NOAA Technical Report NOS CO-OPS 035

HISTORICAL GOLDEN GATE TIDAL SERIES

Silver Spring, Maryland
October, 2002

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services
Products and Services Division

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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October 2002

noaa National Oceanic and Atmospheric Administration

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TABLE OF CONTENTS

Page

I. INTRODUCTION 1

II. HISTORY OF TIDE STATIONS AT THE GOLDEN GATE 1

A. Fort Point 1
B. Sausalito 1
C. Presidio 1

III. BENCH MARK AND LEVELING HISTORY AT THE GOLDEN GATE 3

A. Fort Point 3
B. Sausalito 3
C. Presidio 4
D. Relating the Tide Staff Zeros for the Three Locations to a Common Zero 4

IV. TIDAL DATUMS FOR THE GOLDEN GATE 7

A. Fort Point/Presidio 7
B. Sausalito 8

V. ADJUSTMENTS TO SAUSALITO 1877-1897 TIDAL HEIGHTS 9

VI. DATUM RECOVERY AT SAUSALITO 11

VII. GEODETIC RELATIONSHIPS TO TIDAL DATUMS AT THE GOLDEN GATE . 13

A. National Geodetic Vertical Datum 13

B. North American Vertical Datum 13

VIII. SPECIAL DATUMS. 15

IX. VARIATIONS IN MEAN SEA LEVEL AT THE GOLDEN GATE 17

A. Seasonal Variations in Sea Level 17
B. Interannual-to-Decadal Variations 18
C. Long-TermVariations in Annual Mean Sea Level 19
D. Sea Level Trends 20

X. EXTREME HIGH AND LOW WATER LEVELS AT THE GOLDEN GATE 23

A. Observed Highest Water Levels 23
B. Observed Lowest Water Levels 25
C. One Hundred Year Level 27

D. The Great January 1862 Floods 27
E. Return Period 28

XI. FREQUENCY AND DURATION OF INUNDATION 31

XII. COMPARISON OF OBSERVED AND PREDICTED HIGH AND LOW WATER LEVELS 35

XIII. CONCLUDING REMARKS 37

ACKNOWLEDGMENTS 37

REFERENCES 39

APPENDIX A. History of Tide Gauges A-1
APPENDIX B. Leveling Techniques B-1
APPENDIX C. Comparative Readings and Adjustments to Tidal Heights at Fort Point Between 1855 and 1859 . . . . C-1
APPENDIX D. Water Level Crossings of the Golden Gate D-1

LIST OF FIGURES

		Page
1.	Location of Golden Gate Tide Stations	2
2.	Summary of the relationships between tide staffs at the Presidio and Sausalito . . .	5
3.	Tidal Datum Elevations at the Golden Gate for 7 Different Tidal Epochs Between 1855 and 1998	11
4.	Seasonal Variations in Sea Level for Select Years in the Golden Gate Tidal Series	17
5A.	Seasonal Variations in Sea Level During Several El Nino Events Between 1939 and 1983	18
5B.	Seasonal Variations in Sea Level During Several El Nino Events Between 1990 and 1998	19
6.	Annual Mean Sea Level, 19-Year Moving Average of Sea Level and Sea Level Trend for the Golden Gate	20
7.	Observed Annual Highest Water Levels at the Golden Gate Between 1855 and 1999	23
8A.	Observed Highest Water Level, Predicted and Storm Surge for January 27, 1983 at the Presidio	24
8B.	Observed Highest Water Level, Predicted and Storm Surge for December 3, 1983 at the Presidio	24
9.	Observed Annual Lowest Water Levels at the Golden Gate	25
10A.	Observed Lowest Water Level, Predicted, and Storm Surge for December 26, 1932 at the Presidio	26
10B.	Observed Lowest Water Level, Predicted, and Storm Surge for December 17, 1933 at the Presidio	26
11.	Observed, Predicted and Storm Surge for January 22 - 24, 1862 at Fort Point	28
12A.	Frequency of Inundation for High Waters at the Presidio Between 1922 and 1984	31
12B.	Duration of Inundation for High Waters at the Presidio Between 1922 and 1984 . .	32
12C.	Frequency of Inundation for Low Waters at the Presidio Between 1922 - 1984 . . .	32
12D.	Duration of Inundation for Low Waters at the Presidio Between 1922 and 1984 . .	33
13A.	Frequency Distribution of Differences for High Water Heights at the Presidio . . .	35
13B.	Frequency Distribution of Differences for Low Water Heights at the Presidio	36
A-1.	Self-Registering Tide Gauge Installed at Fort Point in 1854	A-4
A-2.	ADR and Bubbler Tide Gauge Systems in Operation at the Presidio in the 1970s .	A-5
A-3.	NGWLMS Installed at the Presidio in the Late 1980s	A-7
C-1.	Monthly Means of MLLW Elevations at Fort Point Corrected for Wharf Sinking Between 1855 and 1859	C-4

LIST OF TABLES

Page

1. Bench Mark and Leveling History at Fort Point 3

2. Bench Mark and Leveling History at Sausalito 4

3. Primary Bench Marks at the Presidio 4

4. Tidal Datums and Associated Tidal Parameters 7

5. Tidal Datums for Fort Point and the Presidio 8

6. Tidal Datums for Sausalito 8

7. Tidal Datum Elevations at Sausalito Adjusted to Reflect Tidal Datum Elevations at the Presidio 10

8 . Tidal Datum Recovery at Sausalito 12

9. Geodetic Relationships to Tidal Datums at the Golden Gate 13

10. Relationships Between Tidal Datums (1960-1978 Tidal Epoch), NGVD and NAVD at the Presidio 14

11. Tidal Datums (1960 - 1978 Tidal Epoch) Related to Special Datums at the Presidio 16

12 Sea Level TrendsComputed for the Golden Gate 20

13. Highest Observed Water Levels in 100-Year Periods for the Golden Gate, Adjusted for Sea Level Change 27

14. Return Periods for San Francisco (1920 - 1970) 29

Executive Summary

This report is a comprehensive summary of the tide data and tidal datums for the Golden Gate tidal series covering the period from 1854 to 2000. The Golden Gate tidal series is the longest uninterrupted tidal series in the United States and one of the longest tidal series in the world. The Golden Gate is the entrance to the San Francisco Bay Estuary, one of the largest and most important commercial and industrial estuarine areas in the United States. The Golden Gate tidal series serves an important reference for tidal studies conducted within the San Francisco Bay Estuary.

The primary objective of this report is to document the establishment of the common datum relationship between the three long data sets at Fort Point, Sausalito and Presidio locations. Tidal measurements have been recorded in the Golden Gate area since the mid-1800s at Fort Point (1854-1877), Sausalito (1877-1897) and the Presidio (1897- Present). Once the datum relationships were established, the data sets were referenced to one common datum in order to establish the 146 year long data series for the National Ocean Service tidal program. Tidal analyses were performed and tidal datums were computed on the basis of long-term data sets leading to increased reliability of chart datums, and marine boundary determination with San Francisco as the reference station. Comprehensive studies of sea level changes and trends relative to land were possible. Long-term extreme high water levels are an important factor in studies of the influence of storms on the water levels. Return periods were determined with a higher degree of accuracy. Frequency and duration of inundation procedures were developed in which the data set at San Francisco provided ample long-term data. The scientific, engineering and academic communities have found this information useful to support resolution of many developmental and environmental issues related to the Golden Gate region.

* The National Ocean Service was previously named the Survey of the Coast (1807 - 1837), then the Coast Survey (1837 - 1878), followed by the Coast and Geodetic Survey (1878 - 1970). It was called the National Ocean Survey from 1970 until 1982 when it was renamed the National Ocean Service.

I. INTRODUCTION

Long tidal series in the Golden Gate area of California have been observed at four different locations. These include Fort Point (1854-1877), Sausalito (1877-1897) and Presidio (two locations1897- present). This report describes the procedures used to relate the tidal heights from the three locations to a common reference zero for the entire time period 1854-present. This has enabled one continuous time series to be constructed. From this time series, analyses of seasonal and long term variations in sea level and of the observed extremes in high and low water levels are possible. Preliminary results of this effort were reported by Smith (1980).

II. HISTORY OF TIDE STATIONS AT THE GOLDEN GATE

A history of tide gauges that have been used at the Golden Gate are described in Appendix A and locations of the tide stations are shown in Figure 1. San Francisco had the only harbor north of San Diego in the 1850s which was safe to enter all seasons of the year, therefore it proved essential to the Coast Survey to have a tide station in this locality.

A. Fort Point

A self-registering tide gauge was installed at Fort Point on June 30, 1854 at the end of a 500 foot long wharf projecting out from the Golden Gate southern shore. The tide gauge was located approximately 2100 feet east of Fort Point. The wharf on which the gauge and staff rested decayed to the point that it was necessary to abandon the site on November 27,1877.

B. Sausalito

The Sausalito station was established on February 27, 1877. Operation of the Sausalito tide station overlapped that of the Fort Point station for about 9 months. The tide gauge and staff were moved to a new wharf, adjacent to the old location, on October 12, 1881. The wharf at the old location had decayed to the point it was unsafe to continue tide operations. Data collection at Sausalito was discontinued on September 1, 1897 because a decision was made by the Coast and Geodetic Survey to move operations back across the Golden Gate to the Presidio.

C. Presidio

New facilities were established at a tide station at the Presidio on July 15, 1897. This was about one mile east of the Fort Point fortress. The Presidio and Sausalito stations operated simultaneously for less than 2 months. On July 26,1927, the tide gauge and staff were moved east of the 1897-1927 location to the Fort Point Coast Guard wharf at Crissy Field, where tide observations continue to be recorded at this location.

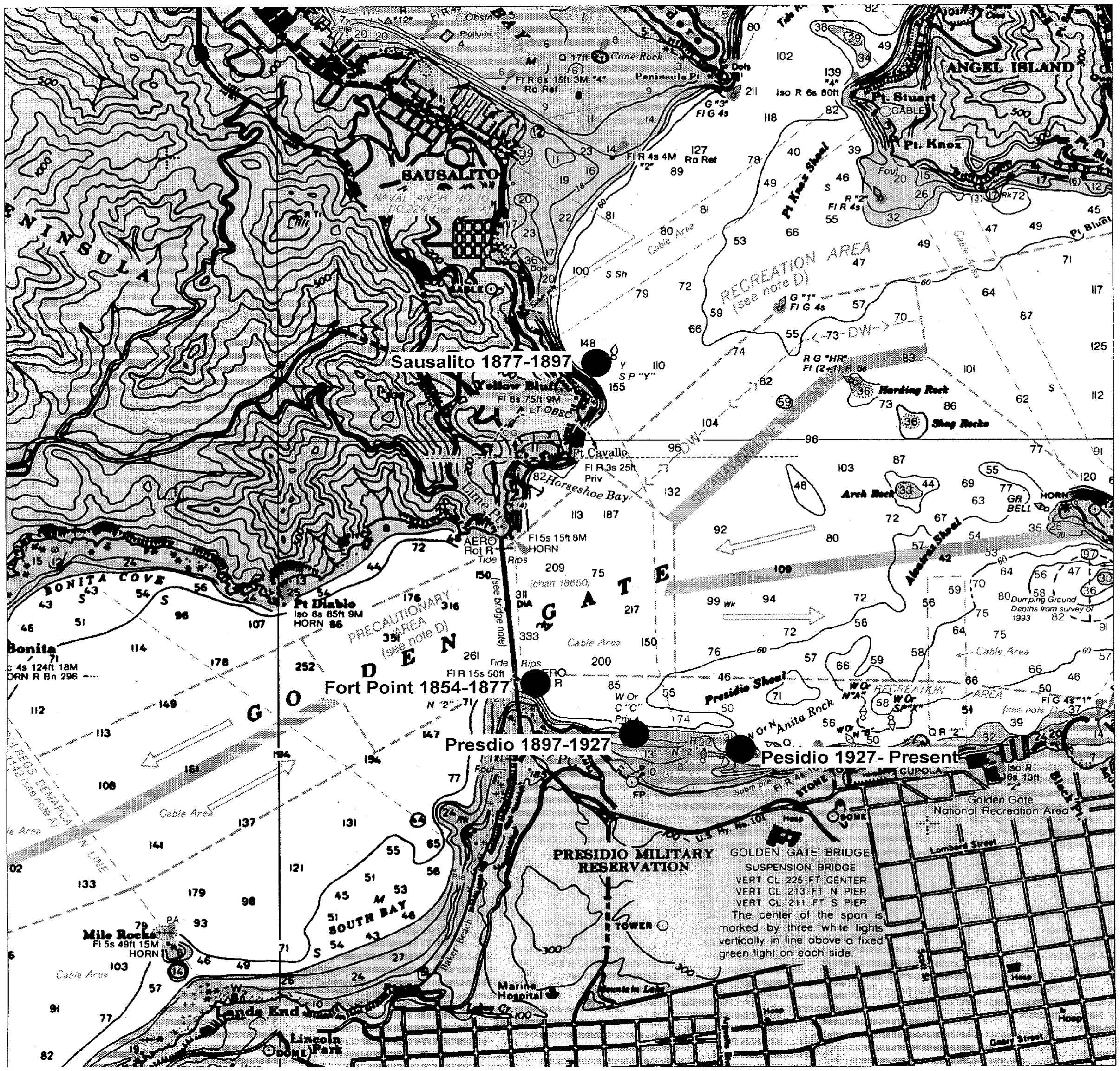

Figure 1. Location of Golden Gate Tide Stations

III. BENCH MARK AND LEVELING HISTORY AT THE GOLDEN GATE

In the early days of the Coast Survey in the 19th century, standard brass disks were not yet in use. Bench marks were often chiseled marks on concrete abutments or other structures that were believed to be relatively stable. The result of levels runs between bench marks and tide staffs in place at the various Golden Gate locations are summarized in Tables 1-3. Leveling techniques are detailed in Appendix B.

A. Fort Point

On June 30, 1854 a bench mark (BM), designated BM I(2), was established at Fort Point. It was a cross cut in the face of a large stone at the shore end of the wharf. In 1872 the Coast Survey established two additional bench marks, designated BM II(3) and BM III(5), to provide a more stable reference network at Fort Point. The history of the leveling to these bench marks is shown in Table 1.

Table 1. Bench Mark and Leveling History at Fort Point

Date of Leveling	BM I (2)	BM II (3)	BM III (5)
Elevations (feet) Related to Zero of Staff in Place			
June 30, 1854	14.445		
January 2, 1858	16.84		
April 2, 1858	14.44*		
June 21, 1859	15.22*		
May 6, 1872	14.523*	19.685	57.111
May 25, 1872	14.513	19.680	57.063
May 1877	14.495	19.665	57.128
November 28, 1877		19.659	

*New Staff

Historic levels show that the wharf and staff settled 2.40 feet between June 30, 1854 and January 2, 1858. A new staff was installed on April 2, 1858 closer to the shore on the same wharf. The 1859 levels indicate a staff settlement of 0.78 feet between April 1858 and June 1859. The wharf and staff were stabilized in 1859 by repairs to the wharf and the use of rock and stone fill in the area around the wharf. The water level heights between 1854 and 1859 were corrected to a common reference to take into account this movement. Appendix C, Figure C-1, shows a plot of the corrected versus uncorrected data and information on the wharf and staff movement.

B. Sausalito

Bench marks were established near the Sausalito tide station in 1877 prior to the water level crossing of the Golden Gate, including bench mark 2 (copper bolt) and bench mark 3 (granite block).

Bench mark 2 is recoverable today and has been virtually undisturbed for over 100 years. Bench mark elevations and the mean elevation difference from the level results are presented in Table 2.

Table 2. Bench Mark and Leveling History at Sausalito

Event	BM 2 (Copper Bolt)	BM 3 (Granite)
May 25, 1877 (1877 Staff)	12.614 ft.	46.093 ft.
October 12, 1881 (1881 Staff) (1886-1896 Levels, Mean of 24 level runs)	12.829 ft.	46.282 ft.
Difference	0.215 ft.	0.189 ft.
Mean Difference	0.202 ft.	

C. Presidio

The zero of the fixed staff to which the automatic tide gauge record at the Presidio wharf was referred was designated as Bench Mark 11. Tidal heights were referred to this tide staff zero from July 1897 to July 1905. Bench Mark 11 was 14.494 feet (mean of level results between 1897 and 1905) below BM 15 (Granite BM) which was designed as the primary bench mark (PBM) at the Presidio. The PBM is the principal mark of a group of tidal bench marks to which the tide staff and tidal datums are referred. New PBM's are established over time to replace PBM's that have become unstable or are destroyed. The other bench marks to replace BM 15 in time as the PBM are shown in Table 3.

Table 3. Primary Bench Marks at the Presidio

PBM	Above 1897 Tide Staff Zero (Elevation in Feet)	Years as PBM
15 (1897)	14.49	1897-1912
166 (1912)	17.05	1912-1927
173 (1927)	15.80	1927-1936
180 (1936)	19.01	1936-1995

D. Relating the Tide Staff Zeros for the Three Locations to a Common Zero

The level crossing of the Golden Gate between Fort Point and Sausalito in 1877 and the water crossing of the Golden Gate in 1906-07, after the "Great San Francisco Earthquake of 1906", were instrumental in relating the water level heights for the three locations to a common datum. The procedures used in the level crossings are described in Appendix B and the level runs are shown in Appendix D. The relationships between the zeros of the respective staffs at the three locations are summarized as follows:

1. Sausalito 1877 tide staff zero is 0.46 feet higher than the Fort Point 1877 staff zero

2. Sausalito 1877 tide staff zero is 0.20 feet higher than the Sausalito 1881 tide staff zero

3. Sausalito 1881 tide staff zero is 0.25 feet higher than the Presidio 1897 tide staff zero

4. Presidio 1897 tide staff zero is therefore 0.01 feet higher than the Fort Point 1877 tide staff zero

Figure 2 illustrates the above relationships in a "stick diagram" format.

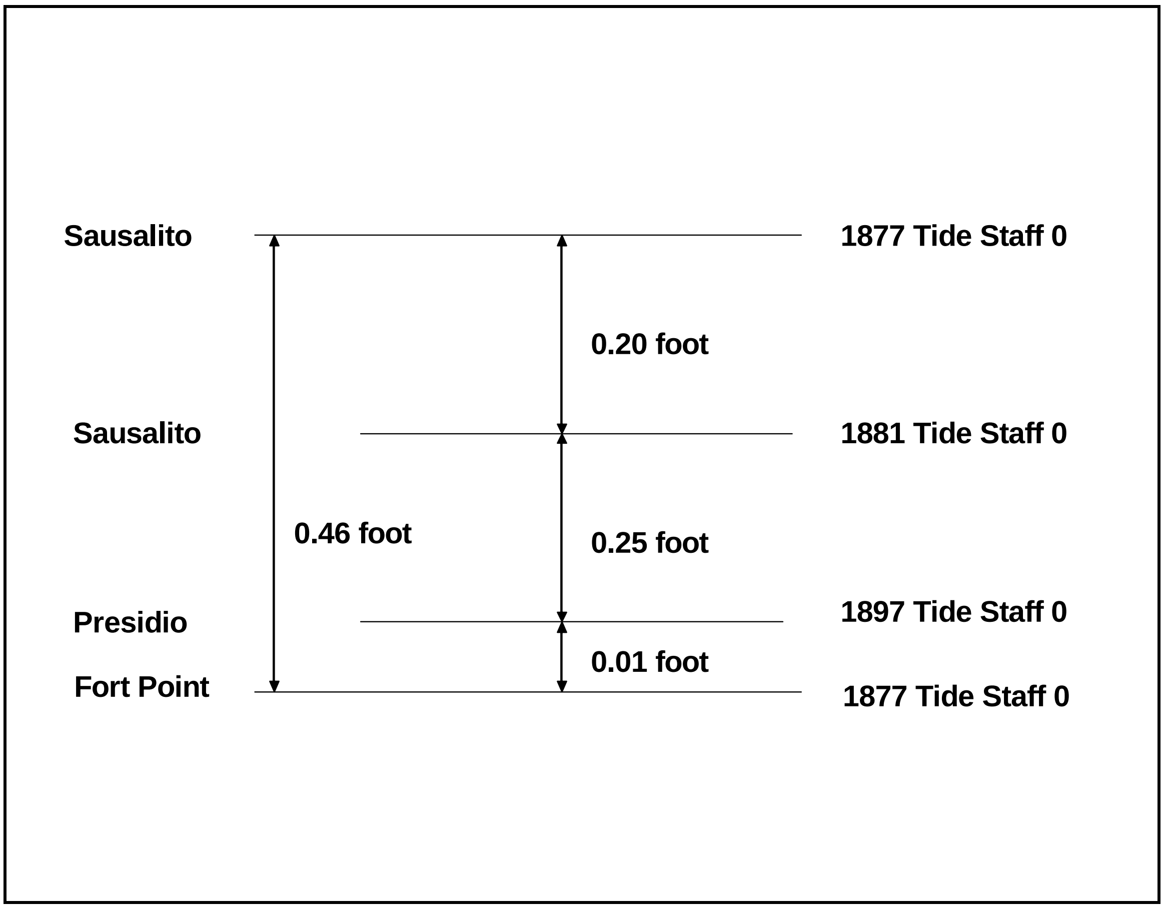

Figure 2. Summary of the relationships of the tide staffs at the Presidio and Sausalito.

IV. TIDAL DATUMS COMPUTED FOR THE GOLDEN GATE

A datum is a base elevation used as a reference from which to reckon heights or depths. It is called a tidal datum when defined in terms of a certain phase of the tide. The seven tidal datums and associated tidal parameters routinely computed by NOS are listed in Table 4 (See National Ocean Service (2000) for definitions).

Table 4. Tidal Datums and Associated Tidal Parameters

Tidal Datums	Tidal Parameters
Mean Seal Level (MSL)	Diurnal High Water Inequality (DHQ)
Mean Tide Level (MTL)	Diurnal Low Water Inequality (DLQ)
Diurnal Tide Level (DTL)	Mean Range of Tide (Mn)
Mean Higher High Water (MHHW)	Diurnal Mean Range of Tide (Gt)
Mean High Water (MHW)	
Mean Low Water (MLW)	
Mean Lower Low Water (MLLW)	

By the middle of the 20th century NOS adopted the concept of a National Tidal Datum Epoch (NTDE). A tidal epoch is a specific 19-year period accepted as the official time segment over which tide observations are taken and averaged to obtain mean values for tidal datums (Marmer, 1951). Establishment of an epoch was necessary to take into account the slowly varying changes in the tides due to the 18.6 year variation in the path of the moon called the regression of the moon's nodes. A tidal epoch is sometimes referred to as the Metonic cycle, which is defined as the period in which the new and full moon would recur on the same day of the year. Changes over time in the specific official 19-year period adopted are necessary because of observed periodic and apparent secular trends in sea level. The 19-year period is also used to "smooth out" the long-period meteorological, hydrologic, and oceanographic fluctuations. NOS has adopted the 1924-1942 (in 1953), 1941-1959 (in 1964) and 1960-1978 (in 1980) tidal epochs. Sea level changes are monitored and approximately every 25 years NOS determines whether sea level has changed at a sufficient number of its National Water Level Observation Network (NWLON) stations (long term continuously operating tide stations) in the United States coastal areas to warrant an update to a more recent tidal epoch. A new epoch update is presently underway in NOS.

A. Fort Point/Presidio

All the tidal datums for Fort Point and Presidio are referred to the station datum (the 1897 tide staff zero at Presidio) as shown in Table 5.

Table 5. Tidal Datums and Tidal Parameters for Fort Point and Presidio

Tidal Datums Elevation (Feet) above 1897 Tide Staff Zero at Presidio						
	Fort Point	Presidio Tidal Epoch				
Datum	1855 -1873	1898 -1916	1924 -1942	1941 -1959	1960 -1978	1980 -1998
MHHW	10.97	11.15	11.31	11.46	11.60	11.12
MHW	10.40	10.57	10.72	10.86	11.00	11.22
MTL	8.50	8.60	8.73	8.86	8.95	9.17
MSL	8.44	8.54	8.67	8.80	8.90	9.11
MLW	6.62	6.64	6.74	6.87	6.90	7.13
MLLW	5.43	5.49	5.61	5.75	5.77	6.00
Tidal Parameters						
Mn	3.78	3.93	3.98	3.99	4.10	4.09
DHQ	0.57	0.58	0.59	0.60	0.60	0.61
DLQ	1.19	1.15	1.13	1.12	1.13	1.13
Gt	5.54	5.66	5.70	5.75	5.83	5.83

B. Sausalito

Tidal datums (1878 - 1896), referred to the station datum (the 1881 tide staff zero) at Sausalito, are summarized in Table 6.

Table 6. Tidal Datums and Tidal Parameters for Sausalito

Tidal Datum (1878-1896)	Elevation (Feet)	Tidal Parameters	Elevation (feet)
MHHW	10.79		
MHW	10.22	Mn	3.57
MTL	8.43	DHQ	0.57
MSL	8.39	DLQ	1.13
MLW	6.65	Gt	5.27
MLLW	5.52		

V. ADJUSTMENTS TO SAUSALITO 1877 - 1897 TIDE HEIGHTS

The difference in the mean level of the sea surface across the Golden Gate between San Francisco and Sausalito was thought to be small enough that adjustments were not made to the MSL elevations at Sausalito when the datum elevations were transferred to the Presidio. The concept of a minimal sea surface slope across the Golden Gate between Fort Point and Sausalito was supported by the computed difference of MSL (1960 - 1978) - NGVD of 0.02 feet between the two locations.

The mean range of tide at Sausalito had an average range ratio (mean range of tide at Sausalito divided by the mean range of tide at Fort Point) of 0.94, therefore adjustments to the mean range of tide at Sausalito were needed. The range ratio was computed from an average of the ranges from the results of simultaneous comparisons between Fort Point and Sausalito. The mean high water and mean low water datum elevations also needed adjustments. The diurnal high water (DHQ = MHHW - MHW) and diurnal low water (DLQ = MLW - MLLW) inequalities were not required to be adjusted in the transfer. The following procedures were used to make adjustments to the tidal datum elevations for Sausalito to obtain values for these parameters for Fort Point/Presidio:

1. $$\frac{\text{Range of tide (1878-96) for Sausalito}}{\text{Range (Mn) Ratio}} = \frac{3.57}{0.94} = 3.80 \text{ Ft}$$

2. MTL and MSL are computed by transferring values to the 1897 tide staff at the Presidio. Station datum at Sausalito is defined as the 1881 tide staff zero which 0.25 foot above the Presidio station datum (1897 tide staff zero).

   MTL + 0.25 = 8.43 + 0.25 = 8.68 Ft
   MSL + 0.25 = 8.39 + 0.25 = 8.64 Ft

3. MLW = MTL - 1/2 Mn = 8.68 - 1/2(3.80) = 6.78 Ft

4. MHW = MLW + Mn = 6.78 + 3.80 = 10.58 Ft

5. MHHW = MHW + DHQ = 10.58 + 0.57 = 11.15 Ft

6. MLLW = MLW - DLQ = 6.78 - 1.13 = 5.65 Ft

All these adjusted values have been combined to reflect the tidal datum elevations reduced to mean values (1878 -1896) at Presidio, referred to the 1897 tide staff zero (Table 7).

Table 7. Tidal Datum Elevations at Sausalito Adjusted to Reflect Datum Elevations at Presidio

Tidal Datum Elevation (Ft)

Tidal Datums (ft)		**Tidal Parameters (ft)**	
MHHW	11.15	Mn	3.80
MHW	10.58	DHQ	0.57
MTL	8.68	DLQ	1.13
MSL	8.64	Gt	5.50
MLW	6.78		
MLLW	5.65		

The tidal datums, reduced to mean values for the 7 tidal epochs previous discussed (Table 5 and Table 7) are summarized in Figure 3.

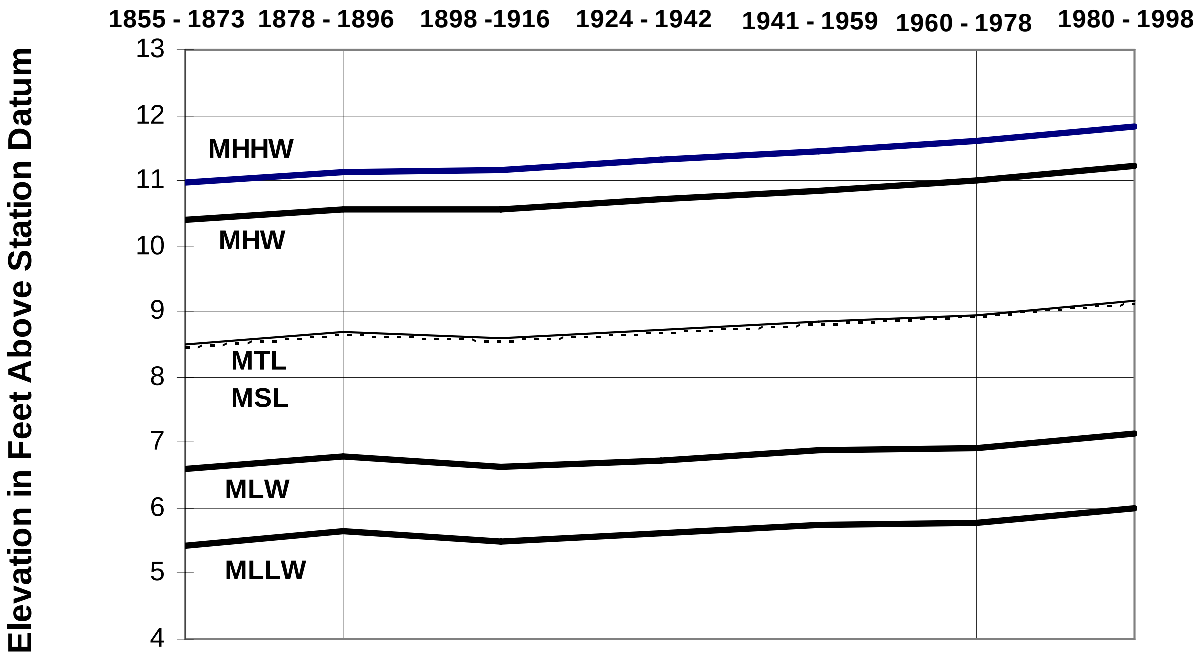

Figure 3. Tidal Datum Elevations at the Golden Gate For 7 Different Tidal Epochs Between 1855 and 1896

VI. DATUM RECOVERY AT SAUSALITO

A datum recovery is made at a tide station to determine how accurate the datum computed from one data set compares with the datum computed from a different period of time. It also assesses how accurate the datum at a location can be transferred from one period in time to another. The difference may also give an indication of how much the datum has changed over time due to man-made/or natural causes. If the recovery of the datum over time between different hydrographic surveys in the area are possible, then a history of the changes in sounding datum between hydrographic surveys can be determined which may provide information on bathymetric or other changes in the area.

Tidal datum recovery at Sausalito has been computed over a 100 year period with the use of the tidal series 1878 - 1896 and 1977 - 1979. Bench mark 2 1877 is a common bench mark to both tidal series in the analysis. The preliminary steps in the datum recovery are shown in Table 8.

Table 8. Tidal Datum Recovery at Sausalito

MTL (on staff 0)	BM 2 Elevation	MTL (on 1881 Staff 0)	Series
8.43 ft.	12.83 ft.	8.43 ft.	First reduction 1878-1896
5.99 ft.	10.11 ft.	8.71 ft.	24 months 1977-1979 datums reduced to mean value to 1960-1978 tidal epoch

The information in Table 8 is used to determine the datum recovery at Sausalito using the following steps:

a. The difference in the elevation of the common bench mark on the respective staffs for the two series is computed. From Table 8, the difference is 12.83 - 10.11 = 2.72 feet.

b. To refer the MTL elevation on the 1977 tide staff to the 1881 tide staff zero , 2.72 feet is added to 5.99 so that the corrected MTL (1878 - 1896) = 8.71 feet.

c. The datum recovery must take into account the change in relative mean sea level over time. This is estimated from Table5. The difference in mean sea level at the Presidio between the 1898-1916 and 1960-78 tidal epochs is 8.90-8.54 = 0.36 feet or a rate 0.0058 ft./yr (0.36ft./62 years).

d. The MTL of 8.43 feet in Table 8 needs to be adjusted as follows to reflect the sea level change between epochs 1878-1896 and 1960-78 (82 years). This difference is 0.48 ft. (0.0058 x 82 years).

   MTL (1878-1896) of 8.43 + 0.48 = 8.91 feet. (Corrected to MTL (1960-78)

e. The computed datum recovery for MTL is therefore 8.91 - 8.71 = 0.20 feet.

This datum recovery 0.20 foot is quite good given that the two tidal series are separated by such a long period of time. This indicates is that there has probably been little movement of BM 2 at Sausalito and the comparison of the results of 19 year datums at Sausalito from 1878 - 1896 compare well with those based on 1977 - 1979 Sausalito data, reduced to mean values (1960 - 1978) through a simultaneous comparison with the Presidio.

There are difficulties in obtaining a precise datum recovery (0.10 foot or better) at tide stations when a station is re-occupied again years later. The factors that affect the datum recovery include: common bench mark(s) available for both series, the bench marks may have been destroyed, settled or disturbed; and the quality of the tide data for one of the tidal series at the location may be questionable. The tidal datums for both series should be reduced to mean values (same tidal epoch) through simultaneous comparison with the same reference station in computing the tidal datums.

VII. GEODETIC RELATIONSHIPS TO TIDAL DATUMS AT THE GOLDEN GATE

The tidal datum of MSL has frequently been incorrectly referred to as a geodetic datum. MSL is a tidal datum determined over a 19-year National Tidal Datum Epoch. It pertains to local mean sea level and should not be confused with the fixed datums of North American Vertical Datum of 1988 (NAVD 88) or National Geodetic Vertical Datum of 1929 (NGVD 29). NGVD 29 and NAVD 88 are fixed geodetic datums whose elevation relationships to local MSL and other tidal datums are not expected to be consistent from one location to another.

A. National Geodetic Vertical Datum

NGVD 29 is a fixed datum that was adopted as a national standard geodetic reference for heights but is now considered superseded. NGVD 29 is sometimes referred to as Sea Level Datum of 1929 or as Mean Sea Level on some early issues of Geological Survey Topographic Quads. NGVD 29 was originally derived from a general adjustment of the first-order leveling networks of the U.S. and Canada after holding mean sea level observed at 26 long term tide stations as fixed. Numerous local and wide-spread adjustments have been made since establishment in1929. Bench mark elevations relative to NGVD 29 are available from the National Geodetic Survey (NGS) data base via the World Wide Web at http://www.ngs.noaa.gov/.

The relationships between NGVD and the local tidal datums for the Golden Gate tidal series for the three different adopted tidal epochs by NOS are listed in Table 9.

Table 9. Geodetic Relationships to Tidal Datums at the Golden Gate Tidal Epoch (Elevation in Feet)

Relationship	1924 - 1942	1941 - 1959	1960 - 1978
MHHW- NGVD	2.71	2.85	2.99
MHW - NGVD	2.12	2.25	2.39
MTL - NGVD	0.12	0.25	0.34
MSL - NGVD	0.06	0.19	0.29
MLW - NGVD	-1.87	-1.74	-1.71
MLLW - NGVD	-3.00	-2.86	-2.84

B. North American Vertical Datum (NAVD 88)

NAVD 88 is a fixed datum derived from a simultaneous, least squares, minimum constraint adjustment of Canadian/Mexican/United States leveling observations. Local mean sea level observed at Father Point/Rimouski, Canada was held fixed as the single initial constraint. NAVD 88 replaces NGVD 29 as the national standard geodetic reference for heights. Bench mark elevations relative to NAVD 88 are available from NGS through the World Wide Web at http://www.ngs.noaa.gov/. Explanations of the datum update can be found at this web site.

Table 10 shows how NAVD 88 derived heights compare to NGVD 29 computed heights in an example using San Francisco where the difference between NGVD 29 and NAVD 88 is 2.72 feet.

Table 10. Relationships to Tidal Datum(1960-1978 Tidal Epoch)
NGVD and NAVD at the Presidio

Datum	MHHW	MHW	MTL	MSL	NGVD	MLW	NAVD	MLLW
Elevation (Ft)	5.83	5.23	3.18	3.13	2.84	1.13	0.12	0.00

VIII. SPECIAL DATUMS

There are several local vertical datums adopted historically at San Francisco that appear on engineering drawings and other documents. For instance, the U.S. Army Corps of Engineers, state, county and local jurisdictions sometimes adopted a local datum as a reference to relate to elevations of structures in the locality. Local datums for San Francisco are listed below with a background on how the values were generated. Table 11 provides a tabular summary of the datum relationships.

1. San Francisco lower low water datum or Standard Lower Low Water.

This elevation is based on miscellaneous tide observations recorded before 1907 as adopted by the U.S. Army Corps of Engineers. It has a value of 5.55 feet above the 1897 tide staff zero at Presidio.

2. Standard Mean Sea Level at San Francisco

Because of the continual variations in sea level recorded at the Presidio, the mean sea level elevation changed as additional sea level measurements were incorporated into the accepted value of mean sea level. It was cumbersome for scientists and engineers to frequently update datums prior use of computers, therefore it was decided to adopted a "standard mean sea level datum" at Presidio of 8.52 feet referred to the 1897 tide staff zero. This datum elevation was determined from the mean of the hourly heights at observed at Presidio over the continuous period from 1898 to 1913. This datum was held fixed and was not updated.

3. Several other tidal datums have been computed and used historically by other countries, but are not used by NOS.

a. Mean High Water Spring (MHWS)
b. Mean Low Water Spring (MLWS)
c. Mean High Water Neap (MHWN)
d. Mean Low Water Neap (MLWN)

Two ways that these tidal datums may be computed are:

a. Mean of the high or low waters around the time of spring tide or neap tide each month over a specific 19-year period. There are 4 high waters and 4 low waters used each month for both the spring tide and the neap tide. Spring tide occurs around the time of new and full moon and neap tide occurs around the time of the first and third quadrature of the moon each month.
   It is sometimes subjective which days and tides to select.

b. The approach that can be used to compute approximate values for these tidal datums involves calculations using amplitudes of selected harmonic constituents from harmonic analysis for the location. The following is an example using the tidal parameters at Presidio for the 1960 -1978 tidal epoch and a 365 day harmonic analysis for 1994.

The harmonic analyses results provide ratios of the mean ranges of tide:

1. Sg/Mn = Spring Range of Tide/Mean Range of tide = 1.182
2. Np/Mn = Neap Range of Tide/Mean Range of tide = 0.792

From the accepted datums for the Presidio:

3. Mn = 4.10 ft. and MTL = 8.95ft. (1960-78 tidal epoch)

Thus:

4. Sg = 4.10 x 1.182 = 4.84 ft.
5. Np= 4.10 x 0.792 = 3.25 ft.
6. MHWS = MTL+1/2 Sg = 11.37 ft.
7. MHWN= MTL+1/2 Np = 10.58 ft.
8. MLWS = MTL-1/2/ Sg = 7.32 ft.
9. MLWN = MTL-1/2 Np = 6.53 ft.

Table 11. Presidio Tidal Datums (1960-1978 Tidal Epoch) Related to Special Datums

Tidal Datum	Elevation (Ft) Above 1897 Tide Staff Zero
MHHW	11.60
MHWS	11.37
MHW	11.00
MHWN	10.58
MTL	8.95
MSL	8.90
STD MSL	8.52
MLWN	7.32
MLW	6.90
MLWS	6.53
MLLW	5.77
STD LLW	5.55

IX. VARIATIONS IN MEAN SEA LEVEL AT THE GOLDEN GATE

The previous sections of this report describe how the tidal observations at the Golden Gate have been referenced to a common datum, the 1897 tide staff zero at the Presidio, resulting in a 146-year continuous record of MSL as well as other tidal datums and tidal parameters. MSL is frequently thought of as an equipotential surface, however it is known that MSL at any given location will deviate from that surface due to the effects of wind, barometric pressure, circulation patterns, and river flow. For tidal work, MSL is computed by averaging all hourly water level over specific time periods. NOS routinely computes monthly MSL, annual MSL, and the accepted tidal datum of MSL. The accepted datum of MSL is computed using 19-years of data over the accepted National Tidal Datum Epoch period. The long sea level series at the Golden Gate may provide important clues to climate and global change investigations. Sea level records are the longest and highest quality records of any oceanographic parameter and the primary evidence suggesting apparent rise in sea level comes from records of tide gauges such as San Francisco. In addition to reflecting changes in sea level, measurements of water level at a tide gauge may reflect changes due to the land movement in the region where the tide gauge is located. The following sections present analyses of the variations in mean sea level for the Golden Gate over various time scales. Previous examination of water level variations along the California coast was carried out by Smith and Leffler (1980).

A. Seasonal Variations in Sea Level

The seasonal variations in sea level over the months of the year differ from year to year due to meteorological and oceanographic influences. Generally sea level is lowest in the spring months and highest in the winter months at the Golden Gate. Seasonal MSL variations are shown in Figure 4 for the four different years separated by 40 years between 1860 and 1980 at the Golden Gate.

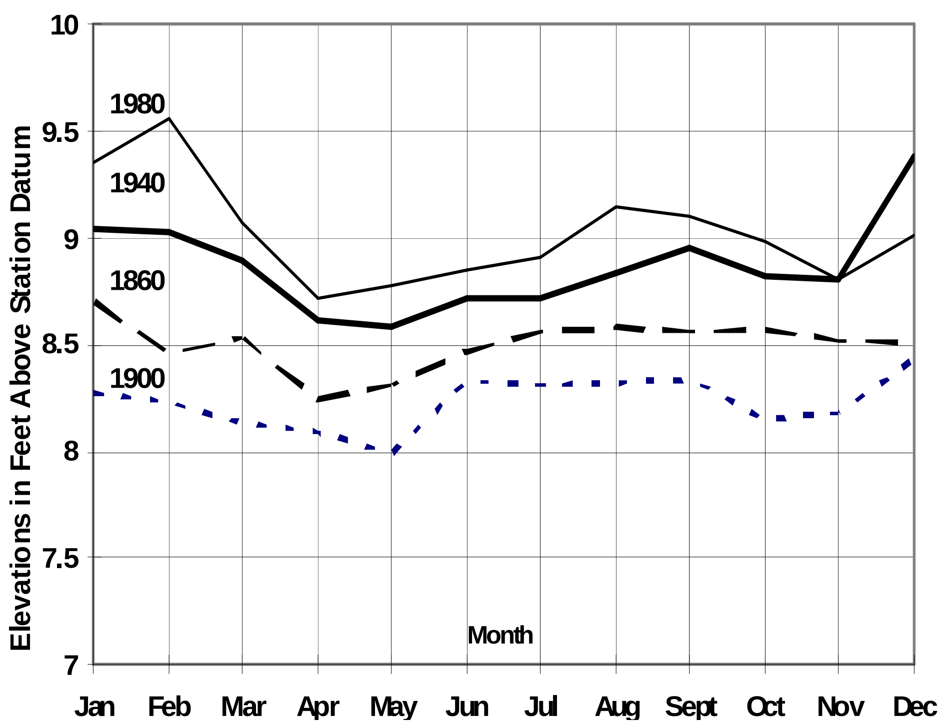

Figure 4. Seasonal Variations in Sea Level for Select Years in the Golden Gate tidal Series.

B. Interannual to Decadal Variations in Sea Level

El Nino events occur in the Pacific Ocean approximately every 3 to 7 years, and cause much higher than expected water levels at locations in the eastern Pacific Ocean. Each event has a life time of at least 15 months. Elevated water levels have been recorded at the Golden Gate during these event years. The most severe El Nino events in the 20th century occurred in the time periods 1939 - 1941, 1956 - 1958, 1981 - 1983 and 1991 - 1993. The monthly sea level variations for these years are shown in Figures 5a and b. Duncan et al (1998) provide detailed descriptions at the data for west coast stations for the 1997-1998 El Nino.

Interannual sea level variations play an important role in understanding climate phenomena such as the El Nino South Oscillation. These events reflect climatic interaction between the ocean and the atmosphere. The long term sea level records such as those at the Golden Gate, provide not only data for the study of sea level rise, but since climatic events such as El Nino vary in size and global influence from decade to decade, these data sets provide the baseline from which to measure future events.

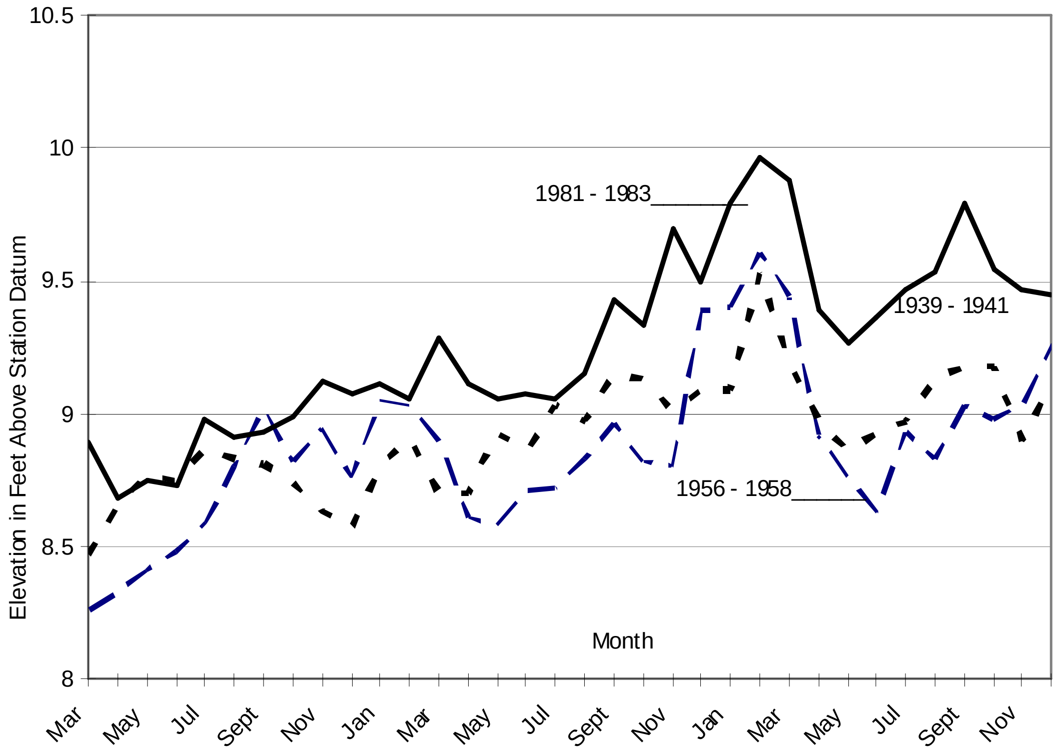

Figure 5A. Seasonal Variations in Sea Level During Several El Nini Events Between 1939 and 1983

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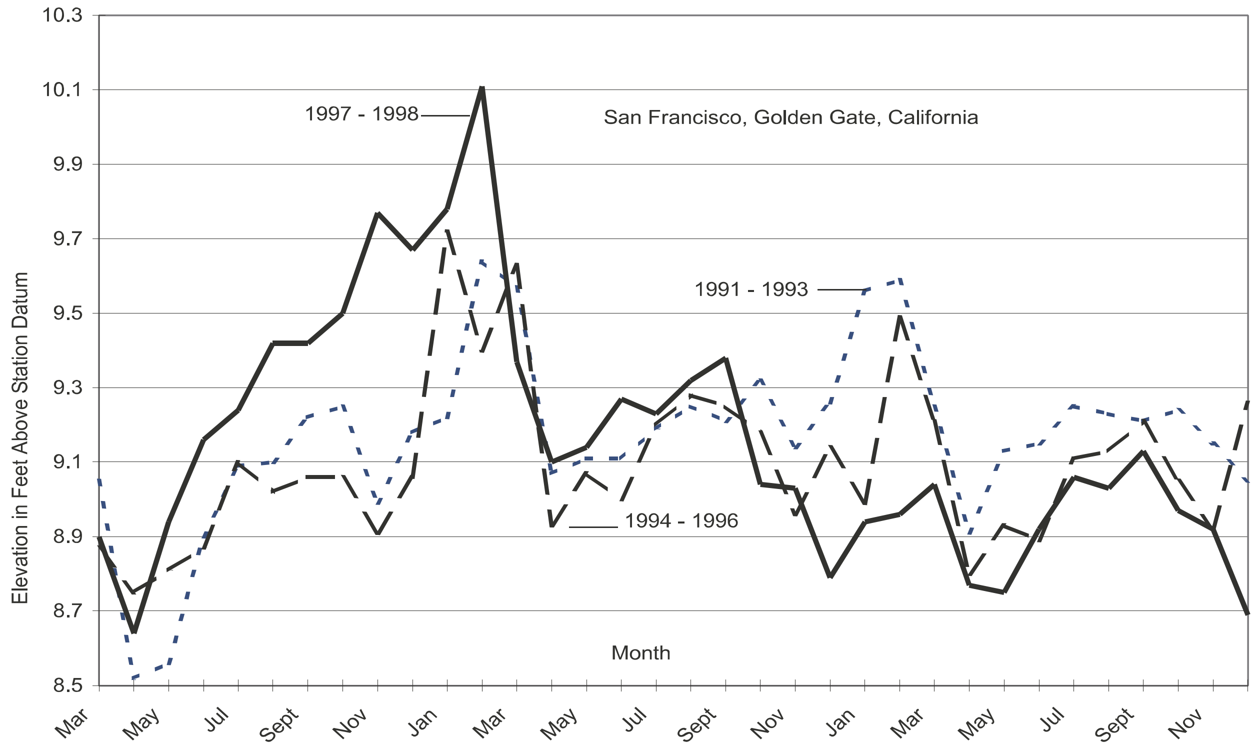


Figure 5B. Variations in monthly MSL during several El Nino events between 1990 and 1999

C. Long-term Variations in Annual Mean Sea Level

The annual means of sea level for the Golden Gate tidal series are available for each year from 1855 through 1998 (Figure 6). The notable upward spikes in the curve have been identified as years when El Nino events were in progress in the Pacific Ocean. El Nino is the name given to a general warming of the surface waters of the tropical Pacific Ocean that happens at irregular interval of years. It is a meteorological and oceanographic phenomenon. It is characterized by warmer surface water temperatures and higher water levels in the Eastern tropical Pacific Ocean with a lowering of the surface water temperatures and water levels in the Western Pacific. More is discussed later with seasonal-to-interannual-to-decadal variations in sea level. The notable downward spikes have not been addressed but may be associated with years of near drought conditions in the region. The annual mean sea level curve shows a rise in sea level relative to land. The amount of rise relative to land over the 140 years, is estimated to be at least 0.7 feet.

The sea level data have been filtered further to eliminate annual variations in the record with a 19-year moving average starting with 1855-1873 and ending with 1976-1998. Each 19-year value has been plotted at the mid-year of the 19-year period in Figure 6. The moving average curve provides a better visual sense of the long term variations than just the annual means themselves because of their high degree of variability.

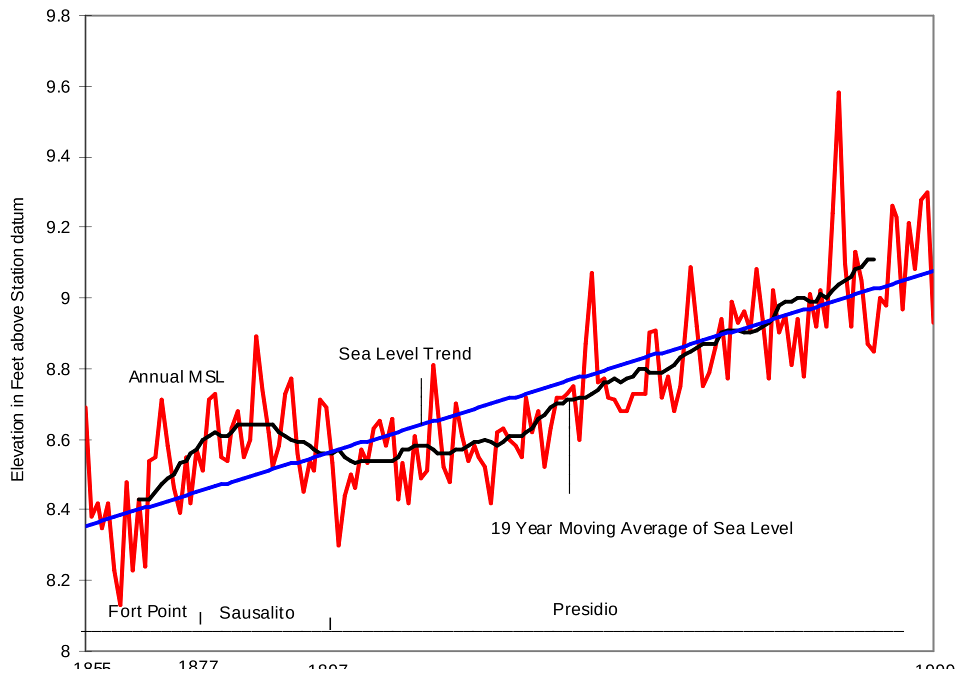


Figure 6. Annual Mean Sea Level, 19 Year Moving Average Sea Level and Sea Level Trend for the Golden Gate

E. Sea Level Trend

Computation of the sea level trend utilizes the regression analysis of a straight line fit. The sea level trend has been computed for 7 different tidal epochs (19 years) between 1855 and 1998 and the entire series, 1855 - 1998. The results are shown in Table 12. The sea level trend over the period 1855 - 1994 appears in Figure 6. Sea level trends for the national network have been compiled by Zervas (2001).

Table 12. Sea Level Trends Computed For the Golden Gate

Period of Record	Sea Level Trend (Feet/year)
1855-1873	+0.006
1875-1893	-0.004
1895-1913	-0.002
1915-1933	+0.002
1935-1953	+0.004
1955-1973	+0.008
1976-1998	+0.011
1855-1998	+0.005

The rates of relative sea level rise is not uniform as the data clearly do not follow a straight line fit. There is, in fact, a downward trend between 1875 and 1913 at the Golden Gate which the annual sea level curve (Figure 6) indicates. This long period variation in the historical record also appears in other comparable long term sea level records around the world.

X. EXTREME HIGH AND LOW WATER LEVELS AT THE GOLDEN GATE

Tabulations and summaries of observed highest water levels values at the Golden Gate are important products for NOAA, USGS, USACE, FEMA, EPA and state and local agencies because of the concern for impacts of coastal flooding the Bay area. Extreme low water levels have not received as much attention as the highest water levels in the Bay area, but these data are important as they relate to drought periods and salt water intrusion into the fresh water areas of the San Francisco Bay Estuary.

The California Department of Water Resources and U.S. Bureau of Reclamation(CADWR, 1970) summarizes the seasonal weather patterns in the bay region that partially drive the variations of the water levels. It is generally dry in summer due to the migrating high pressure systems that deflect storm patterns to the north. In the winter, the high pressures decrease in intensity and move southward and the intrusion of moisture-laden air is no longer blocked. The winter will frequently arrive as a series of storms that move in from the southeast and provide gale winds, heavy rains and large changes in atmospheric pressure.

A. Observed Highest Water Levels

Extreme high water levels result from the combined influence of meteorological and astronomical phenomena. Meteorological phenomena include local barometric pressure and winds, as well as large scale disturbances such as El Nino episodes affecting the San Francisco Bay region. Figure 7 shows the observed annual highest observed water levels between 1855 and 1999. The highest observed water level at the Golden Gate occurred on January 27, 1983 and December 3, 1983 (Figures 8A and 8B). The January 27, 1983 storm was wide spread over the West Coast while the December 3, 1983 storm was highly localized in the San Francisco Bay area.

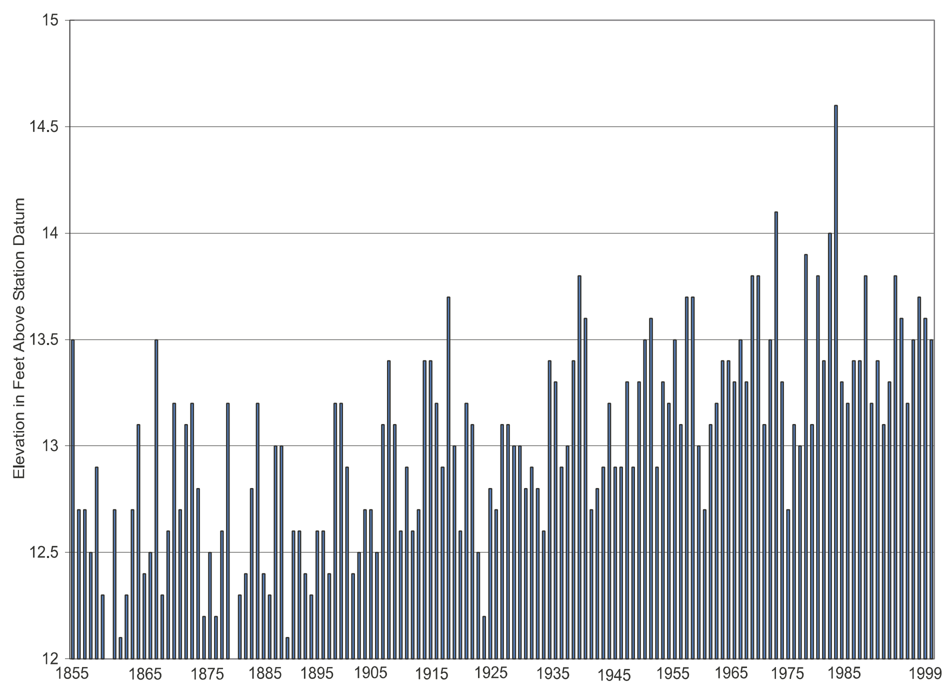


Figure 7. Observed Annual Highest Water Level at Golden Gate Between 1855 and 1999

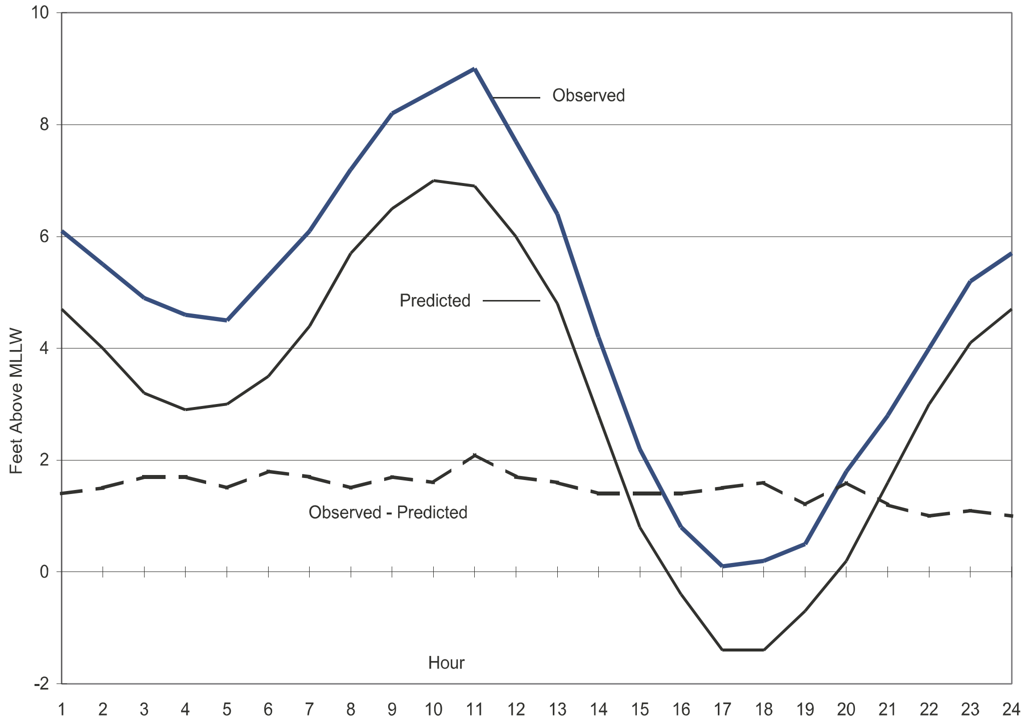


Figure 8A. Observed Highest Water, Predicted and Storm Surge January 27, 1983 at the Presidio

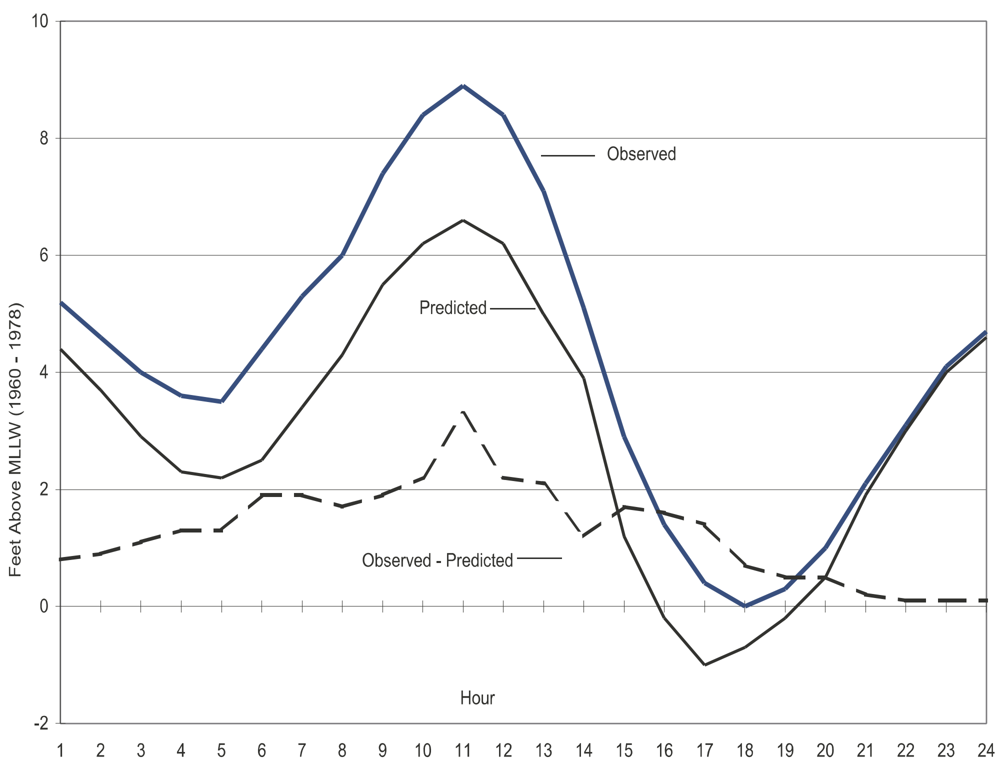


Figure 8B. Observed Highest Water Level, Predicted and Storm Surge for December 3, 1983 at the Presidio

The annual highest water levels for the Golden Gate have elevations between 6.7 and 8.9 feet above MLLW (1960 -1978). The storm surge associated with particular high water levels is of interest. For this report storm surge is defined as the difference between the observed and predicted water levels, both referenced to MLLW. For example, the storm surge for the January 27, 1983 storm event (observed - predicted) is just over 2.0 feet, and for the December 3, 1983 it is over 3.0 feet. The highest water level does necessarily imply the greatest storm surge value because the highest water level is the combination of storm surge with the astronomical tide.

B. Observed Lowest Water Levels

Extreme low water levels in the San Francisco Bay region are caused primarily by the combination of extreme tides to due particular earth-moon-sun alignments and the effects of large scale weather patterns. The lowest water level of record at the Golden Gate occurred on both December 26, 1932 and December 17, 1933. The time series of the hourly heights for both events are shown in Figures 10A and 10B. There are small differences of tenths of a foot in the annual lowest water levels from year to year with the range of annual lowest water levels being between 2.7 below to 1.0 feet below MLLW (1960-78). A value of 5.77 feet can be subtracted from the values of the annual lowest water levels shown in Figure 9 to refer the elevations to MLLW (1960 - 1978).

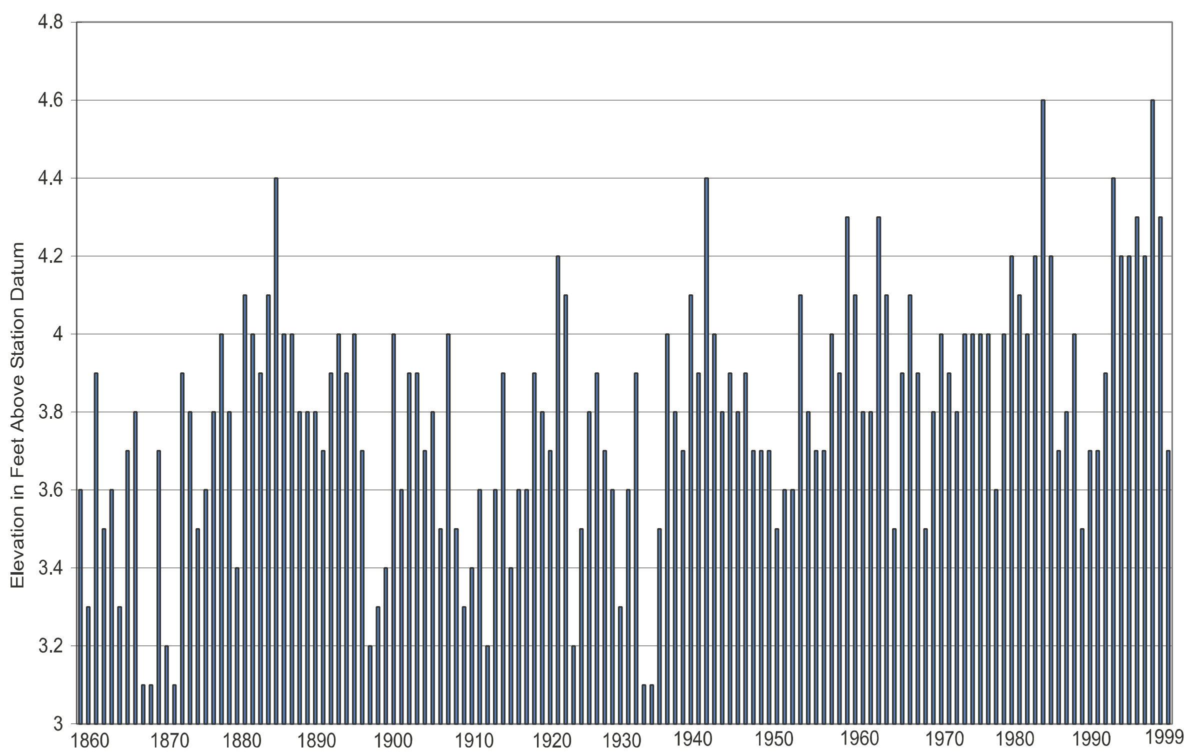


Figure 9. Observed Annual Lowest Water Levels at the Golden Gate
Between 1860 and 1999

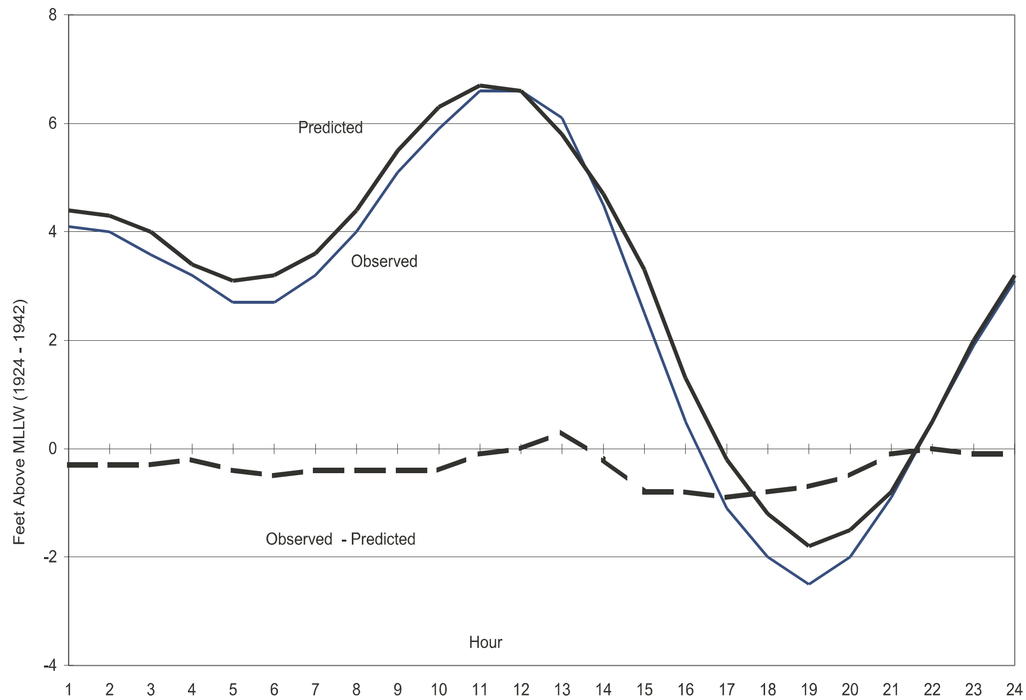


Figure 10A. Observed Lowest Water Level, Predicted and Storm Surge for December 17, 1933 at the Presidio

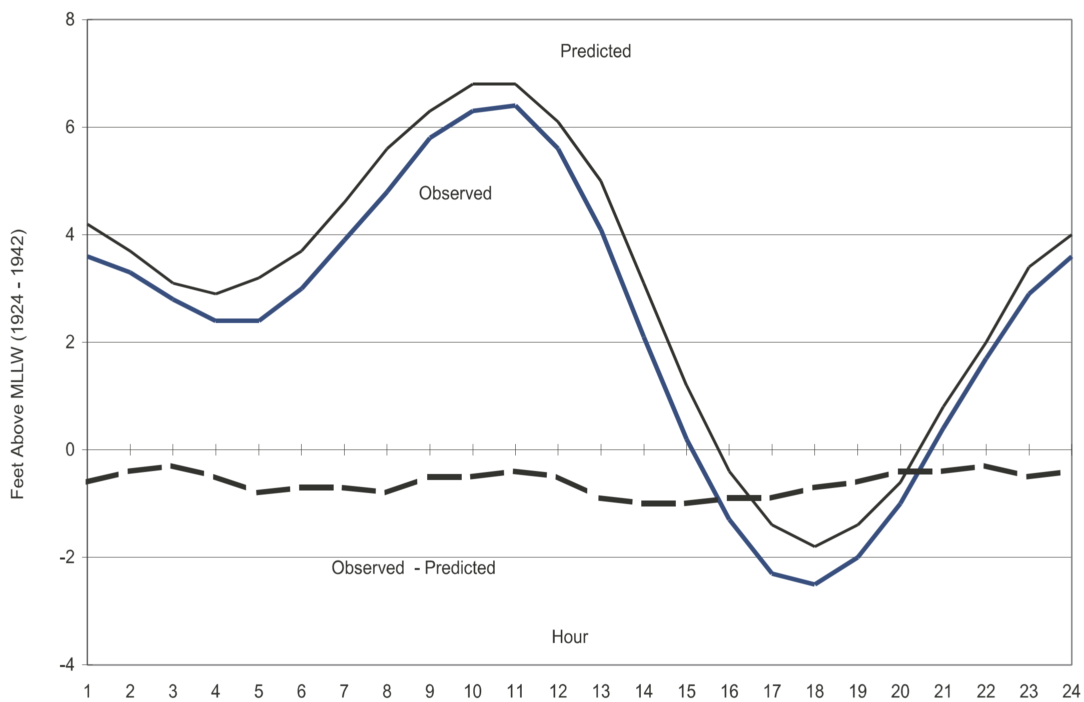


Figure 10B. Observed Lowest Water Level, Predicted and Storm Surge for December 26, 1932 at the Presidio

C. One Hundred Year Flood Level

The observed annual highest water levels of record between 1854 and 1994 at the Golden Gate have been tabulated and summarized . These observed values are not adjusted for the sea level change over the 140 year period and a separate analysis must be performed in order to use the information for some applications. Table 13 is a summarization of 100 year increments with the highest observed water level of record in that period identified.

Table 13. Highest Observed Water level in 100-Year Periods for the Golden Gate

100 Year Period	Date of Highest Water Level in 100 Year-Period	Highest Observed (Feet)
1855-1954	December 20, 1940	13.8
1865-1964	December 20, 1940	13.8
1875-1974	January 16, 1973 January 18, 1973	14.1 14.1
1885-1984	January 27, 1983 December 3, 1983	14.6 14.6
1895-1994	January 27, 1983 December 3, 1983	14.6 14.6

D. The Great January 1862 Floods

A good example of wide spread extreme flooding in the San Francisco Bay Estuary occurred in January 1862. Rains were heavy between November 1861 and January 1862 in the Delta region of Estuary such that Sacramento was under water along with most of the Central Valley. Reports from journals of the time state that for at least ten days "water flowed through the Golden Gate in a steady torrent, blocking tide reversal." Such a flood today would probably cause billions of dollars in damage in the region. The Golden Gate tide records between November 1861 and January 1862 have been reviewed for what influence such floods had on the water levels at that location. The rains were heaviest during January 1862. Figure 11 shows that water levels at the Golden Gate between January 22nd and 24th were influenced by the events. The observed low waters between January 22 and 24, 1862 were higher than normal (the predicted low waters). From the January 23 evening high water to the evening low water there was only a 0.3 foot change in the water level at the Golden Gate. Such occurrences are anomalous at the Golden Gate.

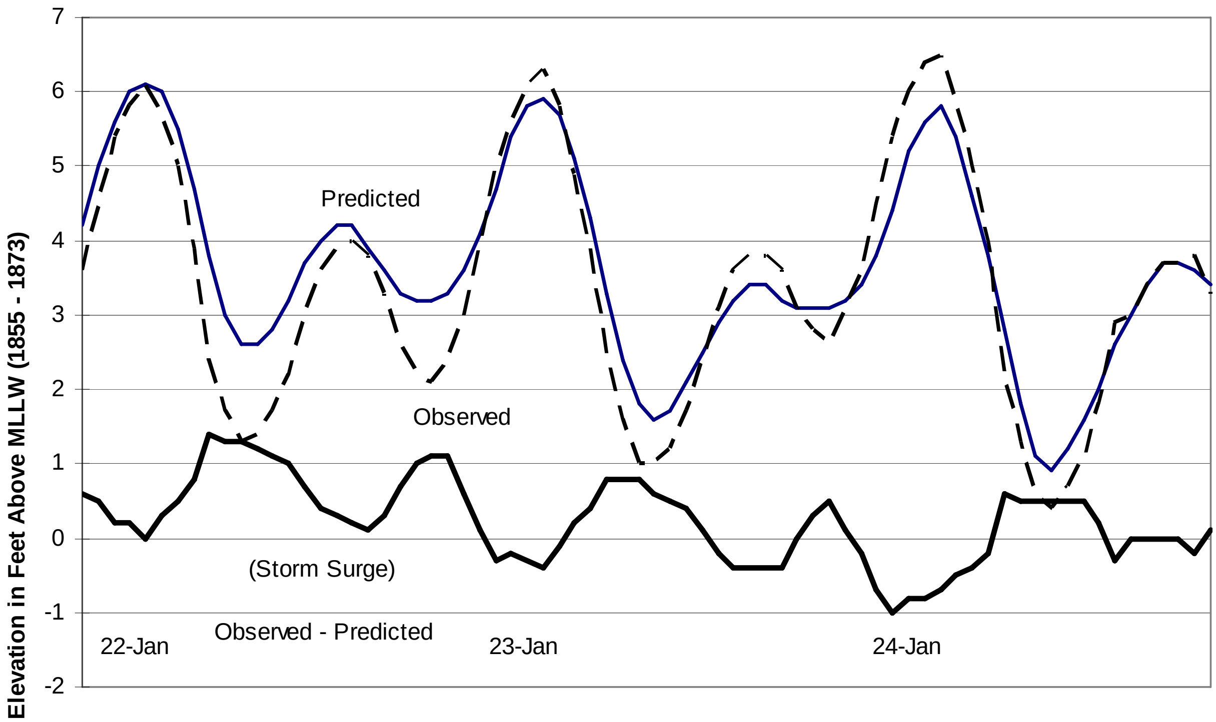


Figure 11. Observed, Predicted and Storm Surge for January 22 - 24, 1862 at Fort Point

Return Period

Earle (1979) defines return periods time intervals between the occurrence of extreme water levels. The return period, or recurrence interval, for a given elevation is the time interval between occurrences of an elevation greater than or equal to the given elevation. Heights of and intervals between storm surges, which add to the astronomical tide, occur in a random manner so that return periods are useful for extreme measured water elevations greater than normally occurring astronomical tides. The values can be obtained from a statistical analysis of extreme measured elevations greater than normally occurring astronomical tides.

Return period results are useful for design elevations for sea walls, levees and other structures along coastal and waterways where extreme high water levels frequent such shores. Universities, coastal engineer firms, U.S. Corps of Engineers and the Federal Emergency Management Administration (FEMA) are among those that have a need for such information where flooding is a concern.

Table 14 provides return periods for San Francisco from a 50 year period between 1920 and 1970 where there is a long history of extreme high water levels and concerns of flooding in the San Francisco Bay region. The 100 year estimate is lower than the maximum observed value (8.8 ft.) since the 1920– 1970 time period of the analysis.

Table 14. Return Periods for San Francisco (1920-1970)*

(50 Years of Record with Least Square Correlation Coefficient of 0.984)			
Return Periods (Years)	**Elevation Above MLLW Feet**	**Upper 90% Confidence Limits**	**Elevation Above MHHW Feet**
5	7.8	7.9	2.0
10	8.0	8.1	2.2
25	8.1	8.3	2.3
50	8.3	8.4	2.5
100	8.4	8.6	2.6

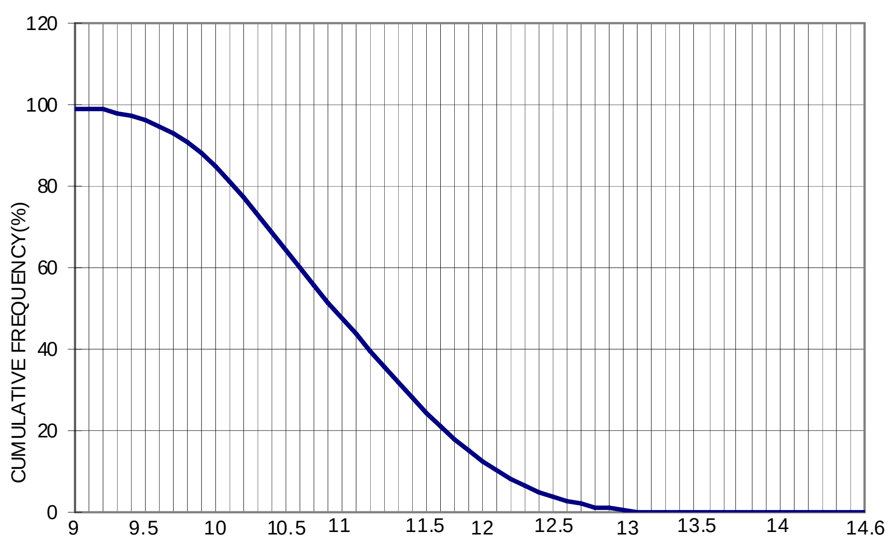
* The values were computed by from tabulated monthly highest water level elevations at San Francisco over the period 1920 - 1970 for select return periods using NOS tide data (Earle 1979)**.**

XI. FREQUENCY AND DURATION OF INUNDATION

Frequency and duration of inundation is a statistical analysis of historic records of water level values. The hourly heights are selected around the period of high water or low water as input to the analysis. The analysis includes the following:

1. Elevations above the station datum in feet at specified increments (e.g. tenths of a foot) over the range of water levels at a station.
2. Frequency of inundation is the number of times the water level has equaled of exceeded each incremental elevation for a period of the analysis.
3. Percent frequency of inundation is the number of inundations in step 2 above expressed as a percentage of the total number of inundations occurring in the period of the analysis.
4. Duration of inundation is the total hours at which the water level remained at or exceeded each incremental height for the period of the analysis.
5. Percent duration of inundation is the number of hours in step 4 expressed as a percentage of the total number of hours in the period of the analysis.

Figures 12A-12D includes plots of the cumulative duration vs. incremental heights and cumulative frequency (%) vs. incremental heights for both the high waters and low waters. The San Francisco data set for the years 1922-1984 have been used in the statistical analysis. The results of such a study are utilized frequently in engineering design of structures to control flooding in an area or biological studies related to frequency and duration of water levels at various heights to growth of particular species in tidal marsh areas.



12A. Frequency of Inundation for High Waters at the Presidio
Between 1922 and 1984

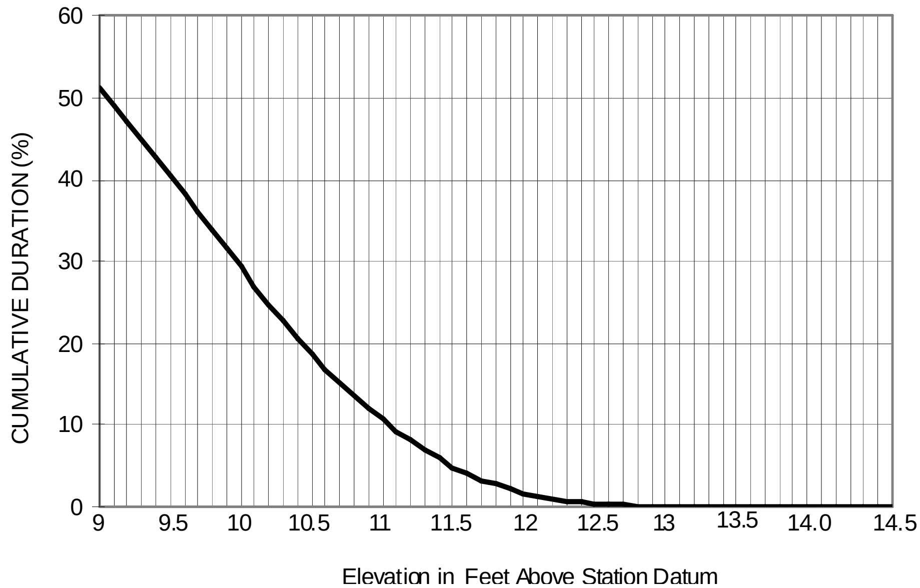


Figure 12B. Duration of Inundation for High Water at the Presidio Between 1922 and 1984

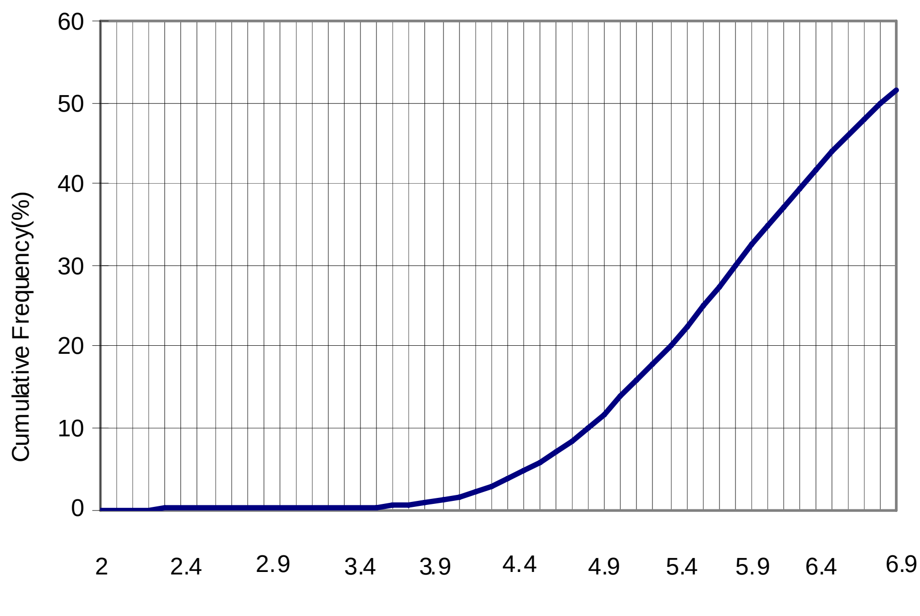


Figure 12C. Frequency of Inundation for low Waters at the Presidio Between 1922 and 1984

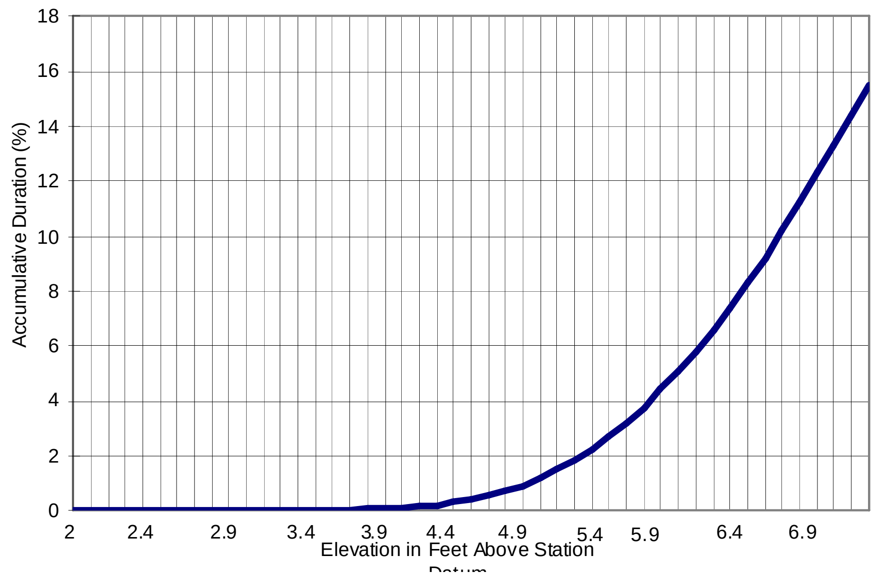


Figure 12D. Duration of Inundation for low Waters at the Presidio Between 1922 and 1984

XII. COMPARISON OF OBSERVED AND PREDICTED HIGH AND LOW WATERS

NOS tide predictions are based on the pre-knowledge of the motions of the earth-moon-sun system. Differences between predicted and observed tides are typically due to the effects of weather on the observed water levels. Table 8 of the NOS Tide Tables for the West Coast provides summary statistics of the accuracy of tide predictions for several west coast stations. For San Francisco, for instance, at the 90% distribution level, the times of the predicted high and low waters are within 0.3 hours and 0.4 hours respectively. The heights of the predicted high and low waters are within 0.4 foot and 0.6 foot respectively. Although there are variations in these observed - predicted differences occurring from year to year, a year of observed and predicted high waters and low waters has been chosen using the year 1981 at San Francisco to further analyze these differences. A frequency distribution of differences between observed and predicted water level heights, referred to MLLW, have been generated from the 1981 data set and the results are presented in Figures 13A and 13B.

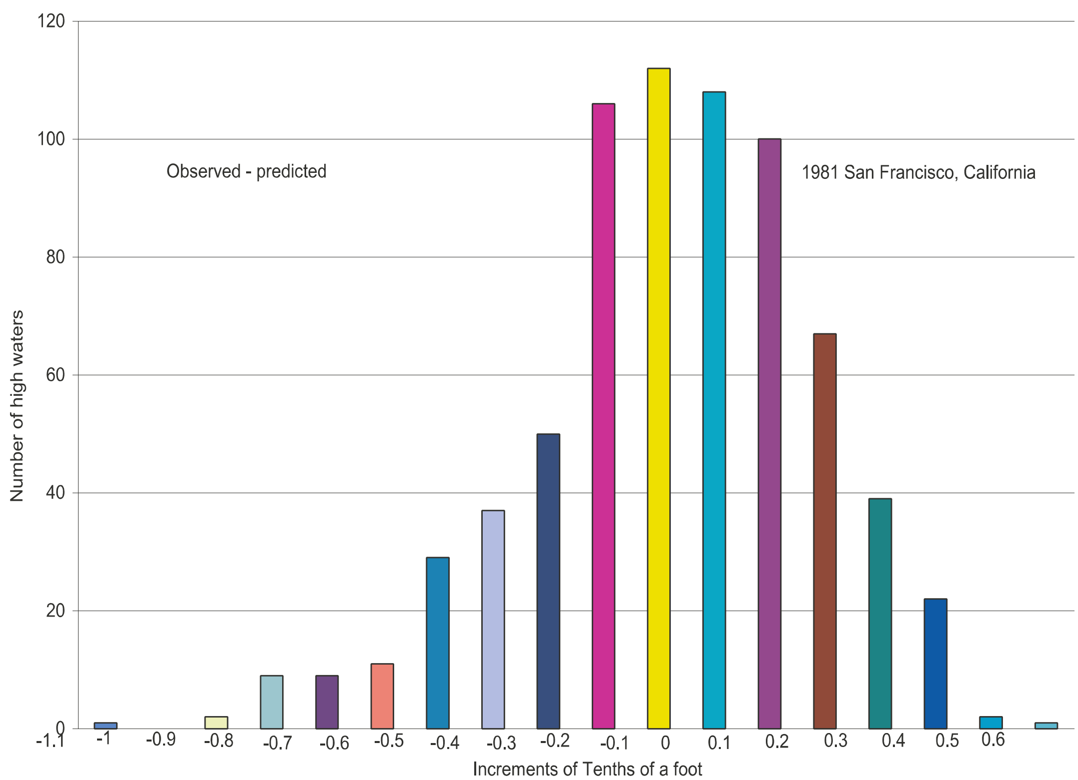


Figure 13A. Frequency Distribution of Differences for High Water Heights at the Presidio

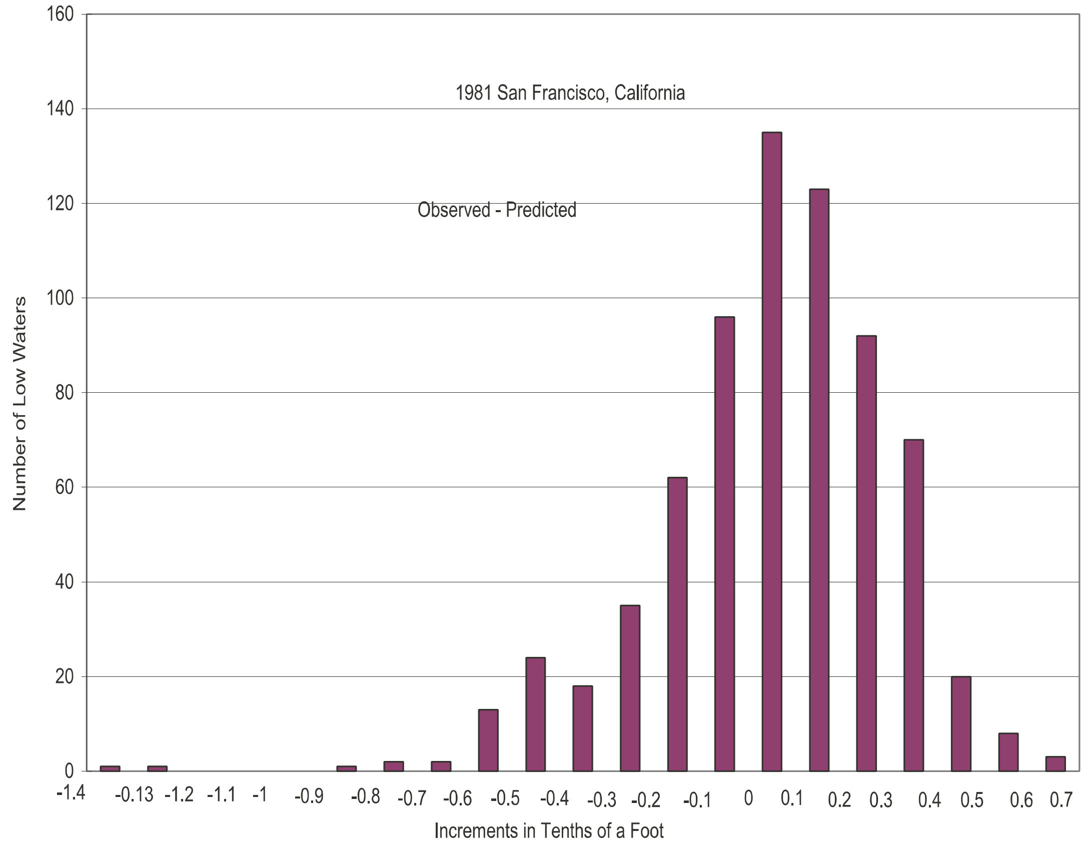


Figure 13B. Frequency Distribution of Differences for Low Water Heights at the Presidio

XIII. CONCLUDING REMARKS FOR THE GOLDEN GATE TIDAL SERIES

With the connection of the three historical data sets at Fort Point, Sausalito and Presidio to one long continuous tidal series it has been possible to tap a wealth of information previously unavailable. Sea level variations over a long continuous data set referred to a common datum for 140 period at one location can now be studied. Tidal datums have been reduced to mean values for any number of tidal epochs between 1855-1873 and 1976-1994. Datum recovery at Sausalito was completed, providing important assessment for one of the Golden Gate tide stations from two different tidal series separated by 100 years. Relative sea level rise determinations and land movements are now accurately measured through the long series at the Golden Gate.

ACKNOWLEDGMENTS

The tide data sets in this report represent the cumulative effort of the National Ocean Service; those who installed and maintained the tide gauges for recording tide measurements and those who analyzed the data, documented the results and summarized them in an accessible manner. Special recognition should to go to those who have made the long tidal series and related historical tide information possible for the Golden Gate tidal series over the many decades since 1854. I thank the members of the CO-OPS review committee for their patience, outstanding effort in the edits and recommendations they have made in this detailed report to help improve the appearance of this report and maintain the high standards of National Ocean Service publications.

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APPENDIX A

HISTORY OF TIDE GAUGES

Many types of tide gauges were proposed and constructed in the 19th century. The first self-registering tide gauge was used in 1831 by Henry Palmer of England. The earliest tide gauges in use are described below:

A. Parts of a Tide Gauge

The essential parts of a tide gauge are composed of a stilling well to dampen wave action; a time piece and some way of recording the height, either in a continuous manner or at discrete intervals of time.

B. Workings of a Tide Gauge

The motion of the float as it rises and falls with the tide is communicated along the recording portion of the gauge by means of a flexible cord which passes over a grooved wheel (float wheel). The motion is transferred, but on a reduced scale, through some mechanism depending upon the particular kind of gauge, to a pencil which traces a curve upon a moving sheet of paper. The paper is driven or carried along by means of a cylinder connected with a well-regulated clock. The pencil is free to move in a direction perpendicular to the line of the motion of the paper.

C. First Coast Survey Tide Gauge

Joseph Saxton, of the Office of United States Weights and Measures, constructed the first self-registering tide gauge in the United States used by the Coast Survey. There were two principal movements provided for in Saxton's gauge. The first being a uniform movement, proportional to time, of the record sheet under the pencil, and the second being a transverse movement of the pencil, strictly proportional to its rise and fall of the float. To give a uniform motion to the sheet of paper, a clock-work was used. The moving parts of the old-fashioned eight-day clock, with the striking parts taken out, were employed for this purpose. The clock-work gives a uniform motion of rotation to the cylindrical roller that revolves 360 degrees once in twelve hours. The second principal movement in the gauge originates in the vertical movement of the float, and extends to the recording pencil. The float was an air-tight cylinder or canister-shaped copper box, which was first thoroughly painted for protection. A small ballasting weight was attached to the center of its bottom. On its top was an eye, in which was fastened the end of a wire leading up through the float box. This box was a water-tight wooden case, large enough to permit a free play of the float, and terminating at the bottom in a funnel, with an orifice at its apex, through which the water could pass as rapidly as necessary, but not so as freely as to make the float oscillate sensibly with the surface waves. Figure A-1 is a diagram of the type of tide gauge installed at Fort Point in 1854. Additional workings of the tide gauge may be obtained from the 1853 and 1876 Superintendent Report of the Coast Survey.

D. Other Tide Gauges Used by NOS

After the tide staff or tide pole, that required an observer to physically be there and record changes in the water level, and the first self-registering tide gauge there have been many innovations in tide gauge technology. These include:

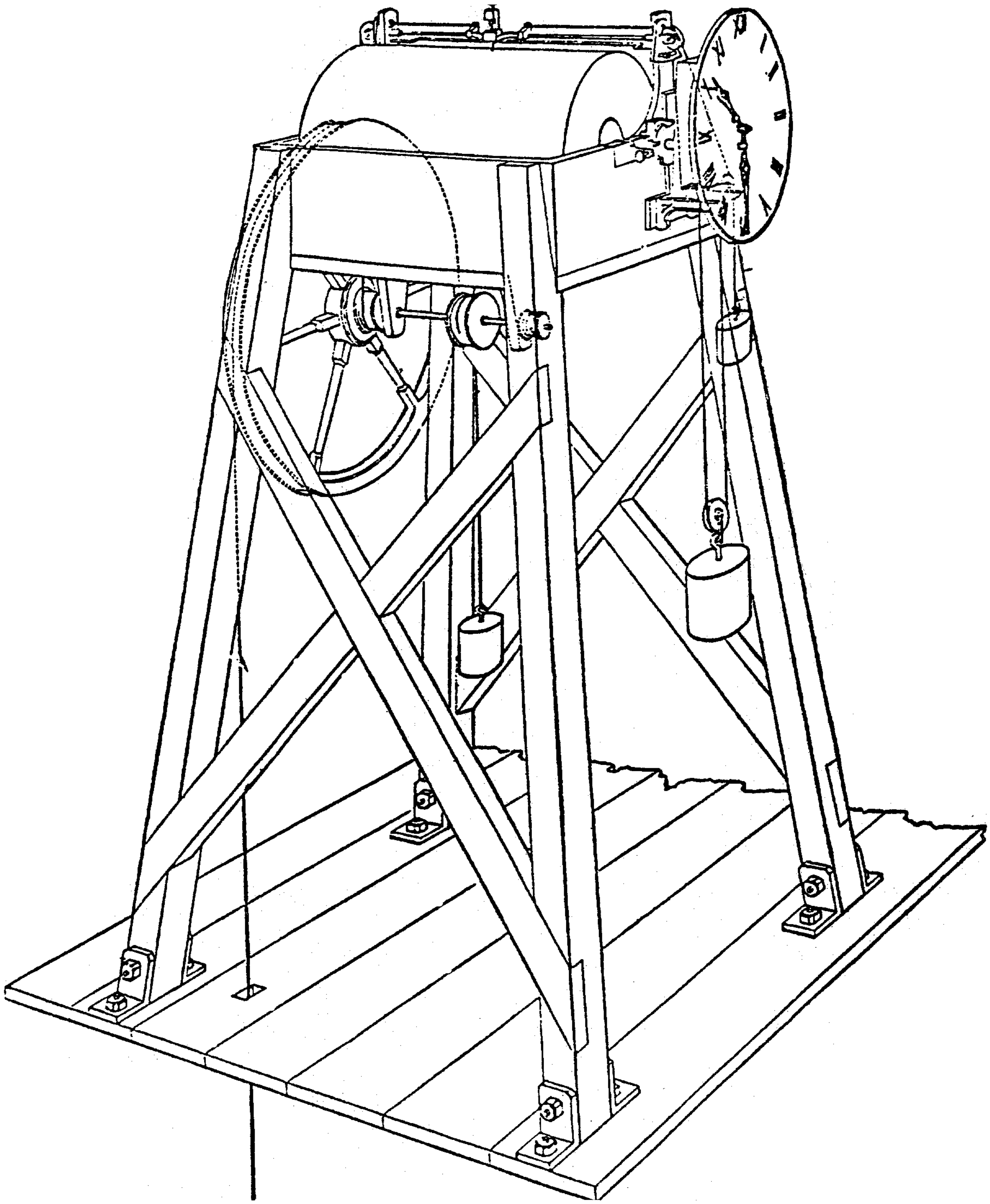

Figure A-1. First Self-Registering Tide Gauge Installed at Fort Point in 1854

1. *Standard Tide Gauge*
The standard automatic tide gauge first appeared in the marine environment in the 1890s with many improvements over the years until it was replaced with a completely new gauge, the analod digital recorder, in the 1960s. By the 1970s, all standard tide gauges operations ceased to be used by NOS. The product of its recordings was a marigram trace of the tide curve. The workings of the standard tide gauge may be found in NOS Publication 30-1 Manual of Tide Observations.

2. *Gas-Purging Pressure Tide Gauge (Bubbler Gauge)*
This tide gauge has made it possible to obtain satisfactory records in areas where the installation of the structure-supported tide gauge was impractical. The compact size and relative ease of installation and operation has lead to its use for reconnaissance surveys for tidal datum purposes. This tide gauge was pioneered at Woods Hole Oceanographic Institution by Alfred Redfield. It was first used by NOS in the 1960s for use at subordinate stations which is a tide station from which a relatively short series of observations is reduced by comparison with simultaneous observations from a tide station with a relatively long series of observations. The bubbler has been used as a back-up tide gauge at control stations starting in the 1970s for use in filling breaks in ADR data records. The workings of the gauge may be found in the NOS publication, "User's Guide for Gas-Purged Pressure Recording (Bubbler) Tide Gauge."

3. *Analog Digital Recorder (ADR)*
This tide gauge was first used in the 1960s and finally replaced the standard tide gauge completely in the 1970s. It is a float actuated tide gauge that records the heights at regular intervals replaced (6 minutes) on a digital punch tape. The internal workings of the gauge can be found in NOS publication, "Special Publication 30-1 Manual of Tide Observations." Figure A-2 is a diagram of the tide gauge setup for the Standard/ADR and bubbler.

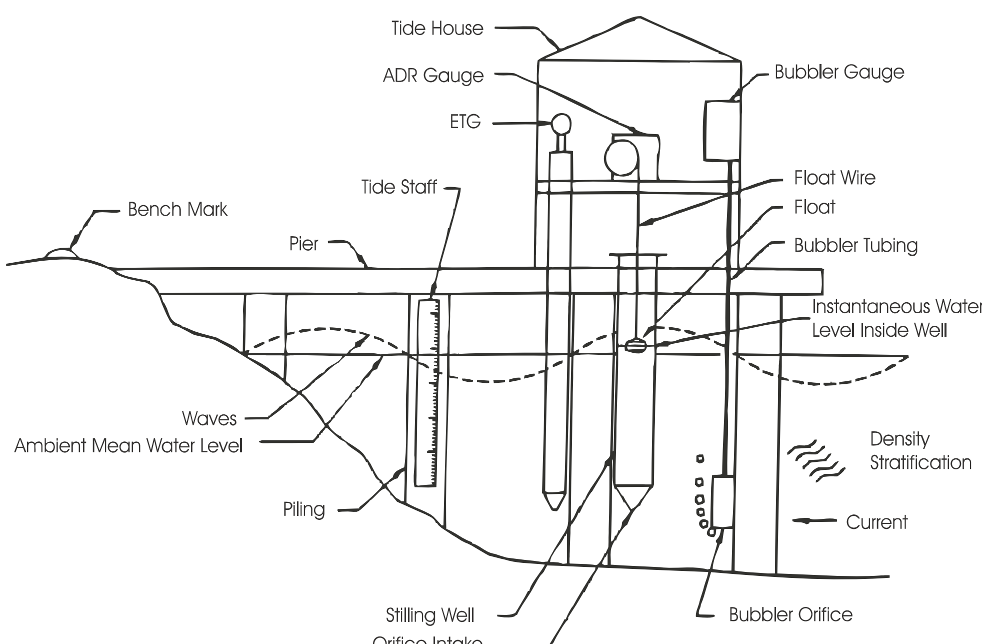

Figure A-2. ADR and Bubbler Gauges Systems in Operation at the Presidio starting in the 1970s

4. ***Next Generation Water Level Measurement System (NGWLMS)***

The Next Generation Water Level Measurement System began to be implemented into operations in the National Water level Observation Network (NWLON) in the late 1980's and ending with complete implementation at Great Lakes stations in 2000. At most locations, the NGWLMS was operated simultaneously present ADR tide gauge system during a transition period, after which the ADR was removed.

The NGWLMS uses state-of-the-art technology that includes self-calibrating downward-looking acoustic water level sensors, back-up pressure sensors, micro-processor based data acquisition and storage, telemetry to the GOES satellite with a telephone as back-up and the capability of automated collection of up to 11 ancillary measurements (meteorological data, for instance).

The NGWLMS acoustic sensor does not have the physical contact of a device with the water surface, such as the float with the ADR, and the NGWLMS does require a full mechanical filter known as the stilling well. A large source of systematic error and uncertainty in the older float operated systems that used stilling wells is being eliminated or reduced using the NGWLMS. The stilling well is replaced by a more open protective well, much less subject to nonlinear filtering effects and biofouling, less conducive to density gradient buildups, and more indicative of the outside environment. The rapid sampling (1 - second pulses) possible with the acoustic sensor of the NGWLMS allows the well to be open to the dynamics of the ocean. High frequency waves are removed by digital filtering (by the microprocessor that is part of the water level measurement system), rather than analog filtering through an orifice in the ADR system.

A significant improvement with the NGWLMS is that leveling from the bench marks can be done directly to the sensor itself (the head of the transducer at the end of the sound tube). The sensor can also be replaced and re-calibrated. The elimination of the tide observer with the replacement of the ADR with the NGWLMS does away with the systematic errors of observations read from a staff and adjustments to the ADR gauge itself. The NGWLMS does not require simultaneous observations from a tide staff and tide gauge to compute the average monthly difference between the tide staff and marigram zero in the process of referring the water level heights to the station datum. The possibility of timer drift is also eliminated with the replacement of the ADR with the NGWLMS.

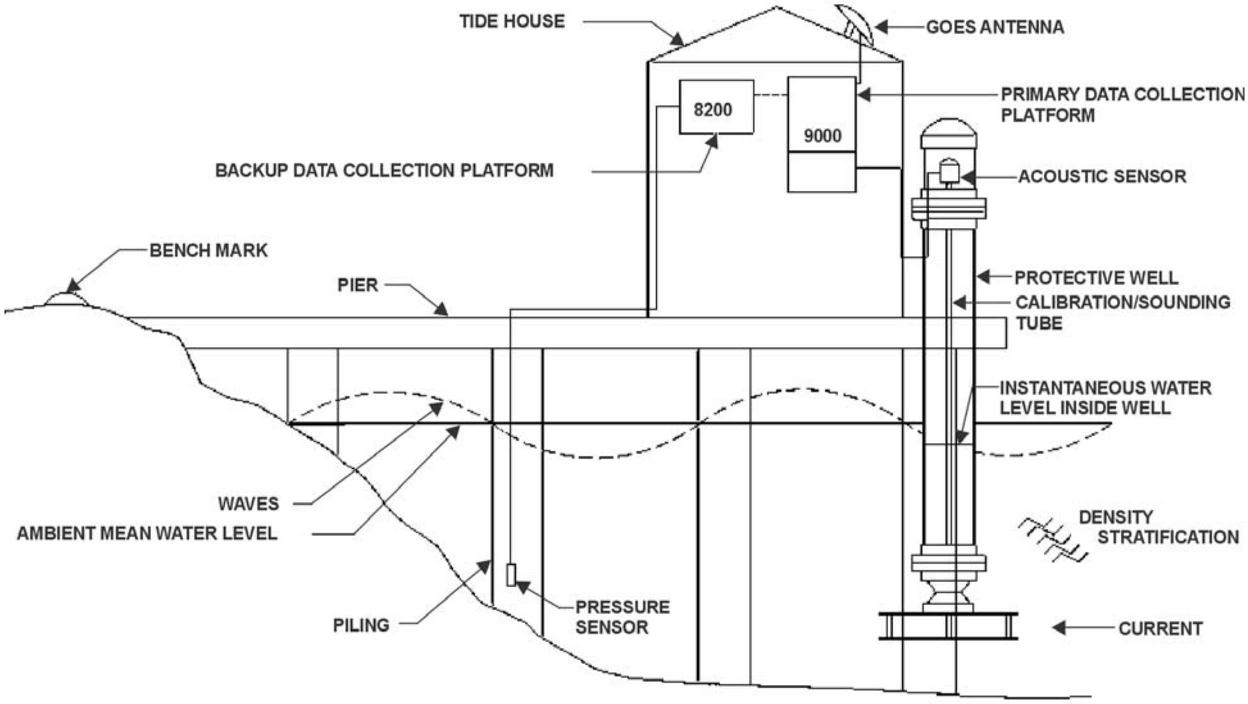

Figure A-3. NGWLMS Installed at the Presidio in the Late 1980s at the Presidio

APPENDIX B

LEVELING TECHNIQUES

A. Methods of Leveling

The method of leveling adopted was known as "leveling from the middle" or more properly defined, that of equidistant backsights and foresights. The manner of taking the sights was to bring the target of the rod nearly into the horizon of the telescope, and to measure with the micrometer the vertical angle between the horizon and the target by repeated pointings, so as to eliminate errors of level and collimation. The target reading on the rod was then reduced to the horizon by computation. With this method, two systems had been in use:

1. Simultaneous Double Leveling in One Direction

   By this method the difference in height between two bench marks was determined by observing from the same station and with the same instrument, backsights on two different rods, set up at unequal distances from the instrument, and foresights on the same two rods, carried forward and placed at the same relative distance previously occupied.

2. Leveling in Opposite Directions

   This procedure consisted of running a line between two bench marks in one direction, and releveling it according to the same method in the opposite direction.

3. Comparison of the Two Systems

   a. System 1 offers the advantage of a considerable savings in time over system 2, and affords a perfect check against errors of observations from station to station, since the difference in height between two rods, obtained in a foresight should be equal to the difference in the following backsights.

   b. System 2, on the other hand, offered the advantage of making the determination in opposite directions under different conditions, and exhibiting with greater certainty the existence of any cumulative error.

B. Water Crossing

When a line of levels was to be carried across a wide body of water, and, where, from the lowness of the banks, the line of sight would pass very near the water, the instrument was elevated so as to be above the vitiating influence of irregular refraction. If possible, two instruments would be mounted on opposite sides of the waterway, and simultaneous observations would be made on targets mounted near the respective instruments.

The elevation of each target above a bench mark on its side of the waterway must be carefully determined and each target and instrument should be as nearby as possible in the horizon of the other.
The observations were made in the usual manner, if the distance across the waterway is not otherwise known with sufficient accuracy. The known value of micrometer would serve to determine it sufficiently for the purpose of reduction, by measuring across the waterway the length of rod or other known length in terms of the micrometer.

If only one instrument was available, observations made in one direction would be repeated as soon as possible in the other direction and several times alternately in opposite directions. With observations in opposite directions, effects of refraction were minimized. Present leveling procedures are available in many NOS manuals such as the Manual of Tide Observations Special Publication 30-1 and NOAA publication "User's Guide for the Installation of Bench Marks and Leveling Requirements for Water Level Stations."

Appendix C

Comparative Readings and Adjustments to Tidal Heights at Fort Point Between 1855 and 1859

A. Comparative Readings

Comparative readings (Table A) were made by tide observers hired to take readings of the water level from the tide gauge and tide staff simultaneously. Both readings were written on the marigram. The monthly means of the differences between the staff and gauge reading were computed and applied to the tidal heights tabulated from the marigram to refer the tidal heights to tide staff zero. Readings in the 1850s at Fort Point were made 3 times a day and daily averages computed. Attempts were made to hold comparative reading results relatively consistent over long periods of time.

Table A. Comparative Readings Between 1854 and 1862 at Fort Point

Period of Time	**Average Staff - Marigram Difference***(ft)	
1854	June 30 - 1856 June 2	+ 1.50
1856	June 2 - 1857 June 16	+ 1.80
1857	June 17 - October 20	+ 3.00
1857	October 21 - 1858 February 16	+ 3.55
1858	April 5 - November 30*	+ 2.75
1858	December 1 - 1859 January 19	+ 2.10
1859	January 20 - July 31	+ 2.00
1859	August 1 - November 24	+ 0.90
1859	December 1 - 1860 June 18	+ 1.80
1860	June 18 - 20	+ 0.30
1860	June 21 - 1861 December 9	1.85
1861	December 10 - 31	+ 2.05
1862	January 1 - June 12	+ 2.00
1862	June 13 - 1868 December 31	+ 2.10

*The change in the staff minus marigram differences between 1854 and 1959 are attributed to:

1. The wharf and staff settling at Fort Point.
2. New staff on April 2, 1858 with 2.4 feet movement of staff between June 30, 1854 and April 2, 1858 and 0.78 foot settlement between April 2, 1858 and June 21, 1859.

B. Adjustments to Fort Point Elevation

Table B. Adjustments to Fort Point Tidal Series Between 1855 and 1859 to Account for Wharf Sinking

Period of Record	**Adjustments (Feet)**
June 1, 1855 - Jan 31, 1857	- 0.7
Feb 1, 1857 - Feb 28, 1857	- 0.8
March 1, 1857 - March 31, 1857	- 1.0
April 1, 1857 - April 30, 1857	- 1.5
May 1, 1857 - May 31, 1857	- 1.8
June 1 , 1857 - Jan 31, 1858	- 2.2
Feb 1, 1858 - Feb 28, 1858	-2.5
March 1, 1858 - March 31, 1858	- 3.0
January 1859	- 0.1
February 1859	- 0.2
March 1859	- 0.3
April 1859	- 0.4
May 1859	- 0.5
June 1859	- 0.6
July 1859	- 0.7

There is a history of leveling between 1855 and 1859 that shows the amount of movement of the staff/wharf. This leveling history appears in Table 1. Table A in Appendix C is a summarization of the average staff - marigram differences between 1854 and 1859. These two NOS historical record files along with the tide data from records for 1860 - 1874 - 1859 were used to develop the adjustment that appears in Table B above. In this way a reduction of the data from 1854 through 1859 was adjusted to a uniform level with the reliable data series 1860 through 1874. The period 1854 - 1859 was then added to the tidal series 1860 through the present, referred to a common datum zero. Figure C - 1 shows the uncorrected and corrected values of MLLW elevations at Fort Point between 1854 and 1859.

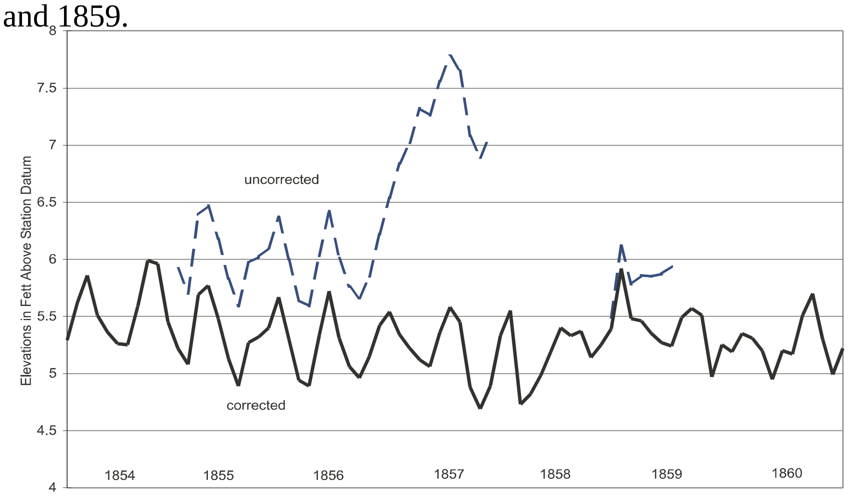

Figure C-1. Monthly Means of MLLW Elevations at Fort Point corrected for the Wharf sinking Between 1855 and 1859

It is believed that the pier settled because it was resting on a peat foundation. The shore in the region was comprised of marsh and peat bogs which were common in the area. According to NOS historical files of the description of the locality, “The peat structure near the Fort Point pier was covered in 1859 by gravel and pebbles to give the appearance of greater stability.” The question that comes to mind also is how piers were constructed in the 1850s. Letters from the National Archives state that the Fort Point wharf was “constructed on piers of a crib filled with stone.” On one of these piers the self-registering gauge was placed. In Webster’s unabridged dictionary a crib is described as the following: “ In the engineering sense, a crib is a frame of logs or beams to be filled with stones, rubble or the like and sunk as a foundation or retaining wall in the building of docks, piers, dams, etc.” This is consistent with literature describing the construction of docks and piers in the text, “The Construction of Harbors’ by Thomas Stevenson and published by the U.S. Coast and Geodetic Survey in 1886.

Marine organisms contributed to the decay of the timbers forming the cribs. This resulted in the shifting of the timbers as they weakened from the decay. In time, the stones within the confines of the timbers also started to shift. The Fort Point wharf being in a high wave and current energy area also contributed in the wharf sinking.

Appendix D

Water Leveling Crossings of the Golden Gate

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A water leveling crossing was made across the Golden Gate in 1877 from Fort Point to Sausalito to establish a relationship between the 1877 tide staff zero at Fort Point with the 1877 tide staff zero at Sausalito. Another crossing was made in 1906 - 1907 after the "1906 San Francisco Earthquake" to determine if there had been any vertical movement on either side of the Golden gate and vicinity. The level runs are show in Tables A and B for these crossings.

A. Level Crossing of the Golden Gate in 1877

Table A. Level Crossing of the Golden Gate in 1877

Level Between Marks	**Differences in Elevations**	**Elevation Above Tide Staff Zero (Feet)**
Fort Point Staff		20.000
A-I	-5.506	14.494
I - II	5.170	19.664
II-III	37.460	57.124
II- IV	1.807	21.471
IV-Target 1	5.153	26.624
Target 1-Target 2	0.586	27.210
Target 2 - V	-1.266	25.944
V - VI	-4.546	21.398
VI - VII	70.465	91.863
VII - VIII	26.296	118.159
VIII -IX	-39.803	78.356
IX- Stone at Sausalito	-31.797	46.559
Stone- X stake	-20.461	26.098
X - 22 Ft Mark	-3.634	22.464

22.464 - 20.000 = 0.464 feet difference in zero of the two staffs in 1877

B. Spirit Level Between the Tide Staff Zero at Fort Point with the Tide Staff Zero at Sausalito in 1877

On most of the spirit levels there were two rods, the Boston rod and the Davidson tod, used together. The two rods were read on the same bench mark by each instruction. As these two readings were taken without a resetting of the instrument, each reading was given a weight of 2/3 of the weight of the independent measure in the computation.

The section of the line from Fort Point to bench mark IV on the extreme north shore of Fort Point was re-leveled about eight times. The several results of differences in level between the bench mark were tabulated with weights in accordance with the remarks above.

C. Level Crossing of the Golden Gate in 1906 - 1907 Between the Presidio and Sausalito

Table B. Level Crossing of the Golden Gate from Sausalito to San Francisco in 1906 - 1907 after the 1906 San Francisco Earthquake

Bench Mark	Elevation Above MSL In Feet		Elevation Above Presidio Tide Staff Zero
2	4.4255	Sausalito	13.0774
4	1.0712		9.7231
3	37.9438		46.5957
5	31.0521		39.7040
6	31.0554		39.7073
7	87.0166		95.6685
8	121.9171		130.5690
9	108.5557		117.2075
10	102.5792		111.2311
11	15.3983	Lime Point	24.0502
12	15.1371		23.7890
13	9.4501		18.1020
14	9.8281		18.4800
15	17.6384		26.2903
16	25.4842		34.1361
17	28.5252		37.1771
64	28.2083	Near Fort	36.8602
65	140.4718		149.1237
66	161.1135		169.7654
9	199.2532		207.9051
6	12.7477		21.4000
62	9.0334		17.6853
4	22.0357		30.6876
63	82.4801		91.3120
5	48.4048		57.0567
67	7.7178		16.3697
68	8.2654		16.9173
69	8.6138		17.2657
70	9.3451		17.9970
71	16.5685		25.2204
72	11.2208		19.8727
15	8.8602		17.5121
Staff	- 8.6519	Presidio	00.0000