U. S. DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Motion of Kilauea Volcano During Sustained Eruption from the Puu Oo and Kupaianaha Vents, 1983-1991: Supplemental Information

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Open-File Report 94-567

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Introduction

This report assesses the precision and accuracy of geodetic measurements made by staff of the Hawaiian Volcano Observatory. The assessment is supplemental to a report summarizing ground-surface motions on Kilauea Volcano, Hawaii, between 1983 and 1991 [*Delaney et al.,* 1993]. Although obtainable in the microfiche edition of the Journal of Geophysical Research as document B93-004 available from the American Geophysical Union, this Open-file Report makes the material herein more readily available, especially for those more interested in the data-collection procedures than the actual motions of Kilauea during the time interval in question. The three sections comprising this report describe procedures for collection of so-called spirit-level tilt, leveling, and electronic ranging data. An earlier report by *Kinoshita et al.* [1974] also provides much useful information.

Accuracy and Precision of Tilt Measurements

The "spirit-level" method employed for measurement of tilt at HVO is described by *Kinoshita et al.* [1974]. Measurements are made with Wild N-3 levels fitted with micrometers and sets of three graduated invar rods. Each of the rods are always placed upon the same monuments, which, at each station, are arranged in an equilateral triangle with 40-m sides. Measurements of height differences are generally rejected if loop-misclosures exceed 0.05 mm. In fact, *Okamura* [1988] reports an average misclosure of 0.02 mm for the more than 3000 measurements made by HVO between 1968 and 1986, a sighting precision that usually requires multiple readings of each of the three sides. By co-locating two spirit-level tilt stations with 50-m-base water-tube tilt stations, *Kinoshita et al.* [1974] found a precision of 2–3 μrad for tilt measurements. *Kinoshita et al.* [1974] note that for small inflation or deflation episodes, the method provides useful results for stations within about 2.5 km of the deformation center at Kilauea summit. Since the inception of the method, however, HVO spirit-level tilt stations have been installed across virtually all of Kilauea.

Furthermore, since 1983, even deformations near the summit have been modest. To confidently identify tilts, therefore, better determination of the procedural accuracy is required. As shown below, the primary source of error arises from unstable, or incoherent, motions of tilt-station monuments rather than from sighting imprecision.

Noting that $-cz = ax + by$ defines a plane, tilts can be calculated by associating the change in height difference between two monuments δh_{ij} with the vertical variable z and the east and north components of distance between the i and j benchmarks with x and y. The equation for the tilt plane is then $-\delta h_{ij} = (a/c)x_{ij} + (b/c)y_{ij}$, where a/c and b/c are inverse tangents of the east and north components of tilt, τ_e and τ_n, respectively. Converting to an azimuthal coordinate ϕ and including the presence of error ϵ, the observation equations for the east and north tilts are $-\delta h_{ij} = \tau_e L \sin\phi_{ij} + \tau_n L \cos\phi_{ij} + \epsilon_{ij}$, where the height-difference change from the ith to the jth monuments is measured along azimuth ϕ_{ij}, the section lengths are L, and ϵ_{ij} is the error to be minimized. For the HVO spirit-level method, the system of equations is $\mathbf{Y} = \mathbf{X}\beta + \epsilon$, in the matrix notation of *Draper and Smith* [1981, p. 108], where

$$\mathbf{Y} = -\left\{\begin{array}{c} \delta h_{12} \\ \delta h_{23} \\ \delta h_{31} \end{array}\right\},\ \mathbf{X} = L\left\{\begin{array}{ll} \sin(\phi_{12}) & \cos(\phi_{12}) \\ \sin\left(\phi_{12}+\frac{2\pi}{3}\right) & \cos\left(\phi_{12}+\frac{2\pi}{3}\right) \\ \sin\left(\phi_{12}+\frac{4\pi}{3}\right) & \cos\left(\phi_{12}+\frac{4\pi}{3}\right) \end{array}\right\},\ \beta = \left\{\begin{array}{c} \tau_e \\ \tau_n \end{array}\right\},\ \epsilon = \left\{\begin{array}{c} \epsilon_{12} \\ \epsilon_{23} \\ \epsilon_{31} \end{array}\right\}.$$

Weighting of these equations by the uncertainties is discussed below.

Knowing τ_e and τ_n, the tilt magnitude τ is $\cos(\tau) = 1/\sqrt{\tau_e^2 + \tau_n^2 + 1}$, which simplifies to $\tau = \sqrt{\tau_e^2 + \tau_n^2}$ for small angles; the azimuth of the tilt direction γ is $\sin(\gamma) = \tau_e/\sqrt{\tau_e^2 + \tau_n^2}$ if τ_n is positive and $\sin(\gamma - \pi) = -\tau_e/\sqrt{\tau_e^2 + \tau_n^2}$ if negative. Least-squares determination of τ_e and τ_n also yields a determination of their standard deviations, σ_e and σ_n. For tilt stations of any orientation that lack a preferred azimuth along which measurements are made, $\sigma_e = \sigma_n \equiv \sigma$ with no covariance between them. The uncertainty of the tilt magnitude is $\sigma_\tau = \sigma/(1 + \tau_e^2 + \tau_n^2) \simeq \sigma$ and the uncertainty of the tilt direction is $\sigma_\gamma = \sigma/\sqrt{\tau_e^2 + \tau_n^2} \simeq \sigma/\tau$ [*c.f., Bevington*, 1969, p. 59].

The uncertainties of computed tilts depend upon the uncertainties of the measurements and the geometry of the tilt station. At least three sources of error affect the spirit-level tilt measurements: (1) sighting error; (2) monument-instability error; and (3) correlated error between successive measuring sessions. Sighting error σ_s is well determined by loop misclosures; for the HVO method of 3 sightings, the average misclosure is 0.02 mm [*Okamura,* 1988] and the average sighting error is therefore less by the factor $3^{-1/2}$, $\sigma_s = 0.01$ mm. Monument instability σ_i is the non-tilting motion among monuments due to the presence of cavities and inhomogeneities (both common in basaltic lavas), temporal variations in temperature and moisture content of near-surface rocks, and unequal motion between the monument and surrounding rocks or soil—all of which are affected by local topography. Benchmark arrays near the San Andreas fault in California have $\sigma_i \simeq 0.25$ mm [*Savage et al.,* 1979], which exceeds by an order of magnitude the HVO estimate for σ_s. Benchmarks that move by incoherent motions may introduce instability error that accumulates with time; errors introduced during one measuring session depend, in part, upon errors present during previous sessions. This last source of error, which is thought to be caused by weathering [*Wyatt,* 1989], is neglected here.

Knowing that measurements are accompanied by the errors σ_s and σ_i, it is possible to deduce the form of the variance-covariance matrix for the data and used to weight that data in the solution for the tilt. During each session, each of the three sightings can be regarded as independent of the other two. As one measures a triangular array of monuments in a clockwise direction, however, a positive apparent tilt due to upward unstable motion of a forward monument in one sighting is a negative apparent tilt due to the relative downward motion of the backward monument in the next sighting. The instability of one benchmark is thus shared by two sightings and each sighting has a contribution to the total error from two benchmarks. For the HVO benchmark arrays, therefore, the variance-covariance matrix for the data is

$$\mathbf{V} = \left\{ \begin{array}{ccc} 2(\sigma_s^2 + \sigma_i^2) & -\sigma_i^2 & -\sigma_i^2 \\ -\sigma_i^2 & 2(\sigma_s^2 + \sigma_i^2) & -\sigma_i^2 \\ -\sigma_i^2 & -\sigma_i^2 & 2(\sigma_s^2 + \sigma_i^2) \end{array} \right\},$$

where the diagonal terms have factors of 2 because error is introduced by both of the measuring sessions required to obtain the three changes in height difference; in the off-diagonal terms, this factor cancels with a factor of 1/2 in the monument-instability covariance, which arises because the two monuments for a sighting each share half of that source of error.

The 3-monument arrays used at HVO determine, but do not overdetermine, a tilt plane, and so monument instabilities cannot be detected in the HVO tilt data without additional constraints. To provide such a constraint, we turn to data collected at Hualalai volcano (Figure A-1), which has not erupted for almost 200 years and is presumably non-deforming, and to data collected on the lower slopes of Mauna Loa, which are also apparently nondeforming. Apparent tilts at such these stations are actually errors, or estimates of σ. For 54 data, the residuals about the means for the 14 stations (Table A-1) reveal that $\sigma \simeq 5.6$ μrad, so that the uncertainty between two measurement sessions is 8 μrad. Accepting this value and using the matrices $\mathbf{X}$ and $\mathbf{V}$, above, we are able to calculate [*Draper and Smith*, 1981, p. 109] that $\sigma_i = 0.25$ mm. This estimate equals that obtained by *Savage et al.* [1979]. We note, however, that whereas monuments installed by HVO staff are either steel concrete nails driven into glassy pahoehoe basalt or benchmarks set into mortar-filled core holes, those used by *Savage et al.* [1979] are clamped to 5–6-m rods driven to refusal, usually in clay-rich soils, and set in casings to remove the benchmarks from near-surface sources of instability.

After completion of an analysis of errors similar to that presented here, *Savage et al.* [1979] found that small aperture arrays (<100 m) exhibit apparently significant tilts not found in arrays of larger aperture. These excursions are attributed to the influence of disturbances that are amplified by local topography [*Harrison*, 1976; *Harrison and Herbst*, 1977] of wavelengths comparable to or larger than the array aperture. They are, therefore, sources of error that cannot be separated from actual tilt solely by examination of the data and the adjunct surveying errors. Spirit-level tilt measurements made at HVO suffer from the additional problem that unstable monuments and inhomogeneous deformation within a tilt array are undetectable. We anticipate, therefore, the $\sigma = 5.6$ μrad is too optimistic an estimate of the error at many tilt stations.

Accuracy and Precision of Leveling

As with the measurement of tilt, leveling at HVO was originally intended for use near Kilauea summit. There, typical inflationary and deflationary events have amplitudes of ~0.5 m and wavelengths of ~10 km, giving rise to characteristic tilts of ~100 μrad (e.g., *Fiske and Kinoshita* [1969]). Under these circumstances and in view of the rapid deformations that characterized Kilauea summit from the 1960s until 1983, the HVO leveling method was devised for rapid traverse [*Kinoshita et al.*, 1974]. As discussed below, the HVO leveling method does not appear to have introduced significant systematic errors into the determination of height. Nevertheless, to monitor the modest deformations acting at Kilauea summit since 1983 and to gain better confidence in results of the 200-km-long levelings that begin at the Hilo tide gauge, the HVO method was abandoned in 1987 in favor of a method generally consistent with that for second-order, class I procedures for micrometer levels [*Federal Geodetic Control Committee*, 1984].

The precision of leveling, as measured by loop misclosures, conducted on a volcano as active as Kilauea depends upon rapid completion of a survey. The requirements of rapid traverse are such that, in 1974, a National Geodetic Survey crew was repeatedly unable to obtain acceptable section closure for first-order leveling north of Kilauea crater because of minor deformations caused by the summit magma chamber centered about 5 km away. Thus, the precisions of HVO leveling cannot be easily separated from some portion of the (usually) ongoing deformation.

The third-order procedure for three-wire leveling that prevailed in the late 1960s was modified at HVO as follows: (1) no limits were placed upon sight length; (2) no limits were placed upon sight-length imbalance at each setup, except to limit the sum of imbalances for each section to less than a few meters; (3) the direction of running was never reversed, although it was the same from one leveling to the next; (4) setups that required sighting of the lowest graduations on the level rod were allowed; (5) the backsight rod was always sighted before the foresight rod; and (6) reading checks for instrument- or rod-setup instability were abandoned. Each of these modifications permitted introduction of systematic errors and blunders. At least four factors, however, helped to assure the quality of the data: (1) instruments were tested daily for collimation error, which was not allowed to exceed 0.01 $mm \cdot m^{-1}$; (2) steel concrete nails were driven into pavement to serve as stable, semi-permanent turning points; (3) systematic errors, if present, would typically cancel between levelings because the method and field procedure were adhered to rigorously; and (4) the frequency of levelings and use of semi-permanent turning points assured that blunders could be easily detected by comparison with previous levelings.

The most serious concern with analysis of the HVO leveling method is unequal refraction error, which is enhanced by sight-length imbalance and setups that employ the bottom graduations of the level rods. This error typically accumulates along gentle slopes [*Holdahl*, 1982], perhaps similar to the route from the Hilo tide gauge to Kilauea summit. This route passes through rain forest, however, and is usually not subjected to strong near-ground temperature gradients. Noting that the bottom reticle employed in the three-wire method is most susceptible to refraction, some levelings were adjusted using only the center-wire data and compared with results using the three-wire data. In three selected levelings from the Hilo tide gauge (1976, 1979, 1986), the apparent heights of benchmarks near Kilauea summit are each found to be 1 cm higher when the center-wire results are compared with the three-wire results. We tentatively conclude that systematic errors in the HVO method are present but small in comparison to the magnitudes of most vertical motions.

The precision of the HVO leveling method is not well determined. As with all leveling, random errors accumulate with the square-root of the distance of traverse. To estimate the magnitude of this error, we examined 15 levelings completed between 1971 and 1986 with one or more degrees of freedom in the network adjustment for height, discussed below, for a total of 25 degrees of freedom. By assuming that the weighted sum-of-squares residual χ^2 should be equal to the degrees of freedom $n - m$, we find that $\chi^2 \simeq n - m = 25$ requires a random-error propagation of $a = 7$ mm$\cdot$km$^{-1/2}$. We accept this estimate of the random error associated with the HVO leveling method.

The method employed for the 1988 and 1989 levelings of Kilauea generally complies with the standards for second-order, class-I micrometer levels set by the *Federal Geodetic Control Committee* [1984]. Specifications that exceed these standards include: (1) set-up lengths are limited to 50 m; (2) sight-length imbalance at each setup is limited to 2 m; (3) the direction of running is typically reversed at half-day intervals, except along the remote Footprints trail that crosses the southwest rift zone; (4) instruments are checked daily for collimation error, which is not allowed to exceed 0.01 mm$\cdot$m^{-1}; and (5) rods are removed from the turning points between sightings so as to minimize pin settling. Also, steel concrete nails serve as semi-permanent turning points; to further minimize pin settling, galvanized washers are placed beneath the nail heads so that the weight of the rods is borne by normal surface forces, as well as the shear forces acting along the shank of the nails. Specifications that do not meet these standards include: (1) distance between network control points exceeds that allowable because the Hilo tide gauge is the only local vertical control; (2) instruments are not releveled between reading of high and low rod scales; and

(3) temperatures are not measured and so certain rod and thermal refraction corrections are not applied to the data. Temperature corrections are probably less important in Hawaii than elsewhere because temperature variations are modest. Except as noted, we use the recommended random-error propagator of $a = 2$ mm$\cdot$km$^{-1/2}$ for second-order, class-I leveling and assume that systematic errors are eliminated by the field procedure.

Table B-1 summarizes results of network adjustments for levelings undertaken since 1983. Level-network adjustments are computed from the observed height differences δh by solving for the heights h of benchmarks at junction and end points by weighted least squares for the observation equations $\delta h_{ij} = h_j - h_i + \epsilon_{ij}$ with variances $\sigma_{ij}^2 = a^2 L_{ij}$, where ϵ_{ij} is minimized, L_{ij} is the length of section between the ith and jth benchmarks, and a is the error-propagation parameter. Heights of the remaining benchmarks are adjusted by interpolation and variances determined by back distribution of residuals [*Vaníček and Krakiwsky*, 1986, p. 437–438]. Orthometric corrections for the gravity field are not applied. During both the 1988 and 1989 levelings, it was necessary to cross an active lava flow; this was achieved by use of short sighting lengths (<30 m) and concurrent double running of the section, which, of necessity, exceeded the length allowable for second-order, class-I leveling. In each case, the resulting loop misclosure was less than 1 mm. Among the levelings that adhere to second order, class I methods, the 1988 survey has only a 0.02% chance of having residuals from the network adjustment due to the expected random error; we thus use the "post-fit", or *a postiori*, estimates of variance based upon the assumption that $\chi^2 \simeq n - m = 5$ degrees of freedom for that leveling, to determine uncertainties in height. This leveling included sections between junction points near Kilauea summit that were completed almost 4 months after others were closed; based upon the average maximum summit subsidence rate of 11 cm$\cdot$yr^{-1}, 4 cm of motion occurred near summit level sections during the 1988 leveling.

Accuracy and Precision of Ranging

Ranging measurements at HVO are accompanied by measurement of end-station pressure and temperature in order to estimate the refractive index of air along the beam path. Pressures are measured with altimeters that read to the nearest 2 m. To measure temperature, thermistors are mounted in perforated, white tubes and placed on 7-m-long, collapsible bamboo fishing poles so as to be above near-ground temperature gradients. Since 1983, the most commonly used instrument has been a K&E Range Master III (RM), although a Hewlett-Packard 3808a (HP) is preferred where baseline distances do not exceed ~10 km. In 1986, a K&E Ranger Va (RV) was acquired and used until late 1988. After 1988, frequency counters were used with each ranging instrument to monitor oscillation of the primary crystal that controls beam modulation. The refractive-index correction for air along the beam path assumes a humidity corresponding to 10 mm of Hg at 25° for all measurements. No beam-curvature corrections are applied to the data; atmospheric measurements to determine beam curvature are not made and any standard correction applied to the data are cancelled when repeat measurements are used to determine line-length change or a series of measurements are used to determine rates of line-length change. All data are converted to mark-to-mark distances and changes in baseline length, or rates of change of baseline length are used to determine relative displacements or velocities.

To determine the precision and relative accuracy of the three instruments used since 1983, a program of repeat measurements was begun in 1988. These data were combined with miscellaneous repeat measurements taken between 1980 and 1987 and with data collected along short ($\lesssim$2 km) lines in an area of apparent tectonic stability near Hilo, to serve as standards for purposes of determining instrument-offset constants (IOCs). In all cases, repeat measurements were accepted only if the possibility of significant intervening deformation could be confidently rejected. Subsets of these data are used for two purposes.

First, we determine the precision of ranging measurements for each instrument. Second, we determine IOCs for each instrument and find it necessary to postulate that one instrument has a systematic length-dependent discrepancy that must be removed with a scale constant. Uncertainties in the determination of these parameters contributes to the overall imprecision of the instruments.

Repeatability of ranging measurements for each instrument used at HVO is shown in Figure C-1 as a function of baseline length. Apparent differences in length are attributed to random fixed error a and scale error b such that the overall random error σ associated with a single measurement is determined by $\sigma = \sqrt{a^2 + b^2 L^2}$, where L is baseline length [*Savage and Prescott,* 1973]. For each instrument, the parameters a and b are estimated by unweighted least-squares fitting. The results (Table C-1) reveal fixed errors in the range of 2–9 mm and scale errors of $0.9\text{–}1 \times 10^{-6}$. These estimates are consistent with precisions generally supposed for ranging measurements accompanied by end-station determination of temperature and pressure [*Laurila,* 1983]. No data used to obtain these results span identified periods when the instruments may have been disturbed or serviced. These estimates of precision, therefore, do not include uncertainties associated with the determination of instrument calibration constants. As discussed below, uncertainties in these constants contribute to the uncertainty of the random errors and are taken into account when computing the overall expected error (Table C-1).

Some ranging measurements made at HVO employ reflectors permanently attached to steel rods driven to refusal in the ground; temperature and pressure are measured only at the instrument station. The use of a fixed reflector reduces random fixed error; the lack of atmospheric data at the reflector station increases random scale error. We need to estimate the fixed and scale errors of these "permanent-glass" measurements, $\hat{a}$ and $\hat{b}$, respectively. For conventional measurements, the primary sources of fixed error a involve the errors associated with the set-ups of the reflector and instrument tripods a_T and any fixed sources of instrumental error, a_I, so that $a^2 = 2a_T^2 + a_I^2$. The permanent-glass measurements remove error associated with set-up of the reflector tripod, so $\hat{a}^2 = a_T^2 + a_I^2 = a^2 - a_T^2$. To estimate a_T, assume that the HP instrument, which has the smallest fixed error of any used at HVO, has $a_I << a$. It follows that $a = 2$ mm $\simeq \sqrt{2}a_T$. A similar line of reasoning can be followed for the determination of the scale error for the permanent-glass measurements. The scale errors for each of the three instruments are about the same, which suggests that its source lies with the measurement of temperature and pressure, rather than the variations in the frequency of the crystal oscillators. We assume, therefore, that $\hat{b} \simeq \sqrt{2}b$. We note that permanent-glass measurements are likely to have systematic errors that differ from those of conventional measurements, and that conventional measurements, in turn, are likely to have systematic errors that differ from those with measurements made from aircraft that sample atmospheric conditions along the entire baseline. Although conventional and aircraft measurements are sometimes made along the same baselines, HVO has avoided permanent-glass measurements of baselines that are normally measured by conventional means.

To determine IOCs for each instrument, we rely upon measurements of short (150 m to 915 m) "calibration" lines installed along a flat section of highway near Hilo and measured with an accuracy of less than 1 mm in 1986 by the National Geodetic Survey (NGS). The five NGS lines are co-located with three lines measured by HVO staff since 1981. The instruments used at HVO suffer from pointing difficulties when measuring short distances, however, and this problem is made worse by vibration from nearby vehicular traffic and near-ground scintillation. Of the 270 calibration measurements, 15% were rejected as blunders attributable to these causes. By assuming that none of the calibration lines have changed length and that each of the instruments have IOCs that change with use, we found the weighted least-squares solutions for 12 IOCs and the lengths of the 3 HVO calibration lines. Of the 12 IOCs, 10 correspond to periods bounded by dates of instrument servicing; the remaining 2 IOCs divide 3- and 6-year periods of no instrument maintenance. All IOCs have uncertainties in the range 0.3–3.5 mm.

To test that each of the three instruments has the same relative accuracy, we examined measurements made with the HP and RV instruments and repeated with the RM instrument (Figure C-2) and found that the RM measures longer apparent lengths than both the HP and RV. We therefore decided to include the repeat-measurement data with the calibration data in the determination of the IOCs. The resulting χ^2 residual (Table C-2), however, yielded an unacceptably low probability of being due entirely to random procedural errors ($p = 0.005$) in comparison to the success of the IOC determination using only the calibration data ($p = 0.62$). We then investigated two methods to correct for the discrepancies among the instruments. Because there are no long, stable baselines of well-determined length in Hawaii, we found it necessary to postulate that either the RM is stable and correct—and that the HP and RV measure distance improperly—or that the HP and RV are stable and correct—and that the RM measures distance improperly. We suspect that the latter is the case.

First, we postulated a constant systematic error in measurement of short lines such that IOCs determined from the calibration data differ from the actual IOCs by some constant, here referred to as an "incremental" IOC (see Table C-2). Assuming that the RM instrument is stable and correct in measurement of distance, we found a fit to the data ($p = 0.05$) that improved only slightly by assuming that the RM measures distances incorrectly ($p = 0.05$), in which case, the "incremental" IOC is -10 ± 2 mm. This postulate is unattractive, however, because no evidence suggests that short lines are measured differently than longer ones.

Second, we postulated a systematic scale error in one or two of the instruments (Table C-2). Such an error might arise, for instance, if one of the crystals controlling frequency modulation was improperly adjusted; the error would be corrected by a scale constant (SC). Assuming that the RM instrument is stable and correct in measurement of distance, we found a fit to the data ($p = 0.10$) by solving for SCs for the HP and RV; the uncertainties associated with the determination of these constants, however, reveal that they are not significantly different at the 95% confidence level. We prefer, therefore, the explanation that one instrument, the RM, is at fault and find that it requires a SC of $-1.9 \pm 0.3 \times 10^{-6}$ to account for the apparent discrepancy among the instruments ($p = 0.11$); this correction is applied to all data collected with the RM instrument used in this report. Because frequency counters were used with all instruments during ranging, improperly adjusted master crystals are not a likely source of error. However, the intensity of the return beam varies (nonlinearly) with distance and is partially adjustable by the operator. It is possible that apparent distances vary with beam intensity, but we were unable to confidently document such behavior. We regard the SC for the RM instrument as an empirical correction to a systematic error of unknown origin.

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Figures

Fig. A-1 Apparent east-west (*a*) and north-south (*b*) tilt as function of time for 14 stations on Hualalai and Mauna Loa volcanoes. There is no evidence that tilts are due to ground-surface deformation at any of the stations.

Fig. C-1 Apparent change in length of baselines as a function of distance for repeated measurements of RM (*a*), HP (*b*), and RV (*c*) ranging instruments. Also shown are lines of $\pm 1\sigma$ and $\pm 2\sigma$ as determined from estimates of the random procedural error (Table C-1).

Fig. C-2 Apparent change in length of baselines as a function of distance for repeated measurements of HP and RM (*a*) and of RV and RM (*b*) ranging instruments. In each graph, the short-dashed line is the best-fit "incremental" IOC that accounts for the discrepancy of the HP or RV with the RM and the long-dashed line is the best-fit scale constant that accounts for the discrepancy, assuming that the RM is the source of the discrepancy. Data in the 0–2-km range are from the "calibration" lines near Hilo that serve as standards for determination of IOCs. Error bars are 2σ.

Table A-1: Tilt errors from data at nondeforming sites[1]

Station Name	Latitude (deg. min.)	Longitude (deg. min.)	Number of Data n	Square Residual about Mean (μrad^2)	Standard Deviation (μrad)
1800 Flow	19 44.50	155 55.64	3	53.8	5.2
Kanaekii	19 30.39	155 45.93	5	133.4	5.8
Kanaekii V	19 30.39	155 45.93	2	13.9	3.7
Kaupulehu	19 42.98	155 54.61	2	0.3	0.5
Kipahee	19 41.78	155 51.26	3	31.1	3.9
Malekule	19 41.63	155 53.06	3	20.5	3.2
Moore Crater	19 39.08	155 48.99	4	128.3	6.5
Pihapono	19 38.08	155 50.90	3	6.3	1.8
Puuhale	19 39.91	155 51.76	2	17.2	4.1
Puuhale V	19 39.91	155 51.76	3	45.3	4.8
Wahapale	19 36.66	155 49.90	4	294.8	9.9
Humuula	19 41.59	155 29.06	7	46.4	2.8
Lua Kalupenui	19 2.89	155 43.65	8	268.4	5.8
Puueo	19 2.21	155 40.21	5	177.7	6.7
all 14 stations			54	1237.4	5.6

[1] All stations, except the last three are on Hualalai volcano, which has not erupted for almost 200 years. The last three stations are on the lower slopes of Mauna Loa.

Table B-1: Leveling Results[1]

Location	Begin Date	End Date	Procedure	Total Length (km)	Number of Data n	Number of Parameters m	Error Propagation (mm·km$^{-1/2}$)	Sum-of-Square Residuals χ^2	Probability p
Kil. summit	2/7/83	2/16/83	HVO 3-wire	57	16	14	7	1.4	0.50
Kil. summit	12/28/83	1/9/84	HVO 3-wire	54	12	10	7	5.1	0.08
Kil. summit	7/23/84	7/28/84	HVO 3-wire	51	13	13	7	0	
Kil. summit	2/5/85	2/15/85	HVO 3-wire	58	14	13	7	0.003	0.96
Kil. summit	7/8/85	7/12/85	HVO 3-wire	60	15	14	7	0.60	0.44
Kilauea	2/10/86	7/24/86	HVO 3-wire	180	24	20	7	4.9	0.30
Kilauea	1/11/88	6/15/88	2nd-order class I	230	30	25	4.4	$n-p$	(0.0002)[2]
Kilauea	6/30/89	2/20/90	2nd-order class I	225	28	23	2	2.5	0.77
Kil. Summit	3/12/91	5/16/91	2nd-order class I	62	18	16	2	0.14	0.93

[1] Kilauea summit levelings include the upper east and southwest rift zones and the Koae fault system.

[2] For 2nd order, class I leveling of 1988, error propagation of 2 mm·km$^{-1/2}$ yields $\chi^2 = 24.7$, which has an unacceptably low probability of being due to random procedural error; according, χ^2 is also set to $n - m$ and error estimates are obtained for error propagation of 4.4 mm·km$^{-1/2}$. Network misclosures for this leveling result from a 3-month interval between beginning and finishing of sections at Kilaeua summit.

Table C-1: Precision of Ranging Instruments[1]

Instrument	Symbol	Maximum Range (km)	Data Range (km)	Number of Data n	Fixed Error Measured (mm)	Scale Error Measured (10^{-6})	Fixed Error Used (mm)	Scale Error Used (10^{-6})
K&E RangeMaster III	RM	50	0–22	100	9 ± 1	0.9 ± 0.1	10	1
Hewlett-Packard 3808a	HP	12	0–10	36	2 ± 1	1.0 ± 0.1	3	1
K&E Ranger Va	RV	25	0–12	10	4 ± 2	1.0 ± 0.3	5	1

[1] Measured setup and scale errors are determined by the least-squares fit to the equation for the standard deviation $\sigma = \sqrt{a^2 + b^2L^2}$, where L is line length. Values used include uncertainties in determination of instrument calibration constants. Errors are shown as $\pm 1\sigma$.

Table C-2: Calibration of Ranging Instruments[1]

Number of Data	Number of Parameters	Sum-of-Square Residuals	Probability	SC_{RM}	SC_{HP}	SC_{RV}	IOC^*_{RM}	IOC^*_{HP}	IOC^*_{RV}
n	m	χ^2	p	(10^{-6})	(10^{-6})	(10^{-6})	(mm)	(mm)	(mm)
230	15	208	0.62						
406	90	384	0.005						
406	92	356	0.05					9 ± 2	11 ± 4
406	91	356	0.05				-10 ± 2		
406	92	346	0.10		2.0 ± 0.3	1.6 ± 0.5			
406	91	345	0.11	-1.9 ± 0.3					

[1] For the first table entry, there are 12 IOCs and 3 line lengths that are not tabulated; for the remaining entries, there are 75 additional line lengths that are also not tabulated. All solutions employ 158 measurements taken along 150-m-to-915-m lines of length determined with a precision of less than 1 mm by the NGS. In the table, columns labelled "SC" are scale constants reflecting postulated systematic length-dependent discrepencies among the instruments; those labelled "IOC*" are "incremental" instrument constants reflecting postulated systematic pointing errors during measurement of short lines, as described in the text. Errors are shown as $\pm 1\sigma$.

Figure A-1

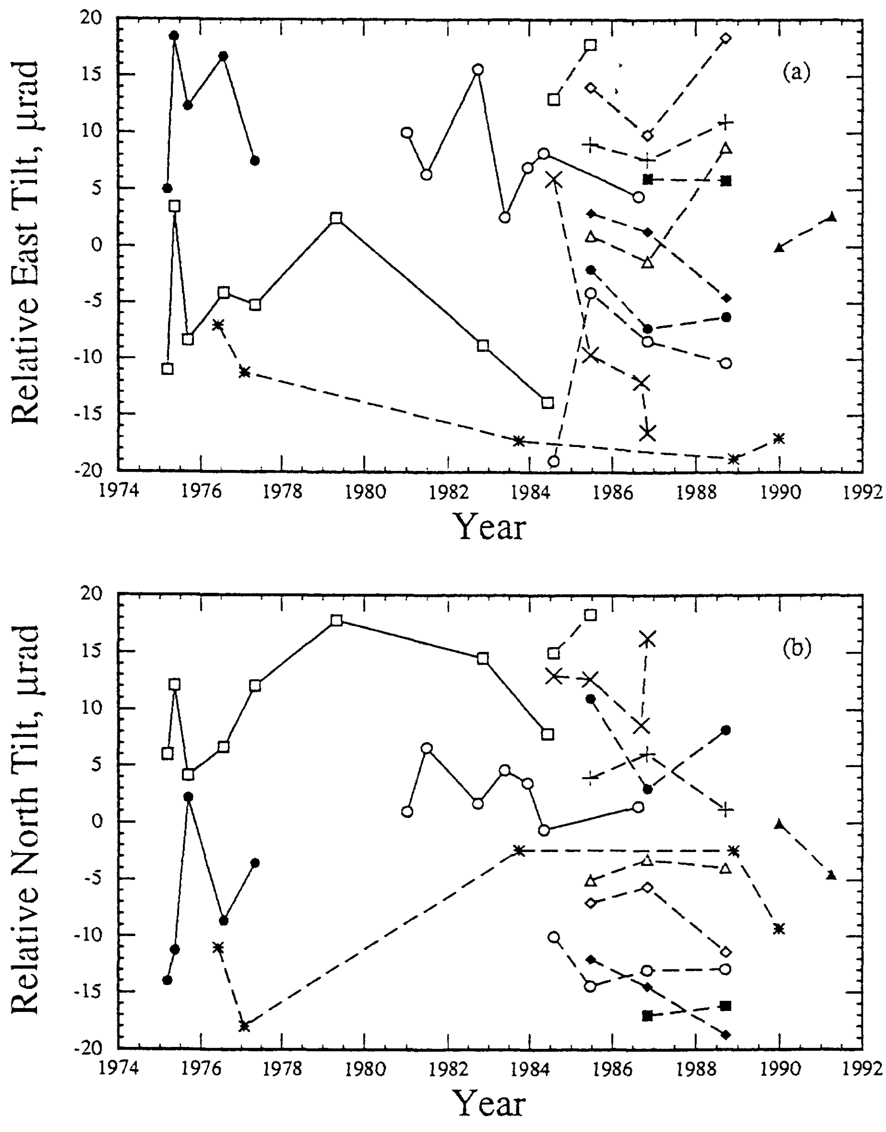

(a)
Relative East Tilt, μrad
20
15
10
5
0
-5
-10
-15
-20
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
Year
(b)
Relative North Tilt, μrad
20
15
10
5
0
-5
-10
-15
-20
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
Year

Figure C-1

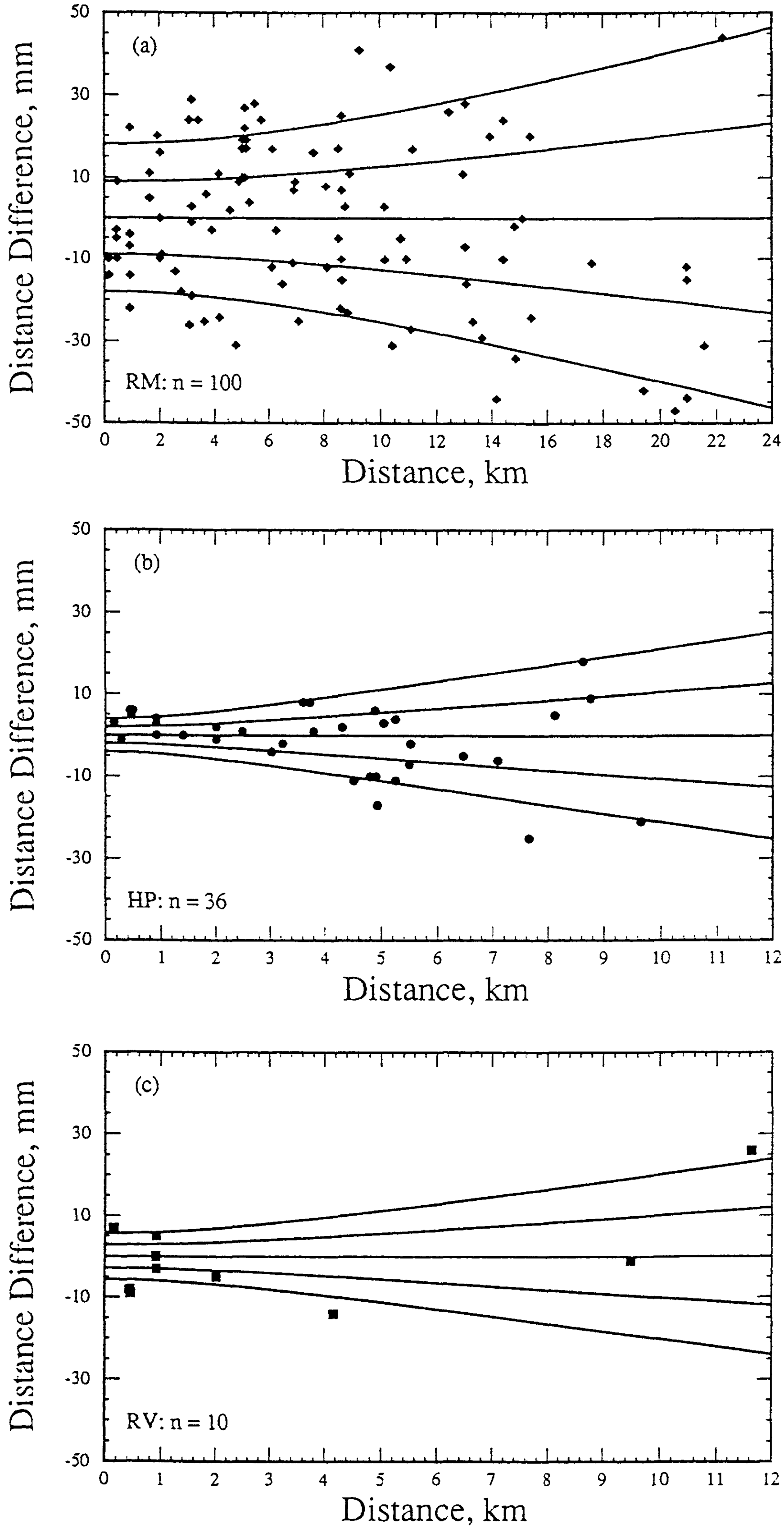
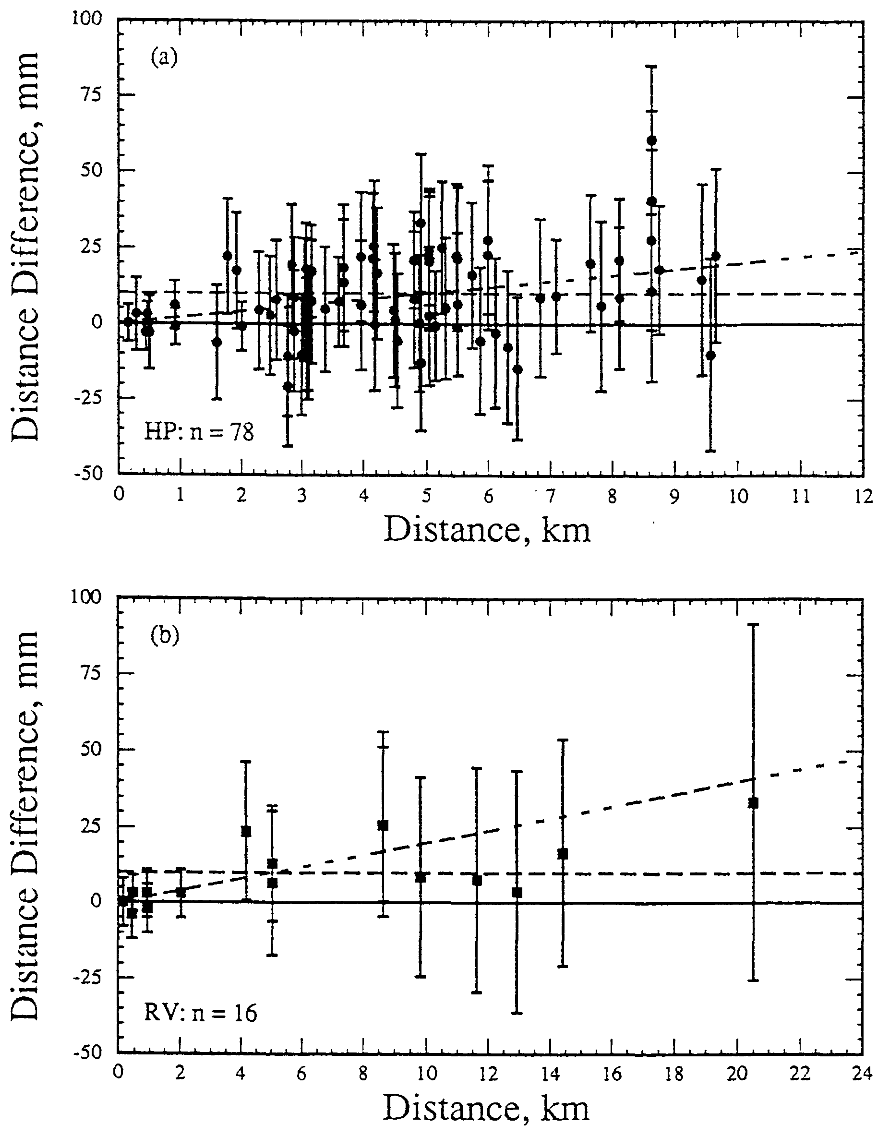

(a)
RM: n = 100
Distance Difference, mm
Distance, km
(b)
HP: n = 36
Distance Difference, mm
Distance, km
(c)
RV: n = 10
Distance Difference, mm
Distance, km

Figure C-2


(a)
HP: n = 78
Distance Difference, mm
Distance, km
(b)
RV: n = 16
Distance Difference, mm
Distance, km