Final Report for Awards G10AP00024/G10AP00022

Title: Intraplate stress and strain in the North American plate interior: Collaborative research with Purdue University and the University of Wisconsin

NEHRP Award: G10AP00024 (UW-Madison) and G10AP00022 (Purdue)

Professor Dennis DeMets
Dept. of Geoscience, University of Wisconsin - Madison
1215 W Dayton St, Madison, WI 53706
Tel: 608-262-8598, Fax: 608-262-0693 – email: chuck@geology.wisc.edu

Professor Eric Calais
Dept. of Earth & Atmospheric Sciences, Purdue University
West Lafayette, IN 47907-1397
Tel: 765-496-2915, Fax: 765-496-1210 – email: ecalais@purdue.edu

Now at: Ecole Normale Supérieure, Dept. of Geosciences, Paris, France – email: eric.calais@ens.fr

Term covered by report: Jan. 1, 2010 to Dec. 31, 2013

Investigations undertaken

The goal of this collaborative project was to estimate bounds on strain in the eastern and central United States and Canada from GPS station velocities updated using advanced GPS processing and post-processing methods. Two spatial scales were envisaged: plate wide, and a focus on the New Madrid Seismic zone. Investigators such as ourselves who seek to use the GPS velocity fields to better understand earthquake hazard in these intraplate regions must cope with at least two important issues. One is the need to process the firehose of continuous GPS data from the many stations in the central and eastern United States, including any reprocessing of those data that may be needed to take advantage of improvements in data processing strategies. A second is the challenge of separating the contributions of correlated GPS station noise, motion of the North America plate, and glacial isostatic rebound to GPS position time series, which is necessary if one hopes to uncover any residual strain patterns that might be indicative of surface strain accumulation, hence of the location of possible future significant earthquakes.

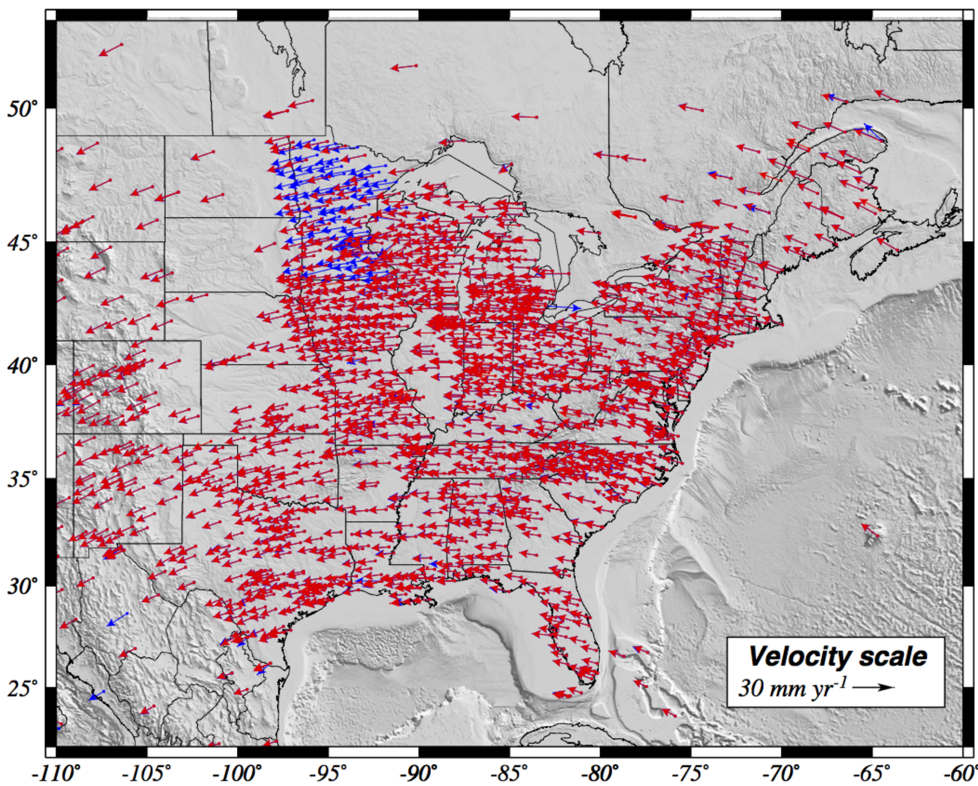

Figure 1: Velocities of North American plate GPS sites relative to ITRF2008 processed in this study. Uncertainty ellipses are 2-D, 1-sigma.

Below, we briefly document our efforts during the past three years toward these goals. Accomplishing the first of the two goals stated above consumed most of the time allotted for the project, principally because two new releases of GIPSY GPS processing software and one new generation of IGS satellite orbits have been released since 2010, when our project began. Consequently, our scientific objectives remain to be accomplished and will require (unfunded) work beyond our award's expiration date. Our NMSZ efforts however confirm earlier findings that the region is

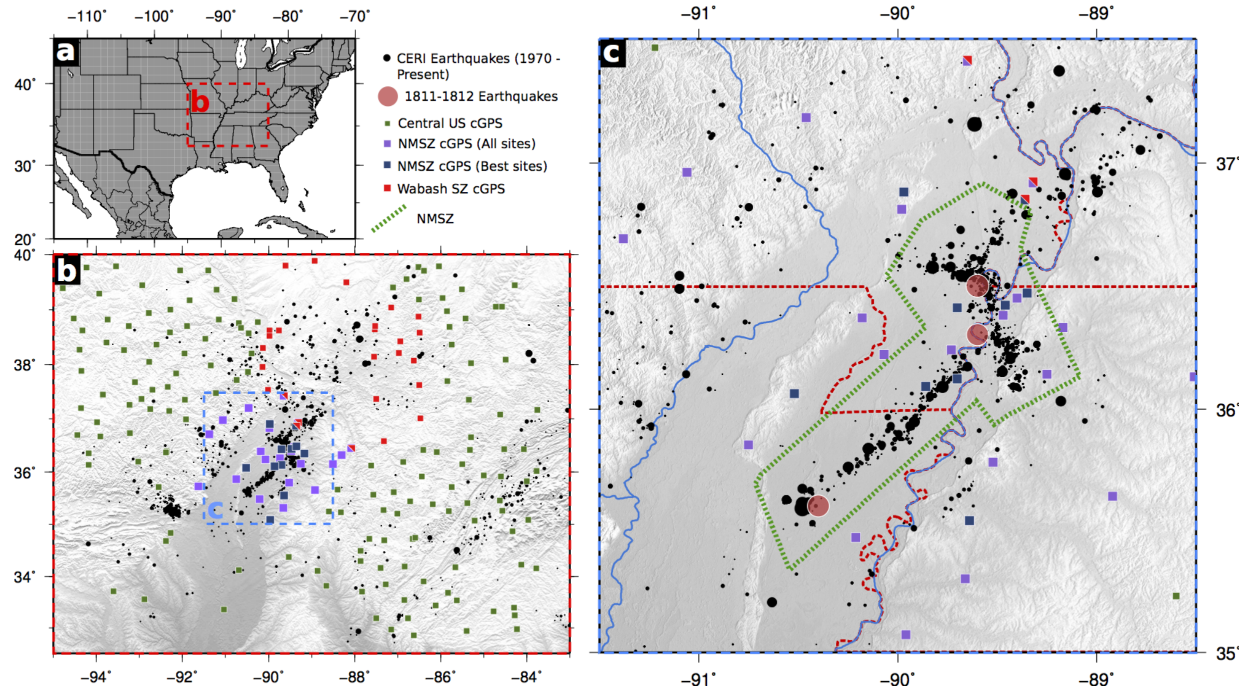

Figure 2: New Madrid and Wabash Valley Seismic Zones: setting, seismicity (circles) and continuous GPS stations used in this study (squares). The green dashed line on panel c shows the contour of the NMSZ sensu stricto.

currently not accumulating measurable surface strain.

During Years 1 and 2 (2010 and 2011), UW co-investigator invested all of his effort transitioning to Release 6.0 of GIPSY processing software, a new release that included assorted new processing features that merited a substantial data reprocessing effort. During these two years, we reprocessed more than five million station-days of legacy GPS data extending from 1996 to 2011. The new results were a major improvement relative to the already fine results we had previously achieved from processing the same data with Gipsy 5.0. In particular, our new GPS position time series exhibited a ∼40 per cent reduction in noise relative to our previous results, primarily due to GIPSY 6.0's new and still unique feature for resolving single-station phase ambiguities. In late 2011, IGS released a new generation of IGS satellite orbit products, which necessitated a second back-processing of the same legacy data in order to remain consistent with IGS's most recent orbit products.

Fig. 1 shows the velocity field for the central and eastern United States that resulted from the latter processing. Consisting of nearly 1400 continuous stations, the velocity field provides superb geographic coverage of this part of the continent. During 2012, we visually inspected the position time series for each site in the study area to identify and repair any uncorrected offsets. This required some iteration because it is essential for our estimation and minimization of spatially-correlated noise in the GPS velocity field.

In early 2013, updates 6.1 and 6.2 of GIPSY were released. Each added further useful new processing features. Despite the amount of work it involved, we elected to once again reprocess all legacy data extending from early 1993 to the present, consisting of more than eight million GPS station-days. We completed this processing less than two months ago and are now identifying and repairing the numerous offsets that degrade estimates of GPS site velocities if they remain unrepaired. Our new velocity field consists of 1560 GPS sites in the study region, including superb new coverage in Iowa, Wisconsin, and Minnesota, where the state Departments of Transportation have constructed dense continuous GPS networks.

We paid special attention to New Madrid Seismic Zone (NMSZ) because it is the locale of the 1811-1812 M7-7.5 earthquakes and of on-going (low magnitude) seismicity, and to the Wabash Valley Seismic Zone (WNSZ). Their location, current seismicity, and cGPS data availability are shown on Fig. 2. Over the course of the project, PU co-investigator has been updating the processing of all continuous GPS stations in the region. We produced solutions that were presented and discussed at USGS-supported workshops (*"New Madrid Geodesy Workshop"*, March 5th, 2011, Norwood, MA; *"Advancing Geodesy in the U.S. Midcontinent Workshop*, October 31 - November 1, 2012, Evanston, IL). In the second half of 2013 we reprocessed the entire NMSZ and surrouding data set (currently about 300 stations) in a consistent way with the latest IGS products and Gamit/Globk software features. This effort followed a published claim that significant strain was observed across the region (Frankel et al., BSSA, 2013). Fig. 3 shows the resulting position time series at a subset of sites, illustrating the variability of the data quality and observation time interval.

Scientific potential of the new velocity field

To illustrate the scientific potential of our new GPS velocity fields, we use a realization of the velocity field from mid-2013 (created prior to reprocessing the data with GIPSY 6.2) to make several salient points (Fig. 1). The velocity field for the eastern and central United States clearly defines the anticlockwise rotation of the North America plate around a pole that intersects Earth's surface in northern South America. The outstanding coverage and coherence of our new velocity field is sufficient to define coherent deformation gradients that perturb the rotational component of the velocity field, including glacial isostatic rebound and possibly coherent patterns of regional strain. For example, Fig. 4 shows the residual velocity field that results if we invert the velocities of all stations south of the U.S.-Canada border to find the rotation of the North America plate relative to ITRF2008 and then remove the predicted plate motion from the velocity at each site. The resulting residual velocity field is revealing. Stations in southern Canada and the northern tier states in the U.S. overwhelming move southward toward the central U.S., representing the mantle's viscoelastic response to rapid unloading of the continent when the ice sheets melted at the end of the last ice age more than 10,000 years ago.

Fig. 4 also reveals that some GPS stations have highly anomalous motions. Most GPS stations with anomalous motions have uncorrected antenna offsets that bias their velocity estimates (a problem that we continue to work on). This illustrates the need for careful visual inspection and repair of the GPS position time series, however time consuming. The results in Fig. 4 also raise the critical question of how to best identify the relative contributions of plate motion and post-glacial rebound to the velocity field. The pattern of residual deformation illustrated in Fig. 4 is non-unique because of our arbitary decision to estimate North America plate motion using only those stations that are south of the U.S.-Canada border. Had we adopted a different geographic limit, the pattern of deformation would have changed. Given that the velocity of every station on the map includes a component of plate motion and a lesser component of post-glacial rebound, all of the velocities should be analyzed via some to-be-determined objective method to find optimal estimates for both the plate rotation and the residual deformation. This is a prerequisite for

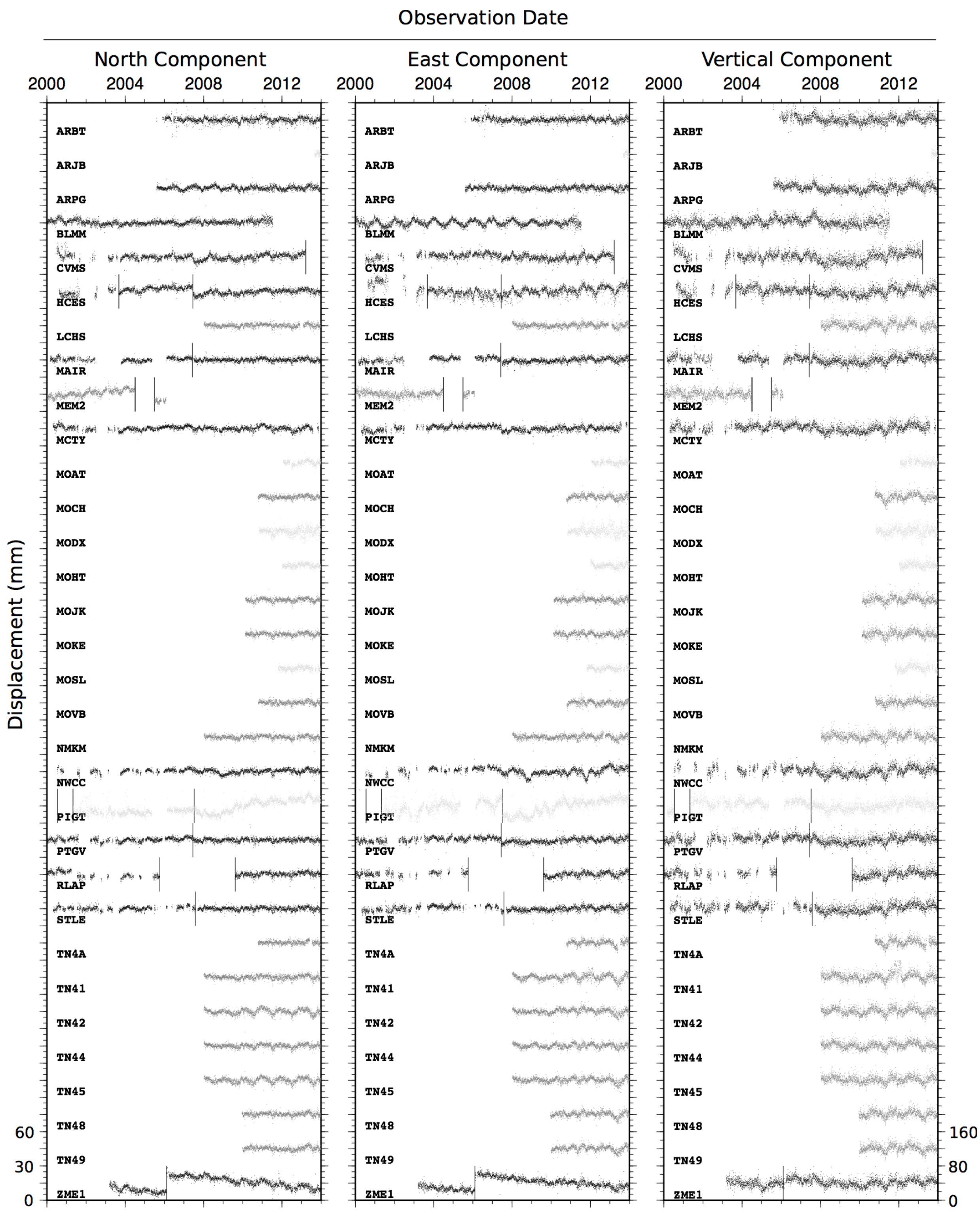

Figure 3: Position time series at New Madrid Seismic Zone continuous GPS sites. Note in particular the poor quality of the observations at sites PIGT and the short duration time series at MODX.

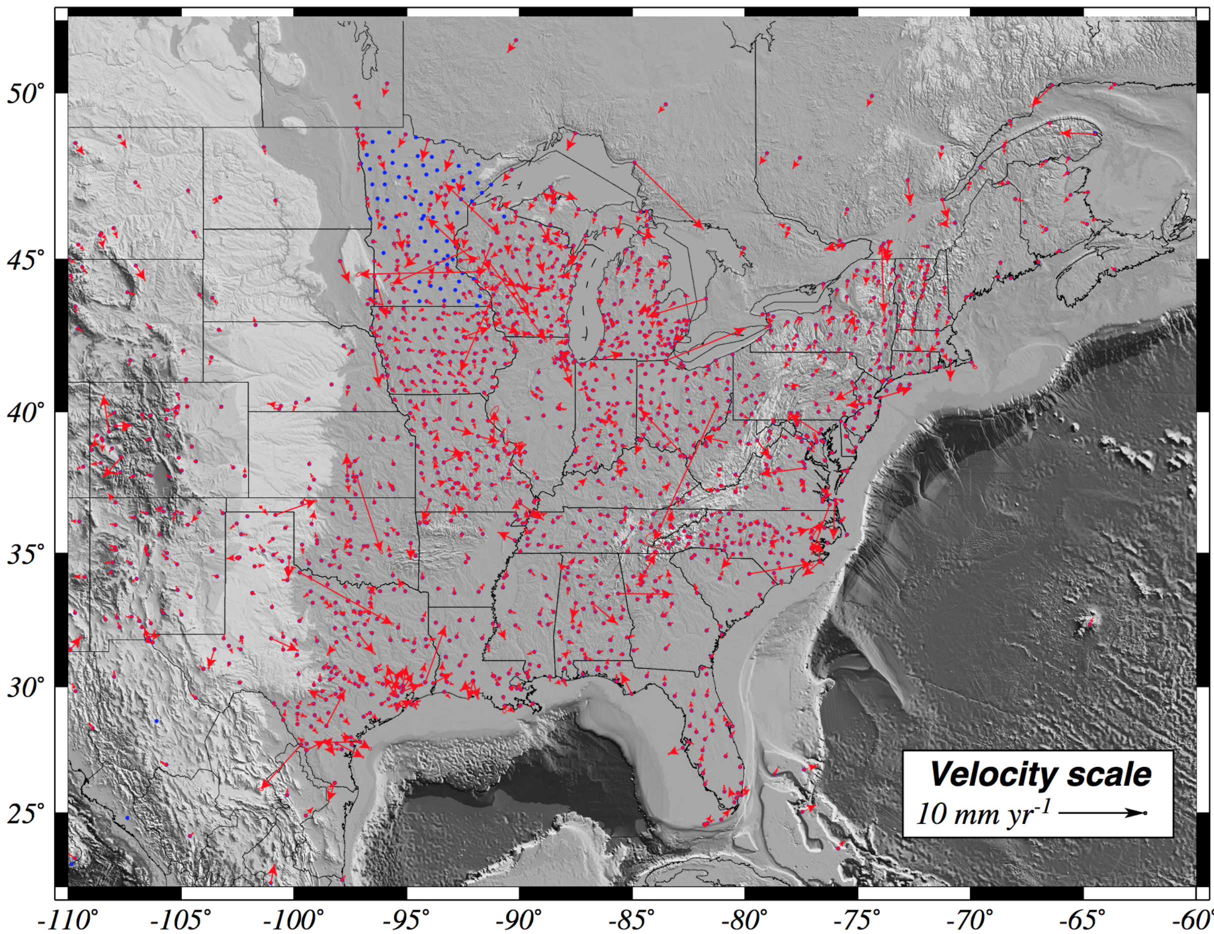

Figure 4: GPS station velocities corrected for the movement of the North America plate in ITRF2008. The North America plate rotation used to correct all the station velocities was estimated by arbitrarily inverting the velocities for all stations south of the U.S.-Canada border.

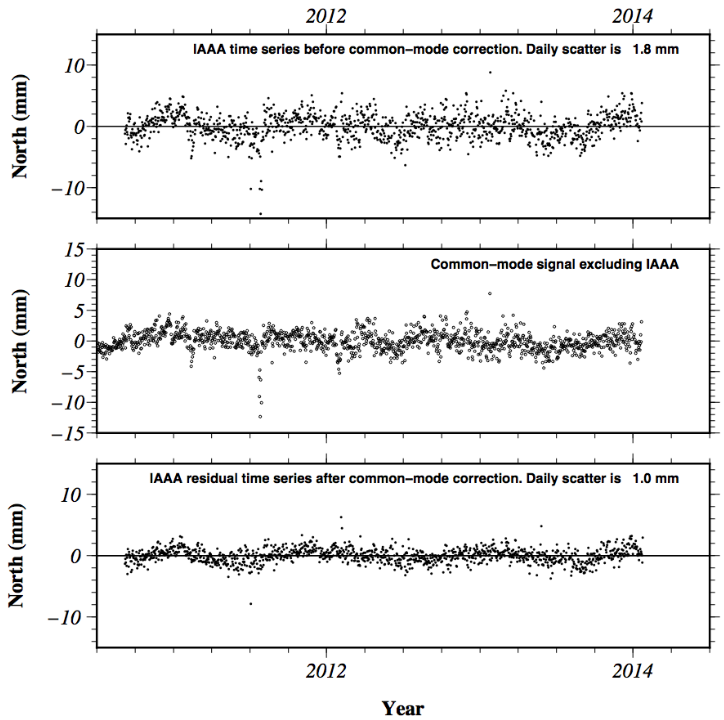

Figure 5: Effect of common-mode noise corrections to latitudinal component of the GPS time series for site IAAA in Iowa. Upper panel shows daily changes in station latitude at IAAA from GIPSY point-positioning before any correction for inter-station, common-mode noise. Center panel shows the correlated daily noise corrections (north component) determined from all continuous GPS sites within a 2000 km radius of IAAA, excluding the following: sites with time series shorter than 2.0 years, the IAAA time series, and stations with unstable motions. The bottom panel shows the IAAA time series after correcting it for the common-mode noise from the center panel. The noise corrections reduce the 1-sigma daily scatter by nearly half, from 1.8 mm to 1.0 mm.

identifying the even slower patterns of regional strain that might be hiding in the velocity field.

Correlated noise, whereby correlated velocity errors that can mimic regional strain affect GPS stations with data that span similar time intervals, also contributes to the pattern of GPS velocities, thereby further complicating efforts to identify plate motion, post-glacial rebound, and regionally significant strain. Fig. 5 illustrates one method we use to estimate and minimize such correlated noise, namely, spatial averaging of the departures from simple linear station motion for many nearby GPS sites in order to identify and remove elements in their time series noise that are correlated between sites. The upper panel illustrates daily latitudes estimated at a station in Iowa based on our processing with Gipsy Release 6.2. The station latitude is repeatable to within 1.8 mm (1-σ) on a daily basis. The middle panel shows spatially-averaged noise from more than 1000 stations surrounding site IAAA, constituting our best estimate of the noise that remains correlated between stations (from sources such as errors in estimated satellite orbits). The lower panel repeats the position time series at IAAA after subtracting the daily common-mode noise from each daily position. This reduces the daily noise in the latitude to only 1.0 mm or nearly 50%. The scatter in the daily site longitudes is also reduced by $\sim$50% when they are corrected for common-mode noise. Corrections such as these improve the consistency of our velocity field

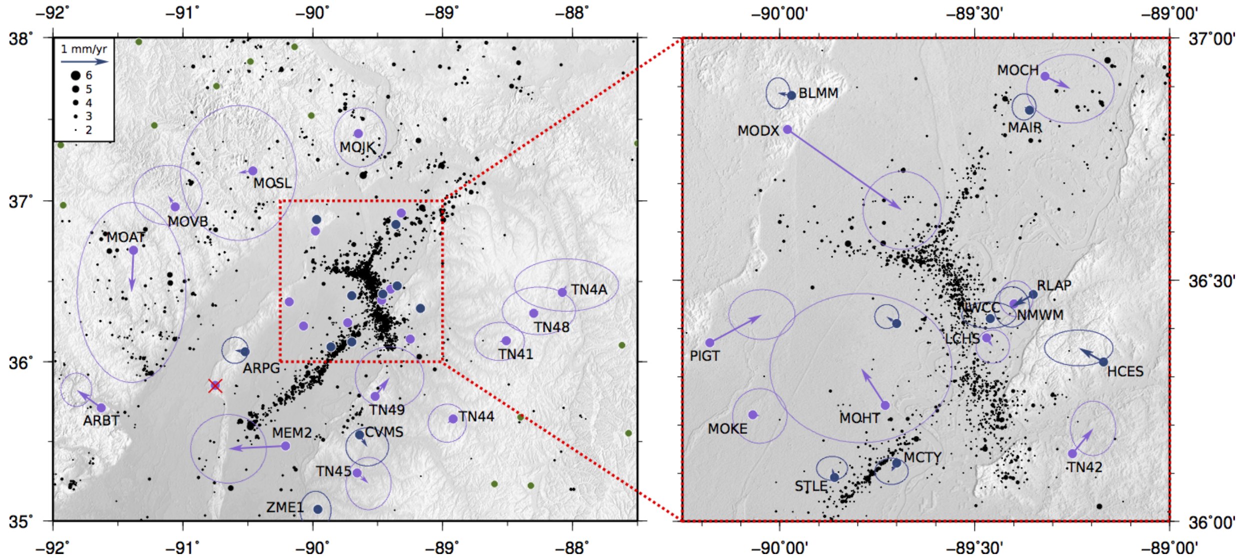

Figure 6: **Left**: Velocities at continuous GPS sites in the NMSZ and surroundings. **Right:** Close-up on the New Madrid seismic zone. Velocities are residuals after removal of a rigid rotation based on about 100 sites west of the Rocky mountains and north of the GIA hinge line. Uncertainty ellipses are 2-D, 1-sigma, and account for colored noise estimated from the data time series.

and should enhance our ability to recover the tectonic signals that we seek.

Our close-up velocity field for the NMSZ is displayed on Fig. 6. Residual velocities w.r.t. to rigid North America are all within 2-sigma (2D) uncertainties except at sites MEM2 (discontinued – benchmark located on an unstable concrete pad resting on soft sediments), PIGT (poor quality time series, see Fig. 3), and MODX (short time series, see Fig. 3). This velocity field is a significant augmentation compared to those published so far for this region. In addition to sites within the NMSZ *stricto sensu*, it shows velocities at sites on either sides of the Mississippi embayment, which should provide an "anchor" into stable North America. Many of these sites are still too young to provide a velocity repeatable within less than 1 mm/yr, but none are indicating far-field residual motions with respect to stable North America or to NMSZ sites. Taken together, these results are not indicative of present-day strain accumulation in the NMSZ at the precision level of the GPS measurements.

CVMS, RLAP, HCES

In order to further quantify the deviation of NMSZ sites from a purely rigid behavior (i.e., where no present-day strain accumulation occurs), we show on Fig. 7 the scatter of horizontal residuals for 11 time intervals over 10 years, i.e., from 2000-2004 to 2000-2014. Note the reduction on scatter with time, as well as the continuous decrease in RMS, currently at 0.2 mm/yr. Three sites are systematically outside of the 1-sigma RMS but still compatible with zero residual at the 95% confidence are CVMS, RLAP, and HCES. The fact that their residual velovity keeps decreasing with time is further indication that they do not represent signals of tectonic origin. A similar plot for the Wabash Valley Seismic Zone (Fig. 8) shows similar results, with only one site out of 25 showing a residual velocity significantly different from zero (KYBT).

We also tested whether the definition of "Stable North America" could influence the results

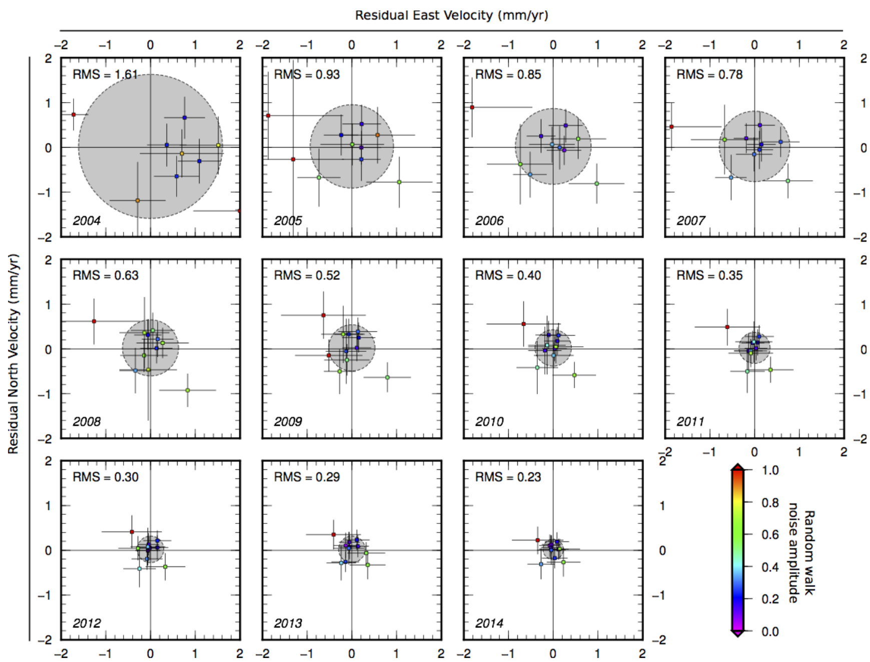

Figure 7: Scatter plot of NS-EW velocity residuals (w.r.t. stable North America) for NMSZ sites, with 95% confidence error bars.

presented above. Fig. 9 shows three possible realization of that definition: using all sites in stable North America (west of the Rockies and south of the current GIA hinge line), using all NMSZ sites, or using the best (lowest residual velocity) NMSZ sites. Results are similar in all three cases. The overall RMS decreases with observation time span and remains within one-sigma of zero. Note that the improvement in RMS is negligeable since about 2010.

Going forward, we plan to complete quality control on our 1560-station stable North America-wide velocity field from our recently finished, GIPSY Release 6.2 reprocessing exercise. We will then estimate and remove common-mode noise from the horizontal and vertical components of all the GPS site positions and derive a corrected continental velocity field suitable for our analysis. We are presently investigating whether principal component analysis or singular value decomposition can be used to decompose the new velocity field into its rotational and non-rotational components, the latter of which would presumably include the combined effects of post-glacial rebound, regional deformation, and noise.

We are currently finalizing a paper describing our latest results for the NMSZ (and WVSZ) which will establich the fact that no strain is currently resolvable in the region at the 0.2 mm/yr level. Previously published claims of significant relative site motions where biased by the post-processing "baseline" analysis. It may be time to accept the fact that the NMSZ is not currently building up resolvable strain, a result that does not necessarily imply that seismic hazard is low.

Publications and presentations

Oral presentation at the Seismological Society of America annual meeting, 2011, Memphis, TN.

Oral presentation at the New Madrid Geodesy Workshop, March 5th, 2011, Norwood, MA.

Oral presentation at the Advancing Geodesy in the U.S. Midcontinent Workshop, October 31 -

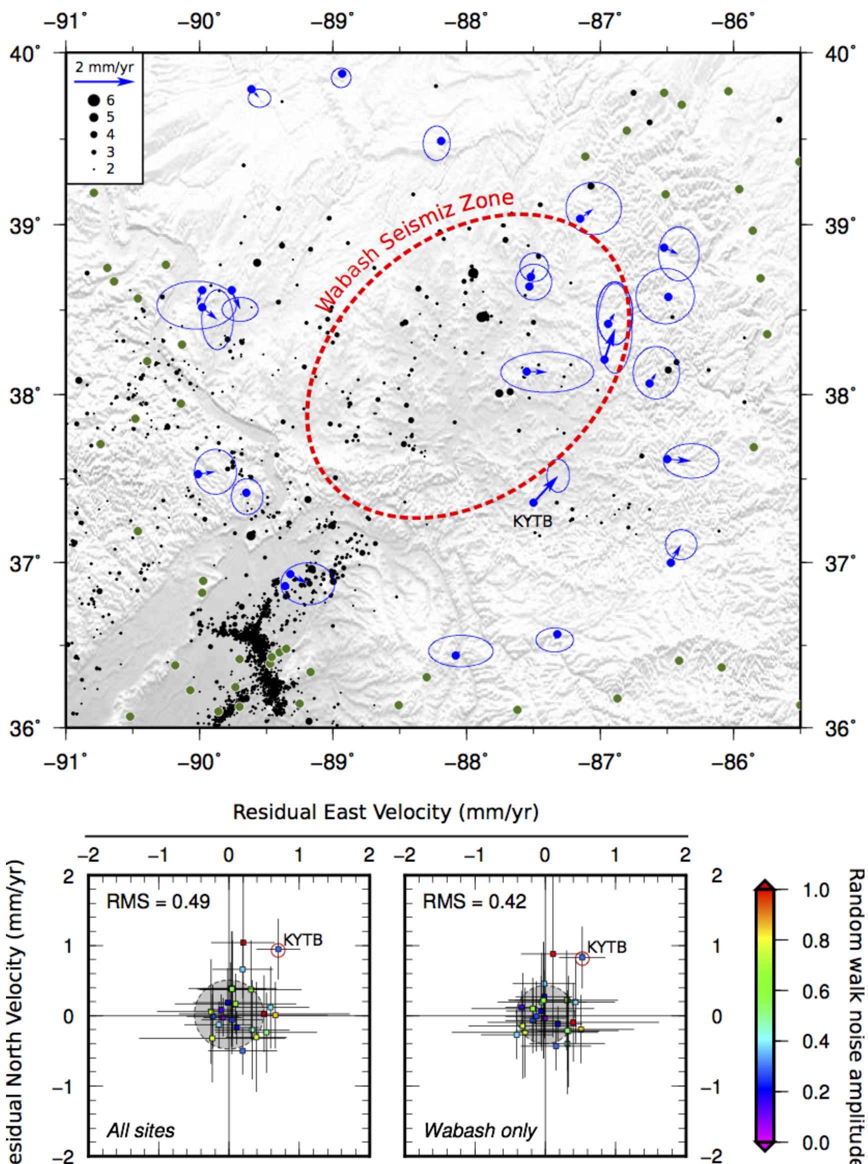

Figure 8: Scatter plot of NS-EW velocity residuals (w.r.t. stable North America) for continuous GPS sites in the Wabash Valley Seismic Zone.

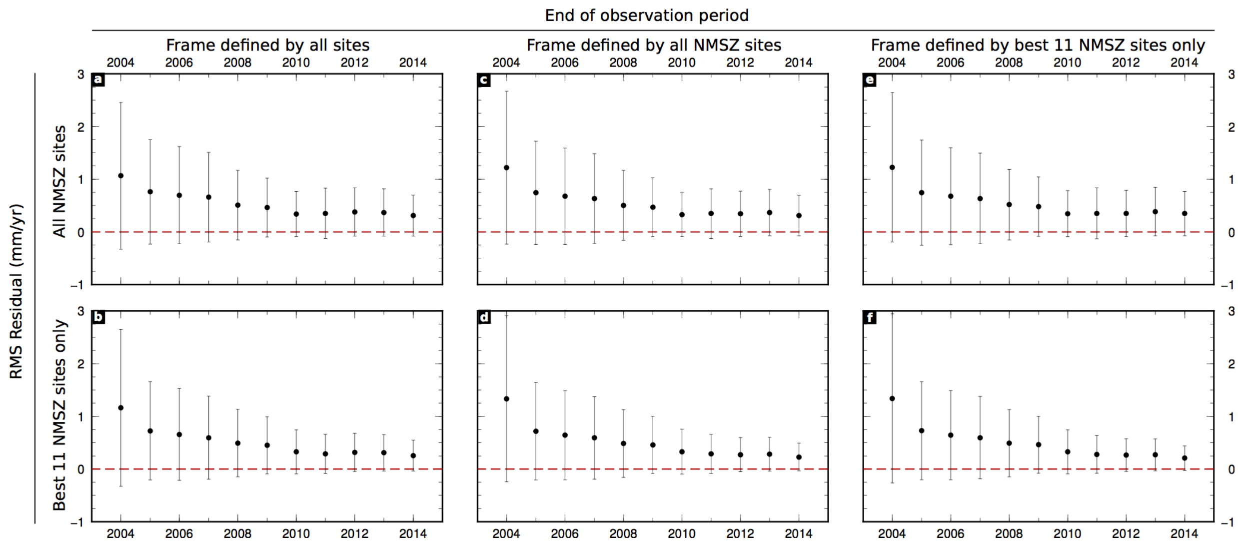

Figure 9: Overall RMS residual with respect to three different realizations of a Stable North America reference (columns) for the entire NMSZ cGPS data set (top row) or the best NMSZ cGPS subset (bottom row). Residual velocities converge towards zero over time and include zero within errors.

November 1, 2012, Evanston, IL).

Craig, T., and E. Calais, Current strain rates in the central U.S. from GPS geodesy, *J. Geophys. Res.*, in preparation.

Data Availability

All GPS data used for our analysis are freely available from the SOPAC, NGS CORS, and UNAVCO archives. Results from processing of the raw data at Purdue and UW-Madison will be made available once quality control is completed for the new velocity solutions