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Global Positioning System Measurements Over a Strain Monitoring Network in the Eastern Two-Thirds of the United States

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

A 45-station geodetic network was established in 1987 using global positioning system (GPS) technology. The objective of this network is to provide a means of monitoring strain and deformation in the central and eastern United States. Reduction of the initial epoch data showed that accuracies of 1 to 3 cm can be achieved for horizontal positioning provided sufficient observations are available and there are four or more fiducial stations whose positions are known *a priori*, for example from Very Long Baseline Interferometry (VLBI) measurements, and can be used to perform orbit improvement computations. Given the station separations involved the accuracies obtained provide the ability to determine strain at the $1:10^7$ to $1:10^8$ level. Vertical positions are less accurate because of problems in modeling refraction and are determined at the 5 to 7 cm level. It is planned to remeasure this network at regular intervals in the coming years to place bounds on the strain occurring in the central and eastern United States. This network is also expected to serve as a reference network for more detailed monitoring networks in areas of high risk such as the New Madrid area. Future measurements are expected to provide more accurate results because of increased numbers of GPS satellites available and improved computation software. The improved software will also allow future upgrading of the accuracy of the 1987 observations. Ultimately this network should allow strain monitoring of the central and eastern United States at the 1 to $2:10^8$ level.

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INTRODUCTION

In November and December of 1987, the National Geodetic Survey (NGS) undertook the establishment of a 45-station Global Positioning System (GPS) network covering the United States approximately east of 105° west longitude (Figure 1). This network was established in support of the Nuclear Regulatory Commission (NRC) for the purpose of monitoring crustal strain in the area. GPS technology was used to perform measurements over this network. In addition to monitoring large-scale strain, the network will provide a basic framework to support more detailed GPS networks (established for geodynamic and surveying applications) which can monitor strain and deformation in the central and eastern United States.

The determination of strain with this 45 station network, which we have designated the Eastern U. S. Strain Network, is a long-term effort, with repeated observations made over a time period of a decade or more. Strains and deformations in this region are expected to be very small. Therefore, accuracy objectives for the survey were set at $1{:}10^7$ or better. As a practical matter, accuracies of distances between stations would need to be at the few centimeters level to be useful for secular strain rate determinations in the eastern United States. Thus, for longer baselines (>500km), accuracies of a few parts in 10^8 will be needed to provide useful strain determination results.

NETWORK PLANNING AND RATIONALE

The stations of the Eastern United States Strain Network were located based on four primary criteria.

(1) Stations were to be distributed over the entire area east of the Rocky Mountains.

(2) Stations were to be somewhat denser in areas of special interest, such as the New Madrid and Charleston areas.

(3) Stations were located so as to span areas of potentially significant seismicity and deformation.

(4) Stations of the network were to be collocated with stations of the Cooperative International GPS Network (CIGNET), and with existing Very Long Baseline Interferometry (VLBI) stations in the area.

Table 1 summarizes the stations selected for the Eastern U. S. Strain Network.

Collocation with stations of the GPS orbit determination network, CIGNET, and with VLBI stations was felt to be extremely important for three reasons. First, long-term monitoring with high accuracy using GPS requires connection to an earth fixed coordinate system, which can be monitored with very high accuracy over time. Second, to validate the accuracy of the GPS results, a second technique must be available at a subset of the strain network stations for comparison purposes. Finally, to obtain results of satisfactory accuracy using GPS, at least four stations of a GPS observing network should have positions known a priori and held fixed during solutions, to permit orbit improvement of the GPS satellite orbits.

In order to compute orbits for GPS satellites for use by the civil community NGS, working within the context of the International Union of Geodesy and Geophysics (IUGG), has, together with organizations in a number of foreign countries, initiated formation of a Cooperative International GPS Network (CIGNET). Currently, there are 9 CIGNET stations, all located in the northern hemisphere (Figure 2). Until such time as CIGNET stations are established in the southern hemisphere, NGS has an agreement with the Defense Mapping Agency (DMA) to obtain GPS tracking data from the 5 station DMA network, including 3 southern hemisphere stations (Figure 2). NGS operates 4 of the 9 CIGNET stations. Three

EASTERN US STRAIN NETWORK

1987 OBSERVATIONS

Figure 1

COOPERATIVE INTERNATIONAL GPS NETWORK
(CIGNET 1987)

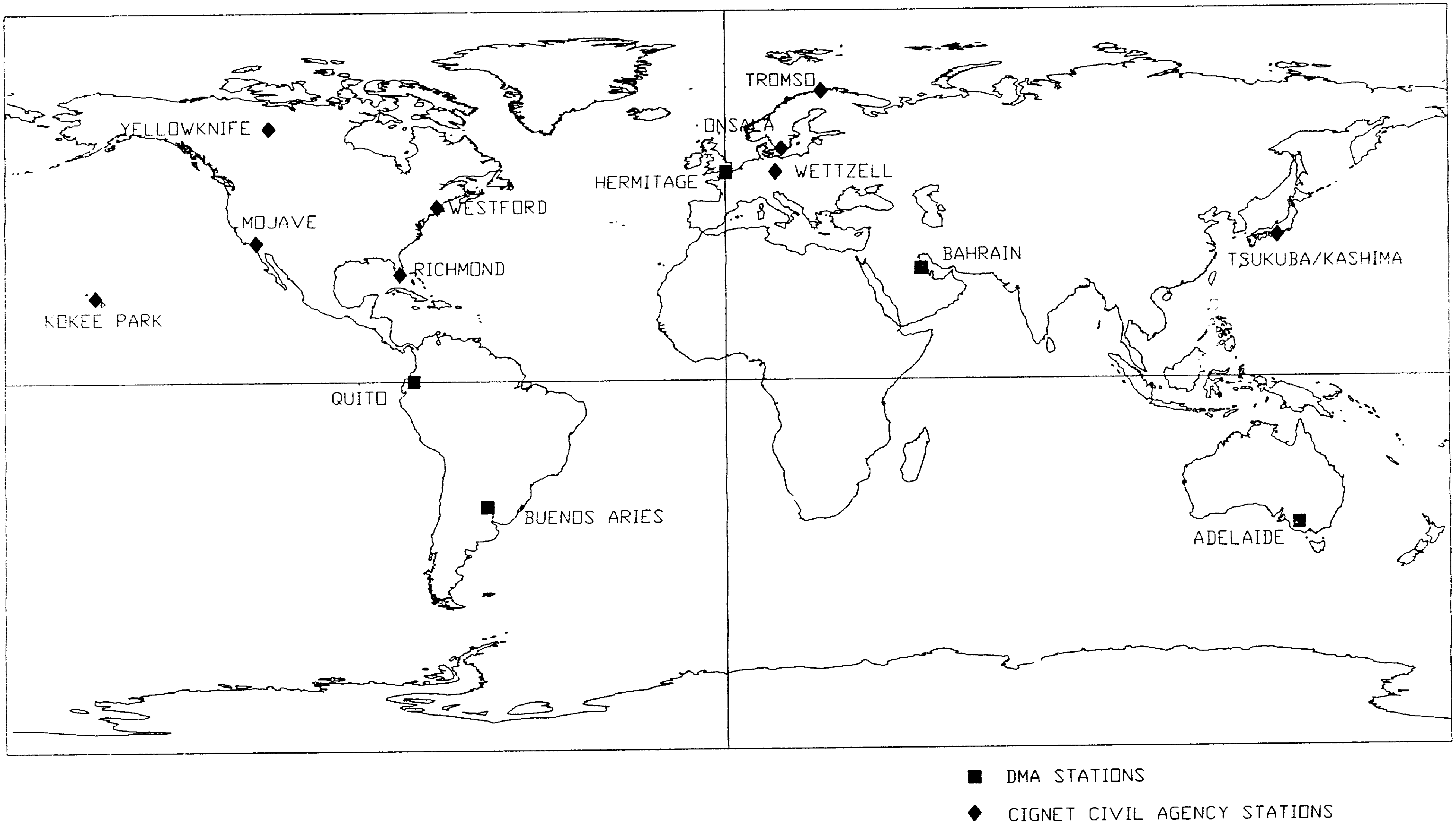

Figure 2

are in the conterminous 48 states (Westford, MA; Richmond, FL; and Mojave, CA), and one in Hawaii. The Westford and Richmond stations were included in the strain network. Although the Mojave station is not a part of the strain network, data from this station (as will be discussed elsewhere in this report) were used to support orbit adjustment during data reduction.

VLBI is a technique which uses radio telescopes (dish antennas) to monitor incoming radio frequency signals from quasars and other celestial objects. Using these signals, it is possible to determine differential positions between telescopes at the centimeter level, even with station separations of thousands of miles, and to derive information on earth orientation (earth rotation, polar motion, precession, and nutation) with extremely high accuracy. VLBI receivers (radio telescopes) can be either fixed or mobile. Within the coterminous 48 states, NGS operates 4 fixed VLBI receivers, located at Westford, MA; Richmond, FL; Mojave, CA; and Ft. Davis, TX. All of these have contributed to the International Earth Rotation Service (IERS), which provides earth orientation services. In addition, fixed VLBI stations are operated by U. S. Navy components at Maryland Point, MD and Greenbank, WV. Collocated GPS stations at all of these fixed VLBI sites except Mojave are a part of the Eastern U. S. Strain Network. In addition to the fixed VLBI sites, six VLBI stations have been established in the strain network area using mobile VLBI. These stations are located at Miles City, MT; Platteville, CO; Leonard, OK; Bloomington, IN; New Carrollton, GA; and Austin, TX. Stations of the strain network were established at all six of these sites.

OBSERVATIONAL ACTIVITIES

Observations over the 45-station network given in Table 1 were performed in November and December 1987. The basic observing plan called for 3 days occupation of each of the 45 stations. It was hoped that enough GPS receivers would be available to complete observations over the network using three 3-day observing periods. Three observing days at each station were selected because it was felt that at least 2 days of usable data were needed at each station to validate results, and that with 3 days of observations, one would normally obtain at least 2 days of usable data. As may be seen from Table 1, after three observing sessions, all but five stations of the network had been occupied. Two additional small observing sessions resulted in 44 of the 45 stations being occupied during the November/December 1987 time period. The two CIGNET stations at Westford and Mojave observed over the entire period. The only station never occupied was the Dallas, Texas station. As will be discussed later, other observations are available, which can be used as initial epoch determinations for this station.

All data for this project were obtained using TI-4100 receivers with standard TI-4100 antennas. At each station, the antenna was plumbed over the measurement point on the monument using an optical plummet. Height of the antenna above the measurement point on the monument was measured both before and after each observing session using a graduated steel rod. Measurements of temperature, pressure, and humidity were recorded several times during each observing session.

Table 2 gives the typical observing scenario. This scenario gives the satellites observed for the group 1 observations. As may be seen, a total of five satellites were observed. Both amount of data and satellite geometry were far from optimal. From 4 to 5 1/2 hours of data were typically obtained with 2 1/2 to 3 hours of simultaneous tracking of four satellites during the middle of the observing period, and tracking of three satellites during the remainder of the time.

GENERAL CHARACTERISTICS OF SOLUTION

GPS observations consist, fundamentally, of measurements of carrier phase of a satellite transmission (together with a time tag) for a number of equispaced (in time) epochs. These types of measurements are recorded for several satellites simultaneously, i.e., the epochs of the measurements are identical in

TABLE 1
STATIONS OF THE EASTERN U. S. STRAIN NETWORK

STATION NAME	ABBREVIATION	STATE OF LOCATION	OBSERVATION GROUP(S)
Alberg	ALBU	Vermont	3
Arp 2	ARP2	New York	4
Ashcoport	ASHC	Ohio	3
Astro	ASTW	Virginia	3
Austin	AUST	Texas	1
Beartown	BEAR	Pennsylvania	3
Bloomington*	BLOO	Indiana	2, 4
Bluffport	BLUF	Missouri	2
Bolton	BOLT	Ohio	4
Bravo	DROP	Minnesota	1
Brinkley	BRIN	Arkansas	1
Bronson	BRON	Mississippi	1
Cheyenne	1169	Wyoming	1
Dallas	DALL	Texas	1
Farm	FARM	Louisiana	1
FLNR	FLNR	Florida	2
Freeman	FREE	Michigan	2
Ft. Davis*	HAR4	Texas	1
Furtrell	FUTZ	North Carolina	3
GP37	GP37	Tennessee	2
GP47	GP47	Tennessee	2
GP57	GP57	Tennessee	2
Greenbank*	T007	West Virginia	3
Hapgood	HAGO	South Carolina	2
Houston	HOUS	Texas	1
K169	K169	Maine	3
Leonard*	LEON	Oklahoma	1
Lime	LIMA	Maine	3
Lincoln	LINC	Nebraska	1
Lubbock	LUBR	Texas	1
Maryland Point*	MDPT	Maryland	3
Miles City*	MILE	Montana	1
New Carrollton*	CARR	Georgia	2
NMB1	NMB1	New Mexico	1
North Liberty	NOLI	Iowa	1
Pierre	HYDE	South Dakota	1
Plattville*	PLAT	Colorado	1
Princeton	PRIN	New Jersey	3
Richmond*	TIME	Florida	3, 4
Rock	ROCK	Wisconsin	1
Stanport	STAN	Kentucky	4
Statesport	STAT	North Carolina	4
Waltport	WALT	South Carolina	2
Westford*	OCP3	Massachusetts	1, 2, 3, 4
Williamson	WILL	Illinois	2

*Collocated with VLBI stations

TABLE 2
NOVEMBER 12-14 OBSERVING SESSION
OBSERVING SCENARIO AND SATELLITE AVAILABILITY

UT Dates	Start UTC	Stop UTC	Satellites SV Numbers
Nov. 12, 13, 14	11:40	13:00	6, 8, 11
	13:00	14:50	6, 8, 9, 11
	14:50	15:20	8, 9, 11, 12
	15:20	17:20	9, 11, 12

time. For each satellite, the quantity recorded at the initial epoch is the fractional part of the current cycle. For succeeding epochs, the quantity recorded is the change in phase, given in terms of number of whole cycles plus a fractional part of a cycle. Thus, in geometric terms, what one has at each epoch is the distance from the receiver antenna to the satellite, expressed in units of cycles, minus a constant. The constant, which is the same at all epochs for a given satellite, is the unknown number of whole cycles to be added to the initial epoch partial cycle measurement to give the distance from receiver to satellite at the time of the initial epoch measurement. The above statements would be strictly true if two conditions were met. The first condition would be for all satellite clocks and receiver clocks to be perfectly synchronized. The other condition would be for all refraction effects to be absent. Since these conditions are not met, the failure to meet them must be taken care of in the reduction process.

The clock problem is taken care of by solving for differences in position between stations, rather than absolute station positions, and, thereby, being able to use as an observable a "double difference." Consider four measurements of phase made at the same epoch. Let k_{11} and k_{12} be measurements of phase by station 1 for signals from satellites 1 and 2 and k_{21} and k_{22} measurements by station 2 for signals from satellites 1 and 2. The double difference observable formed is then

$$Dk^{dd} = (k_{11} - k_{12}) - (k_{21} - k_{22})$$

By differencing between satellites the quantities $(k_{11} - k_{12})$ and $(k_{21} - k_{22})$ are free of receiver clock errors since the receiver clock error is identical for measurements made at the same instant in time to two satellites. Similarly, by taking the difference between $(k_{11} - k_{12})$ and $(k_{21} - k_{22})$, i.e., differencing of measurements to the same satellites at the same instant in time, satellite clock errors are eliminated from the double difference observable.

With respect to refraction, two types of refraction must be considered, ionospheric refraction and tropospheric refraction. Ionospheric refraction is taken care of by employing two frequencies and using yet a third type of differencing. The previous discussion assumed only a single frequency was broadcast by the GPS satellites. In fact, two frequencies are broadcast. Because ionospheric refraction is frequency dependent, one can record phase information from both frequencies and form an ionospheric refraction free residual, Dk^{3dd}, where:

$$Dk^{3dd} = .435\ Dk^{1dd} - .236\ Dk^{2dd}$$

Dk^{1dd} is the double difference phase observable of frequency f_1

and Dk^{2dd} is the double difference phase observable of frequency f_2

The frequencies involved are:

f_1 = 1571.4 MHz

f_2 = 1227.6 MHz

Final answers for high accuracy solutions over long baselines such as were required for this study employ the Dk^{3dd} observable. For reasons that will be discussed below, it is also necessary to carry out solutions using the observables Dk^{1dd} and Dk^{2dd}. At NGS the nomenclature normally used in describing the solutions is to refer to L_1, L_2, and L_3 solutions when using respectively, the Dk^{1dd}, Dk^{2dd} and Dk^{3dd} observables. That nomenclature will be used in this report.

Tropospheric refraction is initially estimated using surface meteorological data (temperature, pressure, and humidity) recorded at the time of observation and employing the Marini refraction model. This model gives refraction in the form of a constant, commonly referred to as zenith delay, multiplied by a function of the elevation angle of the satellite as viewed from the observing station. The computer program used allows for improvements in initial estimates of the tropospheric refraction by allowing corrections to the zenith delay at stations to be unknowns in the solution.

The solution methodology is summarized in broad terms in the following discussion. The simplest solution is one in which it is assumed that satellite positions as a function of time are known, and only two stations are involved. In this case, the known quantities, held fixed in the solutions, are the position of one of the two stations, and the satellite positions at each measurement epoch. The quantities estimated in the solution are then the position of the unknown station relative to the known station (Dx, Dy, Dz) and linear combinations of the initial epoch whole cycle counts. In forming the double difference residuals, one satellite is chosen as the reference satellite. Then the linear combinations of whole cycle counts at the initial epoch involve linear combinations of differences between the whole cycle count of the reference satellite and each of the other satellites in the solution. The zenith delay constant at one or both of the stations may also be included in the solution as an unknown.

A more complex solution is one in which a large number of stations observe during an observing session and three or more (preferably at least four) stations have known positions, a priori. These known positions may be due to results obtained previously from observations using other techniques such as VLBI and/or Satellite Laser Ranging (SLR). In this case, the unknowns determined in the solution could include (in addition to differential positions of one or more stations whose positions are unknown, linear combinations of initial epoch whole cycle counts, and corrections to computed zenith delays at stations) corrections to satellite position parameters. In the programs used at NGS, initial estimates of satellite positions as a function of time during an observing session of 4 to 6 hours in length are expressed for a given observation epoch in the form

$$E\ (a,\ e,\ I,\ \Omega,\ w,\ M,\ (t_e - t_o)) + F\ (t_e),$$

where E gives the best estimate position for the satellite at the observation epoch, t_e assuming ellipsoidal motion and F (t_e) is the deviation from ellipsoidal motion at time t_e.

The location of the satellite due to ellipsoidal motion at a time t_e is expressed as a function of shape of the best fitting ellipsoid (semi major axis, a, and ellipticity, e), orientation of the ellipsoid in space (inclination, I, longitude of ascending node, Ω, and argument of perigee, w) and the mean motion M of the satellite between the time of perigee passage (t_o) and the observation epoch time t_e. In the solution one may solve for corrections to all, or some subset of elliptical parameters a, e, I, Ω, w, M, and t_o.

CYCLE SLIPS

One additional factor complicates obtaining solutions from GPS observations. This complication is referred to as cycle slips. Consider the carrier phase for a single frequency broadcast by a single satellite and received by a single station. As mentioned previously, the observed quantity at all observation epochs after the first epoch is the total change in phase since the initial epoch observation. This total change in phase computed at a subsequent epoch is obtained by counting the number of whole cycles since the initial epoch and adding to it the partial phase measurement. For various reasons (such as temporary loss of lock due to obstruction of the satellite signal), there may be an error introduced in the whole cycle count. This error, called a cycle slip, will cause an abrupt offset in the observational residuals equal to an integer number of cycles. These cycle slips can usually be corrected for, using the knowledge that they are equal to an integer number of cycles. However, locating and correcting cycle slips is usually the most time consuming part of GPS data processing.

REDUCTION PROCEDURE

The steps in reduction of GPS data used to produce the results reported here can be summarized as follows for each observing session:

1. Original GPS observations were transferred from cassette tapes to floppy disk, and then entered into the computer used for reduction.

2. Using a program designated ARGO, the required information for the data reduction was extracted from the raw observation files, and reformatted into files which could be used in the reduction programs.

3. Meteorological information and height of GPS antenna above the station monument were extracted from hard copy field records and entered into appropriate computer files, together with initial estimates of positions of all stations.

4. Appropriate weekly high accuracy satellite orbit files obtained from the Naval Surface Warfare Center (NSWC) were run through a preprocessing program to provide satellite position information in the correct format for use in the reduction programs.

5. The GPS observations, ancillary information, and orbit data were input to an initial reduction program named MERGE. The MERGE program performed the following primary functions: (a) computed tropospheric refraction corrections from the meteorological data observed in the field; (b) carried out gross cycle slip fixing (i.e., removed most cycle slips greater than 100 cycles); and (c) formatted the data for use in the subsequent reduction and refined cycle slip fixing programs.

6. A program designated CYFIX was run on each frequency, L_1 and L_2, independently to remove additional cycle slips with a more refined automatic cycle slip fixing routine.

7. The final reduction program, GPS22, was run on L_1 and L_2 data independently to obtain solutions. Observation residuals were then plotted, and used to identify and correct for remaining cycle slips. This procedure was iterated as required until all cycle slips were identified and corrected.

8. With cycle slips now corrected, GPS22 was used to perform an L_3 solution, If the r m s residuals and the residual plots were satisfactory, this was a final solution. Often, however, it would be found at this stage that one or more cycle slips had been missed, and it would be necessary to go back to step 6.

9. In performing the final solution, the parameters solved for were: station positions of the unknown stations, trospheric scale height parameters for each station, initial constants for all satellites (except the reference satellite) at all stations (except the reference station), and six orbit parameters (all except t_o) for all satellites.

DESCRIPTION OF RESULTS

Results from the reductions of the observations are best summarized in terms of baseline lengths and station positions obtained from the reductions of the 15 observing sessions involved. The derived station positions are given in Tables 1A through 4A of the Appendix. The baseline lengths are summarized in Tables 1B through 4B. Table 1C gives the positions of the reference stations used in the computations. Complete positioning results, in the form of computer printouts, are available from the NRC technical monitor or from the NGS, as are station descriptions.

As may be seen from the Appendix, at least 2 days of reducible observations were obtained from 40 of the 45 stations of the Eastern Strain Network during the November/December 1987 time period. No useful data were obtained from the following stations:

Bravo, Minnesota
Dallas, Texas
Austin, Texas
Houston, Texas
Statesport, North Carolina

Failure to obtain data from the above five stations was the result of several different circumstances. All of the data from station Bravo were very noisy and could not be processed. The cause of this noise is not clear; it could have resulted from instrument problems or from noise due to operation of large radio frequency antennas at the site. Stations at Austin and Houston observed as scheduled and obtained data. However, it was found that the external cesium time standards to which the receivers were connected at these sites had not functioned properly and the data could not be used. Due to a last minute lack of equipment, the station at Dallas was never occupied. The Statesport station was occupied and observed as scheduled. However, the data could not be processed, presumably because of instrument problems.

Despite the lack of data from five sites during the November/December 1987 observing period, it should be possible to obtain initial epoch observations for all of these stations except Statesport using other observations. When it was determined during data reduction that no useable data had been obtained at station Bravo, remedial observations were scheduled. These observations were made in November 1988. At that time, GPS interconnections were made between stations Bravo, Rock, Freeman, and Bloomington. These observations are summarized in Table 3. Analysis of these data should allow positioning of Bravo unless the problem with the November 1987 observations was radio frequency noise at the site. If noise is the problem, this station must be abandoned and another site selected to replace it.

Positions for stations Austin, Dallas, and Houston should be derivable from data observed in 1985 and 1986. At that time, GPS observations were made at these stations and other stations in Texas, simultaneously with GPS observations at the fixed VLBI sites located at Ft. Davis, Westford, Richmond, Mojave, and Owens Valley. The State of Texas Highway Department is also currently reobserving the Austin, Dallas, and Houston sites using dual frequency Wild Magnavox receivers. All of the above data sets are available to NGS for analysis.

The intent was to have GPS observations from a minimum of four receivers collocated at VLBI sites during each observing session. Holding these stations' positions fixed at the VLBI derived position values, the GPS observations taken by them could be used to support orbit adjustment during data reduction. Because of the unexpected failures of the permanent GPS stations at the Mojave, Westford, and Richmond sites, data were not always available and this intent was not realized after the initial (group 1) observations. Table 4 indicates the VLBI sites from which GPS observations were available during each observing session. It will be noted that the data available for orbit adjustment were particularly poor for the group 2 observations. On one day only two collocated GPS stations obtained observations.

The observations undertaken in November 1988 were designed, not only to obtain a position for station Bravo, but also to provide a means for future improvement of the group 2 station positions reported here. Using the November 1988 observations, a position can be established for station Freeman by using the VLBI position of Bloomington and the position for station Rock obtained from the group 1 observations. Freeman could then be used as a station whose position is known to support orbit adjustment in a rereduction of the group 2 data, thereby improving the determination of positions of the other group 2 stations. It should also be possible to improve the group 3 results in the future. The

TABLE 3
STATION OCCUPATIONS SEPTEMBER/OCTOBER 1988

1988 DAY	STATION			
	BRAVO	ROCK	FREEMAN	BLOOMINGTON
9/28	X	X	X	X
9/29	X	X		X
9/30	X	X		X
10/5		X	X	X
10/6		X	X	X

TABLE 4
REFERENCE STATIONS USED FOR SOLUTIONS

OBSERVATION DAY	REFERENCE STATIONS
316	Ft. Davis, Mojave, Westford, Plattville
317	Ft. Davis, Mojave, Westford, Plattville
318	Ft. Davis, Mojave, Westford, Plattville
321	New Carrollton, Bloomington, Mojave
322	New Carrollton, Bloomington, Westford
323	New Carrollton, Mojave
326	Maryland Point, Mojave, Richmond, Westford
327	Maryland Point, Mojave, Richmond
328	Maryland Point, Mojave, Richmond
336	Bloomington, Westford, Richmond
337	Bloomington, Westford, Richmond
342	Bloomington, Mojave, Richmond
343	Bloomington, Mojave, Richmond, Westford
344	Bloomington, Mojave, Richmond, Westford

Greenbank, West Virginia, station which took part in the group 3 observations is located at a fixed VLBI site. However, its position could not be held fixed for performing the reductions reported here because the differential position between the VLBI measurement point and the ground mark occupied by GPS were not available. However, the measurements necessary to obtain this local differential position have been made. Thus, when these measurements have been analyzed and the differential position determined, the Greenbank station can be the fourth station held fixed to improve orbit adjustment, and the group 3 results improved.

The group 1 results may be considered as an example of the type of accuracy attainable with GPS in the differential positioning mode when adequate data for orbit adjustment is available. Tables 1A and 1B summarize the repeatability of not only line length, but also position (latitude and longitude) for the group 1 observations. The deviations from the mean for repeat observations of latitude and longitude are shown in Figure 3. These deviations are plotted at real scale to emphasize the extraordinary accuracy of these results. The average deviation from the mean for the entire data set is 0.3 cm in latitude, 0.9 cm in longitude, and 3.0 cm in height. Since many of the baselines involved are in excess of 1,000 km in length, the horizontal position repeatability attained in this case is at about the 1 part in 10^8 level.

During the group 1 observations, six VLBI sites were occupied. Only four were held fixed in the adjustment to allow orbit improvement. The other two sites, Leonard, Oklahoma, and Miles City, Montana, were allowed to adjust freely. To test the accuracy as well as the precision (i.e., repeatability) of the GPS results from group 1 data reductions, comparisons were made of GPS and VLBI determinations of the baselines between Ft. Davis, Texas, and the Leonard and Miles City stations. The results are given in Table 5. These comparisons show that it is possible to achieve GPS accuracies (as contrasted with precisions) of $1{:}10^8$ in differential latitude determination and 1 to $2{:}10^8$ in differential longitude determination over station separations of 1000 to 2000 km.

Examination of Tables 1B-4B shows that for the other large observation groups (groups 2 and 3) the variations in line length determinations from day to day were at the few centimeter level provided at least three base stations were available to support orbit adjustment. This is only a slight decrease in accuracy from the results obtained from group 1 observations. However, as can be seen in Tables 1A-4A in Appendix B, the decrease in repeatability is much greater for the position components, i.e., latitude and longitude. The conclusion derived from these results is that three fixed stations are not adequate to maintain coordinate system orientation during solutions when the orbit is allowed to adjust.

RELATION TO NAD 83 AND GRS-80

The existing horizontal control in the United States is based on the North American Datum of 1983 (NAD 83) reference system. The reference system is defined by a reference coordinate system and a reference ellipsoid. In defining the NAD 83 reference coordinate system, the fixed VLBI stations in the United States were included in the adjustment. Because the VLBI was not used to define all parameters of the NAD 83 coordinate system, and because the current VLBI/SLR coordinate system has changed slightly since the NAD 83 adjustment, there is a difference between the current coordinate system used here and the NAD 83 coordinate system. Using VLBI station coordinates in the two systems, a seven parameter transformation (three translations, three rotations, and a scale) have been determined to go from the current system to NAD 83. These parameters are given in Table 6.

The reference ellipsoid used to express NAD 83 coordinates in terms of latitude and longitude is the GRS-80 ellipsoid. This ellipsoid has a semimajor axis of 6378.137 m and a flattening of 1/298.2. Since GPS positioning is a geometric procedure, the heights produced are ellipsoid heights derived by subtracting from the geocentric radius vector computed in a GPS solution the radius vector to the ellipsoid at the latitude of the station. As a result, GPS ellipsoid heights are not directly comparable to heights derived from leveling (orthometric heights). An orthometric height is a height above the sea level

REPEATABILITY OF DETERMINATIONS
(Deviations from mean plotted at real scale)
1 cm = 1 cm

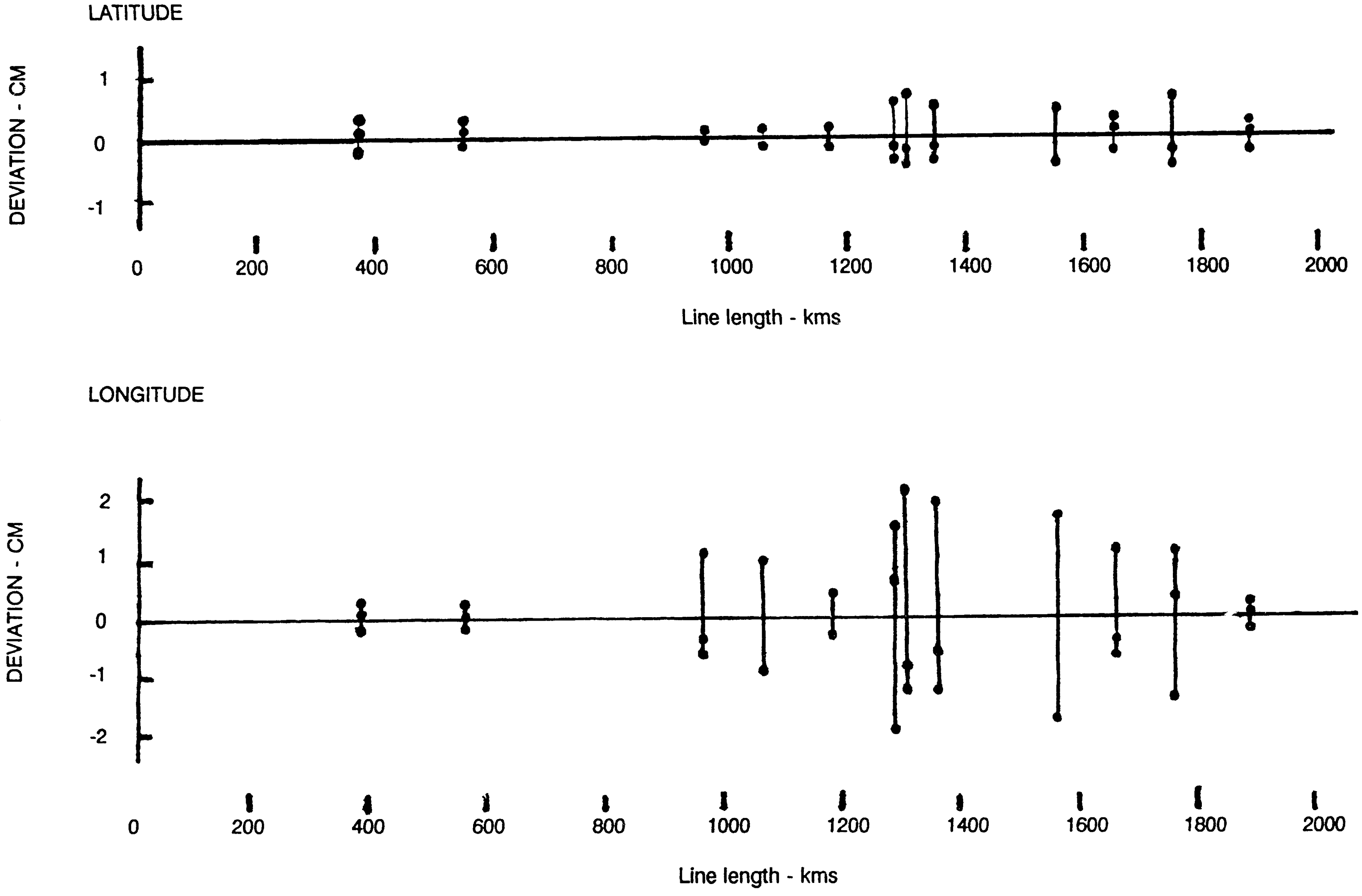

Figure 3

TABLE 5
EVALUATION OF ACCURACY
DIFFERENCE BETWEEN MEAN GPS AND VLBI POSITIONS

MILES CITY
(1752 KM BASELINE)

LATITUDE	LONGITUDE	HEIGHT
4.5 MM	8.2 MM	34.0 MM

LEONARD
(957 KM BASELINE)

LATITUDE	LONGITUDE	HEIGHT
1.8 MM	30.0 MM	47.0 MM

TABLE 6
TRANSFORMATION PARAMETERS FROM VLBI COORDINATE SYSTEM TO NAD 83 SYSTEM

Dx = x translation = 1.055 meters

Dy = y translation = 2.069 meters

Dz = z translation = 0.426 meters

Sc = scale change = -.096 ppm

Rx = rotation about x axis = .0215 arc sec.

Ry = rotation about y axis = .0275 arc sec.

Rz = rotation about z axis = .0010 arc sec.

equipotential surface, i.e., the geoid. In the form of an equation, we have for a point on the earth's surface

$$H = h + N$$

where H = ellipsoid height
h = orthometric height
N = geoid height, i.e., height of the geoid relative to the ellipsoid

To directly compare leveling derived orthometric heights and GPS derived ellipsoid heights, it is necessary to compute geoid heights. Geoid heights can be computed using integration of gravity anomalies over the surface of the earth. By using satellite derived gravity fields for long wavelength components, and local surface gravity measurements for local, short wavelength gravity variations, it is possible to compute geoid heights. Currently, accuracies in the range of ±5 to 10 cm are achievable in the United States. The National Geodetic Survey currently has a program aimed at improved computation methods and an enlarged gravity data base. This program is aimed at achieving accuracies in the ±2 to 4 cm. range. Because geoid height computations will never be perfect, comparisons of GPS derived height differences between stations with leveling derived orthometric height differences will never be as accurate as direct GPS vs. GPS comparison of height differences as a function of time.

CONCLUSIONS AND RECOMMENDATIONS

Examination of the Appendix demonstrates that results obtained for group 1 observations are more accurate than those for the other groups of observations. This is particularly true for baseline components. Table 1A indicates that for the group 1 observations latitude and longitude are as accurate as baseline lengths given in Table 1B. However, as may be seen from the data presented in Appendix B, while the repeatability in baseline length is nearly as good as that of group 1 for some of the other groups, this is by no means the case for baseline components. The cause of repeatability in baseline length, but not in baseline components, must lie in variation from day to day of the orientation of the coordinate system. The difference between group 1 observations and the observations providing answers from other groups lies in the number of stations available to support orbit adjustment, i.e., stations whose positions are known a priori on the basis of VLBI. For all days of the group 1 observations, four stations (Mojave, Ft. Davis, Westford, and Plattville) could be held fixed to support orbit adjustments.

Because of instrument problems either at the fixed VLBI stations (Mojave, Ft. Davis, Westford, Richmond) or at one of the mobile VLBI sites (Bloomington and New Carrollton) being occupied by GPS, there was only 1 day during the remaining observations after the group 1 observations when four stations could be held fixed. It seems clear that less than four stations cannot provide adequate orbit adjustment support to fix orientation. In the case of day 323 of group 2 observations, only two reference stations were available. As may be seen from Table 2B, less than three reference stations does not even support adequate line length determination. The conclusion that one can draw from the above result is that any future observations should be undertaken with the requirement that at least four GPS stations must be collocated at fixed or mobile VLBI sites.

Because of a desire to improve the results for baseline components for groups other than group 1, the question has been explored as to the possibility of other methods of reduction. Software is currently being developed to allow simultaneous reduction of all 3 days of observation of a station group. For such a reduction, the differential station positions would be unknowns that are common to all 3 days, while the orbit adjustment parameters can be day specific. This should allow for better separation of station position and orbit unknowns.

In examining the results of these initial epoch measurements, it was clear that a change in observing strategy would be desirable in any future campaigns. The strategy used did not call for any overlapping between observation groups, other than the permanent GPS stations at the fixed VLBI sites. The result of this approach was that relatively closely spaced stations of the network are not directly connected. In retrospect, it seems clear this is not desirable, particularly since it has been shown that small coordinate system rotations are a possibility. Thus, any future observations should call for a more network like observational approach, with some subset of stations observed in any given observation group observed during another observation group.

A final recommendation is that at some time over the next 2 to 3 years reobservations should be made at the mobile VLBI sites at Miles City, Leonard, Bloomington, and New Carrollton in support of this program. The station at Plattville is also important, but it is anticipated that mobile VLBI observations will continue to be made at this site by NASA.

APPENDIX

STATION POSITIONS AND LINE LENGTHS

TABLE 1-A
GROUP 1
STATION POSITIONS

STATION NAME						
LATITUDE			LONGITUDE			ELLIP. HEIGHT (METERS)
DEGREES	MINUTES	SECONDS	DEGREES	MINUTES	SECONDS	
BRONSON						
31	17	44.53445	89	48	56.38799	47.3576
		.53467			.38896	.4446
		.53420			.38748	.4084
BRINKLEY						
34	53	1.58604	91	10	29.01988	29.0616
		1.58632			.02022	.0624
		1.58583			.01862	.0606
FARM						
32	45	20.70756	93	3	23.44214	81.3903
		20.70572			23.44062	.3154
		20.70546			23.43975	.3415
LINCOLN						
40	45	39.22306	96	42	25.15445	335.1534
		39.22344			25.15556	.0768
		39.22306			25.15417	.1063
LEONARD						
33	54	32.46598	95	47	42.24878	226.2389
		32.46597			42.24931	.2265
		32.46585			42.24858	.2244
NORTH LIBERTY						
41	46	19.28367	91	34	28.68851	204.7268
		19.28373			28.68903	.6468
		19.28363			28.68828	.6751
NMBI						
35	2	29.63628	106	36	52.19789	1597.9082
		29.63622			52.19783	.9010
		29.63635			52.19804	.9481
ROCK						
43	12	1.96763	89	30	5.37511	287.5758
		1.96772			5.37560	.4810
		1.96760			5.37444	.5231
MILLS CITY						
46	23	47.03106	105	51	38.96188	703.9345
		47.03142			38.96215	.8324
		47.03123			38.96152	.8712

LUBBOCK						
33	31	27.75627	101	48	14.11503	937.9730
		27.75620			14.11487	.9695
		27.75607			14.11493	.9172
CHEYENNE						
41	8	2.61949	104	52	2.00519	1867.2941
		2.61946			2.00507	.3496
PIERRE						
44	23	7.03950	100	18	41.02277	531.1099
		7.03924			41.02153	.1388

TABLE 2-A
GROUP 2
STATION POSITIONS

STATION NAME						
LATITUDE			**LONGITUDE**			**ELLIP. HEIGHT (METERS)**
DEGREES	**MINUTES**	**SECONDS**	**DEGREES**	**MINUTES**	**SECONDS**	
ASTRO						
38	12	127.42493	77	22	24.35727	34.542
		.42207			.35026	.802
BLUFFPORT						
36	46	0.04149	90	19	26.15715	68.810
		.04062			.15937	.732
		.04392			.15629	.558
FLNR						
29	34	29.47726	82	20	7.61638	-10.682
		.47733			.61667	.527
		.47707			.62039	.895
FREEMAN						
43	31	22.36192	84	5	26.02083	167.859
		.36003			.01369	168.141
		.35389			.00207	.595
GP37						
35	54	56.81883	85	13	4.09964	221.435
		.81746			.09640	.624
GP47						
35	35	23.75611	89	35	7.91298	53.575
		.75509			.91462	.532
		.75557			.91421	.825
GP57						
35	12	21.05711	88	29	58.24275	155.194
		.05717			.24920	.357
HAPGOOD						
34	3	27.34573	80	34	18.02641	13.979
		.34697			.02677	14.091
		.34613			.02403	.0318
WILLIAMSON						
37	44	54.03067	89	0	51.67745	109.011
		.02987			.67778	108.935
WALTPORT						
32	55	16.56914	80	38	18.47765	-4.0432
		.56945			.47674	.0683

TABLE 3-A
GROUP 3
STATION POSITIONS

STATION NAME	LATITUDE			LONGITUDE			ELLIP. HEIGHT (METERS)
	DEGREES	MINUTES	SECONDS	DEGREES	MINUTES	SECONDS	
ALBERG	44	54	29.31253	73	17	28.49040	36.758
			.31179			.48947	.781
			.31473			.49380	.655
ASHCOPORT	41	46	47.92860	80	42	2.07992	241.363
			.92603			.07509	.219
			.92912			.07836	.234
BEARTOWN	40	4	59.24159	76	0	59.23800	302.165
			.24181			.23882	.129
			.24273			.23968	.067
FURTRELL	36	26	14.81936	77	9	7.89446	-6.796
			.82013			.89492	.799
			.81913			.89446	.883
GREEN BANK	30	26	14.11269	79	49	54.55640	790.223
			.11217			.55533	.164
			.11309			.55655	.176
K169	44	24	16.08784	68	0	43.54436	-18.824
			.08906			.54664	.903
			.09144			.54806	-19.044
LIME	46	8	0.62809	68	4	55.21858	191.217
			.63227			.22367	.372
			.63078			.22433	.384
PRINCETON	40	23	54.76514	74	39	47.25348	2.101
			.76537			.25435	1.998
			.76649			.25615	1.926

TABLE 4-A
GROUP 4
STATION POSITIONS

STATION NAME						
LATITUDE			**LONGITUDE**			**ELLIP. HEIGHT (METERS)**
DEGREES	**MINUTES**	**SECONDS**	**DEGREES**	**MINUTES**	**SECONDS**	
BOLTON						
39	59	29.64438	83	09	15.22273	237.976
		.64514			.22338	.887
ARP 2						
43	59	29.38421	76	01	18.90521	61.045
		.38199			.89973	.421
		.38343			.90353	.400
STATESPORT						
35	45	50.99968	80	57	6.84624	258.854
		.99955			.84702	9.023
		.99944			.84967	9 .035

TABLE 1-B
LINE LENGTH DETERMINATIONS
OBSERVATION GROUP 1

STATION NAME	LINE LENGTH (meters)		
	DAY 316	DAY 317	DAY 318
BRONSOM	1,348,789.553	.535	.564
BRINKLEY	1,282,945.259	.252	.283
FARM	*	1,057,256.564	.584
LINCOLN	1,297,303.971	.958	.970
LEONARD	957,146.442	.428	.441
NORTH LIBERTY	1,654,782.992	.974	.988
NMBI	548,614.002	.000	.006
ROCK	1,885,425.309	.288	.312
MILES CITY	1,752,057.514	.512	.507
LUBBOCK	378,833.555	.555	.550
CHEYENNE	**	1,166,456.353	.353
PIERRE	**	1,555,412.446	.447

* INSUFFICIENT DATA FOR SOLUTION

** NO DATA OBTAINED

LINE LENGTHS COMPUTED RELATIVE TO FT. DAVIS

TABLE 2-B
LINE LENGTH DETERMINATIONS
OBSERVATION GROUP 2

STATION NAME	LINE LENGTH (meters)		
	DAY 321	DAY 322	DAY 323**
ASTRO	*	865,867.913	8.023
BLUFFPORT	592,279.740	.766	.800
FLNR	513,397.142	.143	.085
FREEMAN	1,106,740.999	.979	.853
GP 37	*	223,182.312	.270
GP 47	467,524.803	.824	.832
GP 57	*	360,499.052	.200
HAPGOOD	423,466.742	.741	.806
WILLIAMSON	582,496.403	.385	*
WALTPORT	422,783.341	*	.361
BRAVO	*	*	*

* NO USEFUL DATA OBTAINED

** ONLY TWO REFERENCE STATIONS AVAILABLE

LINE LENGTHS COMPUTED RELATIVE TO NEW CARROLLTON

TABLE 3-B
LINE LENGTH DETERMINATIONS
OBSERVATION GROUP 3

STATION NAME	LINE LENGTH (meters)		
	DAY 326	DAY 327	DAY 328
ALBERG	795,804.308	.297	.330
ASHCOFORT	480,044.662	.525*	.647
BEARTOWN	216,972.608	.603	.617
FURTRELL	214,965.419	.467	.497
GREENBANK	227,234.692	.665	.696
K169	1,019,134.612	.589	.598
LIME	1,142,809.667	.696	.655
PRINCETON	315,398.046	.034	.027

* CAUSE FOR BAD RESULT UNKNOWN

LINE LENGTHS COMPUTED RELATIVE TO MARYLAND POINT

TABLE 4-B
LINE LENGTH DETERMINATIONS
OBSERVATION GROUP 4

STATION NAME	LINE LENGTH (meters)		
	DAY 336	DAY 337	DAY 338
BOLTON	298,136.944	.933	*
STANPORT	*	*	*

STATION NAME	LINE LENGTH (meters)		
	DAY 342	DAY 343	DAY 344
ARP 2	1,021,850.771	.876	.821
STATESPORT	619,560.636	.632	.583

* NO USEFUL DATA OBTAINED

LINE LENGTHS COMPUTED RELATIVE TO BLOOMINGTON

TABLE 1-C
REFERENCE STATION POSITIONS DERIVED FROM VLBI

STATION NAME						
LATITUDE			LONGITUDE			ELLIP. HEIGHT (METERS)
DEGREES	MINUTES	SECONDS	DEGREES	MINUTES	SECONDS	
MOJAVE						
35	19	53.60676	116	53	17.34449	904.553
WESTFORD						
42	36	47.96306	71	29	36.00635	86.329
FT. DAVIS						
30	38	9.60446	103	56	49.11649	1583.508
PLATTVILLE						
40	10	58.06244	104	43	34.83818	1501.351
NEW CARROLLTON						
33	34	21.19125	85	6	34.49384	299.607
BLOOMINGTON						
39	10	45.65345	86	29	54.28572	217.760
MARYLAND POINT						
38	22	24.22672	77	13	53.45068	-26.144
RICHMOND						
25	36	50.75137	80	23	2.62933	-19.298

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11. ABSTRACT *(200 words or less)*

A 45-station geodetic network was established in 1987 using global positioning system (GPS) technology to provide a means of monitoring strain and deformation in the central and eastern United States. Reduction of the initial epoch data showed that accuracies of 1 to 3 cm can be achieved for horizontal position, provided sufficient observations are available and there are four or more fiducial stations whose positions are known a priori, for example from Very Long Baseline Interferometry meansurements. Accuracies obtained provide the ability to determine strain at the $1:10^7$ to $1:10^8$ level. Vertical positions are less accurate because of problems in modeling refraction and are determined at the 5 to 7 cm level. It is planned to remeasure this network at regular intervals in the coming years to place bounds on the strain occurring in the central and eastern United States. This network is also expected to serve as a reference network for more detailed monitoring networks in areas of high risk such as the New Madrid area. Future measurements are expected to provide more accurate results because of increased numbers of GPS satellites available and improved computation software. The improved software will also allow future upgrading of the accuracy of the 1987 observations.

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