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Horizontal Velocities in the Central and Eastern United States From GPS Surveys During the 1987-1996 Interval

Prepared by
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National Geodetic Survey
National Oceanic and Atmospheric Administration

Prepared for
U.S. Nuclear Regulatory Commission

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Horizontal Velocities in the Central and Eastern United States From GPS Surveys During the 1987-1996 Interval

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Horizontal Velocities in the Central and Eastern United States

PREVIOUS REPORTS

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ABSTRACT

The National Geodetic Survey and the Nuclear Regulatory Commission jointly organized GPS surveys in 1987, 1990, 1993, and 1996 to search for crustal deformation in the central and eastern United States (east of longitude 108°W). We have analyzed the data of these four surveys in combination with VLBI data observed during the 1979-1995 interval and GPS data for 22 additional surveys observed during the 1990-1996 interval. These latter GPS surveys served to establish accurately positioned geodetic marks in various states. Accordingly, we have computed horizontal velocities for 64 GPS sites and 12 VLBI sites relative to a reference frame for which the interior of the North American plate is considered fixed on average. None of our derived velocities exceeds 6 mm/yr in magnitude. Moreover, the derived velocity at each GPS site is statistically zero at the 95% confidence level except for the site BOLTON in central Ohio and the site BEARTOWN in southeastern Pennsylvania. However, as statistical theory would allow approximately 5% of the 64 GPS sites to fail our zero-velocity hypothesis, we are uncertain whether or not these estimated velocities for BOLTON and BEARTOWN reflect actual motion relative to the North American plate.

We also computed horizontal strain rates for the cells formed by a 1° by 1° grid spanning the central and eastern United States. Corresponding shearing rates are everywhere less than 60 nanoradians/yr in magnitude, and no shearing rate differs statistically from zero at the 95% confidence level except for a grid cell near BEARTOWN whose rate is 57 ± 26 nanoradians/yr. Also corresponding areal dilatation rates are everywhere less than 40 nanostrain/yr in magnitude, and no dilatation rate differs statistically from zero at the 95% confidence level.

Horizontal Velocities in the Central and Eastern United States

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1. Introduction:

The central and eastern United States (CEUS) lies well interior to the North American tectonic plate, and hence the Earth's crust within this region behaves essentially as a rigid body. However, the occurrence of earthquakes throughout the CEUS--including major events near New Madrid, Missouri, and Charleston, South Carolina--testifies to the fact that the crust must be deforming at some level within this region. To measure the rate of this inferred motion as a function of location, the National Geodetic Survey (NGS) and the Nuclear Regulatory Commission (NRC) jointly initiated an observational program in 1987 involving the then relatively new Global Positioning System (GPS). With several hours of GPS data, each component of the 3-dimensional (3-D) vector connecting two geodetic marks can currently be measured with cm-level accuracy even when the marks are located several hundred km apart.

As part of their observational program, NGS and NRC organized GPS surveys in 1987, 1990, 1993, and 1996 with each survey involving several tens of geodetic marks located mostly east of longitude 108°W. The set of geodetic marks that were occupied for at least two of these surveys is informally known as the Eastern Strain Network (ESN), and these marks essentially cover the area stretching from the eastern face of the Rocky Mountains to the Atlantic seaboard (Figure 1). We analyzed the data for these four ESN surveys in combination with GPS data for 22 additional geodetic surveys observed during the 1990-1996 interval and with very long baseline interferometry (VLBI) data observed by a mobile unit in 1987. Most of the 22 additional GPS surveys are associated with the High Accuracy Reference Network (HARN) program that NGS undertook in cooperation with state and local organizations to enhance the quality of the national spatial reference frame by establishing accurately positioned geodetic marks throughout the country.

Our analysis of the combined dataset generated estimates for the rate of line length change, dL/dt , for 326 baselines which collectively involve 64 geodetic sites. The standard error associated with estimated dL/dt rates equals 2.9 mm/yr when the two geodetic sites defining the corresponding baseline were occupied for all four ESN surveys. We then applied the DYNAPG software program (Snay et al., 1996) to estimate a 3-D velocity field consistent with these dL/dt rates and with velocity vectors that Ma and Ryan (1995) had derived for an international collection of geodetic sites from VLBI data spanning the 1979-1995 interval. Although DYNAPG provides 3-D velocities, only the horizontal components of these velocities are well resolved by the GPS data. Hence we will discuss only horizontal deformation in this report. Also using DYNAPG, we calculated horizontal strain rates associated with our derived velocity field. In particular, we have estimated strain rates for the cells formed by a 1° by 1° grid spanning the CEUS.

1. Introduction

Figure 1. Sites involved in two or more highly accurate GPS surveys during the 1987-1996 interval.

2. Data:

The initial ESN survey (Figure 2) was conducted primarily from 12 November to 10 December, 1987. This campaign was supplemented with observing sessions on five separate days in September-October, 1988. Strange (1991) discusses this survey for which the field crew occupied each participating site with a TI-4100 receiver for three ~5.5-hr sessions with a few exceptions.

During the period from 9 March to 21 May, 1990, the second of the four ESN surveys was conducted (Figure 3). Strange (1996) discusses this second survey for which the field crew occupied each participating site with a Trimble 4000SST receiver for three ~5.5-hr sessions with a few exceptions.

The third ESN survey was conducted from 7 October to 10 October, 1993 (Figure 4). Unlike the first two ESN surveys, the third survey was rather limited in its spatial extent as this survey primarily involved marks located only in the north central section of the United States. Because this survey occurred during the midst of the HARN observational period, NGS and NRC assumed that the remainder of the ESN marks would be occupied for one or more HARN surveys within a few years of 1993. Indeed the third ESN survey was treated somewhat like a HARN survey whereby the field crew occupied several geodetic sites in addition to the participating ESN marks. For this third ESN survey, the field crew occupied each participating ESN site with a Trimble 4000SST receiver for four ~5.5-hr sessions with a few exceptions. The crew used a combination of Trimble 4000SST, Trimble 4000SSE, and Ashtech MD-XII receivers at the non-ESN sites.

The HARN surveys involved highly accurate GPS observations to position geodetic marks throughout the country with distances between adjacent marks ranging from 25 to 100 km. For organizational reasons, each HARN survey spanned a specific state or group of states (Figure 5). The HARN observational strategy involved occupying several existing marks, whose adopted positions were considered highly accurate, for three ~5.5-hr sessions so that these positions could be applied to obtain accurate positions for other marks in the HARN survey. Consequently, each HARN survey usually incorporated all ESN marks located in the vicinity of the state(s) associated with that survey.

Due to budgetary limitations, a preliminary plan for the fourth ESN survey called for only 24 geodetic marks to be occupied. Several organizations, however, recognized that this observational campaign presented an excellent opportunity to bolster the accuracy and density of the national spatial reference frame. Accordingly, these organizations mustered their resources to assist NGS with the field work so that over 100 marks were occupied during the period from 30 April to 23 May, 1996 (Figure 6). Participating ESN sites were occupied for three ~5.5-hr sessions except in a few cases. This enthusiastic response, however, created somewhat of a problem in that the GPS hardware that was deployed for this survey generally differed in type from one organization to another. We consequently had to apply newly developed empirical models for antenna phase center variation (Mader and MacKay, 1996) to process the associated GPS observations in a rigorous manner.

2. Data

Figure 2. Baselines observed during the 1987 ESN survey.

Figure 3. Baselines observed during the 1990 ESN survey.

2. Data

Figure 4. Baselines observed during the 1993 ESN survey.

Figure 5. HARN surveys included in this study and identified by year of observation.

In the summer of 1987, a mobile VLBI antenna was deployed to five ESN sites (AUSTIN, BLOOMINGTON, CARROLLTON, LEONARD, and PLATTEVILLE). Also each of three ESN sites (HARVARD RM 4, MARYLAND PT RM 5, and TIMER) is located within several tens of meters of a fixed VLBI antenna. We used positions that were estimated from the VLBI data (Boucher et al., 1993) and, when necessary, we applied the measured offset between an ESN site and its corresponding fixed VLBI antenna (Bryant and Noll, 1993) to estimate chord lengths for several baselines formed by selected pairs of these eight ESN sites as would have been measured on 1 January 1988. We subsequently combined these VLBI-derived chord lengths with GPS-derived chord lengths to compute dL/dt rates for several baselines as described in the following section.

3. Velocity Estimation Process:

We derived velocity vectors from the GPS and VLBI data using a four-step process. In the first step we converted GPS observables (measurements of the L1 and L2 carrier phases) into 3-D intermark vectors. Each such vector represents the difference in the 3-D positional coordinates for a pair of geodetic marks at a specific time, usually the midpoint of the time interval spanned during the corresponding observing session. We processed all data for each observing session simultaneously and separately from the data for other observing sessions. We used the OMNI software program (Hilla and Schenewerk, 1992) for processing all sessions except those of the 1996 ESN survey whose data we processed with the PAGE4 software program (Mader et al., 1995). Both OMNI and PAGE4 estimate relative 3-D positions among all occupied marks from doubly differenced phase measurements via a least squares process. We saved the results in bluebook format (NOAA, 1994) wherein the derived positional differences for an observing session involving N geodetic marks is represented by a set of N-1 intermark vectors with their associated standard errors and correlations.

This first step is essentially the same as the process described in detail by Strange (1991) to convert GPS observables to intermark vectors. One difference, however, applies for the more recent surveys, including the 1993 and 1996 ESN surveys. Namely for the recent surveys, we had access to satellite ephemerides that are significantly more accurate than those available for the older surveys. Accordingly, for the more recent surveys, we did not need to solve for corrections to the existing ephemerides within OMNI (or PAGE4) as we needed to do for earlier surveys. Moreover, because of the better ephemerides that are available for the more recent surveys, we obtained more accurate intermark vectors for these surveys than what we had obtained for earlier surveys (Table 1).

For the second step, we applied the ADJUST software program (Milbert and Kass, 1987) to estimate, for each GPS survey, a set of positional coordinates for all the geodetic marks that were occupied during that survey. These coordinates were estimated via a least squares process using all intermark vectors from the observing sessions associated with the survey. We associate these coordinates with the location of the marks at the midpoint time of the survey, as we assume that any motion occurring during the time span of the survey (usually less than three months) is

3. Velocity Estimation Process

Table 1. Estimates for the standard error with which the length of individual baselines were determined.

Sample	Degrees of freedom	Standard error, mm
The set of all lengths used to calculate dL/dt rates	343	18.2 ± 0.7
As above with $L < 300$ km	105	15.8 ± 1.1
As above with $300 < L < 500$ km	115	17.5 ± 1.2
As above with $L > 500$ km	123	20.7 ± 1.4
As above with L measured in 1987 ESN	52	22.2 ± 2.2
As above with L measured in 1990 ESN	110	22.2 ± 1.5
As above with L measured in 1992 HARN or 1993 ESN	44	15.1 ± 1.5
As above with L measured in 1996 ESN	44	13.7 ± 1.4

negligible. In obtaining these positions, we needed to constrain the 3-D position of one mark to some prior value because intermark vectors provide only differential positional information. We subsequently derived our velocity vectors, however, in a manner that these vectors do not depend on the values to which the positions were constrained.

For the third step, we applied a new software program, called DLDT, to estimate dL/dt rates for selected baselines from the collection of positions previously derived for the various surveys. Given the two geodetic marks defining a baseline, DLDT first determines the chord length L of that baseline for each survey in which both marks were occupied according to the well known formula

$$L = [(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2]^{0.5} \quad (1)$$

Here (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) denote the cartesian coordinates that we estimated for the two marks in step 2 for a specified survey.

Having estimated the chord length L_i for the given baseline at time t_i with $i = 1, 2, \dots, m$; DLDT then uses this time series of lengths to estimate the corresponding dL/dt rate for that baseline via

4. Baseline Results

a least squares process. We estimated such dL/dt rates for all baselines that were involved in at least two surveys and whose lengths are shorter than 700 km. We also estimated such dL/dt rates for a few extra baselines of special interest. In total, we estimated dL/dt rates for 326 baselines (Figure 7). We discuss these estimated rates in greater detail in the next section.

For the fourth step, we applied the DYNAPG software program (Snay et al., 1996) to estimate a 3-D velocity field that is consistent with the dL/dt rates derived in step 3 and with velocity vectors that Ma and Ryan (1995) had derived for an international collection of geodetic sites from VLBI data spanning the 1979-1995 interval. We postpone our discussion of this step until after we have discussed the dL/dt rates and the VLBI velocities.

Actually we could have omitted steps 2 and 3 and entered the derived intermark vectors directly into DYNAPG to estimate velocity vectors. We elected to take our more indirect route because the intermark vectors of any given survey might be oriented and scaled differently from those of any other survey. By using our approach, we circumvent any problem with orientation differences among the various surveys. Thus we need be concerned only with the problem of possible scale differences among the various surveys. As we shall see later, our results indicate that such scale differences are yet too small to be detected with the currently available data. Another advantage of our approach is that the generated time series of chord lengths provide a useful tool for identifying suspect observations.

4. Baseline Results:

We calculated how well each time series of baseline lengths fits a linear trend so as to estimate the standard error with which the length of individual baselines were determined during the surveys. In particular, if L_i denotes the "observed" baseline length at time t_i and if l_i denotes the predicted baseline length for time t_i as obtained by fitting the time series $L_1, L_2, \dots, L_m$ to a linear function of time, then the statistic

$$s = [\sum_{i=1,m} (L_i - l_i)^2 / (m-2)]^{0.5} \quad (2)$$

estimates the standard error σ with which each L_i was measured provided $m \geq 3$ and provided σ remains the same for all surveys. Accordingly, if a baseline were involved in only four surveys, as is often the case for this study, then the 95% confidence interval for s ranges from 0.16σ to 1.92σ . Because this confidence interval is so wide, we elected to estimate the standard error more robustly by assuming that all baselines were measured with the same level of accuracy regardless of baseline length and regardless of when individual baselines were measured. That is, we computed the pooled estimate

$$s^* = [(\sum_j (m_j-2)s_j^2) / \sum_j (m_j-2)]^{0.5} \quad (3)$$

where the index j ranges over all 326 baselines for which a time series was obtained in step 3.

Figure 7. Baselines for which dL/dt rates were computed.

This computation yielded $s^* = 18.2$ mm as the standard error with which each individual chord length was measured during individual surveys. In actuality we found that this standard error does depend on baseline length and on the time of survey. As might be expected, longer baselines were measured with slightly higher standard errors than shorter baselines. Also lengths were measured with lower standard errors during the more current surveys than they were during the older surveys (Table 1). For simplicity, however, we have neglected the effects of these dependencies in the results presented throughout this report. That is, we assume that each baseline length was measured with a standard error of 18.2 mm for each survey. Accordingly for a baseline whose length was measured in each of the four ESN surveys, the corresponding dL/dt rate has a standard error of 2.9 mm/yr.

Table 2 displays some statistics that we computed for the baselines involving the sites BEARTOWN and/or BOLTON. We chose to discuss the baselines for these two sites because, according to the results of step 4, each has a horizontal velocity relative to the North American plate which differs statistically from zero at the 95% confidence level. That is, these baselines represent a worst case scenario of sorts.

Both BEARTOWN and BOLTON were occupied for the ESN surveys of 1987, 1990, and 1996. Also both were occupied for a 1992 HARN survey that involved several states in the northeastern United States. As shown in Table 2, the 610-km long baseline connecting BEARTOWN and BOLTON is expanding at a rate of 8.7 ± 2.9 mm/yr. (In this report, uncertainties represent one standard error unless specified otherwise.) Although this geodetically derived rate differs statistically from zero at the 95% confidence level, we think that it is too large for a baseline in the eastern United States. Nevertheless, the time series of lengths for this baseline fits a linear trend much better than the time series for most other baselines as can be judged by comparing the estimated standard error, $s = 9$ mm, for the BEARTOWN-BOLTON baseline against the overall standard error, $s^* = 18.2$ mm. (See the last column of Table 2.) Note that even if the true dL/dt rates for all network baselines were exactly zero in value, then the estimated dL/dt rates for 5% of these baselines would differ statistically from zero at the 95% confidence level. We surmise that such may be the case for the BEARTOWN-BOLTON baseline.

Table 2 also lists the estimated strain rate $(dL/dt)/L$ for each baseline. Because of its great length, the strain rate for the BEARTOWN-BOLTON baseline is only 14 ± 5 nanostrain/yr (nstr/yr). In comparison, strain rates for most other baselines emanating from BEARTOWN exceed this value partly because most of these other baselines are shorter in length. In this sense the motion of BEARTOWN is more inconsistent with that of its closer neighbors than it is with the motion of BOLTON. This result illustrates the value of using strain rates to quantify relative deformation. To carry this reasoning further, note that strain rates for most of the baselines emanating from BOLTON are less than the strain rate for the BEARTOWN-BOLTON baseline. Thus the motion of BOLTON is more consistent with that of its closer neighbors than it is with the motion of BEARTOWN. Later in this report we shall use strain rates more extensively to assess relative deformation.

4. Baseline Results

Table 2. Statistics for selected baselines.

Baseline	Length km	Time Span	Count	dL/dt mm/yr	$(dL/dt)/L$ nstr/yr	s mm
BEARTOWN 2						
ALBURG RESET	580	1987-1996	4	-4.1 ± 2.9	-7 ± 5	37
ARP 2 ART	434	1987-1996	4	0.4 ± 2.9	1 ± 7	7
ASHCOPORT	437	1987-1996	4	7.8 ± 2.9	18 ± 7	10
ASTRO WEST PIER	239	1987-1996	4	2.6 ± 2.9	11 ± 12	25
BOLTON CBL 0	610	1987-1996	4	8.7 ± 2.9	14 ± 5	9
DAN	253	1990-1992	3	-5.4 ± 11.1	-21 ± 44	3
GPS S 6	140	1990-1996	3	-4.4 ± 3.8	-31 ± 27	14
MARYLAND PT RM 5	216	1987-1996	4	2.4 ± 2.9	11 ± 13	12
MEDINA	398	1992-1996	2	-1.3 ± 6.7	-3 ± 17	NA
NELSON	234	1990-1996	3	-4.6 ± 3.8	-20 ± 16	29
NORTH GEOS PIER	137	1990-1991	2	30.5 ± 35.4	222 ± 258	NA
PRINCETON 1	120	1987-1996	4	-4.5 ± 2.9	-38 ± 24	10
TANEY	110	1990-1996	4	3.2 ± 3.8	29 ± 35	17
FUTRELL RM 2	416	1987-1996	3	0.9 ± 2.9	2 ± 7	17
GREEN BANK T007	376	1987-1996	3	6.3 ± 2.9	17 ± 8	16
STATESVILLE CBL	646	1987-1996	3	2.7 ± 2.9	4 ± 5	11
BOLTON CBL 0						
ASHCOPORT	294	1987-1996	5	2.0 ± 2.5	7 ± 8	10
ASTRO WEST PIER	534	1987-1996	5	5.1 ± 2.8	10 ± 5	11
BEARTOWN 2	610	1987-1996	4	8.7 ± 2.9	14 ± 5	9
DAN	366	1990-1995	3	4.2 ± 4.8	12 ± 13	13
GPS 37	511	1987-1996	3	-1.3 ± 2.9	-3 ± 6	21
GPS S 6	676	1990-1996	2	3.2 ± 4.2	5 ± 6	NA
MARYLAND PT RM 5	538	1987-1996	3	5.2 ± 2.9	10 ± 5	3
MEDINA	543	1992-1996	2	1.3 ± 6.7	2 ± 12	NA
NELSON	692	1990-1996	2	1.7 ± 4.2	2 ± 6	NA
ROCK	644	1987-1996	4	-4.4 ± 2.8	-7 ± 4	27
TANEY	512	1990-1996	3	6.2 ± 4.2	12 ± 8	14
BLOOMINGTON NCMN	298	1987-1996	4	-1.7 ± 2.8	-6 ± 9	9
FREELAND	410	1987-1996	4	-0.3 ± 2.8	-1 ± 7	31
FUTRELL RM 2	650	1987-1996	3	1.3 ± 2.9	2 ± 4	14
GREEN BANK T007	329	1987-1996	4	2.5 ± 2.5	8 ± 8	7
HAGOOD RESET	686	1987-1996	3	-2.0 ± 2.9	-3 ± 4	13
STANPORT	234	1990-1996	3	-1.3 ± 3.9	-6 ± 16	3
STATESVILLE CBL	497	1987-1996	3	1.5 ± 2.9	3 ± 6	35
WILLIAMSON	561	1987-1996	3	-5.5 ± 2.9	-10 ± 5	9
Y 505	372	1995-1996	2	37.8 ± 31.4	101 ± 84	NA

5. VLBI Velocities:

Using VLBI data spanning the 1979-1995 interval, Ma and Ryan (1995) derived 3-D velocity vectors for a collection of 93 international sites. Twelve of these sites reside either in or near the CEUS (Figure 8). For their solution, known as GLB1014, Ma and Ryan (1995) constrained the velocity of five of these 93 sites so that their derived velocity field would be compatible with the no-net rotation (NNR) NUVEL-1A model for absolute plate motion (DeMets et al., 1994). Consequently in their velocity reference frame, the interior of the North American plate, which includes the CEUS, rotates (more or less as a rigid body) about an axis that passes through the Earth's center. Upon removing this rotation, one obtains horizontal velocities relative to a fixed North American plate as is presented in Figure 8.

Figure 8. Horizontal velocities with 95% confidence ellipses as derived by Ma and Ryan (1995) from VLBI data spanning the 1979-1995 interval. Numbers denote speeds in mm/yr.

6. Derived Velocities

It is important to note that the North American VLBI sites known as WESTFORD and RICHMOND are two of the five sites whose velocities Ma and Ryan (1995) had constrained to enforce compatibility with NNR NUVEL-1A. Hence by constraint, the velocity at each of these two sites approximates zero rather closely when it is expressed relative to the North American plate. Consequently, the accuracy of the velocities displayed in Figure 8 depends in part on the accuracy of the assumption that WESTFORD and RICHMOND do not move relative to the North American plate.

For our study, we doubled the uncertainties given by Ma and Ryan (1995) whereupon only the three VLBI sites located in the southwestern corner of our study region (LA-VLBA, FD-VLBA, and HRAS_085) have horizontal velocities that differ statistically from zero at the 95% confidence level. We suspect that the motions of these three sites are real because the three velocities agree with one another at the 1.5 mm/yr level. Irrespective of this motion, we note that the horizontal speed for each of the 12 VLBI sites is less than 3 mm/yr.

6. Derived Velocities:

We applied the DYNAPG software program (Snay et al., 1996) to estimate a crustal velocity field that is consistent both with our estimated dL/dt rates and with the given VLBI velocities. DYNAPG will also accept various other types of geodetic information for estimating velocities. To apply DYNAPG, one must first specify a 2-dimensional grid for a rectangular region on the Earth's surface which encompasses the geodetic data. For this study, we opted for a grid with a 1° by 1° mesh size such that it spans the region bounded by latitudes 24°N and 50°N and longitudes 66°W and 108°W .

In applying DYNAPG, we implicitly assumed that the velocity field remains constant over the 1979-1996 time interval. Also we implicitly assumed that each of the three velocity components --north, east, and up--varies as a bilinear function of latitude and longitude within each grid cell. Thus the velocity at any given point depends only on the velocities at the four corners of the grid cell containing this point and on the position of this point relative to these four corners. Even though we have defined the overall velocity field in a piecewise fashion (cell-by-cell), the velocities associated with two adjacent cells will agree along their common boundary because the velocity function is linear in both latitude and longitude along a cell's edge. That is, the overall velocity field will be continuous as a function of horizontal position.

Furthermore in applying DYNAPG, we considered each dL/dt rate and each component of each VLBI velocity as an observed quantity with an associated standard error. Accordingly, the code within DYNAPG formulates a system of equations in which each of these "observed" quantities is expressed as a function of the unknown velocities at the grid nodes. Each such equation also is assigned a weight that equals one over the square of the standard error of the observed quantity. The DYNAPG code then computes velocities for the set of grid nodes such that these velocities correspond to the least squares solution for the given system of equations. Our system, however, admits to an infinite number of such solutions because the number of grid nodes greatly

7. Horizontal Strain Rates

exceeds the number of geodetic sites. Consequently, we introduced additional "smoothing" equations, three for each grid node or, more specifically, one for each velocity component at each node. The smoothing equations for a grid node equate the node's velocity to a weighted mean of the velocities at the grid nodes that bound the cells adjacent to the given node. We assigned relatively small weights to these smoothing equations so that they would not squelch the velocity information associated with the dL/dt rates and the VLBI velocities. See Snay et al. (1996) for a more detailed discussion of these and other topics associated with the use of DYNAPG.

Having estimated velocities for the grid nodes, we can now apply the associated bilinear functions to predict velocities for points located anywhere within our study region. Figure 9 and Table 3 present the horizontal velocities that we have thus predicted for the VLBI and GPS sites in this study. These velocities all have magnitudes smaller than 6 mm/yr. Furthermore the only horizontal velocities that differ statistically from zero at the 95% confidence level occur at the three VLBI sites (LA-VLBA, FD-VLBA, and HRAS_085) and the two GPS sites (BOLTON and BEARTOWN). Whereas we suspect that the motions of the three VLBI sites are real, we are uncertain whether or not our estimated velocities for BOLTON and BEARTOWN reflect actual motion because approximately 5% of the 64 GPS sites should fail our zero-velocity hypothesis.

7. Horizontal Strain Rates:

We may gain additional insight into the deformation pattern by inspecting the spatial derivatives of the horizontal velocity field: $\partial u/\partial\phi$, $\partial u/\partial\lambda$, $\partial v/\partial\phi$, and $\partial v/\partial\lambda$. Here u denotes the velocity component in the north direction, v denotes the velocity component in the east direction, ϕ denotes latitude (positive north), and λ denotes longitude (positive east). We evaluated these derivatives at the center of each cell for the same 1° by 1° grid as that for which the velocity vectors were estimated. (Note that these derivatives do not exist along grid lines.) We then calculated the maximum shearing rate

$$d\gamma/dt = [(\partial v/\partial\lambda - \partial u/\partial\phi)^2 + (\partial v/\partial\phi + \partial u/\partial\lambda)^2]^{0.5} \quad (4)$$

and the areal dilatation rate

$$d\Delta/dt = \partial u/\partial\phi + \partial v/\partial\lambda \quad (5)$$

for the center of each 1° by 1° cell.

The quantity $d\gamma/dt$ measures the greatest rate of angular change experienced among the collection of right angles (with sides of infinitesimal length) whose vertices are located at the cell's center. The quantity $d\Delta/dt$ measures the rate at which surface area is expanding (positive dilatation) or contracting (negative dilatation) at the cell's center.

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Table 3. Derived velocities with corresponding standard errors.

Site	Time_span	Latitude degrees_N	Longitude degrees_W	North_velocity mm/yr	East_velocity mm/yr
GPS sites					
ALBURG RESET	1987-1996	44.9081	73.2913	1.1 +/- 2.5	-0.1 +/- 2.9
AMARILLO RGNL PT	1990-1996	35.2115	101.8537	-0.3 +/- 3.5	-4.4 +/- 2.9
ARCADIA GPS	1990-1996	44.2582	91.4734	2.0 +/- 2.8	-2.1 +/- 2.9
ARP 2 ART	1987-1996	43.9915	76.0219	1.2 +/- 1.5	2.0 +/- 2.2
ASHCOPORT	1987-1996	41.7800	80.7006	3.0 +/- 1.4	-1.9 +/- 1.5
ASTRO WEST PIER	1987-1996	38.2021	77.3734	-0.2 +/- 0.9	0.7 +/- 0.7
AUSTIN	1988-1996	30.3393	97.6957	-1.1 +/- 4.0	-1.8 +/- 2.6
BEARTOWN 2	1987-1996	40.0831	76.0140	0.3 +/- 1.5	5.5 +/- 1.5
BEAUMONT RRP	1990-1993	30.1608	94.1793	-2.5 +/- 5.5	1.3 +/- 6.6
BLOOMINGTON NCMN 7291	1987-1996	39.1793	86.4984	1.1 +/- 1.6	-1.4 +/- 1.2
BLUFFPORT	1987-1996	36.7667	90.3239	1.8 +/- 1.9	-0.6 +/- 1.8
BOLTON CBL 0	1987-1996	39.8916	83.1542	2.2 +/- 1.5	-3.8 +/- 1.1
BRINKLEYPORT	1987-1996	34.8838	91.1747	-1.9 +/- 2.4	-1.3 +/- 1.9
BRNSOM	1987-1996	31.2957	89.8157	-0.3 +/- 2.7	-2.2 +/- 3.0
CARROLLTON 2 NCMN	1992-1996	33.5726	85.1096	0.5 +/- 2.9	0.0 +/- 2.8
CARROLLTON NCMN 7228	1987-1990	33.5725	85.1096	0.5 +/- 2.9	0.0 +/- 2.8
DAN	1990-1995	39.5817	78.8974	-1.2 +/- 2.5	1.5 +/- 2.2
DET BRAVO ORIENTATION PIER	1987-1996	44.7304	93.0793	-0.1 +/- 2.3	-1.2 +/- 2.4
EL PASO	1990-1992	31.8918	106.5961	-1.2 +/- 6.5	-1.8 +/- 6.2
FARM	1987-1996	32.7557	93.0565	-2.1 +/- 2.9	0.5 +/- 2.4
FLNRC 1	1987-1996	29.5748	82.3354	1.7 +/- 1.7	1.7 +/- 3.3
FREELAND	1987-1996	43.5229	84.0906	3.5 +/- 1.9	0.4 +/- 1.6
FUTRELL RM 2	1987-1996	36.4374	77.1522	1.4 +/- 1.3	-2.2 +/- 1.6
GPS 37	1987-1996	35.5824	85.2178	2.3 +/- 1.8	-0.3 +/- 1.4
GPS 47	1987-1996	35.5899	89.5855	0.5 +/- 2.0	0.6 +/- 1.7
GPS 57	1987-1996	35.2058	88.4995	0.9 +/- 2.1	-0.9 +/- 1.6
GPS BASE 11699 GSS	1987-1996	41.1341	104.8672	-0.6 +/- 1.9	1.7 +/- 2.4
GPS S 6	1990-1996	38.9143	75.4010	-0.3 +/- 1.8	-0.7 +/- 1.5
GREEN BANK T007 DMATC	1987-1996	38.4372	79.8318	0.2 +/- 0.3	-0.4 +/- 0.2
HAGOOD RESET	1987-1996	34.0576	80.5717	3.2 +/- 1.4	-3.4 +/- 2.0
HARVARD RM 4	1987-1996	30.6360	103.9470	1.2 +/- 0.4	-1.4 +/- 0.4
HYDE	1987-1996	44.3853	100.3114	0.4 +/- 2.9	-0.6 +/- 2.6
K 169	1987-1996	44.4045	68.0121	0.2 +/- 6.0	-5.1 +/- 2.9
LEONARD NCMN 7292	1987-1996	35.9090	95.7951	-1.3 +/- 2.7	-1.6 +/- 1.7
LIME	1987-1996	46.1335	68.0820	3.3 +/- 5.9	-2.8 +/- 4.1
LINCOLN NCMN	1987-1996	40.7609	96.7070	0.1 +/- 2.5	-1.0 +/- 1.8
LUBBOCK RRP	1990-1993	33.5244	101.8039	2.5 +/- 4.8	-4.9 +/- 4.3

(continued on next page)

7. Horizontal Strain Rates

Table 3. Continued from previous page.

Site	Time_span	Latitude degrees_N	Longitude degrees_W	North_velocity mm/yr	East_velocity mm/yr
MANITOWOC GPS	1990-1994	44.0988	87.7294	-0.4 +/- 4.7	1.8 +/- 4.1
MARYLAND PT RM 5	1987-1996	38.3734	77.2315	-0.1 +/- 0.7	0.4 +/- 0.6
MC DAVID RM A	1990-1996	30.8702	87.3412	0.3 +/- 2.9	1.8 +/- 2.9
MEDINA	1992-1996	43.2075	78.3578	-1.7 +/- 2.7	2.5 +/- 2.9
MILES CITY GPS	1987-1996	46.3964	105.8608	0.5 +/- 2.8	2.2 +/- 5.3
MILLPORT	1992-1995	45.6489	68.6919	2.9 +/- 5.6	-2.6 +/- 3.8
NELSON	1990-1996	38.0010	75.5403	0.8 +/- 1.8	-1.7 +/- 1.6
NIAGARA GPS	1990-1994	45.7447	87.9568	1.8 +/- 6.1	2.9 +/- 5.4
NM BASE 1	1987-1996	35.0416	106.6145	-1.1 +/- 1.8	2.2 +/- 2.6
NORTH GEOS PIER	1990-1992	39.0209	76.8275	-0.4 +/- 1.0	-0.9 +/- 0.9
NORTH LIBERTY	1987-1996	41.7720	91.5746	0.7 +/- 0.6	-0.2 +/- 0.5
ODESSA RRP	1990-1993	31.8753	102.3148	3.6 +/- 4.7	-3.7 +/- 4.7
OLD TOWN	1992-1995	44.9524	68.6734	2.1 +/- 5.7	-3.3 +/- 3.6
PLATTEVILLE NCMN 7258	1987-1996	40.1828	104.7263	-0.4 +/- 1.0	-1.2 +/- 0.8
PRINCETON 1	1987-1996	40.3985	74.6631	-0.2 +/- 1.8	1.5 +/- 1.6
RANGELEY	1992-1996	44.9908	70.6601	2.5 +/- 4.6	0.2 +/- 3.5
RIVERSIDE GPS	1990-1996	46.0540	92.2970	3.1 +/- 2.6	-2.8 +/- 3.3
ROCK	1987-1996	43.2005	89.5015	-0.2 +/- 1.9	-2.1 +/- 1.6
STANPORT	1990-1996	37.8491	83.8458	-0.2 +/- 1.9	-1.6 +/- 1.4
STATESVILLE CBL 000	1987-1996	35.7642	80.9519	1.0 +/- 1.3	-0.5 +/- 1.4
TANEY	1990-1996	39.6634	77.1835	-0.6 +/- 1.4	2.8 +/- 1.4
TAOSPORT	1990-1991	36.4603	105.6690	1.7 +/- 2.4	-4.0 +/- 2.5
TIMER	1987-1996	25.6141	80.3841	0.2 +/- 0.1	0.1 +/- 0.1
VA 24	1993-1996	37.5446	78.8470	-0.3 +/- 2.5	-0.6 +/- 2.4
WALTPORT	1987-1996	32.9213	80.6385	2.3 +/- 1.5	-3.5 +/- 2.3
WILLIAMSON	1987-1996	37.7483	89.0144	2.0 +/- 1.7	1.0 +/- 1.7
Y 505	1993-1996	36.9520	81.0858	0.9 +/- 3.1	4.8 +/- 2.9
VLBI sites					
ALGOPARK	1984-1995	45.9558	78.0714	-1.0 +/- 0.3	0.0 +/- 0.3
FD-VLBA	1991-1995	30.6805	104.0151	1.1 +/- 0.3	-1.3 +/- 0.2
GGAO7108	1993-1995	39.0219	76.8265	-0.4 +/- 1.0	-0.9 +/- 0.9
HN-VLBA	1992-1995	42.9336	71.9866	-0.5 +/- 1.0	1.2 +/- 0.9
HRAS_085	1980-1991	30.6805	104.0151	1.1 +/- 0.3	-1.3 +/- 0.2
LA-VLBA	1991-1995	35.7751	106.2456	1.4 +/- 0.3	-2.0 +/- 0.3
MARPOINT	1982-1989	38.3742	77.2306	-0.1 +/- 0.7	0.4 +/- 0.6
NL-VLBA	1992-1995	41.7716	91.5749	0.7 +/- 0.6	-0.2 +/- 0.5
NRAO_140	1979-1995	38.4378	79.8358	0.2 +/- 0.3	-0.4 +/- 0.2
PLATTVIL	1983-1990	40.1828	104.7263	-0.4 +/- 1.0	-1.2 +/- 0.8
RICHMOND	1984-1992	25.6138	80.3839	0.2 +/- 0.1	0.1 +/- 0.1
WESTFORD	1981-1995	42.6129	71.4938	-0.2 +/- 0.1	0.0 +/- 0.1

7. Horizontal Strain Rates

Figure 10 displays the standard error field associated with our estimates for dy/dt . The standard error for a given grid cell depends both on the spatial density of geodetic sites located near that cell and the accuracy of the geodetic information associated with these sites. Accordingly, the lowest standard errors (those having values between 20 and 30 nanoradians/yr (nrad/yr)) occur in the vicinity of central Maryland where two VLBI sites, as well as several GPS sites, reside. Relatively low standard errors (with values between 30 and 40 nrad/yr) also occur near the New Madrid seismic zone (NMSZ) which is located around that part of the Missouri border which extends from Kentucky to Tennessee. Also the cells located east of the Mississippi River generally have higher site densities, and thus lower standard errors, than the cells located to the west of this river. Nevertheless, for almost all cells within the span of our geodetic data, the associated maximum shearing rates have standard errors that are less than 60 nrad/yr.

It should be noted that if we were to increase the mesh size of the grid, for example to 2° by 2° , then the corresponding cells would generally have lower standard errors for their strain rates than the standard errors that the 1° by 1° cells have. Increasing the mesh size, however, would yield comparatively poorer spatial resolution of the strain-rate field.

We do not present a map showing standard errors for the dilatation rates because the magnitudes of these standard errors are very similar, from cell to cell, to those for the maximum shearing rates when the former are expressed in nstr/yr and the latter are expressed in nrad/yr.

Figure 11 displays the maximum shearing rates that we derived. Each of these rates is less than 60 nrad/yr, and no shearing rate differs statistically from zero at the 95% confidence level except that for a cell located in central Maryland whose rate equals 57 ± 26 nrad/yr. The maximum shearing rate for this cell is related to the motion of BEARTOWN. When we repeated our solution with the data for BEARTOWN excluded, then this same cell had a maximum shearing rate of only 34 ± 35 nrad/yr. This result indicates that BEARTOWN's motion, if it is real, is spatially inconsistent with the motions of the other geodetic sites in its vicinity.

Of particular interest we note that our estimates for maximum shearing rate are less than 40 nrad/yr for those cells located near the NMSZ. In contrast to this result, both Liu et al. (1992) and Weber (1995) found maximum shearing rates in excess of 100 nrad/yr near the NMSZ. Both of those previous studies had used geodetic data that differ entirely from the data of this study and from each other. Both of those studies, however, involved geodetic sites which were clustered more densely within the NMSZ than the sites involved in our study. Consequently, the high shearing rates that Liu et al. (1992) and Weber (1995) detected must be limited to a geographic area that does not contain any of the geodetic sites included in this study. Moreover, the results of Snay et al. (1994), when considered together with those of Liu et al. (1992) and Weber (1995), demonstrate that strain rates within the NMSZ exhibit rather large spatial variations. In particular, using geodetic data that are essentially independent from those used here as well as those used in the other NMSZ studies, Snay et al. (1994) found a maximum shearing rate of only 30 ± 19 nrad/yr for the area located immediately north of the area where Liu et al. (1992) and Weber (1995) found maximum shearing rates in excess of 100 nrad/yr.

Figure 9. Horizontal velocities with 95% confidence ellipses as derived in this study. Numbers denote speeds in mm/yr.

7. Horizontal Strain Rates

Figure 10. Standard errors for the maximum shearing rates associated with the 1° by 1° cells. Dark squares identify VLBI sites and stars identify GPS sites.

7. Horizontal Strain Rates

Figure 11. Maximum shearing rates for 1° by 1° cells. Printed values specify the rates with their corresponding standard errors for selected cells having some of the higher rates. Dark squares identify VLBI sites and stars identify GPS sites.

Figure 12. Areal dilatation rates for 1° by 1° cells. Printed values specify the rates with their corresponding standard errors for selected cells having rates with some of the larger magnitudes. Dark squares identify VLBI sites and stars identify GPS sites.

8. Discussion and Conclusions

Figure 12 displays our derived areal dilatation rates. The rate for each cell is less than 40 nstr/yr in magnitude, and no dilatation rate differs statistically from zero at the 95% confidence level. These low dilatation rates imply that possible scaling problems associated with the intermark vectors of the individual surveys are not detectable using the currently available data.

8. Discussion and Conclusions:

We have computed horizontal velocities for 64 GPS sites located in the CEUS, and we have computed the corresponding horizontal strain rates for a set of cells formed by a 1° by 1° grid. As a result of these computations, we have found no horizontal velocity exceeding 6 mm/yr in magnitude, no shearing rate exceeding 60 nrad/yr in magnitude, and no dilatation rate exceeding 40 nstr/yr in magnitude. Moreover, we have found no compelling evidence for motion in the CEUS except perhaps that occurring at three VLBI sites, one located in New Mexico and two in western Texas. The existence of motion even at these three sites must be qualified in that the cited VLBI velocities were derived under the assumption that WESTFORD and RICHMOND do not move relative to the North American plate.

Our results hint that the two GPS sites, BEARTOWN and BOLTON, might be moving relative to the North American plate, but we suspect that these alleged motions reflect statistical artifacts of the data. If, however, the motion at BEARTOWN is real, then this motion must be relatively local because no motion is detected at the VLBI site (GGAO7108) or at any of the four GPS sites (GPS S 6, NORTH GEOS PIER, PRINCETON 1, and TANEY) that are located within 200 km of BEARTOWN. The case that the alleged motion at BEARTOWN is local is further supported by the result that maximum shearing rates for grid cells near BEARTOWN drop by as much as 23 nrad/yr when we remove the BEARTOWN data from our solution. Unfortunately, we are unable to assess whether or not the alleged motion at BOLTON is only local because none of the other geodetic sites in this study are located within 200 km of BOLTON.

While we have found no site whose horizontal speed exceeds 6 mm/yr, we expect that additional geodetic surveys at our sites would provide an even lower upper bound on horizontal speeds. This expectation is substantiated by several studies of daily GPS and/or VLBI observations at 18 sites across stable North America. These studies (Argus and Heflin, 1995; Dixon and Mao, 1996; Larson et al., 1997; and Ma and Ryan, 1995) find that the horizontal speed at each of these well monitored sites is less than 3 mm/yr relative to the North American plate.

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REFERENCES:

- Argus, D.F. and Heflin, M.B., 1995. Plate motion and crustal deformation estimated with geodetic data from the Global Positioning System. *Geophys. Res. Lett.*, 22, 1973-1976.
- Boucher, C., Altamimi, Z. and Duhem, L., 1993. ITRF92 and its associated velocity field. *IERS Technical Note 15*, Observatoire de Paris, F-75014 Paris, France.
- Bryant, M.A. and Noll, C.E., 1993. NASA space geodesy program: catalogue of site information. *NASA Technical Memorandum 4482*, Goddard Space Flight Center, Greenbelt, Maryland 20771.
- DeMets, C.R., Gordon, R., Argus, D. and Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motion. *Geophys. Res. Lett.*, 21, 2191-2194.
- Dixon, T. and Mao, A., 1996. How rigid is the stable interior of the North American plate? *Geophys. Res. Lett.*, 23, 3035-3038.
- Hilla, S.A. and Schenewerk, M.S., 1992. GPS static data processing at the National Geodetic Survey completed projects, current software, and future trends. *Proceedings, Sixth International Geodetic Symposium on Satellite Positioning*, vol. 2, 563-572, The Ohio State University, Columbus, Ohio 43210.
- Larson, K.M., Freymueller, J.T. and Philipson, S., 1997. Global plate velocities from the Global Positioning System. *J. Geophys. Res.*, 102, 9961-9981.
- Liu, L., Zoback, M.D. and Segall, P., 1992. Rapid intraplate strain accumulation in the New Madrid seismic zone. *Science*, 257, 1666-1669.
- Ma, C. and Ryan, J.W., 1995. NASA space geodesy program -- GSFC data analysis -- 1995: VLBI geodetic results 1979-1995.5. <http://lupus.gsfc.nasa.gov/vlbi.html>, Goddard Space Flight Center, Greenbelt, Maryland 20771.
- Mader, G.L. and MacKay, J.R., 1996. Calibration of GPS antennas. *Proceedings, IGS 1996 Analysis Center Workshop*, 81-105, edited by R.E. Neilan, P.A. Van Scoy, and J.F. Zumberge, Jet Propulsion Laboratory, Pasadena, California 91109.
- Mader, G.L., Schenewerk, M.S., Ray, J.R., Kass, W.G., Spofford, P.R., Dulaney, R.L. and Pursell, D.G., 1995. GPS orbit and Earth orientation parameter production at NOAA for the International GPS Service for Geodynamics for 1994. *International GPS Service for Geodynamics 1994 Annual Report*, 197-212, edited by J.F. Zumberge, R. Liu, and R.E. Neilan, Jet Propulsion Laboratory, Pasadena, California 91109.
- Milbert, D.G. and Kass, W.G., 1987. ADJUST: the horizontal observation adjustment program. *NOAA Technical Memorandum, NOS NGS-47*, National Geodetic Survey, NOAA, Silver Spring, Maryland 20910.
- NOAA, 1994. Input formats and specifications of the National Geodetic Survey data base. National Geodetic Survey, NOAA, Silver Spring, Maryland 20910.
- Snay, R.A., Ni, J.F. and Neugebauer, H.C., 1994. Geodetically derived strain across the northern New Madrid seismic zone. *U.S. Geological Survey Professional Paper 1538*, F1-F6.

- Snay, R.A., Cline, M.W., Philipp, C.R., Jackson, D.D., Feng, Y., Shen, Z.K. and Lisowski, M., 1996. Crustal velocity field near the big bend of California's San Andreas fault. *J. Geophys. Res.*, 101, 3173-3185.
- Strange, W.E., 1991. Global Positioning System measurements over a strain monitoring network in the eastern two-thirds of the United States. *NUREG/CR-5777*, U.S. Nuclear Regulatory Commission, Washington, D.C., 20555.
- Strange, W.E., 1996. Global Positioning System reobservations over the eastern United States strain monitoring network. *NUREG/CR-6473*, U.S. Nuclear Regulatory Commission, Washington, D.C., 20555.
- Weber, J.C., 1995. New Madrid seismic zone deformation from repeat Global Positioning System (GPS) surveys. Ph. D. thesis, Northwestern University, 141 pp.