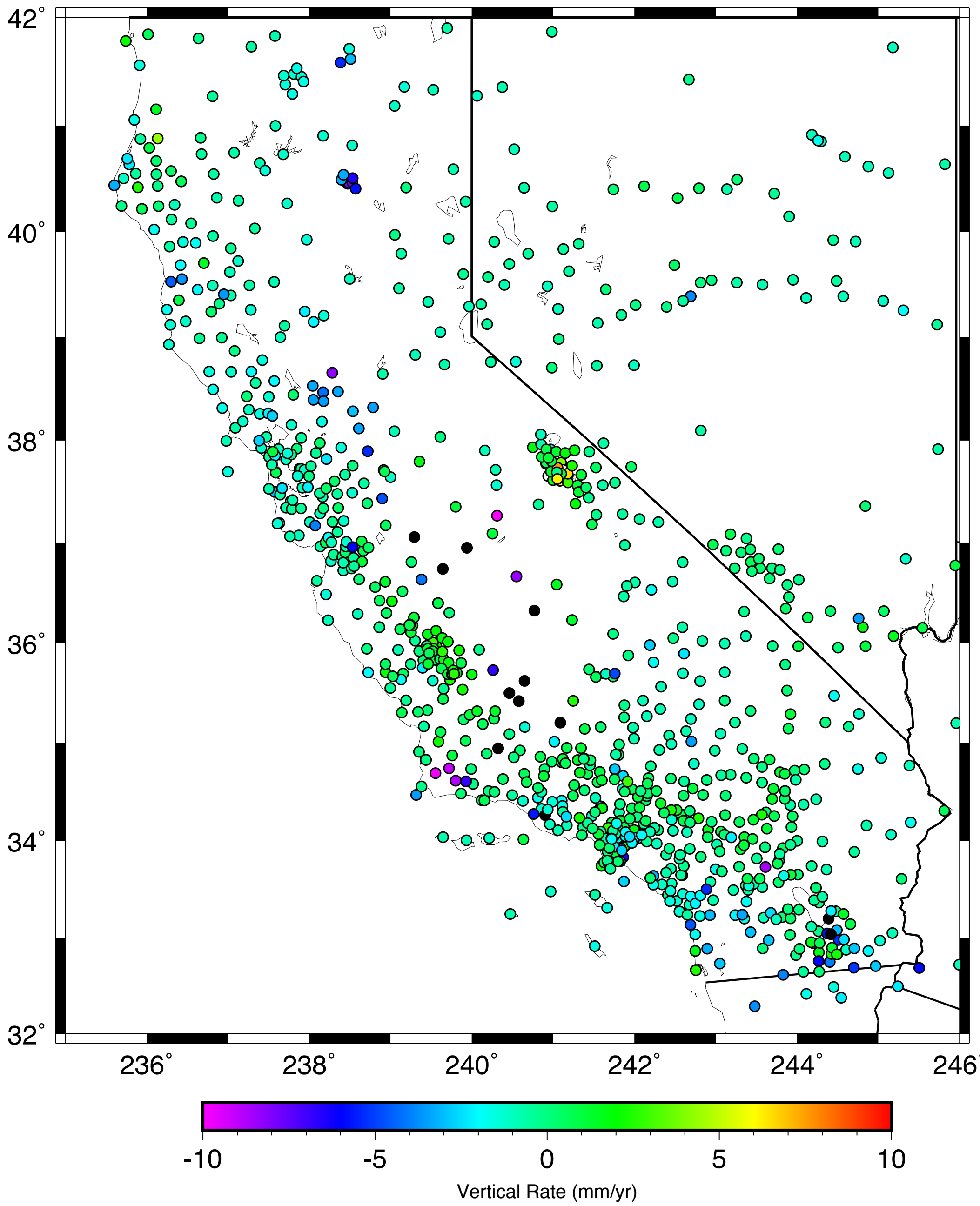

Figure 2: Vertical motions in California. Black symbols show point subsiding faster than 10 mm/yr.

References

Altamimi, Zuheir, Paul Rebischung, Laurent Métivier, and Xavier Collilieux. (2016) "ITRF2014: A New Release of the International Terrestrial Reference Frame Modeling Nonlinear Station Motions." *Journal of Geophysical Research: Solid Earth* 121 (8): 6109–31. https://doi.org/10.1002/2016JB013098.

Altamimi, Zuheir, Laurent Métivier, Paul Rebischung, Hélène Rouby, and Xavier Collilieux. (2017) "ITRF2014 Plate Motion Model." *Geophysical Journal International* 209 (3): 1906–12. https://doi.org/10.1093/gji/ggx136.

Herring, T.A., T. I. Melbourne, M. H. Murray, M. A. Floyd, W. M. Szeliga, R. W. King, D. A. Phillips, C. M. Puskas, M. Santillan, and L. Wang, (2016) Plate Boundary Observatory and Related Networks: GPS Data Analysis Methods and Geodetic Products, *Rev. Geophys*., 54, doi:10.1002/2016RG000529. http://onlinelibrary.wiley.com/doi/10.1002/2016RG000529/full

Floyd, M.A., and T. A. Herring (2019) Fast Statistical Approaches to Geodetic Time Series Analysis in "Geodetic Time Series Analysis in Earth Sciences)", Eds. J.-P. Montillet and M. Bos, Springer Nature Switzerland, *in press.* doi: 10.1007/978-3-030-21718-1