NOAA Technical Report NOS 123 NGS 41

GPS Survey of Crustal Motion Network Near Mammoth Lakes, California

Richard A. Snay
H. Clare Neugebauer
Rudolf J. Fury

Rockville, MD
March 1987

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GPS SURVEY OF CRUSTAL MOTION NETWORK NEAR MAMMOTH LAKES, CALIFORNIA

Richard A. Snay
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ABSTRACT. In the fall of 1984, the National Geodetic Survey observed a 17-station geodetic network in the vicinity of Mammoth Lakes, California, using Global Positioning System (GPS) technology. The GPS survey spans an area of active tectonic and magmatic processes as manifested during the past few years by several decimeters of vertical uplift accompanied by an equivalent amount of horizontal displacement. The survey provides the initial epoch of data for monitoring the deformation using a unified three-dimensional approach. This report documents the 1984 GPS survey and our processing of the GPS data. Intersite distances range from 10 m to 35 km. Observations of intersite vectors are characterized by an internal precision of 3 mm plus 0.7 parts-per-million for each component as revealed by a network adjustment. Subsequent GPS surveys of the network are expected to be more precise as improved understanding of related systematic errors is anticipated.

INTRODUCTION

In the fall of 1984, the National Geodetic Survey observed a 17-station geodetic network in the vicinity of Mammoth Lakes, California, using Global Positioning System technology. The survey served two objectives:

* to establish a three-dimensional network suitable for monitoring local crustal deformation and

* to demonstrate GPS capabilities.

The GPS survey spans an area of active tectonic and magmatic processes. Elevation changes on the order of 0.4 m have occurred since 1979 (Castle et al. 1984) accompanied by relative horizontal displacements as large as 0.5 m (Denlinger and Riley 1984). This deformation is associated with the resurgence of the Long Valley caldera, and together with recent seismic activity, the deformation portends a potential volcanic hazard (Kerr 1982; Miller et al. 1982). Although the deformation is presently monitored via classical geodetic techniques--leveling, gravity, and electro-optical distance measuring (EDM)--GPS technology provides certain features that can complement or perform more effectively the present monitoring operations. In particular, GPS can provide the following: (a) unify the now independent horizontal and vertical monitoring efforts, (b) relate local deformation to distant reference points, (c) reduce costs, and (d) soon may provide a precision comparable or better than that achievable with classical technologies.

The purpose of this report is to document the 1984 survey and our processing of the survey data. The following section presents the geophysical setting for the area. Subsequent sections describe the survey, the data reduction process, and results from a network adjustment. Finally, appendix A provides site descriptions for the stations of the GPS network.

GEOPHYSICAL SETTING

The town of Mammoth Lakes lies within the perimeter of the Long Valley caldera (fig. 1), the crater formed 700,000 years ago by a great volcanic eruption that ejected 600 cubic km of material from within the Earth (Bailey et al. 1976). In comparison, the caldera-forming Krakatau explosion of 1883 ejected 18 cubic km of material, and the eruption of Mount St. Helens in 1980 ejected only 0.6 cubic km. During a caldera's formation, the extrusion of the large volume of magma from a shallow magma chamber removes the underpinning of the chamber's roof. The subsequent collapse of the roof produces the caldera. Over the millenia following the eruption, the emplacement of fresh magma into the chamber causes the caldera floor to gradually dome upwards. This resurgence is followed by episodes of lava effusion from volcanic vents in and around the caldera.

Recent seismic activity and accelerated doming of the local terrain near Mammoth Lakes have been detected, possibly presaging a modern episode of volcanic activity. Seven moderate size earthquakes ($5.8 < M < 6.3$) have been recorded near Long Valley between 1978 and 1984 (Gross and Savage 1985) including the M5.8 Round Valley earthquake which occurred on November 23, 1984 during the GPS campaign reported here. Also, more than 0.4 m of relative uplift has occurred within the perimeter of the caldera since 1979 (Castle et al. 1984).

The Mammoth Lakes region lies on the eastern edge of the Sierra Nevada Physiographic Province and is adjacent to the Basin and Range Province. The regional geology is dominated by the Sierra Nevada batholith which was emplaced during the Mesozoic Era into complexly deformed Paleozoic and Mesozoic strata. Incompletely eroded roof pendants are exposed on the surface, especially to the south and the west.

To the north, east, and southeast of the caldera, volcanic materials cover vast areas, particularly near the floors of Owens, Round, Adobe, and Pumice Valleys. These volcanic rocks range in age from Mesozoic to Quaternary and in composition from mafic to rhyolitic. The pyroclastic structure(s) and rhyolitic composition of many of these extrusive rocks are associated with explosive volcanic activity. Some of the youngest rocks exhibit such structures and compositions. Their dates range from Pliocene (5.3 to 1.6 Ma) to Pleistocene (1.6 to 0.01 Ma) and Recent (0.01 Ma to present). The largest area so covered is by a Pleistocene deposit, the Bishop Tuff [0.708 ± 0.15 Ma (Bailey et al. 1976)], associated with the eruption that produced Long Valley caldera.

The terrain is not solely "volcanic". Rather, it is a mixture of morphologies caused by volcanism and glaciation. Hanging and U-shaped valleys, cirques, glacial deposits and other glacially associated morphology resulted from recent alpine glaciation. Lake deposits in Long Valley attest to the existence of a large Pleistocene lake which eventually drained in the direction of the town of Bishop.

A ring fracture zone encircles the caldera depression but is mostly concealed by a covering of alluvium, glacial till, and volcanic rocks. Collapse of the caldera probably took place along these arcuate faults. Most structural features in the area, however, trend NNW. These features include the Sierra Nevada frontal faults (some transecting the caldera), chains of volcanic necks or domes, and small grabens (Bailey et al. 1976).

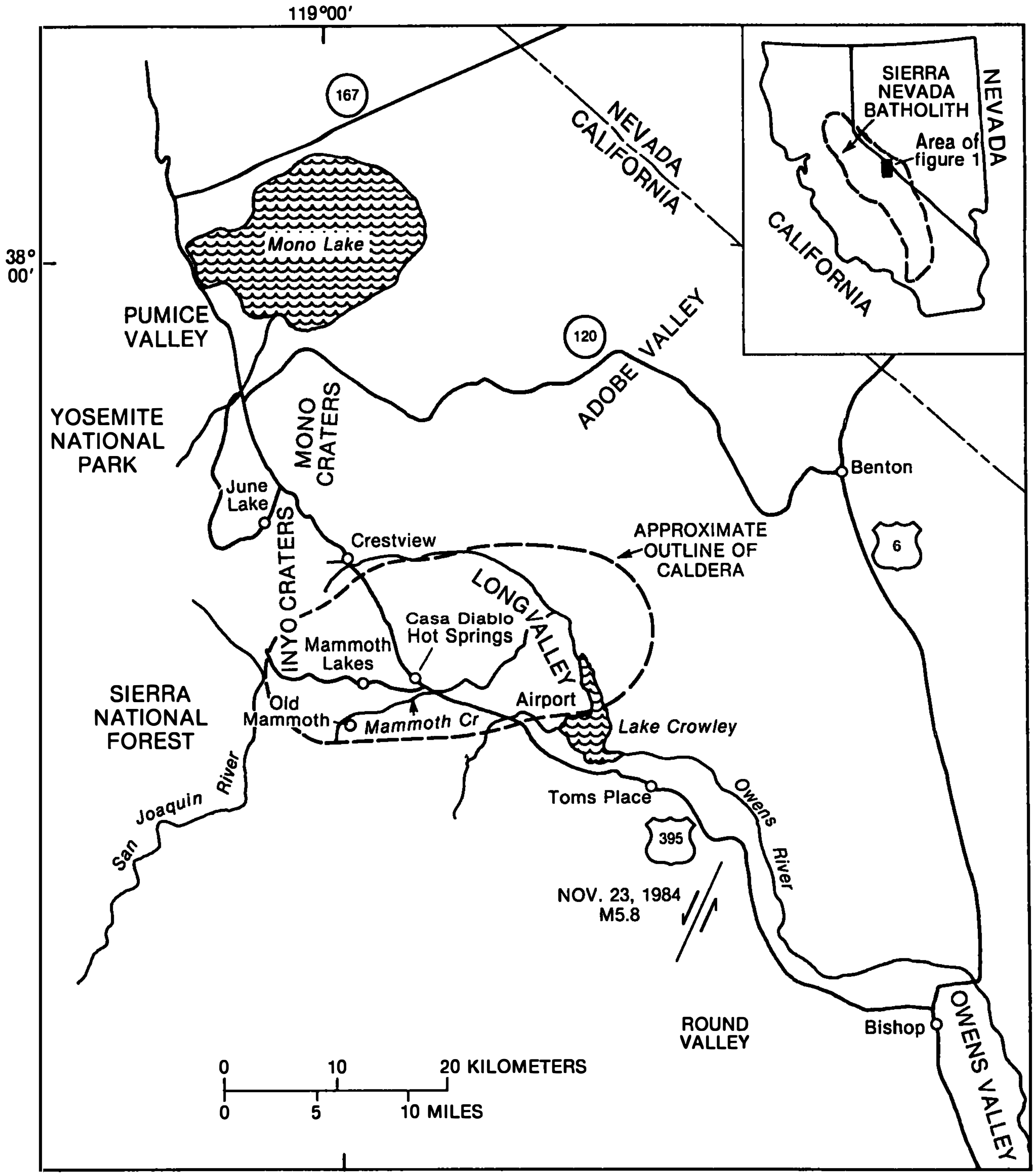

Figure 1.--Index map of the Long Valley area, east-central California. Symbol in the lower right quadrant represents the fault plane and the sense of coseismic slip on this plane as inferred by Gross and Savage (1985) for the M5.8 earthquake of November 23, 1984.

GPS SURVEY

GPS denotes a constellation of Earth-orbiting satellites that broadcast encoded radio signals. By recording the signals from several satellites at two or more simultaneously occupied locations, the three components ($\Delta X, \Delta Y, \Delta Z$) of the associated intersite vectors can be determined. For this survey, these relative coordinates are computed in the World Geodetic System 1972 (WGS-72)--an Earth-centered, Earth-fixed coordinate system (Seppelin 1974). Macrometer™ V-1000 receivers were used for the Mammoth Lakes survey. These receivers measure carrier beat phase, that is, the phase difference of the received signal emitted by a satellite's oscillator and the reference signal generated by the receiver's oscillator. A Macrometer V-1000 is capable of receiving signals from six satellites simultaneously; however, it can track only one of the two satellite-broadcasted frequencies, the L1 frequency (1575.42 MHz).

The surveyed network (fig. 2) includes 17 marks most of which belong to existing EDM or leveling networks that the U. S. Geological Survey regularly survey to monitor crustal deformation near Long Valley (Savage and Cockerham 1984; Castle et al. 1984; Denlinger and Riley 1984; Denlinger et al. 1985). One of the marks (JPL MV 2) is periodically occupied with mobile VLBI instrumentation (NASA 1985). Our GPS survey contains 34 individual observing sessions performed between October 9 and November 30, 1984 (table 1). Each session, except those on November 19 and 20, approximately spanned that 4-hour period of the day (roughly 7:00 a.m. to 11:00 a.m., local time) for which the existing constellation of satellites afforded the best coverage. Two 2-hour sessions were scheduled for each of November 19 and 20. It was on these two days that the shorter network lines near station JPL MV 2 were measured. (See fig. 2 and table 1.)

Assuming the availability of three receivers, we originally designed the network so that each mark would be occupied for at least three different observing sessions (Snay 1986). One of the three receivers, however, was inoperative for most of the campaign. Consequently, only two receivers were deployed for 27 of the 34 sessions. The triple-occupation-per-mark criterion was accomplished, nevertheless, for all but four marks by extending the campaign several extra days. As a consequence good geometric redundancy exists among the set of observations. As described later in this report, this redundancy proved valuable for detecting observational outliers and for determining the precision of the observations.

DATA REDUCTION

The GPS observations were reduced on an HP9000 computer using software entitled SLSQ which incorporates a single-difference reduction algorithm (Remondi 1984; 1985), that is, an algorithm where corresponding phase measurements for two receivers are differenced. In SLSQ these differenced observations are entered into a least squares adjustment procedure to estimate the three components of the intersite vector, relative satellite-to-receiver biases, and timing parameters. Data for each vector were processed independently, even for those vectors measured during the seven sessions for which three receivers were simultaneously deployed.

For SLSQ processing, preliminary station coordinates accurate to about a meter are preferred. Hence, data for individual vectors were first processed through software entitled TLSQ which utilizes a triple-difference algorithm whereby the measured phases are differenced between receiver pairs, between satellite pairs, and between successive data epochs. TLSQ can tolerate many data problems without excessive preprocessing

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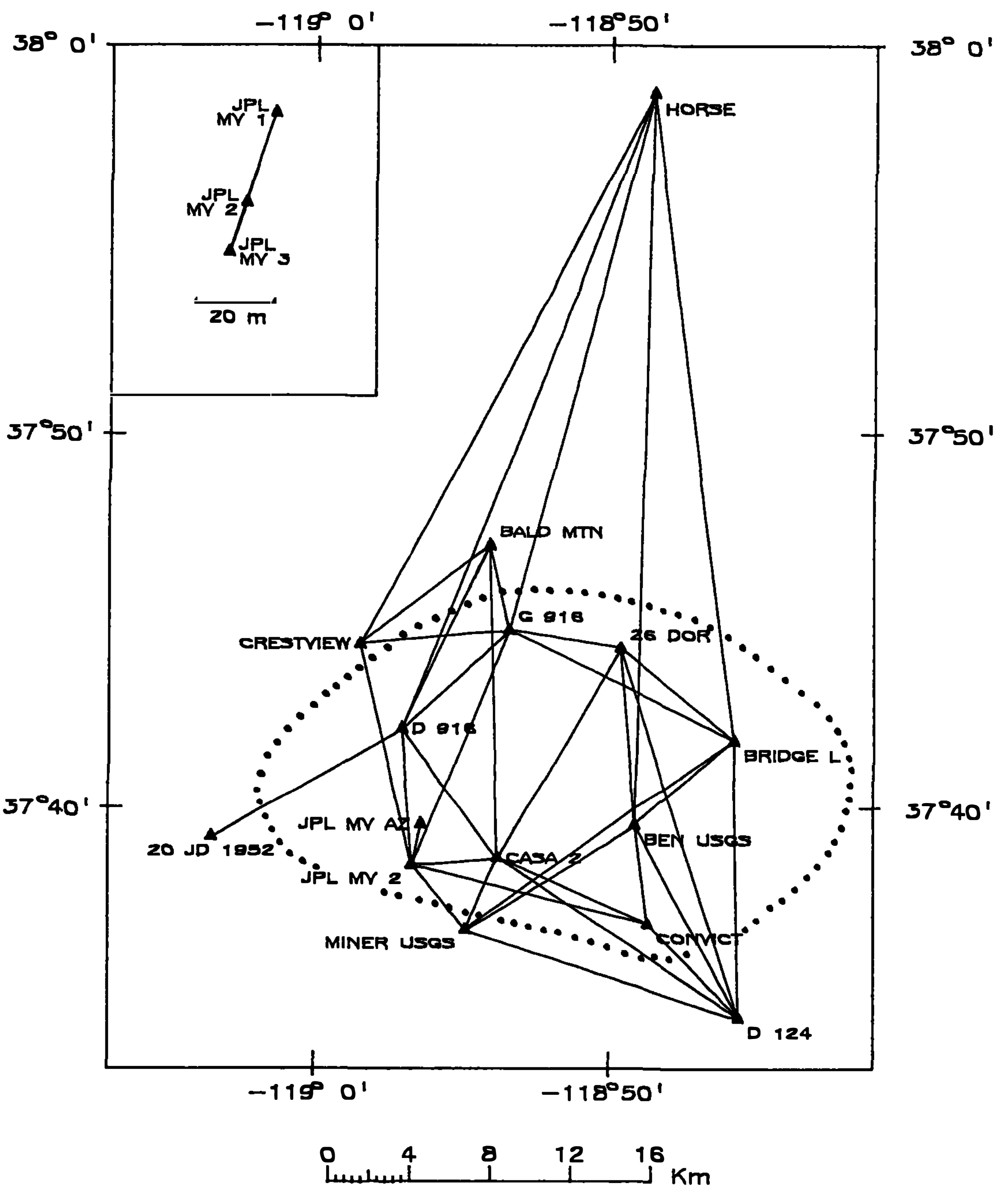

Figure 2.--Geometry of GPS network observed near Mammoth Lakes in the fall of 1984.

because cycle slips, satellite-to-receiver biases, and oscillator instabilities are differenced out. (A cycle slip is an occasional, sudden gain or loss of some whole number of cycles due, for example, to temporary occultation of a satellite.) Although TLSQ presumes that the drift between receiver clocks remains constant over time, this software provides a reasonably accurate estimate for the intersite vector. The intersite vectors obtained with TLSQ were then entered into a network adjustment process whereby a consistent set of WGS-72 coordinates were derived for all network marks. These coordinates served as preliminary positions for the reductions using SLSQ. The network adjustment was constrained by holding station CONVICT at the coordinates:

Table 1.--Summary of GPS observations

Session	Line		Observed Vector (Adjustment Residual) ΔX, meters	ΔY, meters	ΔZ, meters	T_c, msec	T_d, μsec	Adj T_d minus Obs T_d μsec
Oct 9*	BALD MTN	CASA 2	-4066.663 (0.057)	-8220.492 (0.025)	-12442.100 (-.022)	22.00 + ?	32.1 + ?	
OCT 10	CASA 2	JPL MV 2	-3825.898 (-.002)	1938.588 (0.000)	-326.129 (-.004)	14.00 + ?	-1.4**	
OCT 15	CASA 2	CONVICT	5726.576 (-.001)	-5237.352 (0.000)	-2793.666 (0.001)	0.00**	-46.7**	
OCT 16	D 916	20 JD	-10040.459 (0.000)	1331.473 (0.000)	-4002.936 (0.000)	0.00**	44.2**	
OCT 17	BALD MTN	D 916	-6321.247 (-.016)	-2370.313 (-.010)	-7387.145 (0.009)	-2.10 + 0.23	29.0 + 1.9	-6.3
OCT 18	BALD MTN	CRESTVIEW	-6894.174 (0.001)	865.473 (-.004)	-4136.862 (0.007)	0.00**	-39.0**	
OCT 19*	HORSE	CRESTVIEW	-20450.113 (-.013)	-6925.470 (-.149)	-21199.689 (0.010)	-7.43 + ?	-214.3 + 7.6	-252.5
OCT 22	C 916	26 DOR	4641.417 (0.005)	-3124.087 (0.004)	-730.099 (0.002)	-4.50 + 1.80	46.4**	
OCT 23	BRIDGE L	C 916	-8301.824 (0.014)	8266.379 (0.016)	4324.539 (0.004)	0.23 + 0.85	27.3 + 3.4	-9.8
OCT 24	HORSE	BEN	-11027.417 (-.025)	-18320.937 (-.016)	-28377.246 (0.005)	-3.77 + 0.34	21.6 + 6.8	-63.8
OCT 26	BRIDGE L	MINER	-14694.116 (-.001)	1132.479 (-.007)	-7230.270 (-.010)	-4.50 + 0.55	-37.3**	
OCT 29	CRESTVIEW	JPL MV 2	-998.337 (0.004)	-7147.346 (-.003)	-8631.399 (0.000)	-3.10 + 0.20	37.0**	
OCT 30	C 916	BALD MTN	162.291 (-.005)	2289.930 (-.005)	3690.746 (0.006)	0.00**	39.6**	
OCT 31	D 124	CONVICT	-2621.301 (-.011)	4665.190 (-.001)	3733.379 (-.002)	-2.11 ± 0.34	35.5 + 1.7	3.6
NOV 1*	D 124	BRIDGE L	3858.455 (-.211)	7566.628 (0.060)	10953.861 (0.008)	-55.91 + 0.84	-5,000,000**	
NOV 2	BRIDGE L	26 DOR	-3660.382 (-.007)	5142.314 (-.002)	3594.450 (-.004)	-0.91 + 0.57	-39.3 + 2.7	-5.2
NOV 5	C 916	CRESTVIEW	-6731.888 (0.001)	3155.393 (0.002)	-446.098 (-.006)	0.00**	-38.0**	
NOV 6*	MINER	D 124	10835.927 (-.054)	-8699.189 (0.029)	-3723.562 (-.026)	5.38 + 1.20	-39.5 + 7.8	-5.9
NOV 7	MINER	JPL MV 2	-1337.917 (0.003)	3141.972 (-.003)	2477.319 (0.002)	6.55 + 0.41	-31.9 + 1.4	5.3
NOV 8*	MINER	BEN	9083.118 (-.014)	-1106.020 (0.004)	3931.138 (0.020)	-5.60 + 0.72	25.4 + 3.1	-11.6
NOV 9	D 124	BEN	-1752.774 (0.005)	7593.136 (0.008)	7654.749 (-.002)	-0.96 + 0.25	-31.3 + 2.4	0.3
NOV 13	CONVICT	JPL MV 2	-9552.464 (-.010)	7175.938 (0.002)	2467.526 (0.007)	1.57 + 0.74	-46.3**	
NOV 14	D 916	CASA 2	2254.658 (-.001)	-5850.140 (-.004)	-5054.983 (-.003)	3.07 + 0.44	-36.4**	
NOV 19A	JPL MV 2	JPL MV AZ	1141.519 (0.005)	611.566 (-.002)	1692.851 (-.003)	0.00**	-30.0**	
NOV 19B	JPL MV 2	JPL MV 3	-7.139 (0.003)	-4.066 (0.002)	-9.228 (0.000)	0.00**	-79.4**	
NOV 20A	JPL MV 1	JPL MV AZ	1129.248 (-.007)	604.205 (0.001)	1676.969 (0.000)	1.88 + 0.71	19.5**	
NOV 20A	JPL MV 1	JPL MV 3	-19.423 (0.004)	-11.421 (-.002)	-25.103 (-.003)	0.00**	-26.5**	
NOV 20A	JPL MV AZ	JPL MV 3	-1148.659 (-.001)	-615.628 (-.001)	-1702.072 (-.003)	0.00**	-35.2**	
NOV 20B	JPL MV 2	JPL MV 1	12.285 (-.002)	7.359 (0.000)	15.879 (0.000)	0.00**	-46.8**	
NOV 20B	JPL MV 2	JPL MV 3	-7.132 (-.004)	-4.064 (0.000)	-9.230 (0.002)	0.00**	-86.0**	
NOV 20B	JPL MV 1	JPL MV 3	-19.418 (-.001)	-11.423 (0.000)	-25.110 (0.004)	0.00**	-39.2**	
NOV 21	CASA 2	D 124	8347.892 (-.005)	-9902.541 (0.000)	-6527.038 (-.004)	12.58 + 0.29	-61.7 + 2.3	-20.0
NOV 21	CASA 2	MINER	-2487.988 (0.002)	-1203.380 (-.001)	-2803.455 (0.002)	8.00 + ?	-9.2**	
NOV 21	D 124	MINER	-10835.883 (0.010)	8699.161 (-.001)	3723.580 (0.008)	15.78 + 0.42	60.7 + 2.3	28.1
NOV 22	26 DOR	CASA 2	-8545.738 (-.004)	-2806.458 (0.000)	-8021.270 (-.003)	6.83 + 0.23	-32.1**	
NOV 26	D 916	C 916	6158.981 (-.004)	80.400 (-.002)	3696.383 (0.001)	3.95 + 0.23	57.8**	
NOV 26	HORSE	D 916	-19877.235 (0.019)	-10161.410 (-.002)	-24449.958 (-.002)	6.47 + 0.12	-86.9 + 5.0	-29.4
NOV 26	C 916	HORSE	13718.241 (-.002)	10081.025 (-.011)	20753.573 (0.002)	7.18 + 0.13	17.0**	
NOV 27*	HORSE	BRIDGE L	-5416.531 (0.102)	-18347.358 (-.051)	-25078.114 (-.004)	0.00*	0.2**	
NOV 27*	HORSE	BEN	-11027.330 (-.112)	-18321.039 (0.086)	-28377.240 (-.001)	11.40 + 0.15	-56.3**	
NOV 27	BRIDGE L	BEN	-5611.014 (0.001)	26.458 (-.002)	-3299.126 (0.004)	3.70 + 0.38	-55.2 + 1.6	1.4
NOV 28	CONVICT	BEN	868.549 (-.006)	2927.955 (-.001)	3921.373 (-.003)	9.17 + 0.46	67.3 + ?	14.7
NOV 29	26 DOR	BEN	-1950.626 (0.002)	-5115.860 (0.004)	-6893.570 (0.001)	8.51 + 0.26	-44.0 + 4.0	-20.1
NOV 29*	26 DOR	D 124	-197.716 (-.139)	-12709.054 (0.055)	-14548.307 (-.008)	13.90 + 0.23	21.2 + 19.0	20.7
NOV 29	BEN	D 124	1752.780 (-.011)	-7953.149 (0.005)	-7654.746 (-.001)	0.00**	24.5**	
NOV 30	JPL MV 2	D 916	1571.241 (0.002)	3911.558 (-.002)	5381.120 (-.002)	9.32 + 0.28	-23.1**	
NOV 30	C 916	D 916	-6158.979 (0.002)	-80.401 (0.003)	3696.380 (-.004)	2.87 + 0.41	-56.3**	
NOV 30	C 916	JPL MV 2	-7730.222 (0.002)	-3991.964 (0.010)	-9077.500 (-.003)	6.89 + 0.36	0.4**	

* This problematic observation was downweighted in the adjustment.
** This observed value was held fixed in SLSQ.

latitude = 37^{o} 36' 53.37998"(N)
longitude = 118^{o} 48' 40.61808"(W)
ellipsoidal height = (orthometric + geoid) height
= (2138.388 + -27.0) meters
= 2111.388 meters

The WGS-72 latitude and longitude for CONVICT were obtained by transforming this mark's published NAD27 coordinates.

Also before processing with SLSQ, the observations were processed through software entitled TROPC which computes a correction for the delay of the broadcasted radio signal through the troposphere. TROPC incorporates a modified Hopfield troposphere model (Goad and Goodman 1974) for calculating the "wet" component of this delay.

The observations were processed using the "precise" satellite ephemerides provided by the Naval Surface Weapons Center. Orbital uncertainties associated with these ephemerides are thought to be about 20 m or roughly 1 part-per-million (ppm) relative to the altitude of the satellites (B. Remondi, NGS, personal communication, 1986).

With SLSQ, cycle slips and observational outliers are identified with the assistance of graphical displays of the singly differenced residuals. After editing the data for these problems, the user proceeds to estimate relative satellite-to-receiver biases. These biases, except the one corresponding to the user-selected base satellite, are then fixed, whenever possible, to nearby integer values when the user reruns SLSQ to obtain final estimates for the intersite vector components.

In reducing the data, the SLSQ software allows the option to solve for two timing parameters, T_c and T_d. The T_c parameter represents the clock offset from UTC for the user-selected "master" or "base" receiver, and T_d represents the clock offset between the two receivers. In the field the master receiver is synchronized with UTC at the 1 millisecond level using GOES system timing, and then the relative offset between receivers is measured to a fraction of a microsecond. Thus in SLSQ, one would expect that T_c could be set to zero and T_d to the measured offset. Instead we often found it useful to solve for one or both of these parameters in SLSQ. In particular, the SLSQ estimates for T_c were frequently several times larger than their corresponding standard errors (table 1). Similarly, the differences between estimated and measured values of T_d were often more than a factor of two larger than their corresponding standard errors (table 1 also). These apparent discrepancies between field measurements and SLSQ estimates probably do not represent actual timing errors but are the effect of various unmodeled systematic errors (orbits, refraction, multipath, etc.) being mapped onto these two parameters.

Further evidence for the existence of unmodeled systematic error is given in figure 3 where the root mean square (rms) of the single-difference residuals is plotted as a function of intersite distance. This rms provides a measure of how well the SLSQ-generated estimates for the adjusted parameters fit the observed phase data. Figure 3 illustrates how rms increases essentially linearly as a function of intersite distance up through distances of about 15 km. Above this distance there is too much scatter in the derived rms's to draw any conclusion. Eight of the symbols plotted in figure 3 represent vectors whose reduced components disagreed with other GPS observations as revealed by a subsequent network adjustment (discussed in the following section). These eight data should probably be ignored in the interpretation of figure 3. They have been plotted here only for the sake of completeness. Their rms's, however, are not incompatible with those obtained for the other vectors. This result may be explained by the fact that seven of the eight corresponding sessions were truncated

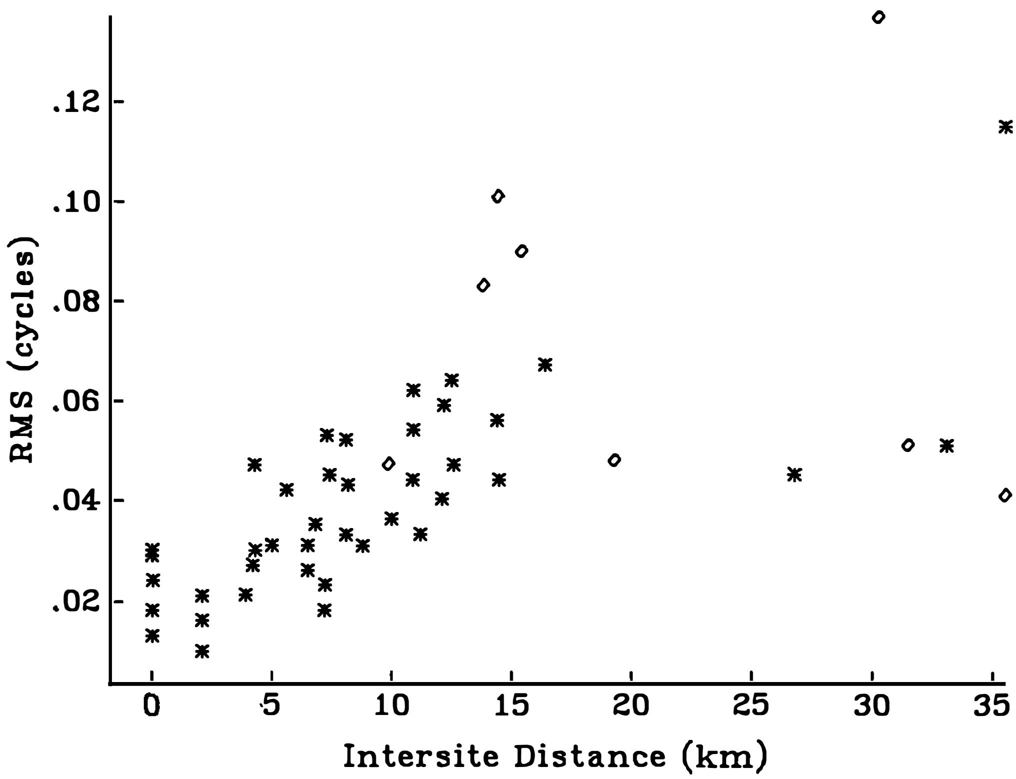

Figure 3.--The rms for single difference phase residuals plotted as a function of intersite distance. One cycle represents approximately 0.19 m. The diamond-shaped symbols represent the rms's for those observed vectors that are incompatible with other observed vectors as revealed by a network adjustment.

as a result of malfunctioning hardware. Consequently, these seven sessions contain only 50 to 75 percent of the number of phase readings normally acquired.

NETWORK ADJUSTMENT

The set of individually reduced vector observations were entered, with corresponding estimates for their uncertainties, into the network adjustment program, NASSTI, which implements the adjustment model of Vincenty (1982). With this input, NASSTI generates least squares estimates for the three-dimensional coordinates of the network marks. The adjustment enables us to assess the internal precision of the network, to test the estimated uncertainties of individual vector observations, and to detect any blunders in the individual determinations. For the network adjustment, the coordinates of station CONVICT were held fixed at their previously stated values. This constraint was introduced because the derived vectors provide no information pertaining to absolute position.

For convenience, the network adjustment included all derived vectors without allowance for the correlations that exist among different vectors. In actuality, however, different vectors are correlated. For example, the three vectors obtained during any one of the seven observing sessions for which all three receivers operated simultaneously are mutually dependent. Also different vectors are correlated because orbit-defining parameters correspond in span to several observing sessions. More rigorous consideration of intervector correlations must await the availability of reduction software with multiple vector and multiple session capability.

Covariance matrices for the individual GPS vectors were originally obtained as a byproduct of the SLSQ processing. The variance elements of these derived matrices, however, were found to be too small relative to the magnitude of the residuals produced in NASSTI. The SLSQ-generated covariances, consequently, are considered unrepresentative of the total error budget. We thus decided to estimate empirically more appropriate covariance matrices. We assumed that the standard error of each vector component is adequately quantified by the formula

$$\sigma_{ab} = (a^2 + b^2L^2)^{1/2} \quad (1)$$

where L represents intersite distance and a and b are parameters to be determined. By trial and error we found that the Mammoth Lakes data were best characterized when a = 3 mm and b = 0.7 x 10^{-6}. For comparison, we estimated values for a and b that approximate the standard errors obtained from SLSQ. These estimates, a = 0.5 mm and b = 0.2 x 10^{-6} (fig. 4), are significantly lower than the empirically derived values because the SLSQ error estimates do not include certain error sources, for example, the satellite ephemerides error.

For lack of information we set to zero all off-diagonal covariance elements for each observed vector entered into NASSTI. SLSQ had produced nonzero values for these elements, but because of the apparent dominance of unmodeled systematic errors, we

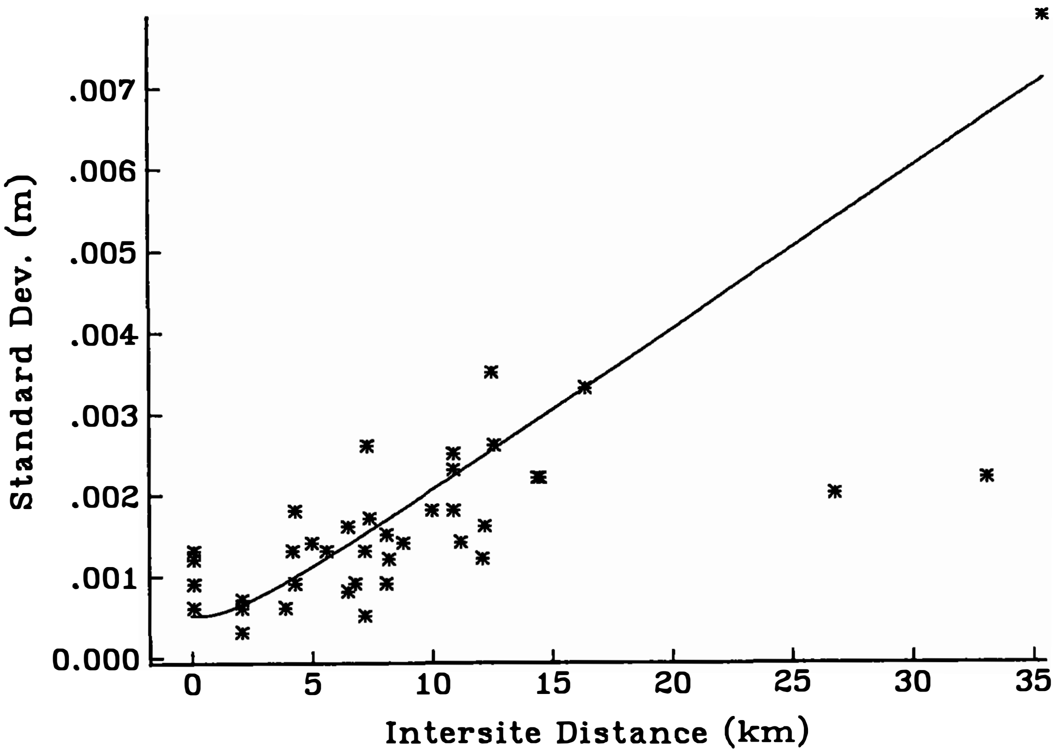

Figure 4.--Standard deviations for selected components of the observed vectors as generated during SLSQ processing and plotted as a function of intersite distance. The curve represents σ_{ab} of eq. (1) with a = 0.5 mm and b = 0.2 x 10^{-6}. A network adjustment reveals that these standard deviations are unrealistically small as compared to corresponding residuals.

place little confidence in the SLSQ values. Consequently, the covariance matrix S assigned to a vector $V = (\Delta X, \Delta Y, \Delta Z)^T$ is given by

$$S = \begin{bmatrix} \sigma^2_{ab} & 0 & 0 \\ 0 & \sigma^2_{ab} & 0 \\ 0 & 0 & \sigma^2_{ab} \end{bmatrix} \tag{2}$$

with $\underline{a}$ = 3 mm and $\underline{b} = 0.7 \times 10^{-6}$. These a- and b-values were chosen so that s_o^2 would equal approximately one in value where

$$s_0^2 = \frac{\sum_{i=1}^{N} (V_i - W_i)^T S_i^{-1} (V_i - W_i)}{3(N-M-1)} \tag{3}$$

where

V_i = observed i-th vector
W_i = adjusted i-th vector
S_i = covariance matrix for i-th vector
N = number of vectors
M = number of marks

These a- and b-values, however, represent only an internal measure of precision. Unmodeled systematic errors might contribute an overall network scale or orientation bias that would be invisible in the adjustment process. Thus the true accuracy for the Mammoth Lakes data may be more appropriately represented by higher values for the a- and b-parameters.

In eq. (1), the a-parameter is thought to reflect in great part the effect of multipath error (Bletzacker 1985), the antenna's phase-center uncertainty (Sims 1985), and the error in positioning the receiver's antenna relative to the mark. The b-parameter is thought to reflect in great part the effect of both ephemerides error and refraction error. We expect that both the a- and the b-values will decline in magnitude for subsequent GPS surveys as the accuracy with which satellite ephemerides can be produced improves and as understanding of refraction and multipath errors improves. With regard to positioning the antenna, the appropriate antenna-mark offsets were measured both before and after each observing session. On a few occasions, mainly for the last few days of the campaign when subfreezing air temperatures were encountered, these before and after measurements disagreed by a few millimeters. Field personnel attributed these discrepancies to ground thaw.

Figures 5, 6, and 7 illustrate various components of the residual vectors plotted as a function of intersite distance. Figure 8 illustrates the distance residual (difference between observed and adjusted value for an intersite distance) also plotted as a function of intersite distance. Figure 8 reveals that the length of the observed vector is determined more precisely than the individual vector components. Distance residuals are roughly characterized by values of 3 mm and 0.5×10^{-6} for $\underline{a}$ and $\underline{b}$, respectively. Unlike the vector components, vector length is independent of uncertainties in orientation.

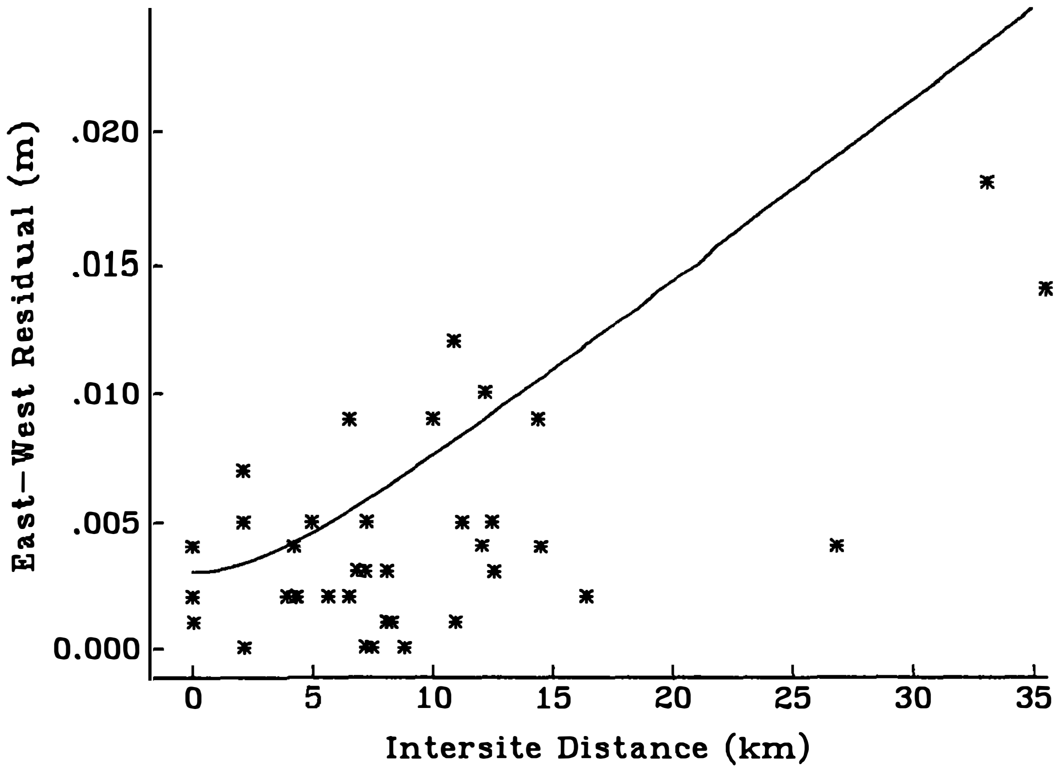

Figure 5.--Magnitude of east-west component of residual vector (from network adjustment) plotted as a function of intersite distance. The curve represents σ_{ab} of eq. (1) with $\underline{a}$ = 3 mm and $\underline{b}$ = 0.7 x 10^{-6}.

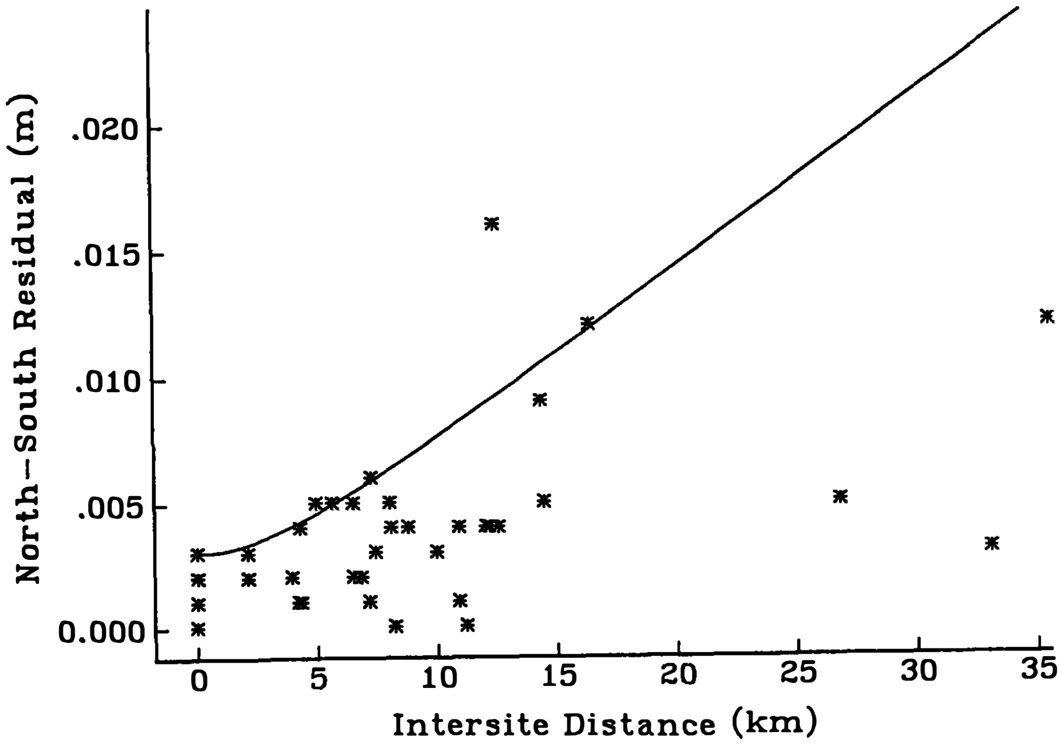

Figure 6.--Magnitude of the north-south component of residual vector (from network adjustment) plotted as a function of intersite distance. The curve represents σ_{ab} of eq. (1) with $\underline{a}$ = 3 mm and $\underline{b}$ = 0.7 x 10^{-6}.

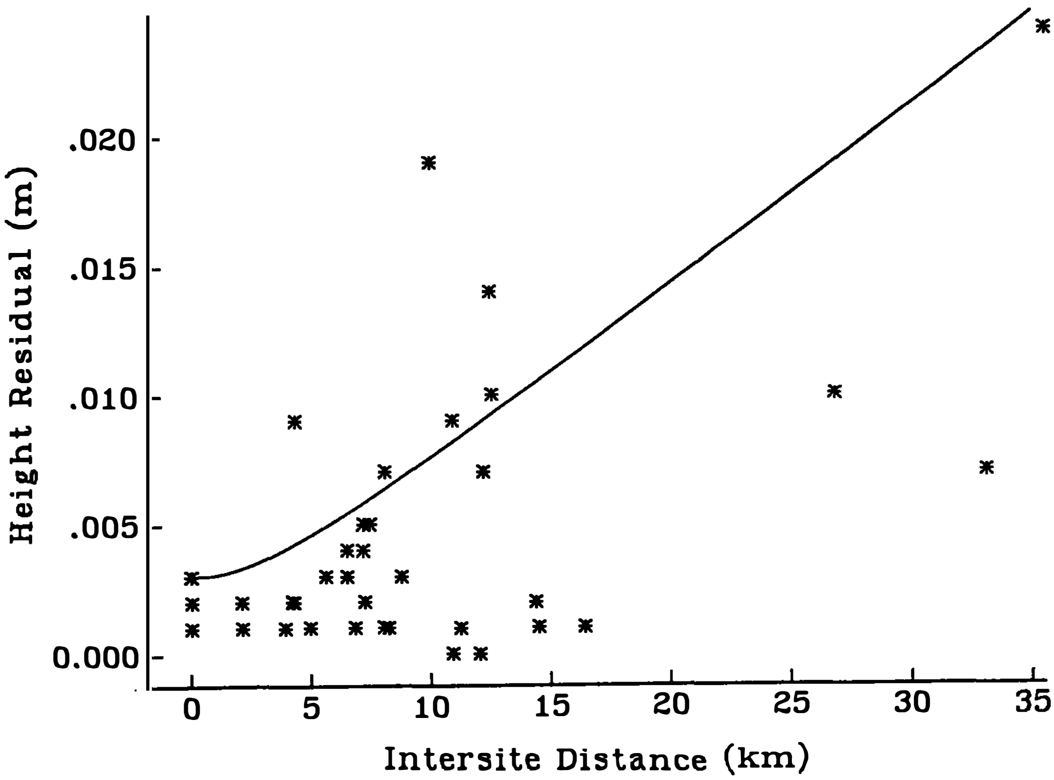

Figure 7.--Magnitude of vertical component of residual vector (from network adjustment) plotted as a function of intersite distance. The curve represents σ_{ab} of eq. (1) with a = 3 mm and b = 0.7 x 10^{-6}.

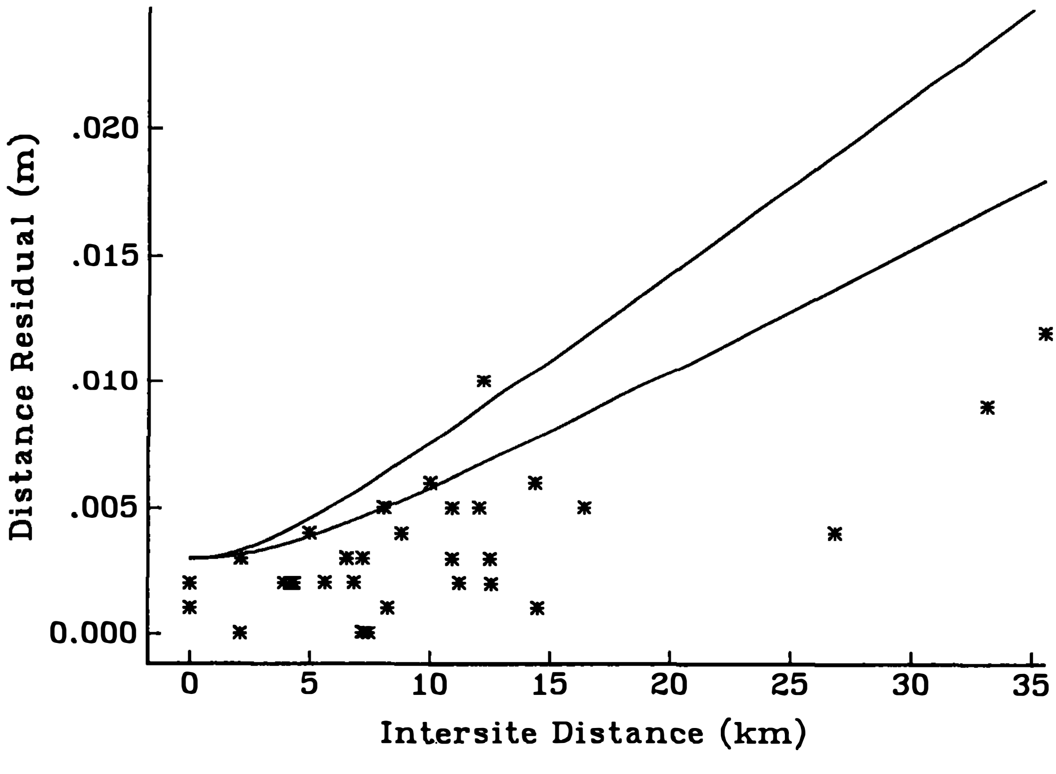

Figure 8.--Magnitude of the distance residual, that is, the difference between observed and calculated intersite distance, plotted as a function of intersite distance. The curves represent σ_{ab} of eq. (1) with a = 3 mm and b = 0.5 x 10^{-6} in one case and b = 0.7 x 10^{-6} in the other.

Table 2.--Adjusted WGS-72 coordinates for Mammoth Lakes network

Station	X meters	Y meters	Z meters	Latitude (N)	Longitude (W)	Ellip. Ht meters
BALD MTN	-2440359.367	-4420451.462	3888198.161	37 47 2.05036	118 54 4.97315	2748.4091
CASA 2	-2444425.974	-4428671.929	3875756.040	37 38 41.22000	118 53 48.13847	2385.0808
JPL MV 2	-2448251.874	-4426733.341	3875429.907	37 38 29.80934	118 56 42.91246	2307.3593
CONVICT 1956	-2438699.399	-4433909.280	3872962.374	37 36 53.37998	118 48 40.61808	2123.6450
D 916	-2446680.631	-4422821.785	3880811.025	37 42 10.80479	118 57 4.05626	2284.8012
20 JD 1952 9175	-2456721.090	-4421490.312	3876808.089	37 39 14.68368	119 3 28.60855	2769.5660
CRESTVIEW 1956	-2447253.541	-4419585.992	3884061.306	37 44 24.82232	118 58 28.47625	2253.4658
HORSE USGS 1934	-2426803.415	-4412660.373	3905260.985	37 58 44.74208	118 48 33.12286	2676.0688
G 916	-2440521.654	-4422741.387	3884507.410	37 44 46.08807	118 53 25.58332	2134.9703
26 DOR USGS	-2435880.232	-4425865.470	3883777.313	37 44 17.52587	118 49 38.03746	2080.2249
BRIDGE L USGS	-2432219.843	-4431007.782	3880182.867	37 41 50.91450	118 45 45.99895	2051.3043
BEN USGS	-2437830.856	-4430981.326	3876883.744	37 39 33.15330	118 49 7.12976	2155.2092
MINER USGS	-2446913.960	-4429875.310	3872952.586	37 36 44.57051	118 54 53.21640	2460.2393
D 124	-2436078.087	-4438574.470	3869228.998	37 34 21.55105	118 45 35.45748	2085.6252
JPL MV AZ MK	-2447110.349	-4426121.776	3877122.755	37 39 34.80683	118 56 14.24386	2480.3295
JPL MV 3	-2448259.010	-4426737.405	3875420.679	37 38 29.43361	118 56 43.08690	2307.2750
JPL MV 1	-2448239.591	-4426725.982	3875445.786	37 38 30.46224	118 56 42.61941	2307.2516

From preliminary network adjustments, the residuals for eight observed vectors were deemed excessive. (See table 1.) These eight observations were given minimal weights or, equivalently, large standard errors (~1 m) in the final NASSTI adjustment so that they would not significantly influence estimates for the adjusted positional coordinates (table 2). Upon inspecting the descriptive text for the observing sessions corresponding to these eight vectors, it was discovered that generator failures account for the problems with five of these eight observations. Gusty winds or receiver malfuntion account for the problems with the other three suspect observations. Because these eight data are considered atypical, their residuals do not appear in figures 5 through 8.

Because the network adjustment assumes that station coordinates remain constant for the duration of the survey, we were concerned about displacements that occurred as a result of the M_L 5.8 Round Valley earthquake of November 23, 1984. Seven of the 34 GPS observing sessions postdate this seismic event. Moreover, each postseismic session includes one or more sites that were also occupied during that part of the survey preceding the earthquake. Based on independent EDM and seismic data, Gross and Savage (1985) model the coseismic deformation as 0.125 ± 0.046 m of left-lateral slip on a 10-km by 10-km dislocation surface in an elastic halfspace. This surface, which represents the disrupted vertical fault, strikes N20°E and is located about 35 km southeast of the town of Mammoth Lakes (fig. 1). Calculations based on dislocation theory (Chinnery 1961) reveal that 0.125 m of slip would produce horizontal strains less than 0.3 ppm and relative elevation changes less than 2 mm for network lines. Such displacements are significantly lower than the noise level attributed to the GPS observations of this survey. Indeed, adjustment residuals (table 1) provide no apparent evidence for identifiable coseismic displacements.

EPILOGUE

The Mammoth Lakes GPS survey demonstrates that GPS technology already provides a viable alternative for monitoring crustal deformation at the 1 ppm level. This level of accuracy suffices to monitor some of the larger crustal-movement features near Long Valley which occur at rates of several centimeters per year. Better accuracy, however, is required to quantify the more subtle movements like those associated with the 1984 Round Valley earthquake. An accuracy level of approximately 0.1 ppm for medium-length lines (~20 km) is desired. Beutler et al. (1987) and Bock et al. (1986) have demonstrated that GPS can already attain ~0.1 ppm accuracy over intersite distances exceeding 70 km. This level of accuracy may also be attainable for shorter lines in the near future with the advent of improved satellite ephemerides and with better understanding of refraction and multipath effects.

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APPENDIX A.--SITE DESCRIPTIONS

This section describes the various sites near Mammoth Lakes which were occupied during the GPS survey performed in the fall of 1984.

Station Designation: JPL MV 2

This site is located in the fenced utility yard of the Sewage Processing Plant. To reach the plant proceed on Highway 395 north through Bishop, CA, and take the Mammoth Lakes exit, Highway 203. Plant is located 1.5 miles west of this intersection on the south side of Highway 203. The reference marks, designated JPL MV 1 and JPL MV 3, are also located in the fenced utility yard.

Station Designation: CASA 2 1975

This site is 175 feet NNE of CASA 1956.The monument is a brass cap set in concrete about 0.5 inch above the land surface. The monument is surrounded by a circle of large chunks of obsidian. To reach CASA 1956 from the junction of Highway 395 and Highway 203, go east on Highway 203 for 0.2 km (0.1 mi) to its end, continue ahead for 0.3 km (0.2 mi) to a T-intersection with former Highway 395, and the azimuth mark. Turn right on the former highway for 0.6 km (0.4 mi) to a dirt road left. Turn left on the dirt road for 0.2 km (0.1 mi) to a fork, keep right for 0.1 km (0.05 mi) to a crossroad. Turn right for 0.2 km (0.1 mi) to a fork, keep left for 0.8 km (0.5 mi) to a fork, keep right for 0.7 km (0.45 mi) to a fork, keep right for 0.3 km (0.2 mi) to a fork, keep right for 0.2 km (0.1 mi) to the summit and the station on the left.

Station Designation: 20 JD 1952 9175

6.1 mi NW of Mammoth Lakes Post Office at Minaret Summit, 40 feet N of center of the road, 8 feet N of sign, 5 feet SE. of small pine tree, in concrete post; standard tablet stamped "20 JD 1952 9175".

Station Designation: 26 DOR 1975

1.4 mi SE of Crestview Highway Maintenance Station along Highway 395 to junction with Owens River Road, thence 8.5 mi E along Owens River Road; 53 feet W of gate, 50 feet N of road, 0.5 feet S of fence; set on copper-coated rod encased in white plastic pipe; standard tablet stamped "26 DOR 1975".

The remaining sites existed as elements of either the national horizontal control network or the national vertical control network previous to the 1984 GPS survey. Their descriptions follow in the adopted NOAA formats.

*************************** R E C O V E R Y   N O T E ***************************

STATION NAME--CRESTVIEW   STATE--CA   COUNTY--MONO   QUAD--N371184   STA--

	YEAR	CP		REACHED BY	PACK TIME	HGT OF TELESCOPE
RECOVERY BY--NGS	1983	CLN	CONDITION--GOOD	LIGHT TRUCK	00 HRS 00 MIN	METERS

CODE	MARK TYPE *********	SETTING/LANDMARK TYPE ***	MAGNETIC PROPERTY
SURFACE--D13	SURVEY DISK	SET INTO THE TOP OF A METAL PIPE SURROUNDED BY CONCRETE	

THE STATION, REFERENCE MARK 1, AND BM X 123 WHICH SERVES AS REFERENCE MARK 2, WERE RECOVERED IN GOOD CONDITION. THE AZIMUTH MARK HAS BEEN DESTROYED BY HIGHWAY WIDENING CONSTRUCTION. THE 1956 DESCRIPTION DOES NOT MENTION AN UNDERGROUND MARK.

THE STATION IS LOCATED 1.6 KM (1 MI) SOUTHEAST OF THE CADH MAINTENANCE STATION AT CRESTVIEW, ALONG SIDE U.S. HIGHWAY 395 AND 31.4 METERS (103 FEET) SOUTHWEST OF THE HIGHWAY.

TO REACH THE STATION FROM THE CADH MAINTENANCE STATION AT CRESTVIEW GO SOUTHEAST ON U.S. HIGHWAY 395 FOR 1.6 KM (1.0 MI) TO THE STATION ON THE RIGHT, SOUTHWEST, SIDE OF THE HIGHWAY.

THE STATION IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---CRESTVIEW 1956--- SET INTO THE TOP OF A METAL PIPE PROJECTING 20 CM (7.9 INCHES) ABOVE THE GROUND LOCATED 31.4 METERS (103 FEET) SW FROM THE CENTER OF U.S. HIGHWAY 395 AND 15.9 METERS (52 FEET) NE FROM A METAL MESH SNOW FENCE.

REFERENCE MARK NO. 1 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---CRESTVIEW NO 1 1956--- SET INTO THE TOP OF A ROUND CONCRETE MONUMENT 30 CM (11.8 INCHES) IN DIAMETER PROJECTING 5 CM (2.0 INCHES) ABOVE THE GROUND LOCATED 28 METERS (92 FEET) SW FROM THE CENTER OF HIGHWAY, 18.3 METERS (60 FEET) NE FROM A METAL MESH SNOWFENCE, AND LOWER THAN THE STATION.

REFERENCE MARK NO. 2 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---X 123 1932--- SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT 30 CM (11.8 INCHES) ON SIDE PROJECTING 10 CM (3.9 INCHES) ABOVE THE GROUND LOCATED 32.6 METERS (107 FEET) NE FROM A METAL MESH SNOWFENCE, 17.1 METERS (56 FEET) SW FROM THE CENTER OF THE HIGHWAY, AND LOWER THAN THE STATION.

************************** R E C O V E R Y   N O T E **************************

STATION NAME--CONVICT STATE--CA COUNTY--MONO QUAD--N371184 STA--

	YEAR	CP		REACHED BY	PACK TIME	HGT OF TELESCOPE
RECOVERY BY--NGS	1983	CLN	CONDITION--GOOD	LIGHT TRUCK	00 HRS 05 MIN	METERS

CODE	MARK TYPE *********	SETTING/LANDMARK TYPE ***	MAGNETIC PROPERTY
SURFACE--D09	SURVEY DISK	SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT	

THE STATION MARK REFERENCE MARKS 3, 4 AND AZIMUTH MARK 2 WERE RECOVERED IN GOOD CONDITION. REFERENCE MARKS 1, 2 AND AZIMUTH MARK 1 WERE DESTROYED IN 1961.

THE STATION IS LOCATED 47.5 KM (29.5 MI) NORTHWEST OF BISHOP, 14.5 KM (9 MI) EAST-SOUTHEAST OF MAMMOTH LAKES, 9.6 KM (6 MI) SOUTHEAST OF CASA DIABLO HOT SPRINGS, 3.2 KM (2.0 MI) WEST OF CROWLEY LAKE, 1 KM (0.6 MI) NORTHWEST OF MCGEE CREEK HIGHWAY MAINTENANCE YARD, ABOUT 61 METERS (200 FEET) NORTH OF THE NORTH END OF A GUARD RAIL, ON THE OUTSIDE OF A CURVE, ON A LOW FLAT RIDGE IN THE SE 1/4, SECTION 7, R29E, T4S, ABOUT 26 METERS (85 FEET) NORTHEAST OF THE NORTHBOUND LANES OF U.S. HIGHWAY 395, ABOUT 6 METERS (20 FEET) HIGHER THAN THE ROAD SURFACE, 7.8 METERS (26 FEET) SOUTHWEST OF A FENCE AND 6 FEET SOUTHWEST OF A WITNESS POST.

TO REACH THE STATION FROM THE MAMMOTH LAKES INTERCHANGE OF U.S. HIGHWAY 395 AND STATE HIGHWAY 203, ABOUT 4.8 KM (3 MI) EAST OF MAMMOTH LAKES GO SOUTHEAST ON HIGHWAY 395 FOR 11.3 KM (7 MI) TO A CROSSROAD (CROWLEY LAKE DRIVE TO THE RIGHT, ENTRANCE ROAD TO MCGEE CREEK MAINTENANCE YARD TO THE LEFT), MAKE A U-TURN AND GO NORTHWEST ON HIGHWAY 395 FOR 1.1 KM (0.2 MI) TO THE AZIMUTH MARK 2 ON THE RIGHT AND THE SOUTHEAST END OF A GUARDRAIL, CONTINUE NORTHWEST ON HIGHWAY 395 FOR 0.5 KM (0.3 MI) TO THE NORTHWEST END OF THE GUARDRAIL AND THE STATION ON THE RIGHT, NORTHEAST.

THE STATION IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---CONVICT 1956--- SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT 30 CM (11.8 INCHES) ON SIDE FLUSH WITH THE GROUND LOCATED 26 METERS (85 FEET) NE FROM THE NORTHBOUND LANES OF HIGHWAY 395, 7.9 METERS (26 FEET) SW FROM A DOUBLE BRACED FENCE POST, AND 1.8 METERS (6 FEET) SW FROM A WITNESS POST, ABOUT 6 M (20 FT) HIGHER THAN ROAD.

THE UNDERGROUND MARK IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---CONVICT 1956--- SET INTO AN IRREGULAR MASS OF CONCRETE 1.1 METERS (4 FEET) BELOW THE SURFACE.

REFERENCE MARK NO. 3 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---CONVICT 1956 NO 3--- SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT 30 CM (11.8 INCHES) ON SIDE PROJECTING 30 CM (11.8 INCHES) ABOVE THE GROUND LOCATED 3.7 METERS (12 FEET) NE FROM THE FENCE, 0.6 METER (2 FEET) NW FROM A METAL POST, AND LOWER THAN THE STATION.

REFERENCE MARK NO. 4 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---CONVICT 1956 NO 4--- SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT 30 CM (11.8 INCHES) ON SIDE PROJECTING 15 CM (5.9 INCHES) ABOVE THE GROUND LOCATED 3 METERS (10 FEET) NE FROM THE FENCE, 0.3 METER (1 FOOT) SE FROM A METAL POST, AND LOWER THAN THE STATION.

AZIMUTH MARK NO. 2 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---CONVICT 1956 RESET 1961--- SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT 30 CM (11.8 INCHES) ON SIDE PROJECTING 20 CM (7.9 INCHES) ABOVE THE GROUND LOCATED 46 METERS (151 FEET) E FROM A GATE AND 13.7 METERS (45 FEET) N FROM A TWO STRAND BARBED WIRE FENCE.

TO REACH THE AZIMUTH MARK FROM THE JUNCTION OF CROWLEY LANE DRIVE AND U.S. HIGHWAY 395, WHICH IS ABOUT 11.2 KM (2 MI) SOUTHEAST OF CASA DIABLE HOT SPRINGS, GO NORTHWEST ON HIGHWAY 395 FOR 1.3 KM (0.8 MI) TO A SIDE ROAD RIGHT AT THE SOUTHEAST END OF A GUARDRAIL.

**************************** R E C O V E R Y   N O T E ****************************

STATION NAME--BALD MTN			STATE--CA	COUNTY--MONO		QUAD--N341184	STA--
	YEAR	CP		REACHED BY	PACK TIME		HGT OF TELESCOPE
RECOVERY BY--NGS	1983	CLN	CONDITION--GOOD	FOUR-WHEEL-DRIVE	HRS	MIN	METERS

CODE	MARK TYPE	SETTING/LANDMARK TYPE	MAGNETIC PROPERTY
SURFACE--P50	PIPE CAP	IN ROCK OUTCROP	

THE STATION WAS RECOVERED IN GOOD CONDITION. NO DATA AVAILABLE AT THE TIME OF RECOVERY AS TO THE ESTABLISHING AGENCY. THE STATION WAS OBSERVED BY USGS IN 1982.

THE STATION IS LOCATED ABOUT 9.6 KM (6 MI) NORTHEAST OF CRESTVIEW, ON TOP OF BALD MOUNTAIN, NEAR THE FOREST SERVICE WEATHER STATION.

TO REACH THE STATION FROM THE CADH MAINTENANCE GARAGE IN CRESTVIEW, GO NORTHWEST ON U.S. HIGHWAY 395 FOR 3.7 KM (2.3 MI) TO A SIDE ROAD RIGHT. TURN RIGHT AS PER SIGN (BALD MOUNTAIN LOOKOUT 7) FOR 2.6 KM (1.6 MI) TO A Y-JUNCTION, KEEP RIGHT AS PER SIGN FOR 3 KM (1.9 MI) TO A Y-JUNCTION, KEEP RIGHT FOR 0.5 KM (0.3 MI) TO A FORK, KEEP RIGHT AS PER SIGN FOR 3.9 KM (2.4 MI) TO A Y-JUNCTION, KEEP RIGHT AS PER SIGN FOR 1 KM (0.65 MI) TO A LOCKED GATE (A USFS STANDARD LOCK, KEY CAN BE OBTAINED FROM USFS), PASS THRU THE GATE FOR 1.3 KM (0.8 MI) TO A USFS WEATHER STATION BUILDING AND THE STATION.

THE STATION IS A 1-INCH CAPPED PIPE THAT PROJECTS ABOUT 8-INCHES. THE CAP HAS A HOLE DRILLED THRU IT, THAT IS IRREGULAR, ABOUT 3/16-INCH IN DIAMETER, NOT IN THE CENTER OF THE CAP AND THE CAP IS SCREWED ONTO THE PIPE. THE CAP IS STAMPED ---BALD MTN--- LOCATED 23 METERS (76 FEET) S FROM THE SOUTHEAST CORNER OF THE BUILDING, 8.5 METERS (28 FEET) N FROM A UTILITY POLE THAT IS SOUTH OF THE BUILDING, AND 5.5 METERS (18 FEET) E FROM A ROCK LINED PATH TO ANIMAL PEN.

**************************** R E C O V E R Y   N O T E ****************************

STATION NAME--HORSE USGS STATE--CA COUNTY--MONO QUAD--N371184 STA--

	YEAR	CP		REACHED BY	PACK TIME		HGT OF TELESCOPE
RECOVERY BY--NGS	1983	CLN	CONDITION--GOOD	FOUR-WHEEL-DRIVE	HRS	MIN	METERS

CODE	MARK TYPE *********	SETTING/LANDMARK TYPE **	MAGNETIC PROPERTY
SURFACE--D50	SURVEY DISK	IN ROCK OUTCROP	

THE STATION, REFERENCE MARKS 1, 2, AND 3 WERE RECOVERED IN GOOD CONDITION. REFERENCE MARK NUMBER 3 SERVES AS THE AZIMUTH MARK.

THE STATION IS LOCATED ABOUT 11.3 KM (7 MI) EAST OF THE SOUTHEAST EDGE OF MONO LAKE, ABOUT 11.3 KM (7 MI) NORTH-NORTHEAST OF STATE HIGHWAY 120 (FROM A PROMINENT SWITCH BACK IN THE HIGHWAY), IN THE NW 1/4, SECTION 5, R29E, T1N, ON THE NORTHEAST END OF COWTRACK MOUNTAIN, ON A SMALL ROCKY POINT, WHICH IS THE HIGHEST ON THE NORTHEAST END OF THE RIDGE.

TO REACH THE STATION FROM THE JUNCTION OF U.S. HIGHWAY 395 AND STATE HIGHWAY 120, ABOUT 8 KM (5 MI) SOUTHEAST OF LEEVINING, GO EAST ON STATE HIGHWAY 120 FOR 27.6 KM (17.15 MI) TO A SIDE ROAD LEFT AT THE NORTHWEST END OF A SWITCHBACK IN THE HIGHWAY, BEAR LEFT, NORTH-NORTHEAST ON THE DIRT ROAD FOR 1.1 KM (0.7 MI) TO A DIAGONAL CROSSROAD, CONTINUE AHEAD, NORTH-NORTHEAST FOR 4.3 KM (2.7 MI) TO A CATTLE WATER TANK AND A LEFT TURN IN THE ROAD, BEAR LEFT ON THE ROAD FOR 2.2 KM (1.35 MI) TO A FORK, KEEP RIGHT FOR 1.7 KM (1.05 MI) TO AN OLD LINE SHACK AT A ROAD SUMMIT, CONTINUE FOR 0.1 KM (0.05 MI) TO A FORK, KEEP RIGHT ON THE TRACK ROAD FOR 0.9 KM (0.55 MI) TO A ROCK BLUFF ON THE LEFT, (ABOUT 0.2 KM (0.1 MI) NORTHWEST OF THE ROAD AND THE AZIMUTH MARK (REFERENCE MARK 3) ON TOP OF THE BLUFF ABOUT 1 FOOT SOUTHEAST OF THE HIGHEST BOULDER), CONTINUE ON THE TRACK ROAD FOR 0.8 KM (0.5 MI) TO THE STATION.

THE STATION IS AN UNSTAMPED USGS BM DISK, SET INTO ROCK OUTCROP, ABOUT 0.5 FEET BELOW THE SURFACE, NEAR THE CENTER OF A LOW SCATTERED ROCK CAIRN.

REFERENCE MARK NO. 1 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---HORSE NO 1 1934--- SET INTO THE TOP OF A BOULDER LOCATED 0.3 METER (1 FOOT) SW FROM A WITNESS POST AND LOWER THAN THE STATION.

REFERENCE MARK NO. 2 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---HORSE NO 2 1934--- SET INTO ROCK OUTCROP LOCATED 0.3 METER (1 FOOT) NW FROM A WITNESS POST AND LOWER THAN THE STATION.

REFERENCE MARK NO. 3 IS A STANDARD US COAST AND GEODETIC SURVEY (NOW NOS) DISK STAMPED ---HORSE NO 3 1934--- SET INTO ROCK OUTCROP ABOUT 800 METERS SOUTHWEST OF THE STATION, ON A SMALL ROCK BLUFF, ABOUT 0.4 METERS SOUTHEAST OF THE HIGHEST BOULDER ON THE BLUFF, ABOUT 0.2 KM (0.1 MI) NORTHWEST OF THE TRACK ROAD.

************************** R E C O V E R Y   N O T E **************************

STATION NAME--BEN USGS   STATE--CA COUNTY--MONO   QUAD--N371184   STA--

	YEAR	CP		REACHED BY	PACK TIME	HGT OF TELESCOPE
RECOVERY BY--NGS	1983	CLN	CONDITION--GOOD	FOUR-WHEEL-DRIVE	00 HRS 05 MIN	METERS

CODE MARK TYPE *********	SETTING/LANDMARK TYPE **	MAGNETIC PROPERTY
SURFACE--D70N SURVEY DISK	IN A BOULDER	NO MAGNETIC MATERIAL

THE STATION WAS RECOVERED IN GOOD CONDITION. THE DISK IS SET IN A CONCRETE CAP ABOUT 2-INCHES THICK, ON A BOULDER.

THE STATION IS LOCATED 63.6 KM (39.5 MI) NORTHWEST OF BISHOP, 13.7 KM (8.5 MI) EAST-NORTHEAST OF MAMMOTH LAKES, 0.8 KM (0.5 MI) SOUTHEAST OF THE HOT CREEK BATH HOUSE PARKING LOT, IN THE NW 1/4, SECTION 30, R29E, T4S, ABOUT 1 METER (3 FEET) WEST OF THREE BOULDERS THAT ARE THE HIGHEST PART OF THE HILL, ABOUT 36.5 METERS (120 FEET) NORTH OF THE ROAD.

TO REACH THE STATION FROM THE MAMMOTH INTERCHANGE OF U.S. HIGHWAY 395 (STATE HIGHWAY 203) GO SOUTHEAST ON HIGHWAY 395 FOR 7.2 KM (4.5 MI) TO HOT CREEK ROAD, TURN LEFT, NORTHEAST ON HOT CREEK ROAD FOR 3.5 KM (2.2 MI) TO A GATE WITH SIGN (CLOSED SUNSET TO SUNRISE), CONTINUE AHEAD FOR 1.1 KM (0.7 MI) TO THE SOUTHWEST ENTRANCE OF THE HOT CREEK BATHS PARKING LOT, CONTINUE AHEAD FOR 0.6 KM (0.35 MI) TO A SIDE ROAD RIGHT, TURN SHARP RIGHT FOR 0.6 KM (0.4 MI) TO A TRACK ROAD LEFT AND A RIGHT TURN IN THE ROAD, TURN LEFT ON THE TRACK ROAD FOR 0.2 KM (0.15 MI) TO THE SUMMIT OF THE ROAD, AND THE STATION ON THE LEFT.

THE STATION IS A CENTER PUNCHED, 2-INCH DIAMETER, PLAIN, BRASS DISK STAMPED---BEN USGS---.

ALTERNATE TO REACH THE STATION FROM THE JUNCTION OF U.S. HIGHWAY 395 AND STATE HIGHWAY 203 (MAMMOTH INTERCHANGE) GO SOUTHWEST ON HIGHWAY 395 FOR 8.7 KM (5.4 MI) TO BENTON CROSSING ROAD, TURN LEFT, NORTHEAST ON BENTON CROSSING ROAD, PASSING THE HIGH SIERRA CHURCH ON THE RIGHT; FOR 1.8 KM (1.15 MI) TO A FORK, KEEP LEFT FOR 2.9 KM (1.8 MI) TO A CROSSROAD, TURN LEFT FOR 1.6 KM (1 MI) TO A T-INTERSECTION, TURN RIGHT FOR 0.6 KM (0.35 MI) TO A LEFT TURN IN THE ROAD AND A TRACK ROAD. STRAIGHT AHEAD, FOLLOW THE TRACK ROAD FOR 0.2 KM (0.15 MI) TO THE ROADS SUMMIT AND THE STATION ON THE LEFT, ABOUT 36.5 METERS (120 FEET) NORTH OF THE ROAD, 1 METER (3 FEET) WEST OF 3 BOULDERS THAT ARE THE HIGHEST PART OF THE HILL.

************************** R E C O V E R Y   N O T E **************************

STATION NAME--BRIDGE L USGS   STATE--CA COUNTY--MONO   QUAD--N371184   STA--

	YEAR	CP		REACHED BY	PACK TIME	HGT OF TELESCOPE
RECOVERY BY--NGS	1983	CLN	CONDITION--GOOD	LIGHT TRUCK	00 HRS 00 MIN	METERS

	CODE MARK TYPE *********	SETTING/LANDMARK TYPE ***	MAGNETIC PROPERTY
SURFACE--Z00	SEE DESCRIPTION	SEE DESCRIPTION	

THE STATION WAS RECOVERED IN GOOD CONDITION.

THE STATION IS LOCATED, 57.1 KM (35.5 MI) NORTHWEST OF BISHOP, 17.6 KM (11 MI) NORTHEAST OF MAMMOTH LAKES, ON THE SOUTHEAST END OF THE BENTLEY CROSSING ROAD, BRIDGE OVER THE OWENS RIVER, IN THE SOUTHWEST 1/4, SECTION 10, R29E, T4S, IN THE EAST END TO THE SOUTHEAST ABUTMENT.

TO REACH THE STATION FROM THE JUNCTION OF STATE HIGHWAY 203 AND U.S. HIGHWAY 395 (MAMMOTH INTERCHANGE), GO SOUTHEAST ON U.S. HIGHWAY 395 FOR 8.7 KM (5.4 MI) TO BENTON CROSSING ROAD, TURN LEFT, NORTHEAST ON BENTON CROSSING ROAD FOR 10.2 KM (6.35 MI) TO THE BRIDGE OVER THE OWENS RIVER AND THE STATION.

THE STATION IS A 5/8-INCH SCREW HEAD, WITH A 3/16-INCH PUNCH MARK IN THE SLOT.

************************** R E C O V E R Y   N O T E **************************

STATION NAME--MINER USGS   STATE--CA COUNTY--MONO   QUAD--N371184   STA--

	YEAR	CP		REACHED BY	PACK TIME	HGT OF TELESCOPE
RECOVERY BY--NGS	1983	CLN	CONDITION--GOOD	FOUR-WHEEL-DRIVE	00 HRS 00 MIN	METERS

	CODE MARK TYPE *********	SETTING/LANDMARK TYPE ***	MAGNETIC PROPERTY
SURFACE--D09	SURVEY DISK	SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT	

THE STATION WAS RECOVERED IN GOOD CONDITION.

THE STATION IS LOCATED 6.4 KM (4 MI) SOUTHEAST OF MAMMOTH LAKES, 4.8 KM (3 MI) SOUTH OF THE JUNCTION OF STATE HIGHWAY 203 AND U.S. HIGHWAY 395, 1.8 KM (1.1 MI) SOUTH OF ROAD, ALONG THE NORTHWEST SIDE OF LAUREL CANYON ROAD, ON THE OUTSIDE OF A CURVE AT A SMALL PULLOUT.

TO REACH THE STATION FROM THE JUNCTION OF U.S. HIGHWAY 395 AND STATE HIGHWAY 203 (MAMMOTH INTERCHANGE) GO SOUTHEAST ON 395 FOR 2.1 KM (1.3 MI) TO A CROSSROAD. TURN RIGHT, WEST ON ROAD FOR 2.4 KM (1.5 MI) TO A SIDE ROAD LEFT. TURN LEFT, SOUTH ON LAUREL CANYON ROAD FOR 1.9 KM (1.15 MI) TO THE STATION ON THE RIGHT AT THE SMALL PULLOUT.

THE STATION IS A STANDARD US GEOLOGICAL SURVEY DISK STAMPED ---MINER 1983--- SET INTO THE TOP OF A SQUARE CONCRETE MONUMENT 36 CM (14.2 INCHES) ON SIDE PROJECTING 6 CM (2.4 INCHES) ABOVE THE GROUND.

ACRN=HR0388 **************** BENCH MARK DESCRIPTION ****************
DESIGNATION--D 916 STATE--CA COUNTY--MONO
QUAD--0371184 QSN-- LINE--101 AREA--
LOCATION-- 4 MI SE OF CRESTVIEW
MONUMENT BY--NGS YR--1957 CP--FXP MARK TYPE--BM DISK
SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
STAMPING--D 916 1957 OTHER CONTROL--
LATITUDE = LONGITUDE =

***************** ORIGINAL DESCRIPTION *****************

4.0 MILES SOUTHEAST ALONG U.S. HIGHWAY 395 FROM THE CALIFORNIA DIVISION OF HIGHWAYS MAINTENANCE STATION AT CRESTVIEW, 4.4 MILES NORTHWEST OF CASA DIABLO HOT SPRINGS, IN R 27 E, T 3 S, NEAR THE CENTER OF THE NORTH SIDE OF THE SOUTHWEST QUARTER OF SECTION 12, 273 FEET NORTHWEST OF THE CENTER OF THE SOUTHWEST END OF 24-INCH CORRUGATED METAL PIPE CULVERT E-233 + 50, IN LINE WITH A ROW OF TELEPHONE POLES, 103 FEET SOUTHWEST OF THE CENTER LINE OF THE HIGHWAY, 31 1/2 FEET EAST OF THE CENTER LINE OF A TRACK ROAD LEADING SOUTH TO A GRADED ROAD, 4 1/2 FEET NORTHWEST OF TELEPHONE POLE M17202V, 1.6 FEET SOUTHEAST OF A WITNESS POST, ABOUT 3 FEET LOWER THAN THE HIGHWAY, AND SET IN THE TOP OF A CONCRETE POST PROJECTING 0.2 FOOT ABOVE THE GROUND.

***************RECOVERED BY NGS IN 1983 CONDITION = GOOD *******

6.4 KM (4 MI) SOUTHEAST ALONG U.S. HIGHWAY 395 FROM THE LADH MAINTENANCE STATION IN CRESTVIEW IN THE SOUTHWEST QUARTER OF SECTION 12, R 27 E, T 39, 83 METERS (273 FT) NORTHWEST OF A 24-INCH CULVERT, 31.4 (113 FT) SOUTHWEST OF THE CENTER OF THE HIGHWAY, 9.5 METERS (31 FT) EAST OF THE CENTER OF A TRACK ROAD, 0.3 METERS (1 FT) NORTHEAST OF A WITNESS POST, ABOUT 61 METERS (200 FT) SOUTH OF AND ACROSS THE HIGHWAY FROM A HIGHWAY SIGN (REST AREA 2 MI), ABOUT 18 METERS (60 FT) WEST OF A RIGHT OF WAY MARK AND POST.

ACRN=HR0374 **************** BENCH MARK DESCRIPTION ***************
DESIGNATION--G 916 STATE--CA COUNTY--MONO
QUAD--0371184 QSN-- LINE--101 AREA--
LOCATION-- 6.8 MI E OF CRESTVIEW
MONUMENT BY--NGS YR--1957 CP--FXP MARK TYPE--BM DISK
SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
STAMPING--G 916 1957 OTHER CONTROL--
LATITUDE = LONGITUDE =

**************** ORIGINAL DESCRIPTION ****************

1.5 MILES SOUTHEAST ALONG U.S. HIGHWAY 395 FROM THE CALIFORNIA DIVISION OF HIGHWAYS MAINTENANCE STATION AT CRESTVIEW, THENCE 0.7 MILE SOUTHEAST ALONG A GRAVELED ROAD, THENCE 3.5 MILES NORTHEAST ALONG AN ASPHALT ROAD, THENCE 1.1 MILES EAST ALONG THE ARCULARIUS RANCH AIRPORT LANDING STRIP, 1.1 MILES EAST OF BENCH MARK F 916, AT THE EAST END OF THE STRIP, 24 FEET NORTH OF THE SOUTH EDGE OF THE RUNWAY, 6 FEET EAST OF THE EAST END OF THE RUNWAY, 1.6 FEET NORTHWEST OF A WITNESS POST, ABOUT LEVEL WITH THE RUNWAY, AND SET IN THE TOP OF A CONCRETE POST PROJECTING 0.4 FOOT ABOVE THE GROUND.

****************RECOVERED BY NGS IN 1983 CONDITION = GOOD *******

0.3 KM (1.4 MI) SOUTHEAST ALONG U.S. HIGHWAY 395 FROM THE LADH MAINTENANCE STATION AT CRESTVIEW, THEN 7.8 KM (4.85 MI) EAST ALONG OWENS RIVER ROAD, THEN 0.2 KM (0.1 MI) NORTH ALONG A DIRT ROAD, IN THE NORTHEAST QUARTER, SECTION 28, R 28 E, T 2 S, ABOUT 36.6 METERS (65.0 FT) WEST OF A FENCE, ABOUT 16.8 METERS (55 FT) SOUTH OF THE CENTER OF A TRACKS ROAD THAT RUNS THRU THE CENTER OF THE FORMER LANDING STRIP, 0.5 METERS (1.5 FT) EAST OF A WITNESS POST.

ACRN=HR0413 **************** BENCH MARK DESCRIPTION ***************
DESIGNATION--D 124 STATE--CA COUNTY--MONO
QUAD--0371184 QSN-- LINE--101 AREA--
LOCATION-- 5 MI NW OF TOMS PLACE
MONUMENT BY--NGS YR--1932 CP-- MARK TYPE--BM DISK
RECOVERY BY--NGS YR--1957 CP--FXP CONDITION--GOOD
SPECIFIC SETTING--BOULDER MONUMENTATION CODE--C
STAMPING--D 124 1932 OTHER CONTROL--
LATITUDE = LONGITUDE =

**************** RECOVERY DESCRIPTION ****************

5.0 MILES NORTHWEST ALONG U.S. HIGHWAY 395 FROM THE CONCRETE BRIDGE OVER ROCK CREEK AT TOMS PLACE, 0.35 MILE NORTHWEST OF THE T JUNCTION OF A GRADED DIRT ROAD LEADING SOUTH TO HILTON LAKES, IN R 29 E, T 4 S, NEAR THE CENTER OF SECTION 7, IN THE TOP OF A LARGE GRANITE BOULDER 380 FEET NORTHWEST OF THE T JUNCTION OF A TRACK ROAD LEADING SOUTHWEST, 85 1/2 FEET SOUTHWEST OF THE CENTER LINE OF THE HIGHWAY, 64 FEET NORTHEAST OF A WOODEN DRIFT FENCE, ABOUT 4 1/2 FEET HIGHER THAN THE HIGHWAY, AND ABOUT 1 1/2 FEET ABOVE THE GROUND.