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

COMPUTATIONAL TECHNIQUES FOR TIDAL DATUMS HANDBOOK

NOAA Special Publication NOS CO-OPS 2

Center for Operational Oceanographic Products and Services

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) collects and distributes observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and coastal current products required to support NOS' Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), and a national network of Physical Oceanographic Real-Time Systems (PORTS®) in major U.S. harbors. The Center: establishes standards for the collection and processing of water level and current data; collects and documents user requirements which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

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C0MPUTATIONAL TECHNIQUES FOR TIDAL DATUMS HANDBOOK

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LIST OF ACRONYMS

CO-OPS	Center for Operational Oceanographic Products and Services
DQA	Data Quality Assurance
DHQ	Mean Diurnal High Water Inequality
DLQ	Mean Diurnal Low Water Inequality
DTL	Diurnal Tide Level
GMT	Greenwich Mean Time
GPS	Global Positioning System
Gt	Great Tropic Range
IGLD 85	International Great Lakes Datum of 1985
HHW	Higher High Water
HLW	Higher Low Water
HWI	High Water Lunitidal Interval
HWL	Highest Water Level
LHW	Lower High Water
LLW	Lower Low Water
LW	Low Water
LWI	Low Water Lunitidal Interval
LWL	Lowest Water Level
MHW	Mean High Water
MHHW	Mean Higher High Water
MLW	Mean Low Water
MLLW	Mean Lower Low Water
Mn	Mean Range of Tide
MSL	Mean Sea Level
MTL	Mean Tide Level
NAVD 88	North American Vertical Datum of 1988
NGWLMS	Next Generation Water Level Measurement System
NGVD 29	National Geodetic Vertical Datum of 1929
NIST	National Institutes of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NTBMS	National Tidal Benchmark System
NTDE	National Tidal Datum Epoch
NWLON	National Water Level Observation Network
NWLP	National Water Level Program
PBM	Primary Bench Mark
QA	Quality Assurance
QC	Quality Control
SOP	Standard Operating Procedure
STND	Station Datum
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
UTC	Universal Time

1. INTRODUCTION

1.1 Intended Audience

This handbook is intended to provide education and training for both internal and external audiences to NOAA. It presents the National Ocean Service (NOS) methodology for the computation of tidal datums and explains how to use the Center for Operational Oceanographic Products and Services (CO-OPS) water level data and bench mark information available on the internet for tidal datum computations. Fundamental background for tide measurement and data processing is also reviewed. Detailed descriptions of tidal datum procedures, the background mathematical formulas, and example spreadsheets are interwoven in the various sections.

The handbook is designed to be both a technical reference and a guidance document for the practical determination of tidal datums using tide gauge measurements. It does not present methods for surveying, or address the problems associated with instrument installation, calibration, data collection, or quality assurance of water level data. Nor does it present specific algorithms for computation, or recommend what software packages should be used. However, a knowledgeable coastal engineer or scientist should be able to follow the key steps and arrive at the same results posted on the CO-OPS website (http://www.tidesandcurrents.noaa.gov).

1.2 Statement of Philosophy

The philosophy of this handbook is that fairly simple, straight-forward examples should be presented. CO-OPS is confident that coastal engineers will be able to compute datums similar to these "straight-forward" examples using this manual. The emphasis is on education and training, illustrated by clear real-world examples of tidal datum calculations. By reading this material, coastal engineers and surveyors will gain an understanding of how to reduce the data that they may have collected themselves, and gain necessary skills to handle more difficult cases. The datum computational methods described in this handbook produce valid datums where the tidal conditions and tide station locations for datum determination are straightforward. Difficult cases should be referred to CO-OPS for consultation. These cases might include project areas of rapidly changing tidal characteristics either temporally or geographically, measurements collected during extreme events, cases of poor data, data records with too many gaps, or poor station coverage. Additional special cases that may render the methods not applicable include situations where the astronomic tide is frequently masked by non-tidal effects (such as areas where wind-driven water level variations dominate and areas affected by river runoff); and where man-made structures (such as locks or water gates) affect the water level variations.

1.3 Prerequisite Knowledge

The reader will need to possess a mathematical understanding of means, standard deviations, differences, and errors. The reader should possess knowledge of suitable computer software such as spreadsheet programs, and have an internet browser and should have some basic scientific knowledge of tides and water levels, and some knowledge of the legal and practical significance of tidal datums (e.g, NOS, 2000).

2. BACKGROUND

2.1 Characteristics of the Tides

The purpose of this section is to provide a brief overview of tidal terms, tidal variations, and tidal characteristics. This overview provides context for the detailed description of the tidal datum computation methodology that follows.

The word "tides" is a generic term used to define the alternating rise and fall of the oceans with respect to the land, produced by the gravitational attraction of the moon and sun. To a much smaller extent, tides also occur in large lakes, in the atmosphere, and within the solid crust of the earth, acted upon by these same gravitational forces of the moon and sun. Additional non-astronomical factors including configuration of the coastline, local depth of the water, ocean-floor topography, and other hydrographic and meteorological influences may play an important role in altering the range of tide, the time interval between high and low waters, and times of arrival of the tides.

There are three basic types of tides: semidiurnal (twice-daily), mixed (also twice-daily), and diurnal (daily) (Figure 1). The first type, semidiurnal, has two high waters (high tides) and two low waters (low tides) each tidal day. A tidal day is the time of rotation of the Earth with respect to the Moon, and its mean value is approximately equal to 24.84 hours. Qualitatively, the two high waters for each tidal day must be almost equal in height. The two low waters of each tidal day also must be approximately equal in height. The second type, mixed, is similar to the semidiurnal except that the two high waters and the two low waters of each tidal day typically have marked differences in their heights. When there are differences in the heights of the two high waters, they are designated as higher high water and lower high water; when there are differences in the heights of the two lows, they are designated as higher low water and lower low water. The third type, diurnal, has one high water and one low water each tidal day.

The most important modulations of the tides are those associated with the phases of the moon relative to the sun. Spring tides are tides occurring during the new and full moon phases. These are the tides of the greatest amplitude, thus the highest and lowest waters are recorded at these times during each lunar month. Neap tides are tides occurring approximately midway between the time of new and full moon. The neap tidal range is usually 10 to 30 percent less than the mean tidal range. In addition to spring and neap tides, there are lesser, but significant monthly modulations due to the elliptical orbit of the moon about the earth (perigee and apogee) and yearly modulations due to the elliptical orbit of the earth about the sun (perihelion and aphelion). Modulations in mixed and diurnal tides are especially sensitive to the monthly north and south declinations of the moon relative to the earth's equator (tropic tides and equatorial tides), and to the yearly north and south declinations of the sun (equinoxes and solstices). Although the astronomical influences of the moon and sun upon the earth would seem to imply a uniformity in the tide, the type of tide can vary both with time at a single location and geographically along the coast. The transition from one type to another is usually gradual either temporally or spatially, resulting in hybrid or transition tides. In Figure 2, semidiurnal tides are illustrated by the one-month plot for New York, mixed-type tides are illustrated by the plot for San Francisco, and the plot for Pensacola illustrates a diurnal tide.

Figure 3 shows the gradual spatial transitions from mixed to diurnal to mixed and back to diurnal in the Gulf of Mexico. It is important to know the location of these transition zones because they limit how far the datum computation procedures described in this document can be applied successfully.

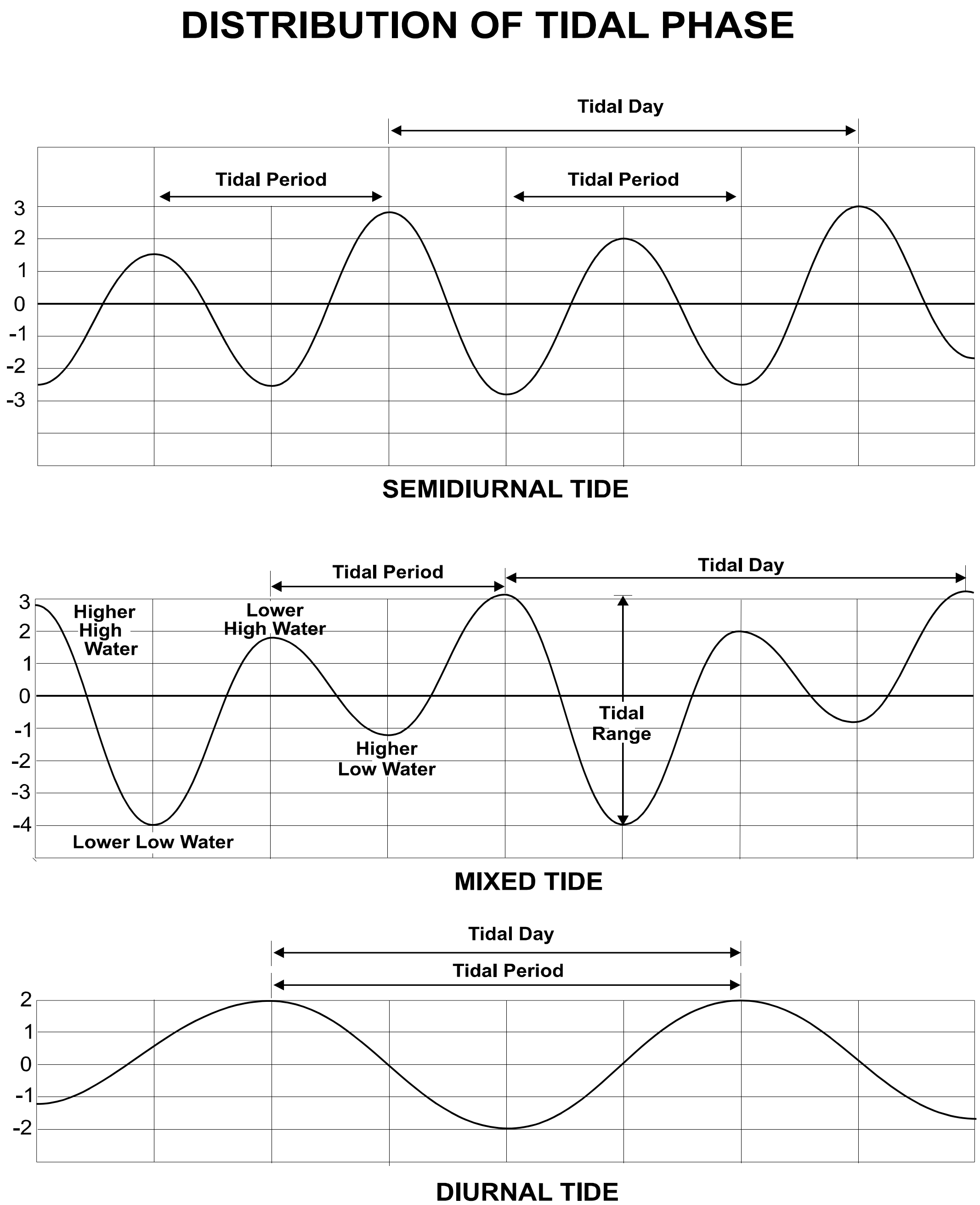


Figure 1. A depiction of the three primary kinds of tides. From the top panel downward they are semidiurnal, mixed, and diurnal. Standard tidal terminology is used to describe the various aspects of the tides. The zero on these graphs is illustrative of the relationship of the tides to Mean Sea Level (MSL).

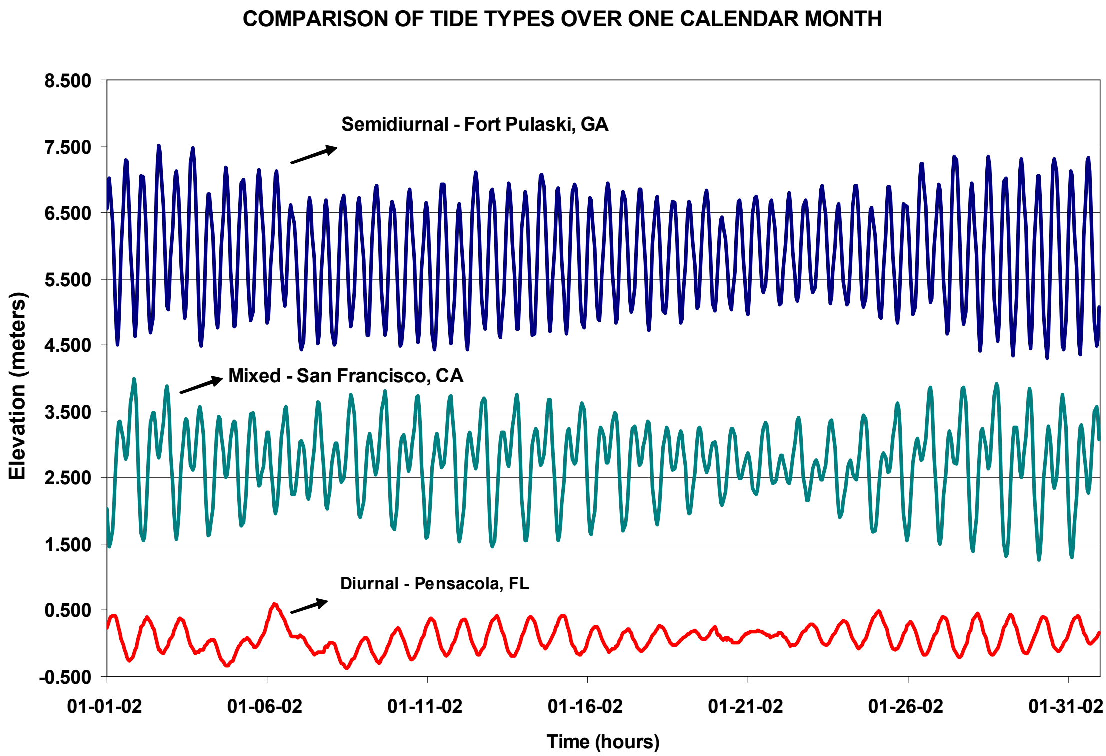


Figure 2. Comparison of types of tide over one-calendar month.

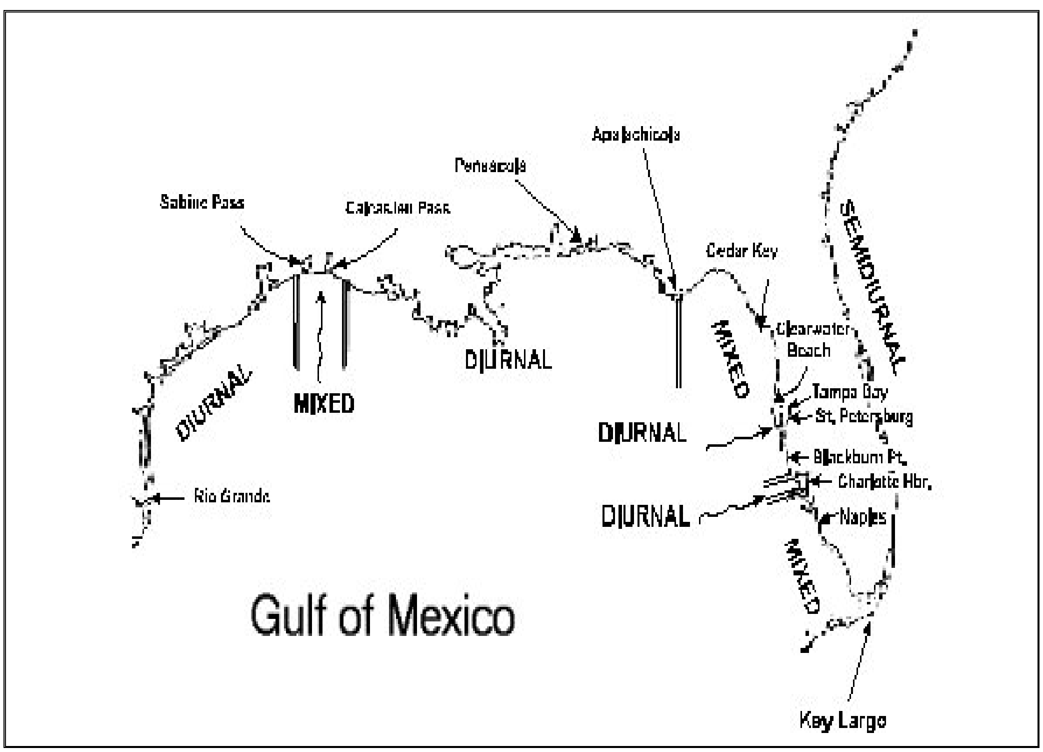


Figure 3. An illustration of the spatial variability of the type of tide in the Gulf of Mexico.

There is a variation in the path of the moon about the earth that has a period of about 18.6 years, and is called the regression of the moon's nodes. The regression of the nodes introduces an important variation into the amplitude of the monthly and annual mean range of the tide, as may be seen in Figure 4. It is the regression of the moon's nodes which forms the basis of the definition of the National Tidal Datum Epoch (NTDE). Because the variability of the monthly mean range is larger than the regression of the nodes, the National Tidal Datum Epoch is defined as an even 19 year period so as not to bias the estimate of the tidal datum.

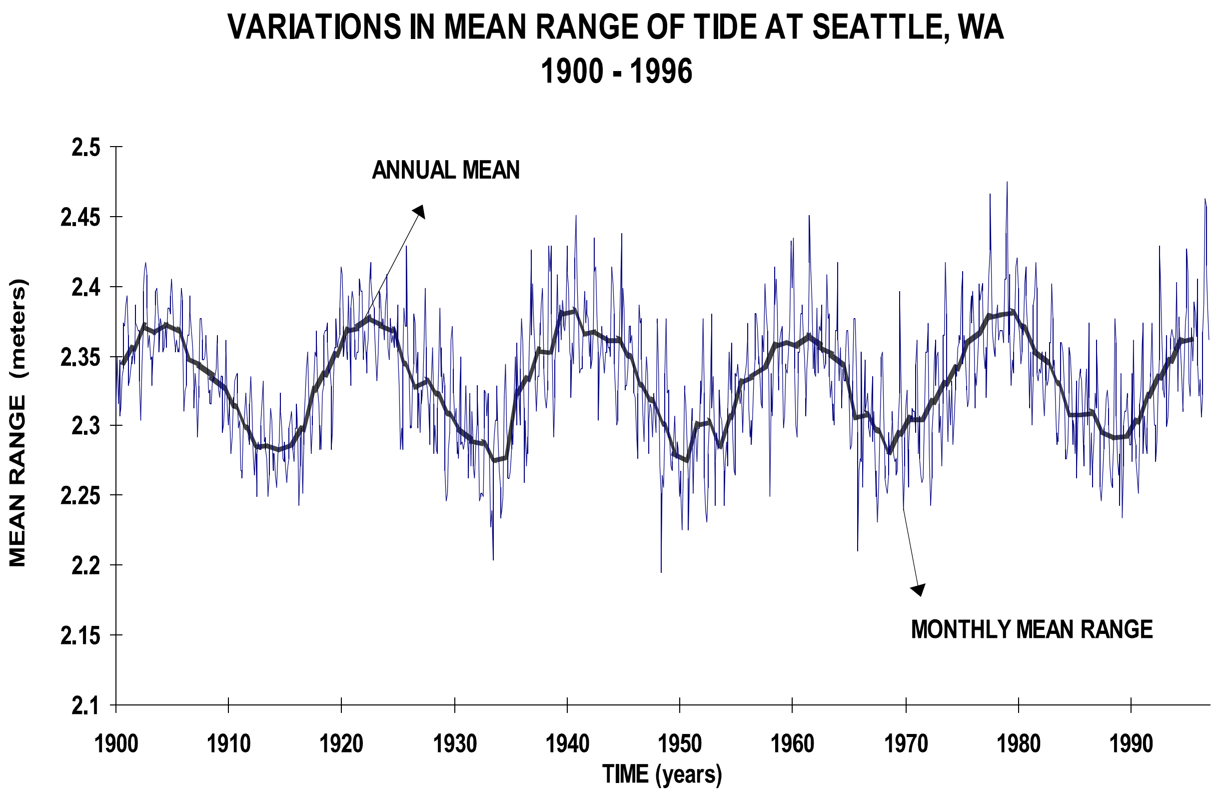


Figure 4. An illustration of the effect of the regression of the moon's nodes on the water levels at Puget Sound, WA. The heavy black curve is the annual mean range, or the difference in height between mean high water and mean low water. The time elapsed between trough to trough, or peak to peak, is the period of oscillation of the regression, and is about 18.6 years. The more rapidly varying curve is the monthly mean range. Changes in the monthly mean range are due to rapidly changing meteorological and oceanographic conditions.

2.2 Lunitidal Intervals

The high and low water phase of the tide at a particular place follows the passage of the moon over the local meridian by nearly a constant interval (Marmer, 1951). The moon, in its apparent rotation about the earth, crosses a given meridian 50 minutes later each day. Thus, the high or low water at given place seems to occur about 50 minutes later each day. The moon's upper meridian passage refers to the instant when the moon is directly above the given meridian. The moon's lower passage refers to the moon being 180° distant in longitude.

A lunitidal interval is the interval in time between the moon's passage over the local or Greenwich meridian and the following high or low water. The average of all high water intervals for all phases of the moon is called the mean high water lunitidal interval. It is abbreviated HWI. Similarly, the average of all low water intervals for all phases of the moon is called the mean low water lunitidal interval, and is abbreviated LWI.

In this handbook, HWI and LWI are calculated as Greenwich intervals. Greenwich intervals refer to the time interval between passage of the moon over the meridian of Greenwich, and the local high or low water of interest. This calculation is found in the section on "Comparison of Simultaneous High and Low Waters". Equivalent 19-year HWI and LWI values are computed at the subordinate station, by using the accepted values of Greenwich HWI and LWI at the control station. The relation in hours between Greenwich and local intervals may be given by,

$$\text{Greenwich interval} = \text{local interval} + 0.069\,L$$

where L is the west longitude of the local meridian in degrees. If L is east longitude, L is negative (Hicks, 1989). Assistance in determining when the moon passes the Greenwich meridian may be obtained from the U.S. Naval Observatory website, http://aa.usno.navy.mil/AA. Assistance in determining accurate local and GMT (UTC) times may be obtained from the website of the National Institute of Standards and Technology (NIST), http://www.nist.gov.

2.3 Other Signals in Water Level Measurements

Tides are not the only factor causing the sea surface height to change. Additional factors include waves and wave setup; ocean and river currents; ocean eddies; temperature and salinity of the ocean water; wind; barometric pressure; seiches; and relative sea level change. All of these factors are location dependent, and contribute various amounts to the height of the sea surface. Examples are: wind setup - up to about 1 meter (~3.2 feet); ocean eddies - up to about 25 centimeters (~0.8 foot); upper ocean water temperature - up to about 35 centimeters (~1.1 foot); ocean currents or ocean circulation - about 1 meter; and global sea level rise (about 0.3 meter (1 foot) per century).

It is NOS procedure to not separate out other sea level effects from the tides for computation tidal datums. There are no mathematical or statistical filters applied to the data before processing. Tidal tabulations will include, for instance, the effects of storm surge. NOS does use a combination mechanical/numerical filter to remove the unwanted effects of high frequency wind waves and currents. The filter is part of the physical design of the sensor and the data collection algorithm in the data collection platform (Scherer, 1986).

2.4 Tide Station Networks

The NOS National Water Level Program (NWLP) provides unique water level and ancillary data sets and information to users in support of a wide variety of critical activities. A priority of the NWLP is to provide the basic data for the vertical, tidal datum control for the nation. For instance, these data specifically support NOAA's Nautical Charting and safe navigation programs. The instrumentation of the NWLP consists of water level stations in the National Water Level Observation Network (NWLON), and any short-term stations operating for special projects such as hydrographic surveys, photogrammetry, and United States Army Corps of Engineers (USACE) dredging activities. The NWLON (Figure 5) is composed (as of year 2000) of approximately 175 long term stations distributed around the country and the world. The applications supported by the NWLON include: nautical charting, hydrography, remote sensing for shoreline, boundary determination, navigation, channel dredging and harbor improvements, tsunami and storm surge warnings, tide predictions, environmental monitoring and habitat restoration, climate and global change, international lake level regulation, international treaty compliance, and international boundary determination.

Except for water level stations in the Great Lakes, most of the stations in the NWLON are in coastal areas that come under the influence of the tide to a significant degree and are referred to as control tide stations. These stations have accepted tidal datums computed over the NDTE or at least over a several year period from which equivalent NTDE accepted values have been computed. This network provides direct datum control for a nearby areas and control for short-term stations for a larger geographic area. The extent of datum control depends upon the complexity of the coastal zone in terms of changes in tidal characteristics, localized effects of river runoff and wind, and differences in long-term sea level trends.

The NWLON is designed to provide a nationwide fundamental tidal datum control network. Most applications require tidal datum information at a higher resolution than that provided by the NWLON network spacing. Depending on the application, networks of shorter-term stations are established.

Control tide stations are generally those which have been operated for 19 or more years, are expected to continuously operate in the future, and are used to obtain a continuous record of the water levels in a locality. Control tide stations are sited to provide datum control for national applications, and located in as many places as needed for datum control. As the records from such a station constitute basic water level data for present and future use, during the installation and maintenance of the station, the aim is to obtain the highest degree of reliability and precision that is practical. The essential equipment of a control tide station includes an automatic water level sensor, protective well, shelter, back-up water level sensor, a system of bench marks, and possibly ancillary geophysical instruments.

Secondary water level stations are those which are operated for less than 19 years but more than 1 year, and have a planned finite lifetime. Secondary stations provide control in bays and estuaries where localized tidal effects are not realized at the nearest control station. Observations at a secondary station are not usually sufficient for a precise independent determination of tidal datums,

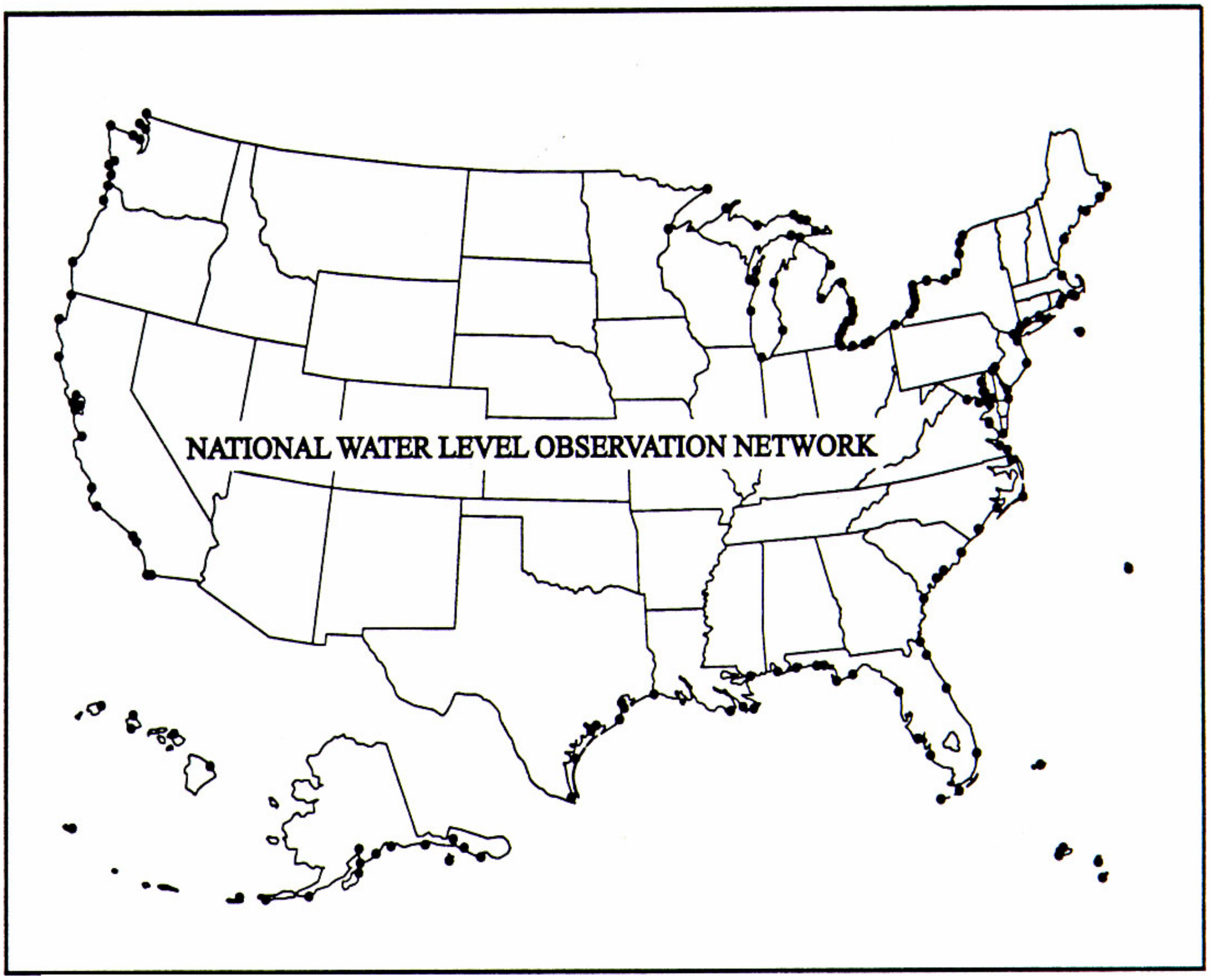


Figure 5. Locations of U.S. NWLON water level stations.

but when reduced by comparison with simultaneous observations at a suitable control tide station very satisfactory results may be obtained. Secondary tide stations may also provide data for the reduction of soundings in connection with hydrographic surveys.

Tertiary water level stations are those which are operated for more than a month but less than 1 year. Short-term water level measurement stations (secondary and tertiary) may have their data reduced to equivalent 19-year tidal datums through mathematical simultaneous comparison with a nearby control station. Short-term data, often at several locations, are collected routinely to support hydrographic surveying. In the Great Lakes, seasonal data are compared to simultaneous observations from adjacent stations for datum determination in harbors.

The locations of tide stations are organized into a hierarchy (Figure 6). Control (or primary) tide stations, secondary stations and tertiary stations are located at strategic locations for network coverage. The site selection criteria include spatial coverage of significant changes in tidal characteristics such as: changes in tide type, changes in range of tide, changes in time of tide, changes in daily mean sea level and changes in long term mean sea level trends. Other criteria include coverage of critical navigation areas and transitional zones, historical sites, proximity to the geodetic network, and the availability of existing structures, such as piers suitable for the location of the scientific equipment.

Site reconnaissance is performed prior to the installation of a new station. Field site visits are made to aid in the design, make measurements, and render technical drawings; to recover bench marks, or plan for new bench marks; and to obtain permission, permits, agreements, etc. The field parties take into consideration the requirements for the installation and protection of the instruments. The most important considerations are the presence of a suitable structure, the necessary benchmark locations, adequate water depth, special materials that might be needed to prevent marine fouling and corrosion, availability of telephone and electrical service, site security, and lightning protection.

There are numerous types of tide gauges and sensors that can be used for tidal datum computation purposes. NOS specifications for tide station installations and data processing and reduction for NOS hydrographic surveys are found in *NOS Hydrographic Survey Specifications and Deliverables* (NOS,2003). International references include the *Manual on Sea level Measurement and Interpretation* (IOC, 2000). The latest update on NOS water level measurement systems and capabilities are found in Mero, 1998. For tidal datum applications, it is important for gauge sensors to be carefully calibrated with either frequent calibration checks or cycled swaps of calibrated sensors for long-term installations. The sensor "zero" must be precisely related to either a tide staff and/or the bench marks through staff/gauge comparisons or direct leveling between the sensor and the bench marks. Vertical stability of the sensor "zero", both physically and internally, must be monitored and any movement taken into account in the data reduction and datum computation.

2.5 Bench marks and Differential Leveling

A network of bench marks is an integral part of every water level measurement station. A bench mark is a fixed physical object or mark (sometimes referred to as a monument) used as a reference for a vertical datum. For example, a tidal bench mark is a mark near a tide station to which the tidal datums are referenced. Since gauge measurements are referenced to the bench marks, it follows that the overall quality of the datums is partly dependent on both the quality of the bench mark installation and the quality of the leveling between the bench marks and the gauge.

Bench marks have site selection considerations much like the tide stations they support. The first consideration is longevity; bench marks are sited to minimize susceptibility to damage or destruction. Bench marks are sited to ease future recovery (locating and leveling to the mark) and to ensure accessibility (open, overhead clearance). Bench marks must also be placed in the most stable structure for the locality. Preference should be given to disks set in bedrock, in large man made structures with deep foundations, or installation of stainless steel rods driven to substantial resistance. Since bench marks are vulnerable to natural disturbances, such as geologic and soil activity, in addition to damage inflicted by man, more bench marks are installed around stations with longer term data series. At primary control stations, where 19 years of observations have been conducted or are planned, a network of at least ten bench marks is installed in the vicinity of the

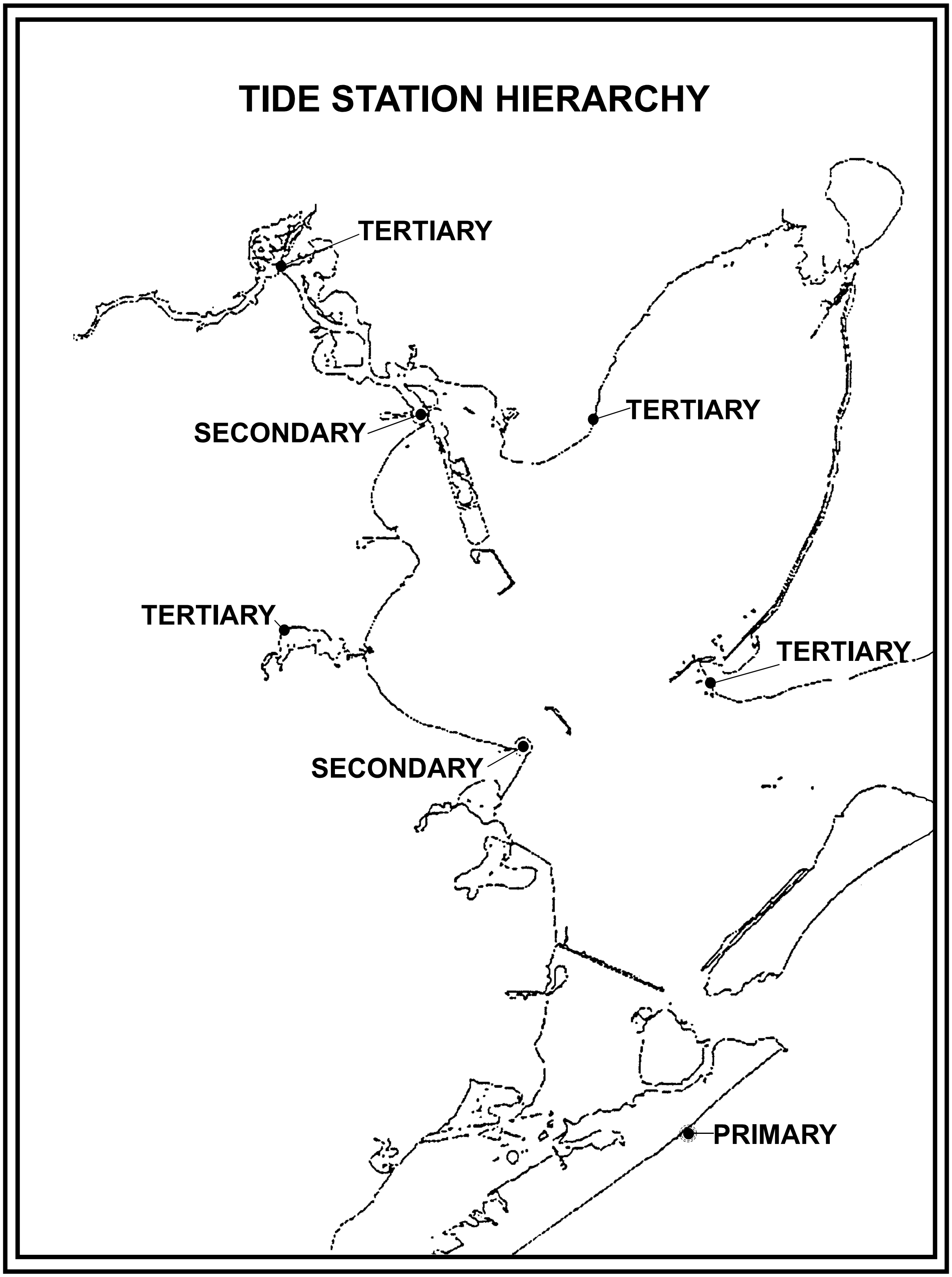


Figure 6. Illustration of tide station network hierarchy.

station. Five bench marks are installed at secondary and tertiary stations. At least three bench marks are installed at short term (less than 30 days) stations.

Bench marks are leveled whenever a new tide station is established, or when data collection is discontinued at a tide station. Bench marks are also leveled before and after maintenance is performed at a station, and at least annually to perform stability checks. In addition, whenever new bench marks are installed, the existing bench marks are re-leveled. Differential levels (Figure 7) are used to check the elevation differences between bench marks, to extend vertical control, and to monitor the stability of the water level measurement gauge. The quality of leveling is a function of the procedures used, the sensitivity of the leveling instruments, the precision and accuracy of the rod, the attention given by surveyors, and the refinement of the computations. Bench marks are leveled by either compensator leveling instruments, or by an electronic digital barcode system. Compensator-type leveling instruments require double running. However, under certain circumstances, electronic digital/barcode systems allow for single running. *The User's Guide for the Installation of Bench Marks and Leveling Requirements for Water Level Stations (Hicks et al., 1987)* and *NOAA Manual NOS N.S. 1 (Floyd, 1978*) provide detailed guidelines for bench mark installations and leveling. The Standards and Specifications for Geodetic Control Surveys includes interim Federal Geodetic Control Subcommittee specifications and procedures to incorporate electronic digital/barcode levels. The National Tidal Benchmark System (NTBMS) provides datum information for previously and currently occupied tidal measurement locations. The number of stations in the NTBMS is approximately 6000. Bench marks may become invalid due to crustal movement, and may also be invalidated by changes in local tidal characteristics due to dredging, erosion, and accretion. In many cases, bench marks in the NTBMS have not been releveled in many years, resulting in some uncertainty in their validity. At present, about 2000 stations have bench marks with valid published elevations.

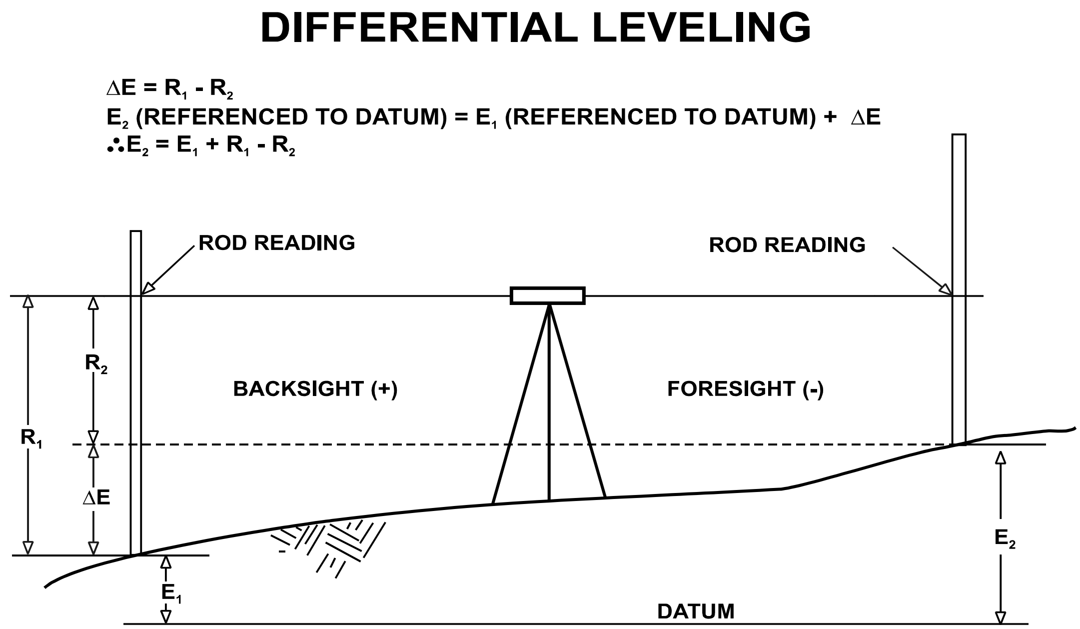
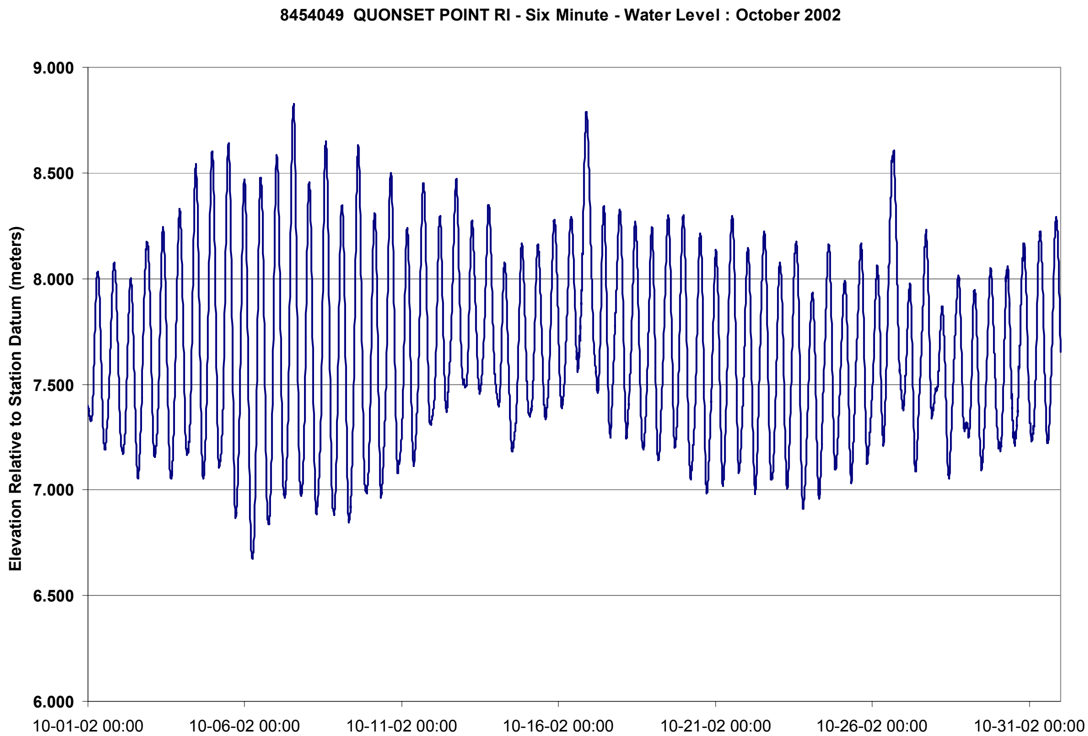


Figure 7. A schematic diagram of extending vertical control inland from the tidal datum by the method of differential leveling.

2.6 Data Processing Procedures

Data collected from the field must be processed and tabulated before tidal datums are computed. This section reviews the procedures used to perform this processing. Raw unedited water level data collected from tide gauges should undergo preliminary quality control such as checking for outliers, gaps, distorted tide curves, and undocumented shifts in datum or scale factor. NOS collects data at 6-minute intervals, but other intervals can be used successfully. Six-minute intervals were chosen to easily allow times of the high and low tides to be estimated to the nearest tenth of an hour. The procedure of preliminary review consists of manually or automated checks of the data, making relevant comparisons with backup sensors, tide staffs, nearby stations, or predicted tides, and scanning any automated instrument and data acquisition reports. Small gaps in data should be filled to get a time series that is as continuous as possible. NOS fills small gaps up to 3 to 4 hours using least-squares curve fits of the 6-minute data. Longer gaps in data up to 3-days are filled in a hierarchical sense depending on location and availability of source data. If data from backup sensors are not available, the gaps are inferred using data from nearby stations or predicted tides. Gaps are left in the data if source data to fill them are insufficient.

Once the gaps are filled, and depending upon the type of station, the tabulation process is carried out that includes generation of hourly heights, generation of high and low tides, and selection of higher high and lower low waters. NOS tabulates the times and heights and high and low waters by using a least-squares polynomial curve fit to the 6-minute tide data. Hourly heights are tabulated as every tenth 6-minute interval value (Figures 8a and b). After this the monthly means computed for the various datums. The time-series data, hourly heights, high and low waters, higher highs and lower lows, and monthly means are subsequently verified by a senior analyst (Figure 9).



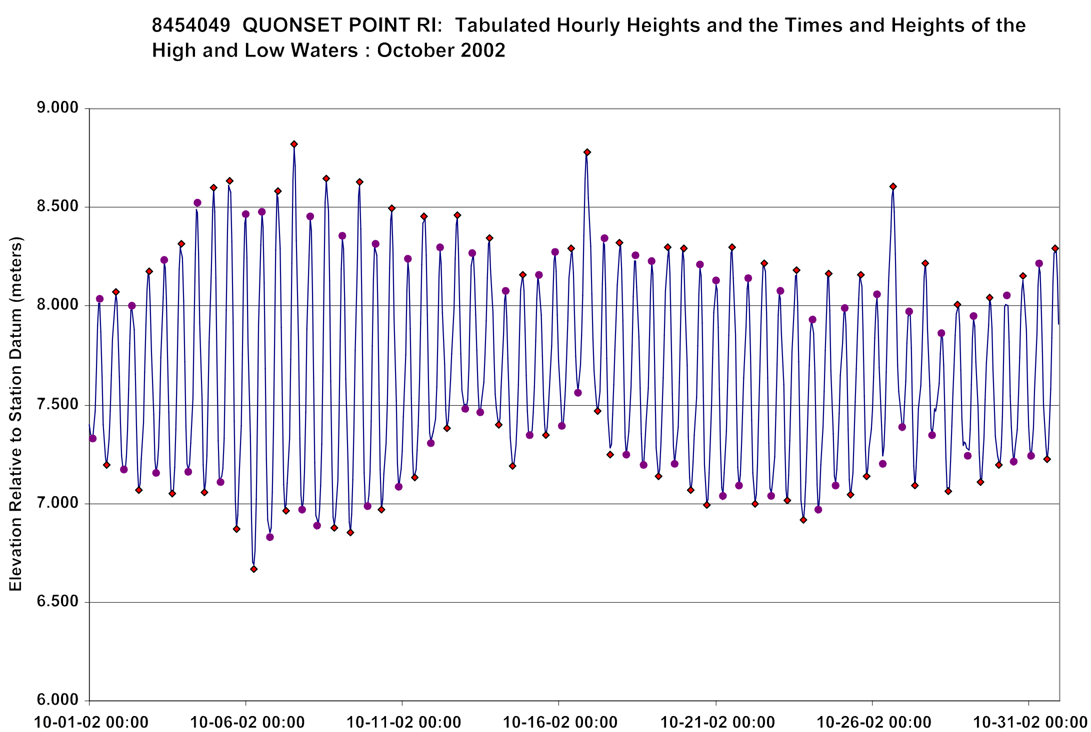


Figure 8a and b. Observed 6-minute data for one month and results from the tabulation of the tide.

Jan 28 2003 08:24 HIGH/LOW WATER LEVEL DATA October, 2002

Station: 8454049 T.M.: 0 W

Name: QUONSET POINT, RI Units: Meters

Type: Mixed Datum: Station Datum

Note: > Higher-High/Lower-Low [] Inferred Tide Quality: Verified

Day	High Time	High Height	Low Time	Low Height	Day	High Time	High Height	Low Time	Low Height
1	7.5	8.037	2.4	7.326	16	> 9.7	[8.292]	2.6	7.394
	> 20.2	8.071	> 12.9	7.197		> 21.3	8.782	14.6	7.563
2	8.8	8.000	2.6	7.173	17	10.6	8.345	> 6.0	7.470
	> 21.4	8.176	> 14.3	7.066		> 22.8	8.323	> 15.4	7.245
3	9.5	8.233	3.2	7.157	18	10.7	8.257	4.0	7.248
	> 22.3	8.314	> 15.6	7.049		23.3	8.230	16.7	7.196
4	10.5	8.525	4.1	7.163	19	> 11.8	8.296	> 4.3	7.140
	> 23.1	8.599	> 16.3	7.057		> 23.4	8.292	17.1	7.204
5	> 11.5	8.632	4.4	7.109	20			> 5.0	7.066
	23.8	8.466	> 17.1	6.873		12.4	8.209	> 17.5	6.994
6			> 5.8	6.670	21	0.4	[8.128]	5.8	7.036
	12.2	8.477	18.2	6.832		> 12.8	8.297	18.1	7.090
7	> 0.5	8.582	> 6.4	6.961	22	0.9	8.142	> 6.5	6.999
	> 13.3	8.819	19.2	6.969		> 13.4	8.216	19.0	7.040
8	1.3	8.457	6.9	6.888	23	1.4	[8.075]	> 6.9	7.013
	> 14.0	8.644	> 20.1	6.877		> 13.7	[8.180]	> 19.1	6.915
9	2.3	8.355	> 7.9	6.852	24	2.1	7.934	7.3	6.969
	> 14.9	8.631	20.9	6.986		> 14.7	8.164	19.9	7.093
10	3.4	8.316	> 8.2	6.969	25	2.9	[7.993]	> 8.0	7.047
	> 15.8	8.497	21.2	7.086		> 15.4	8.156	> 20.3	7.136
11	4.3	8.240	> 9.4	7.129	26	3.8	[8.061]	8.3	7.204
	> 16.7	8.455	22.1	7.305		> 16.2	8.607	23.5	7.389
12	5.2	8.295	> 10.3	7.380	27	4.6	7.974	> 9.1	7.090
	> 17.7	8.462				> 17.1	8.216	21.9	7.348
13	5.9	8.266	0.5	7.481	28	5.4	7.860	> 10.5	7.064
	> 18.7	8.344	11.8	7.461		> 17.9	8.008		
14	6.8	8.077	> 2.2	7.401	29	6.2	7.949	1.5	7.243
	> 20.1	8.161	> 12.7	7.190		> 18.6	8.042	> 11.6	7.109
15	8.3	8.156	2.0	7.349	30	7.3	[8.052]	> 1.5	7.197
	20.9	8.273	> 14.1	7.344		> 20.0	[8.154]	13.0	7.211
					31	8.3	8.215	2.1	7.239
						> 20.7	8.290	> 14.1	7.222

Highest Tide: 8.819 13.3 Hrs Oct 7 2002
Lowest Tide: 6.670 5.8 Hrs Oct 6 2002

Monthly Means: MHHW 8.357
MHW 8.272 DHQ 0.085
MTL 7.707 GT 1.266 HWI 0.42 Hrs
DTL 7.724 MN 1.131 LWI 6.13 Hrs
MSL 7.668
MLW 7.141 DLQ 0.050
MLLW 7.091

Figure 9. Example of a Monthly Tabulation of the Tide

2.7 The National Tidal Datum Epoch

As mentioned in section 2.1, a specific nineteen year period designated as a National Tidal datum Epoch (NTDE) is used to compute tidal datums because it is the closest full year to the 18.6-year nodal cycle, the period required for the regression of the moon's nodes to complete a circuit of 360˚ of longitude (Schureman, 1941). The NTDE is used as the fixed period of time for the determination tidal datums because it includes all significant tidal periods, is long enough to average out the local meteorological effects on sea level, and by specifying the NTDE, a uniform approach is applied to the tidal datums for all stations.

The relative secular sea level change, as well as the variability of the change by geographic region, is readily seen (Figure 10) where the yearly mean sea level is plotted against time. For datum computation, the National Tidal Datum Epoch is used as the fixed period of time for the determination of tidal datums because it includes all significant tidal periods, is long enough to average out the local meteorological effects on sea level, and by specifying the NTDE, uniformity is applied to all the tidal datums. However, because of relative sea level change, as the years pass, tidal datums become out of date for navigational purposes and for other applications. Thus, a new NTDE must be considered periodically (Hicks, 1981). The policy of NOS is to consider a new tidal datum epoch every 25 years to appropriately update the tidal datums to account for the global sea level change and long-term vertical adjustment of the local landmass (e.g., due to subsidence or glacial rebound)(Gill et al, 1998). Figure 11 shows the effect of sea level rise on the elevation of MTL over various NDTE periods. NOS will be updating from the 1960-78 NTDE to a 1983-2001 NTDE in 2003. Estimated relative sea level trends compiled from observations at U.S. tide stations are found in Zervas (2000).

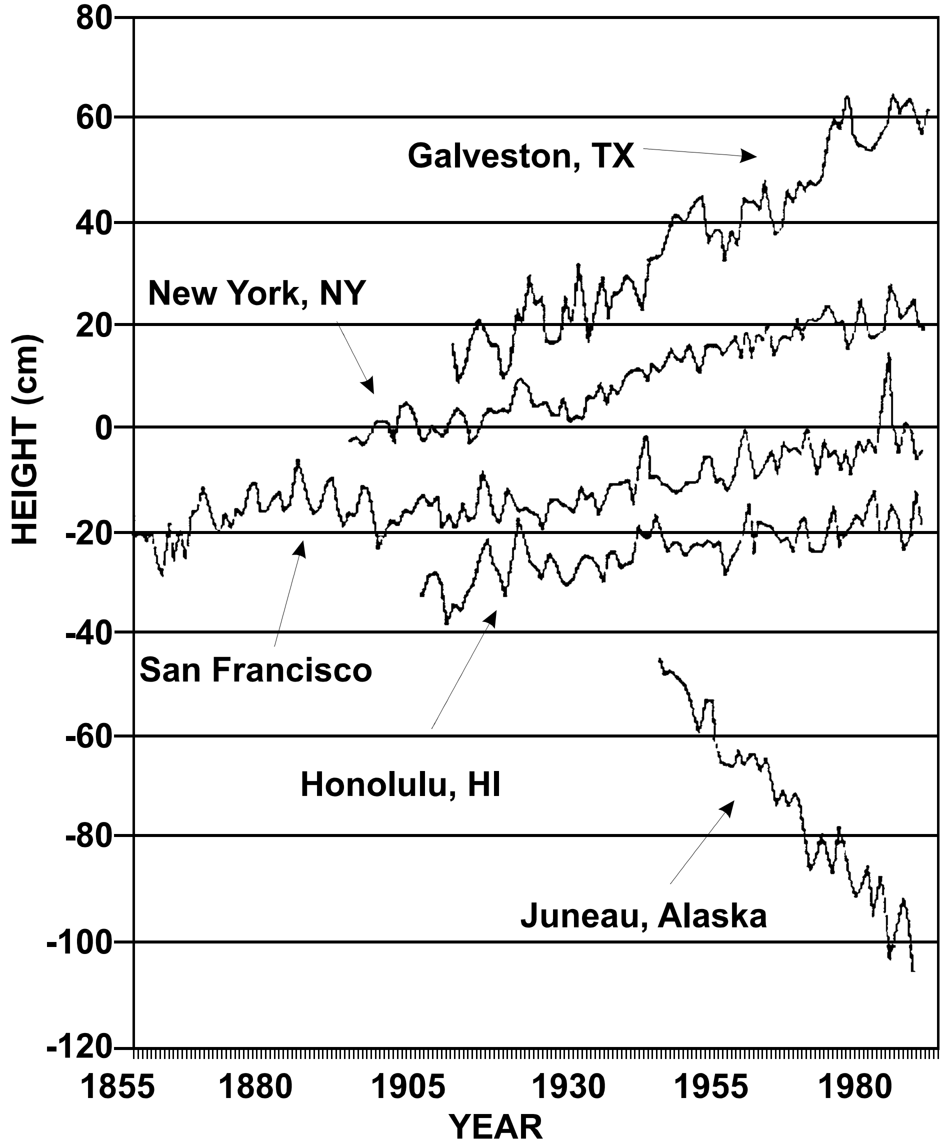


Figure 10. Relative sea level change at several locations in the U.S.

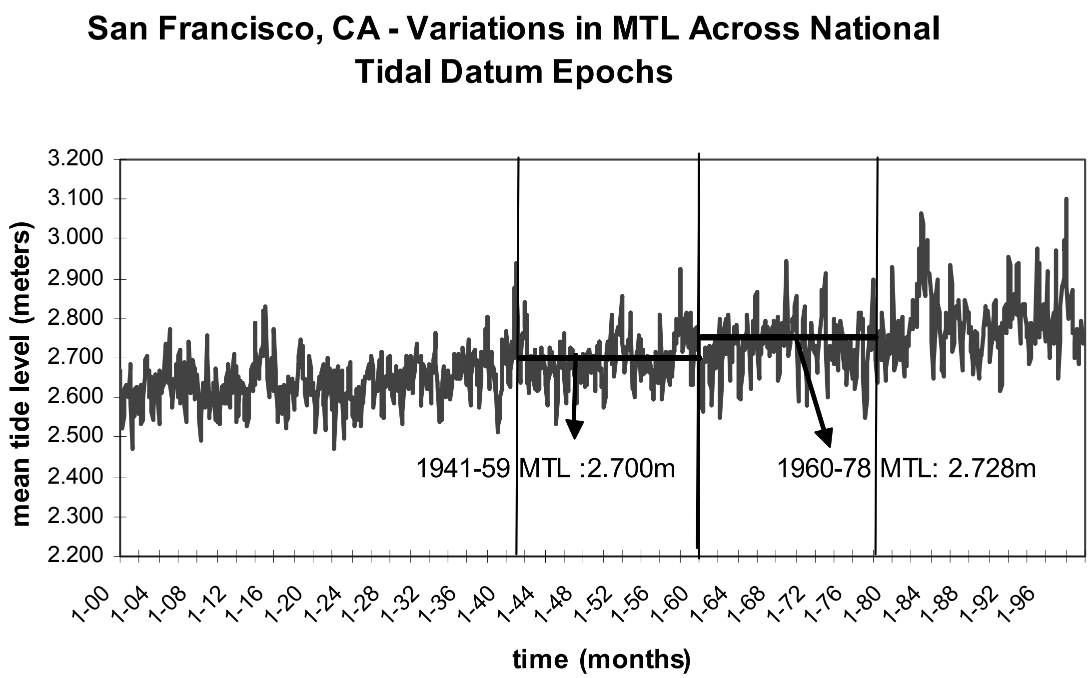


Figure 11. Illustration of the long term changes in sea level causing the need to update tidal datums such as mean tide level (MTL). The graph shows the annual values of mean tide level with horizontal lines drawn to show the 19-year MTL values for the 1941-59 and 1960-78 NTDE.

3. GENERAL TIDAL DATUM COMPUTATION PROCEDURES

3.1 Datum Computation Procedures Overview

A vertical datum is termed a tidal datum when it is defined by a certain phase of the tide. Tidal datums are local datums and should not be extended into areas which have differing hydrographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as bench marks.

1. Make Observations - Tidal datums are computed from continuous water level observations over specified lengths of time. Observations are made at specific locations called tide stations. Each tide station consists of a water level gauge or sensor(s), a data collection platform or data logger and data transmission system, and a set of tidal bench marks established in the vicinity of the tide station. NOS collects water level data at 6-minute intervals.

2. Tabulate the Tide - Once the 6-minute interval data are quality controlled and any small gaps filled, the data are processed by tabulating the high and low tides and hourly heights for each day. Tidal parameters from these daily tabulations of the tide are then reduced to mean values, typically on a calendar month basis for longer period records or over a few days or weeks for shorter-term records.

3. Compute Tidal Datums - First reduction tidal datums are determined directly by averaging values of the tidal parameters over a 19-year NDTE. Equivalent NDTE tidal datums are computed from tide stations operating for shorter time periods through comparison of simultaneous data between the short-term station and a long term station.

4. Compute Bench Mark Elevations - Once the tidal datums are computed from the tabulations, the elevations are referenced to the bench marks established on the land using the elevation differences established by differential leveling between the tide gauge sensor "zero" and the bench marks during the station operation. The bench mark elevations and descriptions are disseminated by NOS through a station specific published bench mark sheet. Connections between tidal datum elevations and geodetic elevations are obtained after leveling between tidal bench marks and geodetic network bench marks. Traditionally, this has been accomplished using differential leveling, however GPS surveying techniques can also be used (NGS, 1997).

A primary determination of any tidal datum is based directly on the average of observations over a 19 year period. For example, a primary determination of Mean High Water is based directly on the average of the high waters over a 19 year period. Tidal datums must be specified with regard to the NTDE. Although many tidal datums are discussed in this report, the principal tidal datums include Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Sea Level (MSL), Mean Low Water (MLW), and Mean Lower Low Water (MLLW) (Marmer, 1951 and NOS, 2000).

MHHW is defined as the arithmetic mean of the higher high water heights of the tide observed over a specific 19-year Metonic cycle (the National Tidal Datum Epoch). Only the higher high water of each pair of high waters of a tidal day is included in the mean (Figure 1). For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of a 19-year value (Marmer, 1951).

MHW is defined as the arithmetic mean of all of the high water heights observed over a specific 19-year Metonic cycle (the NTDE). For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of a 19-year value.

MSL is defined as the arithmetic mean of hourly heights observed over a specific 19-year Metonic cycle (the NTDE). Shorter series are specified in the name, like monthly mean sea level or yearly mean sea level (e.g., Marmer, 1951; Hicks, 1985).

MLW is defined as the arithmetic mean of all of the low water heights observed over a specific 19-year Metonic cycle (the NTDE). For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of a 19-year value.

MLLW is defined as the arithmetic mean of the lower low water heights of the tide observed over a specific 19-year Metonic cycle (the NTDE). Only the lower low water of each pair of low waters of a tidal day is included in the mean. For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of a 19-year value.

In addition, the Mean Tide Level (MTL), Diurnal Tide Level (DTL), Mean Range (Mn), Diurnal High Water Inequality (DHQ), Diurnal Low Water Inequality (DLQ), and Great Diurnal Range (Gt) are defined as follows:

MTL is a tidal datum equivalent to the average of MHW and MLW.

DTL is a tidal datum equivalent to the average of MHHW and MLLW.

Mn is the difference in elevation between MHW and the MLW.

DHQ is the difference in elevation between MHHW and MHW.

DLQ is the difference in elevation between MLW and MLLW.

Gt is the difference in elevation between MHHW and MLLW.

3.2 Other Vertical Datums and Their Relationship to Tidal Datums

In addition to tidal datums, other vertical datums are determined and employed for various applications. Examples are fixed datums of the National Geodetic Reference System, or the National Geodetic Vertical Datum (NGVD 1929) (previously referred to as the Sea Level Datum of 1929), or the North American Vertical Datum of 1988 (NAVD 88). NGVD 1929 is a fixed datum adopted as a standard geodetic reference for heights and was derived from a general adjustment of the first order leveling nets of the US and Canada, in which MSL was held fixed as observed at 26 stations in the US and Canada. Numerous adjustments have been made to these leveling networks since originally established in 1929. The North American Vertical Datum of 1988 (NAVD 88) involved a simultaneous least-squares, minimum constraint adjustment of the Canadian-Mexican-US leveling observations. Local MSL was held fixed at Father Point/Rimouski, Quebec, Canada, as the single constraint. The North American Vertical Datum of 1988 (NAVD 88) and International Great Lakes Datum of 1985 (IGLD 85) are both based upon this simultaneous, least-squares, minimum constraint adjustment of Canada, Mexico, and U.S. leveling observations. These fixed geodetic datums (e.g., NGVD 1929 and NAVD 88) do not reflect the changes in sea level and because they represent a "best" fit over a broad area, their relationship to local mean sea level differs from one location to another. MSL is a tidal datum often confused with NGVD 1929 and they are not equivalent. NGVD 1929 was replaced by NAVD 88 and the National Geodetic Survey no longer supports the NGVD 1929 system.

Figure 12 shows the datums related to Station Datum (STND) at San Francisco Bay, CA. The elevation of the primary bench mark (PBM 180 1936), is 5.794 m above STND. The Highest Water Level (HWL) recorded at San Francisco is 4.462 m above station datum, and the Lowest Water Level (LWL) is 0.945 m . HWL and LWL are not tidal datums, but are the extreme values of the maximum and minimum water levels recorded at the station. For San Francisco Bay, the value of NGVD 29 is below Mean Sea Level (MSL), and NAVD88 is lower still. MSL pertains to local mean sea level and should not be confused with NAVD 88, the ellipsoid or the superseded NGVD 29. Figures 13a and 13b show why the direct transfer of tidal datum relationships through NAVD 88, NGVD 29 or the ellipsoidal differences, even within the same bay, estuary or river, may not be accurate. The graph illustrates that tidal datums are local datums relative to the land and great care must be taken to extrapolate tidal datum differences and relationships to geodetic datums. In some instances, linear interpolation can be used to estimate datum relationships between two known points along a stretch of shoreline that is not very complicated in a topographic and bathymetric sense.

When in doubt of the relationship of a tidal datum to a geodetic datum, establishment of a tide station and connection to geodetic datum using differential levels or GPS is recommended for most applications. NOS establishes geodetic connections at the NWLON stations through differential levels between tidal bench marks and geodetic bench marks. Use of GPS survey equipment to occupy tidal bench marks is the emerging state-of-the-art method for making the connections. See the NOS Web-sites at www.tidesandcurrents.noaa.gov and www.ngs.noaa.gov for further information on geodetic and tidal datum elevations on bench marks.

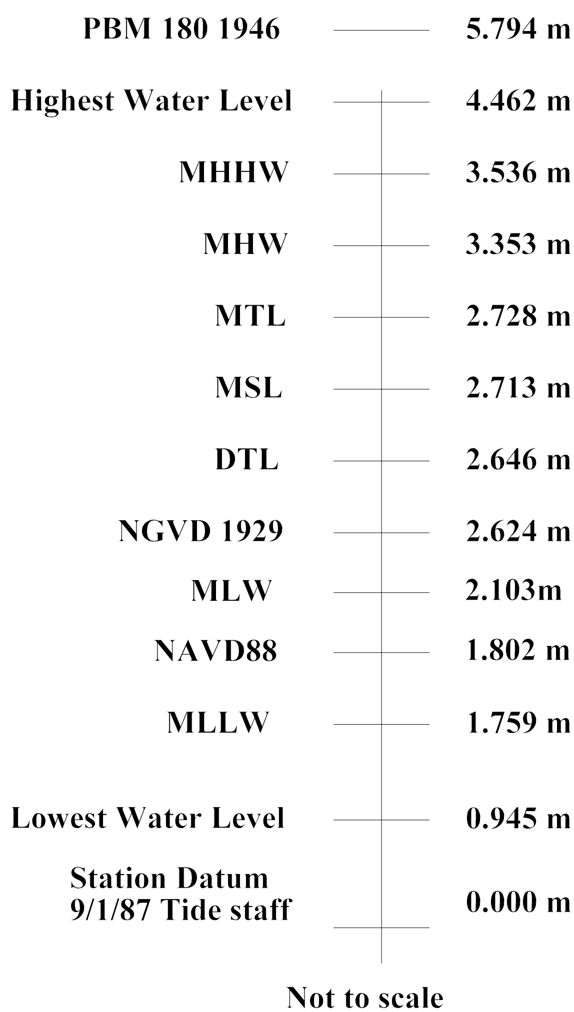


Figure 12. A tidal datum stick diagram for San Francisco, CA showing the relationships of the various tidal and geodetic datums.

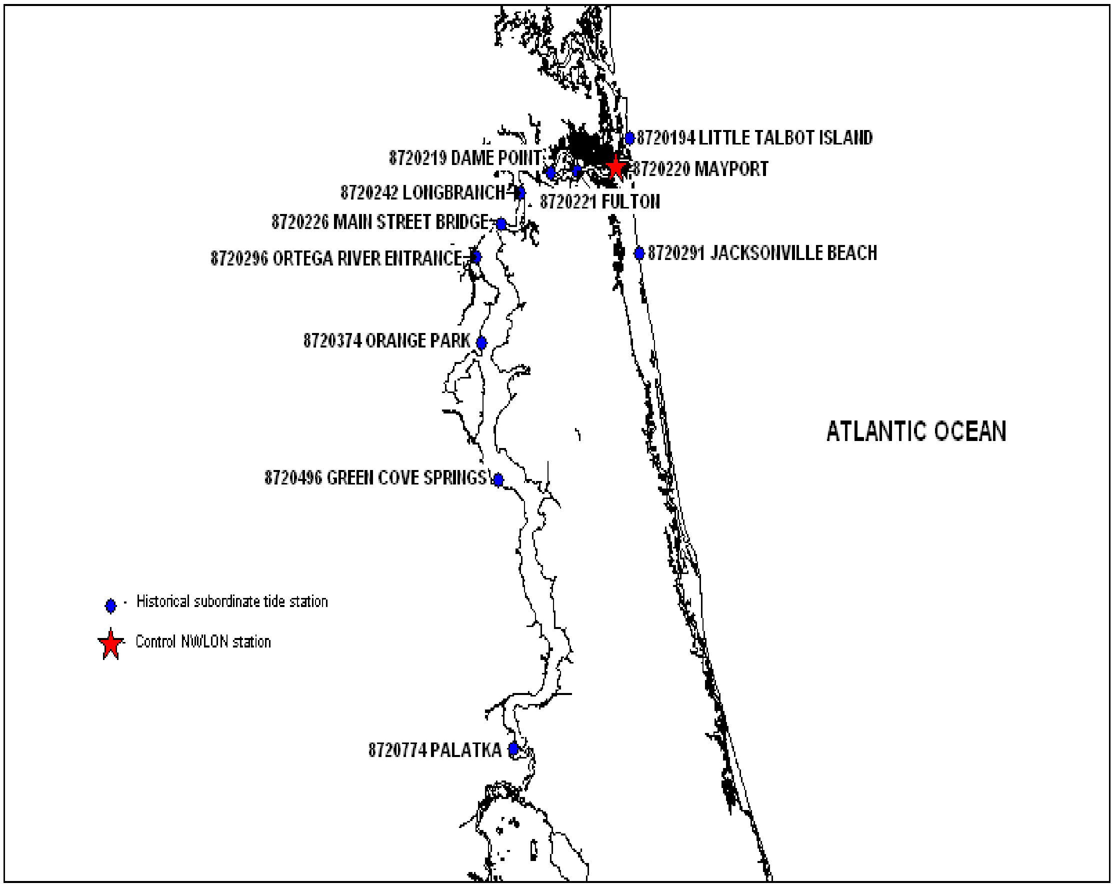


Figure 13a. Locations of stations plotted in Figure 13b.

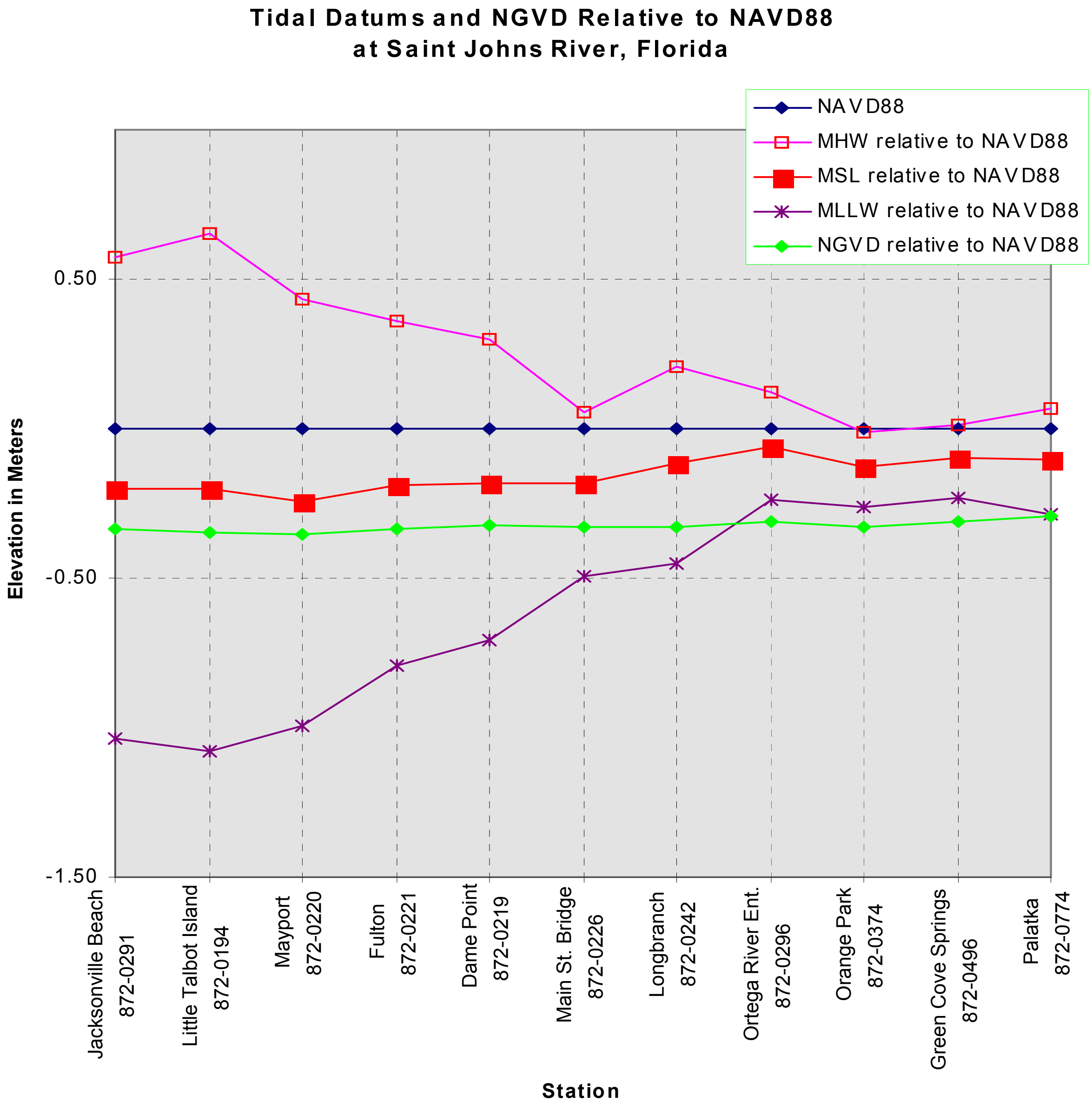


Figure 13b. The relationship of the geodetic datums to tidal datums in the St. John's River, FL. The perspective is going upstream from left to right. The graph was constructed by assigning NAVD88 to a relative zero value at each site, and adjusting the other datums accordingly.

3.3 Steps Required to Compute Tidal Datums at Short-Term Stations

Due to time and resource constraints, primary determinations of tidal datums (i.e. using 19 years of data) are not practical at every location along the entire coast where tidal datums are required. At intermediate locations, a secondary determination of tidal datums can usually be made using observations covering much shorter periods than 19 years. Results are corrected to an equivalent mean value by comparison with a suitable control tide station (Marmer, 1951).

Conceptually, the following steps need to be completed in order to compute equivalent NTDE tidal datums listed in section 3.1 at short term stations using the method of comparison of simultaneous observations:

1) Select the time period over which the simultaneous comparison will be made.

2) Select the appropriate control tide station for the subordinate station of interest based on location, tidal characteristics, and availability of data.

. 3) Obtain the simultaneous data from subordinate and control stations and obtain or tabulate the tides and compute monthly means, as appropriate.

4) Obtain the accepted NTDE values of the tidal datums at the control station from NOS via the CO-OPS Website (www.tidesandcurrents.noaa.gov)

5) Compute the mean differences and/or ratios (as appropriate) in the tidal parameters between the subordinate and control station over the period of comparison.

6) Apply the mean differences and ratios computed in step 5, above, to the accepted values at the control station to obtain equivalent or corrected NTDE values for the subordinate station. The computations use slightly different formulas depending on the type of tide. These differences are explained in section 3.4 and in Chapter 4.

3.4 Datum Computation Methods

There are some key datum computation methods used by NOS (in step 6, above) that differ slightly depending upon the tidal characteristics and the type of tide.

Standard Method. This method is generally used for the West Coast and Pacific Island stations and is also called the Range Ratio Method. First, equivalent NTDE values for MTL, Mn, DHQ and DLQ are determined by comparison with an appropriate control. From these, the following are then computed:

MLW = MTL - (0.5 x Mn)
MHW = MLW + Mn
MLLW= MLW - DLQ
MHHW = MHW + DHQ

Modified-Range Ratio Method. This method is generally used for the East Coast, Gulf Coast and Caribbean Island stations. First, equivalent NTDE values for MTL, DTL, Mn and Gt as determined by comparison with an appropriate control. The difference from the Standard Method is that ratios of the DHQ and DLQ values are not used to compute MHHW and MLLW because numerically the values are very small for semidiurnal tide areas. A Gt ratio about DTL is used instead. From these, the following are computed:

MLW = MTL - (0.5 x Mn)
MHW = MLW + Mn
MLLW= DTL - (0.5 x Gt)
MHHW = MLLW + Gt

Direct Method. This method is usually used only when a full range of tidal values are not available. For example, direct MHW can be computed for situations when low waters are not recorded, such as in the upper reaches of a marsh. Since MTL, DTL, and Mn and Gt cannot be determined if low waters are cut-off, equivalent NTDE values for MHW and MHHW datums are determined directly by comparison of high tides with an appropriate control using the available part of the tidal cycle.

3.5 Accuracy

Generalized accuracies for datums computed at secondary or tertiary stations in terms of the standard deviation error for the length of the record are summarized in Table 1 (see Swanson, 1974). These values were calculated using accepted datums for control station pairs in the NWLON. The values in Table 1 are the confidence intervals for the tidal datums based on the standard deviation.

Table 1. Generalized accuracy of tidal datums for East, Gulf, and West Coasts when determined from short series of record and based on the standard deviation(one-sigma). From Swanson (1974).

Series Length (months)	East Coast (cm)	(ft.)	Gulf Coast (cm)	(ft.)	West Coast (cm)	(ft.)
1	3.96	0.13	5.48	0.18	3.96	0.13
3	3.05	0.10	4.57	0.15	3.35	0.11
6	2.13	0.07	3.65	0.12	2.43	0.08
12	1.52	0.05	2.74	0.09	1.82	0.06

It is helpful to view the data in Table 1 graphically (Figure 14). The Swanson error curves are similarly shaped for each coast. Ranked by coast, the errors are smallest for the East and West coasts, with the largest errors on the Gulf coast. The largest errors coincide with the least data, and decrease asymptotically to a finite value with increasing data. This handbook contains examples which apply datum computation techniques to water level data with series lengths of about 1 week, and also for twelve months. Examples containing a week of data or less should be interpreted as having generalized errors greater than or equal to those for a 1-month data series shown on the first row of Table 1. Examples containing a year of data have generalized errors that correspond to the fourth row.

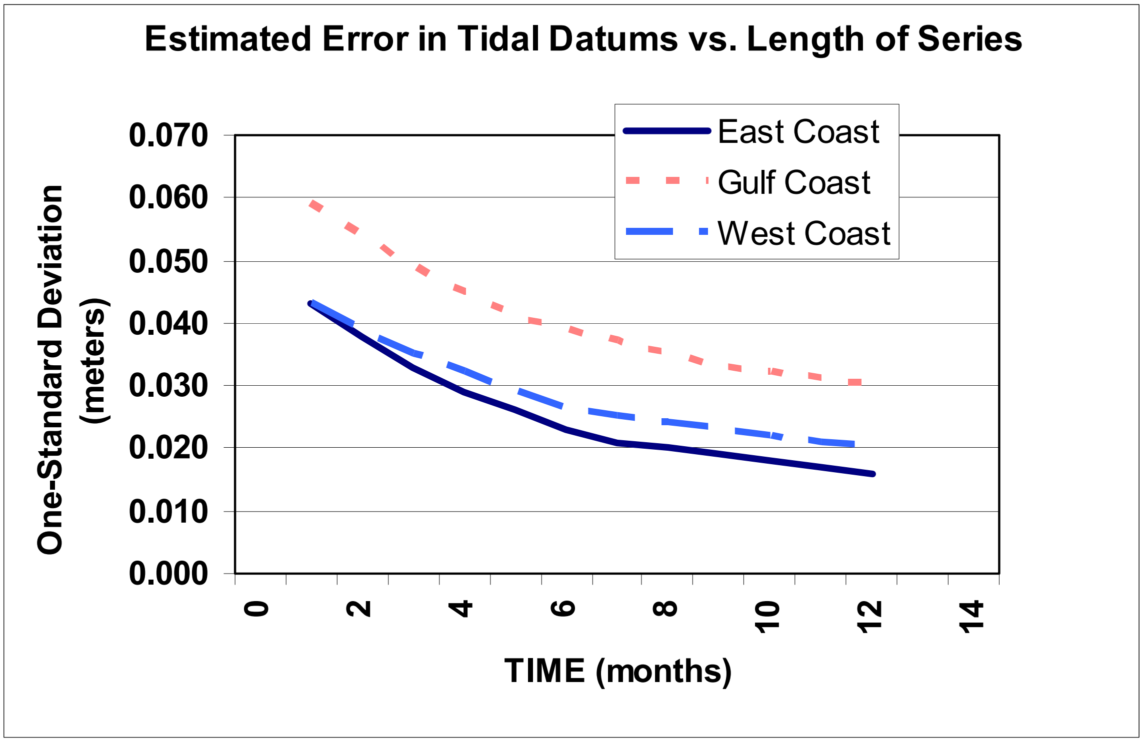


Figure 14. Estimated Error in Tidal Datums from Swanson (1974)

The uncertainty in the value of the tidal datum translates into a horizontal uncertainty of the location of a marine boundary when the tidal datum line is surveyed to the land (Demarcating and Mapping Tidal Boundaries, 1970). Table 2 expresses the uncertainty in the marine boundary as a function of the slope of the land. A slope of 1% means that the land rises 1 meter for every 100 meters of horizontal distance. This is illustrated in Figure 15.

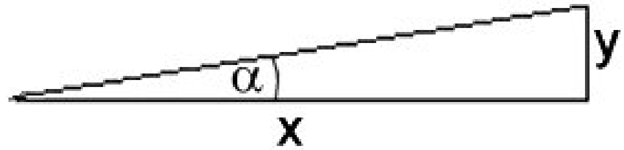


Figure 15. Let x be the horizontal distance inland, and y be the vertical rise of the land. By definition tan(α) = y/x. Likewise, the cotangent of α, denoted cot(α), is given by cot(α) = x/y .

In Figure 15, denote the horizontal distance inland as x, and denote the vertical elevation change as y. Denote the error (i.e., vertical error from Table 1) in the tidal datum as Δy. The upper bound on Δy is 0.03 m from Table 1, based upon 12 months of data from the Gulf coast. This vertical error, Δy, translates into a horizontal error in determining the location of the tidal datum on the ground. Denote this horizontal error as Δx. Given the errors of Table 1, if one knows the slope of terrain, given by y/x, (also presented in the first column of Table 2 in percent form), one can estimate the uncertainty of the horizontal location Δx, by the following formula,

$$\frac{y}{\Delta y} \sim \frac{x}{\Delta x}$$

Rearranging, we find,

$$\Delta x \sim \Delta y \frac{x}{y} = \Delta y \cot(\alpha)$$

Returning to Table 2, the first column of Table 2 is the percent of the slope of the terrain, or (y/x)*100%. The reciprocal of the slope, (x/y), represents cot(α). The second column of Table 2 merely represents the slope in degrees. The first row represents very gentle slopes, and the last row represents steep slopes. The horizontal uncertainty is suggested in column three. The horizontal uncertainty Δx, is defined as (Δy)x[cotangent(α)], using from Table 1, a Δy = 0.03 m, which represents an upper bound for the vertical uncertainty in a tidal datum based on comparison of observations for a year's period of time at a subordinate station. The greatest errors in the determination of the marine boundary obviously occur for relatively flat terrain, which is characteristic of broad sections of the Atlantic and Gulf Coasts, and wetlands.

Thus, an engineer or surveyor who needs to determine the location of private property or state owned tide lands in a coastal zone (Figure 15) with a slope of 0.1% could potentially experience an error of over 30 meters (at the 1-sigma level, twice this at the 2-sigma or 95% confidence level) given a year of observations at a subordinate station installed in the local area. Fewer observations (e.g., one week of data) would make the error larger as illustrated by Tables 1 and 2.

Table 2. Error in position of marine boundary as a function of the slope of the land (12 month series).

% of Slope	Degree of Slope (degrees)	Error (meters)
0.1	0.05	32.3
0.2	0.1	14.9
0.5	0.3	6.1
1	0.6	3
2	1	1.5
5	3	0.61
10	6	0.3
15	9	0.18
20	11	0.15
30	17	0.09
50	27	0.06
100	45	0.03

4. WORKED EXAMPLES OF TIDAL DATUMS

4.1 Procedural Steps

The procedural steps required to compute tidal datums at short-term stations are illustrated in this manual using examples. The first three examples illustrate the method of comparison of simultaneous observations using monthly means from a control and subordinate station in a region of similar tidal characteristics to produce equivalent datums at the subordinate station. Even though these examples use 12 months of data, data sets with more or less months use the same procedure. The second three examples cover the three types of tide using the tide by tide comparison (TBYT) procedure. These are computed by comparison of individual simultaneous high and low waters between the tertiary station and a primary control, or an acceptable secondary control station, in a region of similar tidal characteristics. The last example is one that shows the use of the direct comparison of mean values for high water datum determination.

The examples found in this Chapter provide details of the formulas and procedures required to complete steps 4 through 6 found in Section 3.3. Note that the Standard Method is used on the West Coast, and the Modified Range Ratio method is used for a Gulf Coast example (see section 3.4). The Modified Range Ratio method was adopted procedurally for both diurnal and semidiurnal tide types because the ratios formed from numerically small ranges of tide and small inequalities using the Standard Method become inconsistent from month to month. So in these cases MHHW and MLLW are computed using DTL and Gt.

4.2 Comparison of Monthly Means

4.2.1 Modified Range Ratio Method - Semidiurnal Tides

The first example describes computing tidal datums for secondary stations with a semidiurnal tide. The procedure involves selecting a suitable control station with known 19-year values of the datums, and reducing the subordinate station data to equivalent 19-year mean values. Along the East Coast of the United States the tides are predominantly semidiurnal over large distances of the coast, and many candidate example cases exist. A simple case is offered by the comparison of Fort Pulaski, GA to Charleston, SC. Their locations are shown in Figure 16. For this example, Fort Pulaski is being treated as the subordinate station for which datums need to be computed and Charleston is being treated as the control station.

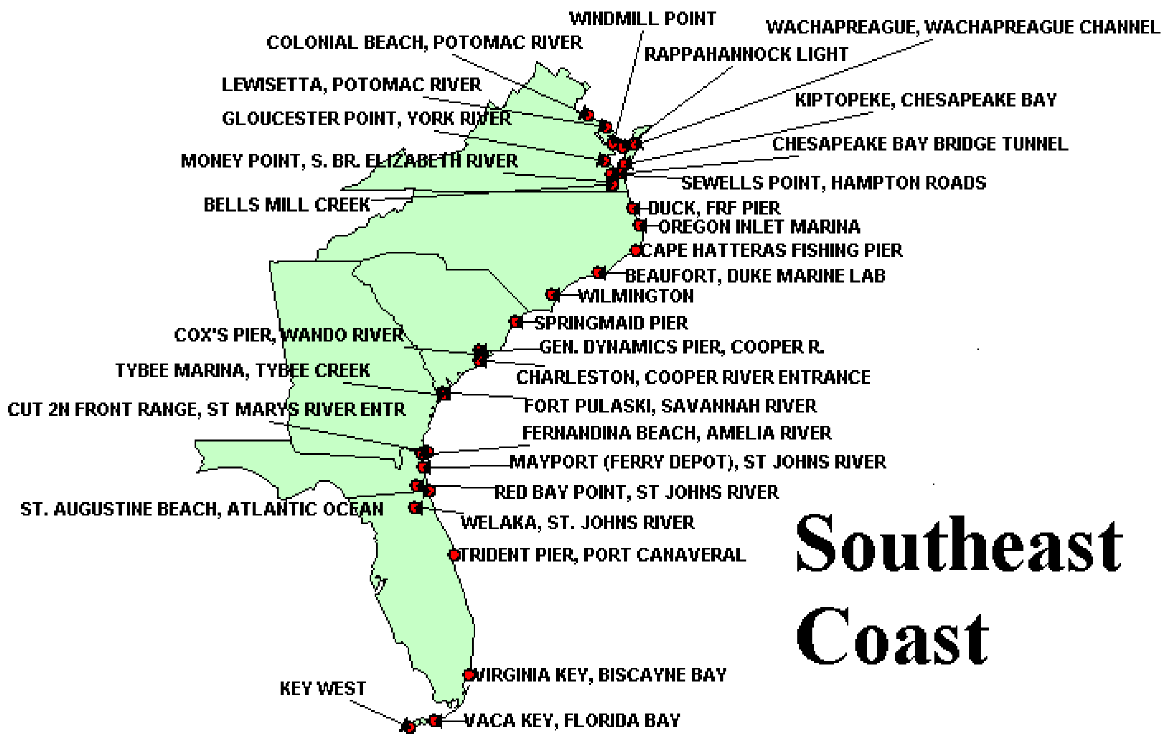


Figure 16. NWLON station locations along the South Atlantic Bight.

From the CO-OPS website, http://www.tidesandcurrents.noaa.gov/, verified, historical, and monthly mean water level data, and accepted datums, may be downloaded. A year of monthly mean data are shown in Tables 3 and 4. Figures 17a and 17b show plots of a subset of these monthly means. The data were downloaded from the hyperlink U.S. and Global Coastal Stations, under Verified/Historical Water Level Data.

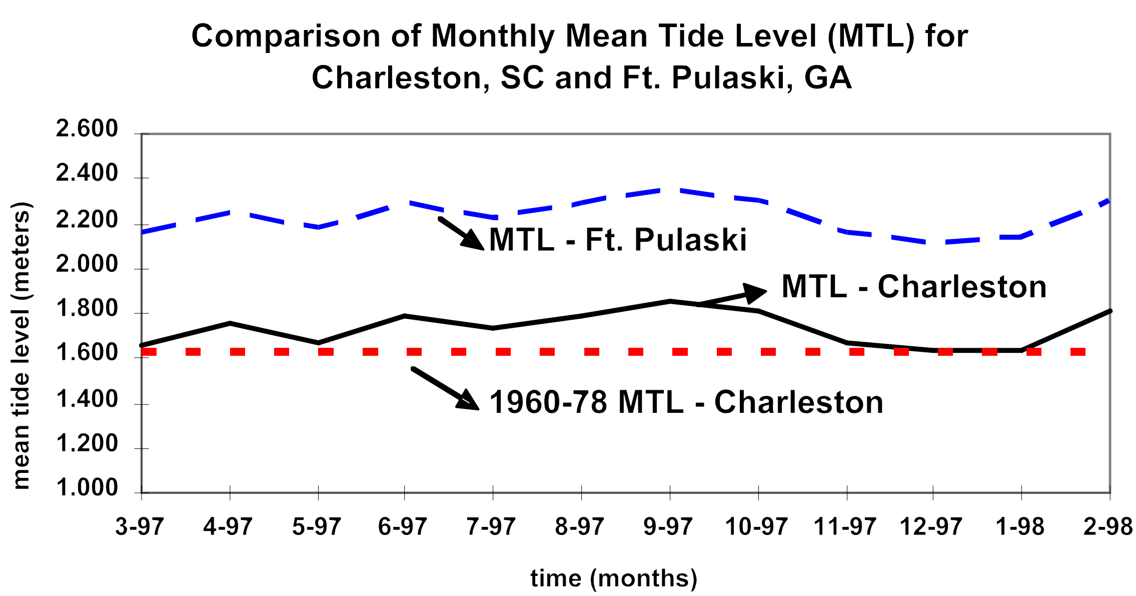


Figure 17a. Time series plots of monthly mean tide level (MTL) for Fort Pulaski, GA and Charleston, SC.

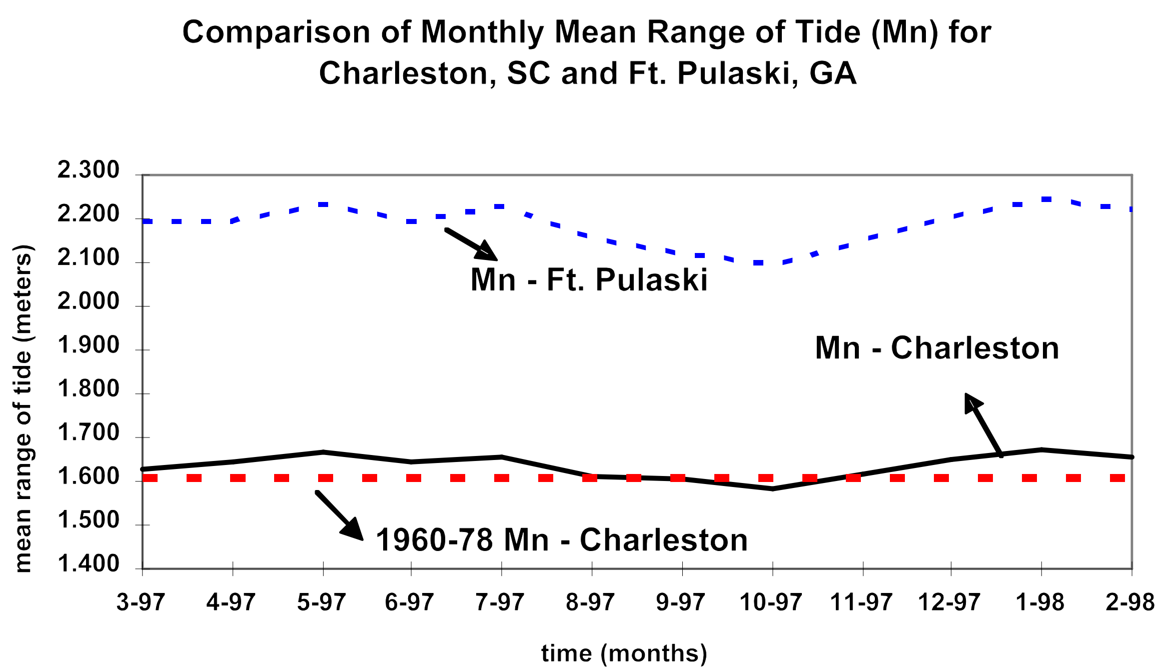


Figure 17b. Time series plot of the monthly mean range of tide (Mn) for Ft. Pulaski, GA and Charleston, SC.

Table 3. NOS monthly mean water levels for Fort Pulaski, GA. These data are verified, monthly mean values. STND refers to station datum, an arbitrary, vertical reference point at a given station.

Data are in Meters above STND and Times are on UTC (GMT)
8670870 FORT PULASKI, SAVANNAH RIVER , GA from 199703 to 199802

Year	Mo	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN	DHQ	DLQ	HWI	LWI
1997	3	3.326	3.254	2.159	2.156	2.201	1.059	0.991	2.335	2.195	0.072	0.068	0.54	6.94
1997	4	3.422	3.344	2.259	2.248	2.296	1.151	1.095	2.327	2.193	0.078	0.056	0.55	6.97
1997	5	3.412	3.306	2.208	2.188	2.238	1.071	1.004	2.408	2.235	0.106	0.067	0.54	6.94
1997	6	3.508	3.389	2.320	2.291	2.342	1.193	1.131	2.377	2.196	0.119	0.062	0.62	7.01
1997	7	3.467	3.340	2.253	2.225	2.278	1.110	1.040	2.427	2.230	0.127	0.070	0.55	6.98
1997	8	3.460	3.371	2.309	2.295	2.350	1.218	1.159	2.301	2.153	0.089	0.059	0.55	6.98
1997	9	3.495	3.415	2.369	2.353	2.408	1.292	1.243	2.252	2.123	0.080	0.049	0.61	7.08
1997	10	3.426	3.353	2.321	2.305	2.359	1.257	1.216	2.210	2.096	0.073	0.041	0.62	7.06
1997	11	3.337	3.233	2.182	2.158	2.206	1.083	1.026	2.311	2.150	0.104	0.057	0.58	7.02
1997	12	3.336	3.221	2.139	2.118	2.169	1.014	0.942	2.394	2.207	0.115	0.072	0.61	7.03
1998	1	3.365	3.257	2.152	2.135	2.182	1.014	0.939	2.426	2.243	0.108	0.075	0.55	6.95
1998	2	3.506	3.411	2.304	2.300	2.349	1.189	1.101	2.405	2.222	0.095	0.088	0.58	7

Table 4. NOS monthly mean water levels for Charleston, SC. These data are verified, monthly mean values. The data fields have the same meaning as in Table3.

Data are in Meters above STND and Times are on UTC (GMT)
8665530 CHARLESTON, COOPER RIVER ENTRANCE , SC from 199703 to 199802

Year	Mo	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN	DHQ	DLQ	HWI	LWI
1997	3	2.555	2.476	1.672	1.662	1.700	0.847	0.789	1.766	1.629	0.079	0.058	0.41	6.65
1997	4	2.648	2.574	1.763	1.751	1.797	0.928	0.877	1.771	1.646	0.074	0.051	0.41	6.66
1997	5	2.609	2.506	1.699	1.673	1.717	0.840	0.789	1.820	1.666	0.103	0.051	0.41	6.67
1997	6	2.725	2.614	1.818	1.792	1.836	0.970	0.910	1.815	1.644	0.111	0.060	0.47	6.77
1997	7	2.673	2.557	1.758	1.730	1.774	0.904	0.843	1.830	1.653	0.116	0.061	0.46	6.70
1997	8	2.683	2.595	1.807	1.789	1.832	0.984	0.932	1.751	1.611	0.088	0.052	0.45	6.66
1997	9	2.732	2.654	1.870	1.851	1.896	1.048	1.008	1.724	1.606	0.078	0.040	0.51	6.72
1997	10	2.672	2.600	1.824	1.807	1.851	1.014	0.975	1.697	1.586	0.072	0.039	0.48	6.71
1997	11	2.579	2.478	1.692	1.669	1.709	0.860	0.805	1.774	1.618	0.101	0.055	0.46	6.68
1997	12	2.572	2.459	1.661	1.635	1.673	0.811	0.749	1.823	1.648	0.113	0.062	0.45	6.71
1998	1	2.588	2.471	1.665	1.634	1.678	0.797	0.742	1.846	1.674	0.117	0.055	0.39	6.63
1998	2	2.724	2.637	1.821	1.811	1.854	0.984	0.917	1.807	1.653	0.087	0.067	0.39	6.7

Table 5. NOS accepted tidal datums for Charleston. Data are accepted. These are the 19-year values of the tidal datums at Charleston, SC, and have been computed by first reduction.

Data are in Meters above STND, time intervals are on UTC (GMT).
8665530 Charleston, Cooper River Entrance, SC, USA

Station	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN
8665530	2.527	2.423	1.643	1.622	1.658	0.817	0.759	1.768	1.606
DHQ	**DLQ**	**HWI**	**LWI**						
0.104	0.058	0.35	6.57						

Definition, MTL. Mean Tide Level, MTL, the average of MHW and MLW, is defined by the equation

$$MTL = \frac{MHW + MLW}{2}. \qquad (1)$$

This value is already calculated and is presented in the above Tables 3-5. MTL is the starting point for the calculation of the equivalent 19 year datums at Fort Pulaski, based on one year of simultaneous observations at Fort Pulaski and Charleston. The subordinate station, Fort Pulaski, is designated as station A, and the control station, Charleston is designated station B. MTL at Fort Pulaski must be reduced to a 19-year equivalent value by using the information from Charleston. In Table 6, column A contains the MTL values from Table 3, and the values in column B are from Table 4. The column designated A-B to the right of column B, is the difference between the two columns. The entry, SUMS, is the sum of the differences A-B. The SUMS are divided by the TOTAL

MONTHS to produce the MEANS, or the mean difference. The entry, ACCEPTED FOR B, is the 19-year accepted mean value of MTL for Charleston from Table 5. The corrected value of MTL at Fort Pulaski, CORRECTED FOR A, is the sum of MEANS + ACCEPTED FOR B. CORRECTED FOR A is the result of this procedure: MTL at Fort Pulaski has been corrected by comparison with an appropriate control. The form of the correction is

$$MTL_{CORRECTED\ FOR\ A} = MTL_{ACCEPTED\ FOR\ B} + \left(\frac{1}{N}\right) \sum_{I=1}^{N} (MTL_A(I) - MTL_B(I)) \quad (2)$$

where I goes from 1 to N, and I represents an individual month and N is the total number of months. In this case, N = 12. If the number of months change, N changes as appropriate. The entry MEANS in Table 6 is equivalent to the second term on the right hand side of Equation 2, ACCEPTED FOR B is the first term of the right hand side, and CORRECTED FOR A is the final result on the left hand side.

Table 6. Worksheet for calculating the corrected MTL for the subordinate station. The purpose of this worksheet is to solve Equation (2).

```
(A) SUBORDINATE STATION 8670870 FORT PULASKI, SAVANNAH RIVER
(B) STANDARD    STATION 8665530 CHARLESTON, COOPER RIVER ENTRANCE

        Mon Year          M T L
                   A       B     A - B
                 METER   METER   METER
        Mar 1997   2.156   1.662   0.494
        Apr 1997   2.248   1.751   0.497
        May 1997   2.188   1.673   0.515
        Jun 1997   2.291   1.792   0.499
        Jul 1997   2.225   1.730   0.495
        Aug 1997   2.295   1.789   0.506
        Sep 1997   2.353   1.851   0.502
        Oct 1997   2.305   1.807   0.498
        Nov 1997   2.158   1.669   0.489
        Dec 1997   2.118   1.635   0.483
        Jan 1998   2.135   1.634   0.501
        Feb 1998   2.300   1.811   0.489

                SUMS                 5.968
                TOTAL MONTHS        12.000
                MEANS                0.497
                ACCEPTED FOR B       1.622
                CORRECTED FOR A      2.119
```

Definition, DTL. Diurnal Tide Level, DTL, is defined as

$$DTL = \frac{MHHW + MLLW}{2}. \qquad (3)$$

DTL is also provided in Tables 3-5 using the above Equation 3 from the MHHW and MLLW data in those tables, and is entered into Table 7 below. In Table 7, Column A is DTL from the values in Table 3. Column B is DTL from values in Table 4. The third column in Table 7 is the difference field A-B. The difference field is summed and stored in SUMS, the mean is computed and stored in MEANS. The ACCEPTED FOR B entry for DTL is obtained from Table 5. The corrected DTL value at Fort Pulaski is the sum of MEANS + ACCEPTED FOR B, and is stored in CORRECTED FOR A entry of Table 7. The mathematical form of the correction is given by Equation 4,

$$DTL_{CORRECTED\ FOR\ A} = DTL_{ACCEPTED\ FOR\ B} + \left(\frac{1}{N}\right) \sum_{I=1}^{N} (DTL_A(I) - DTL_B(I)) \quad (4).$$

Table 7. Worksheet for calculating the corrected DTL for a subordinate station. This worksheet solves Equation 4.

Mon Year	DTL A METER	DTL B METER	A - B METER
Mar 1997	2.159	1.672	0.487
Apr 1997	2.259	1.763	0.496
May 1997	2.208	1.699	0.509
Jun 1997	2.320	1.818	0.502
Jul 1997	2.253	1.758	0.495
Aug 1997	2.309	1.807	0.502
Sep 1997	2.369	1.870	0.499
Oct 1997	2.321	1.824	0.497
Nov 1997	2.182	1.692	0.490
Dec 1997	2.139	1.661	0.478
Jan 1998	2.152	1.665	0.487
Feb 1998	2.304	1.821	0.483
SUMS			5.925
TOTAL MONTHS			12.000
MEANS			0.494
ACCEPTED FOR B			1.643
CORRECTED FOR A			2.137

Definition, MN. The Mean Range, Mn, is defined by

$$Mn = MHW - MLW \qquad (5).$$

Mn is given in Tables 3-5 and was calculated by applying the above equation. The results are organized in Table 8 below. Column A is the Mn from Table 3 and Column B is the Mn acquired from Table 4. Column A/B is the ratio of the values in Column A divided by those in Column B. The sum of the ratios is stored in SUMS. The mean ratio is stored in MEANS. The accepted value of Mn from Charleston is obtained from Table 5. The corrected value for Mn at Fort Pulaski is determined by multiplying ACCEPTED FOR B by MEANS, and is shown in CORRECTED FOR A in Table 8. The mathematical form of the correction is represented by Equation 6,

$$Mn_{CORRECTED\ FOR\ A} = Mn_{ACCEPTED\ FOR\ B} \times \left(\frac{1}{N}\right)\sum_{I=1}^{N}\frac{Mn_A(I)}{Mn_B(I)} \qquad (6).$$

Table 8. Worksheet for correcting the Mn at a subordinate station. This worksheet solves Equation 6.

Mon Year	Mn A METER	Mn B METER	A / B RATIO
Mar 1997	2.195	1.629	1.347
Apr 1997	2.193	1.646	1.332
May 1997	2.235	1.666	1.342
Jun 1997	2.196	1.644	1.336
Jul 1997	2.230	1.653	1.349
Aug 1997	2.153	1.611	1.336
Sep 1997	2.123	1.606	1.322
Oct 1997	2.096	1.586	1.322
Nov 1997	2.150	1.618	1.329
Dec 1997	2.207	1.648	1.339
Jan 1998	2.243	1.674	1.340
Feb 1998	2.222	1.653	1.344
SUMS			16.038
TOTAL MONTHS			12.000
MEANS			1.337
ACCEPTED FOR B			1.606
CORRECTED FOR A			2.146

Definition, Gt. The Great Diurnal Range (Gt) is defined as

$$Gt = MHHW - MLLW \qquad (7)$$

In Table 9 below the values of Gt are obtained from Table 3 and Table 4. The Column A/B is the ratio of the values in Column A divided by the values in Column B. The A/B column is summed and the mean ratio determined. The accepted Gt at Charleston is obtained from Table 5. The CORRECTED for A is the product of MEANS times ACCEPTED for B. The mathematical form

$$Gt_{CORRECTED\ FOR\ A} = Gt_{ACCEPTED\ FOR\ B} \times \left(\frac{1}{N}\right)\sum_{I=1}^{N}\frac{Gt_A(I)}{Gt_B(I)} \qquad (8).$$

of the corrected Gt is given by Equation 8,

Table 9. Worksheet for calculating the corrected Gt at a subordinate station. The purpose of this worksheet is to solve Equation 8.

Mon Year	Gt A METER	Gt B METER	A / B RATIO
Mar 1997	2.335	1.766	1.322
Apr 1997	2.327	1.771	1.314
May 1997	2.408	1.820	1.323
Jun 1997	2.377	1.815	1.310
Jul 1997	2.427	1.830	1.326
Aug 1997	2.301	1.751	1.314
Sep 1997	2.252	1.724	1.306
Oct 1997	2.210	1.697	1.302
Nov 1997	2.311	1.774	1.303
Dec 1997	2.394	1.823	1.313
Jan 1998	2.426	1.846	1.314
Feb 1998	2.405	1.807	1.331

SUMS	15.778
TOTAL MONTHS	12.000
MEANS	1.315
ACCEPTED FOR B	1.768
CORRECTED FOR A	2.325

Once the corrected values of $MTL_{CORRECTED\ FOR\ A}$, $DTL_{CORRECTED\ FOR\ A}$, $Mn_{CORRECTED\ FOR\ A}$, and $Gt_{CORRECTED\ FOR\ A}$, are determined by the above process the following Equations 9-12 may be used to determine the tidal datums at the subordinate station.

$$MLW_{corrected\ for\ A} = MTL_{corrected\ for\ A} - \tfrac{1}{2}\ Mn_{corrected\ for\ A} \qquad (9)$$
$$MHW_{corrected\ for\ A} = MLW_A + Mn_{corrected\ for\ A} \qquad (10)$$
$$MLLW_{corrected\ for\ A} = DTL_{corrected\ for\ A} - \tfrac{1}{2}\ Gt_{corrected\ for\ A} \qquad (11)$$
$$MHHW_{corrected\ for\ A} = MLLW_A + Gt_{corrected\ for\ A} \qquad (12)$$

In each of the four equations above, the numerical values of $MTL_{CORRECTED\ FOR\ A}$, $DTL_{CORRECTED\ FOR\ A}$, $Mn_{CORRECTED\ FOR\ A}$, and $GT_{CORRECTED\ FOR\ A}$, are entered into Equations 9-12 from the appropriate CORRECTED FOR A entry from Tables 6-9 above. Applying Equations 9-12 for Fort Pulaski, the tidal datums are

$$
\begin{aligned}
MLW &= MTL - 0.5 \times Mn = 2.119 - 0.5(2.146) = 1.046 \\
MHW &= MLW + Mn = 1.046 + 2.146 = 3.192 \\
MLLW &= DTL - 0.5 \times Gt = 2.137 - 0.5(2.325) = 0.974 \\
MHHW &= MLLW + Gt = 0.974 + 2.325 = 3.299.
\end{aligned}
$$

Appendix 1. Part A, contains a composite example spreadsheet of the calculations described above. For completeness, values for the diurnal inequalities may also be computed from the values obtained in equations 9-12.

Definition, DHQ. Diurnal High Water Inequality, is defined as

$$DHQ = MHHW - MHW. \qquad (13)$$

Definition, DLQ. Diurnal Low Water Inequality, is defined as

$$DLQ = MLW - MLLW. \qquad (14)$$

Applying these equations to the values computed above, the diurnal inequalities at Ft. Pulaski are

$$DHQ = MHHW - MHW = 3.299 - 3.192 = 0.107$$
$$DLQ = MLW - MLLW = 1.046 - 0.974 = 0.072.$$

4.2.2 Modified Range Ratio Method - Diurnal Tides

Along much the Gulf Coast of the United States the tides are predominantly diurnal. However, over short distances of the coast, the tides may in one location be diurnal, and in another location nearby, semidiurnal or mixed. Few easy candidate example cases exist. However, a simple case is offered by the comparison of Panama City Beach, FL to Pensacola, FL, as shown in Figure 18.

From the CO-OPS website, http://www.tidesandcurrents.noaa.gov/, verified historical monthly mean water level data, and accepted datums, may be downloaded. A year's worth of monthly values for Panama City Beach and Pensacola are shown in Tables 10 and 11. A subset of these monthly mean values are plotted in the graphs found in Figures 19a and 19b. These data were downloaded from the hyperlink U.S. and Global Coastal Stations, under Verified/Historical Water Level Data. The equations used to compute the tidal datums at the subordinate station, Panama City Beach, have been completely developed in the previous section on semidiurnal tides, and are applied in a straightforward manner to diurnal tides.

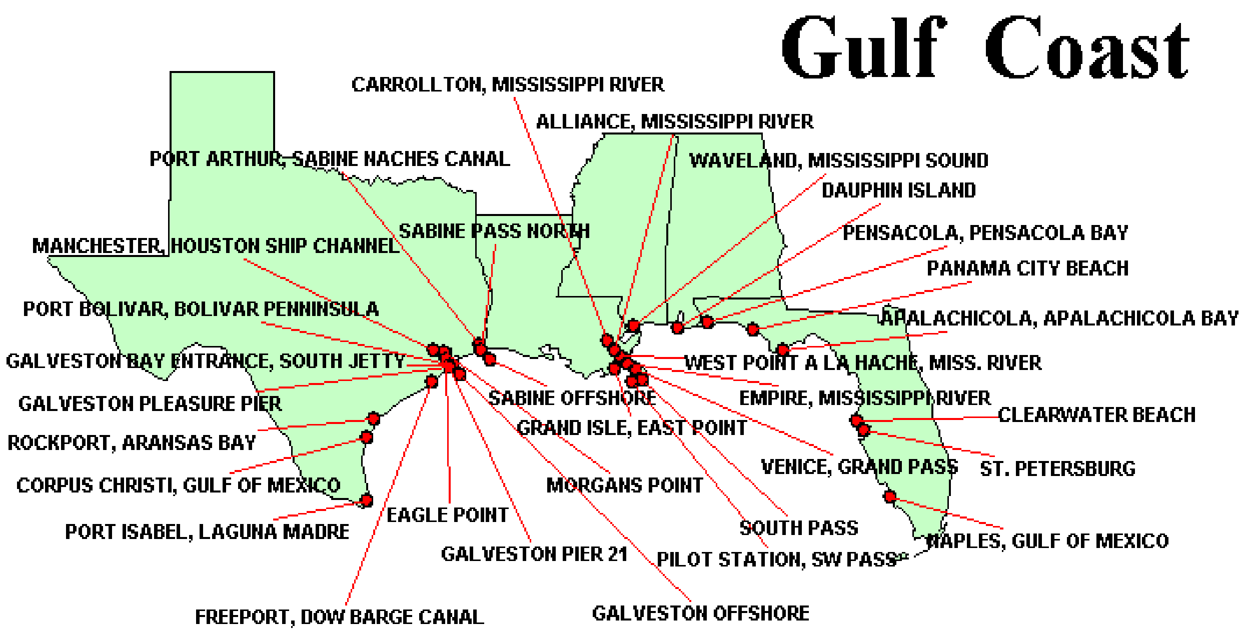


Figure 18. A map showing tide stations in the Gulf of Mexico.

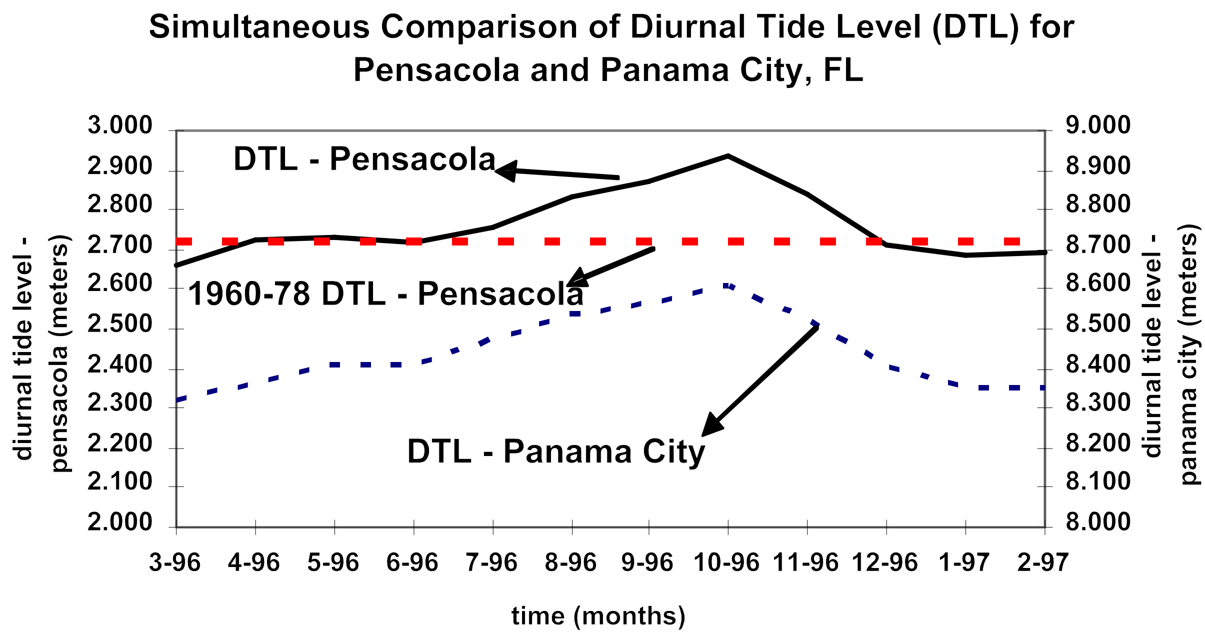


Figure 19a. Time series plots of monthly mean diurnal tide level (DTL) for Pensacola, FL and Panama City, FL.

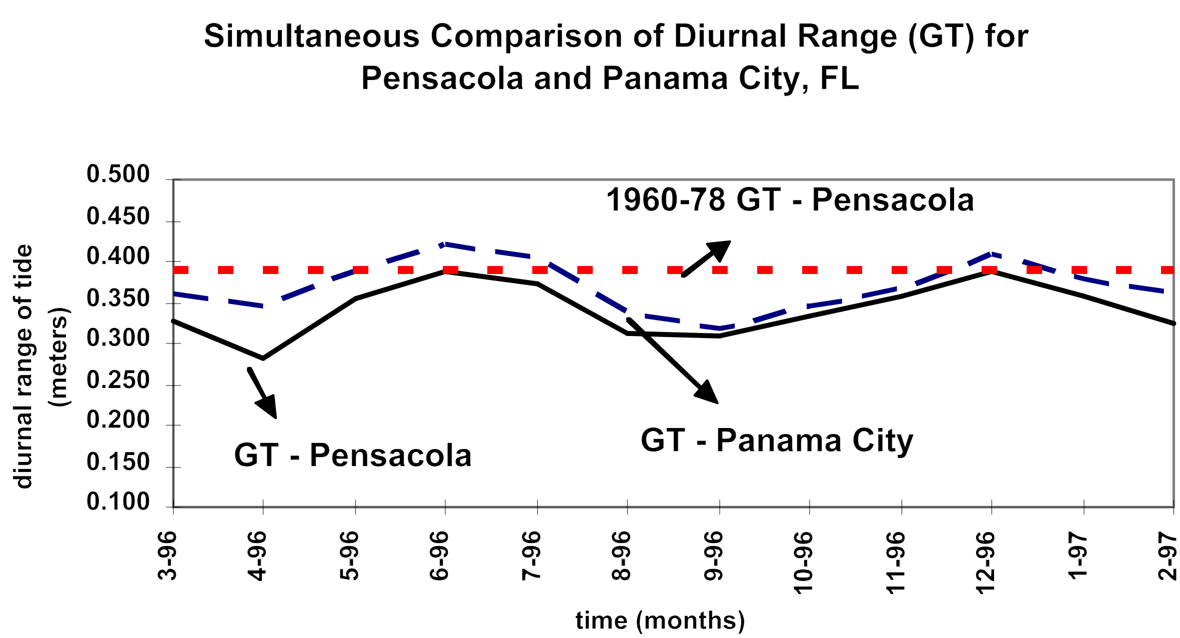


Figure 19b. Time series plots of monthly mean diurnal range of tide (Gt) for Panama City beach, FL and Pensacola, FL.

Table 10. NOS monthly mean water levels for Panama City Beach, FL.

Data are in Meters above STND and Times are on UTC (GMT)
8729210 PANAMA CITY BEACH , FL from 199603 to 1997020

Year	Mo	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN	DHQ	DLQ
1996	3	8.502	8.479	8.321	8.327	8.298	8.175	8.140	0.362	0.304	0.023	0.035
1996	4	8.536	8.492	8.363	8.357	8.354	8.222	8.190	0.346	0.270	0.044	0.032
1996	5	8.603	8.571	8.409	8.399	8.392	8.227	8.215	0.388	0.344	0.032	0.012
1996	6	8.621	8.610	8.411	8.416	8.399	8.223	8.201	0.420	0.387	0.011	0.022
1996	7	8.679	8.660	8.476	8.478	8.462	8.296	8.273	0.406	0.364	0.019	0.023
1996	8	8.708	8.669	8.540	8.529	8.526	8.388	8.372	0.336	0.281	0.039	0.016
1996	9	8.721	8.699	8.563	8.573	8.558	8.448	8.404	0.317	0.251	0.022	0.044
1996	10	8.780	8.741	8.608	8.600	8.605	8.459	8.436	0.344	0.282	0.039	0.023
1996	11	8.706	8.704	8.523	8.531	8.514	8.357	8.340	0.366	0.347	0.002	0.017
1996	12	8.607	8.606	8.402	8.412	8.388	8.219	8.197	0.410	0.387	0.001	0.022
1997	1	8.540	8.521	8.351	8.342	8.347	8.163	8.162	0.378	0.358	0.019	0.001
1997	2	8.531	8.480	8.350	8.329	8.345	8.178	8.169	0.362	0.302	0.051	0.009

Table 11. NOS monthly mean water levels for Pensacola, FL.

Data are in Meters above STND and Times are on UTC (GMT)
8729840 PENSACOLA, PENSACOLA BAY , FL from 199603 to 199702

Year	Mo	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN	DHQ	DLQ
1996	3	2.826	2.826	2.662	2.666	2.655	2.506	2.498	0.328	0.320	0.000	0.008
1996	4	2.868	2.855	2.728	2.722	2.724	2.589	2.587	0.281	0.266	0.013	0.002
1996	5	2.908	2.908	2.730	2.730	2.731	2.552	2.552	0.356	0.356	0.000	0.000
1996	6	2.914	2.911	2.721	2.724	2.718	2.536	2.527	0.387	0.375	0.003	0.009
1996	7	2.944	2.940	2.757	2.759	2.750	2.578	2.571	0.373	0.362	0.004	0.007
1996	8	2.989	2.973	2.833	2.833	2.825	2.694	2.678	0.311	0.279	0.016	0.016
1996	9	3.029	3.015	2.875	2.883	2.872	2.751	2.721	0.308	0.264	0.014	0.030
1996	10	3.100	3.068	2.934	2.923	2.934	2.779	2.767	0.333	0.289	0.032	0.012
1996	11	3.022	3.022	2.843	2.843	2.840	2.663	2.663	0.359	0.359	0.000	0.000
1996	12	2.909	2.903	2.715	2.712	2.704	2.520	2.520	0.389	0.383	0.006	0.000
1997	1	2.865	2.865	2.686	2.686	2.684	2.507	2.507	0.358	0.358	0.000	0.000
1997	2	2.858	2.839	2.696	2.691	2.696	2.542	2.533	0.325	0.297	0.019	0.01

Table 12. NOS accepted tidal datums for Pensacola. These are the 19-year, accepted, official values of the tidal datums at Pensacola, FL, and have been computed by first reduction. Note that HWI -- Greenwich Mean High Water Interval in Hours, and LWI -- Greenwich Mean Low Water Interval in Hours, are not calculated for this station because the type of tide at Pensacola is diurnal. The data are in meters above station datum.

Data are in Meters above STND
8729840 Pensacola, Pensacola Bay, FL, USA

Station	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN
8729840	2.911	2.902	2.719	2.719	2.713	2.536	2.524	0.387	0.366

DHQ	DLQ	HWI	LWI
0.009	0.012	N/A	N/A

Corrected MTL for Panama City Beach. Mean Tide Level, MTL, the average of MHW and MLW, is defined by Equation 1, and is presented in the above Tables 10-12. MTL is the starting point for the calculation of the equivalent 19 year datums at Panama City Beach, based on one year of monthly means between there and Pensacola. The subordinate station, Panama City Beach, is designated as station A, and the control station, Pensacola is designated station B. MTL at Panama City Beach must be reduced to a 19-year equivalent value by using the information from Pensacola. In Table 13 below the values in column A are the MTL values from Table 10, those values in column B are from Table 11. The column to the right of B, is the difference, A-B. The procedure is identical to the semidiurnal case and shall be reiterated here. The entry, SUMS, is the sum of the differences A-B. The SUMS are divided by the TOTAL MONTHS to produce the MEANS, or the mean differences. The entry, ACCEPTED FOR B, is the accepted value of MTL for Pensacola from Table 12. The corrected value of MTL at Panama City Beach, CORRECTED FOR A, is the sum of MEANS + ACCEPTED FOR B. As a result of this procedure MTL observed at Panama City Beach for the period from March 1996 to February 1997 has been corrected to an equivalent 19-year mean value of MTL by comparison with an appropriate control.

Table 13. Worksheet for calculating the corrected MTL for the subordinate station. The purpose of this worksheet is to solve Equation (2).

(A) SUBORDINATE STATION 8729210 PANAMA CITY BEACH
(B) STANDARD STATION 8729840 PENSACOLA, PENSACOLA BAY

Mon Year		M T L	
	A	B	A - B
	METER	METER	METER
Mar 1996	8.327	2.666	5.661
Apr 1996	8.357	2.722	5.635
May 1996	8.399	2.730	5.669
Jun 1996	8.416	2.724	5.692
Jul 1996	8.478	2.759	5.719
Aug 1996	8.529	2.833	5.696
Sep 1996	8.573	2.883	5.690
Oct 1996	8.600	2.923	5.677
Nov 1996	8.531	2.843	5.688
Dec 1996	8.412	2.712	5.700
Jan 1997	8.342	2.686	5.656
Feb 1997	8.329	2.691	5.638

SUMS	68.121
TOTAL MONTHS	12.000
MEANS	5.677
ACCEPTED FOR B	2.719
CORRECTED FOR A	8.396

Corrected DTL for Panama City Beach. DTL is obtained from Tables 10-12 and entered into Table 14 below. Column A is DTL from Table 10, Column B is DTL from Table 11, and the third column is the difference field A-B. The differences are summed and stored in SUMS, the mean is computed and stored in MEANS. The ACCEPTED FOR B is calculated by applying the above equation to the MHHW and MLLW entries in Table 12. The corrected DTL value at Panama City Beach is the sum of MEANS + ACCEPTED FOR B, and is stored in CORRECTED FOR A.

Table 14. Worksheet for calculating the corrected DTL for Panama City Beach. The purpose of this Table is to solve Equation 4 for Panama City Beach.

Mon Year	DTL A METER	DTL B METER	A - B METER
Mar 1996	8.321	2.662	5.659
Apr 1996	8.363	2.728	5.635
May 1996	8.409	2.730	5.679
Jun 1996	8.411	2.721	5.690
Jul 1996	8.476	2.757	5.719
Aug 1996	8.540	2.833	5.707
Sep 1996	8.563	2.875	5.688
Oct 1996	8.608	2.934	5.674
Nov 1996	8.523	2.843	5.680
Dec 1996	8.402	2.715	5.687
Jan 1997	8.351	2.686	5.665
Feb 1997	8.350	2.696	5.654

SUMS	68.137
TOTAL MONTHS	12.000
MEANS	5.678
ACCEPTED FOR B	2.719
CORRECTED FOR A	8.397

Corrected MN for Panama City Beach. The Mean Range, Mn, is defined by Equation 5 and is obtained from Tables 10-12. The results are organized in Table 15 below.

Table 15. Worksheet for correcting the Mn at a subordinate station.

Mon Year	M N A METER	M N B METER	A / B RATIO
Mar 1996	0.304	0.320	0.950
Apr 1996	0.270	0.266	1.015
May 1996	0.344	0.356	0.966
Jun 1996	0.387	0.375	1.032
Jul 1996	0.364	0.362	1.006
Aug 1996	0.281	0.279	1.007
Sep 1996	0.251	0.264	0.951

Oct 1996	0.282	0.289	0.976
Nov 1996	0.347	0.359	0.967
Dec 1996	0.387	0.383	1.010
Jan 1997	0.358	0.358	1.000
Feb 1997	0.302	0.297	1.017

SUMS	11.897
TOTAL MONTHS	12.000
MEANS	0.991
ACCEPTED FOR B	0.366
CORRECTED FOR A	0.363

Column A is the difference, MHW - MLW, from Table 10. Column B expresses the same information but is acquired from Table 11. Column A/B is the ratio of Column A divided by Column B. The sum of the ratios is stored in SUMS. The mean ratio is stored in MEANS. The accepted value of MN from Pensacola is obtained by applying Equation 5 to Table 12. The corrected value for MN at Panama City Beach is determined by multiplying ACCEPTED FOR B by MEANS, and is stored in CORRECTED FOR A. The mathematical form of the correction is represented by Equation 6.

Corrected Gt at Panama City Beach. The Great Diurnal Range (GT) is defined by Eq. 7. In Table 16 below the values of Gt are obtained from the data in Tables 10-12 and entering Gt_A into Column A for the subordinate and Gt_B into Column B for the control. The Column A/B is the ratio of the values in column A divided by the values in column B. The A/B column is summed and the mean ratio determined. The accepted GT at Pensacola is obtained by applying Equation 7 to the accepted data at Pensacola from Table 12. The CORRECTED at A is the product of MEANS times ACCEPTED FOR B. The mathematical form of the corrected GT is given by Equation 8.

Table 16. Worksheet for calculating the corrected Gt at a subordinate station.

Mon Year	G T		
	A METER	B METER	A / B RATIO
Mar 1996	0.362	0.328	1.104
Apr 1996	0.346	0.281	1.231
May 1996	0.388	0.356	1.090
Jun 1996	0.420	0.387	1.085
Jul 1996	0.406	0.373	1.088
Aug 1996	0.336	0.311	1.080
Sep 1996	0.317	0.308	1.029
Oct 1996	0.344	0.333	1.033
Nov 1996	0.366	0.359	1.019
Dec 1996	0.410	0.389	1.054
Jan 1997	0.378	0.358	1.056
Feb 1997	0.362	0.325	1.114

SUMS	12.983
TOTAL MONTHS	12.000
MEANS	1.082
ACCEPTED FOR B	0.387
CORRECTED FOR A	0.419

Once the corrected values of $MTL_{CORRECTED\ FOR\ A}$, $DTL_{CORRECTED\ FOR\ A}$, $Mn_{CORRECTED\ FOR\ A}$, and

$GT_{CORRECTED\ FOR\ A}$, are determined by the above process the Equations 9-12 may be used to determine the other tidal datums at the subordinate station. For Panama City Beach, the tidal datums are

$$
\begin{aligned}
MLW &= MTL - 0.5 \times Mn = 8.396 - 0.5(0.363) = 8.214 \\
MHW &= MLW + Mn = 8.214 + 0.363 = 8.577 \\
MLLW &= DTL - 0.5 \times Gt = 8.397 - 0.5(0.419) = 8.188 \\
MHHW &= MLLW + Gt = 8.188 + 0.419 = 8.607.
\end{aligned}
$$

4.2.3 Standard Method - Mixed Tides

The mixed tides case requires methodology called the standard method (section 3.4). Like the previous cases, the problem involves selecting a suitable control station with known 19-year mean values of the datums, and reducing the subordinate station data to their equivalent 19-year mean. Along the West Coast of the United States the tides are predominantly mixed over large distances of the coast, and many candidate example cases exist. A simple case is offered by the comparison of Alameda, CA (subordinate station) to San Francisco, CA (control station), both located in central California within San Francisco Bay (see Figure 20.) From the CO-OPS website, http://www.tidesandcurrents.noaa.gov/, verified and historical monthly mean water level data, and accepted datums, may be downloaded. A year's worth of monthly values for Alameda and San Francisco are shown in Tables 17 - 19 and monthly mean values for MTL and Mn are plotted in Figures 21a and 21b. This data is downloaded from the hyperlink U.S. and Global Coastal Stations, under Verified/Historical Water Level Data. A full example computational spreadsheet for the full comparison is found in Appendix 1.

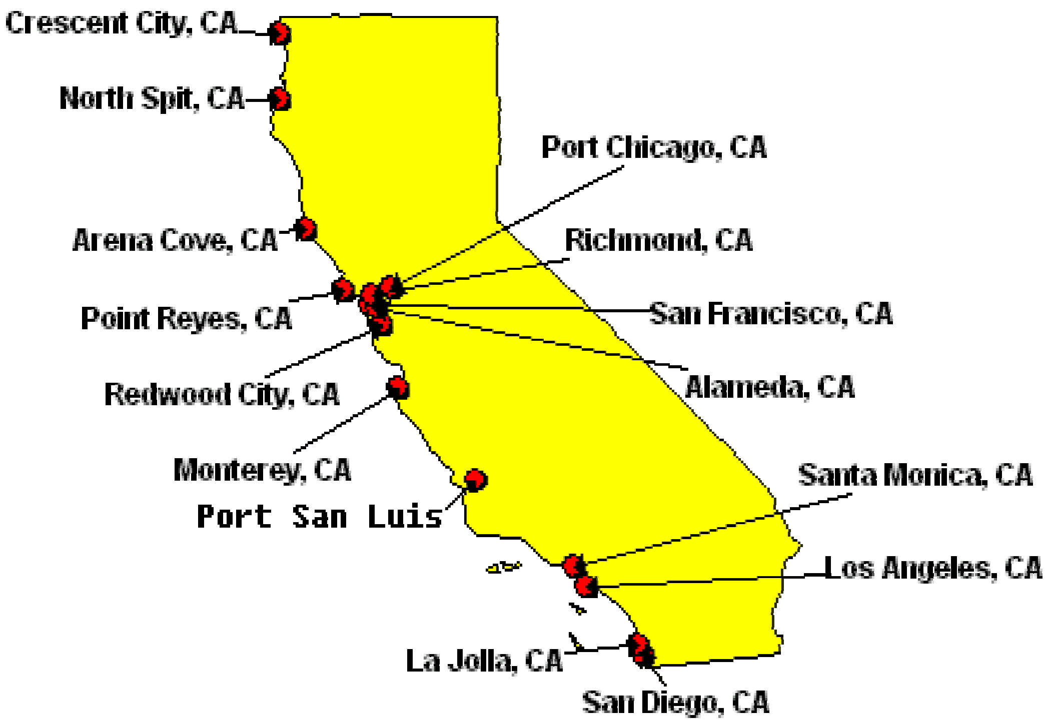


Figure 20. Map of California showing the locations of NWLON stations.

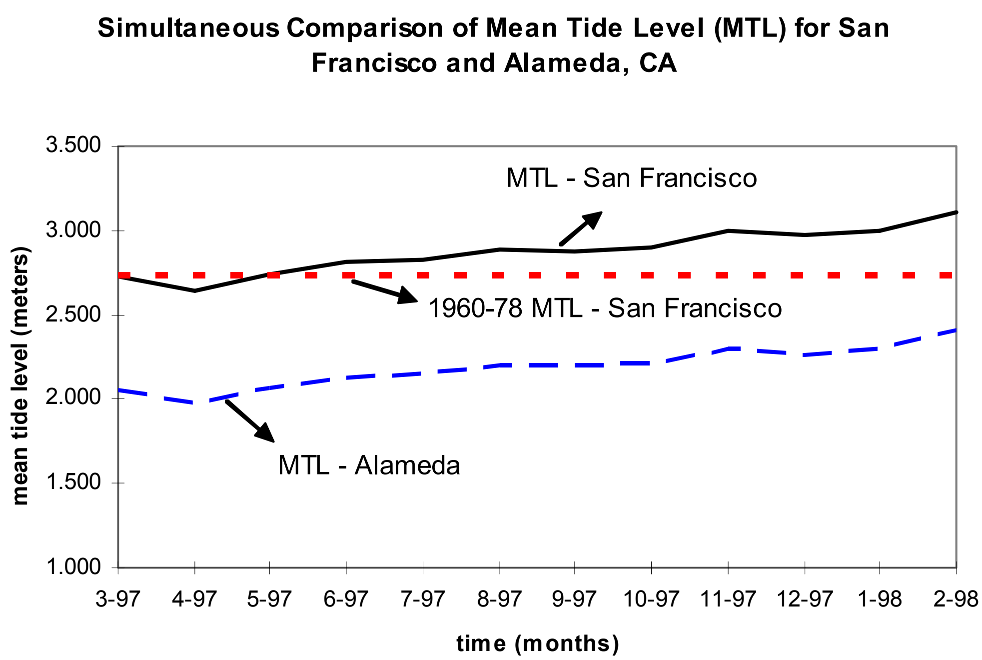


Figure 21a. Time series plots of monthly mean tide level (MTL) for Alameda, CA and San Francisco, CA.

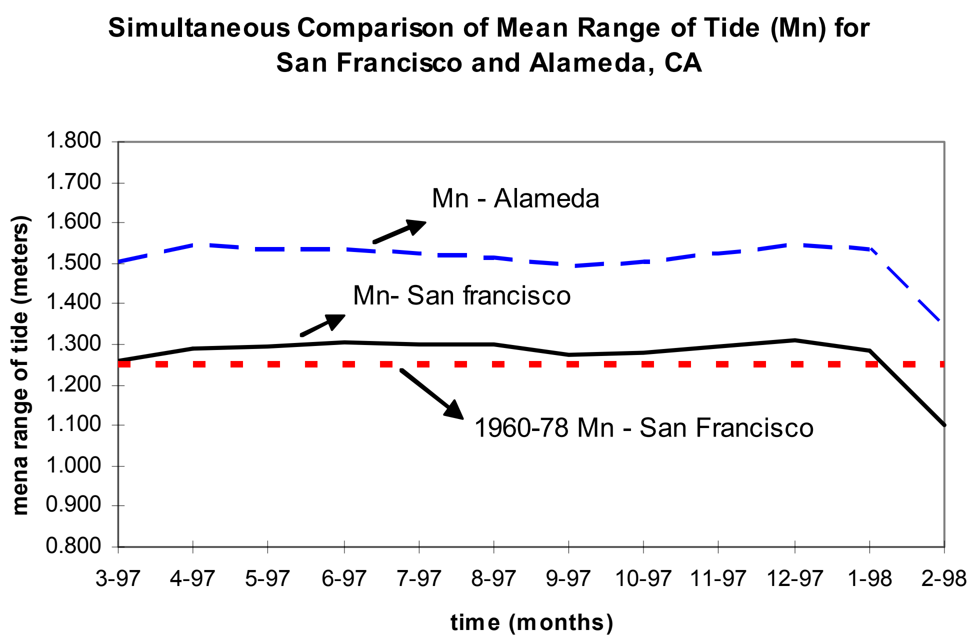


Figure 21b. Time series plots of monthly mean range of tide (Mn) for Alameda, CA and San Francisco, CA.

Table 17. NOS monthly mean water levels for Alameda, CA. The data are verified.

Data are in Meters above STND and Times are on UTC (GMT)
9414750 ALAMEDA, SAN FRANCISCO BAY , CA from 199703 to 199802

Year	Mo	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN	DHQ	DLQ	HWI	LWI
1997	3	2.941	2.809	2.000	2.058	2.029	1.306	1.059	1.882	1.503	0.132	0.247	7.95	1.42
1997	4	2.865	2.749	1.889	1.978	1.951	1.206	0.913	1.952	1.543	0.116	0.293	8.01	1.50
1997	5	2.998	2.832	1.989	2.066	2.039	1.299	0.979	2.019	1.533	0.166	0.320	8.05	1.53
1997	6	3.118	2.900	2.067	2.131	2.105	1.363	1.016	2.102	1.537	0.218	0.347	8.02	1.50
1997	7	3.136	2.911	2.090	2.147	2.123	1.384	1.044	2.092	1.527	0.225	0.340	8.05	1.54
1997	8	3.137	2.953	2.151	2.196	2.175	1.439	1.164	1.973	1.514	0.184	0.275	8.05	1.54
1997	9	3.061	2.945	2.155	2.199	2.177	1.453	1.250	1.811	1.492	0.116	0.203	8.03	1.52
1997	10	3.072	2.967	2.159	2.216	2.191	1.464	1.247	1.825	1.503	0.105	0.217	8.01	1.54
1997	11	3.226	3.060	2.221	2.298	2.265	1.535	1.216	2.010	1.525	0.166	0.319	8.02	1.53
1997	12	3.263	3.039	2.196	2.267	2.231	1.495	1.129	2.134	1.544	0.224	0.366	8.01	1.54
1998	1	3.285	3.070	2.247	2.303	2.265	1.537	1.209	2.076	1.533	0.215	0.328	7.93	1.46
1998	2	3.269	3.082	2.391	2.414	2.375	1.746	1.512	1.757	1.336	0.187	0.234	7.98	1.55

Table 18. NOS monthly mean water levels for San Francisco, CA. The data are verified.

Data are in Meters above STND and Times are on UTC (GMT)
9414290 SAN FRANCISCO, SAN FRANCISCO BAY , CA from 199703 to 199802

Year	Mo	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN	DHQ	DLQ	HWI	LWI
1997	3	3.481	3.359	2.670	2.731	2.715	2.102	1.860	1.621	1.257	0.122	0.242	7.52	0.70
1997	4	3.411	3.294	2.561	2.648	2.634	2.002	1.710	1.701	1.292	0.117	0.292	7.53	0.84
1997	5	3.550	3.388	2.661	2.741	2.727	2.094	1.772	1.778	1.294	0.162	0.322	7.53	0.89
1997	6	3.675	3.462	2.740	2.809	2.795	2.156	1.804	1.871	1.306	0.213	0.352	7.50	0.87
1997	7	3.699	3.480	2.768	2.830	2.816	2.180	1.836	1.863	1.300	0.219	0.344	7.53	0.89
1997	8	3.708	3.532	2.833	2.882	2.872	2.231	1.957	1.751	1.301	0.176	0.274	7.50	0.89
1997	9	3.627	3.514	2.833	2.878	2.870	2.242	2.039	1.588	1.272	0.113	0.203	7.50	0.86
1997	10	3.645	3.544	2.845	2.905	2.894	2.265	2.046	1.599	1.279	0.101	0.219	7.48	0.89
1997	11	3.805	3.643	2.914	2.995	2.978	2.347	2.023	1.782	1.296	0.162	0.324	7.53	0.90
1997	12	3.842	3.625	2.895	2.970	2.948	2.314	1.948	1.894	1.311	0.217	0.366	7.53	0.88
1998	1	3.857	3.644	2.939	3.001	2.981	2.357	2.020	1.837	1.287	0.213	0.337	7.51	0.79
1998	2	3.836	3.653	3.063	3.103	3.082	2.552	2.291	1.545	1.101	0.183	0.261	7.58	0.82

Table 19. NOS tidal datums for San Francisco. Data are accepted. These are the 19-year values of the tidal datums at San Francisco, CA, and have been computed by first reduction. The data are in meters above station datum.

Data are in meters above STND, time intervals in hours (UTC)
9414290 San Francisco, San Francisco Bay, CA, USA

Station	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN
9414290	3.536	3.353	2.646	2.728	2.713	2.103	1.759	1.777	1.250

DHQ	DLQ	HWI	LWI
0.183	0.344	7.56	0.83

Corrected MTL at Alameda. MTL, Equation 1, is the starting point for the calculation of the equivalent 19 year datums at Alameda, based on one year of observations. The subordinate station, Alameda, is designated as station A, and the control station, San Francisco is designated station B. MTL at Alameda must be reduced to a 19-year equivalent value by using the information from San Francisco. In Table 20 below the values in column A are the MTL values from Table 17, those in column B are from Table 18. The column to the right of B, is the difference, A-B. The entry, SUMS, is the sum of the differences A-B. The SUMS are divided by the TOTAL MONTHS to produce the MEANS, or the mean difference. The entry, ACCEPTED FOR B, is the accepted value of MTL for San Francisco from Table 19. From Equation 2, the corrected value of MTL at Alameda, CORRECTED FOR A, is the sum of MEANS + ACCEPTED FOR B.

Table 20. Worksheet for calculating the corrected MTL for Alameda. The purpose of this worksheet is to solve Equation (2).

(A) SUBORDINATE STATION 9414750 ALAMEDA, SAN FRANCISCO BAY
(B) STANDARD STATION 9414290 SAN FRANCISCO, SAN FRANCISCO BAY

Mon Year	M T L A METER	M T L B METER	A - B METER
Mar 1997	2.058	2.731	-0.673
Apr 1997	1.978	2.648	-0.670
May 1997	2.066	2.741	-0.675
Jun 1997	2.131	2.809	-0.678
Jul 1997	2.147	2.830	-0.683
Aug 1997	2.196	2.882	-0.686
Sep 1997	2.199	2.878	-0.679
Oct 1997	2.216	2.905	-0.689
Nov 1997	2.298	2.995	-0.697
Dec 1997	2.267	2.970	-0.703
Jan 1998	2.303	3.001	-0.698
Feb 1998	2.414	3.103	-0.689

SUMS	-8.220
TOTAL MONTHS	12.000
MEANS	-0.685
ACCEPTED FOR B	2.728
CORRECTED FOR A	2.043

Corrected MN at Alameda. The Mean Range, Mn, is defined by Equation 5 and calculated values are found in Tables 17-19. The results are organized in Table 21 below.

Table 21. Worksheet for correcting the Mn at a subordinate station. The purpose of this worksheet is to solve Equation 6.

Mon Year	M N A METER	M N B METER	A / B RATIO
Mar 1997	1.503	1.257	1.196
Apr 1997	1.543	1.292	1.194
May 1997	1.533	1.294	1.185
Jun 1997	1.537	1.306	1.177
Jul 1997	1.527	1.300	1.175
Aug 1997	1.514	1.301	1.164
Sep 1997	1.492	1.272	1.173
Oct 1997	1.503	1.279	1.175
Nov 1997	1.525	1.296	1.177
Dec 1997	1.544	1.311	1.178
Jan 1998	1.533	1.287	1.191
Feb 1998	1.336	1.101	1.213

SUMS	14.198
TOTAL MONTHS	12.000
MEANS	1.183
ACCEPTED FOR B	1.250
CORRECTED FOR A	1.479

Column A is the difference, MHW - MLW, from Table 17. Column B expresses the same information but acquired from Table 18. Column A/B is the ratio of Column A divided by Column B. The sum of the ratios is stored in SUMS. The mean ratio is stored in MEANS. The accepted value of Mn from San Francisco is obtained by applying Equation 5 to Table 19. The corrected value for Mn at Alameda is determined by multiplying ACCEPTED FOR B by MEANS, and is stored in CORRECTED FOR A.

Definition, DHQ. The Diurnal High Water Inequality (DHQ) was previously defined by Equation 13 as

$$DHQ = MHHW - MHW$$

In Table 22 below, the monthly values of DHQ were previously calculated by NOS by applying Equation 13 to the values obtained from Tables 17 and 18. DHQ_A was then entered into Column A for the subordinate station and DHQ_B into Column B for the control station. Column A/B is the ratio of A/B. The A/B column is summed and the mean ratio determined. The accepted DHQ at San Francisco is obtained by applying Eq. 13 to the accepted data at San Francisco from Table 19. The CORRECTED FOR A is the product of MEANS times ACCEPTED FOR B.

The mathematical form of the corrected DHQ is given by Eq. 15,

$$DHQ_{CORRECTED\ FOR\ A} = DHQ_{\mathrm{ACCEPTED}\ FOR\ B} \times \left(\frac{1}{N}\right)\sum_{I=1}^{N} \frac{DHQ_A(I)}{DHQ_B(I)} \quad (15).$$

Table 22. Worksheet for calculating the corrected DHQ at a subordinate station. This worksheet solves Eq. 15.

Mon Year	DHQ A METER	DHQ B METER	A / B RATIO
Mar 1997	0.132	0.122	1.082
Apr 1997	0.116	0.117	0.991
May 1997	0.166	0.162	1.025
Jun 1997	0.218	0.213	1.023
Jul 1997	0.225	0.219	1.027
Aug 1997	0.184	0.176	1.045
Sep 1997	0.116	0.113	1.027
Oct 1997	0.105	0.101	1.040
Nov 1997	0.166	0.162	1.025
Dec 1997	0.224	0.217	1.032
Jan 1998	0.215	0.213	1.009
Feb 1998	0.187	0.183	1.022

SUMS	12.348	
TOTAL MONTHS		12.000
MEANS	1.029	
ACCEPTED FOR B		0.183
CORRECTED FOR A		0.188

Definition, DLQ. The Diurnal Low Water Inequality (DLQ) was previously defined by Equation 14 as

$$DLQ = MLW - MLLW$$

In Table 23 below, DLQ values were previously calculated by NOS by applying Equation 13 to values from Tables 17 and 18. DLQ_A and DLQ_B values were entered into Column A for the subordinate and into Column B for the control. Column A/B is the ratio of A/B. The A/B column is summed and the mean ratio determined. The accepted DLQ at San Francisco is obtained by applying Eq. 15 to the accepted data at San Francisco from Table 19. The CORRECTED at A is the product of the MEANS times the ACCEPTED FOR B.

The mathematical form of the corrected DLQ is given by Equation 16,

$$DLQ_{CORRECTED\ FOR\ A} = DLQ_{\text{ACCEPTED}\ FOR\ B} \times \left(\frac{1}{N}\right) \sum_{I=1}^{N} \frac{DLQ_A(I)}{DLQ_B(I)} \quad (16).$$

Table 23. Worksheet for calculating the corrected DLQ at a subordinate station. This worksheet solves Equation 16.

Mon Year	DLQ A METER	DLQ B METER	A / B RATIO
Mar 1997	0.247	0.242	1.021
Apr 1997	0.293	0.292	1.003
May 1997	0.320	0.322	0.994
Jun 1997	0.347	0.352	0.986
Jul 1997	0.340	0.344	0.988
Aug 1997	0.275	0.274	1.004
Sep 1997	0.203	0.203	1.000
Oct 1997	0.217	0.219	0.991
Nov 1997	0.319	0.324	0.985
Dec 1997	0.366	0.366	1.000
Jan 1998	0.328	0.337	0.973
Feb 1998	0.234	0.261	0.897

SUMS	11.842
TOTAL MONTHS	12.000
MEANS	0.987
ACCEPTED FOR B	0.344
CORRECTED FOR A	0.339

Once the corrected values of $MTL_{\text{CORRECTED FOR A}}$, $Mn_{\text{CORRECTED FOR A}}$, $DHQ_{\text{CORRECTED FOR A}}$, and $DLQ_{\text{CORRECTED FOR A}}$, are determined by the above process. The following Eqs. 17-20 may be used to determine the tidal datums at the subordinate station.

$$MLW_A = MTL_{CORRECTED\ FOR\ A} - 1/2\, Mn_{CORRECTED\ FOR\ A} \quad (17)$$

$$MHW_A = MLW_A + Mn_{CORRECTED\ FOR\ A} \quad (18)$$

$$MLLW_A = MLW_A - DLQ_{CORRECTED\ FOR\ A} \quad (19)$$

$$MHHW_A = MHW_A + DHQ_{CORRECTED\ FOR\ A}\,. \quad (20)$$

In each of the four equations above, the values of $MTL_{CORRECTED\ FOR\ A}$, $Mn_{CORRECTED\ FOR\ A}$, $DHQ_{CORRECTED\ FOR\ A}$, and $DLQ_{CORRECTED\ FOR\ A}$, are entered from the appropriate CORRECTED FOR A entry from Tables 20-23 above. MLW_A, as derived from Eq. 17, is entered into Eqs. 18 and 19. MHW_A , as derived from Eq. 18, is entered into Eq. 20. For Alameda, the tidal datums are

$$MLW_A = MTL_{CORRECTED\ FOR\ A} - 1/2\,Mn_{CORRECTED\ FOR\ A} = 2.043 - 0.5(1.479) = 1.304$$
$$MHW_A = MLW_A + Mn_{CORRECTED\ FOR\ A} = 1.304 + 1.479 = 2.783$$
$$MLLW_A = MLW_A - DLQ_{CORRECTED\ FOR\ A} = 1.304 - 0.339 = 0.965$$
$$MHHW_A = MHW_A + DHQ_{CORRECTED\ FOR\ A} = 2.783 + 0.188 = 2.971.$$

Appendix 1. Part B, contains a composite example spreadsheet of the calculations described above.

4.3 Comparison of Simultaneous High and Low Waters (Tide by Tide Analysis)

The method of Comparison of Simultaneous High and Low Waters or, Tide by Tide Analysis (TBYT), is used to compute datums form short-term stations. For instance, if the simultaneous water level measurements at the subordinate and control stations exist for less than a month or if the data series starts and ends in the middle of two consecutive months. The next three examples illustrate this comparison method for three different types of tide. For each type, equivalent 19-year datums are computed, in addition to lunitidal intervals. The example data may be downloaded from the CO-OPS website. All data are in meters, referenced to station datum, and are on the Greenwich time meridian. Referencing data series to Greenwich meridian is now the standard NOS practice. When calculating time differences in the phase of tide between two stations, it is necessary to factor in any differences in the time zone that the observations were recorded on. The present NOS practice of operating all tide stations on GMT. Five days of simultaneous observations are used in this example for illustration only. The estimated vertical error in the resultant datums for this series length, extrapolating the curve from Figure 14, is expected to be greater than 0.04 m. At least one month of data ensures closure on the significant monthly variations of the tide and provides a proper number of values to get meaningful statistics from the comparisons. Using less than one month of data is proper as long as the user realizes the higher uncertainties in the resulting datums.

The examples follow the procedural steps outlined in section 4.1.2. First, the data from the control and subordinate stations are obtained and put into tabular form for comparisons. Summations of the tides and their simultaneous differences are computed on the same tabular form. Then, based on the summations and differences, a specific sequence of equations is used to form the differences and ratios needed to compute the equivalent NDTE datums. Appendix 2 contains a complete example TYBT spreadsheet for Alameda and San Francisco.

4.3.1 Modified Range Ratio - Semidiurnal Tides

The following exercise illustrates the Modified Range Ratio Method to compute equivalent 19-year datums at Fort Pulaski, GA, using Charleston, SC as a control station, for a short period of observations.

Data for this example may be downloaded from http://www.tidesandcurrents.noaa.gov/. Click on the hyperlink for "Water Level Observations", under the heading "**Verified / Historical Water Level Data**" , click on the hyperlink for U.S. and Global Coastal Stations . The next page is a database menu form, illustrated in Figure 22, filled out as appropriate for Fort Pulaski, GA.

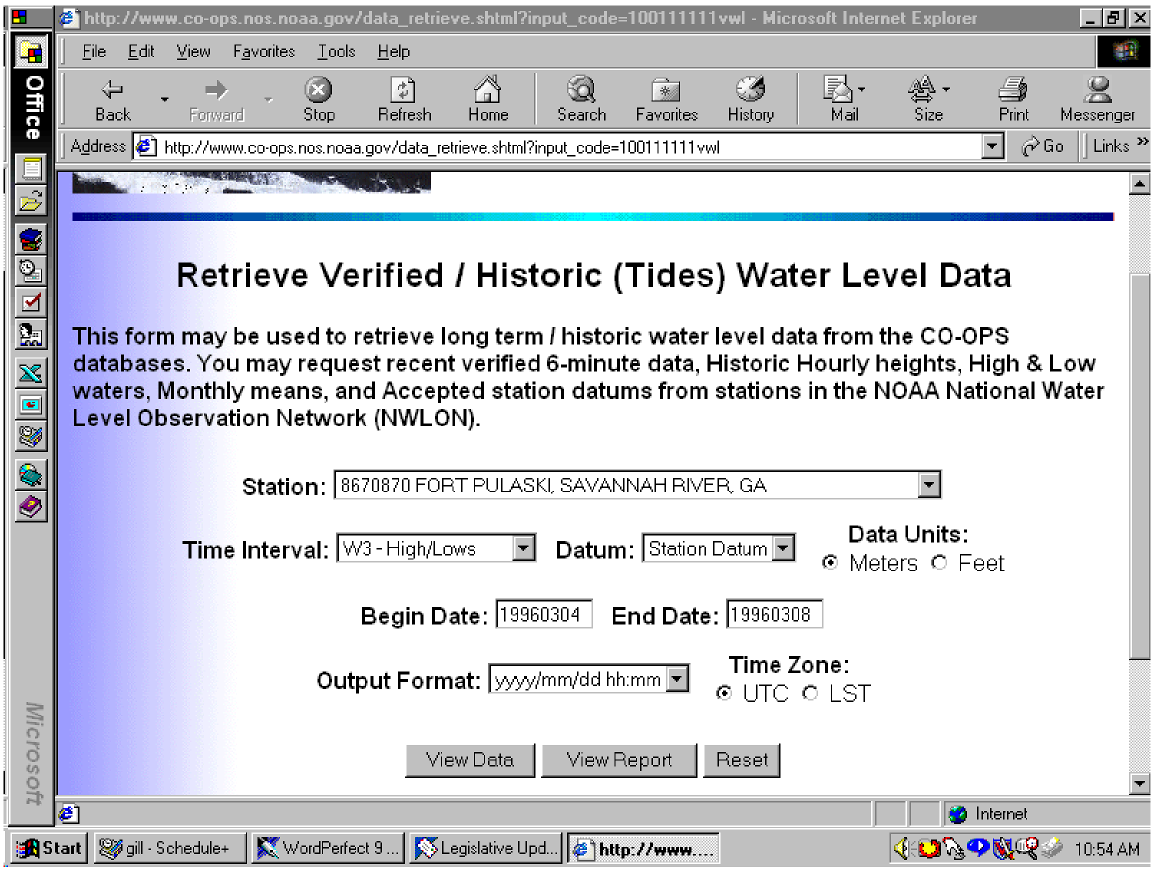


Figure 22. The menu driven interface to the CO-OPS database through the internet. The interface is completed for the Fort Pulaski data of the tide by tide comparison between Charleston and Fort Pulaski.

Note that in the scroll box under “Time Interval”, “W3 - High/Lows”, is selected. By clicking on the button captioned, “View Data/View Report”, the database returns the information presented in Table 24, and Figure 23. The additional hourly water level data presented in Figure. 28, is obtained by selecting “W2- Hourly Heights”, instead of “W3- High/Lows”. The data for Charleston, SC are shown in Table 25, and Figure 24. The composite graph of Fort Pulaski and Charleston is shown in Figure 25.

Table 24. NOS High and Low Waters for 8670870 Fort Pulaski, Savannah River, GA, USA from 19960304 to 19960308. Data are verified. Data are in meters above Station Datum (STND). Times are on UTC (GMT). The fields in the table have the following meanings. Station--Unique seven character identifier for the station. Date Time--Date and time the data were collected by the DCP. WL_Value--Water level height. Type – Designation of Water level height. LL = lower low water, L = low water, H = High water, HH Higher High water. Infer--A flag when that when set to 1 indicates that the water level value has been inferred. Limit--A flag that when set to 1 indicates that either the maximum or minimum expected water level height limit was exceeded.

Station	Date	Time	WL_Value	Type	Infer	Limit
8670870	1996/03/04	00:00	3.066	H	0	0
8670870	1996/03/04	06:06	0.864	LL	0	0
8670870	1996/03/04	12:18	3.178	H	0	0
8670870	1996/03/04	18:36	0.956	L	0	0
8670870	1996/03/05	00:42	3.280	HH	0	0
8670870	1996/03/05	06:48	0.908	LL	0	0
8670870	1996/03/05	12:42	3.227	H	0	0
8670870	1996/03/05	19:18	0.973	L	0	0
8670870	1996/03/06	01:30	3.244	HH	0	0
8670870	1996/03/06	07:36	0.658	LL	0	0
8670870	1996/03/06	13:36	3.153	HH	0	0
8670870	1996/03/06	19:48	0.678	L	0	0
8670870	1996/03/07	01:54	3.061	H	0	0
8670870	1996/03/07	08:18	0.641	L	0	0
8670870	1996/03/07	14:06	3.077	HH	0	0
8670870	1996/03/07	20:24	0.610	LL	0	0
8670870	1996/03/08	02:36	3.027	H	0	0
8670870	1996/03/08	09:06	0.165	LL	0	0
8670870	1996/03/08	14:54	2.681	H	0	0
8670870	1996/03/08	21:06	0.429	L	0	0

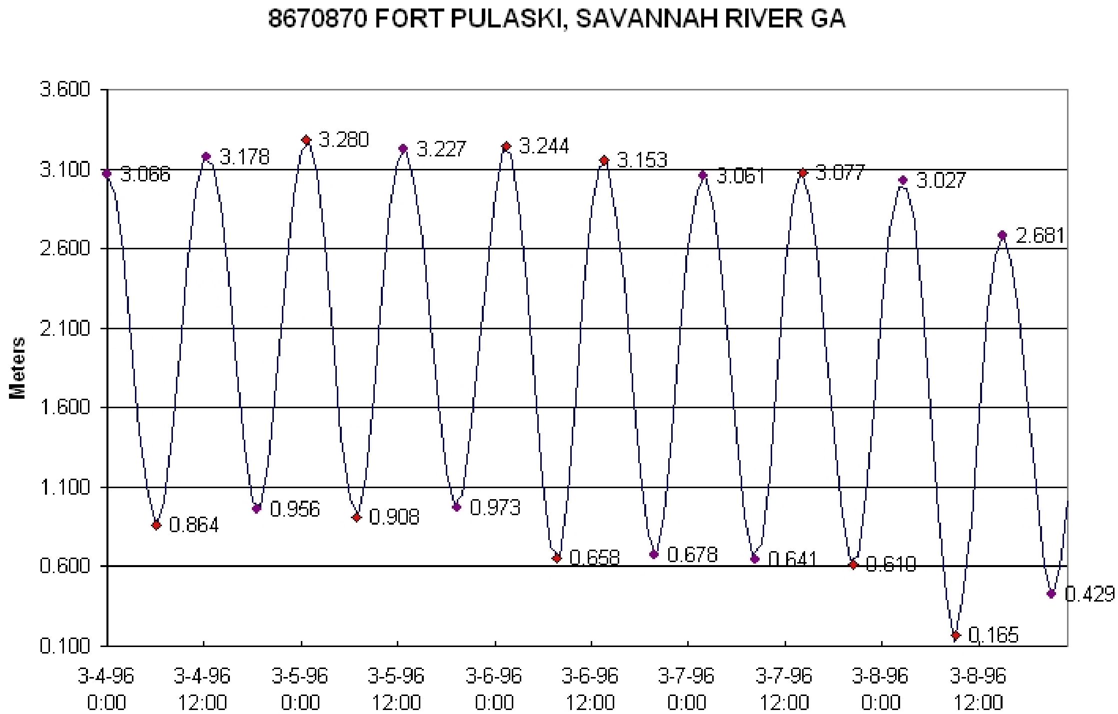


Figure 23. The data returned from the CO-OPS database for Fort Pulaski, GA. Referring to Figure 22, the selection of "W3-Highs/Lows", returns the data denoted by the diamond symbols. Their values are also labeled. The rest of the curve is obtained by selecting "W2-Hourly Heights", and resubmitting the data request.

Table 25. NOS High and Low Waters for 8665530 Charleston, Cooper River Entrance, SC, USA from 19960304 to 19960308. Data are verified. Data are in meters above Station Datum (STND). Times are on UTC (GMT). The fields in the table have the same meanings as Table 24.

Station	Date	Time	WL_Value	Type	Infer	Limit
8665530	1996/03/04	06:00	0.633	LL	0	0
8665530	1996/03/04	12:12	2.411	H	0	0
8665530	1996/03/04	18:30	0.792	L	0	0
8665530	1996/03/05	00:36	2.493	HH	0	0
8665530	1996/03/05	06:36	0.730	LL	0	0
8665530	1996/03/05	12:54	2.401	H	0	0
8665530	1996/03/05	19:06	0.768	L	0	0
8665530	1996/03/06	01:06	2.407	HH	0	0
8665530	1996/03/06	07:06	0.531	L	0	0
8665530	1996/03/06	13:18	2.321	HH	0	0
8665530	1996/03/06	19:36	0.502	LL	0	0
8665530	1996/03/07	01:48	2.227	H	0	0
8665530	1996/03/07	08:00	0.423	LL	0	0
8665530	1996/03/07	14:00	2.241	H	0	0
8665530	1996/03/07	20:12	0.484	L	0	0
8665530	1996/03/08	02:24	2.252	HH	0	0
8665530	1996/03/08	08:54	0.114	LL	0	0
8665530	1996/03/08	14:54	1.848	H	0	0
8665530	1996/03/08	20:42	0.291	L	0	0

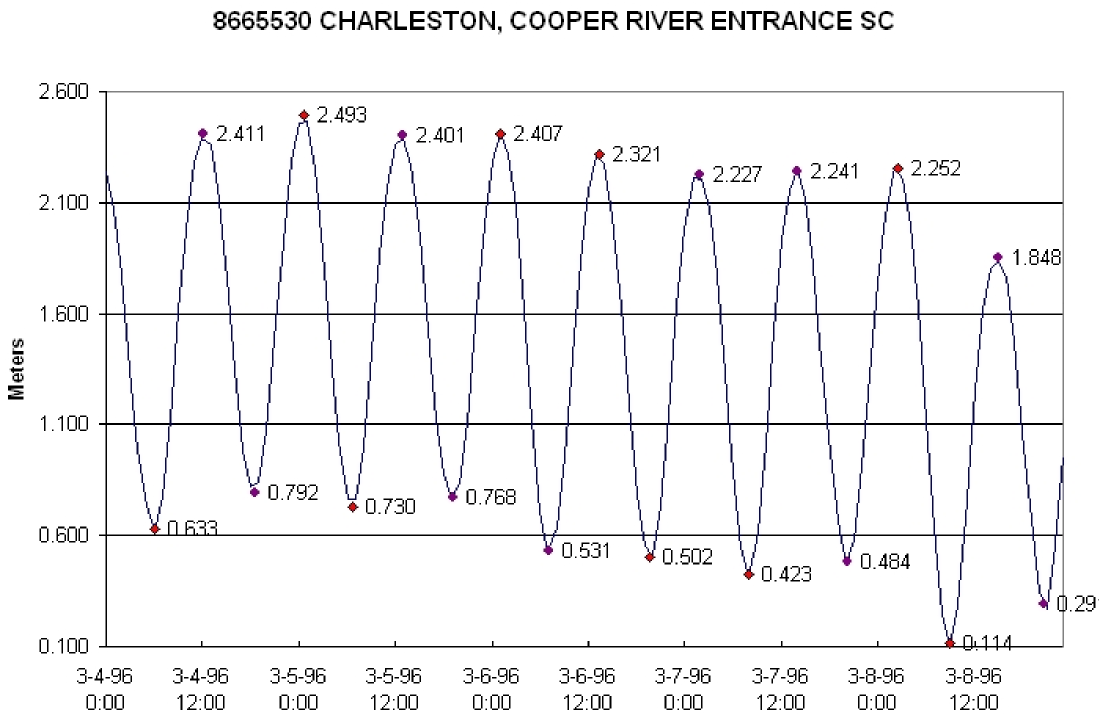


Figure 24. The data returned from the CO-OPS database for Charleston, SC.

Type or Designation Conversion at Subordinate Station

In using Tide by Tide comparisons, it is important that the each of high and low water tide designations are matched between subordinate and control stations (e.g. higher high waters at the subordinate station should be matched with corresponding higher high waters at the control station). Individual tides are designated during tabulation at each station independent of control/subordinate relationship. If the control station is well chosen for the subordinate based upon geographic proximity and type of tide, the corresponding tide designations will agree more often than not. However, the user must be prepared for occurrences in which tide designations differ between the subordinate and control, and must develop a consistent rule that can be applied to resolve differences. This occurs especially in areas with small inequalities and significant effects of meteorology on water levels where a higher high water at the subordinate may actually be designated a lower high water at the control through the independent pairing process at each station. In these cases, the fundamental rule is that the tide designation at the subordinate station is changed to agree with the corresponding tide designation at the control station, if necessary. If the tide designation at the subordinate is already the same as that at the control, a conversion is not done. It is important to note that the numerical value of the water level at the subordinate station is not altered; changes are reflected only in how this numerical value is categorized.

For example, in Figure 25, the first pair of water level values used in the analysis consist of 3.178 m at the subordinate and 2.411 m at the control. From Table 25, the value of 2.411 m is categorized as an "H". From Table 24 at the subordinate, 3.178 m is also categorized as an "H". These values match. In Table 26, the control station is labeled "B", and the subordinate is labeled "A". The categories of {HH, H, L, LL} in Tables 24 and 25, are designated as HHW, LHW, HLW, and LLW in Table 26; translating into words as "higher high water, lower high water, higher low

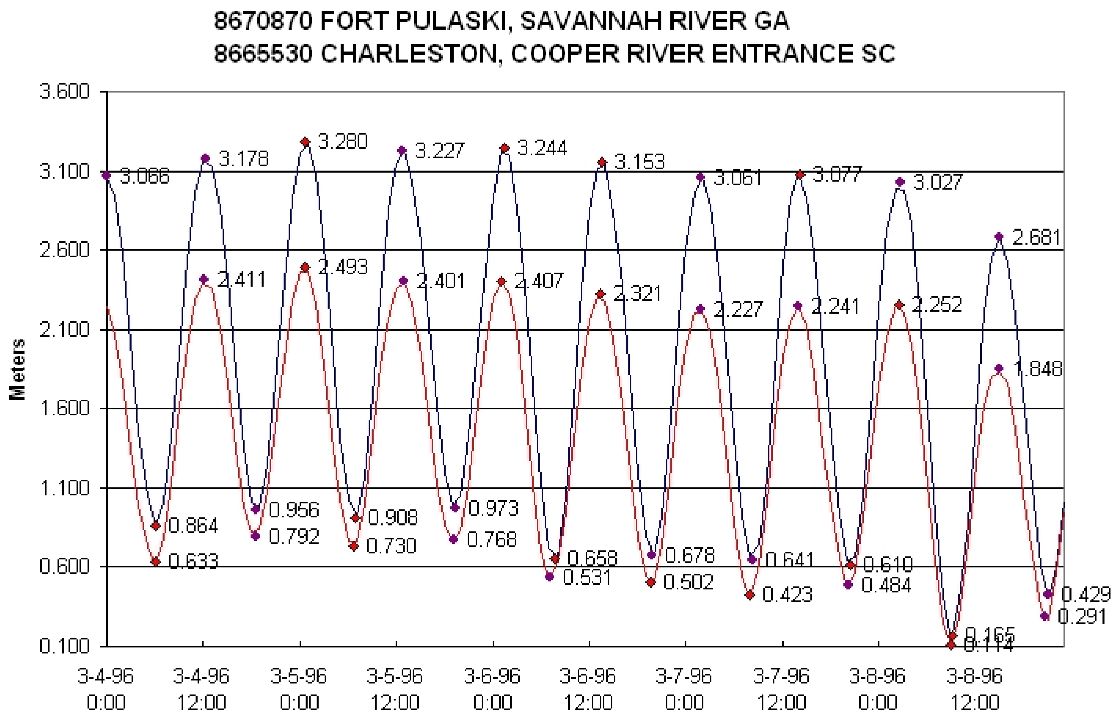


Figure 25. A graph of Charleston (upper curve) and Fort Pulaski (lower curve) data. The high water and low water values required for the tidal datum calculations are printed to illustrate the tide by tide comparison. Refer to this graph when considering the organization of Table 26 below.

water, and lower low water", respectively. In Table 26, the value of 2.411 m is entered as the first value under LHW_B , and 3.178 m is the first value under LHW_A . They are placed under the LHW columns because of the "H" designation at the control. Their difference, $3.178 - 2.411 = 0.767$, is the first entry under the column ΔLHW. The next tide pair are low waters with heights of 0.792 m at the control and 0.956 m at the subordinate. From Table 25, the 0.792 m at the control is an "L", which corresponds to the HLW_B column in Table 26. The value of 0.956 m at the subordinate is also an "L", placing it as the first entry under the HLW_A column. Their difference, $0.956 - 0.792 = 0.164$, is the first entry under ΔHLW. The next pair, 2.493 and 3.280, are entered under HHW because of the HH at the control. Their difference, 0.787 m, is the first entry under ΔHHW. The next pair, 0.730 and 0.980, are the first entries under the LLW columns, because of the "LL" designation at the control. Their difference, $0.908 - 0.730 = 0.178$, is the first entry under ΔLLW. This completes the first row of Table 26, and serves as a model for filling in the rest of Table 26. So far, type conversion at the subordinate has not occurred. However, continuing through this table example type conversion at the subordinate occurs a total of six times as explained below.

Table 26. Comparison of simultaneous observations for 96-3-4 TO 96-3-8.
Datums computed for the 1960-1978 tidal epoch. (A) designates the subordinate station, 8670870, FORT PULASKI, SAVANNAH RIVER, GA. (B) designates the control 8665530, CHARLESTON, COOPER RIVER ENTRANCE, SC.

	(A) STATION HEIGHT OF				(B) STATION HEIGHT OF				(A) - (B) HEIGHT DIFFERENCE			
	HHW_A	LHW_A	LLW_A	HLW_A	HHW_B	LHW_B	LLW_B	HLW_B	ΔHHW	ΔLHW	ΔLLW	ΔHLW
	3.280	3.178	0.908	0.956	2.493	2.411	0.730	0.792	0.787	0.767	0.178	0.164
	3.244	3.227	0.678	0.973	2.407	2.401	0.502	0.768	0.837	0.826	0.176	0.205
	3.153	3.061	0.641	0.658	2.321	2.227	0.423	0.531	0.832	0.834	0.218	0.127
	3.027	3.077	0.165	0.610	2.252	2.241	0.114	0.484	0.775	0.836	0.051	0.126
		2.681		0.429		1.848		0.291		0.833		0.138
SUMS:	12.704	15.224	2.392	3.626	9.473	11.128	1.769	2.866	3.231	4.096	0.623	0.760
NUMBER:	4	5	4	5	4	5	4	5	4	5	4	5
MEANS:	$\overline{HHW_A}$	$\overline{LHW_A}$	$\overline{LLW_A}$	$\overline{HLW_A}$	$\overline{HHW_B}$	$\overline{LHW_B}$	$\overline{LLW_B}$	$\overline{HLW_B}$	$\overline{\Delta HHW}$	$\overline{\Delta LHW}$	$\overline{\Delta LLW}$	$\overline{\Delta HLW}$
	3.176	3.045	0.598	0.725	2.368	2.226	0.442	0.573	0.808	0.819	0.156	0.152

The first instance of type conversion occurs in a HLW pairing. The pair 0.531 and 0.658 in Figure 25, requires type conversion at the subordinate. In Table 25 for the control, 0.531 is designated as an "L". However, in Table 24 at the subordinate, the 0.658 value is designated as an "LL". To rectify this mismatch at the subordinate, the "LL" is changed to an "L". Thus, these two values remain paired in Table 26, by entering the 0.658 under the HLW_A column. Type conversion at the subordinate occurs for the next three low water pairings. In the 0.502 and 0.678 pair, the 0.678 is changed from an "L" to an "LL". In the next low water pair, the value of 0.641 is changed from an "L" to an "LL". In the next pair, the value of 0.610, is changed from an "LL" to an "L". These changes are all reflected in Table 26. Among the high water conversions, in the pair consisting of 2.241 and 3.077, the value 3.077 is changed from an "HH" to an "H". In the next pair, 2.252 and 3.027, the 3.027 is changed from an "H" to an "HH".

Tidal Datums

Table 26 is the fundamental starting point for computing equivalent 19-year tidal datums at the subordinate from individual high and low waters from a short series of data. As in the prior chapter, the sum of the values in a particular column is stored in the "SUMS" row. The number of entries is in the "NUMBER" row, and the average is stored in the "MEANS" position. For example, the sum of the higher high waters at A, is 12.704 m. The average is denoted by

$$\overline{HHW_A} = \frac{12.704}{4} = 3.176\ m \qquad (21)$$

Similar averages are computed as shown in Table 26 for $\overline{LHW_A}$, $\overline{LLW_A}$, $\overline{HLW_A}$ for the subordinate station and for $\overline{HHW_B}$, $\overline{LHW_B}$, $\overline{LLW_B}$, $\overline{HLW_B}$ for the control station. In addition, sums and averages of the four height differences are calculated as shown for $\overline{\Delta HHW}$, $\overline{\Delta LHW}$, $\overline{\Delta HLW}$, $\overline{\Delta LLW}$.

The first set of calculations establishes the diurnal inequalities, the ranges of tide and the mean high water and mean low water elevations at the subordinate station for the comparison period. Directly from Table 26, the Diurnal High Water Inequality at A (DHQ_A), and the Diurnal Low Water Inequality at A (DLQ_A) are given by Equations 22 and 23,

$$DHQ_A = 0.5 \times \left(\overline{HHW_A} - \overline{LHW_A}\right) = 0.5 \times (3.176 - 3.045) = 0.066 \quad (22)$$

$$DLQ_A = 0.5 \times \left(\overline{HLW_A} - \overline{LLW_A}\right) = 0.5 \times (0.725 - 0.598) = 0.064 \quad (23)$$

The mean high water at A, denoted by, $\overline{HW_A}$, is computed from the mean of $\overline{HHW_A}$ and $\overline{LHW_A}$, or

$$\overline{HW_A} = \frac{3.176 + 3.045}{2} = 3.110 \quad (24)$$

Likewise, the mean low water at A, denoted by, $\overline{LW_A}$, is computed from the mean of $\overline{HLW_A}$ and $\overline{LLW_A}$, or

$$\overline{LW_A} = \frac{0.725 + 0.598}{2} = 0.662 \quad (25)$$

The Great Diurnal range at A, Gt_A, is given by

$$GT_A = \overline{HHW_A} - \overline{LLW_A} = 3.176 - 0.598 = 2.578 \quad (26)$$

The Mean range at A, Mn_A, is given by

$$Mn_A = \overline{HW_A} - \overline{LW_A} = 3.110 - 0.662 = 2.448 \quad (27)$$

The Diurnal Tide Level at A, DTL_A, is given by

$$DTL_A = 0.5 \times \left(\overline{HHW_A} + \overline{LLW_A}\right) = 0.5 \times (3.176 + 0.598) = 1.887 \quad (28)$$

The Mean Tide Level at A, MTL_A, is given by

$$MTL_A = 0.5 \times \left(\overline{HW_A} + \overline{LW_A}\right) = 0.5 \times (3.110 + 0.662) = 1.886 \quad (29)$$

The second set of calculations establishes the differences and ratios (as appropriate depending upon method used) in the various tabulated parameters between the subordinate and control station over the comparison time period. The average height differences for HHW, LHW, HLW and LLW are read from Table 26 as 0.808, 0.819, 0.152 and 0.156m, respectively.

The diurnal high water inequality difference is then computed by

$$\Delta DHQ = 0.5 \times \left(\overline{\Delta HHW} - \overline{\Delta LHW}\right) = 0.5 \times (0.808 - 0.819) = -0.006 \quad (30)$$

and the diurnal low water inequality difference is computed by

$$\Delta DLQ = 0.5 \times \left(\overline{\Delta HLW} - \overline{\Delta LLW}\right) = 0.5 \times (0.152 - 0.156) = -0.002 \quad (31)$$

The mean High Water difference, $\overline{\Delta HW}$, is computed from the high water differences by

$$\overline{\Delta HW} = \frac{\left(\overline{\Delta HHW} + \overline{\Delta LHW}\right)}{2} = \frac{0.808 + 0.819}{2} = 0.814 \quad (32)$$

The mean Low Water difference, $\overline{\Delta LW}$, is given by,

$$\overline{\Delta LW} = \frac{\left(\overline{\Delta HLW} + \overline{\Delta LLW}\right)}{2} = \frac{0.152 + 0.156}{2} = 0.154 \quad (33)$$

The Mean Range difference, ΔMn, is given by,

$$\Delta Mn = \overline{\Delta HW} - \overline{\Delta LW} = 0.814 - 0.154 = 0.660 \qquad (34)$$

The Diurnal Tide Level difference, ΔDTL, is given by,

$$\Delta DTL = 0.5 \times \left(\overline{\Delta HHW} + \overline{\Delta LLW}\right) = 0.5 \times \left(0.808 + 0.156\right) = 0.482 \qquad (35)$$

The Mean Tide Level difference, ΔMTL, is given by,

$$\Delta MTL = 0.5 \times \left(\overline{\Delta HW} + \overline{\Delta LW}\right) = 0.5 \times \left(0.814 + 0.154\right) = 0.484 \qquad (36)$$

The Great Diurnal range difference, ΔGt, is given by,

$$\Delta Gt = \overline{\Delta HHW} - \overline{\Delta LLW} = 0.808 - 0.156 = 0.652 \qquad (37)$$

The Mean Range Ratio, Mn_{RATIO} , the Diurnal High Water Inequality Ratio, DHQ_{RATIO}, and the Diurnal Low Water Inequality Ratio, DLQ_{RATIO}, are given by

$$Mn_{RATIO} = \frac{Mn_A}{Mn_A - \Delta Mn} = \frac{2.449}{2.449\ -\ 0.660} = 1.369 \qquad (38)$$

$$DHQ_{RATIO} = \frac{DHQ_A}{DHQ_A - \Delta DHQ} = \frac{0.066}{0.066 - (-0.006)} = 0.917 \qquad (39)$$

$$DLQ_{RATIO} = \frac{DLQ_A}{DLQ_A - \Delta DLQ} = \frac{0.064}{0.064 - (-0.002)} = 0.970 \qquad (40)$$

The Great Diurnal Ratio, Gt_{RATIO} , is given by

$$Gt_{RATIO} = \frac{Gt_A}{Gt_A - \Delta Gt} = \frac{2.578}{2.578 - 0.652} = 1.339 \qquad (41)$$

Table 5 presents the accepted 19-year tidal datums for Charleston, the control station for this example. For this example, the accepted values is for MTL, DTL, MN and Gt are required to derive the accepted datums at the control station using the modified range ratio method (from table 5).

The $MTL_{CORRECTED\ FOR\ A}$ is given by,

$$MTL_{CORRECTED\ \mathrm{FOR\ A}} = MTL_{ACCEPTED\ \mathrm{FOR\ B}} + \Delta MTL$$
$$= 1.622 + 0.484 = 2.106 \quad (42)$$

The $DTL_{CORRECTED\ FOR\ A}$ is given by,

$$DTL_{CORRECTED\ \mathrm{FOR\ A}} = DTL_{ACCEPTED\ \mathrm{FOR\ B}} + \Delta DTL$$
$$= 1.643 + 0.482 = 2.125 \quad (43)$$

The $Mn_{CORRECTED\ FOR\ A}$ is given by,

$$Mn_{CORRECTED\ \mathrm{FOR\ A}} = Mn_{ACCEPTED\ \mathrm{FOR\ B}} \times Mn_{RATIO}$$
$$= 1.606 \times 1.369 = 2.198 \quad (44)$$

The $Gt_{CORRECTED\ FOR\ A}$ is given by,

$$Gt_{CORRECTED\ \mathrm{FOR\ A}} = Gt_{ACCEPTED\ \mathrm{FOR\ B}} \times Gt_{RATIO}$$
$$= 1.768 \times 1.339 = 2.367 \quad (45)$$

From the above results, the equivalent 19-year datums at Fort Pulaski, GA based on a short term period of simultaneous observations with a control tide station can be computed. Then equations following those found in equations 9 through 12 are used.

The Mean Lower Low Water at A, $MLLW_A$, is given by,

$$MLLW_A = DTL_{CORRECTED\ \mathrm{FOR\ A}} - 0.5 \times Gt_{CORRECTED\ \mathrm{FOR\ A}}$$
$$= 2.125 - 0.5 \times 2.367$$
$$= 0.942m \quad (46)$$

The Mean Higher High Water at A, $MHHW_A$, is given by,

$$MHHW_A = MLLW_{\mathrm{A}} + Gt_{CORRECTED\ \mathrm{FOR\ A}}$$
$$= 0.942 + 2.367$$
$$= 3.309m \quad (47)$$

The Mean Low Water at A, MLW_A, is given by,

$$\begin{aligned} MLW_A &= MTL_{CORRECTED\ \mathrm{FOR\ A}} - 0.5 \times Mn_{CORRECTED\ \mathrm{FOR\ A}} \\ &= 2.106 - 0.5 \times 2.198 \\ &= 1.007m \end{aligned} \quad (48)$$

The Mean High Water at A, MHW_A, is given by,

$$\begin{aligned} MHW_A &= MLW_{\mathrm{A}} + Mn_{CORRECTED\ \mathrm{FOR\ A}} \\ &= 1.007 + 2.198 \\ &= 3.205m \end{aligned} \quad (49)$$

Lunitidal Intervals

Lunitidal Intervals can provide a measure of the average difference in time of tide between two locations. When sufficient data are available and monthly mean values are computed for a station, the monthly Greenwich Mean High Water Interval (HWI) and Greenwich Mean Low Water Interval (LWI) are among the means routinely computed by NOS for stations with semidiurnal and mixed tide types. These stations usually have a one-to-one correspondence between the tides (high and low waters) and the transits of the moon relative to the Greenwich meridian. As stated earlier, the Greenwich Intervals represent the mean difference in time between the upper and lower passage of the moon over the Greenwich Meridian and the following high and low tides observed at a station. The monthly mean HWI and LWI can be used to compute the average time difference in the phase of tide between different locations by subtracting one from the other. When only a short series of data is available, as in the present example, the time differences between individual corresponding tides are computed, and then the means of these differences are computed to provide this information.

In this section we compute the equivalent 19-year Greenwich High Water Interval (HWI) and Low Water Interval (LWI) at the subordinate station. To compute the tidal datums above, the notion of time was handled implicitly, simply by organizing the pairs of high or low values sequentially in Table 26. Here, the time aspect is treated explicitly. Table 27, like Table 26, is based upon the information presented in Tables 24 and 25. Table 27 includes the water level heights for stations A and B to show correct matching, but the elevations are not used to compute the HWI and LWI. The first pair of corresponding high waters have heights of 3.178 m and 2.411 m(Figure 34). These are the first entries under the HW column of stations A and B, respectively. The time associated with 3.178 is 1996/03/04 12:18 GMT (Table 27), and the time associated with 2.411 is 1996/03/04 12:12 GMT. These times have been converted from hours: minutes format to decimal hours in Table 27. The difference, 12.3-12.2 = 0.1, is the first entry under the HW Hours Time Difference column. The next pair of values are low waters occurring at 18.6 hours and 18.5 hours on March 4, and are entered under the LW columns of Station A and B, respectively. The difference of 0.1 hours is the first entry under the LW Time difference column. This is the method by which Table 27 is properly constructed. Note that Table 27 has a simpler layout than Table 26, because the computation of HWI and LWI does not distinguish between higher high water and lower high water, or, lower low water and higher low water.

The mean high water time difference is 0.12 hours, and the mean low water time difference is 0.26 hours (Table 27). From Table 5, the accepted HWI at Station B is 0.35 hours, and the accepted LWI interval is 6.57 hours.

$$HWI_{CORRECTED\text{ FOR A}} = HWI_{ACCEPTED\text{ FOR B}} + \overline{HWI}$$
$$= 0.35 + 0.12 = 0.47 hours \qquad (50)$$

Likewise,

$$LWI_{CORRECTED\text{ FOR A}} = LWI_{ACCEPTED\text{ FOR B}} + \overline{LWI}$$
$$= 6.57 + 0.26 = 6.83 hours \qquad (51)$$

Table 27. Calculation of the mean time differences between the subordinate and control stations. The means computed below are entered into Equations 48 and 49 to estimate the Greenwich lunitidal intervals at the subordinate station. The times entered below are in GMT.

(A) SUBORDINATE STATION 8670870 FORT PULASKI, SAVANNAH RIVER
(B) STANDARD STATION 8665530 CHARLESTON, COOPER RIVER ENTRANCE

	(A) STATION TIME OF				(B) STATION TIME OF		(A) - (B) TIME DIFFERENCE		(A) STATION HEIGHT OF		(B) STATION HEIGHT OF	
	HW		LW		HW	LW	HW	LW	HW	LW	HW	LW
DATE	HOURS		HOURS	DATE	HOURS	HOURS	HOURS	HOURS	METERS	METERS	METERS	METERS
MAR 4	12.3	4	6.1	MAR 4	12.2		0.1		3.178		2.411	
			18.6			18.5		0.1		0.956		0.792
5	0.7	5	6.8	5	0.6	6.6	0.1	0.2	3.280	0.908	2.493	0.730
	12.7		19.3		12.9	19.1	-0.2	0.2	3.227	0.973	2.401	0.768
6	1.5	6	7.6	6	1.1	7.1	0.4	0.5	3.244	0.658	2.407	0.531
	13.6		19.8		13.3	19.6	0.3	0.2	3.153	0.678	2.321	0.502
7	1.9	7	8.3	7	1.8	8.0	0.1	0.3	3.061	0.641	2.227	0.423
	14.1		20.4		14.0	20.2	0.1	0.2	3.077	0.610	2.241	0.484
8	2.6	8	9.1	8	2.4	8.9	0.2	0.2	3.027	0.165	2.252	0.114
	14.9		21.1		14.9	20.7	0.0	0.4	2.681	0.429	1.848	0.291
SUMS							1.1	2.3				
NUMBER							9	9				
MEANS							0.12	0.26				

4.3.2 Modified Range Ratio - Diurnal Tides

A comparison of Simultaneous High and Low Waters, also referred to as a Tide by Tide Comparison is used to compute short term datums if the simultaneous water level measurements at the subordinate and control exist for less than a month. Consider Figure 26, which illustrates the period of time from March 10 through March 16, 1996 at Panama City Beach and Pensacola, FL. The moon was in the tropics during this time period, producing a clean example of simultaneous diurnal tides at the subordinate and control. The data downloaded from the CO-OPS website are presented in Tables 28 and 29.

In Figure 26, the values of the high and low waters are plotted to facilitate understanding. The first step is to track the high and low waters correctly. Generally, this can be done by allowing a day to elapse to make sure that a peak and trough cycle have been resolved by each time series. Hence, the analysis begins with the trough of March 11, 1996, and records each high water and low water pair thereafter.

In Table 30, Panama City Beach, the subordinate station, is designated A, and Pensacola, the control station, is B. The left pair of columns represents the height of the high and low waters at Panama City Beach. Units are meters. The middle pair represent the height of the high and low waters at Pensacola. The right pair of columns represent the difference between the high waters at A and B, and the difference between the low waters at A and B. For example the first entry in the right pair is in the LW column, and is simply the low water at A minus the low water at B, or 7.843 - 2.271 = 5.572. For the HW field, the difference is the high water at A minus the high water at B, or 8.167 - 2.578 = 5.589. Focusing now on the leftmost pair, the sum of the high waters at A is 42.253 from 5 observations, hence the mean HHW ($\overline{HHW}_A$)is 8.451. Likewise, the mean lower low water, ($\overline{LLW}_A$) is 8.014. The higher high water at B, ($\overline{HHW_B}$) , is 2.806. The lower low water at B, ($\overline{LLW_B}$)is 2.383. The mean difference of the high waters between A and B,($\overline{\Delta HHW}$) is 5.645. The mean difference of the low waters ($\overline{\Delta LLW}$) is 5.632.

Table 28. NOS high and low waters for 8729210 Panama City Beach, FL, USA from 1996-03-10 to 1996-03-16. Data are verified. Data are in meters above STND. Times are on UTC (GMT).

Station	Date	Time	WL_Value	Type	Infer	Limit
8729210	1996/03/10	04:24	7.869	LL	0	0
8729210	1996/03/10	18:48	8.222	HH	0	0
8729210	1996/03/11	03:06	7.843	LL	0	0
8729210	1996/03/11	17:54	8.168	HH	0	0
8729210	1996/03/12	04:06	7.814	LL	0	0
8729210	1996/03/12	18:12	8.405	HH	0	0
8729210	1996/03/13	05:48	7.960	LL	0	0
8729210	1996/03/13	20:06	8.522	HH	0	0
8729210	1996/03/14	09:30	8.093	LL	0	0
8729210	1996/03/14	21:00	8.544	HH	0	0
8729210	1996/03/15	09:00	8.108	LL	0	0

Table 29. NOS high and low waters for 8729840 Pensacola, Pensacola Bay, FL, USA from 1996-03-10 to 1996-03-16. Data are verified. Data are in meters above STND. Times are on UTC (GMT).

Station	Date	Time	WL_Value	Type	Infer	Limit
8729840	1996/03/10	05:24	2.234	LL	0	0
8729840	1996/03/10	20:36	2.637	HH	0	0
8729840	1996/03/11	06:48	2.271	LL	0	0
8729840	1996/03/11	20:54	2.579	HH	0	0
8729840	1996/03/12	06:54	2.228	LL	0	0
8729840	1996/03/12	21:36	2.740	HH	0	0
8729840	1996/03/13	09:00	2.320	LL	0	0
8729840	1996/03/13	23:48	2.862	HH	0	0
8729840	1996/03/14	11:18	2.444	LL	0	0
8729840	1996/03/15	00:54	2.886	HH	0	0
8729840	1996/03/15	11:24	2.454	LL	0	0
8729840	1996/03/16	02:06	2.963	HH	0	0
8729840	1996/03/16	12:06	2.579	LL	0	0
8729840	1996/03/17	03:36	2.978	HH	0	0

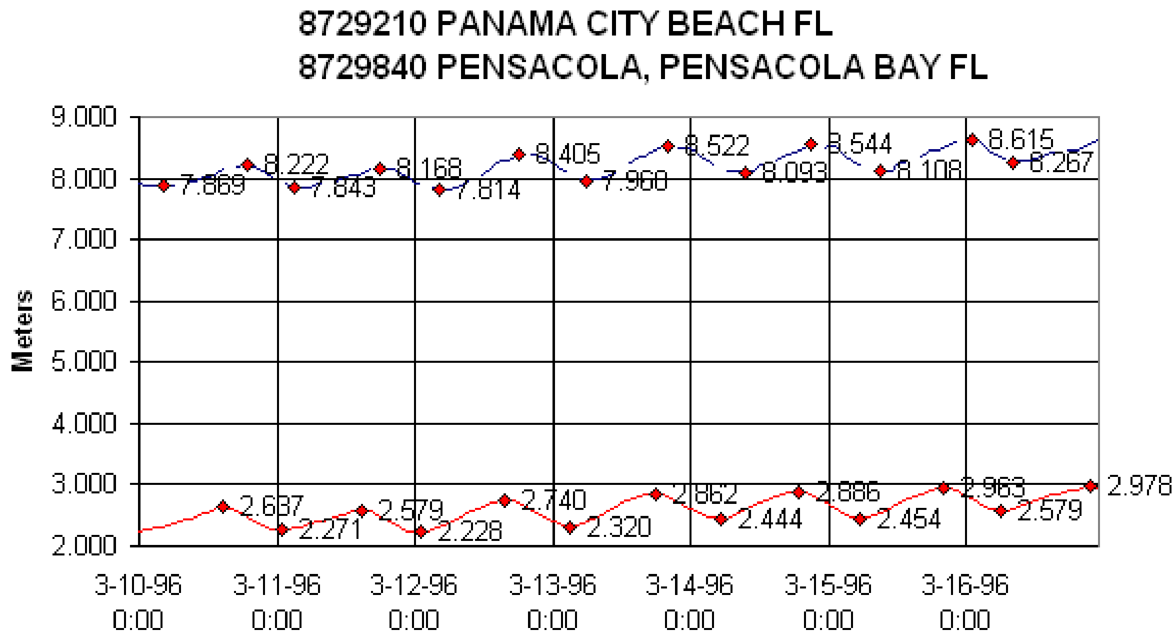


Figure 26. A comparison of corresponding highs and lows for diurnal tides. Panama City is the upper curve and Pensacola is the lower curve.

Table 30. Worksheet for computing a tide by tide comparison of high and low waters, diurnal example. Refer to Figure 26 to see how the high and low waters are matched.

```
(A) SUBORDINATE STATION 8729210  PANAMA CITY BEACH
(B) STANDARD STATION    8729840  PENSACOLA, PENSACOLA BAY
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	(A) STATION HEIGHT OF HHW METERS	(A) STATION HEIGHT OF LLW METERS	(B) STATION HEIGHT OF HHW METERS	(B) STATION HEIGHT OF LLW METERS	(A) - (B) HEIGHT DIFFERENCE HHW METERS	(A) - (B) HEIGHT DIFFERENCE LLW METERS
		7.843		2.271		5.572
	8.167		2.578		5.589	
	8.405	7.814	2.740	2.228	5.665	5.586
	8.522	7.960	2.862	2.320	5.660	5.640
	8.544	8.093	2.886	2.444	5.658	5.649
	8.615	8.108	2.963	2.454	5.652	5.654
	8.267	2.977	2.578		5.689	
	$\overline{HHW_A}$		$\overline{HHW_B}$		$\overline{\Delta HHW}$	
SUMS	42.253		14.029		28.224	
NUMBER	5		5		5	
MEANS	8.451		2.806		5.645	
		$\overline{LLW_A}$		$\overline{LLW_B}$		$\overline{\Delta LLW}$
SUMS		48.085		14.295		33.790
NUMBER		6		6		6
MEANS		8.014		2.383		5.632

Tidal Datums

Recalling the definition of Gt is MHHW - MLLW, the Gt at A for this time period, Gt_A, is formed by Equation 52,

$$Gt_A = \overline{HHW_A} - \overline{LLW_A} = 8.451 - 8.014 = 0.437 \qquad (52)$$

Similarly, the DTL at A may be defined as Equation 53,

$$DTL_A = 0.5 \times \left(\overline{HHW_A} + \overline{LLW_A}\right) = 0.5 \times (8.451 + 8.014) = 8.232 \qquad (53)$$

The average Gt difference, is given by Equation 54,

$$\Delta Gt = \overline{\Delta HHW} - \overline{\Delta LLW} = 5.645 - 5.632 = 0.013 \quad (54)$$

The Gt ratio, is defined by Eq. 55,

$$Gt_{RATIO} = \frac{Gt_A}{Gt_A - \Delta Gt} = \frac{0.437}{0.437 - 0.013} = 1.031 \qquad (55)$$

The DTL difference, is defined by Eq. 56,

$$\begin{aligned}\Delta DTL &= 0.5 \times \left(\overline{\Delta HHW_A} + \overline{\Delta LLW_A}\right) \\ &= 0.5 \times (5.645 + 5.632) = 5.638 \qquad (56)\end{aligned}$$

Recalling from Table 12, the accepted 19 year values of MHHW and MLLW for Pensacola, are 2.911 and 2.524, respectively, the accepted Gt and DTL values may be determined as,

$$Gt_{ACCEPTEDFORB} = MHHW - MLLW = 2.911 - 2.524 = 0.387 \qquad (57)$$

$$DTL_{ACCEPTEDFORB} = 0.5 \times (MHHW + MLLW) = 0.5 \times (2.911 + 2.524) = 2.719 \qquad (58)$$

The Gt, corrected for A, is given by Equation 59,

$$\begin{aligned} Gt_{CORRECTED\ \mathrm{FOR\ A}} &= Gt_{ACCEPTED\ \mathrm{FOR\ B}} \times Gt_{RATIO} \\ &= 0.387 \times 1.031 = 0.399 \end{aligned} \qquad (59)$$

DTL, corrected for A is given by Equation 60,

$$\begin{aligned} DTL_{CORRECTEDFORA} &= DTL_{ACCEPTEDFORB} + DTL_{DIFFERENCE} \\ &= 2.719 + 5.638 = 8.357 \end{aligned} \qquad (60)$$

Recalling Equations 11 and 12 , MLLW and MHHW may now be determined at Panama City Beach as,

$$\begin{aligned} MLLW_{A} &= DTL_{CORRECTEDFORA} - 0.5 \times Gt_{CORRECTEDFORA} \\ &= 8.357 - 0.5 \times (0.399) = 8.156 \end{aligned} \qquad (61)$$

$$\begin{aligned} MHHW_{A} &= MLLW_{A} + Gt_{CORRECTEDFORA} \\ &= 8.156 + 0.399 = 8.555 \end{aligned} \qquad (62)$$

These are the tidal datums for Panama City Beach, FL based on seven days of observations and adjusted to equivalent 19-year mean values through comparison of simultaneous observations at Pensacola, FL, a control station with accepted datums.

Lunitidal Intervals

Values for accepted and monthly HWI and LWI are not computed from tabulations for stations classified as diurnal, such as the case for Pensacola and panama City, FL. Instead, the values for Tropic Higher High Water Interval (TcHHWI), and the Tropic Lower Low Water Interval (TcLLWI) produced by harmonic analyses are used. Thus, this example concludes with the computation of the equivalent 19-year TcHHWI and TcLLWI at Panama City Beach. The values of TcHHWI and TcLLWI may be obtained from CO-OPS by request.

In Table 31 below, to use the TcHHWI and TcLLWI at Pensacola, one should technically be using the mean differences in time between the higher high waters and lower low waters. The tides at Panama City Beach and Pensacola are dominated by the diurnal tide and during this period when there are no secondary tides, in effect all high waters and low waters are actually higher high and lower low waters. Because the characteristics of the tide at the two stations are similar, using TcHHWI and TcLLWI should serve to supply time information at Panama City Beach.

$$TcHHWI_{CORRECTED\text{ FOR A}} \approx TcHHWI_{ACCEPTED\text{ FOR B}} + \overline{HWI}$$
$$\approx 3.95 + 3.00 = 6.95 hours \qquad (63)$$

Likewise,

$$TcLLWI_{CORRECTED\text{ FOR A}} \approx TcLLWI_{ACCEPTED\text{ FOR B}} + \overline{LWI}$$
$$\approx 15.27 + 3.00 = 18.27 hours \qquad (64)$$

These tropic intervals are used to estimate average time differences in the tide between diurnal stations, however they are most accurate during tropic tides (maximum north and south declination of the moon each month) and typically are inaccurate during times of equatorial tides (when the moon is on the equator each month).

Table 31. Computation of the mean time differences between Panama City Beach and Pensacola, FL.

(A) SUBORDINATE STATION 8729210 PANAMA CITY BEACH
(B) STANDARD STATION 8729840 PENSACOLA, PENSACOLA BAY

	(A) STATION TIME OF				(B) STATION TIME OF		(A) - (B) TIME DIFFERENCE		(A) STATION HEIGHT OF		(B) STATION HEIGHT OF	
	HW		LW		HW	LW	HW	LW	HW	LW	HW	LW
DATE	HOURS		HOURS	DATE	HOURS	HOURS	HOURS	HOURS	METERS	METERS	METERS	METERS
MAR 10	18.8	11	3.1	MAR 11		0.8		2.3		7.843		2.271
11	17.9				14.9		3.0		8.167		2.578	
12	18.2	12	4.1	12	15.6	0.9	2.6	3.2	8.405	7.814	2.740	2.228
13	20.1	13	5.8	13	17.8	3.0	2.3	2.8	8.522	7.960	2.862	2.320
14	21.0	14	9.5	14	18.9	5.3	2.1	4.2	8.544	8.093	2.886	2.444
16	1.1	15	9.0	15	20.1	5.4	5.0	3.6	8.615	8.108	2.963	2.454
		16	8.0	16	21.6	6.1		1.9		8.267	2.977	2.578
SUMS:							15.0	18.0				
NUMBER:							5	6				
MEANS:							3.00	3.00				

4.3.3 Standard Method - Mixed Tides

This section presents a mixed tides tide by tide case between Alameda and San Francisco, CA (Tables 32 and 33). Figures 27-29 show a short series of observations from Alameda, San Francisco, and a composite graph of the two. The analysis is different from the purely diurnal case because it involves the tabulation of the full set of observations of Higher High Water (HHW), Lower High Water (LHW), Lower Low Water (LLW), and Higher Low Water (HLW) at both stations. Tabulating the means from Figure 38 requires a more complex table structure (Table 34). A full example spreadsheet showing all aspects of this comparison is found in Appendix 2.

Table 32. NOS high and low waters for 9414750 Alameda, San Francisco Bay, CA, USA from 1997-03-01 to 1997-03-07. Data are verified. Data are in meters above STND. Times are on UTC (GMT).

Station	Date	Time	WL_Value	Type	Infer	Limit
9414750	1997/03/01	00:12	2.332	H	0	0
9414750	1997/03/01	05:36	1.655	L	0	0
9414750	1997/03/01	12:06	2.748	HH	0	0
9414750	1997/03/01	19:06	1.306	LL	0	0
9414750	1997/03/02	01:42	2.250	H	0	0
9414750	1997/03/02	06:24	1.744	L	0	0
9414750	1997/03/02	13:06	2.815	HH	0	0
9414750	1997/03/02	20:12	1.214	LL	0	0
9414750	1997/03/03	03:06	2.304	H	0	0
9414750	1997/03/03	07:48	1.784	L	0	0
9414750	1997/03/03	14:06	2.768	HH	0	0
9414750	1997/03/03	21:24	1.039	LL	0	0
9414750	1997/03/04	04:12	2.352	H	0	0
9414750	1997/03/04	09:06	1.725	L	0	0
9414750	1997/03/04	15:18	2.814	HH	0	0
9414750	1997/03/04	22:18	0.848	LL	0	0
9414750	1997/03/05	05:12	2.468	H	0	0
9414750	1997/03/05	10:06	1.642	L	0	0
9414750	1997/03/05	16:30	2.940	HH	0	0
9414750	1997/03/05	23:06	0.729	LL	0	0
9414750	1997/03/06	06:06	2.641	H	0	0
9414750	1997/03/06	11:12	1.527	L	0	0
9414750	1997/03/06	17:30	3.077	HH	0	0
9414750	1997/03/07	00:00	0.705	LL	0	0
9414750	1997/03/07	06:48	2.784	H	0	0
9414750	1997/03/07	12:06	1.361	L	0	0
9414750	1997/03/07	18:24	3.139	HH	0	0

Table 33. NOS high and low waters for 9414290 San Francisco, San Francisco Bay, CA, USA from 1997-03-01 to 1997-03-07. Data are verified. Data are in meters above STND. Times are on UTC (GMT).

Station	Date	Time	WL_Value	Type	Infer	Limit
9414290	1997/03/01	04:54	2.458	L	0	0
9414290	1997/03/01	11:48	3.340	HH	0	0
9414290	1997/03/01	18:30	2.111	LL	0	0
9414290	1997/03/02	01:24	2.853	H	0	0
9414290	1997/03/02	05:36	2.532	L	0	0
9414290	1997/03/02	12:36	3.417	HH	0	0
9414290	1997/03/02	19:36	2.008	LL	0	0
9414290	1997/03/03	03:00	2.901	H	0	0
9414290	1997/03/03	07:06	2.568	L	0	0
9414290	1997/03/03	13:42	3.361	HH	0	0
9414290	1997/03/03	21:00	1.857	LL	0	0
9414290	1997/03/04	04:06	2.933	H	0	0
9414290	1997/03/04	08:24	2.511	L	0	0
9414290	1997/03/04	15:00	3.391	HH	0	0
9414290	1997/03/04	21:30	1.669	LL	0	0
9414290	1997/03/05	05:00	3.021	H	0	0
9414290	1997/03/05	09:18	2.438	L	0	0
9414290	1997/03/05	15:54	3.488	HH	0	0
9414290	1997/03/05	22:30	1.535	LL	0	0
9414290	1997/03/06	05:42	3.165	H	0	0
9414290	1997/03/06	10:24	2.335	L	0	0
9414290	1997/03/06	17:00	3.603	HH	0	0
9414290	1997/03/06	23:12	1.498	LL	0	0
9414290	1997/03/07	06:30	3.292	H	0	0
9414290	1997/03/07	11:12	2.172	L	0	0
9414290	1997/03/07	17:48	3.648	HH	0	0

Table 34. Worksheet for calculating a tide by tide analysis for a mixed tide case.

```
COMPARISON OF SIMULTANEOUS OBSERVATIONS FOR  97  3  1 TO 97  3  7
(A) SUBORDINATE STATION 9414750  ALAMEDA, SAN FRANCISCO BAY
(B) STANDARD STATION    9414290  SAN FRANCISCO, SAN FRANCISCO BAY
```

	(A) STATION HEIGHT OF				(B) STATION HEIGHT OF				(A) - (B) HEIGHT DIFFERENCE			
	HHW_A	LHW_A	LLW_A	HLW_A	HHW_B	LHW_B	LLW_B	HLW_B	ΔHHW	ΔLHW	ΔLLW	ΔHLW
	2.748	2.250	1.306	1.744	3.340	2.853	2.111	2.532	-0.592	-0.603	-0.805	-0.788
	2.815	2.304	1.214	1.784	3.417	2.901	2.008	2.568	-0.602	-0.597	-0.794	-0.784
	2.768	2.352	1.039	1.725	3.361	2.933	1.857	2.511	-0.593	-0.581	-0.818	-0.786
	2.814	2.468	0.848	1.642	3.391	3.021	1.669	2.438	-0.577	-0.553	-0.821	-0.796
	2.940	2.641	0.729	1.527	3.488	3.165	1.535	2.335	-0.548	-0.524	-0.806	-0.808
	3.077	2.784	0.705	1.361	3.603	3.292	1.498	2.172	-0.526	-0.508	-0.793	-0.811
	3.139				3.648				-0.509			
SUMS:	20.301	14.799	5.841	9.783	24.248	18.165	10.678	14.556	-3.947	-3.366	-4.837	-4.773
NUMBER:	7	6	6	6	7	6	6	6	7	6	6	6
MEANS:	$\overline{HHW}_A$	$\overline{LHW}_A$	$\overline{LLW}_A$	$\overline{HLW}_A$	$\overline{HHW}_B$	$\overline{LHW}_B$	$\overline{LLW}_B$	$\overline{HLW}_B$	$\Delta\overline{HHW}$	$\Delta\overline{LHW}$	$\Delta\overline{LLW}$	$\Delta\overline{HLW}$
	2.900	2.467	0.974	1.631	3.464	3.028	1.780	2.426	-0.564	-0.561	-0.806	-0.796

Tidal Datums

Table 34 is structured as follows. There are three major groups (A), (B), and (A)-(B). Each of these are further subdivided into four columns. Under (A) and (B), HHW, LHW, LLW, HLW, both appear; the differences appear in (A)-(B) as ΔHHW ,ΔLHW, ΔLLW, and ΔHLW. In addition, Table 34 is structured in chronological order with respect to Figure 29 (Figures 27 and 28 support Figure 29 by treating the time series separately), the HHW_A being paired with the HHW_B. Thus, the first entry under ΔHHW, -0.592, is equal to the difference of the $HHW_A - HHW_B = 2.748 - 3.340$. The chief feature of Table 34 is that the pairs (HHW_A ,HHW_B) are matched higher high water to higher high water, lower low water to lower low water. Thus, the difference fields represent differences between pairs of simultaneous observations, as a visual check with Figure 29 demonstrates. The means at A and B are denoted by the overbar, the mean difference is denoted with an overbar and is preceded by the Δ operator. The means and the mean differences are stored in the MEANS row.

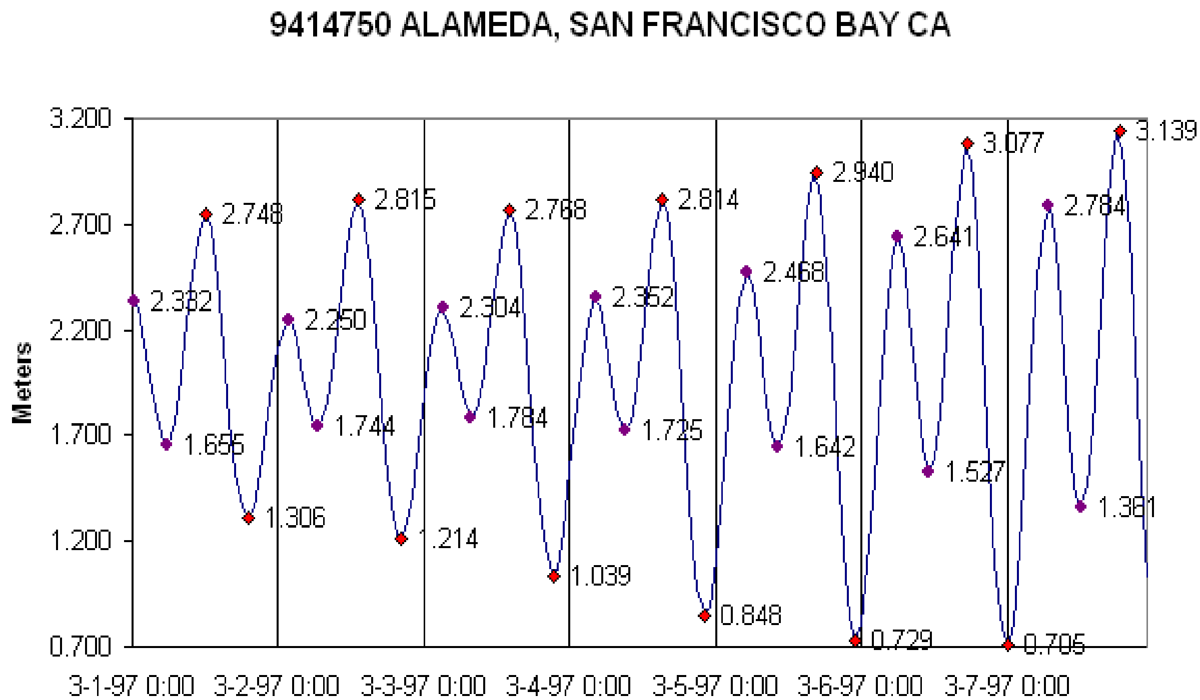

Figure 27. The water level time series for Alameda with the highs and lows plotted. The data are referenced to station datum.

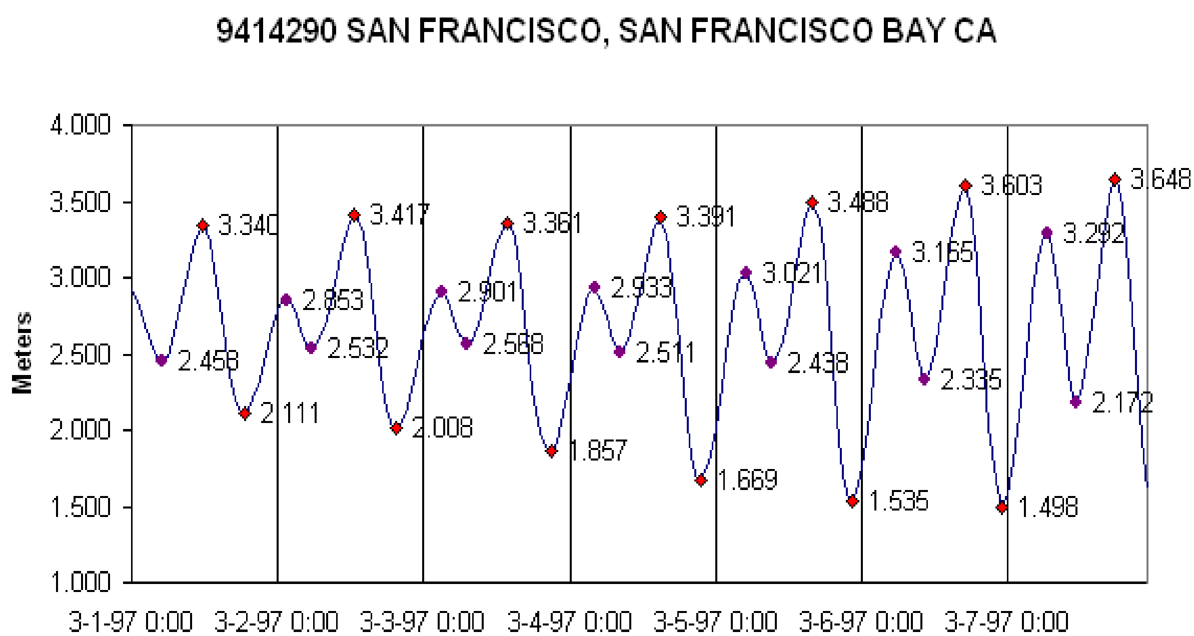

Figure 28. The water level time series for San Francisco with the highs and lows plotted. The data are referenced to station datum.

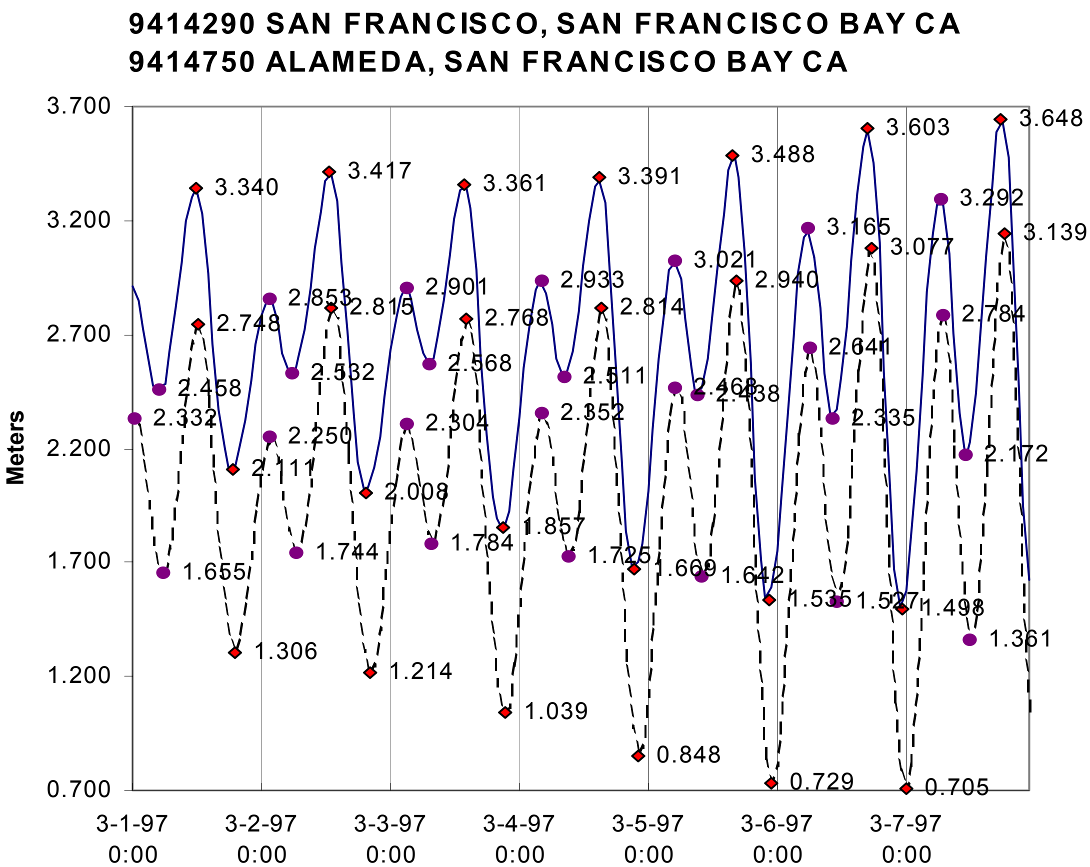

Figure 29. A composite graph of Alameda (lower curve) and San Francisco (upper curve). The time series at Alameda is represented by the dashed curve. The data are referenced to station datum at each site.

Directly from Table 34, the Diurnal High Water Inequality at A (DHQ_A), and the Diurnal Low Water Inequality at A (DLQ_A) is given by Equations 65 and 66,

$$DHQ_A = 0.5 \times \left(\overline{HHW_A} - \overline{LHW_A}\right) = 0.5 \times (2.900 - 2.467) = 0.216 \quad (65)$$

$$DLQ_A = 0.5 \times \left(\overline{HLW_A} - \overline{LLW_A}\right) = 0.5 \times (1.631 - 0.974) = 0.328 \quad (66)$$

The Mean High Water Height at A, $\overline{HW_A}$, and the Mean Low Water Height At A, $\overline{LW_A}$, is calculated in Equations 67 and 68,

$$\overline{HW_A} = 0.5 \times \left(\overline{HHW_A} + \overline{LHW_A}\right) = 0.5 \times (2.900 + 2.467) = 2.684 \quad (67)$$

$$\overline{LW_A} = 0.5 \times \left(\overline{HLW_A} + \overline{LLW_A}\right) = 0.5 \times (1.631 + 0.974) = 1.302 \quad (68)$$

From Equations 26 and 28, the Mean Range at A, (Mn_A), and Mean Tide Level at A (MTL_A) are shown in Equations 69 and 70,

$$Mn_A = \overline{HW_A} - \overline{LW_A} = 2.684 - 1.302 = 1.382 \quad (69)$$

$$MTL_A = 0.5 \times \left(\overline{HW_A} + \overline{LW_A}\right) = 0.5 \times (2.684 + 1.302) = 1.993 \quad (70)$$

Returning to Table 34 to utilize the mean differences, the difference in DHQ and DLQ, denoted by Δ DHQ and Δ DLQ, respectively, are calculated as,

$$\Delta DHQ = 0.5 \times \left(\overline{\Delta HHW} - \overline{\Delta LHW}\right) = 0.5 \times \left(-0.564 - (-0.561)\right) = -0.002 \quad (71)$$

$$\Delta DLQ = 0.5 \times \left(\overline{\Delta HLW} - \overline{\Delta LLW}\right) = 0.5 \times \left(-0.796 - (-0.806)\right) = 0.005 \quad (72)$$

The Mean High Water Difference, $\overline{\Delta HW}$, and Mean Low Water Difference, $\overline{\Delta LW}$, are given by

$$\overline{\Delta HW} = 0.5 \times \left(\overline{\Delta HHW} + \overline{\Delta LHW}\right) = 0.5 \times \left(-0.564 + (-0.561)\right) = -0.562 \quad (73)$$

$$\overline{\Delta LW} = 0.5 \times \left(\overline{\Delta HLW} + \overline{\Delta LLW}\right) = 0.5 \times \left(-0.796 + (-0.806)\right) = -0.801 \quad (74)$$

The Mean Range Difference, ΔMn, and the Mean Tide Level Difference, ΔMTL, are given by

$$\Delta Mn = \overline{\Delta HW} - \overline{\Delta LW} = -0.562 - (-0.801) = 0.239 \quad (75)$$

$$\Delta MTL = 0.5 \times \left(\overline{\Delta HW} + \overline{\Delta LW}\right) = 0.5 \times \left(-0.562 + (-0.801)\right) = -0.682 \quad (76)$$

Three quantities designated as Mn_{RATIO}, DHQ_{RATIO}, and DLQ_{RATIO}, may now be calculated as

$$Mn_{RATIO} = \frac{Mn_A}{Mn_A - \Delta Mn} = \frac{1.382}{1.382 - 0.239} = 1.209 \qquad (77)$$

$$DHQ_{RATIO} = \frac{DHQ_A}{DHQ_A - \Delta DHQ} = \frac{0.216}{0.216 - (-0.002)} = 0.991 \qquad (78)$$

$$DLQ_{RATIO} = \frac{DLQ_A}{DLQ_A - \Delta DLQ} = \frac{0.328}{0.328 - 0.005} = 1.015 \qquad (79)$$

Four quantities designated as $MTL_{CORRECTED\ FOR\ A}$, $Mn_{CORRECTED\ FOR\ A}$, $DHQ_{CORRECTED\ FOR\ A}$, and $DLQ_{CORRECTED\ FOR\ A}$, may now be calculated as

$$MTL_{CORRECTEDFORA} = MTL_{ACCEPTEDFORB} + \Delta MTL = 2.728 + (-0.682) = 2.046 \qquad (80)$$

$$Mn_{CORRECTEDFORA} = Mn_{ACCEPTEDFORB} \times Mn_{RATIO} = 1.250 \times 1.209 = 1.511 \qquad (81)$$

$$DHQ_{CORRECTEDFORA} = DHQ_{ACCEPTEDFORB} \times DHQ_{RATIO} = 0.183 \times 0.991 = 0.181 \qquad (82)$$

$$DLQ_{CORRECTEDFORA} = DLQ_{ACCEPTEDFORB} \times DLQ_{RATIO} = 0.344 \times 1.015 = 0.349 \qquad (83)$$

Employing the Standard Method the tidal datums at Alameda are,

$$MLW_A = MTL_{CORRECTEDFORA} - 0.5 Mn_{CORRECTEDFORA} = 2.046 - 0.5(1.511) = 1.290 \quad (84)$$

$$MHW_A = MLW_A + Mn_{CORRECTEDFORA} = 1.290 + 1.511 = 2.801 \qquad (85)$$

$$MLLW_A = MLW_A - DLQ_{CORRECTEDFORA} = 1.290 - 0.349 = 0.941 \qquad (86)$$

$$MHHW_A = MHW_A + DHQ_{CORRECTEDFORA} = 2.801 + 0.181 = 2.982 \qquad (87)$$

These are the tidal datums for Alameda, CA based on seven days of observations and adjusted to equivalent 19-year mean values through comparison of simultaneous observations at San Francisco, CA, a control station with known accepted datums.

Lunitidal Intervals

The accepted 19-year values at San Francisco (Table 19) includes HWI and LWI. Using the mean differences from Table 35, the equivalent HWI and LWI at Alameda are determined to be 7.91 and 1.54 hours, respectively.

$$\begin{aligned} HWI_{CORRECTED\ FOR\ A} &= HWI_{ACCEPTED\ FOR\ B} + \overline{HWI} \\ &= 7.56 + 0.35 = 7.91 hours \end{aligned} \qquad (88)$$

Likewise,

$$\begin{aligned} LWI_{CORRECTED\ FOR\ A} &= LWI_{ACCEPTED\ FOR\ B} + \overline{LWI} \\ &= 0.83 + 0.71 = 1.54 hours \end{aligned} \qquad (89)$$

Table 35. Computation of the mean time differences between Alameda and San Francisco, CA.
(A) SUBORDINATE STATION 9414750 ALAMEDA, SAN FRANCISCO BAY
(B) STANDARD STATION 9414290 SAN FRANCISCO, SAN FRANCISCO BAY

	(A) STATION TIME OF				(B) STATION TIME OF		(A) - (B) TIME DIFFERENCE		(A) STATION HEIGHT OF		(B) STATION HEIGHT OF	
DATE	HW HOURS		LW HOURS	DATE	HW HOURS	LW HOURS	HW HOURS	LW HOURS	HW METERS	LW METERS	HW METERS	LW METERS
MAR 1	12.1	1	5.6	MAR 1	11.8		0.3		2.748	1.655	3.340	
			19.1			18.5		0.6		1.306		2.111
2	1.7	2	6.4	2	1.4	5.6	0.3	0.8	2.250	1.744	2.853	2.532
	13.1		20.2		12.6	19.6	0.5	0.6	2.815	1.214	3.417	2.008
3	3.1	3	7.8	3	3.0	7.1	0.1	0.7	2.304	1.784	2.901	2.568
	14.1		21.4		13.7	21.0	0.4	0.4	2.768	1.039	3.361	1.857
4	4.2	4	9.1	4	4.1	8.4	0.1	0.7	2.352	1.725	2.933	2.511
	15.3		22.3		15.0	21.5	0.3	0.8	2.814	0.848	3.391	1.669
5	5.2	5	10.1	5	5.0	9.3	0.2	0.8	2.468	1.642	3.021	2.438
	16.5		23.1		15.9	22.5	0.6	0.6	2.940	0.729	3.488	1.535
6	6.1	6	11.2	6	5.7	10.4	0.4	0.8	2.641	1.527	3.165	2.335
	17.5	7	0.0		17.0	23.2	0.5	0.8	3.077	0.705	3.603	1.498
7	6.8		12.1	7	6.5	11.2	0.3	0.9	2.784	1.361	3.292	2.172
	18.4				17.8		0.6		3.139		3.648	
SUMS:							4.6	8.5				
NUMBER:							13	12				
MEANS:							0.35	0.71				

4.4 Direct Method

The Direct Method is usually used only when a full range of tidal values are not available. For example, direct MHW can be computed for situations when low waters are not recorded, such as in the upper reaches of a marsh. Since MTL, DTL, and Mn and Gt cannot be determined if low waters are cut-off, equivalent NTDE values for MHW and MHHW datums are determined directly by comparison of high tides with an appropriate control using the available part of the tidal cycle. The equation for computation of MHW from monthly means or using a TBYT would be:

$$MHW_{CORRECTED\ FOR\ A} = MHW_{ACCEPTED\ FOR\ B} + \left(\frac{1}{N}\right) \sum_{I=1}^{N} (MHW_A(I) - MHW_B(I)) \quad (90)$$

and the equation for MHHW would be:

$$MHHW_{CORRECTED\ FOR\ A} = MHHW_{ACCEPTED\ FOR\ B} + \left(\frac{1}{N}\right) \sum_{I=1}^{N} (MHHW_A(I) - MHHW_B(I)) \quad (91)$$

where N would represent either monthly means or the number of individual tides depending on the type of comparison. Figure 30 shows the nature of the tide curve of a station requiring the Direct Method for datum determination.

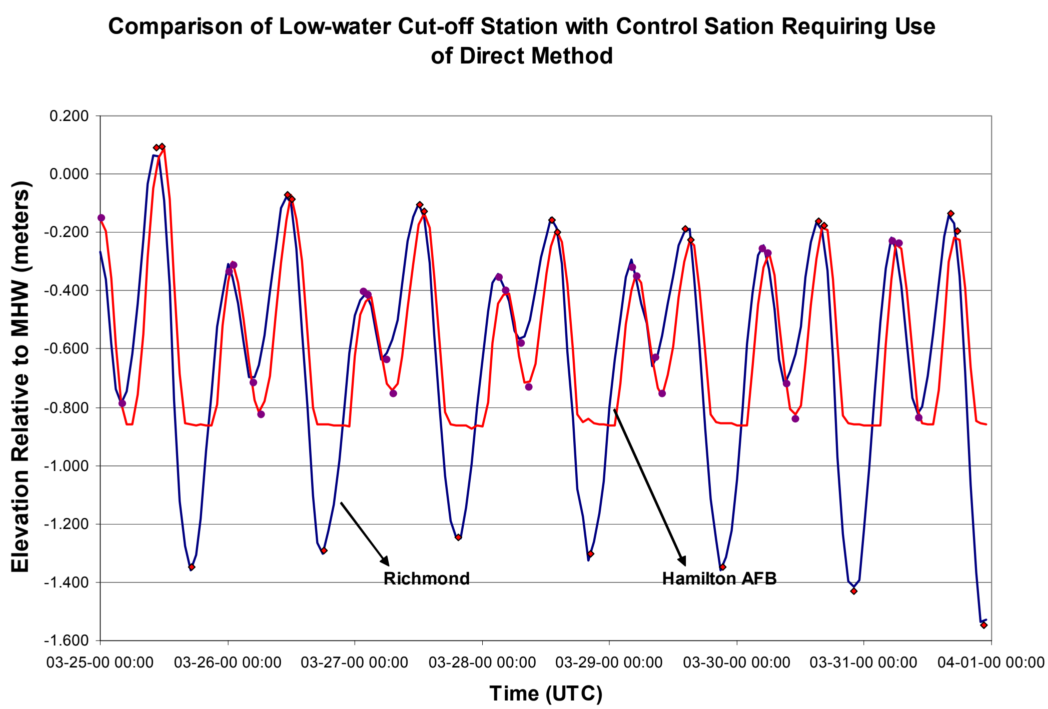

Figure 30. Comparison of data for a typical 7-day period showing low waters cut-off at the subordinate station.

The following two tables show the direct comparisons for 3-month time period used to obtain MHW and MHHW datums for the station pair shown in Figure 30.

Table 36. Worksheet for computing MHW at subordinate station using the Direct Method.

(A) SUBORDINATE STATION 9415126 HAMILTON AFB, SAN FRANCISCO BAY
(B) STANDARD STATION 9414863 RICHMOND, SAN FRANCISCO BAY

Mon Year	M H W A METER	B METER	A - B METER
Mar 2000	0.893	5.121	-4.228
Apr 2000	0.873	5.113	-4.240
May 2000	0.889	5.127	-4.238

SUMS	-12.706
TOTAL MONTHS	3.000
MEANS	-4.235
ACCEPTED FOR B	5.128
CORRECTED FOR A	0.893

Table 37. Worksheet for computing MHHW at subordinate station using the Direct Method

(A) SUBORDINATE STATION 9415126 HAMILTON AFB, SAN FRANCISCO BAY
(B) STANDARD STATION 9414863 RICHMOND, SAN FRANCISCO BAY

Mon Year	M H H W A METER	B METER	A - B METER
Mar 2000	1.013	5.242	-4.229
Apr 2000	0.964	5.208	-4.244
May 2000	1.040	5.291	-4.251

SUMS	-12.724
TOTAL MONTHS	3.000
MEANS	-4.241
ACCEPTED FOR B	5.310
CORRECTED FOR A	1.069

5.0 SUMMARY

The techniques used in this handbook are the NOS methodology for the computation of tidal datums. These techniques must be used to perform work according to NOS standards and specifications. To perform tidal datum computations, the tides at the subordinate and control must have similar tidal characteristics and similar ranges. The selection of the proper control station is more difficult for diurnal tides than for semidiurnal or mixed, because diurnal tides frequently change their character both temporally at a site, and spatially over short distances. Lastly, all measurements contain some error or uncertainty in their values. Vertical errors translate into horizontal errors when surveyed to land. Horizontal errors are exacerbated by low slopes. In general, the accuracy of tidal datums increases as the amount of data used in the computations increases.

5.1 SUMMARY OF TIDAL DATUMS

Regardless of type of tide or datum computation methodology, the following tidal datums and tidal parameters are typically desired:

Datums:

Mean Higher High Water	(MHHW)
Mean High Water	(MHW)
Mean Tide Level	(MTL)
Diurnal Tide Level	(DTL)
Mean Sea Level	(MSL)
Mean Low Water	(MLW)
Mean Lower Low Water	(MLLW)

Ranges of Tide and Inequalities

Mean Range of Tide	(Mn)
Great Diurnal Range of Tide	(Gt)
Diurnal High Water Inequality	(DHQ)
Diurnal Low Water Inequality	(DLQ)

Lunitidal Intervals (not computed for Diurnal Tides)

High Water Interval	(HWI)
Low Water Interval	(LWI)

5.2 SUMMARY OF PROCEDURES FOR COMPUTATION OF TIDAL DATUMS

A vertical datum is called a tidal datum when it is defined by a certain phase of the tide. Tidal datums are local datums and should not be extended into areas which have differing hydrographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as bench marks.

Basic Procedures:

1. Make Observations - Tidal datums are computed from continuous observations of the water level over specified lengths of time. Observations are made at specific locations called tide stations. Each tide station consists of a water level gauge or sensor(s), a data collection platform or data logger and data transmission system, and a set of tidal bench marks established in the vicinity of the tide station. NOS collects water level data at 6-minute intervals.

2. Tabulate the Tide - Once water level observations are quality controlled and any small gaps filled, the data are processed by tabulating the high and low tides and hourly heights for each day. Tidal parameters from these daily tabulations of the tide are then reduced to mean values, typically on a calendar month basis for longer period records or over a few days or weeks for shorter-term records.

3. Compute Tidal Datums - First reduction tidal datums are determined directly by meaning values of the tidal parameters over a 19-year NDTE. Equivalent NDTE tidal datums are computed from tide stations operating for shorter time periods through comparison of simultaneous data between the short-term station and a long term station.

4. Compute Bench Mark Elevations - Once the tidal datums are computed from the tabulations, the elevations are transferred to the bench marks established on the land through the elevation differences established by differential leveling between the tide gauge sensor "zero" and the bench marks during the station operation. The bench mark elevations and descriptions are disseminated by NOS through a published bench mark sheet for each station. Connections between tidal datum elevations and geodetic elevations are obtained after leveling between tidal bench marks and geodetic network bench marks. Traditionally, this has been accomplished using differential leveling, however GPS surveying techniques can also be used (NGS, 1997).

The locations of tide stations are organized into a hierarchy:

Control tide stations are generally those which have been operated for 19 or more years, are expected to continuously operate in the future, and are used to obtain a continuous record of the water levels in a locality. Control tide stations are sited to provide datum control for national applications, and located in as many places as needed for datum control.

Secondary water level stations are those which are operated for less than 19 years but more than 1 year, and have a planned finite lifetime. Secondary stations provide control in bays and estuaries where localized tidal effects are not realized at the nearest control station. Observations at a secondary station are not usually sufficient for a precise independent determination of tidal datums, but when reduced by comparison with simultaneous observations at a suitable control tide station very satisfactory results may be obtained.

Tertiary water level stations are those which are operated for more than a month but less than 1 year. Short-term water level measurement stations (secondary and tertiary) may have their data reduced to equivalent 19-year tidal datums through mathematical simultaneous comparison with a nearby control station.

Control (or primary) tide stations, secondary stations and tertiary stations are located at strategic locations for network coverage. The site selection criteria include spatial coverage of significant changes in tidal characteristics such as: changes in tide type, changes in range of tide, changes in time of tide, changes in daily mean sea level and changes in long term mean sea level trends. Other criteria include coverage of critical navigation areas and transitional zones, historical sites, proximity to the geodetic network, and the availability of existing structures, such as piers suitable for the location of the scientific equipment.

Procedure for Simultaneous Comparison:

Conceptually, the following steps need to be completed in order to compute equivalent NTDE tidal datums at short term stations using the method of comparison of simultaneous observations:

1) Select the time period over which the simultaneous comparison will be made.

2) Select the appropriate control tide station for the subordinate station of interest.

3) Obtain the simultaneous data from subordinate and control stations and obtain or tabulate the tides and compute monthly means, as appropriate.

4) Obtain the accepted NTDE values of the tidal datums at the control station from NOS via the CO-OPS Website (www.tidesandcurrents.noaa.gov)

5) Compute the mean differences and/or ratios (as appropriate) in the tidal parameters between the subordinate and control station over the period of simultaneous comparison.

6) Apply the mean differences and ratios computed in step 5, above, to the accepted values at the control station to obtain equivalent or corrected NTDE values for the subordinate station. The computations use slightly different formulas depending on type of tide. These differences are explained in section 3.4 and in Chapter 4.

Datum Computation Methods:

There are some key datum computation methods used by NOS (in step 6, above) that differ slightly depending upon the tidal characteristics and the type of tide.

Standard Method. This method is generally used for the West Coast and Pacific Island stations and is also called the Range Ratio Method. First, equivialent NTDE values for MTL, Mn, DHQ and DLQ are determined by comparison with an appropriate control. From these, the following are then computed:

MLW = MTL - (0.5 x Mn)
MHW = MLW + Mn
MLLW= MLW - DLQ
MHHW = MHW + DHQ

Modified-Range Ratio Method. This method is generally used for the East Coast, Gulf Coast and Caribbean Island stations. First, equivalent NTDE values for MTL, DTL, Mn and Gt as determined by comparison with an appropriate control. The difference from the Standard Method is that ratios of the DHQ and DLQ values are not used to compute MHHW and MLLW because numerically the values are very small for semidiurnal tide areas. A Gt ratio about DTL is used instead. From these, the following are computed:

MLW = MTL - (0.5 x Mn)
MHW = MLW + Mn
MLLW= DTL - (0.5 x Gt)
MHHW = MLLW + Gt

Direct Method. The Direct Method is usually used only when a full range of tidal values are not available. For example, direct MHW can be computed for situations when low waters are not recorded, such as in the upper reaches of a marsh. Since MTL, DTL, and Mn and Gt cannot be determined if low waters are cut-off, equivalent NTDE values for MHW and MHHW datums are determined directly by comparison of high tides with an appropriate control using the available part of the tidal cycle.

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6. REFERENCES

Bowditch, N., The American Practical Navigator, An Epitome of Navigation, Defense Mapping Agency Hydrographic/Topographic Center, Bethesda, MD, pp. 873, 1995.

Floyd, R.P., Geodetic Bench Marks, NOAA Manual NOS NGS 1, U.S. Department of Commerce, NOAA, National Ocean Survey, Rockville, MD, pp.51, September 1978.

Gill, S.K., J.R. Hubbard, and W.D. Scherer, Updating the National Tidal Datum Epoch for the United States, in Proceedings Ocean Community Conference, Marine Technology Society Annual Conference, November 16-19, 1998, 1040-1043, 1998.

Hicks, S.D., Tidal Datums and Their Uses - A Summary, Shore and Beach, 27-33, 1985.

Hicks, S.D., P.C. Morris, H.A. Lippincott, and M.C. O'Hargan, Users's Guide for the Installation of Bench Marks and Leveling Requirements for Water Levels, NOAA National Ocean Service, Silver Spring, MD, pp. 73, 1987.

International Oceanographic Commission (IOC), Manual on Sea level Measurement and Interpretation, Volume 3 - Reappraisals and recommendations as of the Year 2000, Manuals and Guides 14, UNESCO 2000.

Marmer, H.A., Tidal Datum Planes, NOAA National Ocean Service, Special Publication No. 135, U.S. Coast and Geodetic Survey, U.S. Govt. Printing Office, revised ed.,1951.

Mero, T.N., NOAA/National Ocean Service Application of Real-Time Water Levels, in Proceedings, Volume 2, Ocean Community Conference, The Marine Technology Society Annual Conference, November 16-19, 1998, 1036-1039,1998.

National Geodetic Survey, Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2CM and 5CM) Version 4.3, NOAA Technical Memorandum NOS NGS-58, November 1997.

National Ocean Service, Tide and Current Glossary, NOAA National Ocean Service, Silver Spring, MD, 2000.

National Ocean Service, Tidal Datums and Their Applications, NOAA Technical Report NOS CO-OPS 1, Center For Operational Oceanographic Products and Services, Silver Spring, MD, 2000.

National Ocean Service, NOS Hydrographic Surveys Specifications and Deliverables, NOAA National Ocean Service, Silver Spring, MD, pp. 91, 2003.

Scherer, W.D., National Ocean Service's Next Generation Water level Measurement System, Vol. 4, International Congress of Surveying, Toronto, Ontario, Canada, pp 232-243, 1986.

Schureman, P., Manual of Harmonic Analysis and Prediction of Tides, Special Publication No. 98 (1940), U.S. Coast and Geodetic Survey, U.S. Govt. Printing Office, revised ed.,1941.

Swanson, R.L., Variability of Tidal Datums and Accuracy in Determining Datums from Short Series of Observations, NOAA Tech. Rep. NOS 64, Silver Spring, MD, pp. 41, 1974.

Zervas, C., Sea Level Variations of the United States 1854 - 1999, NOAA Technical Report NOS CO-OPS 36, Silver Spring, MD, pp186, 2001.

Appendix 1:

EXAMPLES OF TIDAL DATUM COMPUTATION SPREADSHEETS

A. SEMIDIURNAL TIDE TYPE: MODIFIED RANGE RATIO METHOD

B. MIXED TIDE TYPE: STANDARD METHOD

SUBORDINATE STATION A: FORT PULASKI, GA **ELEVATIONS IN METERS, TIME IN HOURS**
CONTROL STATION B: CHARLESTON, SC

	MTL			**DTL**			**HWI**		
	Station A	**Station B**	**A - B**	**Station A**	**Station B**	**A - B**	**Station A**	**Station B**	**A - B**
1997 03	2.156	1.662	0.494	2.159	1.672	0.487	0.54	0.41	0.13
1997 04	2.248	1.751	0.497	2.259	1.763	0.496	0.55	0.41	0.14
1997 05	2.188	1.673	0.515	2.208	1.699	0.509	0.54	0.41	0.13
1997 06	2.291	1.792	0.499	2.320	1.818	0.502	0.62	0.47	0.15
1997 07	2.225	1.730	0.495	2.253	1.758	0.495	0.55	0.46	0.09
1997 08	2.295	1.789	0.506	2.309	1.807	0.502	0.55	0.45	0.10
1997 09	2.353	1.851	0.502	2.369	1.870	0.499	0.61	0.51	0.10
1997 10	2.305	1.807	0.498	2.321	1.824	0.497	0.62	0.48	0.14
1997 11	2.158	1.669	0.489	2.182	1.692	0.490	0.58	0.46	0.12
1997 12	2.118	1.635	0.483	2.139	1.661	0.478	0.61	0.45	0.16
1998 01	2.135	1.634	0.501	2.152	1.665	0.487	0.55	0.39	0.16
1998 02	2.300	1.811	0.489	2.304	1.821	0.483	0.58	0.30	0.28
SUMS			5.968			5.925			1.70
# MONTHS			12.000			12.000			12.00
MEANS			0.497			0.494			0.14
ACCEPTED VALUE FOR B:			1.622			1.643			0.35
CORRECTED AT A:			2.119			2.137			0.49

	MN			**GT**			**LWI**		
	Station A	**Station B**	**A /B**	**Station A**	**Station B**	**A / B**	**Station A**	**Station B**	**A - B**
1997 03	2.195	1.629	1.347	2.335	1.766	1.322	6.94	6.65	0.29
1997 04	2.193	1.646	1.332	2.327	1.771	1.314	6.97	6.66	0.31
1997 05	2.235	1.666	1.342	2.408	1.820	1.323	6.94	6.67	0.27
1997 06	2.196	1.644	1.336	2.377	1.815	1.310	7.01	6.77	0.24
1997 07	2.230	1.653	1.349	2.427	1.830	1.326	6.98	6.70	0.28
1997 08	2.153	1.611	1.336	2.301	1.751	1.314	6.98	6.66	0.32
1997 09	2.123	1.606	1.322	2.252	1.724	1.306	7.08	6.72	0.36
1997 10	2.096	1.586	1.322	2.210	1.697	1.302	7.06	6.71	0.35
1997 11	2.150	1.618	1.329	2.311	1.774	1.303	7.02	6.68	0.34
1997 12	2.207	1.648	1.339	2.394	1.823	1.313	7.03	6.71	0.32
1998 01	2.243	1.674	1.340	2.426	1.846	1.314	6.95	6.63	0.32
1998 02	2.222	1.653	1.344	2.405	1.807	1.331	7.00	6.73	0.27
SUMS			16.038			15.779			3.67
# MONTHS			12.000			12.000			12.00
MEANS			1.337			1.315			0.31
ACCEPTED VALUE FOR B:			1.606			1.768			6.57
CORRECTED AT A:			2.146			2.325			6.88

	METERS
MLW(A) = MTL(A) - 1/2 MN(A)	**1.046**
MHW(A) = MLW (A) + MN(A)	**3.193**
MLLW(A) = DTL(A) - 1/2 GT(A)	**0.974**
MHHW(A) = MLLW(A) +GT(A)	**3.299**

HOURS

GHWI: 0.49 **GLWI: 6.88**

SUBORDINATE STATION A: ALAMEDA, CA **ELEVATIONS IN METERS;TIMES IN HOURS**
CONTROL STATION B: SAN FRANCISCO, CA

	MTL			MN			HWI		
	Station A	**Station B**	**A - B**	**Station A**	**Station B**	**A /B**	**Station A**	**Station B**	**A - B**
1997 03	2.058	2.731	-0.673	1.503	1.257	1.196	0.54	0.41	0.13
1997 04	1.978	2.648	-0.670	1.543	1.292	1.194	0.55	0.41	0.14
1997 05	2.066	2.741	-0.675	1.533	1.294	1.185	0.54	0.41	0.13
1997 06	2.131	2.809	-0.678	1.537	1.306	1.177	0.62	0.47	0.15
1997 07	2.147	2.830	-0.683	1.527	1.300	1.175	0.55	0.46	0.09
1997 08	2.196	2.882	-0.686	1.514	1.301	1.164	0.55	0.45	0.10
1997 09	2.199	2.878	-0.679	1.492	1.272	1.173	0.61	0.51	0.10
1997 10	2.216	2.905	-0.689	1.503	1.279	1.175	0.62	0.48	0.14
1997 11	2.298	2.995	-0.697	1.525	1.296	1.177	0.58	0.46	0.12
1997 12	2.267	2.970	-0.703	1.544	1.311	1.178	0.61	0.45	0.16
1998 01	2.303	3.001	-0.698	1.533	1.287	1.191	0.55	0.39	0.16
1998 02	2.414	3.103	-0.689	1.336	1.101	1.213	0.58	0.30	0.28
SUMS			-8.220			14.197			1.70
# MONTHS			12.000			12.000			12.00
MEANS			-0.685			1.183			0.14
ACCEPTED VALUE FOR B:			2.728			1.250			0.35
CORRECTED AT A:			2.043			1.479			0.49

	DHQ			DLQ			LWI		
	Station A	**Station B**	**A /B**	**Station A**	**Station B**	**A /B**	**Station A**	**Station B**	**A - B**
1997 03	0.132	0.122	1.082	0.247	0.242	1.021	6.94	6.65	0.29
1997 04	0.116	0.117	0.991	0.293	0.292	1.003	6.97	6.66	0.31
1997 05	0.166	0.162	1.025	0.320	0.322	0.994	6.94	6.67	0.27
1997 06	0.218	0.213	1.023	0.347	0.352	0.986	7.01	6.77	0.24
1997 07	0.225	0.219	1.027	0.340	0.344	0.988	6.98	6.70	0.28
1997 08	0.184	0.176	1.045	0.275	0.274	1.004	6.98	6.66	0.32
1997 09	0.116	0.113	1.027	0.203	0.203	1.000	7.08	6.72	0.36
1997 10	0.105	0.101	1.040	0.217	0.219	0.991	7.06	6.71	0.35
1997 11	0.166	0.162	1.025	0.319	0.324	0.985	7.02	6.68	0.34
1997 12	0.224	0.217	1.032	0.366	0.366	1.000	7.03	6.71	0.32
1998 01	0.215	0.213	1.009	0.328	0.337	0.973	6.95	6.63	0.32
1998 02	0.187	0.183	1.022	0.234	0.261	0.897	7.00	6.73	0.27
SUMS			12.349			11.841			3.67
# MONTHS			12.000			12.000			12.00
MEANS			1.029			0.987			0.31
ACCEPTED VALUE FOR B:			0.183			0.344			6.57
CORRECTED AT A:			0.188			0.339			6.88

	METERS
MLW(A) = MTL(A) - 1/2 MN(A) :	**1.304**
MHW(A) = MLW (A) + MN(A):	**2.782**
MLLW(A) = MLW(A) - DLQ(A):	**0.964**
MHHW(A) = MHW(A) +DHQ(A):	**2.971**

	HOURS		
GHWI:	**0.49**	**GLWI:**	**6.88**

Appendix 2:

EXAMPLE OF TIDAL DATUM COMPUTATION SPREADSHEET FOR TIDE BY TIDE COMPARISON

TIDES: Comparison of Simultaneous Observations (Tide by Tide)

PAGE 1

A) Subordinate Station: **9414750 Alameda, SanFrancisco Bay** Lat: 37 46.3 n Long: 122 17.9 w
B) Standard Station: **9414290 San Francisco, San Francisco Bay** Lat: 37 48.4 n Long: 122 27.9 w

Time Meridian: (A) 0° (UTC) (B) 0° (UTC)
units: meters

Date	(A) Station = TIME				(B) Station = TIME				(A) Station = HEIGHT (STATION DATUM)				(B) Station = HEIGHT (MLLW)				(A) - (B) TIME DIFFERENCE (minutes)				(A) - (B) (A) - (B) HEIGHT DIFFERENCE			
	HHW	LHW	HLW	LLW	HHW	LHW	HLW	LLW	HHW	LHW	HLW	LLW	HHW	LHW	HLW	LLW	HHW	LHW	HLW	LLW	HHW	LHW	HLW	LLW
03/01/97	12.1			19.1	11.8			18.5	2.748			1.306	3.340			2.111	0.3			0.6	-0.592			-0.805
03/02/97		1.7	6.4			1.4	5.6			2.250	1.744			2.853	2.532			0.3	0.8			-0.603	-0.788	
	13.1			20.2	12.6			19.6	2.815			1.214	3.417			2.008	0.5			0.6	-0.602			-0.794
03/03/97		3.1	7.8			3.0	7.1			2.304	1.784			2.901	2.568			0.1	0.7			-0.597	-0.784	
	14.1			21.4	13.7			21.0	2.768			1.039	3.361			1.857	0.4			0.4	-0.593			-0.818
03/04/97		4.2	9.1			4.1	8.4			2.352	1.725			2.933	2.511			0.1	0.7			-0.581	-0.786	
	15.3			22.3	15.0			21.5	2.814			0.848	3.391			1.669	0.3			0.8	-0.577			-0.821
03/05/97		5.2	10.1			5.0	9.3			2.468	1.642			3.021	2.438			0.2	0.8			-0.553	-0.796	
	16.5			23.1	15.9			22.5	2.940			0.729	3.488			1.535	0.6			0.6	-0.548			-0.806
03/06/97		6.1	11.2			5.7	10.4			2.641	1.527			3.165	2.335			0.4	0.8			-0.524	-0.808	
	17.5			24.0	17.0			23.2	3.077			0.705	3.603			1.498	0.5			0.8	-0.526			-0.793
03/07/97		6.8	12.1			6.5	11.2			2.784	1.361			3.292	2.172			0.3	0.9			-0.508	-0.811	
	18.4				17.8				3.139				3.648				0.6				-0.509			

			HHW (A)	LHW	HLW (A)	LLW (A)	HHW (B)	LHW (B)	HLW (B)	LLW (B)	Δ HHW	Δ LHW	Δ HLW	Δ LLW
HHW =	Higher High Water	Sums :	20.301	14.799	9.783	5.841	24.248	18.165	14.556	10.678	-3.947	-3.366	-4.773	-4.837
LHW =	Lower High Water	Number :	7	6	6	6	7	6	6	6	7	6	6	6
HLW =	Higher Low Water	Means :	2.900	2.467	1.631	0.974	3.464	3.028	2.426	1.780	-0.564	-0.561	-0.796	-0.806
LLW =	Lower Low Water													

Average HW time difference : 0.35 minutes
Average LW time difference : 0.71 minutes
Average HW/LW time difference : 0.53 minutes

TIDES: Comparison of Simultaneous Observations (Tide by Tide)

Value	Equation	Eq. #
0.217	= DHQ (A) = 0.5*(HHW (A) - LHW (A))	22
0.329	= DLQ (A) = 0.5*(HLW (A) - LLW (A))	23
2.683	= HW (A) = 0.5*(HHW (A) + LHW (A))	24
1.302	= LW (A) = 0.5*(HLW (A) + LLW (A))	25
1.927	= Gt (A) = HHW (A) - LLW (A)	26
1.381	= Mn (A) = HW (A) - LW (A)	27
1.937	= DTL (A) = 0.5*(HHW (A) + LLW (A))	28
1.993	= MTL (A) = 0.5*(HW (A) + LW (A))	29
-0.001	= D DHQ =0.5*(D HHW - D LHW)	30
0.005	= D DLQ= 0.5*(D HLW - D LLW)	31
-0.562	= D HW = 0.5*(D HHW + D LHW)	32
-0.801	= D LW = 0.5*(D HLW +D LLW)	33
0.238	= D MN = D HW - D LW	34
-0.685	= D DTL = 0.5*(D HHW + D LLW)	35
-0.682	= D MTL = 0.5*(D HW + D LW)	36
0.242	= D GT = D HHW - D LLW	37
1.209	= MN RATIO = MN (A) / (MN (A) - D MN)	38
0.993	= DHQ RATIO = DHQ (A) / (DHQ (A) - D DHQ)	39
1.017	= DLQ RATIO = DLQ (A) / (DLQ (A) - DDLQ)	40
1.144	= Gt RATIO = Gt (A) / (Gt (A) - D Gt)	41

Standard Method: Datum Planes (relative to station datum)

Value	Equation	Eq. #
2.984	= MHHW (A) = MHW (A) + DHQ corrected for A	87
2.802	= MHW (A) = MLW (A) + MN corrected for A	85
1.291	= MLW (A) = MTL corrected for A - 0.5 * MN corrected for A	84
0.941	= MLLW (A) = MLW (A) - DLQ corrected for A	86

Modified Range Ratio Method: Datum Planes (relative to station datum)

Value	Equation	Eq. #
2.977	= MHHW (A) = MLLW (A) + Gt corrected for A	62
2.802	= MHW (A) = MLW (A) + MN corrected for A	49
1.291	= MLW (A) = MTL corrected for A - 0.5 * MN corrected for A	48
0.945	= MLLW (A) = DTL corrected for A - 0.5* Gt corrected for A	61

Note 1: Accepted values are from NOAA, Accepted Datums Epoch:1960-78

Internet address:http://www.co-ops.nos.noaa.gov/

Station	MHW	MLW	MSL	Mn	MTL	MHHW	MLLW	DHQ	DLQ	Gt	DTL	HWI	LWI
94142	3.353	2:28	2.713	1.250	2.728	3.536	1.759	0.183	0.344	1.777	2.646	7.560	0.830

Value	Equation	Eq#
2.046	= MTL corrected for A = MTL accepted for B + Δ MTL	42
1.961	= DTL corrected for A = DTL accepted for B + Δ DTL	43
1.511	= MN corrected for A = MN accepted forB * MN ratio	44
2.033	= GT corrected for A = GT accepted for B * GT ratio	45
0.182	= DHQ corrected for A = DHQ accepted for B * DHQ ratio	15
0.350	= DLQ corrected for A = DLQ accepted for B * DLQ ratio	16

Compiled by: .... (Date)

Computed by: .... (Date)

Verified by: .... (Date)