NOAA Technical Memorandum NOS NGS 20

GEODETIC LEVELING AND THE SEA LEVEL SLOPE ALONG THE CALIFORNIA COAST

Rockville, Md.
September 1979

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Ocean Survey

(Continued)

NOAA Technical Reports, NOS/NGS subseries

NOS 65 NGS 1 The statistics of residuals and the detection of outliers. Allen J. Pope, May 1976, 133 pp (PB258428). A criterion for rejection of bad geodetic data is derived on the basis of residuals from a simultaneous least-squares adjustment. Subroutine TAURE is included.

NOS 66 NGS 2 Effect of Geoceiver observations upon the classical triangulation network. R. E. Moose and S. W. Henriksen, June 1976, 65 pp (PB260921). The use of Geoceiver observations is investigated as a means of improving triangulation network adjustment results.

NOS 67 NGS 3 Algorithms for computing the geopotential using a simple-layer density model. Foster Morrison, March 1977, 41 pp (PB266967). Several algorithms are developed for computing with high accuracy the gravitational attraction of a simple-density layer at arbitrary altitudes. Computer program is included.

NOS 68 NGS 4 Test results of first-order class III leveling. Charles T. Whalen and Emery Balazs, November 1976, 30 pp (GPO# 003-017-00393-1) (PB265421). Specifications for releveling the National vertical control net were tested and the results published.

NOS 70 NGS 5 Selenocentric geodetic reference system. Frederick J. Doyle, Atef A. Elassal, and James R. Lucas, February 1977, 53 pp (PB266046). Reference system was established by simultaneous adjustment of 1,233 metric-camera photographs of the lunar surface from which 2,662 terrain points were positioned.

NOS 71 NGS 6 Application of digital filtering to satellite geodesy. C. C. Goad, May 1977, 73 pp (PB-270192). Variations in the orbit of GEOS-3 were analyzed for M_2 tidal harmonic coefficient values which perturb the orbits of artificial satellites and the Moon.

NOS 72 NGS 7 Systems for the determination of polar motion. Soren W. Henriksen, May 1977, 55 pp (PB274698). Methods for determining polar motion are described and their advantages and disadvantages compared.

NOS 73 NGS 8 Control leveling. Charles T. Whalen, May 1978, 23 pp (GPO# 003-017-00422-8) (PB286838). The history of the National network of geodetic control, from its origin in 1878, is presented in addition to the latest observational and computational procedures.

NOS 74 NGS 9 Survey of the McDonald Observatory radial line scheme by relative lateration techniques. William E. Carter and T. Vincenty, June 1978, 33 pp (PB287427). Results of experimental application of the "ratio method" of electromagnetic distance measurements are given for high resolution crustal deformation studies in the vicinity of the McDonald Lunar Laser Ranging and Harvard Radio Astronomy Stations.

NOS 75 NGS 10 An algorithm to compute the eigenvectors of a symmetric matrix. E. Schmid, August 1978, 5 pp (PB287923). Method describes computations for eigenvalues and eigenvectors of a symmetric matrix.

NOS 76 NGS 11 The application of multiquadric equations and point mass anomaly models to crustal movement studies. Rolland L. Hardy, November 1978, 63 pp (PB293544). Multiquadric equations, both harmonic and non-harmonic, are suitable as geometric prediction functions for surface deformation and have potentiality for usage in analysis of subsurface mass redistribution associated with crustal movements.

NOAA Manuals, NOS/NGS subseries

NOS NGS 1 Geodetic bench marks. Lt. Richard P. Floyd, September 1978, 56 pp (GPO# 003-017-00442-2) (PB296427). Reference guide provides specifications for highly stable bench marks, including chapters on installation procedures, vertical instability, and site selection considerations.

CONTENTS

GEODETIC LEVELING AND THE SEA LEVEL SLOPE ALONG THE CALIFORNIA COAST

Emery I. Balazs
Bruce C. Douglas
National Geodetic Survey
National Ocean Survey, NOAA
Rockville, Md. 20852

ABSTRACT: Comparisons between "free" adjusted normal orthometric leveling elevations and mean sea level at tide stations are given in Braaten and McCombs (1963) for the U.S. coastlines. Their report indicated an apparent systematic difference between the 1963 free adjustment, which had a mean epoch of 1939, and mean sea level along the coasts. Since that time new leveling surveys, performed primarily by the National Ocean Survey's National Geodetic Survey (NGS), have been accomplished between the San Francisco and San Pedro tide stations for the epochs 1968-69, 1968-71, 1971-72, 1973-75, and 1977-78.

The observed elevations at these tide stations are compared to mean sea levels of the 1941-59 epoch. Leveling surveys show very good consistency with a steady trend from negative to positive between 1968 and 1978. This trend indicates that San Pedro is rising with respect to San Francisco or that San Francisco is subsiding with respect to San Pedro at an average rate of about 70 mm/yr. However, an examination of the tidal records does not reveal large changes in the trend of mean sea level with respect to the land at the tide stations. Hicks and Crosby (1972) report the mean sea level trend with respect to land (1940-72 series) is -0.3 mm/yr at San Pedro and +1.8 mm/yr at San Francisco. Thus, the indicated relative movement rate (70 mm/yr) from leveling is about 30 times greater than the rate indicated by tidal observations. The reason for the large discrepancy between relative movement rates from repeat levelings and tidal observations is unknown.

INTRODUCTION

During the development of the National Geodetic Vertical Control Network in the United States the heights of Local Mean Sea Levels (LMSL) above the Vertical Reference Surface (VRS) at various epochs have been determined at many tide stations along the coastlines.

The first consistent set of LMSL heights was computed from the "free" adjustment of the 1929 vertical network. (A free adjustment is one in which only one elevation is held fixed.) William Bowie (1929), chief of the Coast and Geodetic Survey's Geodesy Division, compared the geodetic elevations of LMSL and found that the LMSL determined by tidal observations does not lie in the same level surface as determined by geodetic leveling. In his article, "Tilting of Mean Sea Level," Bowie stated that LMSL in St. Augustine, Fla., was 55 cm lower than at Portland, Me., and that LMSL in San Diego, Calif., was 26 cm lower than at Seattle, Wash. These figures represent an approximate overall slope of 40 mm per degree latitude on the Atlantic coast and a slope of 18 mm per degree latitude on the Pacific coast. He also estimated that the corresponding tidal planes of the Pacific Ocean are higher than those of the Atlantic by about 6 decimeters (dm).

A second comprehensive study of LMSL variations was made in 1963 by Braaten and McCombs (1963)in which they computed geodetic elevations of LMSL of the 1941-59 epoch at all primary tidal stations connected to the National Geodetic Vertical Datum (NGVD) in 1963. The elevations were derived, as in 1929, from the "free" adjustment of the entire U.S. Vertical Network. The mean epoch of leveling for the network was 1939.7. The results, which were similar to the first study, showed a systematic slope from north to south of approximately 30 mm per degree of latitude on the Atlantic coast and approximately 26 mm per degree of latitude on the Pacific coast. The corresponding tidal planes of the Pacific Ocean were again higher than those of the Atlantic by 6 to 7 dm across the same latitudes.

A third study of LMSL in relation to geodetic leveling was completed by the NGS in 1973. This study was based on first-order leveling completed after 1963. Although the results were not published, a paper on this study was presented to the Fourth GEOP conference (Balazs 1973).

The LMSL elevations in 1973 were determined from the adjustment of two special networks. On the Atlantic coast, extending from Key West, Fla., into Canada, the special vertical network had a total length of 18,600 km; about 2,000 km of these lines were in Canada and were leveled by the Geodetic

Survey of Canada. In addition, 21 control tide stations were connected to the net on the Atlantic and Gulf coasts. The second special net was developed in California. Thirty-two closed circuits were formed in the California net, with a total leveling length of about 6,000 km. Seven primary tide stations were connected to the net.

On the Atlantic coast between Eastport, Maine, and Savannah, Ga., the LMSL elevations derived from these post-1963 levelings were very different from those derived in the previous two studies. The systematic north-south slope of mean sea level (MSL) disappeared, and the elevations varied inconsistently above or below the VRS for the length of the Atlantic coast. But between Savannah and Key West, the systematic north-south slope reappeared and even increased to 40 mm per degree latitude.

On the California coast the changes observed were even more dramatic. The MSL slope, as computed from the adjustment of the special California net, increased to about 60 mm per degree latitude.

These large changes observed in LMSL could have originated from the protracted nature of the surveying program. It took several decades to complete the leveling of all the lines included in the 1929 and 1963 adjustments. Leveling data for a 10-year period were included in the two adjustments of the 1973 study. When level lines that have been leveled during different years are combined into one network, junction bench mark stability is a matter of concern. Unfortunately, the effect of possible movement of the junction bench marks on the LMSL elevations in these studies cannot be evaluated.

To eliminate some of the uncertainties caused by the large time intervals between leveling epochs, the relative heights of four LMSL on the California coast were investigated using a different procedure. This new effort was based on repeated first-order levelings along single lines between tide stations and carried out in the shortest possible time period. The four tide stations are located at the Presidio in San Francisco, Avila Beach, the Los Angeles Outer Harbor in San Pedro, and San Diego. The station records contain more than 19 years of tidal data. Altogether during 1968-78, NGS performed leveling between the tide stations in San Francisco and San Pedro five different times.

Reasons other than the availability of large amounts of leveling and tidal data determined the selection of the California coast for this study. First, the three previous studies indicated the MSL slope was persistently present and very large. Second, oceanographers have better data because ocean circulation is less complicated along the Pacific coast than the Atlantic.

CONNECTION OF LOCAL MEAN SEA LEVEL TO A REFERENCE POINT (BENCH MARK)

Mean sea level has maintained an important role in geodesy. The geoid was formerly defined by MSL. The U.S. 1929 National Geodetic Vertical Datum was also based on MSL. Mean sea level will be an important consideration when the future reference surface for the North American Geodetic Vertical Control Network is selected.

Local mean sea level is important for many practical reasons, too. Elevations of local tidal planes above the VRS must be considered in property surveys, construction, mapping, and related activities. For example, if a State law defines the property line as the intersection of land with one of the mean water levels, the surveyor should be able to stake the property using the nearest NGVD bench mark. Therefore, the relationship between VRS and the local tidal datum should be known precisely at each tide station. To aid the local surveyor we should consider publishing two elevations in the coastal areas for every bench mark of the NGVD--one for the NGVD and the other above a selected and adjusted tidal datum. When a new VRS is selected, consideration should be given to keeping the difference between LMSL and VRS at all tide stations as close to zero as practical.

Constantly changing water level heights are recorded by different methods at tide stations. Eventually these observations are meaned and a mean height is then related to a tide staff or permanent bench mark. The Nation Ocean Survey's (NOS) Office of Oceanography is responsible for most tide stations in the United States. NOS publishes descriptions and elevations above the local tide datum for all the Tide Gage Bench Marks (TGBM) at each station. The transfer of water level heights from the tide staff to the permanent bench mark is accomplished by geodetic leveling. Figure 1 shows the relationship between the tide staff and the TGBM and between the tidal datum and the VRS. At primary tide stations the staff and/or the automatic reading tape remains at the station. Therefore, when NGS field personnel level to these tide stations they usually level to the tide staff, in addition to all the tide gage bench marks. If the tide staff is not in place when NGS levels to the station, the difference "d" is used to compute the elevation of LMSL. This "d" is usually the mean of many leveling observations made by special tide units or by local surveyors. If an NGS unit levels to the staff, then "b" and "c" are used in the computations.

CONNECTION BETWEEN LOCAL MEAN SEA LEVELS

Local mean sea levels observed at widely separated tide stations can be related to each other. This is done by

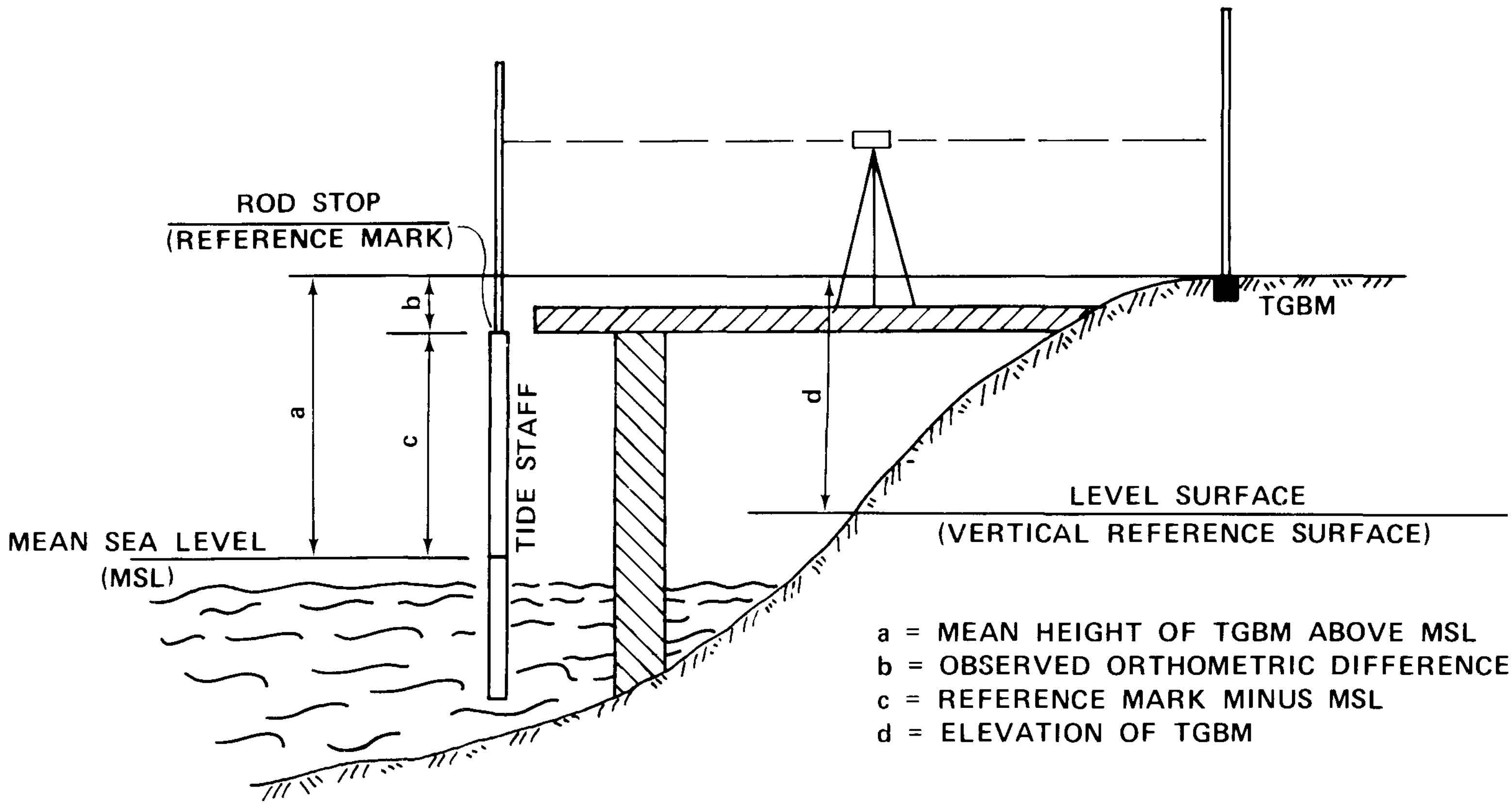


Figure 1.--Connection between tide gage bench mark and tidal datum planes.

either assuming that all LMSL of the same epoch are on the same level surface or by using oceanographic leveling (steric or geostrophic) (Montgomery 1969) or geodetic leveling. That oceanographic and geodetic leveling often disagree is well known (Sturges 1974a). Disagreement pertains to the size and the direction of the slope. Some oceanographers estimate the elevation difference of MSL between San Diego, Calif., and Neah Bay, Wash., to be 7 cm ± 5 cm from south to north. Another factor is the inconsistency between LMSL elevations determined by geodetic leveling of different epochs.

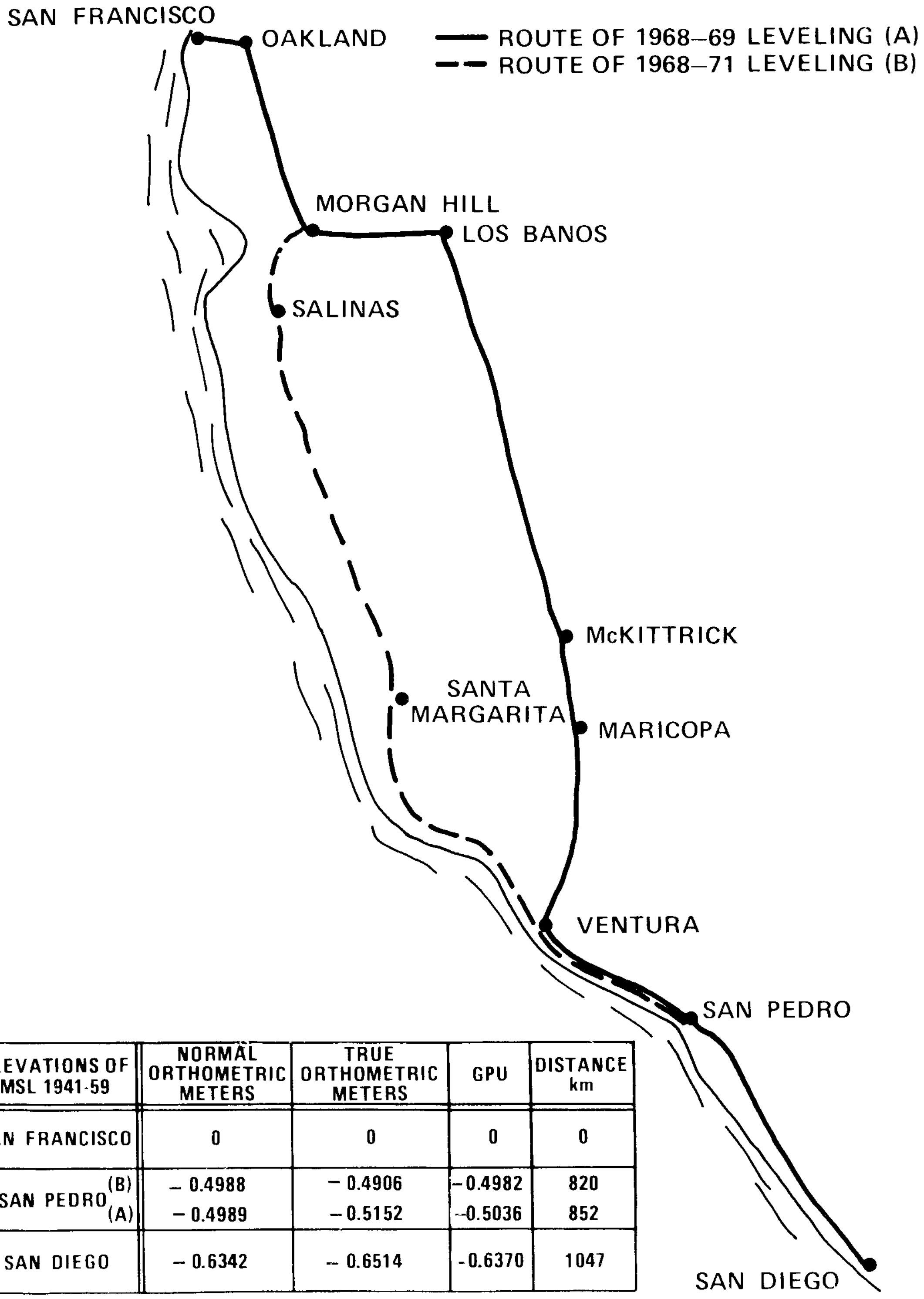
Figures 2 through 5 show five different level routes between San Francisco and San Pedro. Leveling along these lines was performed during the following years:

Line no.	Years	Mean epoch
1	1968-69	1969.2
2	1968-71	1970.1
3	1971-72	1972.3
4	1973-75	1974.8
5	1977-78	1978.2

Lines 1 and 2 have a common segment from San Francisco to Morgan Hill, which is about 15 percent of the total length. Therefore, the two results for the elevation of the LMSL at San Pedro are not independent.

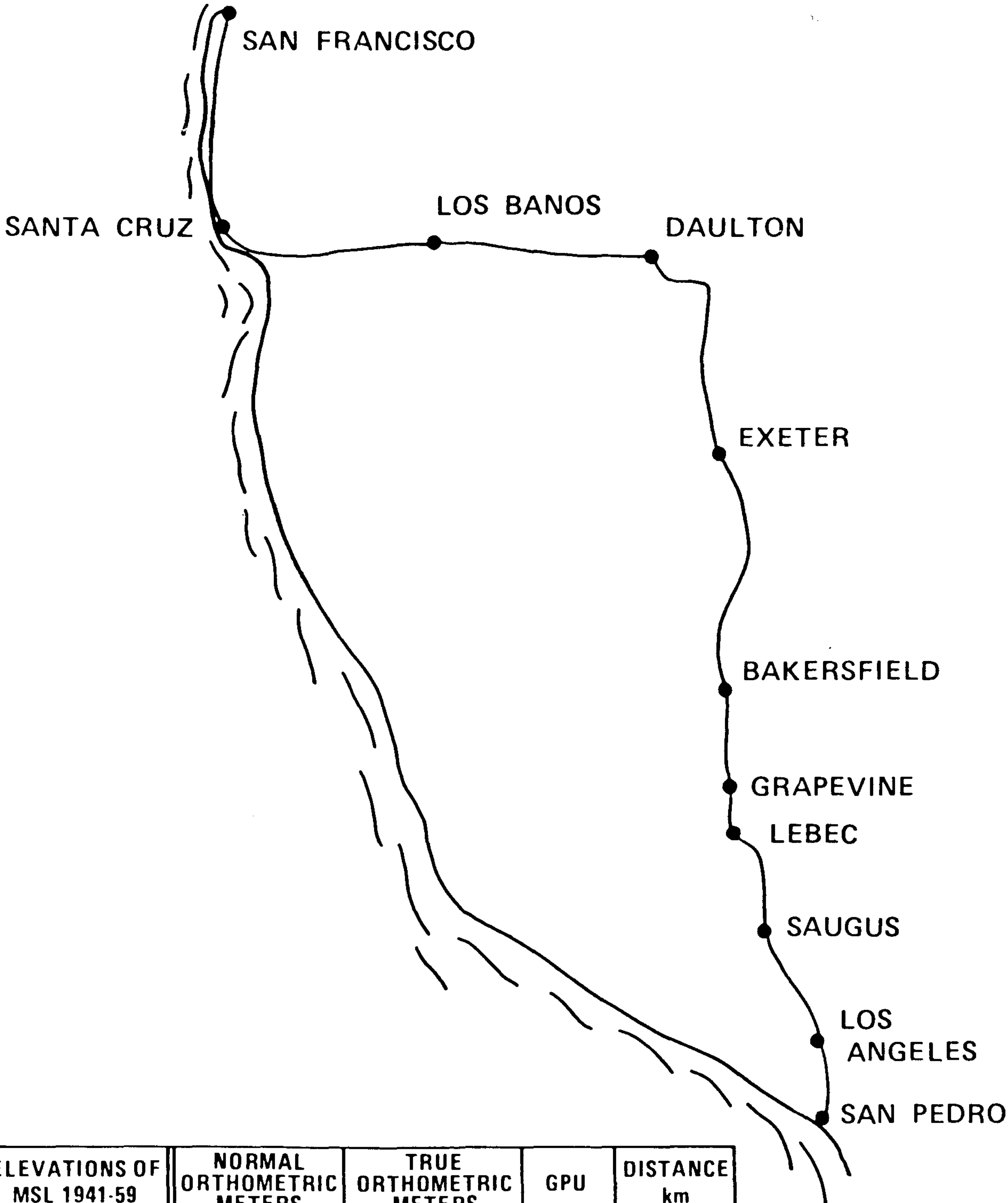
However, agreement between the two elevations (computed from lines 1 and 2) is very close and gives virtually the same elevation for the LMSL at San Pedro above the VRS. The agreement is even more remarkable when we consider that the second line was "open" for two years at Santa Margarita. Several bench marks in bedrock were used to hold the elevations for the 2-yr period. In the meantime the Feb. 9, 1971, San Fernando earthquake occurred during the leveling of the second line in the vicinity of Ventura. The epicenter of the earthquake, which had a magnitude of 6.4 on the Richter scale, was less than 100 km from the area of the leveling party. Several sections of the line were releveled after the earthquake, but no change was detected between consecutive bench marks. Therefore, the leveling was continued as planned to the San Pedro tide station. These two surveys agreed very closely but disagreed greatly with oceanographic leveling.

The National Geodetic Survey repeated the leveling between San Francisco and San Pedro in 1971-1972 with the cooperation of the Los Angeles City and County governments (fig. 3). The route of the survey was carefully designed to bypass the rapidly subsiding areas of the San Joaquin Valley and San Jose. The line was tied to the two previous level lines shown in figure 2 and to other vertical control lines in the area. Loop misclosures with the other level lines were acceptable and all



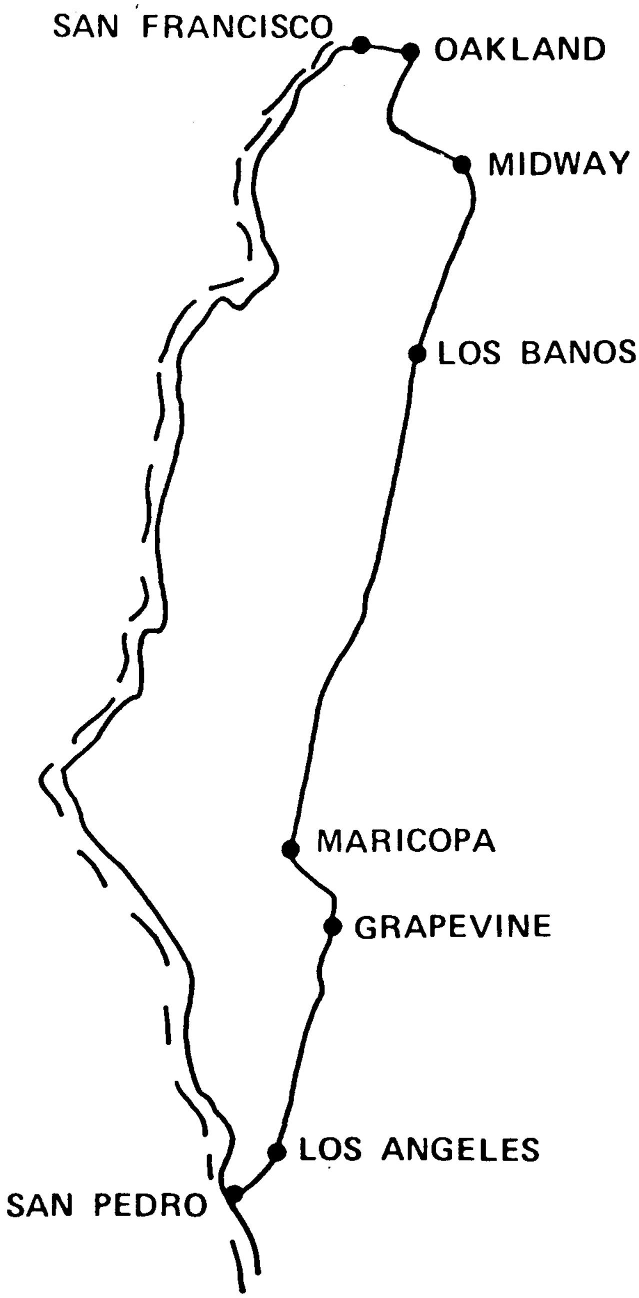
ELEVATIONS OF MSL 1941-59	NORMAL ORTHOMETRIC METERS	TRUE ORTHOMETRIC METERS	GPU	DISTANCE km
SAN FRANCISCO	0	0	0	0
SAN PEDRO (B)	−0.4988	−0.4906	−0.4982	820
SAN PEDRO (A)	−0.4989	−0.5152	−0.5036	852
SAN DIEGO	−0.6342	−0.6514	-0.6370	1047

Figure 2.--Routes of 1968-69 and 1968-71 levelings. Values show relative heights of local mean sea level for 1941-59 epoch.



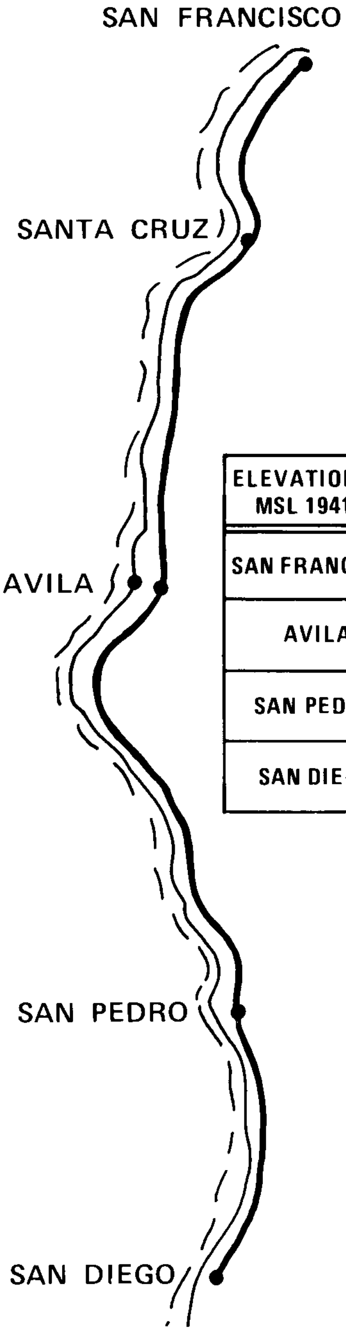
ELEVATIONS OF MSL 1941-59	NORMAL ORTHOMETRIC METERS	TRUE ORTHOMETRIC METERS	GPU	DISTANCE km
SAN FRANCISCO	0	0	0	0
SAN PEDRO	−0.3122	−0.3004	−0.2942	947

Figure 3.--Route of 1971-72 leveling survey. Values show relative heights of local mean sea level for 1941-59 epoch.



ELEVATIONS OF MSL 1941-59	NORMAL ORTHOMETRIC METERS	TRUE ORTHOMETRIC METERS	GPU	DISTANCE km
SAN FRANCISCO	0	0	0	0
SAN PEDRO	0.0256	0.0253	0.0248	804

Figure 4.--Route of 1973-75 leveling survey. Values show relative heights of local mean sea level for 1941-59 epoch.



ELEVATIONS OF MSL 1941-59	NORMAL ORTHOMETRIC METERS	TRUE ORTHOMETRIC METERS	GPU	DISTANCE km
SAN FRANCISCO	0	0	0	0
AVILA	0.0592	0.0605	0.0592	450
SAN PEDRO	0.1849	0.1800	0.1763	829
SAN DIEGO	0.1565	0.1504	0.1472	1040

Figure 5.--Route of 1977-78 leveling survey. Values show relative heights of local mean sea level for 1941-59 epoch.

three lines will be incorporated into the NGVD. The three lines were also included in the 1973 special California adjustment undertaken to study MSL (referred to here as the third study).

In June 1974, in preparation for another leveling between the two tide stations, NGS leveled from San Francisco to Oakland, through the BART tunnel, just prior to the opening of the subway system. On the Oakland side the line was extended into the mountains to several bedrock marks to minimize the effect of possible movement of the junction points while the line was open. During November 1974, the level party returned from the north and continued the leveling from Oakland (fig. 4). The project assignment was to relevel the line along the California Aquaduct through the San Joaquin Valley and connect the line at Grapevine to the leveling carried out by leveling parties of the Los Angeles County and City Engineering Departments. The overall difference between the two LMSL was about 25 mm. The results of this new survey agreed within millimeters of the difference estimated from steric leveling, which created the suspicion that either the new survey contained systematic errors or that previous surveys were considerably less precise than previously assumed. The questions that had previously been raised about sloping MSL suddenly changed to questions about the accuracy and reliability of geodetic leveling over long distances. None of the leveling surveys discussed so far were specifically designed to study the relationship between local mean sea levels.

After the fourth GEOP conference report in 1973 on the slope of MSL, geodesists from the United States and Canada discussed the problem with oceanographers at various American Geophysical Union meetings and workshops. Several papers also were published on the subject (Chew 1977, Sturges 1974b). From these discussions NGS developed a plan to relevel the line between the San Francisco, Avila, San Pedro, and San Diego tide stations in the shortest possible time interval, using coastal routes nearest the ocean. This leveling was performed between November 1977 and May 1978. Figure 5 shows the route of leveling for this epoch and the relative heights of the 1941-59 LMSL at the four primary tide stations.

Simultaneously with the leveling survey, very long base line inferometry (VLBI) observations were carried out by the Jet Propulsion Laboratory, California Institute of Technology, in the vicinity of the tide stations at San Francisco and La Jolla. The purpose was to compare the relative elevations of level surfaces obtained from VLBI and gravity measurements with the leveling results. However, the results of the 1977-78 leveling surveys were such as to cause the reconsideration of all previous surveys before proceeding further.

Figure 6 shows all five determinations of the LMSL at San Pedro relative to San Francisco by single-line leveling. Each of the five projects was observed under first-order, class I specifications (Whalen 1978), which allowed 3 mm $\sqrt{K}$ tolerance limits between forward and backward observations, where K is the distance between bench marks in kilometers. A maximum sight length of 50 m was required and levels equipped with optical micrometers and double scale invar rods. The horizontal line in figure 6 represents a level surface that coincides with the LMSL of the 1941 to 1959 epoch at San Francisco and also the VRS for each leveling epoch. It is assumed here that this level surface did not change during the time of leveling.

The systematic rise of elevations at San Pedro with respect to San Francisco indicated by the five level lines (or, if we reverse the starting point, the systematic subsidence at San Francisco with respect to San Pedro) gives a new dimension to the "slope" problem. The overriding concern now is not the direction and magnitude of the sloping MSL, but whether it is possible to have a crustal tilt of about 78 mm/yr without the tidal records indicating any significant change in the trend of water levels. An examination of the tidal records does not reveal large changes in the trend of MSL relative to land at the San Francisco and San Pedro tide stations. Hicks and Crosby (1972) have reported the trends of yearly MSL based on the 1940 to 1972 series of tidal records; for San Pedro their figure is -0.3 mm/yr and for San Francisco +1.8 mm/yr. If we correct each of these trends by -1.0 mm/yr for eustatic rise and reverse the signs, we have an approximate movement rate of land relative to MSL. These rates are +1.3 mm/yr at San Pedro and -0.8 mm/yr at San Francisco, or a relative movement rate of only 2.1 mm/yr between the two tide stations.

The tidal records of the same two stations were also examined for the time period of the new levelings, i.e., from August 1968 to December 1977. Using the monthly means instead of the yearly means, the trend of MSL relative to land is 1.5 mm/yr at San Pedro and -4.4 mm/yr at San Francisco. The relative land movement rate between the two tide stations computed from these MSL trends is 5.9 mm/yr. The relative rate computed from monthly means for the 10-yr duration is almost three times larger than the one computed from the yearly MSL of the 1940 to 1972 epoch. The movement computed from monthly means, however, is in the opposite direction from the movement computed from yearly means. The difference is probably due to the different time intervals rather than the use of yearly versus monthly means.

COMPUTATION OF ELEVATION DIFFERENCES

Tables 1 through 5 show the step-by-step computation of elevations for each epoch. The designations and localities of

Table 1.--Height differences for the 1968-69 epoch

From BM	From Place	To BM	To Place	Distance km	Height Differences: Normal Orthometric m	Height Differences: Helmert Orthometric m	Height Differences: Geopotential gpu	Data Source
MSL	San Francisco	Staff12'	San Francisco	0.0	2.060	2.060	2.019	NOS C31*
Staff12'		TGBM 176	San Francisco	0.4	1.887	1.887	1.849	L21932-1
TGBM 176		B 109	Oakland	8.7	3.224	3.225	3.160	L21932-1
B 109		V 1197	Oakland	14.7	-4.662	-4.662	-4.569	L21932-2
C 1077 X	Morgan Hill	V 1197	Oakland	99.1	-100.104	-100.108	-98.094	L21748
C 1077 X		Q 1096	Gustine	95.3	-35.128	-35.127	-34.423	L21969-1
Q 1096		C 926	Los Banos	34.8	21.057	21.058	20.631	L21703-1
C 926		167.36 R	Kettleman C.	134.2	10.814	10.814	10.588	L21703-1
167.36 R		Y 1159	Kettleman C.	22.7	165.360	165.363	162.003	L21703-7
Y 1159		197.2 A	Devils Den	39.6	-166.555	-166.558	-163.178	L22024-1
197.2 A		207.5 A		17.0	-0.694	-0.694	-0.681	L22024-1
207.5 A		Q 326	Maricopa	103.1	258.164	258.173	252.895	L22024-20
Q 326		TBM 20 M		52.8	725.167	725.240	710.284	L21369
TBM 20 M		F 1099	Ventura	134.2	-1079.842	-1079.945	-1057.750	L21366
F 1099		21-62 A	Wilmington	80.6	41.108	41.108	40.270	L21537$
Sub-total:				837.3	42.066	42.049	41.193	
Spur to San Pedro Tidal Station:								
TGBM 8	San Pedro	21-62 A		15.1	39.199	39.200	38.400	L21727@
TGBM 8		MSL	San Pedro	0.0	-3.365	-3.365	-3.296	NOS C31
Total:				852.3	-0.499	-0.515	-0.504	
21-62 A		CC 5	Los Alamitos	33.1	-31.187	-31.187	-30.552	L21537$
CC 5		C 1002	Seal Beach	9.2	-9.217	-9.217	-9.029	L21596$$
C 1002		V 282	San Onofre	66.9	1.584	1.584	1.552	L21862$$
V 282		TGBM 13 M	San Diego	100.7	0.899	0.900	0.881	L21529**
TGBM 13 M		MSL	San Diego	0.0	-2.981	-2.981	-2.920	NOS C31
Total:				1047.2	-0.634	-0.651	-0.637	

*National Ocean Survey, Tides and Water Levels Branch.
$ Los Angeles County
@ City of Los Angeles
$$ Orange County
**San Diego County

Table 2.--Height differences for the 1968-71 epoch

From		To			Height Differences			
BM	Place	BM	Place	Distance km	Normal Orthometric m	Helmert Orthometric m	Geopotential gpu	Data Source
MSL	San Francisco	Staff12'	San Francisco	0.0	2.060	2.060	2.019	NOS C31*
Staff12'		TGBM 176	San Francisco	0.4	1.887	1.887	1.849	L21932-1
TGBM 176		B 109	Oakland	8.7	3.224	3.225	3.160	L21932-1
B 109		V 1197	Oakland	14.7	-4.662	-4.662	-4.569	L21932-2
C 1077 X	Morgan Hill	V 1197	Oakland	99.1	-100.104	-100.108	-98.094	L21748
L 903	Santa Margarita	C 1077X	Morgan Hill	267.1	-243.982	-243.987	-239.010	L21602
L 903		TGBM 8	San Pedro	429.7	-343.730	-343.748	-336.765	L22292
TGBM 8		MSL	San Pedro	0.0	-3.365	-3.365	-3.296	NOS C31
Total:				819.6	-0.499	-0.508	-0.498	

*National Ocean Survey, Tides and Water Levels Branch.

Table 3.--Height differences for the 1971-72 epoch

From		To			Height Differences			
BM	Place	BM	Place	Distance km	Normal Orthometric m	Helmert Orthometric m	Geopotential gpu	Data Source
MSL	San Francisco	Staff12'	San Francisco	0.0	2.060	2.060	2.019	NOS C31*
Staff12'		TGBM 176	San Francisco	0.4	1.887	1.887	1.849	L22869
14	Santa Cruz	TGBM 176	San Francisco	149.5	-0.146	-0.145	-0.142	L22869
X 926	Los Banos	14	Santa Cruz	144.9	-30.019	-30.024	-29.418	L22841
X 798	Raymond	X 926	Los Banos	85.9	-140.468	-140.476	-137.636	L22810
Bert	Ducar	X 798		232.1	-19.112	-19.104	-18.702	L22801
H 537	Crapevine	Bert		125.9	-575.208	-575.242	-563.434	L22757
H 537		U 370	Saugus	84.6	-460.188	-460.194	-450.775	L22391
U 370		60-35 A	Los Angeles	22.4	71.006	71.007	69.549	L22427$
TCBM 8	San Pedro	60-35 A	Los Angeles	101.1	376.664	376.686	368.973	L22429@
TCBM 8	San Pedro	MSL	San Pedro	0.0	-3.365	-3.365	-3.296	NOS C31
Total at San Pedro:				946.8	-0.312	-0.300	-0.294	

*National Ocean Survey, Tides and Water Levels Branch.
$ Los Angeles County
@ City of Los Angeles

Table 4.--Height differences for the 1973-75 epoch

From BM	From Place	To BM	To Place	Distance km	Height Differences: Normal Orthometric m	Height Differences: Helmert Orthometric m	Height Differences: Geopotential gpu	Data Source
MSL	San Francisco	Staff12'	San Francisco	0.0	2.060	2.060	2.019	NOS C31*
Staff12'	San Francisco	TCBM 176	San Francisco	0.4	1.891	1.891	1.853	L23297
TCBM 176	San Francisco	F 1199	Oakland	39.0	490.300	490.316	480.460	L23297
F 1199	Oakland	M 1068	Midway	82.7	-416.895	-416.908	-408.525	L23596
M 1068	Midway	Y 1259	San Louis D	105.4	1.628	1.629	1.590	L23599
Y 1259		118.49 L	Panoche Jct.	80.0	24.241	24.243	23.747	L23760
118.49 L		U 1097	Kettlem.C	93.5	-6.160	-6.161	-6.040	L23763
U 1097		241.06 A	Tupman	110.6	-2.783	-2.784	-2.734	L23781
241.06 A		H 537	Grapevine	86.1	675.009	675.036	661.208	L23784
102-79	Sandberg	H 537		30.8	-260.367	-260.437	-255.021	L23673$
102-79		U 370	Saugus	56.9	-720.514	-720.592	-705.758	L23675$
102-79		U 370		61.3	-720.555	-720.634	-705.799	L23757$
Mean				59.1	-720.534	-720.613	-705.778	
U 370	Saugus	1171 USGS		8.0	47.485	47.490	46.515	L23677$
RS 10	Los Angeles	1171 USGS		20.7	-22.897	-22.897	-22.426	L23691$
338 Re '36	Los Angeles	RS 10	Los Angeles	41.9	276.087	276.113	270.454	L23614@
21-03690	Los Angeles	338 Re '36	Los Angeles	30.8	90.321	90.322	88.477	L23611@
TCBM 8	San Pedro	21-03690	Los Angeles	14.7	9.706	9.706	9.508	L23644@
TCBM 8	San Pedro	MSL	San Pedro	0.0	-3.365	-3.365	-3.296	NOS C31
Total:				803.6	0.026	0.025	0.025	

*National Ocean Survey, Tides and Water Levels Branch.
$ Los Angeles County
@ City of Los Angeles

Table 5.--Height differences for the 1977-78 epoch

From		To			Height Differences			
					Normal	Helmert		
BM	Place	BM	Place	Distance km	Orthometric m	Orthometric m	Geopotential gpu	Data Source
MSL	San Francisco	Staff12'	San Francisco	0.0	2.060	2.060	2.019	NOS C31*
Staff12'	San Francisco	TGBM 180	San Francisco	0.1	1.052	1.052	1.031	NOS C31
TGBM 180	San Francisco	TGBM 176	San Francisco	0.3	0.836	0.836	0.820	L24298
TGBM 176	San Francisco	E 828	Avila Beach	444.6	6.338	6.339	6.210	L24298
Sub-total from San Francisco MSL:				445.0	10.287	10.288	10.080	
Spur to Avila Beach Tidal Station:								
E 828	Avila Beach	TGBM 12	Port San Luis	5.0	-6.485	-6.485	-6.353	L24298
TGBM 12		MSL	Port San Luis	0.0	-3.743	-3.743	-3.667	NOS C31
Total at Port San Luis:				450.0	0.059	0.060	0.060	
E 828	Avila Beach	TGBM N	San Pedro	382.9	-7.377	-7.384	-7.234	L24301-1
Sub-total from San Francisco MSL:				827.9	2.909	2.904	2.846	
TGBM N	San Pedro	TGBM 8	San Pedro	0.9	0.640	0.640	0.627	L24301-1
TGBM 8	San Pedro	Staff12'	San Pedro	0.0	-1.321	-1.321	-1.294	NOS C31
Staff12'	San Pedro	MSL	San Pedro	0.0	-2.044	-2.044	-2.002	NOS C31
Total at San Pedro:				828.8	0.185	0.180	0.177	
TGBM N	San Pedro	TGBM 14A	San Diego	211.6	0.432	0.431	0.422	L24301-1
TGBM 14A	San Diego	Gage 50'	San Diego	0.0	0.436	0.436	0.427	L24301-1
Gage 50'	San Diego	MSL	San Diego	0.0	-3.621	-3.621	-3.547	NOS C31
Total at San Diego:				1040.4	0.156	0.150	0.148	

*National Ocean Survey, Tides and Water Levels Branch.

junction bench marks, distances, and three-height differences between bench marks are tabulated. The L-numbers shown in the data source column (far right) are the NGS archival numbers for the level line. Symbols after the L-numbers refer to the agency that leveled the line; the code is explained at the bottom of the table. Lines without symbols were leveled by NGS. Table 6 shows the accumulated observed elevations of the 1941-59 MSL at four primary tide stations.

Table 6.--Observed elevations of the 1941-59 mean sea level at tidal stations

Tide stations	Type elevation*	Date of leveling 1977-78	1973-75	1971-72	1968-71	1968-69
941-4290	N.O.	0	0	0	0	0
San	T.O.	0	0	0	0	0
Francisco	gpu	0	0	0	0	0
941-2110	N.O.	0.0592				
Avila	T.O.	0.0605				
Beach	gpu	0.0592				
941-0660	N.O.	0.1849	0.0256	-0.3122	-0.4988	-0.4989
San	T.O.	0.1800	0.0253	-0.3004	-0.5085	-0.5152
Pedro	gpu	0.1763	0.0248	-0.2942	-0.4982	-0.5036
941-0170	N.O.	0.1565				-0.6342
San	T.O.	0.1504				-0.6514
Diego	gpu	0.1472				-0.6370

* N.O. = normal orthometric height in meters.
T.O. = true orthometric height in meters (Helmert).
gpu = geopotential unit

For this investigation, zero elevation was assigned for the MSL of the 1941 to 1959 epoch at the San Francisco tide station for all five level lines. Therefore, the VRS for these lines is the level surface that coincides with the MSL of the 1941 to 1959 epoch at the San Francisco tide station.

Because new gravity values have been observed or interpolated for each bench mark in California, these lines were recently recomputed. Observed elevations are also available in geopotential units (gpu) in addition to the normal orthometric elevations for each bench mark.

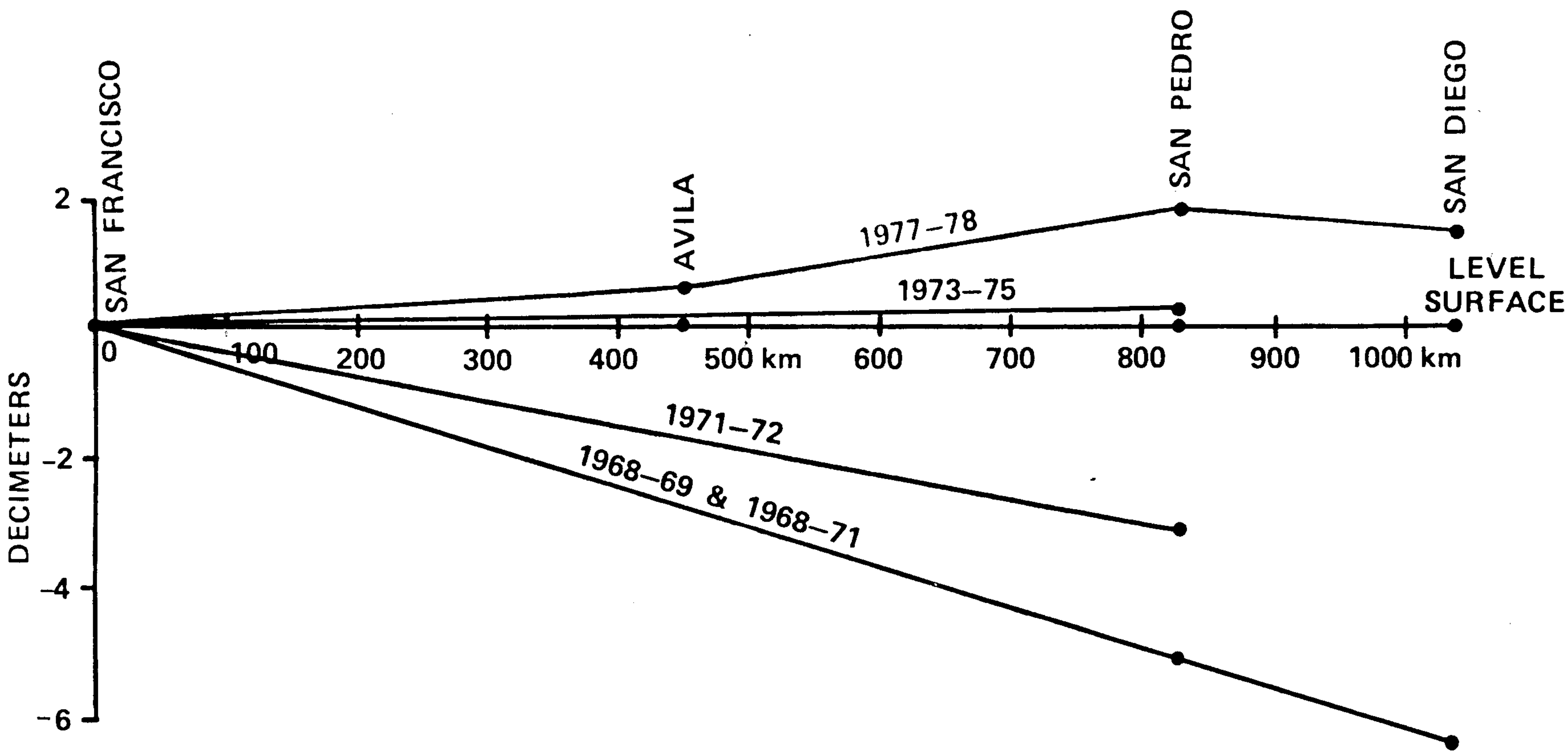


Figure 6.--Height of local mean sea level relative to a level surface at various leveling epochs.

The Helmert orthometric height differences were computed by converting the elevations in gpu to Helmert height with the following formula:

$$H = \frac{C}{gm}$$

where H is the orthometric height, C is the geopotential number of the bench mark, and gm is the mean value of gravity along the plumb line between the geoid and the bench mark. The gm was evaluated for each bench mark by means of Helmert's formula (Kaarianen 1966):

$$gm = g + g\left(1 - \frac{3}{2} \cdot \frac{Q}{Qm}\right) \frac{H}{R}$$

where g is the gravity at the bench mark, Q is the density of the surface rock (standard density = 2.67 gm/cc), Qm is the density of the Earth (5.52 gm/cc), and R is the radius of the Earth (6,370 km).

The starting gpu elevation for each line within an epoch was recomputed to be consistent with the bench mark on the previous line to ensure that the elevations were accumulated from the zero reference point in San Francisco.

CONCLUSIONS

Figure 7 shows the relative elevation of southern California with respect to San Francisco, as a function of the mean epoch of each leveling survey. The mean epoch (T) is defined as

$$T = \frac{\Sigma\ (\text{date} * \text{length})}{\Sigma\ \text{length}} .$$

This reflects more accurately the time of the survey than a statement about the beginning and ending dates of the leveling program.

Two phenomena are apparent in figure 7. First, note that the two surveys nearer in time give close agreement for the relative elevation of LMSL of San Francisco-San Pedro. Second, the overall change in elevation over the last 10 years is monotonic. Thus, whatever is responsible for the apparent change in height of San Pedro with respect to San Francisco would appear to be highly systematic and have a time-dependent effect. The apparent change in height is one order of magnitude greater than what could reasonably be expected from leveling errors based on the analysis of loop misclosures.

The original intention of investigating the slope of mean sea level was to compare geodetic and steric leveling using an independent third method, i.e., VLBI. However, the leveling results suggest that a time-dependent phenomenon exists. Thus,

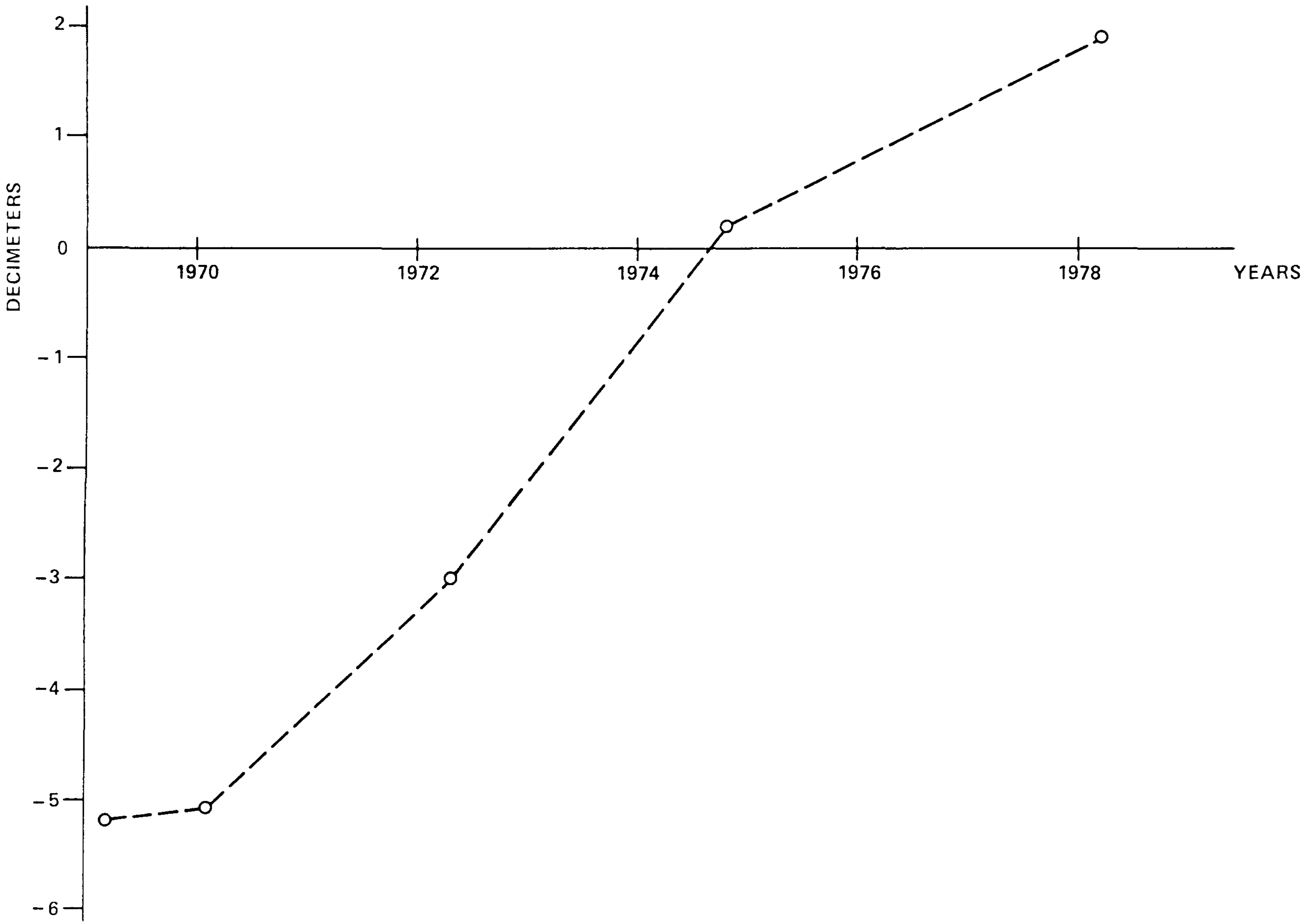


Figure 7.---Apparent change of elevations in the San Pedro area relative to San Francisco for the epochs 1969.2, 1970.1, 1972.3, 1974.8, and 1978.2.

our priorities have been altered to reconsider the leveling process and study the details of past work, along with postulating geophysical models.

REFERENCES

Balazs, E. I., 1973: Local mean sea level in relation to geodetic leveling along the U. S. coastlines. Paper presented at the Fourth Geodesy/Solid-Earth and Ocean Physics Conference, Boulder, Colorado, 18 pp.

Bowie, W., 1929: Tilting of mean sea level. Gerlands Bertrage zur Geophysik, XXIII, 97-98.

Braaten, N. F. and McCombs, C. E.(U.S. Department of Commerce, Coast & Geodetic Survey, Washington),1963: Mean sea level variations as indicated by a 1963 adjustment of first-order leveling in the United States. Paper presented at the International Union of Geodesy/International Assn. of Geodesy, General Assembly, Berkeley, Calif., 22 pp. (On file at National Geodetic Survey, NOS/NOAA, Rockville, Md.)

Chew, F., 1977: The advection effect of planetary vorticity on sea level slope in a western boundary current. Marine Geodesy, vol. 1, Crane, Russak & Co., Inc., New York, 103-116.

Hicks, S. D. and Crosby, J. E., 1972: Trends and variability of yearly mean sea level, 1893-1972, NOAA Technical Memorandum 13, Dept. Comm., NOAA/National Ocean Survey, Rockville, Md., 14 pp.

Kaarianen, E., 1966: The second leveling of Finland in 1935-1955. Finnish Geodetic Institute Report 61, Helsinki, Finland.

Montgomery, R. B., 1969: Comments on oceanic leveling, Deep-Sea Research. Supplement to vol. 16, Pergamon Press, Oxford, 147-152.

Sturges, W., 1974a: Sea level slope along continental boundaries. Journal of Geophysical Research, 79, 825-830.

Sturges, W., 1974b: Small longshore slopes induced by tidal interactions. Deep-Sea Research, vol. 21, Pergamon Press, Oxford, 1035-1038.

Whalen, C. T., 1978: Control leveling. NOAA Technical Report NOS 73 NGS 8, 21 pp. (Available from National Technical Information Service, Springfield, Va. 22161, accession no. PB286838; and from Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, document no. 003-017-00422-8.)

NOAA Technical Publications

National Ocean Survey/National Geodetic Survey subseries

The National Geodetic Survey (NGS) of the National Ocean Survey (NOS), NOAA, establishes and maintains the basic National horizontal and vertical networks of geodetic control and provides governmentwide leadership in the improvement of geodetic surveying methods and instrumentation, coordinates operations to assure network development, and provides specifications and criteria for survey operations by Federal, State, and other agencies.

NGS engages in research and development for the improvement of knowledge of the figure of the Earth and its gravity field, and has the responsibility to procure geodetic data from all sources, process these data, and make them generally available to users through a central data base.

NOAA Technical Memorandums and some special NOAA publications are sold by the National Technical Information Service (NTIS) in paper copy and microfiche. Orders should be directed to NTIS, 5285 Port Royal Road, Springfield, VA 22161 (telephone: 703-557-4650). NTIS customer charge accounts are invited; some commercial charge accounts are accepted. When ordering, give the NTIS accession number (which begins with PB) shown in parentheses in the following citations.

Paper copies of NOAA Technical Reports, which are of general interest to the public, are sold by the Superintendent of Documents, U.S. Government Printing Office (GPO), Washington, DC 20402 (telephone: 202-783-3238). For prompt service, please furnish the GPO stock number with your order. If a citation does not carry this number, then the publication is not sold by GPO. All NOAA Technical Reports may be purchased from NTIS in hard copy and microform. Prices for the same publication may vary between the two Government sales agents. Although both are nonprofit, GPO relies on some Federal support whereas NTIS is self-sustained.

An excellent reference source for Government publications is the National Depository Library program, a network of about 1,300 designated libraries. Requests for borrowing Depository Library material may be made through your local library. A free listing of libraries currently in this system is available from the Library Division, U.S. Government Printing Office, 5236 Eisenhower Ave., Alexandria, VA 22304 (telephone: 703-557-9013).

NOAA geodetic publications

Classification, Standards of Accuracy, and General Specifications of Geodetic Control Surveys. Federal Geodetic Control Committee, John O. Phillips (Chairman), Department of Commerce, NOAA, NOS, 1974 reprinted annually, 12 pp (PB265442). National specifications and tables show the closures required and tolerances permitted for first-, second-, and third-order geodetic control surveys.

Specifications To Support Classification, Standards of Accuracy, and General Specifications of Geodetic Control Surveys. Federal Geodetic Control Committee, John O. Phillips (Chairman), Department of Commerce, NOAA, NOS, 1975, reprinted annually, 30 pp (PB261037). This publication provides the rationale behind the original publication, "Classification, Standards of Accuracy, ..." cited above.

NOAA Technical Memorandums, NOS/NGS subseries

NOS NGS-1 Use of climatological and meteorological data in the planning and execution of National Geodetic Survey field operations. Robert J. Leffler, December 1975, 30 pp (PB249677). Availability, pertinence, uses, and procedures for using climatological and meteorological data are discussed as applicable to NGS field operations.

NOS NGS-2 Final report on responses to geodetic data questionnaire. John F. Spencer, Jr., March 1976, 39 pp (PB254641). Responses (20%) to a geodetic data questionnaire, mailed to 36,000 U.S. land surveyors, are analyzed for projecting future geodetic data needs.

NOS NGS-3 Adjustment of geodetic field data using a sequential method. Marvin C. Whiting and Allen J. Pope, March 1976, 11 pp (PB253967). A sequential adjustment is adopted for use by NGS field parties.

NOS NGS-4 Reducing the profile of sparse symmetric matrices. Richard A. Snay, June 1976, 24 pp (PB-258476). An algorithm for improving the profile of a sparse symmetric matrix is introduced and tested against the widely used reverse Cuthill-McKee algorithm.

NOS NGS-5 National Geodetic Survey data: availability, explanation, and application. Joseph F. Dracup, June 1976, 45 pp (PB258475). The summary gives data and services available from from NGS, accuracy of surveys, and uses of specific data.

(Continued at end of publication)

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Survey
National Geodetic Survey, C13x4
Rockville, Maryland 20852

OFFICIAL BUSINESS

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-210

U.S.MAIL

PRINTED MATTER