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TESTING FOR LONG–TERM STABILITY OF TWO-COLOR GEODIMETERS; JANUARY 1986 TO AUGUST 1989

by

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ABSTRACT

Currently, there exists 3.6 years of measurements which can define the long-term, relative stability of the electronic and optical components of several two-color geodimeters. These measurements consist of nearly simultaneous measurements of baseline lengths with different two-color geodimeters. However, because of instrument failures in the last 1.3 years, the relative stability of the instrumentation can only be assessed over the initial 2.3 years. The stability, which is expressed as a length dependent scale factor, indicate that the apparent lengths measured with one geodimeter drifts away from the second at an insignificant rate, 0.064 ± 0.051 *ppm/yr*. However, the standard deviation of the residuals about this trend is 0.12 *ppm*, which is significantly greater than the predicted 0.04 *ppm* standard error of length scale of one instrument relative to the second. The data from the comparison of the two instruments are also useful for estimating the change in instrument path length due to break-down and subsequent repair or replacement of one of the two instruments. When the instrument comparison data are augmented with frequent measurements of line-length made in Long Valley caldera, it becomes possible to accurately determine the size of the offset in distance when the instrumentation is changed. The results from both data sets indicate that the offset between the two instruments is length dependent. The physical mechanism for the length dependence is unknown at this time.

INTRODUCTION

Previous to July 1988, the USGS had been monitoring the lengths of many baselines with a portable version of a two-color geodimeter (*Slater and Huggett*, 1976). However, in late June, the electro-optic modulator failed in that particular instrument. To continue our measurements, particularly in the Long Valley caldera (*Langbein*, 1989), I started using a second, portable, two-color instrument, which had just undergone several years of repair and laboratory tests (Table 1). In order to be able to compare length measurements made with the first instrument with those of the second, it is necessary to establish the value of the offset in path length. If simultaneous measurements existed on several baselines using both instruments, then the determination of the value of the offset would be straight forward. However, this situation does not exist and I must indirectly estimate the offset using two different data sets. Furthermore, as the following analysis demonstrates, the offset is length dependent and is characterized by a fairly complex function. In contrast, my initial expectation was for a length–independent offset. The other result of this study demonstrates that this second instrument has repeatability or precision similar to the first (*Langbein et al.*, 1987a and *Langbein*, 1989).

Even though the USGS owns two instruments, only one of these portable, two-color geodimeters had been used to monitor the lengths of baselines in number of geodetic networks in eastern and southern California. Both instruments were made by Terra Technology of Seattle. A condensed history of the three instruments discussed here is shown in Table 1. The first portable instrument, which was made in 1981, had been used briefly in the field during 1982, but proved to yield data with systematic errors on the order of 0.3 ppm. This instrument, now termed #11, was withdrawn from field use and worked on by both myself and Terra Technology. Along with several component failures, I identified the source of the systematic error within the instrument. Fortuitously, this instrument was ready for field testing in mid 1988 when the second instrument failed.

The second portable, two-color geodimeter, termed #21, has been used nearly continuously since its delivery in early 1983. An exception was in late 1983 when both the modulator and microwave power amplifier failed. The change of path length in the second instrument due to the repairs has been discussed by *Langbein et al.*(1987a). However, at the end of June 1988, #21 was brought to Menlo Park for repair of an optical prism mounted on the back of the electro-optical modulator housing. At that time, it was observed that the glue joint which attaches an optical window to the modulator crystal had failed. After consulting with the fabricator of the crystal, I decided to replace the crystal. The replacement was completed in early November 1988. For the next 2 months, two instruments were available make baseline measurements. However, during that period, the modulator temperature steadily increased in the refurbished instrument, termed #22. In January 1989, I decreased the modulator temperature by removing indium from the crystal's circumference. However, the performance of the instrument in field showed a steady deterioration relative to November. Investigation revealed that the modulator crystal had cracked due to either thermal stress from high temperature of the modulator crystal or from the process of removing indium. At this time, the crystal has been replaced and the instrument is nearly ready for field testing.

Fortunately, a third two-color geodimeter exists and has functioned reliably until mid 1989. This instrument, termed the Cmeter, has been used to monitor the lengths of several baselines near Parkfield, California since 1984 (*Langbein et al.*, 1990). This instrument was built at the University of Washington in 1975 and is now operated by the University of Colorado. It is operated from an observatory because the instrument consists of several large modules that are difficult to transport and set-up. From early 1986, periodic, simultaneous measurements of more that a dozen baselines at Parkfield were made using both the Cmeter and #21 or the Cmeter and #11. Typically, these comparison measurements were obtained over the course of a couple of evening sessions, then repeated at intervals between 3 and 4 months. The results of these instrument comparisons quantify the long-term stability of one instrument relative to the second. *Langbein* (1989) has reviewed these measurements and concluded that the relative instrument length scale have remained stable to within 0.1 ppm. The instrument length scale is analogous to the actual distance separating the tick marks on a ruler. With a ruler, the spacing between the tick marks can change with temperature and this variation would affect the measurement of the true distance. With comparison data from Parkfield, it is not possible to distinguish which instrument is defective. Other data or circumstances are needed. However, these comparison measurements are important when one of the two instruments has a failure which results in a change in its length scale. This occurred when instrument #11 was substituted for #22 and more recently, when several factors contributed to a systematic length change of the Cmeter in May 1989.

The Parkfield comparison experiment addresses two issues concerning the geodimeters. As stated above, the data compares the long-term stability of one geodimeter to a second. Secondly, if there is a change in instrumentation, the comparison data can be used to determine the offset in path length due to the instrumental change. This report addresses both the long-term stability and the determination of the offset in distances between the two portable instruments.

To aid in estimating the offset in path length due to change in instrumentation, a second data set is used that includes on frequently repeated line-length measurements from the station CASA to 19 baselines near Mammoth Lakes, California. These measurements were made initially with instrument #21 until June 1988. After early July 1988, the measurements were continued using #11. In November and December 1988, many of the baselines were measured using both #11 and the refurbished second instrument, #22. Since the measurements using #11 and #22 were made within a few hours of each other, a good estimate can be made of the offset of #22 relative to #11. Furthermore, if a reasonable assumption can be made of the function with time of the deformation, the tear between June and July 1988 can be estimated, yielding a second measure of the offset of #21 relative to #11. As the two next sections show, the estimate of the offset of #21 relative to #11 yield slightly different results, which justifies combining both data sets for a simultaneous adjustment. Finally, the precision of both portable geodimeters can be reconfirmed (*Langbein*, 1989) with the frequently repeated length measurements from Long Valley.

PARKFIELD COMPARISON

The instrument comparison experiment at Parkfield consists of nearly simultaneous measurements of baseline lengths using two instruments, the Cmeter and one of the two portable instruments. The portable geodimeter is set up over a monument 30 m northwest of the monument occupied by the Cmeter. The length of each baseline shown in Figure 1 is measured using both instruments and the measurements are made within 5 minutes of each other using a common set of weather data consisting of temperature, pressure, and relative humidity at the central station at CARR. Typically, about 90% of the baselines are measured in a single evening session and then remeasured on the following evening. Thus, from January 1986 through August 1989, we have 15 measurements of the calibration network shown in Figure 1. To examine the observations, I have subtracted the length measured by the Cmeter from the length measure by the portable instrument and these differential measurements are plotted in Figure 2. The standard errors are simply the geometric sum of the standard error of each instrument which have been characterized by *Langbein et al.*(1987b) and *Langbein* (1989) as $\sigma^2 = a^2 + (b/l)^2$ where l is the baseline length in millimeters, $a = 0.12$ ppm and $b = 0.3$ mm. In order to keep the plotted data on scale, the measurements using the portable instrument #11 have had 10 mm added to the observations.

The changes in the differential measurements shown in Figure 2 are due to two processes; localized displacement of the monument used by the portable instrument relative to the monument occupied by the Cmeter, and most importantly, variations in the length scale of one instrument relative to the second. Unfortunately, with this test procedure, identification can not be made of the specific drifting instrument or the specific displacing monument. *Langbein et al.*(1987a) discussed a least squares technique used to extract both changes in instrument length scale and monument displacement from the differential length measurements. To review, the differential distance, d_{ij}, measured on the i^{th} baseline at j^{th} time is related to these relative parameters by:

$$d_{ij} = \bar{D}_i + s_j D_i + e_j \cos\theta_i + n_j \sin\theta_i$$

where $\bar{D}_i$ is the length difference due to the separation of the two monuments at CARR, D_i is the nominal baseline length, s_j is the length scale of one instrument relative to the second during the j^{th} survey, and e_j and n_j are the magnitudes of the relative monument displacement resolved into an east–west, north–south coordinate system with θ_i being the baseline azimuth with 0°is reckoned as east and 90°is north. This observation equation is used to solve for unknown parameters, $\bar{D}_i$, s_j, e_j and n_j, using standard least squares procedure where the weight of each observation is the inverse of the observational standard error. Since this system of equations is singular with regards to absolute measures of the relative length scale and relative monument displacement, three extra constraints are added as 3 more observation equations. These constraints state that the sums of the length scale changes and the sums of the relative monument displacements are equal to zero for a specified interval.

The results of computing the relative change in instrument length scale and monument displacements at CARR have been discussed in *Langbein* (1989) for the interval from January 1986 through July 1988. They discovered that the data from the portable instrument in January 1987 is not reliable because of an intermittent electrical connection. Part of the results in Figure 3 reproduces the previous estimates and excludes the January 1987 data. Although the figure show estimates for the scale and monument displacements for surveys after March 1989, these results will be discussed shortly and it should be noted that I have constrained the three summations to be equal to zero for the interval between January 1986 and May 1988.

The results shown in Figure 3 show that the relative monuments displace with a peak to peak variation of 2 *mm* and that the relative length scales vary by as much as 0.3 *ppm*. However, the long–term drift of the instrument #21 relative to the Cmeter computed with the data before July 1988 show an insignificant rate of -0.064 ± 0.051 *ppm/yr*. The standard deviation of the scatter of the 8 estimates of relative length scale comes to 0.12 *ppm* and is larger than the expected 0.04 *ppm* formal standard error in each estimate of length scale. The formal standard deviation is derived from propagating the standard errors of each differential measurement through the least squares adjustment procedure. As I will demonstrate shortly, the calibration model does fit the data implying that the a priori standard error of each datum is appropriate. The inference is that there appears to be some long–term variations in length scale of either one or both geodimeters. Since the measurements are nearly simultaneously, both the atmospheric refractivity and the displacements of the remote monuments are common mode signals which should not affect the inferred length scale since differential data is used. Thus the apparent changes in instrument scale imply that these variations are more likely to be instrumental (electronic or optical) in origin.

The instrument comparison data can also be used to estimate the offset in length of the two portable instruments assuming that the Cmeter remained stable. In one method, the differential measurements made in July 1988 could be subtracted from the differential measurements made in May 1988. Assuming that the Cmeter remained stable and the two monuments at CARR did not displace during that interval, an accurate offset would be determined for #21 relative to #11. Initially, this calculation was carried-out, but included data from mid 1987 through early 1989 and allowed for variations in monument displacement and length scale from mid 1987 up to July 1988 and from July 1988 through March 1989. With the sum of monument displacements, e_j and n_j, and instrument length scale, s_j, forced to be zero for two intervals, from mid 1987 to May 1988 and from July 1988 to March 1989, an offset in distance for each baseline is estimated by the following observation equation:

$$d_{ij} = \bar{D}_i + s_j D_i + e_j \cos\theta_i + n_j \sin\theta_i + o_i$$

where o_i is the inferred offset in distance measured using #21 relative to #11 on the i^{th} baseline.

The result of estimating the offset of each baseline is plotted as a function of baseline length in Figure 4a. Rather than a constant offset as I would have expected, the offset between the two instruments appear to depend upon the baseline length. Roughly, the results indicate that for lengths less than 2.0 *km*, the offset is 10 *mm*, reduces to 8 *mm* for lengths between 2.0 and 4.5 *km*, then increases to 12 *mm* at longer distances. The remaining discussion refines these estimates.

The results of analyzing the deformation data from the Cmeter from March 1989 through August 1989 implies that this instrument became unstable between late April and mid May, and finally resulted in a systematic change in its length scale. This inference is illustrated in Figure 5 showing the dilatation computed at Parkfield using the Cmeter measurements, the dilatation in the Long Valley caldera using measurements from the portable instrument #11, and the changes in length scale of the Cmeter relative to #11 over the 6 month interval. Because fault slip is a prominent signal in the Parkfield data, this parameter is estimated along with dilatation and tensor shear strain according to the formulation of *Langbein et al.*(1990) and *Langbein* (1989). The comparison data includes the measurements made on two successive evenings in May which are not shown in Figure 3. The results demonstrate that the dilatation at Mammoth as measured by #11 is stable in the long–term which is in contrast to the large fluctuations of dilatation in late April and May recorded at Parkfield using the Cmeter. Furthermore, the results of the comparison of the two instruments track the fluctuations in dilatation measured by the Cmeter and imply that the Cmeter became unstable. Finally, the dilatation recorded by the Cmeter stabilized during the summer, and along with the comparison results, show that the lengths measured by the Cmeter shorted by 0.5 *ppm* over the 6 month interval.

The analysis presented above indicates a substantial length dependence of the offset of instrument #21 relative to #11 and a change in the instrument scale of the Cmeter during mid 1989. Using an extension of the observation equations presented above, it is possible to simultaneously estimate the parameters of a function describing the offset between the two portable instruments, the change in length scale of the Cmeter, the relative displacements of the two monuments, and the variation of the relative length scales between the portable instrument and the Cmeter. To accomplish this task, the original observation equation is modified to:

$$d_{ij} = \bar{D}_i + s_j D_i + e_j \cos\theta_i + n_j \sin\theta_i + f(D_i) + cD_i$$

where $f(D_i)$ is a length dependent function which is equal to zero for measurements made with instrument #11, and c is the change in length scale of the Cmeter and is equal to zero for surveys before July 1989. In order to keep this set of observation equations non–singular, five constraints are added as observations. The first 2 constraints force the sum of the monument displacements to equal zero for the entire period under analysis. The third constraint forces the sum of the instrument length scale s_j to equal zero for the entire time period. Finally, to be able to estimate the parameters of the function, $f(D_i)$, and the change in the Cmeter length scale, c, two more constraints are made on the sum of s_j. For the surveys from July 1988 through August 1989, the sum of s_j is set to 0 and for the surveys of July 1989 and August 1989, the sum of s_j is set to 0. For the analysis presented in Table 2, I specify the offset function as follows:

$$\begin{aligned} f(D_i) &= a_1 + a_3 \quad \text{for} \quad D_i \leq a_4 \\ &= a_1 \qquad\quad \text{for} \quad a_4 < D_i \leq a_5 \\ &= a_1 + a_2 \quad \text{for} \quad D_i > a_5 \end{aligned}$$

The function is simply a reflection of the length dependence of the offset with baseline length shown in Figure 4a. Although $f(D_i)$ is expressed in this awkward fashion, the reason will become clear later when I reconcile the estimates between instruments #21 and #22. Even though the parameters, a_1, a_2, and a_3, can be estimated using linear least squares, the other 2 parameters are determined using trial and error.

The results of estimating the 5 parameters of $f(D_i)$ are shown in Table 2 using the Parkfield comparison data. For values of a_5 between 3.8 and 4.5 *km* and for a_4 between 1.7 and 2.1 *km*, the misfits in terms of χ^2 are minimized where χ^2 is the sum of the squares of the ratio of the misfit of the model and the data to the a priori standard error of the data. Since the value of the minimum χ^2 is less than the number of degrees of freedom, the offset function is considered as a satisfactory fit to the data. The offset function states that distances measured by #21 are longer than #11's by 10.4 *mm* for the distances less than 2 *km*, longer by 12.9 *mm* for distances greater than 4.5 *km*, and longer by 7.8 *mm* for intermediate distances.

Justification of the length dependent function becomes clear when two other offset functions are fit to the data and resulting in a large χ^2 statistic compared with those in Table 2. The simplest function is a length independent offset, which is estimated to be 9.60 ± 0.15 *mm*, and yields $\chi^2 = 1000.8\ (mm/mm)^2$, which is significantly greater than any of the values in Table 2. Adding a linear dependence with distance reduces the value of χ^2 to 732.3 $(mm/mm)^2$, but this value greatly exceeds results in Table 2. Both of these models of offset can be rejected with better than 99% confidence on the basis of the χ^2 goodness-of-fit test.

LONG VALLEY MEASUREMENTS

With the frequent measurements of line-lengths of 19 baselines from CASA in the Long Valley Caldera (*Langbein*, 1989), it is possible to obtain the offset in distances measured using instruments #21 and #22 relative to #11. The key assumption is that the form of the time dependent function of deformation is known for each baseline. This assumed function is necessary to tie the measurements made before and after July 1988 when the switch was made between instruments #21 and #11. However, since the measurements made with instruments #22 and #11 were made within a few hours to within a few days of each other, the form of the function is not critical in estimating the offset between these two instruments. After examining the line-length change data on the 7 baselines with the most observations between January 1988 and March 1989, it became apparent that the changes are proportional to a secular term plus a second order term which characterizes the baseline's acceleration. To obtain estimates of the offsets in distance on each baseline using the three instruments, the following equation is fit to the observed distances, l_{ij}, made at time t_j:

$$l_{ij} = \bar{L}_i + v_i t_j + \dot{v}_i t_j^2 + o21_i + o22_i$$

where $\bar{L}_i$ is the nominal distance of the i^{th} baseline, v_i and $\dot{v}_i$ characterize the velocity (secular rate) and the acceleration of the i^{th} baseline, and $o21_i$ and $o22_i$ are the estimates of the offset in distance of each baseline measured using instruments #21 or #22 relative to #11. The results of estimating the offsets for each of the 19 baselines from CASA are shown in Figures 4b and 4c. Since there are approximately 150 observations on each of 7 baselines over the period of 15 months, good estimates are determined of both the velocity and acceleration terms. On the remaining 12 baselines, measurements averaged once-per-month also yield good estimates of secular rate but the estimates of acceleration are not necessarily well determined because of sparse data. None the less, when the model of velocity and acceleration is fit to the length change data and the estimates of offset are determined, the fit is very satisfactory. With 1147 degrees of freedom, the $\chi^2 = 1071.9\ (mm/mm)^2$ assuming that the variance of each datum is characterized by *Langbein et al.*(1987b) and *Langbein* (1989).

Data from 3 additional baselines ranging between 1.0 and 2.0 km augment the extensive CASA data and are used to confirm the length dependence in offset at ranges less than 2 km that is apparent in the Parkfield data. Since these data consists of only 2 to 3 measurements on each baseline using instruments #11 and #22 between December 1988 and January 1989, estimates of v_i and $\dot{v}_i$ are poorly constrained and are assumed to be equal zero.

The results from the above analysis are shown in Figure 4b and 4c and they replicate the same length dependence as the Parkfield comparison data. However, the magnitudes of the dependence differ slightly from those in Table 2. The magnitudes of the offset function can be estimated using the same methods as before by combining the observation function for l_{ij} with the offset function $f(L_i)$ as:

$$l_{ij} = \bar{L}_i + v_i t_j + \dot{v}_i t_j^2 + f21(L_i) + f22(L_i)$$

where the forms of $f21(L_i)$ and $f22(L_i)$ are the same as the function describing the Parkfield results.

The results of estimating the coefficients of the two offset functions for the Long Valley data are listed in Table 3. Again, trial and error is used to determine the transition lengths, a_4 and a_5. I have constrained the transition distances to be the same for the two offset functions describing #21 and #22. Physically, instruments #21 and #22 are the same except for a change in the modulator crystal. The expectation is that the parameters of the two offset functions would have the same transition distances, a_4 and a_5, and the same values in a_2, the size of offset between short and long ranges. Furthermore, since the change of the modulator crystal should only affect the optical center of the instrument, I would only expect that only the value of a_1 would differ between the two instruments. The results shown in Table 3 indicate that the transition distance, a_5, ranges between 4.2 and 4.8 *km*, where the values of the misfits, χ^2 are minimized. However, for the optimal fits, a difference of 1 *mm* is obtained in the values of a_2 between instruments #21 and #22. Furthermore, comparison of the values of a_1 and a_2 for instrument #21 deduced from the Parkfield data and the Long Valley data show significant differences. Finally, the value of a_3 associated with #21 can not be estimated from the Long Valley data since 2.5 *km* is the shortest baseline measured.

Examination of the χ^2 statistic would imply that the optimal models with χ^2 between 1233.8 and 1241.4 $(mm/mm)^2$ would be rejected as valid with a 90% confidence. The rejection criteria is predicated that the a priori data error is known with a high degree of certainity and that the second order polynomial with time is an adequate description of the time-dependence of the observations. By relaxing either one or both of these constraints, the optimal models of the offset function provide adequate estimates of the differences between the three instruments. For instance, if the length proportional term in the equation for the standard error of each datum was increased from 0.1200 *ppm* to 0.1202 *ppm*, then the χ^2 for the optimal model in Table 3 would be reduced below the threshold for rejection at 90% confidence.

SIMULTANEOUS ADJUSTMENT

The results from Table 2 and 3 indicate that the values of the offset function need to be reconciled. The easist parameters to reconcile are the two transition distances, a_4 and a_5. Examination of the two tables indicate that $4.2 \le a_5 \le 4.5$ *km* and $1.7 \le a_4 \le 2.1$ *km*. However, better resolution to within 10 *m* of the transition distances is not available at this time. Limited information based upon repeated measurements of length changes measured at Pinon Flat in southern California, would place $a_5 = 4.45$ *km*. More difficult is to reconcile the value of a_2. For instrument #21 relative to #11, the Parkfield data implies that $a_2 = 5.02 \pm 0.20$ *mm* whereas the Long Valley data yields a value of 3.09 ± 0.19 *mm*. I would expect that these estimates should be equivalent. Furthermore, because instrument #22 is physically the same as #21 with the exception of repositioned modulator crystal, I expected that the value of a_2 to be equal for both instruments. Analysis of the Long Valley data yields an estimate of $a_2 = 4.14 \pm 0.19$ *mm* for instrument #22, which happens to be equal to the mean of values obtained for a_2 for instrument #21 from Parkfield and Long Valley data. A similar argument can be made for the equivalence of a_3.

To test for the possible equivalence of a_2 and a_3 between the two instruments, I have combined the observation equations of both the Parkfield and Long Valley data set into one large least squares adjustment of the parameters of the offset function. In accomplishing the adjustment, the columns of the observation matrix that involve instrument #21 are combined, and the remaining parameters involving nominal distances, monument displacements, variations in length scale, secular rates, acceleration, instrument #22, and Cmeter offset occupy separate columns in the observation matrix. Furthermore, the constraints concerning the summation over time of both the length scale changes, s_j, and monument displacements remain as observations as outlined in the Parkfield section.

The results of testing 4 hypothesis of the equality of a_2, and a_3 are listed in Table 4. In model 1, both a_2 and a_3 are taken to be equal for instruments #21 and #22. As expected, the inferred values of a_1 and a_2 associated with #22 agree closely for the results using just the Long Valley data. The values estimated for the offset of #21 are essentially the mean value of the results that were independently estimated from the Parkfield and Long Valley data. Comparison of the χ^2 of the misfits imply rejection at the 95% confidence level that the model of averaging the two independent estimates of the offset of instrument #21 fits both the Parkfield and Long Valley data sets. However, as stated before, by inflating the a priori length scale term in the equation for the standard error of each datum from 0.1200 *ppm* to 0.1209 *ppm*, or by assuming a slightly more complex function characterizing the time-dependence of the Long Valley data, the model of averaging the offset function for instrument #21 becomes acceptable.

Reduction in the misfits from model 1 due to increasing the number of parameters in models 2 through 4 are, at best, marginal. Model 2 allows for the possibility that a_3 for instruments #21 and #22 are different. The f-statistical test indicates that the addition of the extra free parameter improves the fit to the data at the only 90% confidence level. Model 3 tests for the possibility that a_2 differs for the two instruments while model 4 tests whether both a_2 and a_3 differ. The f-test indicates that the improvement in fit is not significant for these last two models.

Model 5 tests the hypothesis of the constraint of no length proportional offset between the two intervals, January 1986 through May 1988 and from July 1988 through March 1989 for the Parkfield data reduction. Recall that this constraint was added to the Parkfield observations equations so that the offset function could be estimated. The result listed as model 5 in Table 4 indicate only an insignificant change in the length scale, a_s.

The results of above analysis shown in Table 4 indicates that model 1 is the preferred model of the two offset functions. Confirmation that model 1 is an acceptable offset function for each of the two data sets considered is shown as the last entries in Table 2 and 3. Examination of the χ^2 statistic show that the parameters of the preferred model fit the Parkfield observations satisfactorily, and only is marginally inconsistent with the Long Valley observations. The degree that the preferred model is consistent with the observations is illustrated in Figure 4 where the solid line indicates the predicted offset as a function of distance. The variation of the relative length scale and relative monument displacements for the Parkfield data shown in Figure 3 are computed using the coefficients of model 1 for the offset function. Finally, the inference from Table 4 is that the new modulator crystal was repositioned within 0.70 *mm* of its orginal position when it was installed resulting in instrument #22 and that the Cmeter had a change in its length scale of 0.52 *ppm* in May 1989

CONCLUSIONS

By using a combination of two data sets, I am able to estimate the offset of instruments #21 and #22 relative to #11. Furthermore, the offset appears to be length dependent as shown in Figure 4. However, the electronic mechanism for the length-dependence is not known, but could be determined when both instruments are operating together.

The relative stability of instruments #21 and the Cmeter show larger variations than would be predicted using the standard error of the estimated length scale. The tentative conclusion is that these variations in length scale are real and have a RMS noise level of 0.12 *ppm*. At this time, the source of the variations can not be isolated to either the portable instrument or to the Cmeter, but probably has a source that is either electrical or optical in origin since first order atmospheric variations are canceled due to simultaneous measurements with both instruments.

Finally, the results from Long Valley indicate that the precision of instrument #11 is equivalent to that of instrument #21. This is good news since the original measurements using #11 in 1982 indicated large variations in the data. The analysis of the Long Valley data in this report confirms the precision of the portable instruments as determined by *Langbein* (1989).

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Table 1.
A brief history of the two-color geodimeters

Instrument name	Date	History
Cmeter	1975	Built by Univ. of Washington (Slater & Huggett, 1976).
	Sept. 1975	Moved to Hollister, Ca. (Huggett *et al.*, 1977).
	Early 1979	Moved to San Juan Bautista, Ca.
	Oct. 1980	Moved to Pearblossom, Ca. (Langbein *et al.*, 1982).
	Feb. 1982	Moved to San Juan Bautista, Ca.
	Aug. 1982	Moved back to Pearblossom, Ca. after first portable instrument showed systematic dilatations.
	Mar. 1984	Moved to Parkfield, Ca. (Langbein *et al.*, 1990).
	May 1989	Possible systematic offset (this report).
First portable	1980	Built by Terra Technology.
	Late 1981	Delivered to USGS and designated as instrument #10.
	Sept. 1982	Data from its measurements from Pearblossom, Ca. showed bimodal distribution of dilatation. Comparison with Cmeter indicated that this was not stable.
	Oct. 1982-June 1988	Several components were changed or repaired. Determined that systematic error was due to stray capacitance in voltage-controlled oscillators.
	July 1988	Returned to field as instrument #11.
Second portable	Early 1983	Built by Terra Technology and delivered to USGS as instrument#20.
	Sept. 1983	Failure of both modulator and microwave power amplifier.
	Dec. 1983	Returned to operation as instrument #21. (Langbein *et al.*, 1987 a&b).
	June 1988	Modulator failed.
	Nov. 1988	Returned to service as instrument#22.
	Jan. 1989	Modulator failed.
	June 1989	Has seen intermittent operation as instrument #23.

Table 2

Fit of offset function to Parkfield intercomparion data

N_{obs}=388, N_{para}=61, $N_{\text{degrees of freedom}}$=327

a_4 km	a_5 km	a_1 mm	a_2 mm	a_3 mm	a_c ppm	χ^2 $(\text{mm}/\text{mm})^2$
2.0	3.6	7.85±0.13	4.35±0.20	2.49±0.22	0.50±0.04	390.7
2.0	3.7	7.85±0.13	4.37±0.20	2.49±0.22	0.50±0.04	390.7
2.0	3.8	7.83±0.12	5.04±0.20	2.52±0.20	0.54±0.04	321.6
2.0	4.4	7.83±0.12	5.04±0.20	2.52±0.20	0.54±0.04	321.6
2.0	4.5	7.83±0.12	5.04±0.20	2.52±0.20	0.54±0.04	321.6
2.0	4.6	8.44±0.14	4.51±0.25	1.99±0.25	0.50±0.05	491.3
2.2	4.4	7.81±0.14	5.02±0.21	2.26±0.23	0.55±0.04	366.2
2.1	4.4	7.83±0.12	5.04±0.20	2.52±0.20	0.54±0.04	321.6
1.7	4.4	7.83±0.12	5.04±0.20	2.52±0.20	0.54±0.04	321.6
1.6	4.4	8.00±0.14	5.01±0.22	2.84±0.35	0.56±0.05	393.9
1.0	4.4	8.72±0.11	4.35±0.23		0.58±0.05	474.4
2.0	4.4	8.26	4.05	1.90	0.52	349.6

Table 3
Fit of offset function to Mammoth Lakes data
N_{obs}=1255, N_{para}=68, $N_{degrees\ of\ freedom}$=1168

		Instrument 21		Instrument 22			
a_4 km	a_5 km	a_1 mm	a_2 mm	a_1 mm	a_2 mm	a_3 mm	χ^2 (mm/mm)^2
2.0	4.0	8.61±0.14	2.02±0.20	7.26±0.13	3.15±0.19	1.72±0.29	1546.0
2.0	4.1	8.58±0.14	2.13±0.20	7.28±0.13	3.16±0.19	1.69±0.29	1528.0
2.0	4.2	8.62±0.11	3.10±0.19	7.57±0.10	4.14±0.19	1.40±0.25	1233.8
2.0	4.4	8.62±0.11	3.10±0.19	7.57±0.10	4.14±0.19	1.39±0.25	1233.8
2.0	4.6	8.66±0.11	3.09±0.19	7.57±0.10	4.15±0.19	1.36±0.26	1240.8
2.0	4.8	8.66±0.11	3.09±0.19	7.57±0.10	4.15±0.19	1.40±0.25	1241.4
2.0	4.9	8.97±0.11	3.72±0.25	8.10±0.10	4.33±0.25	0.87±0.27	1410.1
2.0	5.0	8.97±0.11	3.72±0.25	8.10±0.10	4.33±0.25	0.87±0.27	1410.1
2.0	4.4	8.62±0.11	3.10±0.19	7.57±0.10	4.14±0.19	1.39±0.25	1233.8
1.9	4.4	8.62±0.11	3.10±0.19	7.65±0.10	4.07±0.19	1.35±0.30	1244.4
1.0	4.4	8.62±0.11	3.10±0.19	7.71±0.09	4.01±0.19	1.32±0.39	1253.7
0.5	4.4	8.62±0.11	3.10±0.19	7.79±0.09	3.93±0.19		1266.1
2.0	4.4	8.26	4.05	7.56	4.05	1.90	1266.0

Table 4
Estimates of the offset function using the combined data
from Parkfield and Long Valley

	model 1		model 2		model 3		model 4		model 5	
	O_{21}	O_{22}	O_{21}	O_{22}	O_{21}	O_{22}	O_{21}	O_{22}	O_{21}	O_{22}
a_1 (mm)	8.26	7.56	8.23	7.60	8.28	7.53	8.24	7.58	8.21	7.57
	±.07	±.07	±.08	±.09	±.08	±.09	±.08	±.10	±.09	±.09
a_2 (mm)	4.05		4.05		3.98	4.18	4.01	4.12	4.02	
	±.11		±.11		±.14	±.18	±.14	±.19	±.11	
a_3 (mm)	1.90		2.11	1.57	1.90		2.10	1.59	1.89	
	±.15		±.19	±.23	±.15		±.19	±.23	±.14	
a_c (ppm)	0.522		0.521		0.519		0.520		0.539	
	±.040		±.040		±.040		±.040		±.043	
a_s (ppm)	---		---		---		---		0.042	
									±.036	
N–M	1521		1520		1520		1519		1520	
χ^2	1615.5		1611.8		1614.6		1611.6		1614.0	

FIGURE CAPTIONS

Figure 1. Map showing the location of a subset of baselines of the two–color geodimeter network near Parkfield, California. The lengths of these baselines are measured to compare the long–term stability of one two-color geodimeter relative to the second instrument. This network includes 5 baselines, MILEPOST, POLE, BREAK, PF3 and PF5 which are not measured in the normal monitoring of the Parkfield two-color network, because these monuments are known to be poorly anchored to the ground. Local monument movements at the remote locations are automatically subtracted from the data since differential length measurements are used in the comparison.

Figure 2. Plot of the differences between the observed line–length measured using the Cmeter and the portable, two-color geodimeters for the network shown in Figure 1. The error bars represent the one standard deviation level of each differential distance measurement. The length measurements have been normalized by the nominal baseline length and the results have been plotted in parts-per-million (ppm). The vertical line at July 1, 1988 represents the change in portable instruments, the vertical line at May 25, 1989 represents the repair of the Cmeter which is associated with a possible change in its length scale. The measurements made with the portable instrument after July 1, 1988 have had 10 mm added to the observations to account for the the instrument offset between instruments #21 and #11.

Figure 3. Results from the comparison measurements taken at Parkfield. Change in the differential lengths at Parkfield are resolved into 2 components of relative monument displacement and relative instrument length scale. The upper plot shows the calculated displacement of the monument used for the portable instrument relative to that of the Cmeter at CARR. The lower plot shows the variation of the relative length scale of the portable instruments relative to the Cmeter. The first vertical line represent the time of the exchange between portable instruments #21 and #11 in July 1988 and the second line in May 1989 shows the time of servicing of the Cmeter. In computing these results, several constraints have been made. It is assumed that the monument displacements for the entire interval sum to zero. More importantly, the sums of the relative instrument scales are forced to equal zero for three time intervals; specifically, from January 1988 to August 1989, from July 1988 to April 1989, and from July 1989 to August 1989. With these constraints, it becomes possible to compute the offset in instrument length of instrument #21 relative to #11 and the offset in the Cmeter length in May 1989. Finally, contrary to the data plotted in Figure 2, the comparison measurements of January 1987 and May 1989 have not been used because one of the two instruments was not properly functioning.

Figure 4. Estimates of the offset of instruments #21 and #22 relative to #11 as a function of baseline length for the Parkfield and Long Valley data sets.

Superimposed is the function showing the preferred model (model 1 in Table 4) of the offset in distances measured using the two instruments. Figure 4a show for the Parkfield data the estimates of offset in distances of #21 relative to #11 that have been derived on the basis of the comparison data between mid 1987 and March 1989 assuming that, on average, the monuments at CARR did not move relative to each other between two intervals, from mid 1987 to May 1988 and from July 1988 to March 1989. The results in Figure 4b and 4c are for the offset of instrument #21 and #22 relative to #11. The estimates are based upon line-length changes measured in Long Valley and assume that the line-length changes can be characterized as a second order polynomial in time.

Figure 5. Comparison of deformation at Parkfield and Long Valley which illustrate possible changes in the length scale of the Parkfield instrument. Results of determining fault slip near CARR, shear strain, and dilatational strain are from frequent measurements of the baselines at Parkfield (*Langbein et al.*, 1990). These estimates are made with measurements from the Cmeter. In contrast, the bottom trace shows the inferred dilatational strain from frequent measurements of the network in Long Valley made using the portable instrument #11. In comparing the dilatation, note that the Cmeter results show large, 1 *ppm*, variations in dilatation during late April and May 1989 whereas the results from #11 show significantly smaller variations. The result of measuring the changes in instrument length scale of the Cmeter relative to #11 is plotted in the second from the bottom trace. The instrument scale has been multiplied by 2 in order to correspond to areal dilatation. The change in length scale of the Cmeter correlates with the inferred dilatation measured at Parkfield.

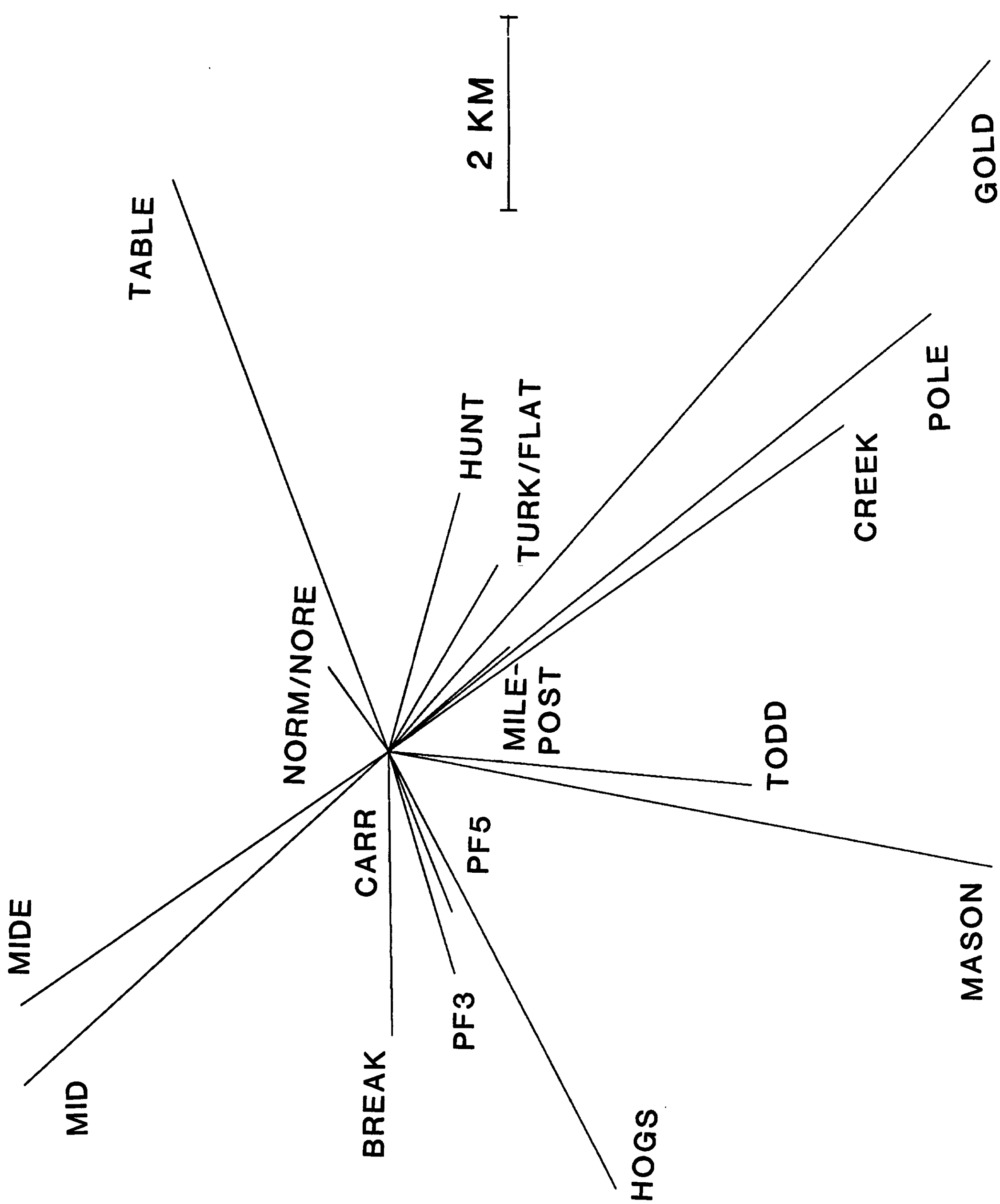


TABLE
2 KM
GOLD
HUNT
TURK/FLAT
POLE
CREEK
NORM/NORE
MILE-
POST
TODD
CARR
PF5
MIDE
MASON
PF3
BREAK
MID
HOGS

Figure 1

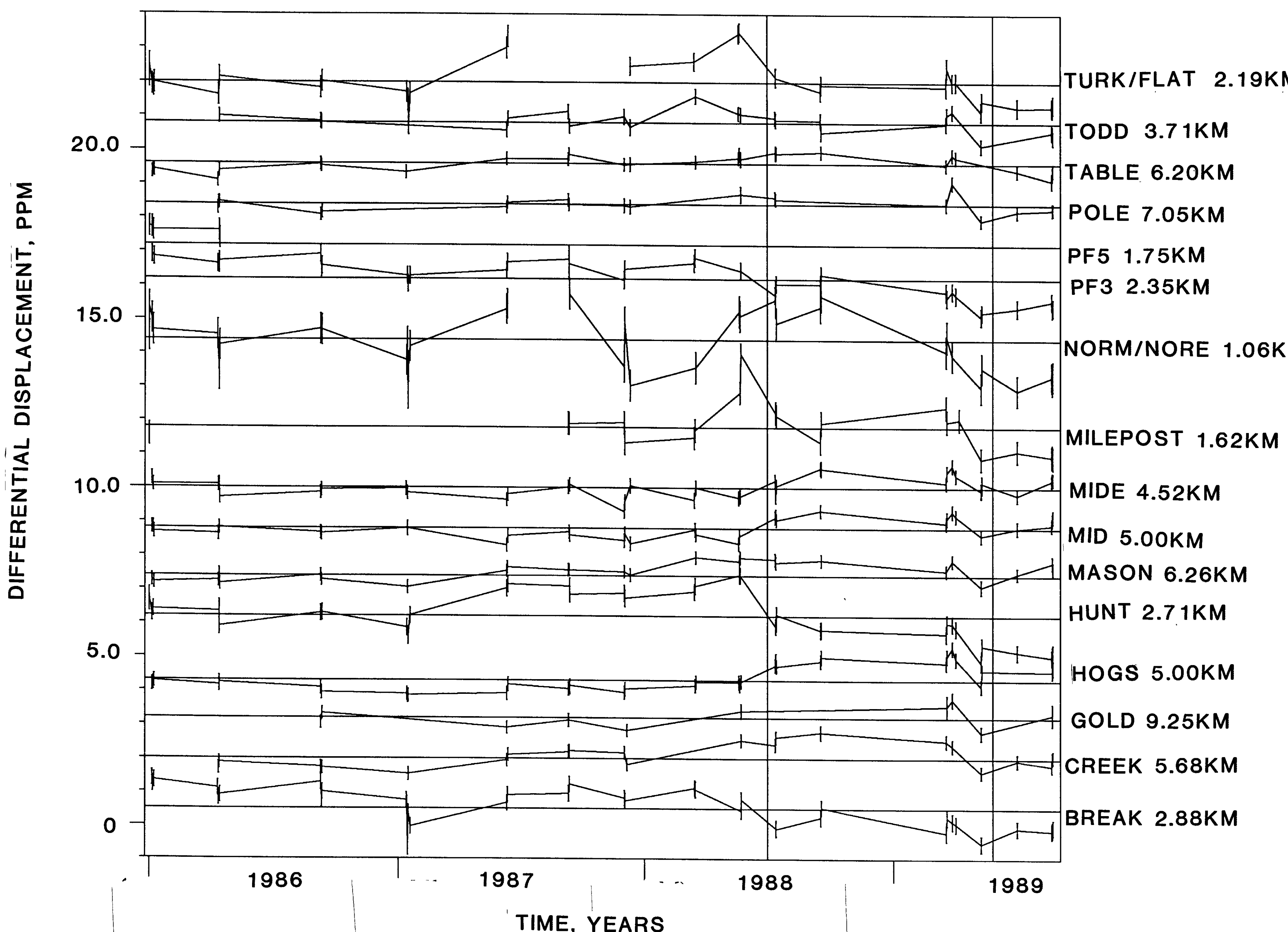
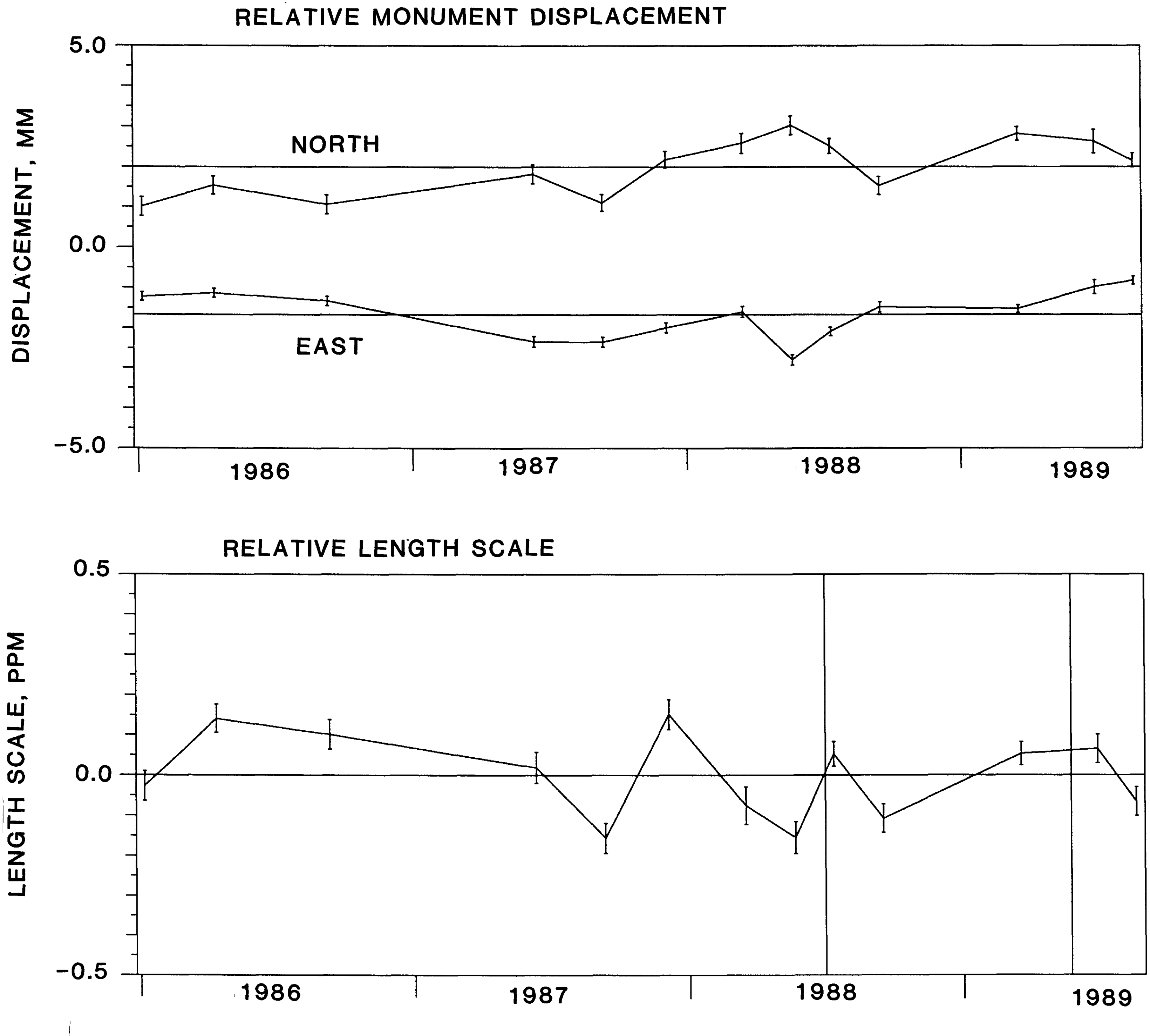

TURK/FLAT 2.19KM
TODD 3.71KM
TABLE 6.20KM
POLE 7.05KM
PF5 1.75KM
PF3 2.35KM
NORM/NORE 1.06KM
MILEPOST 1.62KM
MIDE 4.52KM
MID 5.00KM
MASON 6.26KM
HUNT 2.71KM
HOGS 5.00KM
GOLD 9.25KM
CREEK 5.68KM
BREAK 2.88KM
20.0
15.0
10.0
5.0
0
DIFFERENTIAL DISPLACEMENT, PPM
1986
1987
1988
1989
TIME, YEARS

Figure 2



RELATIVE MONUMENT DISPLACEMENT
DISPLACEMENT, MM
5.0
0.0
-5.0
NORTH
EAST
1986
1987
1988
1989
RELATIVE LENGTH SCALE
LENGTH SCALE, PPM
0.5
0.0
-0.5
1986
1987
1988
1989

Figure 3

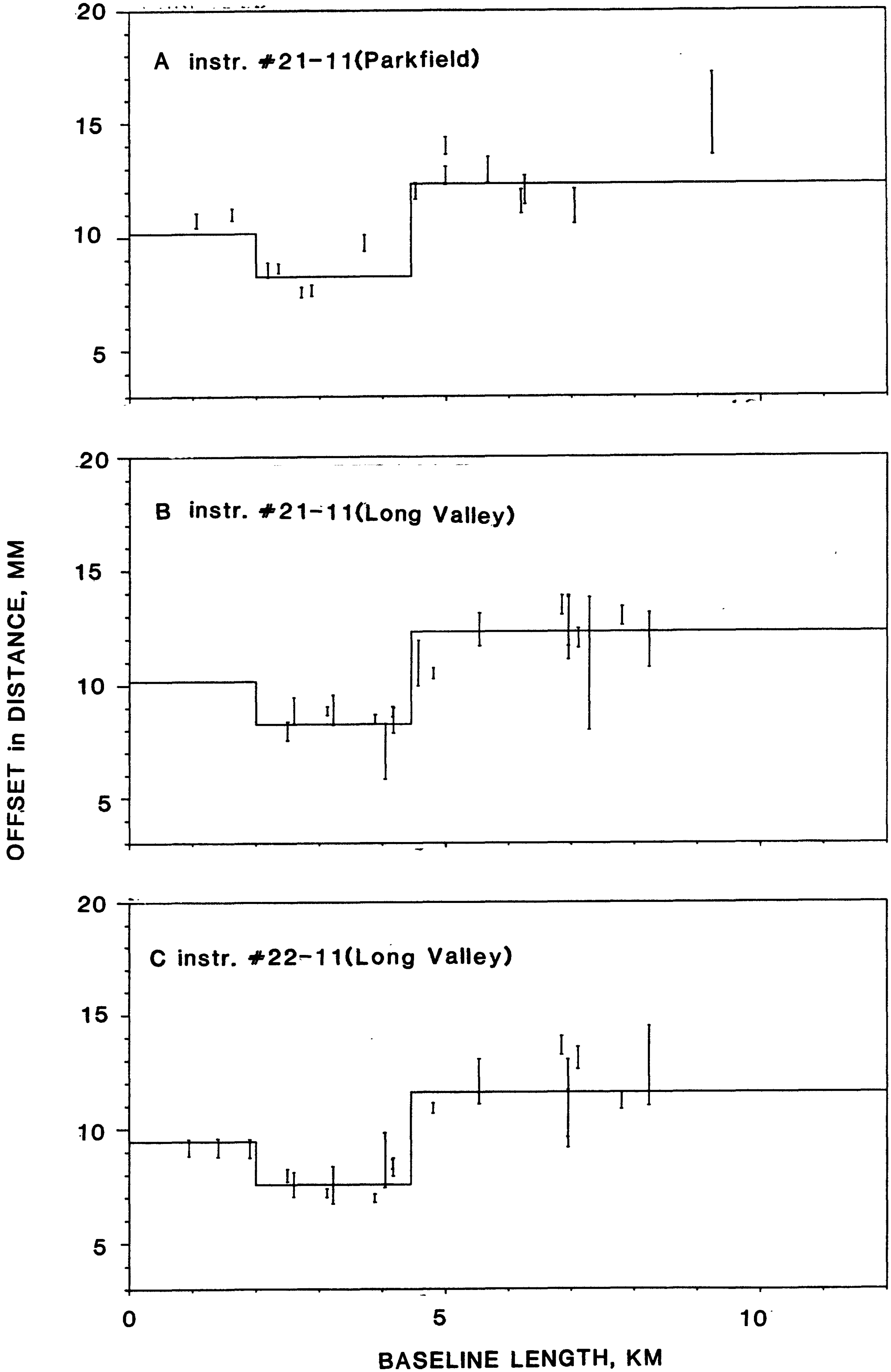

A instr. #21-11(Parkfield)
B instr. #21-11(Long Valley)
C instr. #22-11(Long Valley)
OFFSET in DISTANCE, MM
BASELINE LENGTH, KM
20
15
10
5
0
5
10

Figure 4

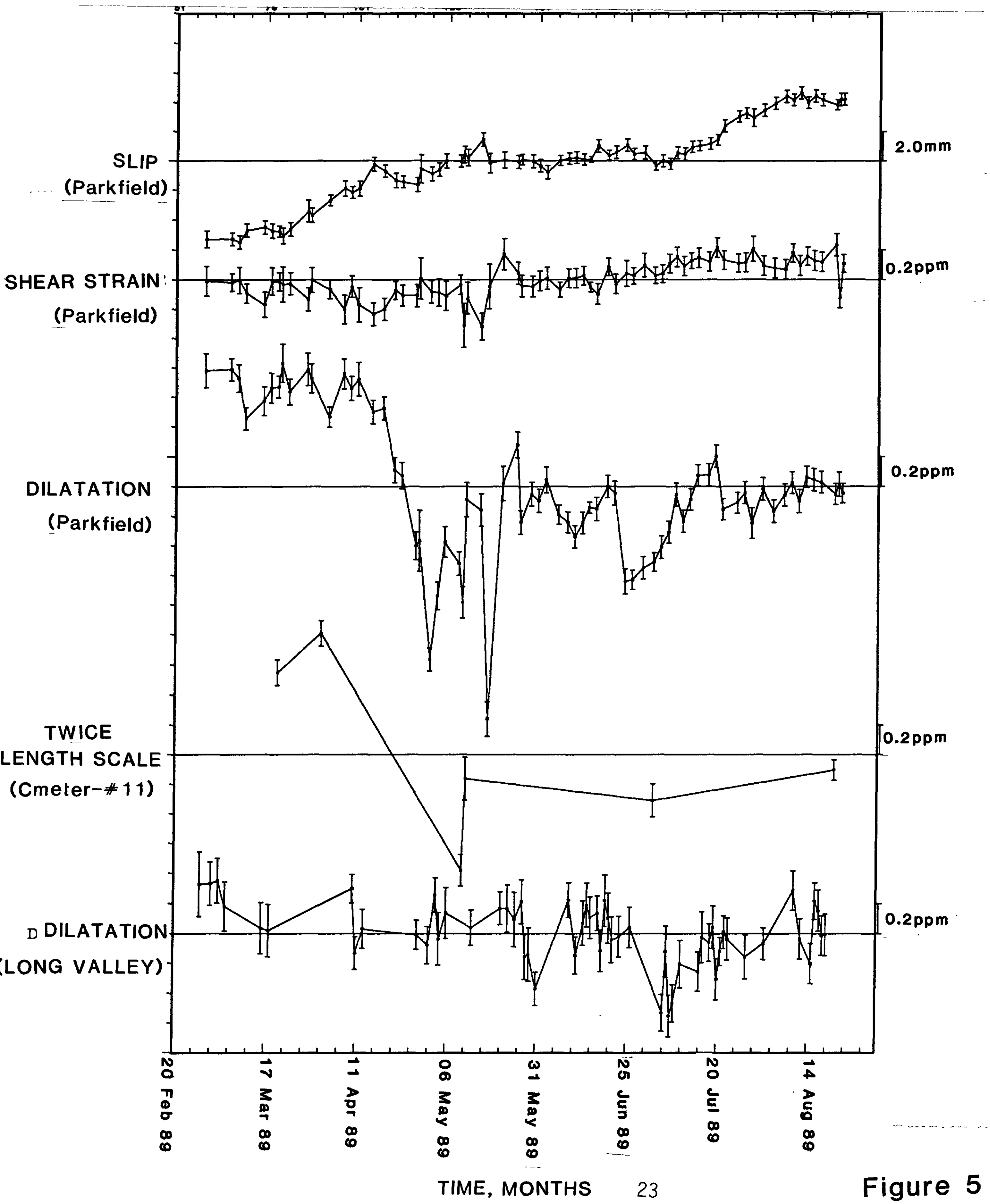

SLIP
(Parkfield)
2.0mm
SHEAR STRAIN
(Parkfield)
0.2ppm
DILATATION
(Parkfield)
0.2ppm
TWICE
LENGTH SCALE
(Cmeter-#11)
0.2ppm
D DILATATION
(LONG VALLEY)
0.2ppm
20 Feb 89
17 Mar 89
11 Apr 89
06 May 89
31 May 89
25 Jun 89
20 Jul 89
14 Aug 89
TIME, MONTHS

Figure 5