FINAL REPORT

August 17, 2007

Evaluation of monument stability and noise associated with campaign and continuous GPS geodesy in the New Madrid seismic zone and other areas of unconsolidated sediment

Grant award number: 02HQGR0107
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Element I

Key Words: GPS continuous, GPS campaign, monument noise

NON-TECHNICAL SUMMARY

Two new continuous GPS sites were established in the New Madrid Seismic Zone at Portageville, MO and Troy, TN. These sites employ a deep, drill-braced, pyramid-shaped structural design composed of carbon steel pipe, whose four legs and central column reach over 35 feet below the antenna mount. The new sites are co-located at existing GPS sites, which use a single, vertical I-beam structural element. Results from our analysis of archived continuous GPS data obtained between 1999 to 2007 from the NMSZ are consistent with very small residual motions (< 2 mm/yr) relative to a fixed North American plate. Comparison of the new monuments with the existing ones over the 2006 to 2007 period demonstrates that deep, drill-braced monuments more precisely record regional deformation and thus are better suited for any future GPS infrastructure development in the NMSZ or other regions of low strain in poorly consolidated sediments.

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SUMMARY

This project report is submitted in keeping with requirements as described in the award. This report is final and covers the nominal award period of two years with the start date of the project on July 1, 2002 through June 30, 2004 as well as the one-year no-cost extension period from June 30, 2004 until December 31, 2005. In addition, because the project was delayed for numerous personnel, technical, and logistical reasons discussed below, and thus GPS observations on the two new continuous sites installed with funding from this award did not begin until January 17, 2005 for one site and July 7, 2006 for the second site, we have also included in this report analysis up to August 2007.

Our last report was submitted on April 9, 2003, only nine months into the award period. At that time we had not yet obtained significant results, but only had purchased and received the necessary GPS geodetic equipment, contacted personnel about monument construction, forged collaboration with the Center for Earthquake Research and Information (CERI) at the University of Memphis, identified potential sites for installation, and pursued graduate student involvement.

Since April 9, 2003, we have completed nearly all of the tasks outlined in the original proposal. These include the complete installation of two new continuous GPS sites (deep, drilled-braced, SCIGN-type monuments) in the New Madrid seismic zone co-located with existing GAMA sites at Hill Crest Elementary School in Troy, TN and the Delta Research Center in Portageville, MO, analysis of all existing GAMA network GPS observations through early 2005 (see the this URL for details http://comp.uark.edu/~mattioli/research/nmsz/Intro.html) which resulted in a publication in the electronic version of *Nature*, submission of two proposals to the National Science Foundation for additional infrastructure development within the NMSZ, and finally, analysis and comparison of our experimental investigation of monument stability in NMSZ. While both NSF proposals were declined, significant new analysis and modeling was completed as part of the proposal generation process. It is likely, that those models and results obtained from our ongoing analysis of the new, co-located GPS sites will strengthen our chances to leverage additional funding from NSF and other sources.

Our most robust and significant conclusion to date, based on the results of our independent analysis of the existing GAMA data, is that residual motions in the NMSZ are small and currently within error at the 95% confidence limit (Calais, Mattioli et al.,

2005). This is in contrast to the conclusions of Smalley et al., 2005, who used the same data, but applied different GPS processing methods and a different error model. Smalley et al. (2005), argued that NMSZ surface deformation was ongoing and strains were comparable to those observed along active plate boundary faults, such as the San Andreas system in California.

Although the time accumulated to date on the new GPS sites is still rather short at one year, it is clear that the deep, drill-braced monuments are yielding time series that result in lower component site velocity errors when compared to data from the corresponding co-located vertical, I-beam monuments over the same time period. In addition, analysis of baseline evolution from the new deep, drill-braced sites, HCEX and PTGX (separated by 48.2 km and spanning much of the active seismicity in the NMSZ) versus the existing co-located sites of HCES and PTGV demonstrates that the SCIGN-type monuments are yielding residual motions that are more correlated, better fit by a linear model, and slightly greater and more precise (0.9±0.5 mm/yr for HCEX-PTGX vs. 0.5±0.7 mm/yr HCES-PTGV). We believe that these preliminary results indicate that the newer tetrapod monuments are responding better to the regional surface deformation rather than hydrological, climatalogical, or other more local effects. The results of our experimental investigation strongly support the need for additional deep, drill-braced monuments in the NMSZ to better constrain the slow deformation in this area of poorly consolidated sediments.

INVESTIGATIONS UNDERTAKEN

Overview and background: In the winter of 1811-12, three of the most powerful earthquakes in U.S. history struck the New Madrid region of the central United States (Johnston and Schweig, 1996). The zones of severe liquefaction and ground failure associated with these events are >10,000 km^2 (Obermeier, 1988). Because events similar to these have tremendous destructive power were they to occur today, much work has been done in recent years to assess recurrence intervals, strain accumulation, and fault displacements within the New Madrid seismic zone (NMSZ) (*e.g.* Russ et al., 1978; Russ, 1979; Kelson et al., 1992; 1996; Tuttle and Schweig, 1995; Liu et al., 1992; Weber et al., 1998; Newman et al., 1999). Paleoseismological field evidence is consistent with significant earthquakes occurring every 500 to 800 years (Tuttle et al., 1999). For example, an observation of fault-related folding yielded a slip rate of 5-6 mm/yr across the Reelfoot scarp that translates into a major earthquake (low magnitude 7) every 500 years (Mueller et al., 1999). Determination of displacement rates and recurrence intervals is critical to assessing seismic hazard. Frankel et al. (1996) calculated that the predicted peak ground acceleration expected in 50 years at 2% probability for the NMSZ exceeds that of San Francisco assuming a magnitude 8 event occurs every 1,000 years.

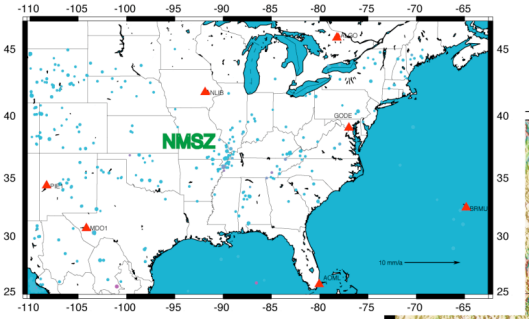
To assess surface strain accumulation in the NMSZ, two groups of investigators began Global Positioning System (GPS) geodetic studies in the region in the 1990's. Initially these groups reached remarkably different conclusions. One group argued for 5-7 mm/yr slip in the southern NMSZ and short recurrence intervals (Liu et al., 1992), whereas the other favored little or no motion within error and, thus, lower hazard with magnitude 7 and 8 events recurring approximately every 1,000 and 10,000 years, respectively (Weber et al., 1998; Newman et al., 1999). Snay et al. (1994) reported rates indistinguishable from zero for the northern NMSZ. Additional measurements of the Liu

et al. (1992) network resulted in revised velocity estimates, which yielded less displacement as they included longer GPS data time series (Kerkela et al., 1998; Zoback, 1999; Kenner and Segall, 2000). Nevertheless, the lower rate model is difficult to reconcile with interpretations of high earthquake recurrence intervals from paleoseismology. Recently, attention has been directed to models in which far-field stresses act on either a lower crustal detachment fault (Stuart et al., 1997) or zone of weakness (Kenner and Segall, 2000). Both models predict small average strain rates, on the order of $1x10^{-8}$ per year, that are difficult to detect with geodetic techniques despite the significant probability of another large-magnitude event in the next few to several hundred years. The real question is whether either model could be distinguished based on any geodetic dataset. To compound the problem, errors associated with monument instability, atmospheric variability, measurement accuracy, observation interval, and site distribution may overwhelm the tectonic signal. Furthermore, Langbein and Johnson (1997) demonstrated that although spatial averaging can reduce the size of both white and random-walk noise components, it does not mitigate their relative effects on the resulting strain accumulation model. Long-term correlations have a large effect on estimating deformation rates.

Importance of monument motion: All geodetic data, including GPS velocity estimates, contain both colored, or time-correlated, and white, or time independent, noise. Because several years may be required to obtain accurate site velocity estimates from GPS data time series in areas of small strain, a variety of errors with different timescales may corrupt the data. In addition, the nature of the error source may change with time. Time-correlated noise includes effects associated with potential monument motion, satellite orbit uncertainties, and atmospheric and local environmental variables (Langbein and Johnson, 1997; Zhang et al., 1997; Mao et al., 1999). Although frequent measurement and averaging can minimize white noise, these methods are less useful for time-correlated noise (Mao et al., 1999). Models that incorporate only white noise, however, underestimate the uncertainty (Johnson and Agnew, 1995; Mao et al., 1999). Regionally correlated noise can be reduced by implementation of a filtering algorithm that subtracts the common mode, nontectonic signals from the GPS time series (Zhang et al., 1997; Wdowinski et al., 1997). This method is most applicable to a relatively dense network of continuous sites.

Monument instability is an important noise source in geodetic studies (Wyatt, 1982, 1989) and is likely a substantial source of time-correlated noise in long-term GPS experiments, introducing spurious position shifts unrelated to tectonic signals (Johnson and Agnew, 1995; Langbein et al., 1995; Langbein and Johnson, 1997). Assumptions of monument behavior generally are not well constrained, particularly for different types of monuments in various geologic settings. Monument motion is likely significant in the NMSZ, which is dominated by unconsolidated sediments of the Lower Mississippi Valley. Detailed study of the error budget, however, has not been undertaken to date within the NMSZ.

Initial Objectives: We proposed to conduct a systematic analysis of monument stability and noise characteristics for selected sites in the NMSZ (Figure 1) to constrain errors associated with continuous and campaign sites. The purpose is twofold: one, to assess quantitatively noise related to monument motion in different geological substrates; and two, to evaluate the suitability of different monument types in low strain environments.



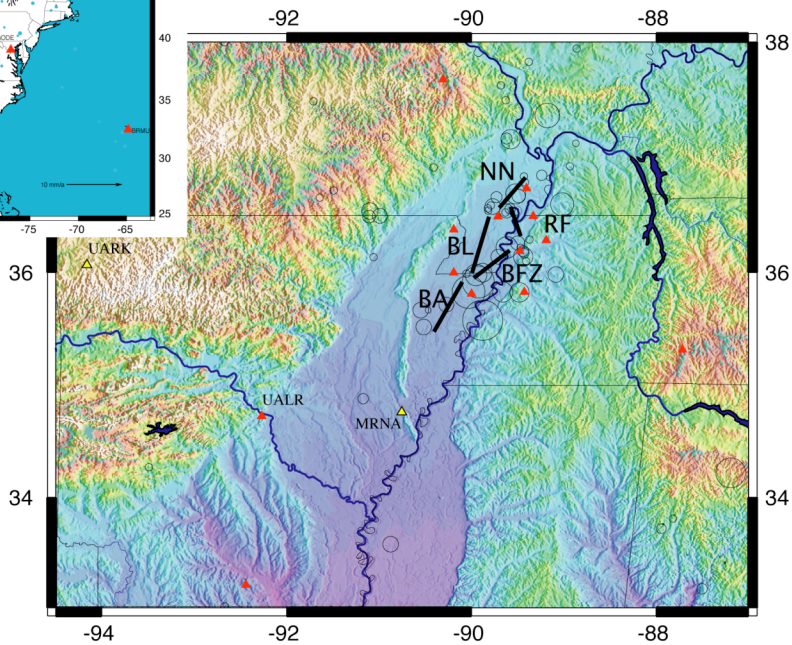


Figure 1: Above) Map showing seismicity. NMSZ is New Madrid seismic zone that extends from southern Illinois southwestward into Arkansas. Red triangles are IGS sites. Right) Map showing location of major structures. BA: Blytheville Arch. BFZ: Blytheville Fault Zone. BL: Bootheel Lineament. NN: North New Madrid Fault. RF: Reelfoot Fault. Red triangles are continuous GPS sites of CERI network. Yellow triangles are CGPS sites to be installed by UofA at some future time.

Two sets of two monuments equipped with continuous geodetic GPS receivers were to be established, for a total of four sites. To assess if monument instability in the NMSZ is typical for that in unconsolidated sediment, GPS data time series of the NMSZ were to be compared to those from non-bedrock sites in the Caribbean where we have maintained an extensive continuous and campaign GPS geodetic network since 1994. Our objectives were:

- to install two sets of two monuments each along a baseline <10 km long in the NMSZ to measure directly monument instability; this objective was completed in November 2004. Receivers and telemetry components were installed in early 2005, but continuous data flow could not be established until mid-2006.
- to determine if monument motion for existing pillars in the NMSZ is similar in magnitude to that of reference sites through analysis of colored noise and random walk motion; a preliminary analysis of 1 year of observations has recently been completed and its discussion is included below in the Results section.
- to assess potential errors associated with different spatial subsets of the total NMSZ network; this objective was completed as part of the kinematic analysis published in Calais et al., 2005.
- to compare results from measurements in the NMSZ with those from the Caribbean region for both bedrock and unconsolidated sediment sites to determine if the magnitude of errors are comparable in the two regions and
- to evaluate the contribution of seasonal effects and troposheric wet delay variability on noise estimates; time series at the two new sites, HCEX and PTGX, are still too short to complete this objective with any scientific or

statistical rigor. As more data accumulate, this objective will be completed and the analysis will be published in an appropriate technical journal.

In addition, several new campaign sites were to be established in the southwestern extreme of the NMSZ, extending the CERI network into southeastern Arkansas. Several new sites were established in eastern Arkansas in 2003 as part of Anita Marshall's MS thesis. These sites were reoccupied in 2004 and again in early 2005. Additional sites will be established in the near future as part of a collaborative effort with students at University of Arkansas Pine Bluff as funded by a pilot project from the NSF Opportunities for Enhancing Diversity in Geosciences program.

RESULTS

Installation of new continuous GPS monuments

To avoid duplication of efforts and to maximize resources, collaboration has been established with Bob Smalley of the Center for Earthquake Research and Information (CERI) at the University of Memphis. All logistical efforts were coordinated with CERI personnel from the outset of this award. After extensive discussions with Prof. Smalley, the UARK team determined that the two new sites would be co-located at the existing sites of PTGV at the Delta Research Center of the University of Missouri in Portageville,

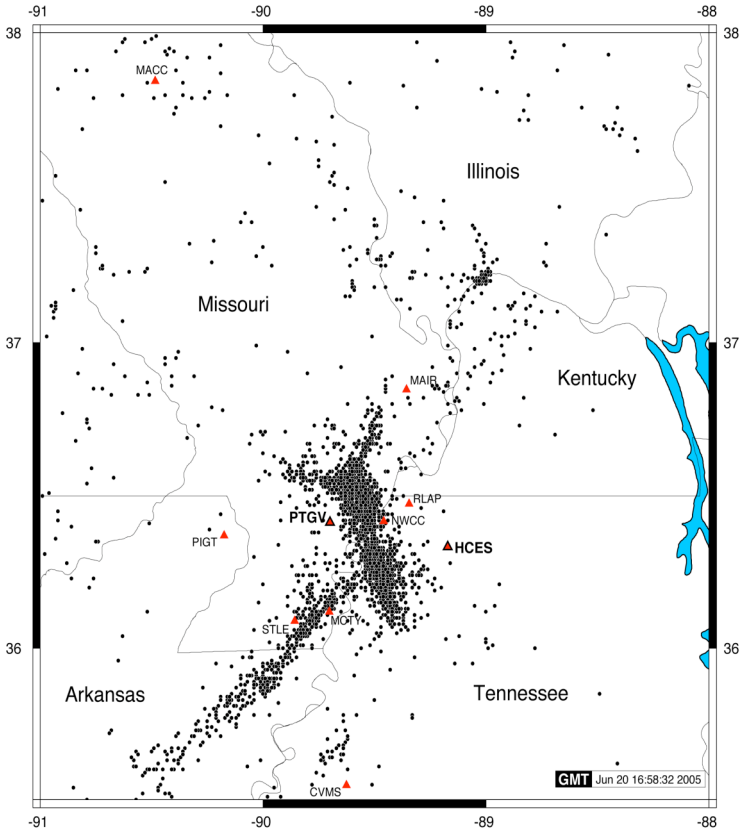


Figure 2. Regional map of GAMA cGPS sites along with recent seismicity recorded by the USGS. cGPS sites are shown as red triangles. The PTGV and HCES sites, at Portageville, MO and Troy, TN, respectively are highlighted with bold font. Two new sites, PTGX and HCEX, are co-located within 10 m of PTGV and HCES, respectively.

MO and HCES at the Hillcrest Elementary School in Troy, TN. The existing continuous GPS sites maintained by CERI, referred to as the GAMA network, are shown in Figure 2. The PTGV and HCES sites were selected for a number of reasons: 1) the baseline between the two sites spans most of the active seismicity in the NMSZ; 2) existing infrastructure at both sites would allow direct access and download of the new sites to be

completed using standard TCP/IP protocols over the public internet; 3) both sites were located in different mapped geological units, allowing one to assess to some degree the effect of "bedrock" geology on monument noise; and 4) ease of access for routine maintenance.

Once the sites were selected, a request for competitive bids to complete drilling, pressure grouting, and installation the new UNAVCO-type, deep, drilled-braced monuments (Figure 3) was requested from several regional drilling companies. Three bids were received and Tri-State Testing Services, Inc. of Memphis, TN was selected as the contractor for the new sites. The installation of both sites was completed over a five-day period in mid-November 2004. After grouting, the apex of each monument was arc-welded in situ and the SCIGN precision level, Ashtech dorn-margolin choke ring antenna and radome were installed. Procedures developed by UNAVCO for its installation of the EarthScope Plate Boundary Observatory sites were followed. Details may be found here: http://facility.unavco.org/project_support/permanent/monumentation/DrillerInstructionsDDBMGPSv3.1.pdf. A digital photo archive of the entire installation process may be found at http://comp.uark.edu/~mattioli/research/nmsz/nmsz_photos/index.htm.

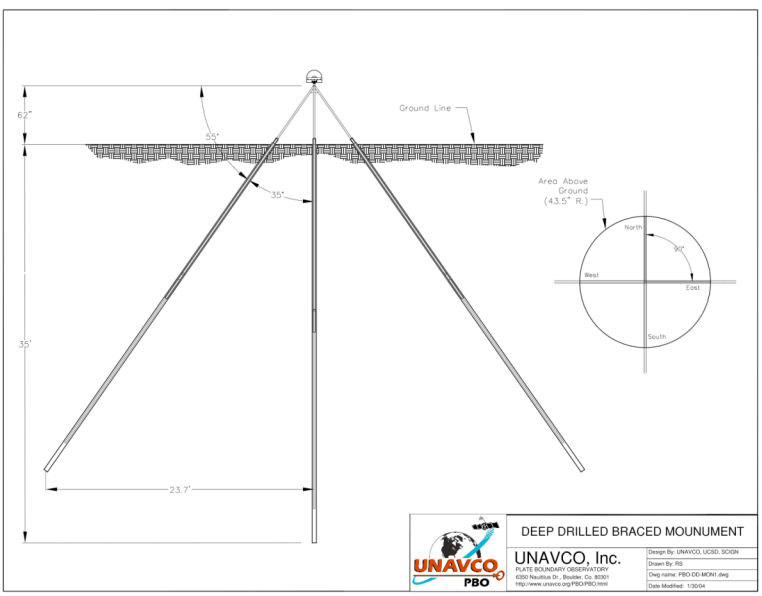


Figure 3. UNAVCO Facility schematic for deep, drilled-braced monument. Each monument is comprised of 5 legs made of 1.25" carbon steel pipe. The central leg of the pyramidal structure terminates at a depth of ~40 ft. below the apex of the pyramid. Both PTGX and HCEX sites conform to this design.

New sites were installed at PTGX and HCEX. Note that the upper 20 ft. of each leg has been isolated from the ground by an external PVC sleeve. All legs were pressure-grouted in situ. Both sites are located approximately 10 m away from the existing CERI monuments. In contrast to the new PTGX and HCEX monuments, the existing GAMA-network monuments at PTGV and HCES are comprised of two structural steel I-beams (20 ft. sections, bolted together) that together make a single vertical structural element that was pile-driven to approximately 40 ft. depth. The upper several meters of the monument was isolated from the ground by a large PVC conduit and the antenna was mounted on a vertical 2 m steel extension that was bolted onto the I-beam. Figure 4 is a photo from the HCES and HCEX sites located at the Hillcrest Elementary School in Troy, TN.

Figure 4. Co-located cGPS monuments at Hillcrest Elementary School in Troy, TN. The monument in the foreground is HCES, the original GAMA I-beam style monument installed in 2000. The monument in the background (to the right) is HCEX, the newly installed UNAVCO-style deep, drill-braced monument.

Sites at the Delta Research Center in Portageville (PTGV and PTGX) and at the Hillcrest Elementary School in Troy, TN share an electronics cabinet, which houses the GPS receivers, backup 12 V battery power, and data telemetry equipment.

At the time of the installation of the new monuments in late 2004, all sites were equipped with Ashtech micro-Z dual-frequency, code-phase geodetic receivers coupled with Ashtech choke-ring antenna. Several technical problems arose using these receivers with TCP/IP communications related to the RS232 serial to IP conversion devices (Lantronix UDS-10). These problems caused data interruptions for much of the last quarter of 2004 calendar year. As a result, no continuous data was acquired from either PTGX or HCEX. In early 2005, it was determined that all Ashtech micro-Z receivers would be replaced with new Trimble NetRS dual-frequency, code-phase geodetic receivers, which are IP compatible and also capable of multiple sync-rate session programming. The Ashtech GPS receivers were replaced with Trimble NetRS receivers by CERI personnel in April 2005. Unfortunately, the new Trimble NetRS units also seemed to experience several technical problems, including failure to record data and intermittent failure to allow external access by FTP or HTTP. It was determined by CERI in concert with UNAVCO personnel that the SmartCard internal memory modules

included in the initial manufacturing run of the Trimble NetRS units were temperature sensitive and could result in a fault when a critical temperature was exceeded. As a result, the units would temporarily fail. All UARK NetRS units (6 in total, but only two designated for this project) were returned to Trimble for repair in the fall of 2005. The repaired units, including the two originally installed at PTGX and HCEX were returned to UARK after several weeks. The repaired units were then re-installed by CERI personnel in June 2006 and have been functioning without incident since that time. Initially, UARK's units were only programmed to acquire raw GPS data at 30 s sync rate. Since May 2007, both PTGX and HCEX now also acquire data at 1 hz rates. All data are downloaded by personnel at CERI and are archived there and at UARK. After an initial data acquisition period in which the final statistical analysis and experimental comparison of the co-located sites is completed, all data from the new PTGX and HCEX sites will flow directly into the UNAVCO Facility data archive.

GIPSY-OASISII processing and analysis of long-term GAMA cGPS data

In 2004, data from the CERI GAMA cGPS network was made publicly available through the SOPAC and UNAVCO GPS data archives. As part of our scientific objectives, as outlined above, all existing GAMA data were downloaded and processed at UARK. The raw GPS observations were converted to RINEX using TEQC and processed using JPL's GIPSY-OASIS-II software (v. 4 for Linux), final precise orbits, clocks, and earth orientation parameters with a free-network, absolute point-positioning strategy. Ocean-loading coefficients for each site were obtained using the Scherneck model of the Onsala Space Observatory. Initial free-network solutions were transformed into ITRF2000 using JPL's xfiles and the secular motion of the North American plate was removed based on current realization of the DeMets et al. (2000) NAM-ITRF00 Euler pole. Common mode errors at each site were removed (up to Sep. 2004) using the NLIB cGPS site as a regional reference with a method modified after Wdowinski et al., 1997. The resulting residual position time series are then fit after outliers are removed using a linear least-squares inversion with formal estimates of white and flicker noise and an assumed random walk monument noise of 1 mm/sqrt(yr) as discussed by Mao et al. (1997). No offsets (*e.g.* for equipment changes) of any kind were included in the analysis. Final results are graphed and displayed using GMT. Each red dot represents a 24-hour point position estimate in the online figures. Formal errors for each position are not shown for clarity. All gaps in the time series are the result of data loss because of equipment and communication breakdowns in the GAMA network (Smalley, pers. comm.). The calculated time series through mid-2005 for seven long-running (most sites came on line in 2000, but a few have data from 1999) are published electronically at http://comp.uark.edu/~mattioli/research/nmsz/Intro.html. A summary of the kinematic results for these sites in ITRF00 and a NAM-fixed frame may be found in Table 1A in the appendix.

In June 2005, Smalley et al., published an analysis of the GAMA cGPS surface deformation field and concluded that there was indeed detectable strain in the NMSZ (http://www.nature.com/nature/journal/v435/n7045/abs/nature03642.html). They reported "Rates of strain are of the order of 10^{-7} per year, comparable in magnitude to those across active plate boundaries, and are consistent with known active faults within the region." Based on our analysis (discussed above) and independent analysis by Prof. Eric Calais at

Purdue University, we concluded that while there may be some motion (in this case shortening) across the RLAP-NWCC baseline, the estimated rate was smaller and the error for the baseline change was nearly twice as large as reported by Smalley et al., 2005. Our finding was published in Nature's electronic journal as a Brief Communication Arising (Calais et al., 2005, http://www.nature.com/nature/journal/v438/n7070/full/nature04428.html). In that report, Calais et al. stated "we find no statistically significant deformation in three independent analyses of the data set used by Smalley *et al*., and conclude therefore that only the upper bounds of magnitude and repeat time for large earthquakes can be inferred at present."

GAMA I-beam vs. Drill-braced monument comparison and noise analysis

We have recently completed an updated analysis of a subset of the GAMA data focusing on the PTGV and HCES sites. All processing procedures were as outlined above, but the new time series are now referenced to the newest realization of the International Terrestrial Reference Frame, ITRF05 (http://itrf.ensg.ign.fr/) and an appropriately updated Euler pole for NAM (C. DeMets, pers. comm.). The results for HCES are shown in Figure 5. This time series spans from mid-2000 until August 1, 2007 and yields a residual horizontal site rate of 2.2±1.5 mm/yr dominantly to the west. While small and measurable, at 95% confidence, however, this rate remains indistinguishable from zero. This result confirms that deformation in the NMSZ is likely to be quite small and less than 2 mm/yr (Calais et al., 2005). Also note that the CERI-type I-beam monument at HCES is extremely sensitive to non-linear motions, which are especially evident in the latitude component of the time series, although similar annual-scale signals are observed in the longitude and vertical components. The gray-shaded area in Fig. 5 is the period of continuous operation of the new co-located site HCEX. A direct comparison of the two sites over the same time span is shown in Figure 6. It is clear from Fig. 6 and the derived component velocities and their uncertainties, that the new UNAVCO-type deep, drill-braced monument at HCEX is yielding velocity estimates that are already more precise than those of HCES.

The results for PTGV are shown in Figure 7. This time series spans from mid-1999 until August 1, 2007 and yields a residual horizontal site rate of 0.6±0.8 mm/yr to the north. At 95% confidence this rate is indistinguishable from zero again confirming that deformation in the NMSZ is likely to me quite small and may be as low as 0.5 mm/yr. Again note that the CERI-type I-beam monument at PTGV is extremely sensitive to non-linear motions, which are especially evident in the latitude component of the time series, although similar annual-scale signals are observed in the longitude and vertical components. The gray-shaded area in Fig. 7 is the period of continuous operation of the new co-located site PTGX. A direct comparison of the two sites over the same time span is shown in Figure 8. It is clear from Fig. 8 and the derived component velocities and their uncertainties, that the new UNAVCO-type deep, drill-braced monument at PTGX is

Site name	Site ID	Lat (N)	Long (E)	HAE (m)	ITRF2005 (mm/yr)												
					Vn	Error	WN	FN	Ve	Error	WN	FN	Vv	Error	WN	FN	RWN
Portageville	PTGV	36.414	270.300	57.20	0.4	1.6	1.9	3.6	-14.0	1.5	2.9	2.8	0.6	2.3	5.7	7.0	2.0
Portageville	PTGX	36.414	270.300	57.20	0.7	1.5	1.8	2.8	-13.3	1.4	3.0	1.7	1.3	1.7	5.7	3.8	2.0
Hillcrest	HCES	36.333	270.828	77.11	-1.8	3.3	2.0	4.0	-14.3	3.2	3.7	3.8	13.0	4.4	6.9	5.7	2.0
Hillcrest	HCEX	36.333	270.828	77.29	2.6	2.6	2.1	2.6	-11.9	2.3	4.0	1.6	5.4	4.8	8.0	6.3	2.0

Table 1. Estimated site velocities in ITRF05 for co-located sites at PTGV and HCES

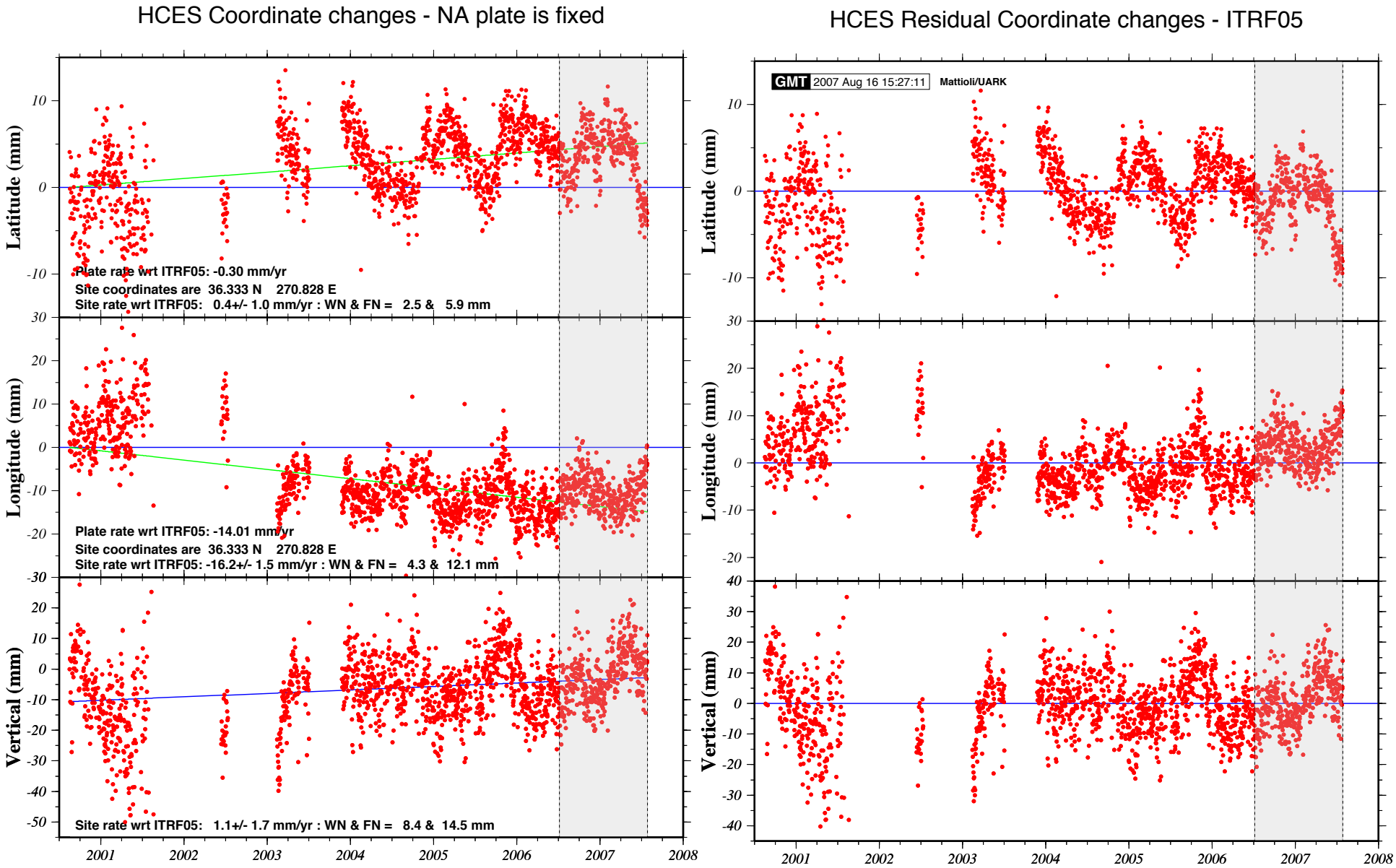


Figure 5. Daily absolute point position time series for the GAMA site HCES at Hillcrest Elementary School in Troy, TN. HCES monument is the standard GAMA-type, which is a 40 ft. vertical, steel I-beam, pile-driven into the poorly consolidated sediments of the Mississippi Embayment. Raw 30 s GPS observations were decimated and processed using GIPSY-OASISII (v.4) with final precise orbits, clocks, and earth orientation parameters as provided by NASA's Jet Propulsion Lab. Each red dot represents an average position for 24 hours of observation. Free network solutions were transformed, rotated, and scaled in the current realization of the global reference frame (ITRF05) using x-files from JPL. Formal component site errors are omitted for clarity but are used in the calculation of the component site velocities and their covariances shown in the figure labels. In the left plate, the site motion is relative to fixed North American plate (DeMets et al., 1991 and pers. comm.), with best-fit motion depicted as a green line. Note that site is moving north and west relative to NAM at less than 2 mm/yr. Vertical motion is referenced to the earth's barycenter. Right plate shows residual motion in ITRF05 after removing the secular motion of NAM. Note the strong annual signal, which is best observed in the latitude component. Gray areas refer to periods when both HCES and HCEX (new site, Fig. 6.) were online together.

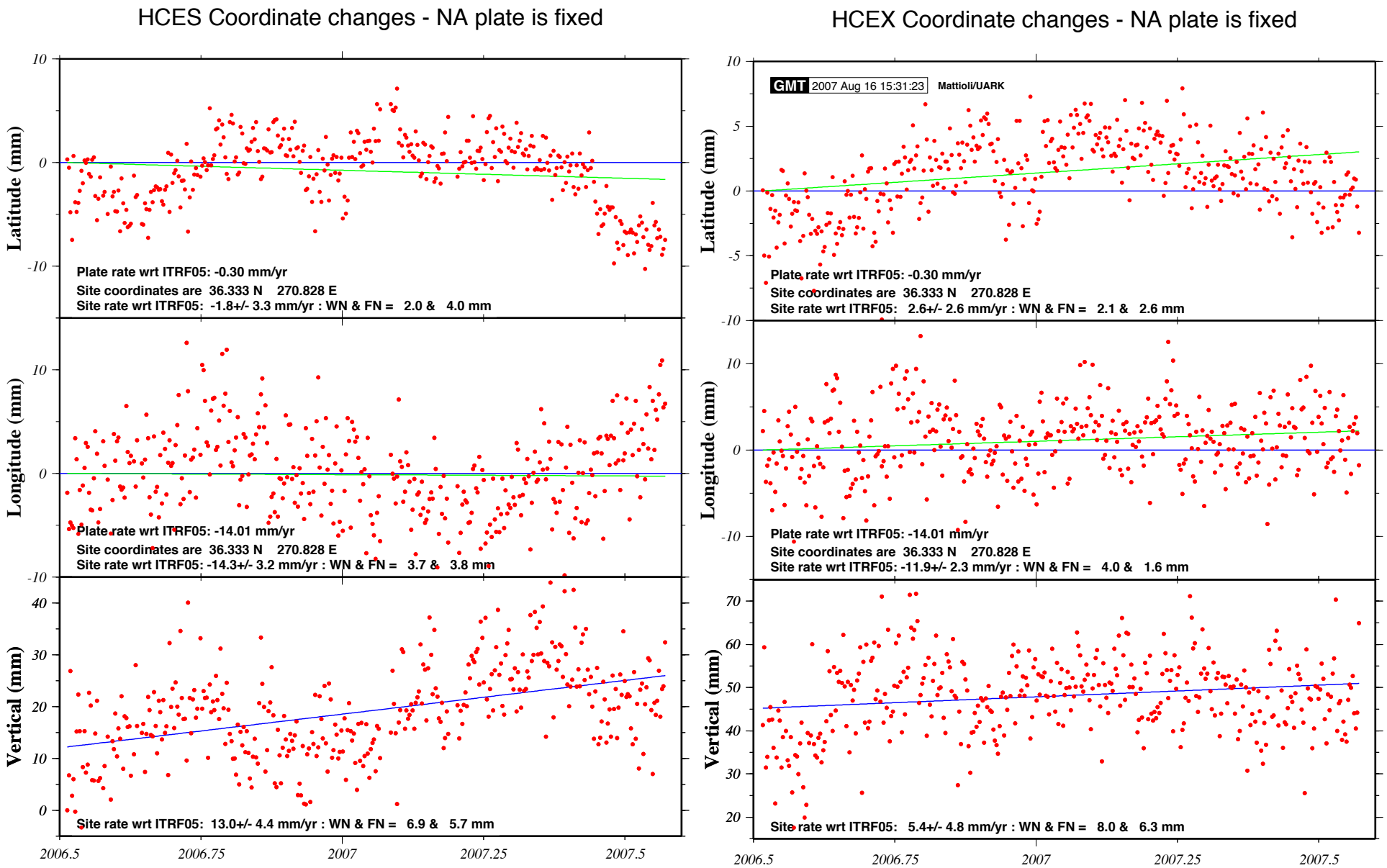


Figure 6. Daily absolute point position time series for the GAMA site HCES and the newly installed HCEX site (USGS NEHRP funding) at Hillcrest Elementary School in Troy, TN. HCES monument is the standard GAMA-type, which is a 40 ft. vertical, steel I-beam, pile-driven into the poorly consolidated sediments of the Mississippi Embayment. In contrast, the HCEX site is a deep, drilled-braced SCIGN-type, tetrapod monument. The central "leg" of the monument is 40 ft. long and all five legs of the structure were pressure grouted into place, prior to final welding at the apex. GPS processing procedures are as described in the caption for Fig. 5. The period of time shown here for HCES is depicted in gray in Fig. 5 and is limited to the period when HCES and HCEX were operating simultaneously. Note that calculated site motions for both monuments are small relative to NAM, but that the two monuments, which are separated by less than 10 m, are showing slightly different residual motions over this 1 year time span. Vertical motion is referenced to the earth's barycenter and the largest difference between the two sites is observed in this component. The strong annual signal, which is best observed in the latitude component of HCES and PTGV (see Fig. 5 & 7) is not nearly as strong in the HCEX time series. Also note that the latitude and longitude component's velocity uncertainties are smaller for HCEX.

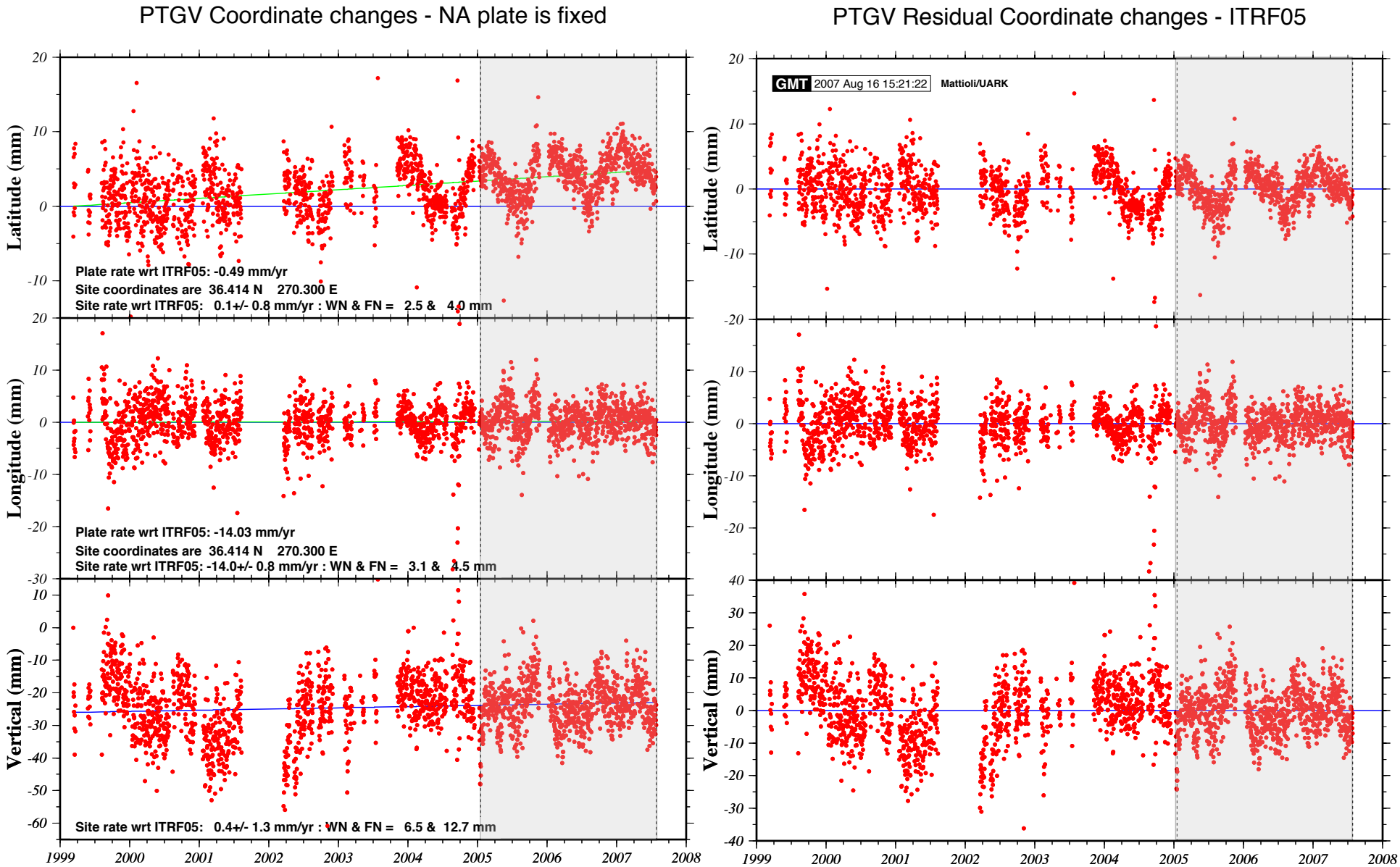


Figure 7. Daily absolute point position time series for the GAMA site PTGV at Delta Research Center (UM) in Portageville, MO. PTGV monument is the standard GAMA-type, a 40 ft. vertical, steel I-beam, pile-driven into the poorly consolidated sediments of the Mississippi Embayment. Raw 30 s GPS observations were decimated and processed using GIPSY-OASISII (v.4) with final precise orbits, clocks, and earth orientation parameters as provided by NASA's Jet Propulsion Lab. Each red dot represents an average position for 24 hours of observation. Free network solutions were transformed, rotated, and scaled in the current realization of the global reference frame (ITRF05) using x-files from JPL. Formal component site errors are omitted for clarity but are used in the calculation of the component site velocities and their covariances shown in the figure labels. In the left plate, the site motion is relative to fixed North American plate (DeMets et al., 1991 and pers. comm.), with best-fit motion depicted as a green line. Note that site is moving slightly north relative to NAM at less than 0.5 mm/yr. Vertical motion is referenced to the earth's barycenter. Right plate shows residual motion in ITRF05 after removing the secular motion of NAM. Note the strong annual signal, which is best observed in the latitude component. Gray areas refer to periods when both PTGV and PTGX (new site, Fig. 8.) were online together.

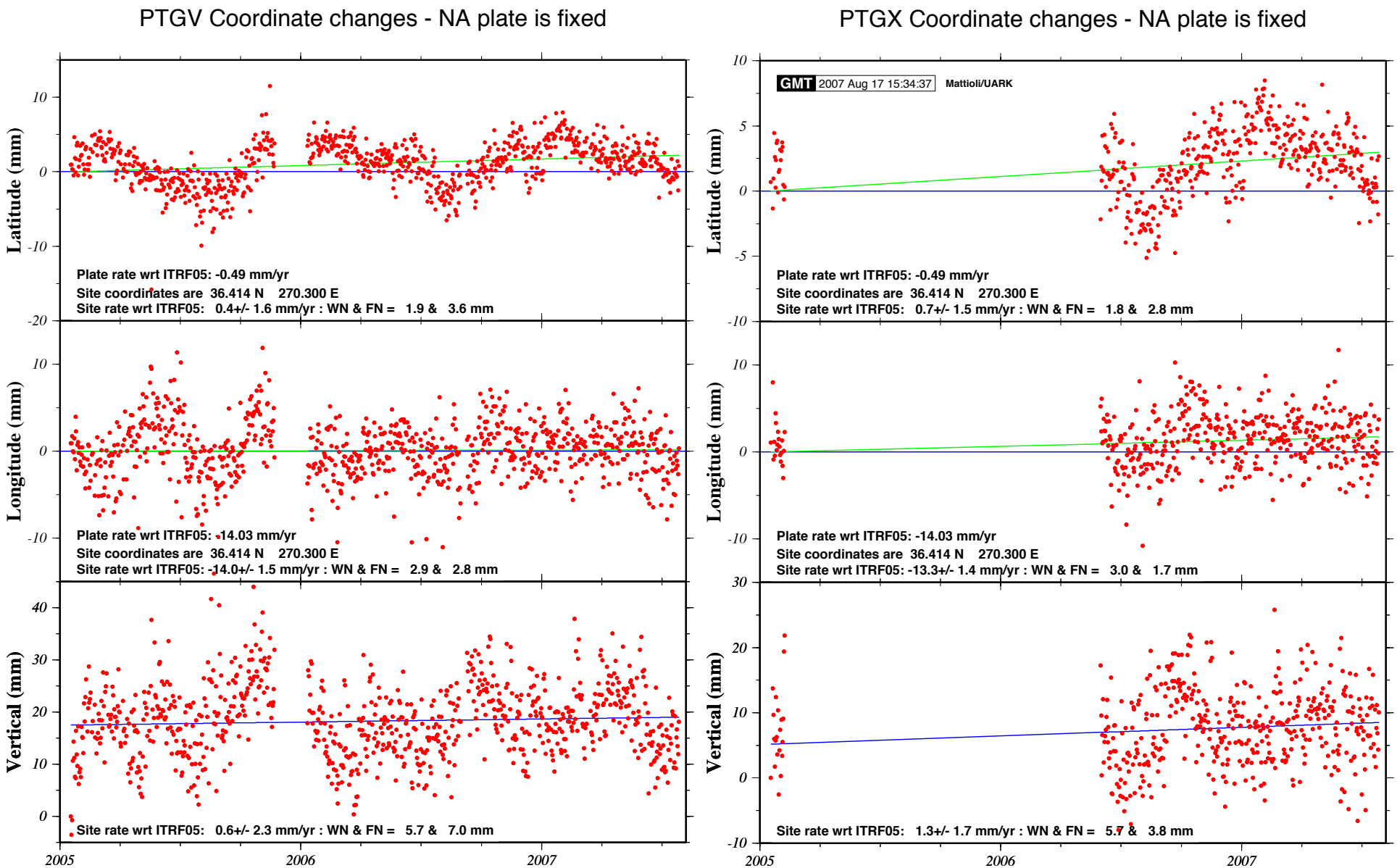


Figure 8. Daily absolute point position time series for the GAMA site PTGV and the newly installed PTGXsite (USGS NEHRP funding) at Delta Research Center, Portageville, MO. PTGVmonument is the standard GAMA-type, which is a 40 ft. vertical, steel I-beam, pile-driven into the poorly consolidated sediments of the Mississippi Embayment. In contrast, the PTGX site is a deep, drilled-braced SCIGN-type, tetrapod monument. The central "leg" of the monument is 40 ft. long and all five legs of the structure were pressure grouted into place, prior to final welding at the apex. GPS processing procedures are as described in the caption for Fig. 5. The period of time shown here for PTGV is depicted in gray in Fig. 7 and is limited to the period when PTGV and PTGX were operating simultaneously. Note that calculated site motions for both monuments are small relative to NAM, but that the two monuments, which are separated by less than 10 m, are showing similar residual motions over this 1 year time span. Vertical motion is referenced to the earth's barycenter and the largest difference between the two sites is observed in this component. The strong annual signal, which is best observed in the latitude component of HCES and PTGV (see Fig. 5 & 7) is not nearly as strong in the PTGX time series. Also note that all three component's velocity uncertainties are smaller for PTGX than PTGV.

yielding velocity estimates that are already more precise than those of PTGV.

A summary of the comparison of the two monument types at PTGV-PTGX and HCES-HCEX is shown in Table 1. This table includes site component velocity estimates, total one-sigma uncertainties, and the white and flicker noise components. The epoch for the PTGV-PTGX comparison is 17 January 2005 to 01 August 2007, while the epoch for the HCES-HCEX comparison is 07 July 2006 to 01 August 2007. Note that these site velocity estimates are only based on data when the two co-located sites were operating concurrently and that each site includes an estimate of 2.0 mm/sqrt(yr) of random walk noise in the component velocity uncertainty. No correction for common mode errors has been applied in this analysis. After subtracting the current estimate of NAM motion the residual sites are small and in both cases <2 mm/yr. The results are summarized in Table 2 below.

Site name	Type	Site ID	NAM rate (mm/yr)		NAM Fixed Velocity (mm/yr)					
			Vn	Ve	Vn	Error	Ve	Error	Vv	Error
Portageville	I-beam	PTGV	-0.49	-14.03	0.89	1.60	0.03	1.50	0.60	2.30
Portageville	UNAVCO	PTGX	-0.49	-14.03	1.19	1.50	0.73	1.40	1.30	1.70
Hillcrest	I-beam	HCES	-0.30	-14.01	-1.50	3.30	-0.29	3.20	13.00	4.40
Hillcrest	UNAVCO	HCEX	-0.30	-14.01	2.90	2.60	2.11	2.30	5.40	4.80

Table 2. Estimated NAM-fixed residual site velocities different monument types

In order to explore the temporal evolution of the different site pairs, PTGV-HCES and PTGX-HCEX, we have constructed baseline length change versus time plots. Position estimates in earth-centered, earth-fixed Cartesian coordinates were obtained from GOA-II as outlined above and all free-network positions were transformed, rotated, and scaled into ITRF05. The difference between the site estimates (absolute point positions) was used to calculate the baseline components as expressed as north, east, and up components. The largest change of any of these components is in the slant range or baseline length. The average baseline length was calculated over the entire epoch (same as for the site velocity estimates reported in Tables 1 and 2) for each site yielding 48215.399 m for HCEX-PTGX and 48216.431 m for HCES-PTGV and this was then subtracted from each of the daily baseline length estimates resulting in a residual baseline length change, which were fit assuming a linear model and an assumption of Gaussian (white noise) errors only. The correction for common mode errors has been applied. The results are shown below in Figure 9. The HCEX-PTGX baseline, which corresponds to the newly installed UNAVCO-type, deep, drill-braced monuments, yields a baseline change of 0.9±0.5 mm/yr for the 1 year time span that the two sites were operating concurrently. In contrast, the HCES-PTGV baseline, which corresponds to the GAMA I-beam monuments, yields a baseline change of 0.5±0.7 mm/yr over the same epoch. While both baselines agree within error, even after a short observation period of 1 year, the HCEX-PTGX baseline is more precise by nearly 30%. In addition, inspection of the plots reveals that the HCEX-PTGX baseline is well modeled by a linear fit, while the HCES-PTGV baseline retains significant non-linear motion. We believe this that is a direct result of the individual monuments at HCES and PTGV being more influenced by hydrological, climatological, or other local effects and moreover that these effects, while broadly correlated on an annual basis for the entire GAMA network remain out of phase yielding the sinusoidal (time-correlated) pattern observed in the residuals. The results of

our experimental investigation strongly support the need for additional deep, drill-braced monuments in the NMSZ to better constrain the slow deformation in this area of poorly consolidated sediments. Such monuments may be able to distinguish between models that seek to explain the small residual motions in the NMSZ as elastic strain accumulation, which could be released in future great earthquakes similar in magnitude to the 1811-1812 sequence (see for example Smalley et al., 2005) versus ongoing viscoelastic relaxation of the crust after the events of 1811-1812 (Rydelek and Pollitz, 1994) or other models (Kenner and Segall, 2000).

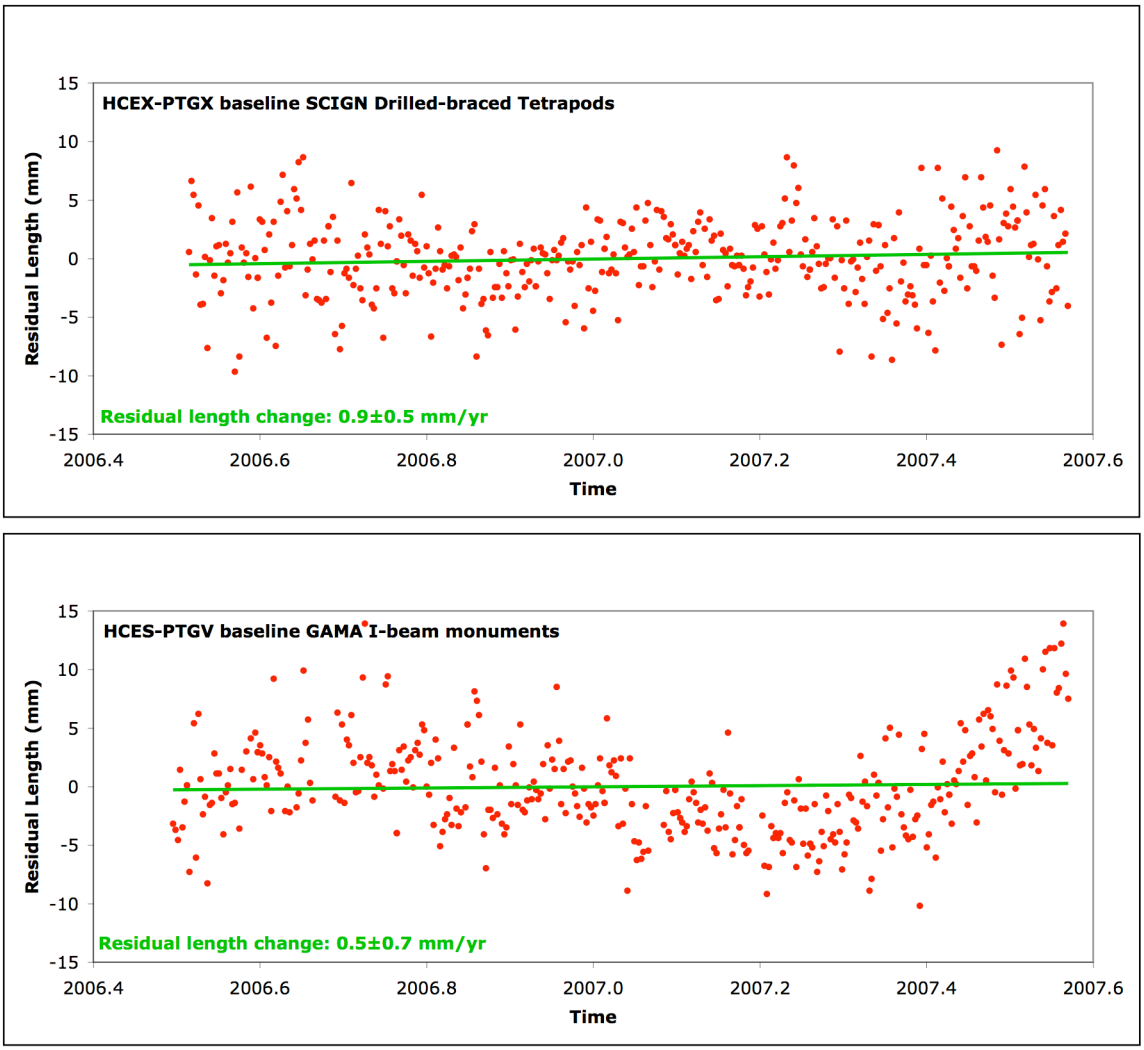


Figure 9. Baseline evolution plots for the two different monument types. In the upper plate, the baseline change between the newly installed UNAVCO-type deep, drill-braced monuments at HCEX and PTGX are compared. The average baseline is 48215.399 m. In the lower plate, a similar comparison is made for the GAMA I-beam-type monuments. The average baseline is 48216.431 m. Note how well modeled the HCEX-PTGX baseline is using a linear fit, the lower residual variance during the winter months of 2006-2007, and the well expressed time-correlated (sinusoidal pattern) noise in the HCES-PTGV baseline.

REPORTS PUBLISHED/SUBMITTED/IN PREPARATION

Calais, E., Mattioli, G.S., DeMets, C., Nocquet, J.M., Stein, S., Newman, A., and P. Rydelek, 2005, Tectonic strain in plate interiors? Comment on "Space geodetic evidence for rapid strain rates in the New Madrid seismic zone of the central USA by Smalley et al., 2005, *Nature,*"doi:10.1038/nature04428, *Nature* **438**, p. E9-10.

ABSTRACTS

Mattioli, G.S., Jansma, P.E., Davis, C.Y., Davis, J. and R. Smalley, 2005, Experimental Investigation of Monument Stability in the New Madrid Seismic Zone, 77th Eastern Section Meeting (Memphis, TN), Seismological Society of America.

Calais, E., Mattioli, G.S., C. DeMets, Nocquet, J.M., Stein, S., Newman, A., and P. Rydelek, 2005, An Upper Bound on Tectonic Strain in the Central U.S. from Continuous GPS Measurements, 77th Eastern Section Meeting (Memphis, TN), Seismological Society of America.

Mattioli, G.S., Jansma, P.E., Davis, J. and R. Smalley, 2007, Experimental Investigation of Monument Stability in the New Madrid Seismic Zone, EarthScope Annual Meeting, Monterey, CA.

GRANTS SUBMITTED RELATED TO THIS AWARD

NSF-EAR, Instrumentation and Facilities program, submitted 9/06, "Collaborative Research: A multidisciplinary continuous GPS array facility for the central U.S.," P.I., $54.5K (UARK) and $315K (total for all institutions) for 5 years, 2007-2011. Proposal was declined.

NSF-EAR Geophysics Program, submitted 12/05 "Collaborative Research: Deformation in "stable" North America: imaging the New Madrid seismic zone using continuous GPS geodesy," P.I. with one co-P.I., $258.5K (UARK) with total request from three institutions of $996.9K for 5 years. Proposal was declined.

DATA AVAILABILITY

All GPS data from the newly installed sites at HCEX and PTGX are archived at CERI. Data will be archived and made publicly available through the UNAVCO Facility in the near future.

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Site	Description	Coordinates		Site Rate wrt ITRF00												Plate Rate wrt NAP		Site Rate wrt NAP		Smalley et al., 2005	
						noise				noise				noise							
		lat	long	lat (mm/yr)	lat error (mm/yr)	WN (mm)	FN (mm)	long (mm/yr)	long error (mm/yr)	WN (mm)	FN (mm)	vertical (mm/yr)	vertical error (mm/yr)	WN (mm)	FN (mm)	lat (mm/yr)	long (mm/yr)	lat (mm/yr)	long (mm/yr)	lat (mm/yr)	long (mm/yr)
CVMS	Crestview Middle School P.S.	35.541 N	270.356 E	-1.600	0.900	2.300	4.700	-14.700	1.000	4.100	5.900	-1.600	2.400	7.600	15.000	-1.300	-14.790	-0.300	0.090	-0.350	0.400
CJTR	Camp JT Robinson P.S.	34.822 N	267.727 E	-2.300	0.500	1.600	2.300	-14.400	0.600	2.900	3.300	0.200	1.300	6.400	9.400	-2.270	-14.540	-0.030	0.140		
HCES	Hillcrest Elementary School P.S.	36.333 N	270.828 E	-0.100	0.700	2.200	3.300	-19.100	1.600	4.700	9.800	1.000	2.200	9.100	13.600	-1.120	-15.010	1.020	-4.090		
MACC	Mineral Area Community College	37.845 N	269.515 E	-1.300	0.500	1.600	2.600	-15.500	0.600	2.800	3.500	-0.100	1.400	5.600	10.600	-1.610	-15.390	0.310	-0.110		
STLE	U.S. Supply Handling Equipment P.S.	36.089 N	270.142 E	-0.900	0.600	1.600	2.800	-14.800	0.700	2.900	3.600	0.600	1.600	6.000	10.800	-1.380	-14.930	0.480	0.130	0.890	0.570
RLAP	Reelfoot Lake Airport P.S.	36.474 N	270.655 E	-1.900	0.500	1.500	2.900	-15.500	0.600	3.400	4.200	-1.100	1.100	6.500	10.800	-1.180	-15.040	-0.720	-0.460	-0.810	-1.130
PTGV	Delta Research Center P.S.	36.414 N	270.300 E	-1.100	0.600	1.600	3.300	-15.200	0.700	3.100	4.400	-0.200	1.300	5.900	10.600	-1.320	-15.020	0.220	-0.180	0.640	-0.070
PIGT-1	Water Treatment Plant P.S. (not corrected)	36.370 N	269.825 E	-5.900	2.600	3.800	17.400	-16.600	2.200	6.600	14.000	2.100	2.900	9.100	19.100	-1.490	-15.000	-4.410	-1.600		
PIGT-2	Water Treatment Plant (windowed)	36.370 N	269.825 E	-2.400	0.800	2.700	3.300	-13.500	2.000	6.100	10.100	1.000	4.200	8.100	22.100	-1.490	-15.000	-0.910	1.500	-0.180	0.720
NWCC	Northwest Correctional Facility	36.417 N	270.542 E	-1.300	0.600	1.700	1.800	-14.700	0.900	3.000	4.000	-0.800	2.500	5.900	13.600	-1.230	-15.030	-0.070	0.330	1.010	0.890
MCTY	Pemiscot County R-III P.S.	36.120 N	270.298 E	-1.400	0.700	1.700	3.400	-14.900	0.700	2.900	3.900	0.800	1.600	5.900	10.300	-1.320	-14.940	-0.080	0.040	0.280	0.440
BLMM	Bloomfield, MO	36.880 N	270.027 E	-2.200	0.600	2.200	3.200	-16.000	0.900	4.300	5.900	0.200	2.200	9.400	15.700	-1.420	-15.140	-0.780	-0.860		
MAIR	Mississippi County Airport P.S.	36.847 N	270.643 E	-1.000	0.600	1.600	2.800	-15.400	0.700	3.000	3.200	0.400	1.700	6.100	11.200	-1.190	-15.140	0.190	-0.260	0.540	0.270
		Averages		-1.800	0.785	2.008	4.138	-15.408	1.015	3.831	5.831	0.192	2.031	7.046	13.292	-1.409	-14.998	-0.391	-0.410	0.253	0.261
		Standard Deviation		1.388	0.558	0.654	4.042	1.346	0.552	1.279	3.370	0.984	0.851	1.418	3.825	0.294	0.195	1.322	1.309	0.643	0.632
								REFERENCE POINTS													
GODE		39.022 N	283.173 E	3.300	0.600	2.800	3.900	-14.500	0.900	5.500	6.500	0.100	1.600	9.400	12.300	3.470	-15.560	-0.170	1.060	0.790	-0.520
MD01		30.681 N	255.985 E	-6.600	0.500	1.800	4.100	-12.400	0.600	3.600	5.800	0.800	0.800	7.100	8.700	-6.550	-12.900	-0.050	0.500	0.420	0.530
NLIB		41.772 N	268.425 E	-2.400	0.600	2.200	3.000	-14.700	0.900	4.500	6.200	-2.100	1.600	8.000	12.800	-2.010	-16.360	-0.390	1.660	0.300	-0.520
PIE1		34.302 N	251.881 E	-9.600	0.500	1.600	2.300	-12.700	0.600	3.300	3.400	3.100	1.100	6.300	8.000	-7.980	-13.590	-1.620	0.890	0.540	-0.350

RLAP-NWCC	
convergence	1.1917
Error (1 sigma)	1.8627