150 YEARS OF TIDES ON THE WESTERN COAST:

THE LONGEST SERIES OF TIDAL OBSERVATIONS IN THE AMERICAS

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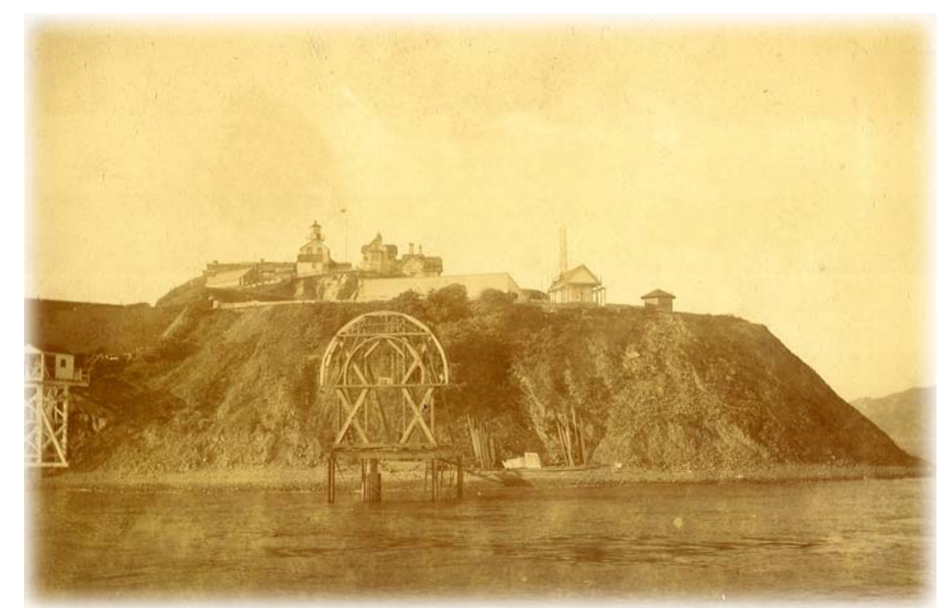
Abstract

The same year as the acquisition of California by the United States Government, the United States Coast Survey had been authorized to begin surveying the coast of Oregon Territory from the northern border of Alta California to the Puget Sound area of Washington Territory. Discovery of gold in 1848 and the subsequent gold rush added urgency to the requirement to chart our western coast including California. Small crews of Coast Surveyors headed west, either around Cape Horn or to Chagres, Panama, thence overland to Panama City, and then by ship to California. Accurate astronomic latitudes and longitudes of prominent points and landmarks on the Coast were first determined, magnetic declinations at these points observed, thence topographic surveys of critical areas including suggested locations for lighthouses were conducted, and finally reconnaissance hydrographic surveys based primarily on astronomic positioning and dead reckoning were run. Once this critical first work was accomplished, local triangulation schemes tied into the established astronomic positions were observed, and then topographic and offshore hydrographic surveys controlled by the triangulation were conducted. After years of work, an arc of triangulation parallel to the coast tied together all of the local triangulation networks and a coherent set of charts of our western seaboard based on a common geodetic datum were produced. In the early years, a final step prior to conducting hydrographic surveys was the installation of a tide staff in the local area of a survey so as to be able to determine the stage of tide during the time of survey work and relate the observed soundings to an arbitrary zero point. This arbitrary zero point could be the mean tide level, mean high water, mean low water, or, as in the case of the western shores of North America, mean lower low water. As technology improved with the development of self-recording instruments and a network of permanent gauges was installed, many serendipitous geophysical and oceanographic discoveries were made over and above the primary mission of providing safe passage for mariners. Remarkably, the self-recording gauge installed at Fort Point at the entrance to the Golden Gate and its successors have subsequently survived storms, earthquakes, the potential for human error and intervention, and produced the longest running series of tidal observations in the Americas. Since the early surveys, the study of tides has matured and accurate long-term tide predictions have been developed and coupled with real time water-level and meteorological observations to guide the shipping of America into its ports.

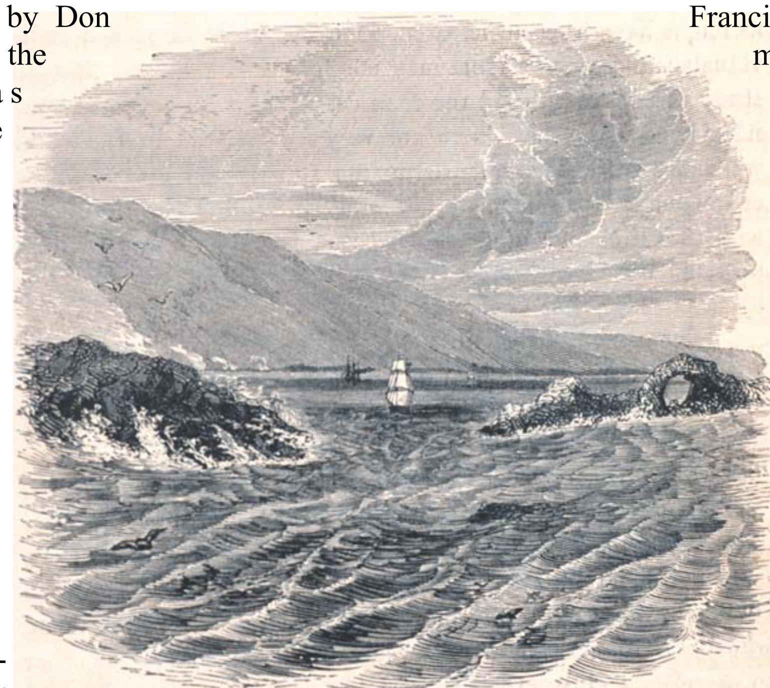
150 Years of Tides



Construction of an early visual Tide Elevation Recorder at Alcatraz Island

The Colonial Period

For two hundred years Spanish mariners had been skirting the coast of California on the return leg of the Mexico-to-Manila trade route but had always stayed well offshore from the rock-bound coast of California. However by the late 1700's other colonial powers had begun casting lustful eyes upon the western coast of North America. In response, in 1769 the Spanish sent out an overland expedition to establish a series of missions along the coast of Alta California both to convert the native Americans and to consolidate their claim to this territory . Led by Don Gaspar de Portola, the expedition was searching for the harbor described by earlier explorers at Monterey. Not recognizing the bay or any harbor when passing through the area (in fact there is not much of a natural harbor at Monterey), the expedition continued to the north, crossed over the coast ranges and camped near present-day Palo Alto in late October, 1769. Portola sent out a group of scouts to investigate the surrounding area. On November 3, 1769, Sergeant Jose Francisco Maria de Ortega returned to camp after a three day-excursion to report that he had discovered a great estuary and ridden up its east side for quite a distance before turning back.


Entrance to the Golden Gate

Ironically, this great estuary, since named San Francisco Bay, had been discovered by a sergeant in the Spanish colonial army. However, it was another five years before the entrance to the bay would be viewed from the site of the present city of San Francisco and another year before a first European ship would sail through its entrance. This first ship, the *San Carlos* which was commanded by Frigate-Lieutenant don Juan Manuel de Ayala, entered the bay on August 5th, 1775. Carrying full sail with a stiff WNW wind blowing from astern, his little ship strained to stem the current of an ebb-tide flowing out of the narrow entrance. Ayala estimated the current at 6 knots (perhaps an exaggeration but three knot currents are common), the first inkling of the nature of the tides and tidal currents in San Francisco Bay. Over the next month and a half, an initial survey of San Francisco Bay was produced. Although few observations of range of tide were made, there were numerous comments concerning tidal currents.

The following year Captain Juan Bautista de Anza led an expedition to the San Francisco Peninsula for the purpose of choosing the site of a mission and a fort. The site chosen for the fort, or presidio, was just to the east of a point that he named Cantil Blanco. The site for a mission was also selected and a first mass celebrated by Fathers Palou and Cambron on June 29, 1776, marking the founding of both the mission and the city of San Francisco. The birth of the city pre-dates the birth of our Nation by 5 days.

The Spanish charts of this era were inaccurate and it was not until the winter of 1826-27 that the English surveyor Captain Frederick Beechey arrived in San Francisco and produced the first accurate chart of the bay. It was he who designated the prominent point, earlier named Cantil Blanco, on the south side of the entrance Fort Point.

Over the next twenty years United States interest in this area grew. Exploring expeditions came overland; American maritime traders headed around Cape Horn and traded for cattle hides and sea otter furs. Some stayed to increase the American presence in the region. Ironically, the gateway to the San Francisco Bay was baptized *Chrysopylae*, or "Golden Gate" by overland explorer John Charles Fremont in 1846 because he felt the wide entrance to the Bay would be advantageous for commerce. "To this gate I gave the name of Chrysopylae, or GOLDEN GATE; for the same reasons that the harbor of Byzantium (Constantinople afterwards) was called Chrysoceras or GOLDEN HORN." This same year Commodore

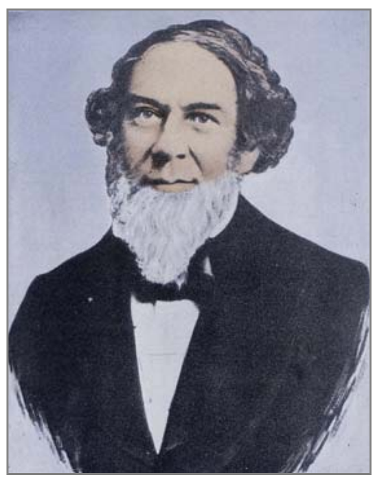

Early surveying along the Pacific Coast

Robert F. Stockton took possession of Upper California for the United States on July 7 and in 1848 the Treaty of Guadalupe-Hidalgo was signed ceding California and much of the American Southwest to the United States.

Prior to signing of this treaty, a world-changing event occurred on January 24, 1848, at Sutter's Mill in northern California. James Marshall discovered gold. With the announcement by President James Polk on December 5, 1848, to Congress that, "Recent discoveries render it probable that these mines are more extensive and valuable than was anticipated," the rush was on. The Golden Gate became the port of entry for thousands of miners headed to the gold fields and, virtually overnight, San Francisco became a metropolis. Clipper ship captains headed to California with children's school atlases or copies of old maps produced by Spanish explorers, George Vancouver, Charles Wilkes of the United States Exploring Expedition, or those of a few other mariners and surveyors who had given the coast a cursory reconnaissance years before. The best of these charts were generally inaccurate with prominent points being in error by as much as fifteen miles and virtually no depths recorded outside of major harbors. Although the channel islands were known, the orientation and location of virtually all of the islands were either significantly in error or not even shown on the various explorers' charts.

Early Coast Survey Work on the Western Coast

Because of immigration to the Oregon country, the Coast Survey had been making plans to survey the coast of Oregon Territory as early as 1846. In 1848, Congress authorized this work and the Coast Survey sent its first crews to the West Coast in 1849. Unfortunately, the gold rush was on; labor, transportation, and costs of supplies skyrocketed with an accompanying stoppage of field operations. One crew, under Assistant James Williams, was sent for the land operations and another, under Lieutenant William P. McArthur, USN, for the offshore hydrographic surveying operations. The Coast Survey Schooner EWING arrived in San Francisco after fighting its way around Cape Horn after a seven-month trip on August 1, 1849. The EWING was a topsail schooner 91 feet in length. For a variety of reasons including desertions and a mutiny, the EWING also was stymied in 1849 and retired with the land crew to the Hawaiian Islands for the winter of 1849-50 to obtain new crew members and to resupply at cheaper rates.



ALEXANDER DALLAS BACHE
The second Director of the Coast Survey

Because of the above frustrations, Alexander Dallas Bache, Superintendent of the Coast Survey, decided that a crew of young energetic men with "reputation to make" and a desire to overcome all hardships should be sent to the West Coast in 1850. This group of four men was led by George Davidson, who would become the leader of the West Coast scientific community over the next half century. James Lawson, A. M. Harrison, and John Rockwell comprised the remainder. Davidson, Lawson, and Rockwell sailed from the East Coast on May 5 on the steamer PHILADELPHIA for Panama. They landed at Chagres, hired native Indians for traveling by canoe to the head of the Chagres River, and then joined a mule train to go the rest of the way to the city of Panama. On May 30 they embarked on the Pacific Mail Steamship TENNESSEE and arrived in San Francisco on June 20. After a few weeks spent establishing a base of operations, they proceeded to Point Conception, landing at El Coxo in mid-July.

In Lawson's words, "Pt. Conception is one of the most notable points on the California coast, and its accurate position was particularly desirable, as it marked, in fact is the key to, the Northern entrance to the Santa Barbara Channel." Harrison, the chief topographer of this group, joined them during the Point Conception work. By the end of September an accurate latitude and longitude of Point Conception had been obtained by precise astronomic means, its magnetic declination determined, a site for a lighthouse selected, and a topographic survey of the area about the selected location conducted. The labor involved with this was quite difficult involving the carrying of large heavy instruments from El Coxo to Point Conception and a 300-pound instrument stand.

Relative to the wages of the times, each of the young Coast Surveyors was paid $30.00 per month. A cook they hired in San Francisco was paid $125.00 per month, making more than this whole group of skilled engineers. Lawson suggested the weather was better than the storied "Italian skies" for this sojourn at Point Conception but noted the continual offshore fog hid the Channel Islands from view for the first six weeks of their stay. Finally, early in October the work was finished and the crew hired a pack train and headed into Santa Barbara to await transportation to San Francisco. They "did the town" while there and met the famous otter hunters George Nidever and Isaac Sparks. They had earlier made friends with Don Luis Carillo, son of Don Anastasio Carillo, the owner of the Point Conception area. They stayed at Don Anastasio's home while awaiting transportation and had many conversations with Don Luis. He felt they were near to transgressing the truth when they described the multi-story buildings of the East Coast and the railways, but "morally certain they lied" when they described the wonders of the telegraph.

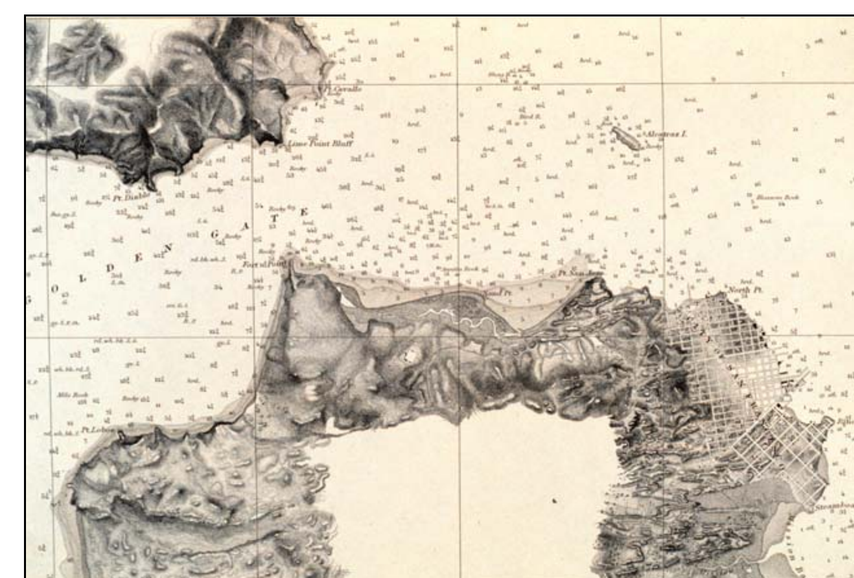
Little was accomplished in southern California the following year as the Coast Survey

concentrated its efforts to the north of San Francisco. Although a source of supplies, southern California was still considered a relative backwater at this time. However, an astronomic position, magnetic declination, and site for a lighthouse were determined at San Diego and a triangulation scheme and topography carried southward to the Mexican border from San Diego. The EWING proceeded north in a first reconnaissance survey from San Francisco to the Columbia River entrance and conducted a few surveys at the river entrance as well.

In 1852, the Coast Survey Steamer ACTIVE, under the command of Navy Lieutenant James Alden (one of approximately 800 Navy officers who served with the Coast Survey in the Nineteenth Century), made a first reconnaissance hydrographic survey from San Francisco to San Diego. On this trip George Davidson was put ashore with his equipment and acquired astronomic positions at San Luis Obispo, Santa Barbara, Prisoner's Harbor on Santa Cruz Island, San Pedro, Santa Catalina Island, San Clemente Island, San Nicolas Island, and Cuyler's Harbor on San Miguel Island. This marked the first time that these islands had been adequately located. By the end of 1852, most of the major headlands and points of interest for mariners between the California-Mexico border and Cape Flattery, Oregon Territory, had been accurately determined by George Davidson and his assistant John Rockwell. Rudimentary charts of many of the observed harbors and islands of Southern California were produced by the end of 1852.

During these first three years of Coast Survey operations on the western coast, a relatively accurate general outline of the coast was sketched in and many dangerous errors corrected, the geographic positions of the major headlands and landmarks determined, magnetic declinations at strategic points observed, and locations for lighthouses recommended. The detail work of connecting the various independent astronomically determined locations by triangulation (much more rigid positioning than attainable through astronomic means), conducting topographic mapping of the shoreline and offshore hydrographic surveying that would be controlled by the triangulation network was ready to begin. However, little had been done with observing tides other than the establishment of a few tide staffs to measure tides during hydrographic survey operations such that water depths could be reduced to a local plane of reference. To obtain readings, either a sailor attached to the survey party or a local citizen was hired to read the water level on the tide staff either every hour or some fraction of an hour never less than every 15 minutes.

Of the four young men who came west in 1850, George Davidson (1825-1911) and James Lawson (1828 – 1893) would remain on the West Coast for most of the remainder of their lives. Davidson made his home in San Francisco and was by far the most well-known of the group as he was considered California's most prominent scientist for many years and had many geographic features named after him including Mount Davidson in San Francisco and Davidson Seamount to the southwest of Monterey. Lawson made his home in Olympia, Washington. A.M. Harrison and John Rockwell



Section of U.S. Coast Survey Chart engraved in 1859 returned to the East Coast. Rockwell died an early death in 1857 and Harrison passed away in 1881.

The Tides

Golden Gate view from the San Francisco tide gauge

There are few backdrops as dramatic as the Golden Gate to observe the nature of our clockwork universe. Twice daily the tides rush into the bay on the floods and twice out on the ebbs. Ships plan sailing times and arrival times on these daily risings and fallings. The commercial and naval wharves, seawalls, the great bridges of the Bay Area, underwater communications cables, pipelines, and other engineering works all have been designed and built taking the tides into consideration. Fishing trips are planned to coincide with stages of the tide, recreational beachcombing and tidepooling are planned to coincide with favorable stages of the tide, surfers plan trips to favorite breaks based on tide predictions, and even those who come to the shore for love, friendship and renewal can be affected by the action of the tides. How do we predict the stages of the tides for ship operations, engineering purposes, commercial and recreational fishing, or other recreational and personal activities?

There is a grand symphony that has been played out for billions of years – an orchestration of moon, sun, earth, and ocean. There are physical consequences to the Earth and Moon revolving about a common center of gravity, the Earth-Moon system revolving about the sun, the varying distances between Earth and Moon and Earth and Sun, and the progression of continually changing declination of the moon and sun relative to the earth. All of these motions and interactions are manifested by predictable, but changing, gravitational forces acting upon the atmosphere, the oceans, and the solid earth itself. The most visible result of these forces, particularly for those who live along our coastlines, is the continual changing of the level of the sea as the tide rushes in and out.

Although humankind has observed these phenomena for thousands of years, it was not until relatively recently that we took to studying, attempting to understand, and predicting the tides. Coming from areas adjacent to the Mediterranean Sea, both Alexander the Great in 325 B.C. and Julius Caesar in 55 BC almost met disaster because of tidal phenomena. Alexander's fleet almost met its end on the Indus River as the result of tides and a similar occurrence caused Caesar to retreat from the shores of England after suffering damage to his fleet after anchoring in tidal waters. There is a continuing but unfounded rumor that in 322 BC Aristotle committed suicide because he was unable to determine the cause of the tides.

Some progress was made in understanding the tides in the classical era and even through the Dark Ages. The relationship between phases of the moon and tidal range was noted by many observers and even crude tide tables were produced for a few areas. However, it was not until 1687 that Sir Isaac Newton developed the concept of tides being caused as a result of predictable but varying gravitational forces resulting from the changing relative positions of sun and moon relative to the Earth. But, recognizing the cause of tides and being able to predict them are two different things. The configuration of oceanic basins and local conditions such as water depth, configuration and slope of bottom, and meteorological effects all combined to confound attempts to understand the nature of tides. This situation was exacerbated by inadequate technology to observe tides under a variety of conditions, lack of accurate solar and lunar tables, lack of accurate time-keeping instruments, and lack of any scientific infrastructure to coordinate observations from geographically dispersed locations.

This remained the situation until the early to mid-Nineteenth Century. By this time more accurate sun and moon tables had been developed, better time-keeping mechanisms to coordinate observations had been invented, and perhaps, most importantly, dedicated scientists and cadres of engineers in organizations such as the United States Coast Survey had begun turning their energy to solving the problems of tide observations and tide predictions. Until the mid-Nineteenth Century the only method for observing the tide was to place a vertical staff in the water graduated in some unit of linear measure (feet in the United States Coast Survey) and station an observer close enough to the tide staff such that he could read the stand of the tide on the staff every hour or some increment of an hour and record these values.

Portable tide gauge installation with tide staff

Although challenging in confined harbors with easy access to piers and other structures, on open coasts the observation of tides was difficult if not impossible. In the case of tide staffs installed in harbors, a slight variation over fixed-staff observations was the introduction of a floating staff encased in a stilling well that would move vertically with the tides. The top of this moving staff would be equipped with rollers that slid up and down in guides attached to a fixed staff graduated in feet and decimal parts of feet. The observer would read the value that was adjacent to the very top of the moving staff. This arrangement of fixed and moving staff often was enclosed in a small tide house not unlike those in use in many locations along the United States coastline today. The advantage of this arrangement was that the observer was not exposed to the elements and that it was possible, on average, to make much more accurate observations than was possible from a remotely viewed fixed staff. The tide staff method, whether fixed or floating, was subject to human error, carelessness, and to some degree subjectivity. Although there were a few professional tide observers in the Coast Survey, notably Gustavus Wurdemann who was repeatedly praised in annual reports for his accuracy and devotion to duty, in most cases the observations were entrusted to members of the hydrographic party or local citizens who did not always meet the same high standards as Wurdemann.

The problem of varying quality of observations was noted in the first attempt to obtain accurate tide observations on the western coast of the United States. Two coordinated sets of observations were planned from staffs at Rincon Point (famous now for being close to Pac Bell Park and the site of Barry Bonds' homerun marathon) and Sausalito. These observations were conducted for a little less than a month in late January through early February of both 1852 and 1853. The Rincon Point observations, under the direction of Lieutenant James Alden, commanding officer of the Coast Survey Steamer ACTIVE, were praised for their accuracy and attention to detail. Conversely, it was suggested that the Sausalito observations "were not made with the same care which appears to characterize" the Rincon Point observations.

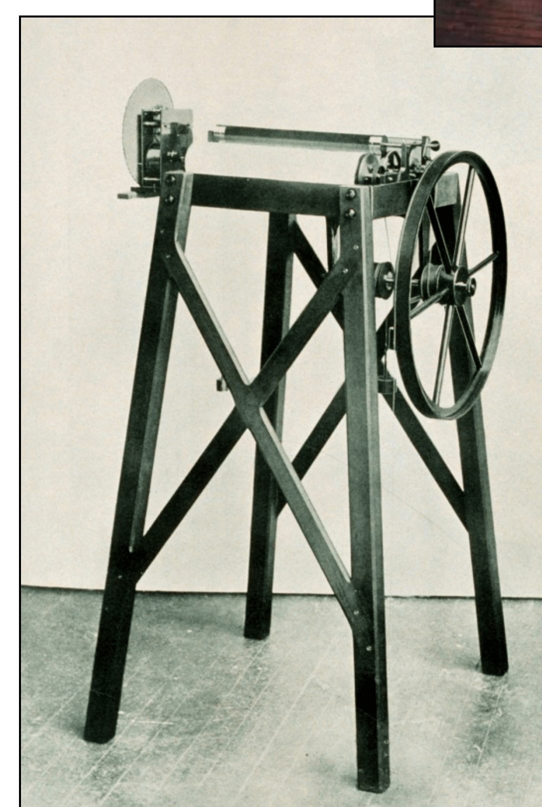
As a result of the short series of Rincon Point observations, Alexander Dallas Bache, Superintendent of the Coast Survey and great-grandson of Benjamin Franklin, was able to draw many conclusions of importance to the navigation of San Francisco Bay. The first of these was that there was a large diurnal inequality between the successive high and low waters of each lunar day (24 hours and 50 minutes for moon to complete a revolution about the Earth). What this meant to navigators was that an obstruction having three and a half feet of water over it at a first low tide of the day could be awash at the time of the second low tide of the day. This had great significance both for the immediate needs of assuring safe passage of commerce but also relative to choosing a plane of reference for soundings for charting purposes. Ultimately, mean lower low water was chosen as the plane of reference for Coast Survey charts on the West Coast and Alaska as opposed to mean low water as used on the East Coast and Gulf Coast. As hydrographic surveys were performed for creating updated nautical charts of the region, the data from the tide gauges were used to correct the soundings for stage of tide and refer them to a common datum. Other information obtained from this short series of observations were rules for determining times of high and low water relative to the declination of the moon, average range of tides between highest high water and lowest low water, and probable greatest range of tides in the Bay.

Although these first tide observations provided the mariner with a rough means to determine the times of high and low water in the Bay, it was understood that only a small inroad had been made in understanding the Pacific tides. Fortunately a new technology had been recently developed. The great instrument-maker Joseph Saxton invented a self-registering tide gauge in 1851 which ran twenty-four hours per day with minimal human care. This gauge was not the first self-recording tide gauge but was considered to be a marked improvement over existing instruments. It consisted of a float attached by wire to a gearing mechanism. The gearing mechanism drove the location of a pencil relative to a rotating drum covered with a paper tide record sheet. The whole system was time synchronized such that the pencil tracings of the risings and fallings of the tide in a sinusoidal curve could later be scaled for heights and times of various stages of the tides. This new system effected a revolution in both the quantity and quality of tide records acquired by the Coast Survey. Shortly after the introduction of and possibly as a result of this new technology, a new tidal division was established in the Washington, D.C., headquarters of the Coast Survey under Count Louis F. de Pourtales, a Swiss immigrant like Ferdinand Hassler (1770-1843), the founder of the Coast Survey. An interesting aspect of this new division was that Alexander Dallas Bache hired Mary Thomas as a tides computer, the second woman science professional in the Federal Government. The first was Maria Mitchell, the great astronomer, who had been hired by Bache to do observations for the Coast Survey in the mid-1840's and then hired by the Nautical Almanac Office. Not only was the Coast Survey the pioneer surveying organization on our coastlines, but it was the pioneer agency in hiring talented women scientists and mathematicians to work side-by-side with their male counterparts.

In 1853 Superintendent Bache sent a dedicated tides party under Army Lieutenant

William P. Trowbridge to the West Coast with three of the new self-registering tide gauges. These gauges were to be installed at San Francisco and San Diego in California and at Astoria, Oregon. Trowbridge accompanied by Army enlisted man Andrew Cassidy and a few other observers (apparently all Army enlisted men), who were chosen for their intelligence and devotion to duty, traveled to California via steamship to Panama, proceeded over the nearly complete Panama Railroad to Panama City, and continued to San Francisco by Panama steamer, arriving in July 1853. They established a self-registering gauge in the North Beach area of San Francisco and then proceeded to San Diego where Cassidy was left in charge of the newly installed gauge. From there Trowbridge proceeded to Astoria.

Presidio tide station



Self-registering tide gauge "Saxton"

Although a self-registering gauge was established in San Francisco in 1853, it was decided to move the gauge to Fort Point on the grounds of the Presidio in July 1854 as portions of San Francisco were in turmoil because of land squatters causing civil unrest. Amazingly, since that time this gauge and its successors have produced the longest running unbroken series of tidal observations in the Americas. It is probable that there is no other geophysical phenomena in the Western Hemisphere that has a longer continuous record.

Although the San Francisco record is the longest continuous tidal record, it is noted that self-registering tide gauges were established at four other permanent locations at that time – Governor's Island, New York; Old Point Comfort, Virginia; San Diego, California; and Astoria, Oregon. Because of storm, disaster, carelessness, or any of a myriad of other possible causes, the only gauge able to survive with an unbroken record of observations was the San Francisco gauge. For one hundred and fifty years observations from this gauge have assisted the mariners of the world entering and sailing from the ports of the Bay Area as well as having helped in the planning and construction of all the waterfront facilities of this great port.

Serendipitous Science

Observation of tides for commercial and naval shipping interests was and remains the primary purpose of the San Francisco tide gauge. However, this particular gauge has a record of adding to our knowledge of the oceans and its relationship to the Earth in general that is without peer. Within six months of the installation of the gauge at Fort Point, a great earthquake occurred on December 23, 1854, near the central coast of Japan raising a series of great tsunamis along portions of the Japanese coast. The tsunamis traveled across the Pacific Ocean and were recorded as attenuated waves on the self-registering tide gauges along the western coast. These waves were superimposed upon the regular tidal record as a series of sinusoidal squiggles. The first person to recognize the significance of these squiggles was Lieutenant Trowbridge who wrote to Superintendent Bache in early 1855, "There is every reason to presume that the effect was caused by a sub-marine earthquake." This was an amazing insight given that recording seismographs were still twenty-five years in the future and that no earthquake had ever been remotely sensed by any means up to this time.

Trowbridge's insight was validated when word of a major earthquake occurring on the coast of Japan on December 23 reached Superintendent Bache. Armed with knowledge of the time of the earthquake, its location, times of arrival of the tsunami waves at both San Francisco and San Diego (from the tide gauge records), and times between crests of the various waves, Superintendent Bache was able to estimate the average depth of the Pacific Ocean. Bache was familiar with the latest basic research published by Sir George Biddell Airy and his treatise on Waves and Tides in the Encyclopaedia Metropolitana in 1849. Airy had mathematically developed theoretical expressions that govern the motion of waves in canals of uniform depth and compiled tables for expressing the relationships between wave length, wave period, wave velocity and depth of water. Bache interpolated the Airy table values using his distance estimates and the tide gauge measurements for the theoretical tsunami wave travel lines between Shimoda, Japan and both San Diego and San Francisco. Using two separate estimates for the times of the disturbance due to the tsunami on the tide gauge curve at San Francisco, Bache estimated the average depth of the Pacific between Shimoda and San Francisco to be 13,380 feet and 15,000 feet. For the line between Shimoda and San Diego, the average depth was estimated to be 12,600 feet. Considering that these were estimates of the average depth of the Pacific Ocean using indirect measurement and theoretical relationships of waves for canals of uniform depth, these numbers agree remarkably well with modern published values based upon modern measurement technology. Modern day estimates for the average depth for the depth profile from Shimoda to San Francisco are 15,504 feet and 15,221 feet from Shimoda to San Diego. Bache published his estimates at a time when deep sea sounding technology was in its infancy, inaccurate soundings ranging between 30,000 to 50,000 feet were fairly common, and there was great

uncertainty concerning the true average depth of the oceans.

Over the next 150 years the San Francisco tide gauge recorded many of the great tsunamigenic events of the Pacific Ocean. It even recorded tsunami waves from the great Krakatau explosion of August 26, 1883, a few hours after the event and the Coast and Geodetic Survey published notice of an extraordinary event prior to any notice of the details or location of the disaster were known. The gauge has also survived many major events in its vicinity including the Hayward earthquake of 1868 which did major damage to the East Bay and to land fill areas in San Francisco, the great earthquake of 1906, and the 1989 Loma Prieta earthquake.

It may seem strange, but elevations throughout the United States and North America have been determined relative to mean sea level as determined at Coast and Geodetic Survey tide stations. Attempts to determine elevations of points inland from coastal tide stations began as early as 1857 when a line of levels was run up the Hudson River between tidal bench marks in New York City and Albany, New York. Bench marks, usually distinct monuments in the form of concrete cylinders with brass monuments on top that are set in the ground, or in the early years of tidal observations marks etched on permanent rock surfaces, are established at all tide stations in order to assure that there has been no change of position of a tide staff between the water surface and the land surface. After a series of tidal observations have been made, local mean sea level can be determined at a gauge location and the elevation above sea level of the bench marks in the general area can be determined. It was not until 1904 that the first trans-continental line of levels connecting the tide gauge at Seattle, Washington with the one at Sandy Hook, New Jersey was completed. Over the next twenty years there were a number of additional connections made between Atlantic and Pacific gauges. In 1929 the Sea Level Datum of 1929 was introduced by the Coast and Geodetic Survey which incorporated data from twenty-one tide stations in the United States and five in Canada. This datum was the basis of elevation determination for all government mapping and for the planning and design of all major engineering projects in the United States. Prior to this time there was no standard means of determining elevations in the United States and the establishment of this datum began with the tidal observations of the Coast Survey. Since 1929 there have been two major readjustments of the vertical geodetic datum [1](see footnote).

An issue related to the determination of mean sea level as an elevation datum is the concept of changing sea level. The San Francisco tide gauge is the longest continuous record of sea level change in existence in the western hemisphere. Whether sea level is increasing, decreasing, or remaining static is of major importance to people living in coastal regions. The determination of changing sea level is a difficult issue. Because of tectonic forces, subsidence caused by withdrawal of subsurface fluids or mineral material from coastal areas, isostatic adjustment or rebound of land areas previously covered by glaciers, or a combination of these effects, coastal lands can be rising relative to the sea, sinking relative to the sea, or remaining static. However, after taking into account these perturbing forces, most of the last century has shown a steady rise in sea level as determined by tidal records augmented over the last decade by satellite altimetry. Tidal records show rise rates of approximately 2 mm per year over the last century while satellite altimetry is showing even higher rates of rising sea levels (Note: the satellite altimetry record is only 10 years long, so several

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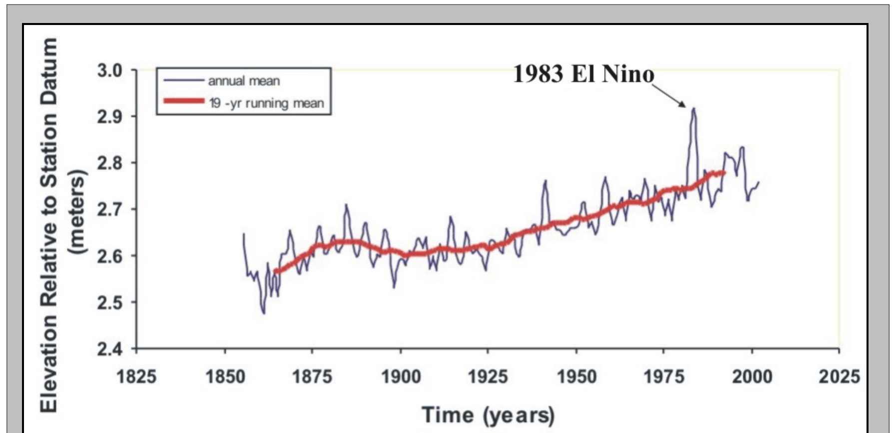
[1] This Sea Level Datum of 1929 was re-named as National Geodetic Vertical Datum of 1929 (NGVD29) and superseded by North American Vertical Datum of 1988 (NAVD88) so that geodetic datums could be de-coupled from mean sea level observations at tide gauges. There is no consistent vertical relationship between NGVD29, NAVD88 and mean sea level around the coast. The long-term tide gauge records show us that trends in relative mean sea level are highly variable around the coast due to varying rates of vertical land movement and using them together as baseline geodetic datum un-ravels over time. Modern tide gauges, precisely tied to the new geodetic networks and GPS reference frames, are helping to distinguish regional sea level trends from global sea level rise due to climate change and from vertical land movement.

more years of record are required to establish a trend). These rates of sea level rise have many ramifications for human occupation of coastal areas. If sea level continues rising at present rates, engineering works will have to be rebuilt or modified; less area will be available for human habitation; wetland habitats will be drowned and lost; low-lying islands will be inundated; and many areas immune today from storm surges caused by coastal storms will in the future be subject to the walls of water that accompany major wind events



Variations in Annual Mean Sea Level at San Francisco: 1856 - 2002

Extreme high water events during periods of El Nino are clearly seen in the San Francisco historical tide record. El Nino events generally occur every 3 to 7 years in the Pacific Basin and are caused by the interaction between unusually warm sea surface currents and high sea levels generated in the tropical Pacific drifting eastward and colliding with lower temperatures in the Eastern Pacific. According to historical records, the most severe El Nino events have occurred in the 20th Century, and most recently during the period 1997-1998.

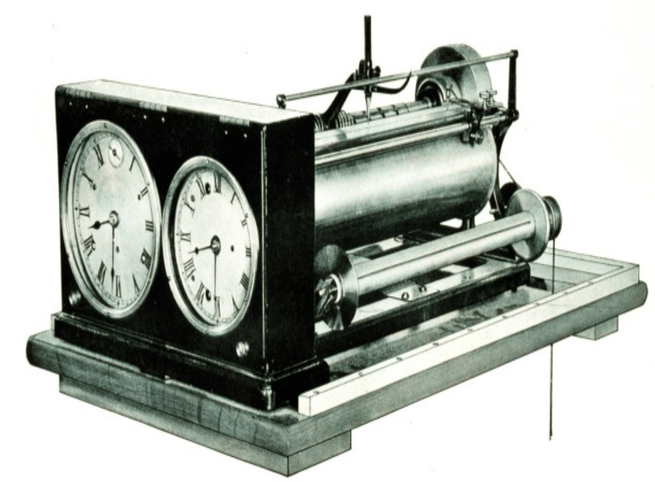
As shown in the plot above, the effect of the 1983 El Nino is clearly pronounced and is the event of record in the monthly and annual mean sea levels. By analyzing the Interannual to Decadal variations in sea level, especially from a long baseline record like San Francisco, it's now possible to better understand the El Nino Southern Oscillation phenomenon and help predict future events.

Sea level records from the San Francisco gauge are indispensable for conducting climate change research, investigations of global warming and predicting El Nino events and the impacts of sea level change on coastal communities. Analysis of localized sea level trends also provide insight and better understanding of regional tectonic changes and accompanying seismic activity. San Francisco's 150 years of sea level record adds a wealth of information to the knowledge of global climate change and relative rates of sea level rise. In fact, the San Francisco record indicates that the positive sea level trend (1.41 mm/year) has not always been uniform over time and experienced a downward trend between 1875 and 1913. This sea level anomaly has also been noted in the historical records of comparable long term sea level records world wide.

Establishing the Record

To obtain a continuous record of the tides in San Francisco since 1854 has been a monument to human perseverance and ingenuity coupled with improvements in the technology of water level measurement. The self- registering tide gauge, established at Fort Point in June 1854, was accompanied by the establishment of bench marks, which are permanently fixed vertical reference points; in this case, the bench mark was a cross cut in the face of a large stone near the wharf where the gauge was installed. Leveling surveys were conducted on a yearly basis between the bench mark and tide gauge to insure that stability of the gauge was maintained. Tide observers made daily visits to the gauge to make tide staff readings and check gauge time. Problems with wharf settlement were soon discovered, but were corrected by stabilizing the area around the wharf with rock and

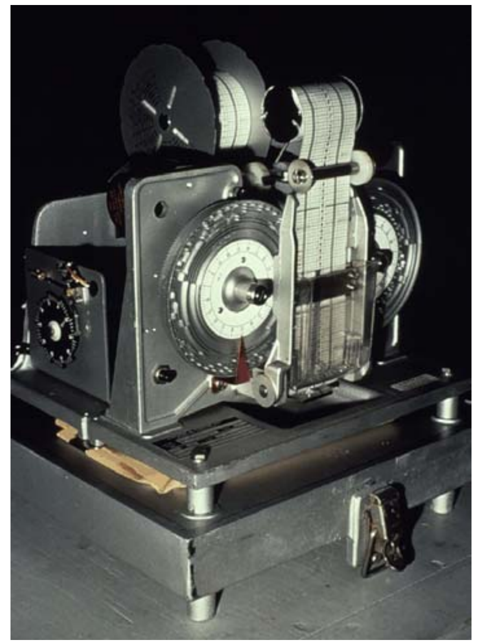
stone fill. In 1877, the wharf came under disrepair and was abandoned. A new gauge site was chosen across the Golden Gate at Sausalito. Meticulous care was taken to preserve the Fort Point data series through the simultaneous operation of the Fort Point gauge and Sausalito gauge coupled with the transfer of tide staff elevations by a water crossing technique. This involved limiting the refraction effect during survey leveling operations by simultaneously observing targets at bench mark sites at Fort Point and on the north shore at Lime Point, a little more than a mile distant across the Golden Gate, and then transferring elevations through repeated leveling and eventually to bench marks at the new Sausalito gauge on Government Wharf at the Fort Baker military reservation. In 1881, the Sausalito wharf began to deteriorate and the gauge was moved to a more stable site; then in1897, it was finally decided to move the gauge back across the San Francisco Bay to the Presidio area, which was just east of the original Fort Point site and in the approximate vicinity of the present day gauge.


Standard Tide Gauge

This era in the history of the San Francisco tide gauge was also marked by the association of two major Bay Area authors with the work of NOAA ancestor agencies. It is little-known, but both John Muir and Jack London were associated with the Coast and Geodetic Survey and the United States Fisheries Commission respectively. Muir worked through the Sierra Nevada and the Great Basin as a guide and artist for the Coast Survey during reconnaissance work for the 39th Parallel Survey which was the first great survey line connecting the Atlantic and Pacific coasts of the United States. This work was done with Coast Survey Assistant Augustus Rodgers, brother of the naval hero Rear Admiral John Rodgers. Muir's only published work on this part of his wilderness life was "Snowstorm on Mount Shasta" although diaries of his Great Basin experiences are still in existence. Jack London worked for and against the Fisheries Commission in his youth as both a fisheries enforcement agent and oyster pirate on San Francisco Bay and as a deck hand on a sealing schooner in the Bering Sea. His San Francisco Bay experience is recounted in "The Raid on the Oyster Pirates," a delightful tale in which London, on the right side of the law, captures a group of oyster pirates by stealing their boats and using the rising tide to force their surrender and arrest them. "The Sea Wolf", the dark tale of seal poacher Wolf Larsen, draws on his sealing schooner experiences.


The Harris-Fischer Tide prediction machine or "Old Brass-Brains."

Tide gauge technology evolved little from 1854 until the early 1960's. The processing of tidal records also changed little and was very labor intensive during these years as it required manual scaling of tidal heights and time from the pen-recorded sinusoidal record. The scaled observations were entered into record books for further processing. Tide predictions were computed manually in the early years of the Coast Survey Tidal Division. However, in 1867 a new method of computing tides, termed the harmonic method, was introduced by Sir William Thomson of Great Britain. This method, although showing promise of greater accuracy in tide predictions, was impractical because it was extremely labor intensive. Thomson solved this by inventing a tide prediction machine that summed ten constituents of the harmonic analysis equations in 1876. The values of the constituents were obtained manually from the observed high and low waters. William Ferrel of the Coast and Geodetic Survey designed a second computing instrument of this type in 1880 which was operational by 1884. Reducing harmonic analysis to a series of gears, pulleys, and levers, the Ferrel machine computed times and heights of tidal maxima and minima using nineteen constituents. The harmonic method of tide prediction has been used by NOAA since that time. A second tide prediction machine was built by the Coast and Geodetic Survey and became operational in 1912. This machine, formally known as the Harris-Fischer Tide Prediction Machine, or "Old Brass-Brains" as it came to be affectionately termed, summed 37 constituents and was used until the advent of digital computers in the early 1960's. This machine has a long and honorable history and was used not only to compute domestic tide predictions, but during the Second World War computed tide predictions for world-wide for use by our naval and amphibious forces. Obtaining the values of the harmonic constituents for input into the tide prediction machine was also accomplished manually up to the time of computers using a series of forms and stencils on the tabulated hourly heights of the tide gauge record.



The ADR Gauge,
a mechanical "punch" recorder.

In January 1976, a digital paper punch recorder termed an analog to digital recorder (ADR) replaced the venerable pencil and drum recording mechanism. This instrument recorded the height of the tide at set time intervals, usually every six minutes, by punching holes indicating the observed times and float height on an aluminum-backed paper tape. As the paper punch tapes could be machine-read, this system sped up the processing of tide records but the gauge itself still relied on a float/wire water level sensor and gearing mechanism on the recorder that synchronized time and rate of advance of the paper record. A tide observer was also required to maintain the gauges on correct time and to make daily tide staff readings.

This instrument had a life-span of approximately one human generation as beginning in 1985, the National Ocean Service embarked on a major upgrade of what had become termed the National Water Level Observation Network. The network of old float/wire systems was replaced by the Next Generation Water Level Measurement System (NGWLMS) which consisted of an air acoustic water level sensor coupled with an electronic data acquisition system. These systems have numerous advantages including the direct leveling of the water level sensor to local benchmarks (tide observers and tide staffs are no longer required), electronic data storage, a backup

pressure water level sensor with its own data logger, and ancillary sensor capability such as water and air temperature, wind speed and direction and barometric pressure. The acoustic sensor capability allowed much more accurate water level readings but what really set this system apart from the earlier systems was the ability to transmit data to a central facility via telephone line or via NOAA's Geostationary Operational Environmental Satellite (GOES) data collection system for near real-time data analysis, processing, and distribution. By comparison, prior to introduction of this system, tidal data rolls were removed monthly from the ADR gauges and mailed to the National Ocean Service for processing. The NGWLMS system replaced the ADR gauge at San Francisco in January 1996.The modern day ports in San Francisco Bay region continue to play a vital role in the nation's economy. Approximately 95% of foreign trade in and out of the U.S. is by ship and every U.S. citizen, not just those living along the coast, relies upon the nation's ports for energy delivery, exports, transportation, and cost effective consumer goods. The new water level measurement gauges have also been integrated into the NOAA Physical Oceanographic Real-Time System (PORTS), that has been introduced into many major United States harbors including San Francisco Bay. This system measures real-time

The Next Generation Water Level Measurement System

water levels, currents, and meteorological phenomena such as winds and visibility and makes these data immediately available to the local user for operational decision-making.

These decisions include when to load or off-load more cargo, when the best time to make transits, when there is enough clearance to go under a bridge, or when to sail or not to sail with or against the currents and tides. This information is critically important considering that there is an average of 261 deep-draft vessels entering San Francisco Bay each month and that there are approximately 85,000 registered pleasure boats using approximately 100 yacht clubs in the Bay system.

Summary

A U.S. Coast Survey tide gauge was installed at San Francisco on June 30, 1854 and will soon have produced the continuous recording of water level for 150 years. The tide station, now operated by NOAA, is part of a network of 175 long-term tidal and Great Lakes water level stations that have been established throughout the continental United States, Alaska, Hawaii, Pacific Island territories, Puerto Rico and the Virgin Islands.

The historical record from the tide station at San Francisco transcends the maritime history of the San Francisco Bay, from the days when clipper ships relied upon tide predictions provided by the station to navigate the dynamic waters of the Golden Gate, to the modern day mariner that obtains real-time water levels so that the huge ship and crane barge operators can tell if they have enough depth in the channels and enough clearance under the bridges.

The record from the station continues to be used to update national nautical chart and shoreline reference datums. The data record itself contains the signatures of important maritime events that have affected human populations and the California culture over time, from the traces of Pacific Ocean Tsunamis, to high tides from storm surges, to high sea levels due to El Nino, and to the long term record of sea level rise since the turn of the century. It is one of the longest continuous records of sea level in the world and has been used by the scientific community in research for estimating global sea level rise.

Today, the San Francisco tide gauge plays a central role in the San Francisco Bay Physical Oceanographic Real-Time System (PORTS) which supports safe, cost efficient navigation and provides shipping interests with accurate real-time tide, current and meteorological data and is an important component of the NOAA Tsunami Warning System. It continues to provide information critical to maintaining and improving economic prosperity for California and for maintaining and monitoring port activities important for Homeland Security. And finally, the data from the gauge are used to provide water level and reference datum information needed for the increasing number habitat and marsh restoration programs in the bay region.


Crane barge with just enough bridge clearance during transit