GPS data analysis and results from the Geodesy Advancing Geosciences and EarthScope (GAGE) project

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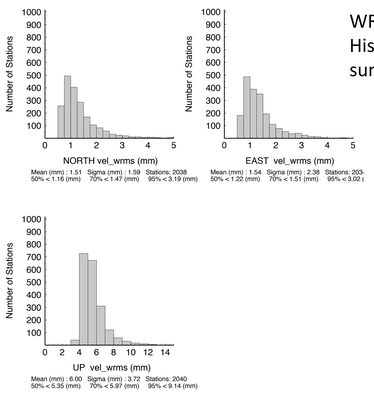
ABSTRACT: We report on the methods and results from the GPS data analysis part of the NSF Geodesy Advancing Geosciences and EarthScope (GAGE) project operated by UNAVCO. Current analyses include GPS data from the 1100 Plate Boundary Observatory (PBO) sites and approximately 700 other sites used to densify the network in some locations and to provide spatial extent on the North America and Pacific plates. Analyses from 1996 to present collectively include approximately 2050 unique sites over the 18-year period. The results from these analyses are updated daily for rapid solutions (~1 day latency) and weekly for initial analyses using IGS final orbits (2-3 week latency). Analyses are also run with 12- and 26-week latencies to add sites that were not available (either telemetry failures or manual download sites) during the initial analyses. Raw data are processed using two different GPS analysis programs: GAMIT at New Mexico Tech and GIPSY at Central Washington University. Combined results are then produced with GLOBK at MIT. All results are available through the UNAVCO web site in the form of time series and velocity fields in the NAM08 (ITRF2008 North America Euler pole from Altamimi et al., 2012) and IGS08 frames. Daily SINEX files are provided in fiducial free and NAM08 frames. Event files are generated within a few days of earthquakes in the GAGE analysis region that generate co-seismic displacements greater than 1 mm. The median weighted root-mean-square (WRMS) scatters of combined position time series are less than 1 mm in north and east (NE) and 4 mm for vertical (U) over monthly durations. For all results processed thus far (~18 years of data for the longest running sites), WRMS scatters of the position residuals about linear trends, with offsets for earthquakes and antenna changes removed, are ~1.5 mm NE and 6.5 mm U. The top 10% of sites have short period scatters (month duration) of 0.5 mm NE and 1.9 mm U, while the long-term scatters increase to 0.8 mm NE and 3.3 mm U. The noisiest sites are generally in volcanic areas and/or affected by snow and ice on antennas. We will present results from GAGE analyses in terms of secular rates across the Pacific/North America plate boundary and non-secular signals arising from earthquakes (co- and post-seismic deformation) and other natural and human-induced processes.

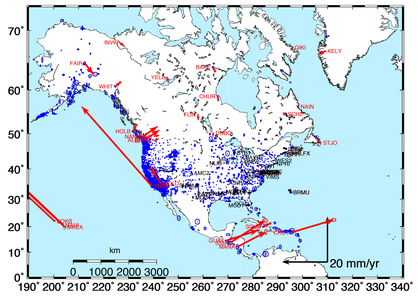
- **AC routine products: Rapid Analysis** :
  - Started at ~18:00 UTC for previous day using IGS rapid products. Starts when IGS rapid orbit becomes available (generally this is very regular)
  - Products: 24-hour latency (i.e., 6-hours to process data)
  - –Loosely constrained SINEX file with station position estimates with bias fixing
  - –Root-mean-square (RMS) scatters of and numbers of phase residuals by site.
  - **Aim:** These products are for quality checking of sites and "rapid" response after "events" (mainly earthquakes or volcanic eruptions).
- **AC routine products: "Final" Analysis**
  - "Final" here comes from the use of the name "final" IGS orbit.
  - Started: Normally Friday of each week when IGS final orbit for two weeks prior becomes available. CWU analysis uses JPL products, NMT uses IGS products.
  - Products: 13-19 day latency depending on day of week data collected.
  - **Aim:** Highest quality products generated near in time to data collection. Differences from rapid analysis:
  - –Orbit quality (small effect)
  - –More stations available due to some latency in data returns
- **AC routine products: "Supplemental" Analyses 12 and 26 week latency**
  - Run with 12/26-week latency and adds stations that were missed in the "finals" run. Combined with finals runs to generate merged analysis. 26-week latency analysis replaces 12-week on.
  - Generally 10-40 stations added in this analysis. Designated with name suppl or supp6 (added site) or suppf (site originally in final).
- **Reprocessed results:**
  - Reprocessing complete from 1996 to 2014 using ITRF2013 model standards and products in the ITRF2008 system.
- **ACC routine products**
  - –For both rapid, final and supplemental products:
  - AC and merged SINEX file: Frame resolved
  - Time series results for AC and merged results. Frame definition using Pacific, Eastern Russian, Canada and North America. Time series currently available in ASCII format. Statistics of station phase data and time. Event files after eqarthquakes.
- **Products available via http://www.unavco.org/instrumentation/networks/status/pbo**



WRMS scatters of 1996-2014 reprocessed time series. Histogram is for the combined PBO series. The table shows summaries for the combined PBO and NMT/CWU analyses

Center	North (mm)	East (mm)	Up (mm)
Median (50%)			
PBO	1.2	1.3	5.5
NMT	1.2	1.3	5.6
CWU	1.4	1.4	6.5
70%			
PBO	1.5	1.6	6.1
NMT	1.6	1.7	6.4
CWU	1.8	1.7	7.5
95%			
PBO	3.4	3.1	9.1
NMT	3.4	3.2	8.8
CWU	3.8	3.5	11.4

NAM08 Reference Frame realization and comparisons

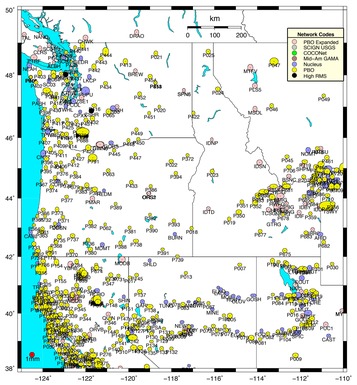


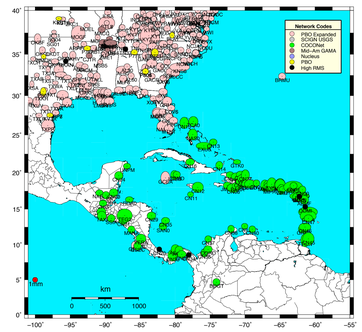
Reference sites used to define the North American plate in the NAM08 reference frame. The (39) red vectors show the IGb08 reference sites that are used to define NAM08. The (38) black vectors are the observed motions at the sites used to define the North America plate Euler pole in Altamimi et al., [2012]. The blue error ellipses show the 95% confidence error ellipses of the site in the PBO analysis with velocity standard deviations less than 0.5 mm/yr. The WRMS scatter of the 38 North America defining sites (black) are 0.33, 0.46 and 1.11 mm/yr in North, East and Up, respectively.

Comparison on velocity solutions generated in GLOBK and from time series

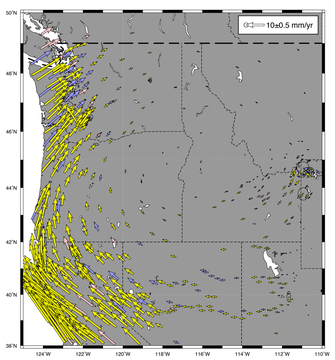
Solution	# Sites	Horizontal WRMS (mm/yr)	NRMS	Height WRMS (mm/yr)	NRMS	Mean Scale rate (ppb/yr)
Comparison to IGb08 North America Fixed						
PBO Initial Reprocessed solution (GLOBK)	21	0.52	1.65	2.53	2.39	0.025
PBO Reprocessed solution (GLOBK)	28	0.15	1.35	0.57	1.09	-0.047
CWU time series	38	0.19	3.07	1.06	3.32	0.035
NMT time series	38	0.17	2.85	0.70	3.16	0.020
PBO time series.	38	0.15	3.05	0.74	3.45	0.025
Comparison to PBO time series						
PBO Initial Reprocessed solution	1193	0.51	2.09	1.37	1.59	0.046
PBO Reprocessed solution (GLOBK)	1717	0.25	1.61	1.45	2.00	-0.022
CWU time series	2025	0.06	0.70	0.32	0.70	0.000
NMT time series	2023	0.08	0.97	0.35	0.85	0.008
CWU-NMT	2013	0.11	1.27	0.60	1.30	-0.022

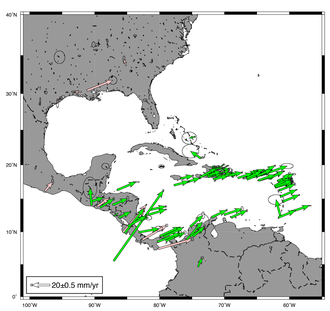
RMS scatter of horizontal position time series and velocity estimates





Distribution of the RMS scatters of horizontal position estimates from the PBO combined analysis for the Northern Western United States and Caribbean. 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 interval.

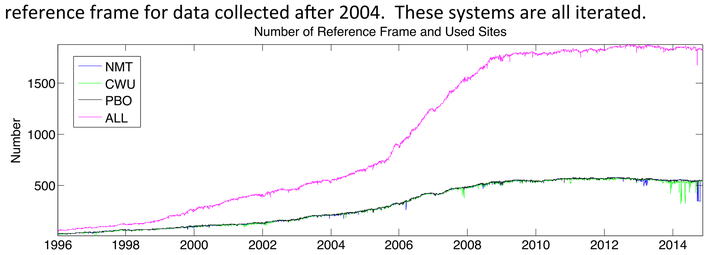




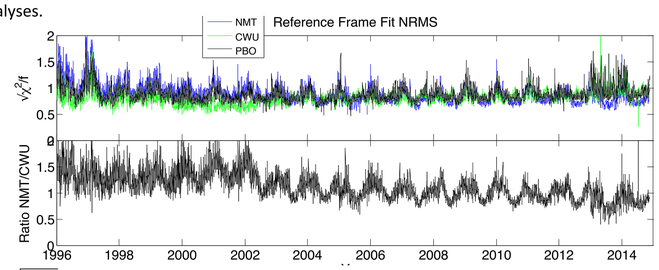
Velocity field estimates from the combined PBO solutions generated using time series analysis and the FOGMEX error model. 95% confidence interval error ellipses are shown. The color scheme of the vectors matches the network type legend above. Only velocities with horizontal standard deviations less than 2 mm/yr are shown in North Western United States and 5 mm/yr in the Caribbean.

Time series realization and characteristics

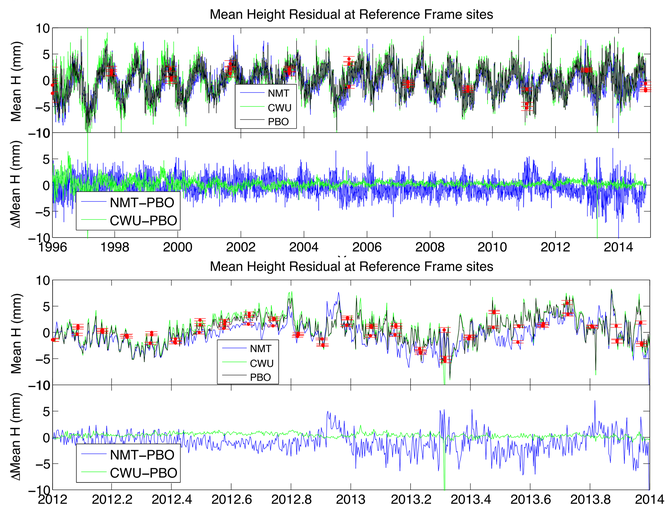
The time series for GAGE are formed by aligning the NMT and CWU and their combination (PBO) to an hierarchical list of high quality (based on time series correlated noise characteristic) reference frame sites. The hierarchical list is formed on 150km sided grid that covers the PBO region. Within each grid cell with sites, only one site (the best available) is used as a reference frame site in the daily reference frame realization. The reference frame site positions are determined in the velocity analysis. Only translation and rotation are used to align to the reference frame. **Scale is not estimated.**
The relative variance-covariance scaling between the NMT and CWU solutions is constant (0.7 and 4.8) and is determined from the average χ^2/f (f is degrees of freedom) fit to reference frame for data collected after 2004. These systems are all iterated.



Total number of sites (magenta) and number of reference sites used daily for NMT, CWU and PBO analyses.



The $\sqrt{\chi^2/f}$ (NRMS) of the fit to the reference frame sites for NMT, CWU and PBO. The covariance matrices are scaled to make these values ~1 after 2004). For the 11 years of results from 2004 to 2015, the average NRMS for NMT, CWU and PBO are 0.96, 0.91 and 1.10 indicating the relative weighting is consistent.



The GAGE reference frame realization does not estimate scale (with antenna models fixed, GPS scale is not intrinsically uncertain). A proxy for scale is the average height residuals and the above figures show these results for the NMT, CWU and PBO solutions. The lower figure is a zoom of the 2012-2014. The "annual" signal (it may be draconitic) is also seen in global GPS results. If scale is estimated, this mean height signature would be removed from all sites in the network. The lower parts of the figure show the differences between NMT/CWU and the PBO scale. It is clear from these figure that the scale of the combined solution closely follows the CWU scale even though the NMT height uncertainties, over are less than the CWU ones. The reason for the PBO scale tracking the CWU scale is not clear but it may be related to inter-site correlations in the NMT solutions where the satellite clocks are effectively estimated versus the CWU solution where they are fixed in the precise-point-positioning (PPP).

Summary: All of the GAGE analysis results and the algorithms used by NMT, CWU and MIT are available through the UNAVCO web and ftp sites. The median RMS scatters of the time series at < 1.5 mm NE and 6.5 mm H. Velocity estimates between the NMT and CWU solutions have RMS differences of 0.11 NE and 0.60 U mm/yr. Scale treatment in the GAGE analysis is different to most other analyses and the inferred scale of the PBO solution is controlled by the CWU solution because of the neglect of inter-site correlations in the PPP solutions.