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EARTH STRAIN MEASUREMENTS  
WITH THE TRANSPORTABLE LASER RANGING SYSTEM:  
FIELD TECHNIQUES AND PLANNING

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## ABSTRACT

We have conducted a feasibility study to examine the potential of the Transportable Laser Ranging System (TLRS) for monitoring the ground deformation around satellite ranging stations and other geodetic control points. Emphasis has been placed on testing the usefulness of the relative lateration technique. The temporal variation of the ratio of the length of each survey line to the mean length of all survey lines in a given area is directly related to the mean shear strain rate for the area. The data from a series of experimental measurements taken over the Los Angeles basin from a TLRS station at Mt. Wilson show that such ratios can be determined to an accuracy of one part in  $10^7$  with a measurement program lasting for three days and without using any corrections for variations in atmospheric conditions. A numerical experiment using a set of hypothetical data indicates that reasonable estimates of the present shear strain rate and the direction of the principal axes in southern California can be deduced from such measurements over an interval of one to two years. Thus, the relative lateration from the TLRS appears to be a very economical way to monitor ground deformations, although there has been no opportunity yet to measure the actual ground strain by reoccupying the Mt. Wilson site.

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## I. INTRODUCTION

With the recent development in ground-to-satellite laser ranging and Very Long Baseline Interferometry (VLBI) techniques, it is now possible to measure precisely distances between locations separated by several hundreds to thousands of kilometers. This makes it possible to monitor relative movements of globally distributed points on the earth for geodynamic studies. However, one question that must be answered is how representative each of these positions thus occupied is for the region in which it is located. If some of these locations are experiencing localized movements which are not representative of the region, the global measurement would give erroneous results. An answer to this questions can be found by measuring regional deformations around each location.

A conventional method for determining regional deformations is to perform repeated survey using an electro-optical distance measuring (EDM) device (e.g. Savage *et al.* [1981]). However, such surveys are expensive, and are rather limited in range. We, therefore, have looked for a better alternative. The development of the Transportable Laser Ranging System (TLRS) for ground-to-LAGEOS (Laser Geodynamics Earth Orbiting Satellite) ranging [Silverberg and Byrd, 1981] has given us an opportunity to test such an alternative. Because of its high sensitivity, being capable of detecting single photon returns, the TLRS can measure distances to small targets (retro-reflectors) at any visible points much beyond the normal ranges of other EDM devices. Thus, this system may provide economical measurements of strain fields in areas more than 200 km in diameter. If successful, such measurements will be valuable not only in the immediate neighborhood of satellite ranging stations, but also in understanding the dynamic behavior of both plate boundaries and areas internal to plates.

We have conducted a limited feasibility study to examine this potential. Although the TLRS is a powerful system, it also has certain limitations when used for a ground-to-ground ranging. The most important is the uncertainty of measurement results due to variability in atmospheric conditions. To bypass this problem and avoid the expense of flying an aircraft to monitor the atmospheric conditions along the path of the laser beam, we have examined the use of the relative lateralization, or the ratio method, which was used earlier by Carter and Vincenty [1978] in an experimental survey around the McDonald Observatory.

We originally planned repeated field experiments at several sites in the western United States. However, because of many scheduling conflicts and delays associated with the overall TLRS-LAGEOS ranging experiments, the only field experiment we could perform during the current contract was a four-day measurement at Mt. Wilson over the Los Angeles basin in January, 1981. We have been unable to reoccupy this site for an actual strain measurement.

The present study, however, has given us some very encouraging results. Even with no atmospheric correction at all, the range ratios could be determined to an accuracy of one part in  $10^7$ . This is sufficient for an order-of-magnitude estimate of incremental shear strain in the southern California region if two measurements separated by one to two years are available. Higher accuracies would be attainable with repeated measurements.

In this report, we first describe the advantages and problems of ground-to-ground ranging by a TLRS, leading to the use of relative lateration, or range-ratio method, and its relationship to the regional strain (Section II). Then, we present the data and analysis of the Mt. Wilson experiment (Section III). This is followed by a short treatment of regional strain determination using hypothetical data (Section IV). Finally, we present the conclusions from this feasibility study and offer some recommendations. Some pertinent data are presented in the Appendix.

## II. TLRS GROUND-TO-GROUND RANGING

### Advantages and Problems

The TLRS is a highly mobile satellite laser ranging system designed to perform ground-to-LAGEOS range measurements. It is also highly sensitive, being capable of determining the range to a LAGEOS satellite with return signals as low as one photoelectron every 20 to 50 laser shots [Silverberg et al. 1982]. Used as a ground-to-ground ranging device, it can measure the distance to any single 1 inch (25 mm) corner reflector within sight at very low laser power level. The measureable range is limited only by the curvature of the earth. The required power level is so low that, unlike some systems used for similar measurements, the laser beam can be maintained many orders of magnitude below the eye-damage threshold.

The practical precision of the TLRS range measurements is limited to about 1.5 cm for a one minute average, which is somewhat worse than those of conventional EDM devices using modulated laser beams. However, the long range capability of the TLRS reduces the relative error to well within the limits of interest in conventional surveys. The TLRS has an automatic pointing system, an automatic calibration system and other features which lend themselves to providing many horizontal (ground-to-ground) line measurements on an operational basis. Thus it will be a good device to use if the data it provides is sufficient to determine the regional deformation at a high-enough accuracy.

The most serious problem in using the TLRS for ground-to-ground ranging is the atmospheric effect. The temperature, pressure, and to a lesser degree water vapor influence the index of refraction of air, and thus the speed of a laser beam through the atmosphere. To obtain the absolute distance between two points from a time of flight measurement through air, one must make corrections for these atmospheric variables.

Estimates of these atmospheric variables along the beam path may be made based on measurements at the two end points. This, however, is unsatisfactory for long lines. A more precise way is to measure directly the atmospheric condition along the beam path by flying an aircraft during the ranging. This, though done in practice, is a costly operation. A third alternative is to use more than one wavelength for ranging. Using the dispersive characteristics of light in air, one can correct for the atmospheric effects [Huggett, et al. 1977].

The present TLRS operates in a single color. Flying an aircraft, we judged, is too costly for repeated measurements in many directions. Thus we had to look for another alternative.

### Relative Lateration

One way to improve the accuracy of range measurements without relying on expensive in-flight measurement of atmospheric conditions is to use a relative lateration technique, or the "ratio method" (Robertson, 1972). Instead of attempting to measure the absolute length of each survey line to high accuracy, this technique determines only the ratios of distances. This method is based on a supposition that the temporal changes of atmospheric conditions along several survey lines within a given region are similar to each other. Therefore, even when the time of flight of a laser beam in each line fluctuates with changing atmospheric conditions, the ratios of the times of flight along different survey lines tend to vary little with time.

Carter and Vincenty [1978] used this method in an experimental EDM survey around the McDonald Observatory in 1977. They obtained sets of measurements, one month apart, consistent to one to two parts in  $10^7$ . They have just repeated this experiment and the data is now being analyzed. Since the results of Carter and Vincenty appear to be quite promising, we have decided to try the same for our TLRS measurements.

### Relationship Between Relative Lateration and Strain

Unlike absolute measurements of distances, the relative distance measurements repeated after a certain time period will not give all of the components of deformation, or incremental strain, for the time period unless at least one survey line is measured absolutely. However, a clear relationship exists between the changes of relative distances and incremental shear strain.

Let us consider  $n$  survey lines radiating from a central station. In the present case, the TLRS is located at the central station and a retroreflector is located at the end of each radiating line. Assume that all lines lie in a horizontal plane, neglecting both the curvature of the earth's surface and topographic height differences. Choosing a coordinate system with the origin at the central station, positive  $x$  towards east and positive  $y$  towards north, the original length of line  $i$  to the reflector at coordinates  $(x_i, y_i)$  at the time of the initial survey is given by

$$s_i = (x_i^2 + y_i^2)^{\frac{1}{2}} \quad (1)$$

Now assume that between the initial survey and a subsequent survey the entire area of the survey undergoes a uniform deformation represented by incremental strain components  $\epsilon_{xx}$ ,  $\epsilon_{xy}$  and  $\epsilon_{yy}$ . Then, the line length becomes

$$\begin{aligned}
s_i' &= [(x_i + \epsilon_{xx}x_i + \epsilon_{xy}y_i)^2 + (y_i + \epsilon_{xy}x_i + \epsilon_{yy}y_i)^2]^{1/2} \\
&= [x_i^2 + y_i^2 + 2\epsilon_{xx}x_i^2 + 4\epsilon_{xy}x_iy_i + 2\epsilon_{yy}y_i^2]^{1/2} \\
&= s_i [1 + 2\epsilon_{xx}\sin^2\alpha_i + 4\epsilon_{xy}\sin\alpha_i\cos\alpha_i + 2\epsilon_{yy}\cos^2\alpha_i]^{1/2} \\
&= s_i [1 + \epsilon_{xx}\sin^2\alpha_i + \epsilon_{xy}\sin 2\alpha_i + \epsilon_{yy}\cos^2\alpha_i] \quad (2)
\end{aligned}$$

where  $\alpha_i = \tan^{-1}(x_i/y_i)$  is the azimuth of the line  $i$  measured clockwise from north, and the higher order terms in strain have been neglected. Then, the range increment  $\delta_i$  is given by

$$\delta_i = s_i' - s_i = s_i [\epsilon_{xx}\sin^2\alpha_i + \epsilon_{xy}\sin 2\alpha_i + \epsilon_{yy}\cos^2\alpha_i] \quad (3)$$

Next define original mean range and range ratios to the mean, respectively, as

$$\bar{s} = \frac{n}{\sum_{i=1}^n} s_i/n \quad (4)$$

and

$$r_i = s_i/\bar{s} \quad (5)$$

Then, the subsequent mean range and range ratios are

$$\bar{s}' = \frac{n}{\sum_{i=1}^n} s_i'/n = \bar{s} + \frac{n}{\sum_{i=1}^n} \delta_i/n \quad (6)$$

and

$$\begin{aligned}
r_i' &= s_i'/\bar{s}' = (s_i + \delta_i)/(\bar{s} + \frac{n}{\sum_{i=1}^n} \delta_i/n) \\
&= r_i (1 + \delta_i/s_i - \frac{n}{\sum_{i=1}^n} \delta_i/n\bar{s}) \quad (7)
\end{aligned}$$

where the higher order terms are again neglected. The increment of the range ratio is, therefore,

$$r_i' - r_i = r_i (\delta_i/s_i - \frac{n}{\sum_{i=1}^n} \delta_i/n\bar{s}) \quad (8)$$



Then, range ratio increment normalized by the original range ratio is given by

$$\gamma_i = (r_i' - r_i)/r_i = \delta_i/s_i - \frac{n}{\sum_{i=1}^n \delta_i} \delta_i/n\bar{s} \quad (9)$$

Substituting eq. (3) into eq. (9), and using (5), we obtain

$$\begin{aligned} \gamma_i = & [\sin^2 \alpha_i - \frac{n}{\sum_{i=1}^n (r_i \sin^2 \alpha_i)}/n] \epsilon_{yy} \\ & + [\sin 2\alpha_i - \frac{n}{\sum_{i=1}^n (r_i \sin 2\alpha_i)}/n] \epsilon_{xy} \\ & + [\cos^2 \alpha_i - \frac{n}{\sum_{i=1}^n (r_i \cos^2 \alpha_i)}/n] \epsilon_{yy} \end{aligned} \quad (10)$$

Equation (10) may give one an impression that a set of measurements of the normalized range ratio increments  $\gamma_i$  would give the incremental strain components  $\epsilon_{xx}$ ,  $\epsilon_{xy}$  and  $\epsilon_{yy}$ . However, this impression is incorrect because the coefficients of  $\epsilon_{xx}$  and  $\epsilon_{yy}$  are not independent of each other, as their sum vanishes, and therefore  $\epsilon_{xx}$  and  $\epsilon_{yy}$  cannot be determined uniquely.

Now let

$$\Theta = \epsilon_{xx} + \epsilon_{yy} \quad (11)$$

and

$$\Psi = \epsilon_{xx} - \epsilon_{yy} \quad (12)$$

Then,

$$\epsilon_{xx} = \frac{1}{2} (\Theta + \Psi) \quad (13)$$

and

$$\epsilon_{yy} = \frac{1}{2} (\Theta - \Psi) \quad (14)$$

Substituting (13) and (14) into (10), we obtain

$$\begin{aligned} \gamma_i = & [\sin 2\alpha_i - \frac{n}{\sum_{i=1}^n (r_i \sin 2\alpha_i)}/n] \epsilon_{xy} \\ & - \frac{1}{2} [\cos 2\alpha_i - \frac{n}{\sum_{i=1}^n (r_i \cos 2\alpha_i)}/n] \Psi \end{aligned} \quad (15)$$

The coefficients of  $\epsilon_{xy}$  and  $\Psi$  are known quantities for the initial setup of the survey lines. Thus, for a set of measurements of the normalized range ratio increments  $\gamma_i$ , the incremental shear strain components  $\epsilon_{xy}$  and  $\Psi$  can be determined by a least-square inversion of eq. (15).

Finally, the maximum incremental shear strain  $S$  and the direction of the principal strain axes  $\beta$  are given by

$$S = [(2\epsilon_{xy})^2 + \Psi^2]^{1/2} \quad (16)$$

and

$$\beta = \frac{1}{2} \tan^{-1} (2\epsilon_{xy}/\Psi) \quad (17)$$

The dilation  $\Theta$  of eq. (11) disappears from eq. (15), and thus cannot be determined. This is expected because any uniform compression or expansion of the entire area causes no change in range ratios.

The treatment above assumes uniform deformation of the entire region. If for some reason, such as the existence of active faults within the area, the regional deformation is not uniform, large residuals will show up in the least-square inversion of eq. (15). Thus, any residuals significantly larger than the measurement errors will indicate heterogeneous strain.

The remaining question is how accurately we can estimate the normalized range ratio increments  $\gamma_i$ . Since the measurements are done in terms of time of flight of light beams, the uncertainty in speed of light is the determining factor. The average speed of light,  $c_i$ , between the central station and a reflector  $i$  may be expressed as the sum of four components:

$$c_i = c_0 + \ell_i + w_c + w_i \quad (18)$$

where  $c_0$  is the speed of light in standard air, which is constant for all survey lines at all times;  $\ell_i$  is the correction attributable to the reflector location, which is time invariant for a given reflector;  $w_c$  is a component of correction attributable to weather common to all reflectors at a given time; and  $w_i$  is the residual weather correction. The line length  $s_i$  is given in terms of round-trip time of flight,  $t_i$ , as

$$s_i = \frac{1}{2}(c_0 + \ell_i + w_c + w_i)t_i \quad (19)$$

the mean range as

$$\bar{s} = \frac{1}{2}(c_0 \bar{t} + \sum_{i=1}^n \ell_i t_i / n + w_c \bar{t} + \sum_{i=1}^n w_i t_i / n) \quad (20)$$

where  $\bar{t} = \sum_{i=1}^n t_i / n$  is the mean time of flight, and the range ratio to the mean as

$$r_i = u_i [1 + (\ell_i - \sum_{i=1}^n \ell_i t_i / n \bar{t} + w_i - \sum_{i=1}^n w_i t_i / n \bar{t}) / c_0] \quad (21)$$

where  $u_i = t_i / \bar{t}$  is the time-of-flight ratio to the mean, and the higher-order terms have been neglected. Finally, the normalized range ratio increment is given as

$$\gamma_i = \eta_i + [(w_i' - w_i) - \sum_{i=1}^n (w_i' - w_i) t_i / n \bar{t}] / c_0 \quad (22)$$

where  $\eta_i = (u_i' - u_i)/u_i$  is the normalized time-of-flight ratio increment and quantities with primes designate those at subsequent measurement as before. The higher-order terms are again neglected. Note that the common weather component,  $w_c$ , is eliminated by taking the range ratio (21), and the location specific components,  $l_i$ 's, are eliminated by normalization (22), leaving only the residual weather components  $w_i$ 's.

The normalized time-of-flight ratio increment,  $\eta_i$ , thus approximates the range ratio increments,  $\gamma_i$ , with a small error due to residual weather term. The latter is not location specific, and is not common to all lines at a given time. If this term is sufficiently small, then we can substitute  $\eta_i$  for  $\gamma_i$  in calculating the shear strain increment using (15).

### III. MT. WILSON EXPERIMENT

#### Field Experiment

At the request of the NASA Crustal Dynamics Project, the TLRS team from the McDonald Observatory of the University of Texas, led by Dr. Eric Silverberg, deployed the TLRS at Mt. Wilson, California, in January of 1981. At the same time, two of us (H.J.D. and T.C.) scouted the surrounding area for suitable target sites and selected the reflector locations. Then, a field party from the National Geodetic Survey (NGS), which was dispatched at the request of NASA to help us, deployed retroreflectors at the chosen sites. The survey lines selected for the site are shown in Figure 1. Table 1 lists the nominal coordinates of the base station (TLRS site) at Mt. Wilson and of the end points of the lines, where the retroreflectors were installed. Also listed in Table 1 are the approximate look angles from Mt. Wilson and ranges as computed from the indicated coordinates using the IAG standard ellipsoid Geodetic Reference System 1967.

Each reflector except the one at Cahuenga was a metal box containing an array of three  $1\frac{1}{2}$  inch (38mm) corner cubes, supplied by the NGS. The box was mounted on a tripod and placed directly over the station mark using an optical blumb bob. This elaborate configuration made it necessary to guard the reflector continuously for the entire duration of the experiment. The reflector used at Cahuenga was designed by one of us (T.C.) for unmanned operation. It contained a single 1 inch (25mm) corner cube and was fastened to an outcrop with anchor bolts at a site off the station mark, thus concealed from public view.

The reference point of the TLRS, from which the raw time-of-flight measurements were made, was slightly offset from the Mt. Wilson station mark given in Table 1. The measured coordinates of the station mark relative to the TLRS were:

$$x = -1.4873 \text{ m (west)}$$

$$y = 0.5093 \text{ m (north)}$$

$$z = -3.3709 \text{ m (below)}$$

The resulting corrections, to be applied to the observed quantities to reduce them to the reference mark, are listed in Table 2. The corrections can be applied at any stage of data reduction.

After the initial setup, which began on January 9, 1981, the horizontal ranging data were collected over the four-day interval January 23 through 26, 1981, in cooperation with the NOAA National Geodetic Survey. Each of the reflector sites except Cahuenga was manned continuously during the entire experiment to record the temperature, pressure and relative humidity at the site at about 30 minute intervals. The details of the data acquisition are given in Silverberg *et al.* [1982].

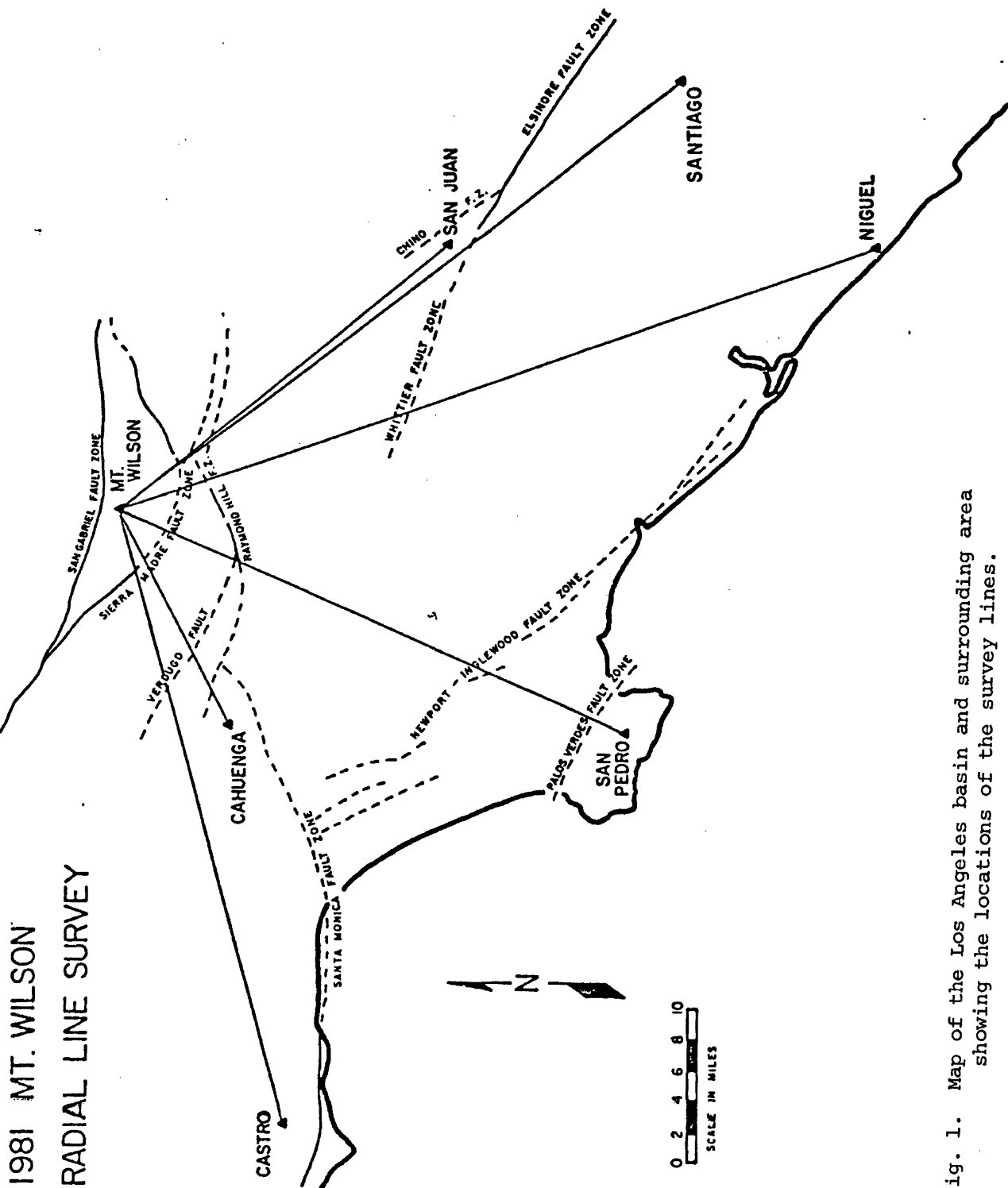


Fig. 1. Map of the Los Angeles basin and surrounding area showing the locations of the survey lines.

Table 1. Stations Used in Mt. Wilson Line Survey

Station	Longitude	Latitude	Elevation m	Look Angle		Range m	Note
				Azimuth	Altitude		
Mt. Wilson	241° 56' 17.85"	34° 13' 21.58"	1722.0				1
Castro	241° 12' 55.40"	34° 05' 08.57"	858.9	257.366	-1.030	68393	2
Cahuenga	241° 40' 29.81"	34° 08' 13.00"	554.1	248.687	-2.681	26104	3
San Pedro	241° 39' 55.73"	33° 44' 40.88"	447.1	205.506	-1.508	58729	4
Niguel	242° 16' 00.18"	33° 30' 44.83"	288.0	158.814	-1.353	84459	
Santiago	242° 28' 00.10"	33° 42' 37.89"	1733.0	139.168	-0.329	74933	
San Juan	242° 15' 45.99"	33° 54' 49.47"	543.0	138.751	-1.688	45536	

1 New marker 9.408m from Mt. Wilson E10A @345°17'

2 Solitice Canyon B2 Aux. 1, which is 14.107m ENE of Castro 1898

3 Reference mark #3 of Cahuenga #2, 13.329m @257°47' from Cahuenga #2

4 L7 Ecc. San Pedro Hills, which is 12.576m @318°57' from San Pedro #3

Table 2. Corrections to be Applied to Observations to Reduce to Mt. Wilson Gound Marker

Station	Round-Trip Time of Flight ns	Range m	Range Ratio*	
			(1)	(2)
			ppm	
Castro	-9.344	-1.4003	-25.08	-26.78
Cahuenga	-9.054	-1.3568	-23.35	-23.51
San Pedro	-1.798	-0.2694	-5.91	-7.93
Niguel	6.222	0.9325	13.61	9.93
Santiago	8.931	1.3385	20.64	17.07
San Juan	8.432	1.2636	20.09	17.64

\* (1) Ratio to mean range

(2) Same but excluding Cahuenga and Niguel

### The Data

The raw field data were initially processed at the University of Texas at Austin by the McDonald Observatory group. As described in detail by Silverberg *et al.* [1982], the processing of the raw data involved accumulation of individual photon returns into 200 psec bins, smoothing of the coadded returns by three-bin (600 psec) running averages, cross-correlation with a reference standard to eliminate long-term drift in the calibration constants, adjustments to account for certain measurement irregularities, and removal of a 86.8 nsec constant calibration correction.

The calibrated round-trip time-of-flight data, shown in Figure 2 and listed in Table A1 in the Appendix, have not been corrected for the offset of the TLRS from the ground marker (Table 2). The data for Cahuenga were not used for the analysis because of certain processing difficulties encountered for the data for this station.

The data gap during the second day of observation was due to an interruption in data acquisition caused by rain which accompanied the passage of a cold front. The meteorological data taken at Mt. Wilson site and other stations are shown in Figures A1 through A3, and are listed in Table A2 in the Appendix.

As expected, the raw time-of-flight data show large fluctuations, which are only partially correlated with the meteorological data. The relative RMS deviations of the time-of-flight data (Table 3, column 3) range from 1.53 ppm for Niguel, which was surveyed only after the passage of the cold front, to 3.78 ppm for San Juan, which was the shortest line. The weighted average for all lines is 2.84 ppm.

### Range Ratios to a Single Reference Line

Silverberg *et al.* [1982] calculated the time-of-flight ratios and atmosphere-corrected range ratios to a reference line following the procedure used by Carter and Vincenty [1978]. The reference line they chose was a smoothed curve (a cubic spline) through the Santiago data. Their results (Table 3, column 5) show relative RMS deviations of time-of-flight ratios ranging from 0.4 ppm for Niguel to 1.6 ppm for San Juan. The weighted average for all lines is 1.0 ppm, which is about a factor of three improvement from the fluctuation of the time-of-flight data.

Their results for the range ratios with atmospheric corrections based on end-point meteorological data did not fare as well. In fact the relative RMS deviations increased typically about 40% from those of uncorrected time-of-flight ratios [Silverberg *et al.* 1982].

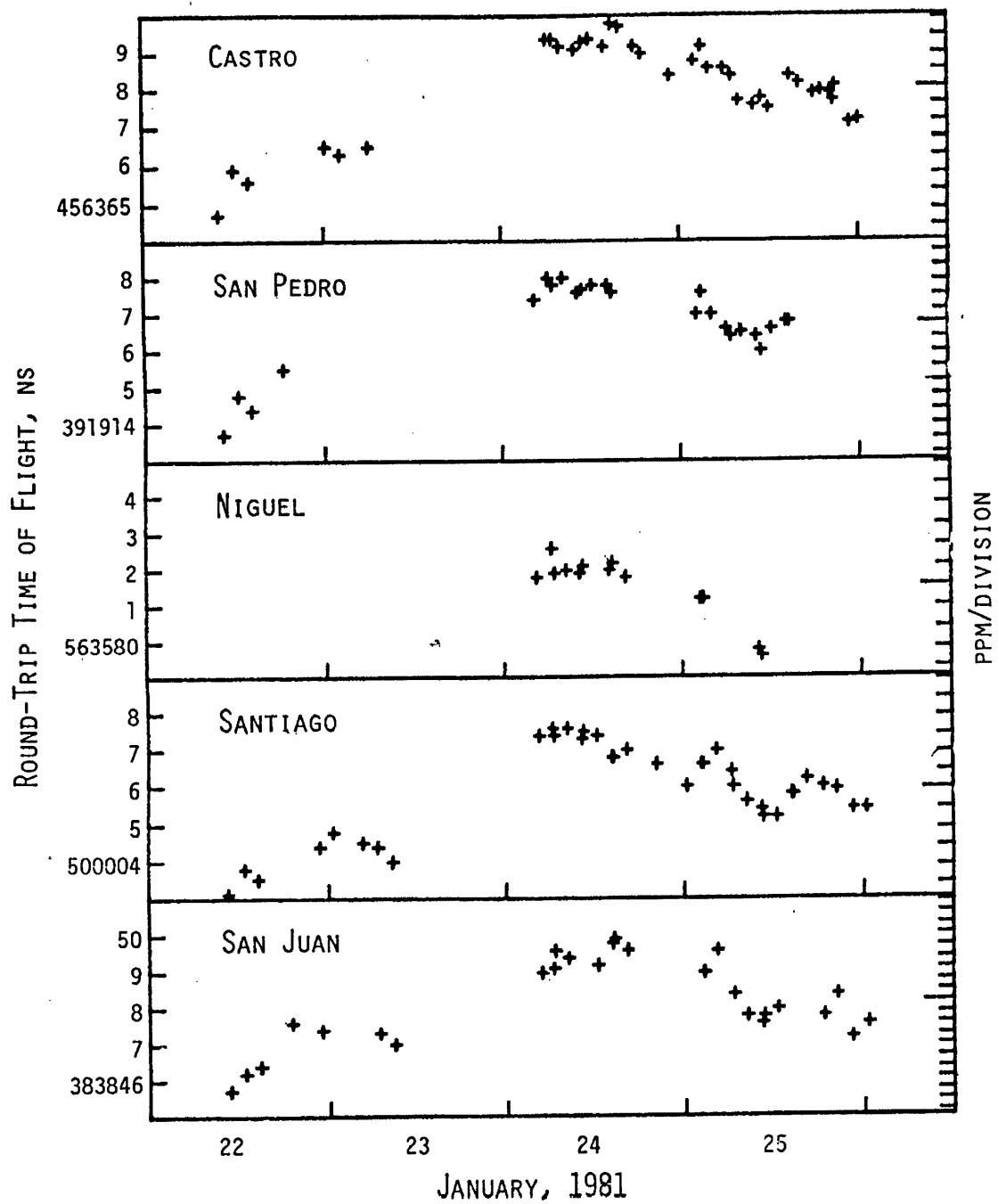


Fig. 2. Round-trip time of flight from Mt. Wilson. The data are not corrected for the marker offset.



The main reason for the poor performance of atmosphere-corrected values is the difficulty of making proper atmospheric corrections. A comparison of the variations of the group index of refraction calculated from the temperature and pressure at end points (Figure 3; also listed in Table A3 in the Appendix) with the time-of-flight variations (Figure 2) clearly shows that long-term variations are fairly well matched but shorter diurnal fluctuations are larger for the index of refractions than for the times-of-flight. Thus the index-of-refraction correction per Carter and Vincenty [1978] over-compensates for diurnal variations.

#### Time-of-Flight Ratios to the Mean

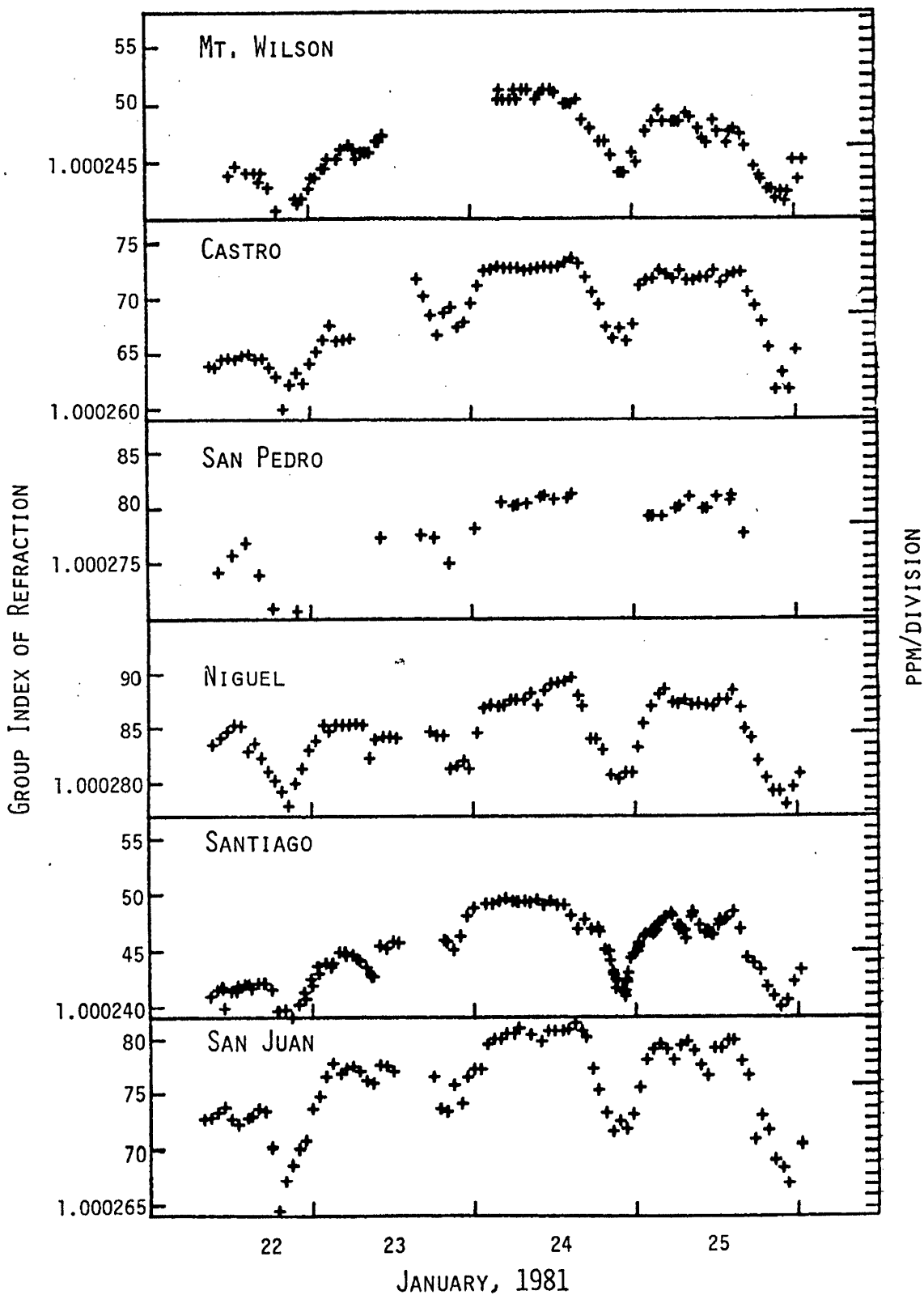
In order to be consistent with the range-ratio/strain relationship of the preceding section, we calculated the time-of-flight ratios to the mean. Since the time-of-flight measurements to all targets were not made exactly simultaneously, the data were linearly interpolated before the mean time-of-flight for a given time was calculated. (Higher order interpolations or a spline approximation might be better, but we judged the difference would be small.) Also, since we had data for Niguel only during the last half of the experiment, this station was excluded from the mean time-of-flight calculation.

The resulting time-of-flight ratios to the mean (Figure 4; also listed in Table A4 in the Appendix) show a further improvement in the fluctuations of the results. The relative RMS deviations (Table 3, column 5) now range from 0.36 ppm for Niguel to 1.24 ppm for San Juan, with the weighted average of 0.71 ppm for all lines, a factor of four improvement from the raw time-of-flight data.

#### An Alternative Atmospheric Correction

As stated earlier, the short-term, diurnal fluctuations in the index of refraction at end points exceed the observed fluctuations in the time-of-flight values. This is probably due to the larger fluctuation of the atmospheric temperature near the ground than those in most of the intervening air mass; a result of the base station and most of the target stations being located well above the intervening terrain. In this situation, a standard correction procedure like that of Carter and Vincenty [1978] is not really applicable, and some alternate procedures are needed.

An experimental procedure we tried was to estimate the average temperature of the air mass by low-pass filtering the mean of the temperatures measured at the end points. The filter we used was a simple one of adding all previous temperature readings each weighted by a factor proportional to a negative exponential of the elapsed time. After



Fgi. 3. Group index of refraction computed from atmospheric data at end points.

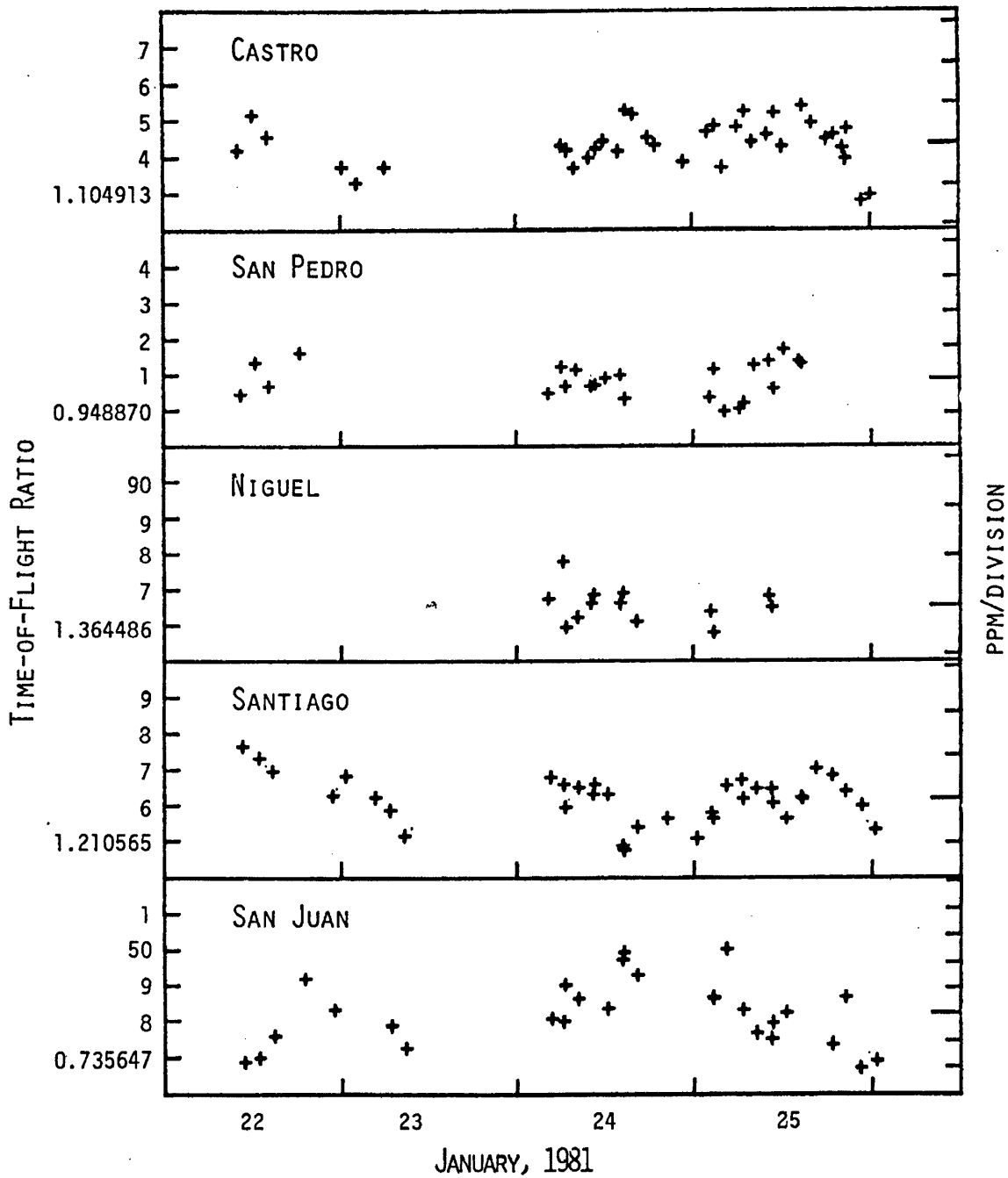


Fig. 4. Time-of-flight ratios to the mean.

trials with such filters of several different time constants, a time constant of 12 hours was found to give the best result. The resulting relative RMS deviations of the ranges thus corrected for atmospheric conditions (Table 3, column 4) range from 0.96 ppm for Castro to 2.05 ppm for San Juan with the weighted average of 1.38 ppm for all lines. This is about a factor of two improvement from the raw time-of-flight data. However, the range ratios calculated from these corrected ranges do not show any significant improvement over those of the uncorrected ratios. The relative RMS deviations of the corrected range ratios (Table 3, last column) range from 0.52 ppm for Niguel and Santiago to 1.21 ppm for San Juan, with the weighted average of 0.72 ppm for all lines.

A comparison of the relative RMS deviations of various quantities in Table 3 reveals that the best result is obtained for the uncorrected time-of-flight ratios to the mean. The atmospheric corrections did not improve the RMS deviations at all when ratios were taken.

#### A Test for Systematic Error Due to Atmospheric Conditions

The reliability of the relative lateration depends on the validity of the assumption that the temporal changes of atmospheric conditions are similar for all survey lines in the area so that their effects cancel out when ratios are taken. If this assumption is incorrect, a systematic error due to varying atmospheric conditions is introduced into the measured time-of-flight ratios. The greatly different atmospheric conditions before and after the passage of a cold front during the experiment gave us an opportunity to test this assumption.

The test we performed is the likelihood ratio test. We divided the time-of-flight ratios of Table A4 for each line into two subsets, the first half and the last half, of equal size (the last half was one greater than the first half if the total number was odd). If the systematic error due to atmospheric conditions is significantly large, the mean ratio,  $\mu_1$ , for the first subset will be significantly different from that,  $\mu_2$ , for the second subset. Setting up a null hypothesis  $H_0: \mu_1 = \mu_2$ , if it is true, then the likelihood ratio statistic

$$t = [n_1 n_2 / (n_1 + n_2)]^{1/2} (\mu_1 - \mu_2) / [(n_1 \sigma_1^2 + n_2 \sigma_2^2) / (n_1 + n_2 - 2)]^{1/2} \quad (23)$$

has a t distribution with  $n_1 + n_2 - 2$  degrees of freedom, where  $n_1$  and  $n_2$  are the sample sizes of the two subsets and  $\mu_1, \mu_2, \sigma_1^2$  and  $\sigma_2^2$  are used to designate the sample means and the sample variances of the first and the second subsets, respectively, for convenience.

At 90% significance level, the t distribution has values of 1.69 for 34 degrees of freedom and 1.80 for 11 degrees of freedom, while the t values computed from the data, Table 4, are much smaller. Therefore, the null hypothesis cannot be rejected at this level of significance.

Table 3. Comparison of Relative RMS Deviations in ppm

Station	Number of Data Points	Uncorrected Time of Flight	Corrected Range(a)	Uncorrected T-o-F Ratio to Santiago(b)	Uncorrected T-o-F Ratio to the mean	Corrected Range Ratio to the mean
Castro	36	2.68	0.96	0.7	0.56	0.54
San Pedro	24	2.91	1.12	0.8	0.52	0.54
Niguel	13	1.53	1.01	0.4	0.36	0.52
Santiago	36	2.45	1.03	(0.2)	0.54	0.52
San Juan	27	3.78	2.05	1.6	1.24	1.21
All	136	2.84	1.38	1.0	0.71	0.72

(a) Corrected by using 12-hour low-pass filtered temperature

(b) From Silverberg et al. [1982]. The deviation for Santiago is from the smoothed curve, and is not included in calculating the average for all stations.

Table 4. Likelihood Ratio Test for Non-equality of Means

Station	Subset 1			Subset 2			Degree of Freedom	t
	$n_1$	$\mu_1$	$\sigma_1$	$n_2$	$\mu_2$	$\sigma_2$		
Castro	18	1.104914282	0.000000513	18	1.104914438	0.000000694	34	0.745
San Pedro	12	0.948870911	0.000000356	12	0.948870818	0.000000598	22	0.445
Niguel	6	1.364486713	0.000000572	7	1.364486460	0.000000365	11	0.889
Santiago	18	1.210566249	0.000000774	18	1.210566130	0.000000515	34	0.531
San Juan	13	0.735648159	0.000000830	14	0.735648288	0.000000983	25	0.353

In other words, no significant difference is found between the mean time-of-flight ratios in the first and second halves of the experiment for any of the lines surveyed.

### Results

Since there is no evidence for systematic errors caused by atmospheric conditions, the most likely estimates of the mean time-of-flight ratios and their variances (and standard deviations) can be calculated from the entire data set. The results are shown in Table 5. Also listed in this table are the mean time-of-flight and the mean distances. The latter were calculated using atmospheric corrections based on the low-pass filtered temperatures described earlier and pressures interpolated to the average height of the beam from the end-point measurements (extrapolation in case of Santiago because the average height of the beam was lower than either end point). A group index of refraction of  $n = 1.00028975$  at the wavelength of  $0.5320 \mu\text{m}$ , calculated from the formula<sup>9</sup> given in American Institute of Physics Handbook [1972, p. 6-111] for standard dry air with 0.03% carbon dioxide at  $15^\circ\text{C}$  and 760 mm Hg, is used. No other corrections have been applied to the calculated distances; thus they are subject to minor systematic errors.

The estimated relative standard deviations of the mean time-of-flight ratios are approximately  $1 \times 10^{-7}$  except for San Juan, which is the shortest line. In comparison, Savage and Prescott [1973] estimate that the standard deviation of their Geodolite measurements of distances are 3 and 8 mm for lengths of 1 and 37 km, respectively. Thus, the precision of the present time-of-flight ratios is at least a factor of two better than that of their distance measurements. Furthermore, their distances had to be corrected for temperature and humidity readings made with an aircraft flying along the line of sight, while the present time-of-flight ratios required no atmospheric correction at all.

Multiwavelength measurements of distances are definitely better than the above two in terms of relative accuracy. Huggett and Slater [1975] and Slater and Huggett [1976] show the standard deviation of individual distance measurements to be less than  $1 \times 10^{-7}$  on a 10.1 km line. By taking the mean of many measurements, which is practical in this case, the accuracy can be improved further. The ranges attainable with the multiwavelength system, however, are quite limited compared with the TLRs measurements.

Table 5. Mean Time of Flight, Distance and Ratios\*

Station	Mean Time of Flight ns	Mean Distance m	Mean T-o-F Ratio	S.D. of Mean T-o-F Ratio	Relative S.D. ppm
Castro	456358.75	68388.52	1.10488758	0.00000010	0.09
San Pedro	391914.94	58730.88	0.94886293	0.00000010	0.11
Niguel	563587.77	84456.72	1.36449651	0.00000014	0.10
Santiago	500014.83	74931.62	1.21058326	0.00000011	0.09
San Juan	303856.63	45535.87	0.73566587	0.00000018	0.24

\* These results have been corrected for the TLRs/ground-marker offset.

Table 6. Increment in Normalized Ratio Due to Hypothetical Strain Increment and Rounded Values for Testing

Station	Normalized Ratio Increment ppm	Rounded to 0.1 ppm
Castro	0.052	0.1
San Pedro	-0.158	-0.2
Niguel	-0.030	0.0
Santiago	0.068	0.1
San Juan	0.070	0.1

#### IV. SHEAR STRAIN DETERMINATION USING HYPOTHETICAL DATA

We have been unable to reoccupy the Mt. Wilson site for a repeat measurement, which would allow a testing of the ratio method for a shear strain determination in the region. This section, therefore, describes an exercise we have conducted to see how well we can determine the regional shear-strain increment using a set of hypothetical data.

We assume a hypothetical strain increment described by

$$\begin{aligned} \epsilon_1 &= 0.1 \times 10^{-6} & : & \text{maximum extension} \\ \epsilon_2 &= -0.2 \times 10^{-6} & : & \text{maximum compression} \\ \epsilon_1 - \epsilon_2 &= 0.3 \times 10^{-6} & : & \text{maximum shear} \\ \beta &= 110^\circ & : & \text{azimuth of maximum positive principal} \\ & & & \text{axis (extension) measured clockwise} \\ & & & \text{from north} \end{aligned}$$

This strain increment is approximately the annual strain increment in southern California observed by Savage *et al.* [1981]. The resulting increments in normalized range ratios for the five survey lines used in the Mt. Wilson experiment are listed in the center column of Table 6. Since we will not be able to measure these ratio increments at this accuracy, we use the values rounded to  $1 \times 10^{-7}$ , as given in the rightmost column of Table 6.

Substituting these rounded ratio increments into eq. (15), and inverting it in a least-squares sense, we obtain the following results:

$$\begin{aligned} \epsilon_1 - \epsilon_2 &= 0.40 \times 10^{-6} \\ \beta &= 109.5^\circ \end{aligned}$$

The result describes the original hypothetical shear-strain increment reasonably well. A trial with a rounding to  $1 \times 10^{-8}$  results in almost complete duplication of the hypothetical strain increment.

The likelihood ratio test of the preceding section can be used to estimate the required number of measurements to achieve a given level of accuracy at a given confidence level. We use the standard deviation of individual range ratio measurements of  $5 \times 10^{-7}$  as estimated from the present data (Table 3, excluding San Juan). Thus, substituting  $\sigma_1 = \sigma_2 = 10^{-6}$  and  $|\mu_1 - \mu_2| = 10^{-7}$  into eq. (18), we find that  $n_1 = n_2 = 200$  will give  $t = 1.99$ , which exceeds the value of  $t$  distribution, 1.97, for 198 degrees of freedom at 95% confidence level. Thus a variation in the range ratio of  $10^{-7}$  found by averaging 200 ratio measurements is significant at 95% level of confidence.

At a rate of one measurement every hour, it will take slightly more than a week to complete this many measurements. Two such series of



measurements one year apart is sufficient to determine the shear strain increment in southern California.

For a given set of  $t$  and  $\sigma$ 's,  $n$ 's are approximately inversely proportional to the square of the difference in  $\mu$ 's in equation (18). Thus doubling the measurement interval, thereby doubling the expected ratio variations, approximately quarters the required number of measurements. For example, a pair of 50-measurement sets two years apart will give the shear strain rate in southern California.

## V. CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

Even though the field experiment we performed during this contract was quite limited compared with our original plan, we obtained several interesting and important results. The following is a list of conclusions drawn from these results:

1. The increment of the ratio of the length of a survey line to the average of several survey lines in a region is directly related to the incremental shear strain in the region. Thus, the shear strain rate can be calculated from observations of temporal variations in such ratios.
2. Using the TLRS, the time-of-flight ratios could be determined to an accuracy (one standard deviation) of  $1 \times 10^{-7}$  by averaging measurements over a four day period. This accuracy was obtained without using any atmospheric corrections at all. No improvement was obtained when atmospheric corrections based on end-point measurements were applied.
3. A calculation using a hypothetical data simulating the observed strain field in southern California indicates that two sets of TLRS ratio measurements separated by one to two years will be sufficient to determine the direction and rate of shear strain in the region.
4. Thus relative lateration using the TLRS has been demonstrated to be a good method for monitoring the regional shear strain field around satellite ranging stations. The TLRS operates successfully over long distances. The ratio method is extremely economical. It requires no environmental measurements and can be performed with small unattended retroreflectors distributed over a wide area. Thus these techniques greatly surpass the capability of conventional EDM techniques.

### Recommendations

1. The results of the present experiment are thus very encouraging. However, they are based on only one experiment. Before this technique is put to a practical use, further demonstration is needed to confirm the above results. Therefore, it is recommended that this feasibility study be continued at least to include reoccupation of the Mt. Wilson site and two measurements at another properly selected site, preferably with a different meteorological environment.

2. Relative lateration is not limited to the data taken by the TLRS. The data reduction procedure used in the present study can be applied to other data from distance measurements. Therefore, it is recommended that we reanalyze some of existing ranging data to see if improvements in determination of shear strain rate can be achieved. This can be done without further field measurements.
3. Additional feasibility test measurements similar to the Mt. Wilson experiment may be obtained from fixed satellite ranging stations. It is therefore, recommended that this possibility be examined.
4. Horizontal ranging to distant targets on the ground does not require all the sophistication of the TLRS system. Therefore, when the capability of the present technique is fully demonstrated, a smaller, more portable single-photon ranging unit should be developed for this purpose.
5. Finally, the technology is advancing in other fields also. Such techniques as miniature interferometer terminals [Counselman and Shapiro, 1979] may someday be more useful in surveys of regional extent. Therefore, development in these other techniques should be reviewed while developing the present technique.

#### Acknowledgements

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APPENDIX

Table A1. Calibrated Round-Trip Time of Flight

Castro			San Pedro			Niquel			Santiago			San Juan		
dy	hr	ns	dy	hr	ns	dy	hr	ns	dy	hr	ns	dy	hr	ns
22	10	04	22	10	18	24	04	28	22	10	41	22	10	51
22	12	02	22	12	21	24	06	19	22	12	43	22	12	51
22	14	05	22	14	15	24	06	46	22	14	34	22	14	48
23	00	09	22	18	23	24	08	18	22	22	49	22	18	55
23	02	09	24	04	20	24	10	15	23	00	41	22	22	54
23	06	05	24	06	16	24	10	40	16	23	04	23	06	47
24	06	08	24	06	51	24	14	15	10	23	06	23	08	47
24	06	58	24	08	09	24	14	40	18	23	08	24	04	40
24	08	00	24	10	10	24	16	18	20	24	04	24	06	29
24	09	59	24	10	45	25	02	21	58	24	06	24	06	35
24	10	55	24	12	10	24	02	48	49	24	06	24	08	25
24	12	00	24	14	11	25	10	16	05	24	08	24	12	25
24	14	01	24	14	45	25	10	41	13	24	10	24	14	25
24	14	55	25	02	13	25	02	35	15	24	10	24	14	39
24	16	01	25	02	53	24	10	35	15	24	12	24	16	28
24	18	00	25	04	09	25	04	20	03	24	14	25	02	33
24	18	57	25	06	10	25	06	10	05	24	14	25	02	36
24	22	44	25	06	45	25	06	45	43	24	16	25	04	25
25	02	05	25	08	11	25	08	11	36	24	20	25	06	32
25	02	58	25	10	10	25	10	16	16	25	00	25	08	23
25	04	00	25	10	45	25	10	45	23	25	02	25	10	23
25	06	01	25	12	10	25	12	10	30	25	04	25	10	30
25	06	55	25	14	15	25	14	15	11	25	06	25	12	25
25	08	04	25	14	40	25	14	40	42	25	06	25	18	51
25	10	01	25	16	00	25	16	00	28	25	08	25	20	25
25	10	55	25	18	00	25	18	00	19	25	10	25	22	23
25	12	04	25	20	07	25	20	07	42	25	12	25	22	23
25	14	51	25	20	37	25	20	37	24	25	14	26	00	32
25	20	49	25	22	51	25	22	51	57	25	18	26	00	32
26	00	05	26	00	05	26	00	05	27	26	00	26	00	50

Table A2. Temperature, T, Pressure, P, and Saturated Vapor Pressure, V

Time		T		P		V		Time		T		P		V	
dy	hr	mn	sc	deg	C	mmHg	mmHg	dy	hr	mn	sc	deg	C	mmHg	mmHg
Mt. Wilson															
22	12	08	01	8.0	624.1	8.0422	4.5814	24	13	54	08	0.0	621.8	4.5814	6.0973
22	13	08	54	7.0	624.1	7.5104	4.5814	24	14	28	00	0.0	621.8	4.5814	4.5814
22	14	53	40	8.0	624.8	8.0422	4.5814	24	14	54	16	0.0	621.8	4.5814	6.0973
22	15	59	57	8.0	624.8	8.0422	4.5814	24	15	53	26	3.0	623.3	5.6817	8.0724
22	16	31	16	9.0	624.8	8.6062	5.2917	24	16	41	49	2.0	622.6	5.2917	9.2050
22	16	57	27	8.0	624.8	8.0422	6.5398	24	17	53	26	4.0	622.6	6.0973	9.2050
22	17	59	44	10.0	625.6	9.2048	7.0108	24	19	06	29	4.0	622.6	6.0973	7.9210
22	19	14	19	12.0	624.8	10.5136	7.0108	24	21	54	25	6.0	620.3	7.0108	7.6258
22	21	57	23	10.0	623.3	9.2048	7.0108	24	22	52	51	6.0	620.3	7.0108	7.7721
22	22	25	11	11.0	624.1	9.8401	6.0973	24	23	55	10	4.0	620.3	6.0973	7.9210
22	23	02	15	10.0	623.3	9.2048	6.5398	25	00	34	16	5.0	620.3	6.5398	7.9210
23	00	00	56	9.0	623.3	8.6062	5.2917	25	02	00	11	2.0	620.3	5.2917	8.2263
23	00	28	23	8.0	623.3	8.0422	4.9249	25	03	03	19	1.0	620.3	4.9249	7.9210
23	01	03	14	8.0	623.3	8.0422	4.5814	25	03	55	51	0.0	620.3	4.5814	9.5532
23	02	01	37	7.0	623.3	7.5104	4.9249	25	04	32	31	1.0	620.3	4.9249	9.5532
23	02	24	05	7.0	623.3	7.5104	4.9249	25	05	54	44	1.0	620.3	4.9249	10.2830
23	02	48	26	6.0	623.3	7.0108	4.9249	25	06	28	44	1.0	620.3	4.9249	11.4747
23	04	13	00	6.0	623.3	7.0108	4.9249	25	07	01	06	1.0	620.3	4.9249	8.5418
23	04	53	34	5.0	623.3	6.5398	4.5814	25	07	56	42	0.0	619.6	4.5814	7.9210
23	05	57	22	5.0	624.1	6.5398	4.5814	25	08	36	19	0.0	618.8	4.5814	7.6258
23	06	37	07	5.0	623.3	6.5398	4.9249	25	09	48	16	1.0	618.8	4.9249	7.9210
23	06	55	29	6.0	623.3	7.0108	5.2917	25	10	28	22	2.0	618.8	5.2917	7.3403
23	07	52	58	5.0	622.6	6.5398	5.2917	25	11	00	51	2.0	618.1	5.2917	7.6258
23	08	20	32	5.0	622.6	6.5398	4.5814	25	11	59	30	0.0	618.1	4.5814	7.6258
23	08	54	34	5.0	622.6	6.5398	4.9249	25	12	34	14	1.0	618.1	4.9249	7.6645
23	09	56	13	4.0	622.6	6.0973	5.2917	25	13	57	00	2.0	618.1	5.2917	8.0724
23	10	29	17	4.0	622.6	6.0973	4.9249	25	14	26	09	1.0	618.1	4.9249	8.8679
23	10	55	37	3.0	621.8	5.6817	4.9249	25	14	56	49	1.0	618.8	4.9249	9.9131
24	04	06	03	0.0	622.6	4.5814	5.2917	25	15	55	10	2.0	619.6	5.2917	8.8679
24	04	22	39	-1.0	622.6	4.2589	5.6817	25	16	36	22	3.0	619.6	5.6817	8.5418
24	04	55	29	0.0	622.6	4.5814	6.5398	25	17	55	39	5.0	619.6	6.5398	8.8679
24	05	56	14	0.0	622.6	4.5814	7.0108	25	18	45	58	6.0	619.6	7.0108	8.8679
24	06	34	27	-1.0	622.6	4.2589	7.0108	25	19	05	52	6.0	618.8	7.0108	8.2263
24	07	04	10	0.0	622.6	4.5814	7.5104	25	19	55	15	7.0	618.8	7.5104	7.3403
24	07	51	41	-1.0	622.6	4.2589	7.5104	25	20	31	54	7.0	618.8	7.5104	6.7978
24	08	31	26	-1.0	622.6	4.2589	8.0422	25	21	06	50	8.0	618.8	8.0422	7.0645
24	09	46	20	0.0	622.6	4.5814	7.5104	25	21	54	44	7.0	618.1	7.5104	6.7978
24	10	28	48	-1.0	621.8	4.2589	8.0422	25	22	32	53	8.0	618.1	8.0422	6.7970
24	11	00	43	-1.0	622.6	4.2589	7.5104	25	23	02	07	7.0	618.1	7.5104	6.5400
24	11	55	50	-1.0	622.6	4.2589	6.0973	25	23	48	19	4.0	618.8	6.0973	6.5400
24	12	34	12	-1.0	621.8	4.2589	7.0108	26	00	36	21	6.0	618.8	7.0108	6.5400

Castro

Table A2. (continued)

Time			T			V			Time			T			V					
dy	hr	mn	sc	deg	C	mmHg	mmHg	mmHg	dy	hr	mn	sc	deg	C	mmHg	mmHg	mmHg			
24	09	00	00	6.1	693.1	6.2908	6.2908	6.2908	22	12	20	00	13.4	719.3	9.2050	9.2050	9.2050	18.1	740.3	11.8974
24	10	00	00	5.9	693.1	6.0500	6.0500	6.0500	22	14	20	00	12.6	720.1	9.2050	9.2050	9.2050	19.2	739.6	12.3337
24	11	00	00	5.8	693.1	5.8176	5.8176	5.8176	22	16	20	00	15.6	720.1	9.9131	9.9131	9.9131	16.7	738.8	13.2406
24	12	00	00	6.0	693.1	5.8176	5.8176	5.8176	22	18	20	00	19.1	720.8	10.6688	10.6688	10.6688	15.3	738.8	11.8974
24	13	00	00	5.8	693.1	5.8176	5.8176	5.8176	22	22	00	00	18.7	719.3	11.8118	11.8118	11.8118	13.9	739.6	11.4747
24	14	00	00	5.5	693.1	5.5931	5.5931	5.5931	23	10	20	00	11.5	718.6				13.1	739.6	11.0653
24	15	00	00	5.1	693.1	5.5931	5.5931	5.5931	23	16	20	00	12.1	720.8	9.5532	9.5532	9.5532	11.6	739.6	11.0653
24	16	00	00	5.6	693.1	5.8176	5.8176	5.8176	23	18	20	00	12.4	720.8	10.2850	10.2850	10.2850	12.3	739.6	10.6688
24	17	00	00	6.8	693.1	6.5400	6.5400	6.5400	23	20	30	00	14.7	720.8	11.8974	11.8974	11.8974	11.6	739.6	10.2850
24	18	00	00	8.2	693.1	6.7978	6.7978	6.7978	24	00	30	00	11.3	720.1	9.3777	9.3777	9.3777	11.7	739.6	10.2850
24	19	00	00	9.3	693.1	7.2012	7.2012	7.2012	24	04	20	00	9.1	720.8	8.6708	8.6708	8.6708	11.6	739.6	10.2850
24	20	00	00	11.2	692.3	7.6258	7.6258	7.6258	24	06	10	00	9.4	720.8	8.8679	8.8679	8.8679	11.2	738.8	9.9131
24	21	00	00	12.0	691.6	7.6258	7.6258	7.6258	24	06	45	00	9.3	720.8	8.7361	8.7361	8.7361	11.3	738.8	9.9131
24	22	00	00	11.0	691.6	8.2263	8.2263	8.2263	24	08	10	00	9.0	720.1	7.7721	7.7721	7.7721	14.1	738.1	9.5532
24	23	00	00	12.0	690.8	8.2263	8.2263	8.2263	24	10	10	00	8.3	720.1	8.2263	8.2263	8.2263	12.7	739.8	10.6688
25	00	00	00	10.3	690.8	7.3403	7.3403	7.3403	24	10	45	00	8.2	720.1	7.8610	7.8610	7.8610	12.4	738.8	10.2850
25	01	00	00	6.6	690.8	6.0500	6.0500	6.0500	24	12	10	00	8.6	720.1	7.7721	7.7721	7.7721	12.5	738.8	10.2850
25	02	00	00	5.8	690.1	6.0500	6.0500	6.0500	24	14	10	00	8.4	720.1	7.6258	7.6258	7.6258	12.4	738.8	10.2850
25	03	00	00	5.7	690.1	6.5400	6.5400	6.5400	24	14	45	00	8.1	720.1	7.6258	7.6258	7.6258	13.1	741.8	11.4747
25	04	00	00	5.3	690.8	5.8176	5.8176	5.8176	25	02	10	00	9.8	719.3	8.5418	8.5418	8.5418	13.5	741.8	13.2486
25	05	00	00	5.7	690.8	5.3762	5.3762	5.3762	25	02	52	00	9.8	719.3	8.7036	8.7036	8.7036	13.5	741.8	11.0653
25	06	00	00	5.7	690.1	5.1659	5.1659	5.1659	25	04	10	00	9.8	719.3	8.2263	8.2263	8.2263	16.3	741.1	12.3337
25	07	00	00	5.0	690.1	5.3762	5.3762	5.3762	25	06	10	00	9.4	720.1	6.7978	6.7978	6.7978	16.0	741.1	11.4747
25	08	00	00	5.6	689.3	5.3762	5.3762	5.3762	25	06	46	00	8.6	718.6	6.4143	6.4143	6.4143	15.5	741.1	11.4747
25	09	00	00	5.5	689.3	5.3762	5.3762	5.3762	25	08	10	00	7.8	718.6	6.0500	6.0500	6.0500	16.2	741.1	11.0653
25	10	00	00	5.3	689.3	5.3762	5.3762	5.3762	25	10	10	00	8.0	718.6	6.7978	6.7978	6.7978	13.0	741.1	9.9131
25	11	00	00	5.3	689.3	5.5931	5.5931	5.5931	25	10	45	00	8.8	718.6	6.7978	6.7978	6.7978	11.0	741.8	9.2050
25	12	00	00	4.7	689.3	5.3762	5.3762	5.3762	25	12	10	00	7.8	718.6	6.2908	6.2908	6.2908	10.7	741.8	9.2050
25	13	00	00	5.5	688.6	5.8176	5.8176	5.8176	25	14	10	00	7.8	717.8	7.0645	7.0645	7.0645	10.8	741.8	9.2050
25	14	00	00	5.2	689.3	5.3762	5.3762	5.3762	25	14	22	00	7.6	718.6	6.7978	6.7978	6.7978	10.7	741.8	9.2050
25	15	00	00	5.3	690.1	5.5931	5.5931	5.5931	25	16	10	00	11.4	719.3				10.3	741.8	9.2050
25	16	00	00	5.4	690.8	5.3762	5.3762	5.3762										10.3	741.8	9.2050
25	17	00	00	7.3	690.8	5.9327	5.9327	5.9327										10.3	741.8	8.8679
25	18	00	00	8.5	690.8	6.2908	6.2908	6.2908										10.2	741.8	8.8679
25	19	00	00	10.0	690.8	6.6678	6.6678	6.6678										9.7	741.8	8.5418
25	20	00	00	12.3	690.1	6.7978	6.7978	6.7978	22	09	28	00	13.2	738.8	8.8679	8.8679	8.8679	10.4	741.1	9.2050
25	21	00	00	16.2	689.3	8.2263	8.2263	8.2263	22	10	32	00	12.5	738.8	9.2050	9.2050	9.2050	9.2	741.1	8.5418
25	22	00	00	14.1	688.6	6.5400	6.5400	6.5400	22	11	30	00	12.0	738.8	9.2050	9.2050	9.2050	8.5	741.1	8.2263
25	23	00	00	16.1	689.3	7.3403	7.3403	7.3403	22	12	30	00	11.4	738.8	9.2050	9.2050	9.2050	8.4	741.1	8.2263
25	00	00	00	12.5	690.1	6.7978	6.7978	6.7978	22	13	31	00	11.5	738.8	9.7318	9.7318	9.7318	8.0	740.3	7.9210
									22	14	30	00	14.1	739.6	9.9131	9.9131	9.9131	7.7	740.3	7.6258
									22	15	41	00	13.6	740.3	9.5532	9.5532	9.5532	9.3	740.3	8.5418
									22	16	36	00	15.0	740.3	10.6688	10.6688	10.6688	10.6	741.1	9.2050
									22	17	30	00	16.2	740.3	11.0653	11.0653	11.0653	13.6	741.1	9.9131
22	10	21	00	14.7	718.6	9.9131	9.9131	9.9131	22	18	31	00	17.1	740.3	12.3337	12.3337	12.3337	13.5	741.1	9.9131

San Pedro

Niguel



Table A2. (continued)

Time		T	P	V	Time		T	P	V	Time		T	P	V																				
dy	hr	mn	sc	deg	C	mmHg	mmHg	deg	C	mmHg	dy	hr	mn	sc	deg	C	mmHg	mmHg																
24	19	15	00	14.2	740.3	10.2850	22	14	40	00	9.8	623.3	5.3762	24	05	45	00	1.0	622.6	4.3764														
24	20	23	00	16.0	738.9	11.0653	22	15	00	00	10.2	623.3	5.7043	24	06	25	00	1.1	622.6	4.2774														
24	21	40	00	16.1	738.1	10.6688	22	16	30	00	10.0	624.1	5.5931	24	06	40	00	1.2	622.6															
24	22	30	00	15.5	738.1	10.2850	22	16	45	00	10.0	624.1	6.5400	24	07	40	00	.7	621.8	4.5811														
24	23	30	00	15.4	738.1	10.2850	22	17	30	00	10.0	624.1	7.3403	24	08	20	00	.8	621.8	4.4780														
25	00	27	00	13.1	738.1	9.0350	22	18	00	00	10.8	624.1		24	09	20	00	.5	621.8	4.1783														
25	01	15	00	11.0	738.1	8.8679	22	18	45	00	13.0	624.1		24	10	20	00	.8	621.1															
25	02	27	00	9.4	738.1	8.2263	22	19	00	00	13.0	624.1		24	11	20	00	.4	621.1															
25	03	30	00	8.4	738.1	7.6258	22	20	00	00	12.5	623.3		24	12	20	00	.8	621.1	3.8100														
25	04	23	00	7.9	738.1	7.3403	22	21	00	00	13.0	622.6		24	13	20	00	.8	621.1															
25	05	40	00	8.8	737.3	6.7978	22	22	00	00	11.6	622.6	6.2908	24	14	20	00	1.8	621.1	4.5811														
25	06	25	00	8.9	737.3	6.7978	22	22	45	00	10.3	622.6		24	15	20	00	3.2	621.1	4.0843														
25	07	28	00	8.5	737.3	6.5400	22	23	00	00	11.0	622.6	7.0645	24	16	20	00	2.2	621.1															
25	08	23	00	8.7	736.6	6.7978	22	23	45	00	9.2	623.3		24	17	20	00	3.5	621.8	5.0648														
25	09	29	00	8.3	735.8	6.7978	23	00	00	00	9.2	621.8	6.0500	24	18	20	00	3.4	621.8															
25	10	30	00	8.4	735.8	6.7978	23	00	45	00	7.2	621.8		24	18	37	00	3.8	621.8															
25	11	35	00	8.5	735.8	7.0645	23	01	00	00	8.0	621.8	6.5400	24	19	20	00	5.2	621.1	7.6258														
25	12	29	00	8.0	735.8	7.3403	23	02	00	00	7.2	622.6		24	20	00	00	5.4	621.1	5.8176														
25	13	30	00	7.9	735.8	7.0645	23	02	45	00	7.7	622.6	6.5400	24	20	15	00	6.3	621.1															
25	14	25	00	7.1	735.8	7.6258	23	03	00	00	7.3	622.6		24	20	30	00	7.1	620.3	6.4397														
25	15	30	00	8.9	736.6	7.6258	23	04	00	00	6.2	622.6		24	20	40	00	7.3	620.3															
25	16	17	00	11.1	737.3	8.8679	23	04	45	00	6.2	622.6		24	20	50	00	7.5	620.3															
25	17	15	00	12.3	738.1	9.2050	23	05	00	00	6.5	622.6	5.4836	24	21	00	00	8.0	620.3															
25	18	16	00	14.1	737.3	10.2850	23	06	00	00	6.5	622.6	6.2908	24	21	05	00	7.5	619.6															
25	19	24	00	15.1	735.8	10.2850	23	06	40	00	6.8	622.6		24	21	15	00	7.9	619.6															
25	20	20	00	16.0	735.1	10.6688	23	07	00	00	7.0	622.6	4.9647	24	22	00	00	8.7	619.6	7.0645														
25	21	24	00	16.0	735.1	9.9131	23	08	00	00	7.3	621.8		24	22	15	00	8.9	619.6															
25	22	20	00	16.9	734.3	10.6688	23	08	40	00	7.7	621.1		24	22	20	00	8.8	619.6															
25	23	26	00	15.3	734.3	10.2850	23	09	00	00	7.9	621.1	7.2012	24	22	23	00	9.4	619.6															
25	00	20	00	14.4	735.1	9.9131	23	09	00	00	8.0	621.1		24	22	32	00	7.8	619.6															
Santiago																																		
22	09	00	00	11.0	623.3	5.5710	23	10	00	00	4.8	621.1	5.3762	24	22	35	00	7.5	619.6	6.6937														
22	10	00	00	10.3	623.3		23	19	30	00	4.9	622.6		25	00	15	00	4.3	618.8	5.0648														
22	10	40	00	10.1	623.3		23	20	00	00	5.1	622.6		25	00	20	00	4.0	619.6															
22	10	46	00	10.2	623.3		23	21	00	00	5.5	621.8		25	00	25	00	3.8	619.6															
22	11	00	00	12.4	623.3		23	22	00	00	4.2	621.8		25	00	29	00	3.9	618.8															
22	12	00	00	10.2	622.6		23	23	00	00	2.2	621.8		25	01	15	00	2.8	618.8															
22	12	42	00	10.5	623.3		24	00	00	00	1.4	621.8		25	01	20	00	2.7	618.8															
22	12	46	00	10.3	623.3		24	01	45	00	1.0	621.8		25	02	15	00	2.4	618.8	4.7696														
22	12	50	00	10.3	623.3		24	02	45	00	1.0	621.8		25	02	27	00	2.3	618.8															
22	13	00	00	10.0	623.3		24	03	45	00	1.0	622.6		25	02	32	00	2.5	618.8															
22	14	00	00	9.8	623.3		24	04	45	00	.8	622.6	4.3764	25	02	39	00	2.3	618.0															

Table A2. (continued)

Time		T	P	V	Time		T	P	V	Time		T	P	V				
dy	hr	mn	sc	deg C	mmHg	dy	hr	mn	sc	deg C	mmHg	dy	hr	mn	sc	deg C	mmHg	mmHg
25	02	43	00	2.3	618.8	26	00	20	00	5.5	617.3	24	04	45	00	8.5	719.3	8.3828
25	02	51	00	2.4	618.8							24	05	00	00	8.5	719.3	8.2263
25	03	00	00	2.3	618.8							24	05	30	00	8.0	719.3	8.0724
25	03	15	00	1.7	618.8							24	06	37	00	8.0	719.3	7.8313
25	03	27	00	1.5	618.8							24	08	28	00	8.6	719.3	7.6840
25	04	15	00	1.1	618.8							24	10	05	00	9.0	718.6	7.5258
25	04	25	00	1.0	618.8							24	11	01	00	8.0	718.6	7.3403
25	05	15	00	.5	618.8							24	12	00	00	8.0	718.6	7.3403
25	05	25	00	.8	618.8							24	13	10	00	8.0	718.6	7.1737
25	06	15	00	1.8	618.8							24	14	00	00	7.5	717.8	7.0645
25	06	23	00	2.1	618.8							24	15	02	00	7.0	717.8	7.0645
25	06	26	00	2.0	618.8							24	16	03	00	8.0	718.6	7.4534
25	06	35	00	1.9	618.8							24	16	33	00	8.6	718.6	7.6548
25	06	37	00	1.9	618.8							24	17	31	00	11.5	718.6	8.4778
25	06	50	00	2.1	618.8							24	18	29	00	13.2	717.8	9.7318
25	07	15	00	2.3	618.8							24	19	34	00	15.0	717.1	9.8402
25	07	25	00	2.8	618.1							24	20	30	00	16.5	716.3	9.7318
25	08	15	00	.6	618.1							24	21	30	00	15.5	716.3	9.0350
25	08	20	00	.2	618.1							24	22	30	00	16.0	715.6	9.5532
25	08	24	00	.1	618.1							24	23	30	00	14.5	715.6	9.0350
25	09	20	00	1.1	617.3							25	00	30	00	12.0	715.6	8.0724
25	10	15	00	1.9	617.3							25	01	30	00	9.5	715.6	8.0724
25	10	20	00	1.8	617.3							25	02	36	00	8.5	715.6	7.9210
25	10	23	00	1.8	617.3							25	03	30	00	8.0	715.6	7.6258
25	10	35	00	1.6	617.3							25	04	35	00	8.5	715.6	7.8610
25	10	38	00	1.7	617.3							25	05	30	00	9.5	715.6	8.2885
25	10	50	00	1.8	617.3							25	05	35	00	8.2	715.6	7.8645
25	11	15	00	2.1	617.3							25	07	30	00	7.5	714.8	7.2012
25	11	20	00	2.1	617.3							25	08	32	00	8.0	714.1	6.6678
25	12	15	00	.8	616.6							25	09	30	00	9.0	713.3	6.3894
25	12	20	00	.3	616.6							25	10	31	00	10.0	713.3	6.1935
25	12	23	00	.4	616.6							25	11	30	00	7.5	713.3	6.6678
25	13	15	00	.6	617.3							25	12	31	00	7.5	713.3	6.7978
25	13	20	00	.5	617.3							25	13	35	00	7.0	714.1	6.4594
25	14	20	00	-.3	617.3							25	14	29	00	9.3	714.8	7.5969
25	15	20	00	1.9	618.1							25	15	32	00	9.3	714.8	7.5969
25	16	20	00	4.7	618.1							25	16	32	00	11.0	715.6	8.5058
25	17	20	00	5.5	618.8							25	17	33	00	17.0	715.6	9.2050
25	18	20	00	6.2	618.8							25	18	33	00	14.4	714.8	8.5418
25	19	20	00	7.7	618.1							25	19	30	00	15.5	714.1	8.2263
25	20	20	00	8.3	617.3							25	20	35	00	18.0	713.3	8.3828
25	21	20	00	9.4	617.3							25	21	45	00	18.5	712.6	7.9210
25	22	20	00	8.8	617.3							25	22	33	00	20.0	712.6	7.6840
25	23	20	00	6.8	617.3							26	00	35	00	16.5	713.3	7.4018





Table A3. (continued)

Time		Time		Time		Time		Time		Time							
dy	hr	mn	sc	dy	hr	mn	sc	dy	hr	mn	sc						
24	05	45	00	25	02	43	00	26	00	20	00	1.00024337	24	04	45	00	1.00028056
24	06	25	00	25	02	51	00	26	00	20	00	1.00024679	24	06	00	00	1.00028056
24	06	40	00	25	03	03	00	26	00	20	00	1.00024679	24	06	30	00	1.00028056
24	07	40	00	25	03	15	00	26	00	20	00	1.00024733	24	06	37	00	1.00028106
24	08	20	00	25	03	27	00	26	00	20	00	1.00024751	24	08	28	00	1.00028106
24	09	20	00	25	04	15	00	26	00	20	00	1.00024787	24	09	28	00	1.00028045
24	10	20	00	25	04	25	00	26	00	20	00	1.00024796	24	10	05	00	1.00027979
24	11	20	00	25	05	15	00	26	00	20	00	1.00024842	24	11	01	00	1.00028079
24	12	20	00	25	05	25	00	26	00	20	00	1.00024815	24	12	03	00	1.00028079
24	13	20	00	25	06	15	00	26	00	20	00	1.00024724	24	13	10	00	1.00028079
24	14	20	00	25	06	23	00	26	00	20	00	1.00024697	24	14	00	00	1.00028097
24	15	20	00	25	06	26	00	26	00	20	00	1.00024706	24	15	02	00	1.00028148
24	16	20	00	25	06	35	00	26	00	20	00	1.00024715	24	16	03	00	1.00028079
24	17	20	00	25	06	37	00	26	00	20	00	1.00024715	24	16	33	00	1.00028099
24	18	20	00	25	06	50	00	26	00	20	00	1.00024697	24	17	31	00	1.00027733
24	18	37	00	25	07	15	00	26	00	20	00	1.00024679	24	18	29	00	1.00027538
24	19	20	00	25	07	25	00	26	00	20	00	1.00024679	24	19	34	00	1.00027339
24	20	00	00	25	08	15	00	26	00	20	00	1.00024607	24	20	30	00	1.00027168
24	20	15	00	25	08	15	00	26	00	20	00	1.00024805	24	21	30	00	1.00027262
24	20	30	00	25	08	20	00	26	00	20	00	1.00024841	24	22	30	00	1.00027188
24	20	40	00	25	09	20	00	26	00	20	00	1.00024850	24	23	30	00	1.00027330
24	20	50	00	25	10	15	00	26	00	20	00	1.00024655	25	01	30	00	1.00027509
24	21	00	00	25	10	20	00	26	00	20	00	1.00024664	25	02	30	00	1.00027813
24	21	05	00	25	10	23	00	26	00	20	00	1.00024664	25	02	36	00	1.00027912
24	21	15	00	25	10	35	00	26	00	20	00	1.00024664	25	03	30	00	1.00027961
24	22	00	00	25	10	38	00	26	00	20	00	1.00024682	25	04	35	00	1.00027912
24	22	15	00	25	10	50	00	26	00	20	00	1.00024673	25	05	30	00	1.00027813
24	22	20	00	25	11	15	00	26	00	20	00	1.00024664	25	06	35	00	1.00027942
24	22	23	00	25	11	20	00	26	00	20	00	1.00024638	25	07	30	00	1.00027980
24	22	32	00	25	12	15	00	26	00	20	00	1.00024638	25	08	32	00	1.00027903
24	22	35	00	25	12	20	00	26	00	20	00	1.00024726	25	09	30	00	1.00027773
24	22	45	00	25	12	23	00	26	00	20	00	1.00024772	25	10	31	00	1.00027675
24	23	15	00	25	13	15	00	26	00	20	00	1.00024762	25	11	30	00	1.00027921
24	23	35	00	25	13	20	00	26	00	20	00	1.00024772	25	12	31	00	1.00027921
25	00	15	00	25	14	20	00	26	00	20	00	1.00024782	25	13	35	00	1.00028002
25	00	20	00	25	15	20	00	26	00	20	00	1.00024854	25	14	29	00	1.00028002
25	00	25	00	25	15	20	00	26	00	20	00	1.00024687	25	15	32	00	1.00027802
25	00	29	00	25	16	20	00	26	00	20	00	1.00024439	25	16	32	00	1.00027666
25	01	15	00	25	17	20	00	26	00	20	00	1.00024396	25	17	33	00	1.00027094
25	01	20	00	25	18	20	00	26	00	20	00	1.00024335	25	18	33	00	1.00027309
25	02	15	00	25	19	20	00	26	00	20	00	1.00024178	25	19	30	00	1.00027178
25	02	27	00	25	20	20	00	26	00	20	00	1.00024095	25	20	35	00	1.00026914
25	02	32	00	25	21	20	00	26	00	20	00	1.00024001	25	21	45	00	1.00026842
25	02	39	00	25	22	20	00	26	00	20	00	1.00024052	25	22	33	00	1.00026704
25	02	39	00	25	23	20	00	26	00	20	00	1.00024224	26	00	35	00	1.00027054

San Juan

Table A4. Time-of-Flight Ratios

Castro			San Pedro			Niquel			Santiago			San Juan		
dy	hr	mn sc	dy	hr	mn sc	dy	hr	mn sc	dy	hr	mn sc	dy	hr	mn sc
1.104+			0.948+			1.364+			1.210+			0.735+		
22 10 04 29	914198		22 10 18 55	870439		24 04 28 32	486752		22 10 41 41	567622		22 10 51 17	646866	
22 12 02 41	915170		22 12 21 52	871345		24 06 19 58	487793		22 12 43 11	567332		22 12 51 51	646994	
22 14 05 43	914546		22 14 15 03	870661		24 06 46 28	485966		22 14 34 32	566961		22 14 48 04	647619	
23 00 09 40	913745		22 18 23 39	871637		24 08 18 26	486255		22 22 49 55	566262		22 18 55 03	649189	
23 02 09 25	913337		24 04 20 40	870474		24 10 15 13	486647		23 00 41 06	566832		22 22 54 50	548337	
23 06 05 03	913747		24 06 16 19	871245		24 10 40 16	486867		23 04 33 04	566222		23 05 47 01	647875	
24 06 08 46	914336		24 06 51 04	870690		24 14 15 10	486632		23 06 39 34	565878		23 08 47 14	647293	
24 06 58 17	914200		24 08 09 40	871172		24 14 40 18	486914		23 08 39 44	565151		24 04 43 14	648099	
24 08 00 19	913737		24 10 10 03	870674		24 16 18 20	486108		24 04 40 08	566802		24 05 29 45	647995	
24 09 59 54	914011		24 10 45 34	870708		25 02 21 58	486409		24 06 25 43	566603		24 06 36 37	649039	
24 10 55 03	914255		24 12 10 04	870911		25 02 48 49	485806		24 06 41 31	565969		24 08 25 49	648657	
24 12 00 58	914457		24 14 11 30	870981		25 02 16 05	486836		24 08 22 17	566526		24 12 25 00	648343	
24 14 01 34	914142		24 14 45 60	870330		25 10 41 13	486512		24 10 21 13	566338		24 14 25 20	649772	
24 14 55 05	915268		25 02 13 18	870356					24 10 35 15	566618		24 14 30 04	649958	
24 16 01 03	915165		25 02 53 27	871173					24 12 20 03	566316		24 16 28 54	649330	
24 18 00 06	914538		25 04 09 53	869977					24 14 20 03	564893		25 02 33 03	648673	
24 18 57 39	914327		25 06 10 05	870052					24 14 35 11	564750		25 02 36 56	648634	
24 22 44 42	913891		25 06 45 43	870209					24 16 29 53	565410		25 04 25 60	650026	
25 02 05 25	914683		25 08 11 36	871274					24 20 18 04	565626		25 06 32 42	648312	
25 02 58 04	914826		25 10 10 16	871390					25 00 25 13	565089		25 08 23 56	647699	
25 04 00 52	913710		25 10 45 23	870584					25 02 29 30	565803		25 10 25 11	647534	
25 06 01 17	914789		25 12 10 30	871738					25 02 39 51	565623		25 10 30 03	647975	
25 06 55 21	915255		25 14 15 11	871417					25 04 22 37	566544		25 12 25 03	648233	
25 08 04 49	914402		25 14 40 42	871316					25 06 22 51	566702		25 16 31 55	647344	
25 10 01 53	914614								25 06 35 48	566195		25 20 25 59	648666	
25 10 55 08	915208								25 08 20 32	566483		25 22 28 50	646712	
25 12 04 05	914277								25 10 20 08	566462		26 00 32 50	645933	
25 14 51 54	915409								25 10 35 11	566062				
25 16 00 28	914909								25 12 21 02	565658				
25 18 00 19	914473								25 14 21 41	566251				
25 18 59 43	914613								25 14 35 02	566204				
25 20 07 42	914243								25 16 20 06	567037				
25 20 37 24	913952								25 18 39 42	566858				
25 20 49 58	914766								25 20 20 59	566413				
25 22 51 57	912706								25 22 37 54	565985				
26 00 05 27	912961								26 00 26 53	565337				

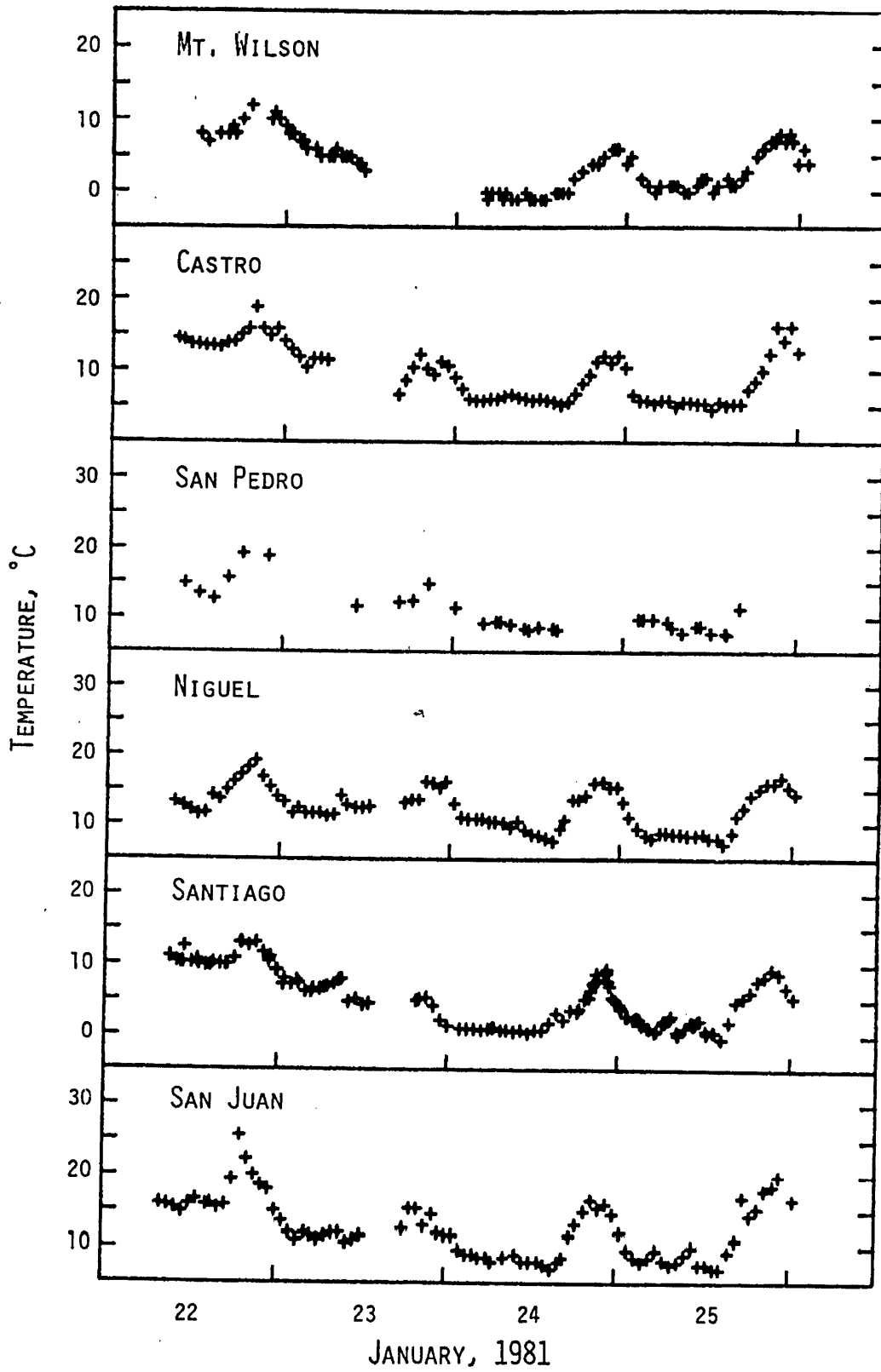


Fig. A1. Observed atmospheric temperature.

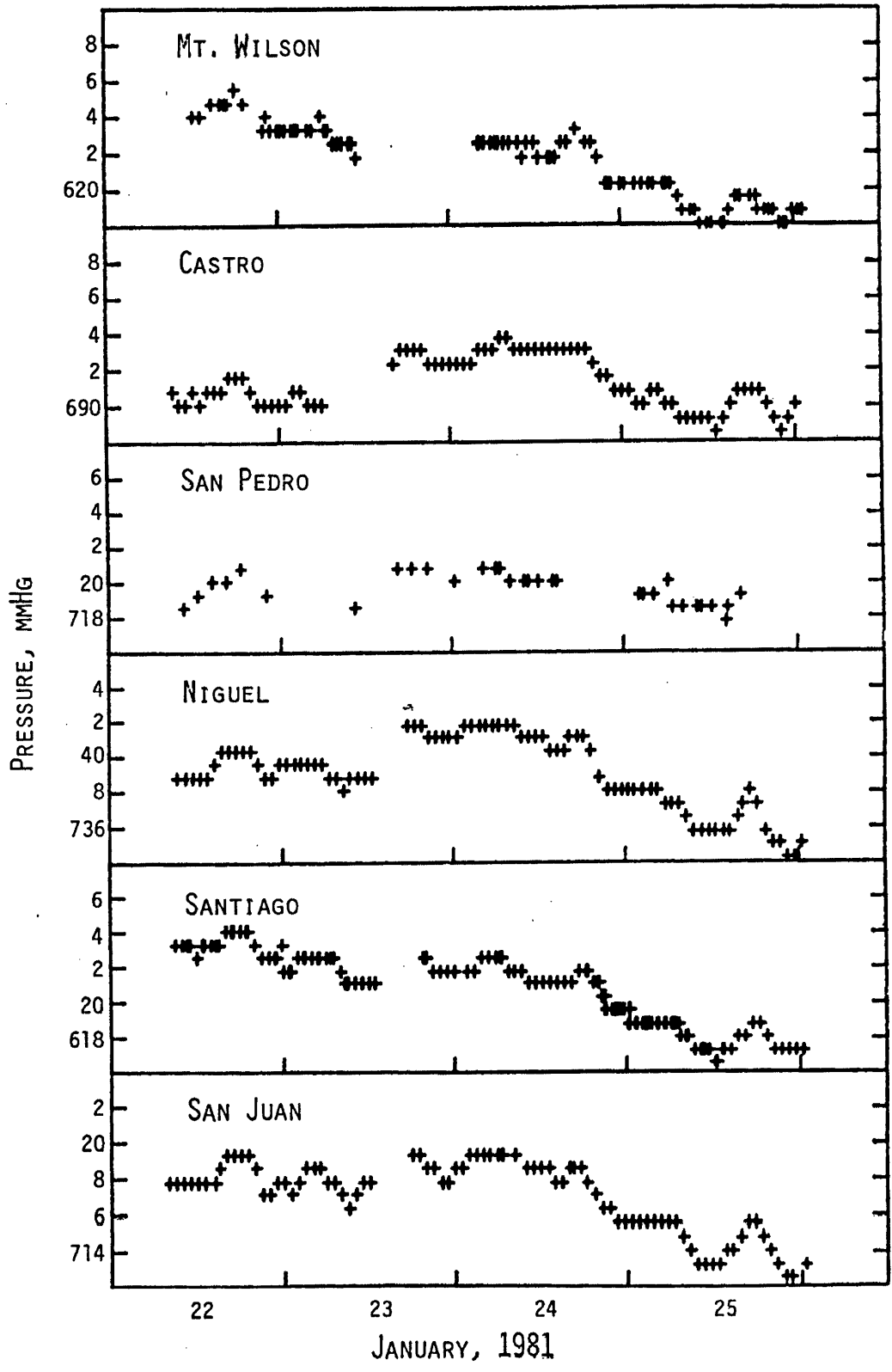


Fig. A2. Observed atmospheric pressure.



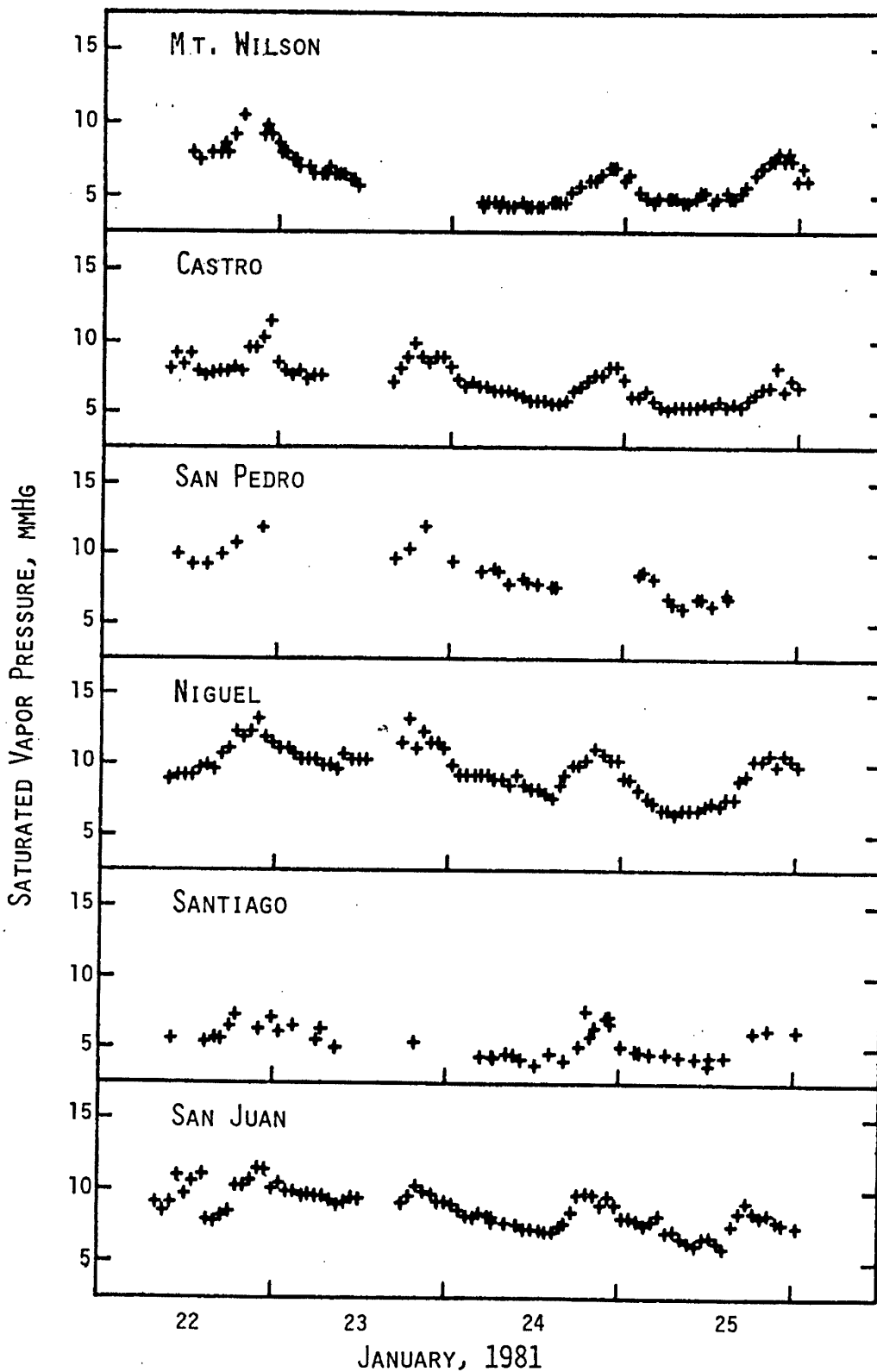


Fig. A3. Saturated vapor pressure.

