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

TIDAL DATUMS AND THEIR APPLICATIONS

NOAA Special Publication NOS CO-OPS 1

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noaa National Oceanic and Atmospheric Administration

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U.S. Department of Commerce

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TIDAL DATUMS AND THEIR APPLICATIONS

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FOREWARD

The United Nations declared 1998 to be the International Year of the Ocean. This declaration provides an opportunity to raise public awareness of a fundamental boundary defined by the intersection of the ocean with the land. This intersection is not as simple as it may seem. It is determined by a plane called a tidal datum, and refers to an average height of the water level at particular phases of the tidal cycle. This vertical reference surface is derived from water level measurements recorded along coastlines, estuaries, and tidal rivers of the United States. Tidal datum planes, referenced to a system of bench marks, are fundamental to the determination of the spatial coordinates of latitude, longitude, and elevation relative to mean sea level.

Tidal datums are chiefly used to determine horizontal boundaries, and for estimating heights or depths. The legal determinations of private and public lands, state owned tide lands, state submerged lands, U.S. Navigable waters, U.S. Territorial Sea, Contiguous Zone, and Exclusive Economic Zone, and the High Seas, or international waters, depend on the determination of tidal datums and their surveyed intersection with the coast. Navigation in U.S. Harbors, shipping channels, and intracoastal waterways requires an accurate knowledge of the depth of the ocean and submerged hazards at the low-water phase of the tidal cycle. Passage underneath bridges requires knowledge of the clearance at the high water phase of the tide. In addition, coastal construction and engineering requires knowledge of the tidal cycle; significant wave heights, periods, and directions; the heights of storm surges, or tsunami waves; and, the frequency and horizontal extent of flooding in the coastal zone. Organizing these environmental data into meaningful, decision-making contexts requires the establishment of tidal datums, and their reference to the geodetic control network.

Other countries publish tidal datums that may differ significantly from those of the U.S. In fact, there are hundreds of local datums used throughout the world. This has led to efforts to define a global vertical datum. The ellipsoid serves as a suitable candidate because of its horizontal and vertical accuracy, its relative ease of calculation, and its global accessibility via GPS. A set of vertical transformation functions are required to translate the vertical coordinate provided by GPS into a coordinate referenced to a tidal datum plane. Preliminary research suggests promising results in the construction of a seamless vertical reference system.

This document has been prepared by NOAA's Center for Operational Oceanographic Products and Services Division to provide background information about tidal datum planes. The chapters present overviews of the history of tidal datums in the U.S., domestic and international legal regimes, water level measurement system and bench marks, derived products available from NOAA, and examples of the practical and legal applications of tidal datums.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ADR	Analog-to-digital recorder
AFOS	Automation of Field Operations and Services
ATWC	Alaska Tsunami Warning Center
AWIPS	Advanced Weather Interactive Processing System
CBN	Cooperative Based Network
CO-OPS	Center for Operational Oceanographic Products and Services
CORMS	Continuous Operational Real-time Monitoring System
CORS	Continuously Operating Reference Stations
CZM	Coastal Zone Management
DAC	Damage Assessment Center
DAD	Damage Assessment Division
DCP	Data Collection Platform
DEM	Digital Electronic Model
DGPS	Differential GPS
DHQ	Mean Diurnal High Water Inequality
DLQ	Mean Diurnal Low Water Inequality
DOD	Department of Defense
DOE	Department of Energy
DPAS	Data Processing and Analysis Subsystem of NGWLMS
EEZ	Exclusive Economic Zone
ECDIS	Electronic Chart Display and Information Systems
EPA	Environmental Protection Agency
ESI	Environmental Sensitivity Index
ESSA	Environmental Science Services Administration
FBN	Federal Based Network
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Studies
GIF	Graphics Interchange Format
GIS	Geographical Information System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GRS80	Geodetic Reference System 1980
GT	Great Diurnal Range of Tide
IGLD 85	International Great Lakes Datum of 1985
IJC	International Joint Commission
ITIC	International Tsunami Information Center
HAZMAT	Hazardous Materials Response and Assessment Division
HWI	High Water Interval
LAT	Lowest Astronomical Tide
LHW	Lower High Water
LLW	Lower Low Water
LLWD	Lower Low Water Datum

LW	Low Water
LWD	Low Water Datum
LWI	Low Water Interval
MHW	Mean High Water
MHHW	Mean Higher High Water
MHHWL	Mean Higher High Water Line
MHWL	Mean High Water Line
MHWS	Mean High Water Springs
MLW	Mean Low Water
MLLW	Mean Lower Low Water
MLLWL	Mean Lower Low Water Line
MLWL	Mean Low Water Line
MLWS	Mean Low Water Springs
MMS	Minerals Management Service
Mn	Mean Range of Tide
MSL	Mean Sea Level
MTL	Mean Tide Level
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NEPA	National Environmental Policy Act of 1969
NESDIS	National Environmental Satellite, Data and Information Service
NFIP	National Flood Insurance Program
NGS	National Geodetic Survey
NGWLMS	Next Generation Water Level Measurement System
NGVD 29	National Geodetic Vertical Datum of 1929
NIMA	National Imagery and Mapping Agency
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRC	National Research Council
NSRS	National Spatial Reference System
NTBMS	National Tidal Benchmark System
NTDE	National Tidal Datum Epoch
NWLON	National Water Level Observation Network
NWLP	National Water Level Program
NWS	National Weather Service
OAR	Office of Oceanic and Atmospheric Research
OCRM	Office of Ocean and Coastal Resource Management
OCS	Office of Coast Survey
ORR	Office of Response and Restoration
QC	Quality Control
PMEL	Pacific Marine Environmental Laboratory
PORTS	Physical Oceanographic Real-Time System
RAM	Random Access Memory
RTK	Real Time Kinematic GPS

RTU	Remote Terminal Unit
SFHA	Special Flood Hazard Areas
SOP	Standard Operating Procedure
USACE	U.S. Army Corps of Engineers
USC&GS	U.S. Coast and Geodetic Survey
USCG	U.S. Coast Guard
USC	U.S. Code
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
WGS84	World Geodetic System
YSI	Yellow Springs Instruments Corporation

1. INTRODUCTION

Purposes of Water Level Observations

Water level measurements are made by the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service's (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) to serve the needs of the mariner, the engineer, the scientist, and the general public. This work began with the charting of coastal waters and the need to establish a uniform level, or datum plane, to which observed water depths could be referred, the soundings being taken at different water level stages or phases during hydrographic surveys. In addition to satisfying the charting requirements of NOS, water level measurements are made for the following purposes. The list is meant to be illustrative, not exhaustive. Some examples include:

- Real-time depth of water available in harbors, estuaries, and lakes. The mariner uses real-time water levels to estimate draft under keel while in transit.
- Determination mean sea level and other tidal datums for surveying and engineering purposes and to establish a system of tidal bench marks to which these datums can be referred, maintained, and recovered.
- Datum control of remote sensing (i.e. photogrammetry) surveys.
- Representation of the shoreline, defined as Mean High Water (MHW), on nautical charts.
- Datum control for dredging projects and coastal engineering projects.
- Data for production of tide and tidal current predictions.
- Investigation of variations of sea level and crustal movements of the earth.
- Information for special estuarine studies and numerical hydrodynamic models.
- Information for legal cases regarding marine boundaries — Private, State, Federal, and International.
- Data and datum reference for storm surge monitoring.
- Monitoring and datum reference for coastal wetland loss and restoration programs.

Tidal datums derived from water level measurements provide the salient points for baseline determinations of the offshore boundaries of State submerged lands at 3 nautical miles (nm) from Mean Low Water (MLW), the Territorial Sea and Contiguous Zone at 12 nm from Mean lower Low Water (MLLW)(the Territorial Sea and Contiguous Zone are coterminous in the U.S., but not necessarily so for other countries), and the Exclusive Economic Zone (EEZ), at 200 nm from MLLW. Beyond the EEZ lies international waters, often called the High Seas. (*NOAA Manual of Tide Observations, 1965; Shalowitz, 1962; Slade et al., 1997; U.S. Dept. Of State Dispatch Supplement, 1995*).

The most common boundaries are those defined by geological formations; including such features as mountain ridges, cliffs, rivers, and ocean shores. Geological features have the advantages of being easily recognizable by all parties concerned and are relatively permanent (*Hicks, 1980*). In recent times, series of artificial markers, parallels of latitude, meridians of longitude, and other lines recoverable by surveying techniques have been added covering the seas. However, these seemingly abstract offshore boundaries have their origins in the most logical of boundaries: the intersection of land and ocean.

Since the oceans (and continents) move up and down in both periodic and non-periodic motions, the location of the land-water intersection line moves up-the-shore-landward and down-the-shore-seaward as a function of time. If this intersection is to be used as a boundary (or the source of a boundary), it must be mathematically "fixed." The up-down motion of the water surface must also be mathematically fixed to obtain a reference for depths and depth contours on nautical charts and bathymetric maps; and, finally, a reference is needed for elevations of the predicted tide. A mathematically fixed elevation of the ocean surface at a particular phase of the tidal cycle is known as a tidal datum. It is determined by officially adopted definitions and procedures of the National Ocean Service (*Hicks, 1980*; *Federal Register, 1980*), and is recognized by the Department of State's Inter-Agency Task Force on the Law of the Sea (sometimes called the Baselines Committee).

For marine applications, a vertical datum is defined as a base elevation used as a reference from which to determine relative heights or depths. It is called a tidal datum when 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 (*Marmer, 1951*). In order that they may be recovered when needed and be linked to land-fixed horizontal and vertical control points (e.g., geodetic datums), such datums are referenced to fixed points known as bench marks. The horizontal location of where a tidal datum intersects the land, at the exact elevation of the tidal datum, is usually called a "mark" or "line." For example, the horizontal location of the intersection of the tidal datum, MLLW, with land is called the Mean Lower Low Water Line, MLLWL. In legal terminology, this is sometimes called the "ordinary low water mark." Legal terminology is context specific and needs to be carefully understood before assigning it the value of a particular tidal datum. Indeed, different legal authorities, agencies, and international agreements have different terminology and methodologies associated with tidal datums. One of the goals of this report is to present the standard definitions of tidal datums adopted by NOS.

Report Purpose and Organization

The purpose of this report is to provide a general reference on the subject of tidal datums. This report explains, in brief, many topics — including the history of the NOS tides and water levels program, the domestic and international legal significance of the marine boundaries defined by tidal datums, the modern measurement program designed to support NOS's statutory authority, and the NOS products produced from the water level data. It also provides a discussion of the applications of tidal datums.

Chapter 2 discusses the general characteristics of the tides used in the determination of tidal datums. Chapter 3 discusses the history of the U.S. tidal program and the legal history and significance of tidal datums, respectively. Chapter 4 concerns a discussion of the National Water Level Program (NWLP), while Chapter 5 discusses the standard NOS analysis methods utilized to determine tidal datums. The output products produced from the NWLP are discussed in Chapter 6, and the applications of tidal datums are covered in Chapter 7. References, and Appendices follow. The publication ends with a glossary of terms appropriate for tidal datums. This companion glossary is an abridged edition of *Hicks (1989).* The full glossary is available on the internet at http://co-ops.nos.noaa.gov.

2. TIDAL OVERVIEW

Characteristics of the Tides

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, the atmosphere, and within the solid crust of the earth, also caused by the gravitational forces of the moon and sun. Additional non-astronomical factors such as 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 times of arrival of the tides, and the time interval between high and low water. There are three basic types of tides: semidiurnal (semi-daily), mixed, and diurnal (daily).

The first type, semidiurnal (Figure 1, top), 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. In Figure 2, semidiurnal tides are illustrated by the marigrams at Boston, New York, Hampton Roads, and Savannah. 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 (Figure 1, middle), is similar to the semidiurnal except that the two high waters and the two low waters of each tidal day 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. In Figures 2 and 3, mixed-type tides are illustrated by the marigrams at Key West, San Francisco, Seattle, Ketchican, and Dutch Harbor. The third type, diurnal (Figure 1, bottom), has one high water and one low water each tidal day. In Figure 2, the marigram at Pensacola illustrates a diurnal tide.

The most important modulations of the tides are those associated with the phases of the moon relative to the sun (Figure 4). Spring tides are tides occurring at the time of the new and full moon. These are the tides of the greatest amplitude, meaning the highest and lowest waters are recorded at these times. 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 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).

There is another important longer period modulation in the amplitude of the tide due to orbital paths of the earth and moon. The apparent path of the Earth about the Sun, as seen from the Sun, is called the ecliptic. This path may be represented on a globe of the Earth by drawing a great circle about the Earth which makes an angle of 23° 27' relative to the Earth's equator (Figure 5). Likewise, the apparent path of the moon about the sun may be referenced to the ecliptic, such that the moon's path about the sun makes an angle of 5° with respect to the ecliptic. When the moon's ascending node corresponds to the vernal (i.e., spring) equinox (the equinoxes are the two times of the year, March 21 and September 23, when the sun crosses the earth's equator, and day and night have the same length), the angle of the path of the moon about the sun is about 28.5° (Schureman, 1941). When the moon's descending node corresponds to the vernal equinox, the angle of the moon's path about the sun is about 18.5° . This variation in the path of the moon about the sun 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 annual mean range of the tide, as may be seen in Figure 6. It is the regression of the moon's nodes which forms the basis of the definition of the National Tidal Datum Epoch (NTDE) (see Chapter 6). Figure 6 also shows the monthly mean range which is due to seasonal and meteorological effects. Because the variability of the monthly mean range is larger than that due to the regression of the nodes, the NTDE is defined as an even 19-year period to obtain closure on a calendar year so as not to bias the estimate of the tidal datum.

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 (Figures 2 and 3) and in distance along the coast (Figure 7). The transition from one type to another is usually gradual either temporally or spatially, resulting in hybrid or transition tides. A good example in Figure 2 is Galveston which transitions from diurnal to semidiurnal to mixed. Key West (Figure 2) transitions from mixed to semidiurnal to mixed. Dutch Harbor (Figure 3) shows similar transitions. Figure 7 shows the gradual spatial transitions from mixed to diurnal to mixed and back to diurnal.

Photocopies of the NOAA pamphlet *Our Restless Tides* presents a layman's overview of tide producing forces and tidal observations and is available from CO-OPS.

DISTRIBUTION OF TIDAL PHASE

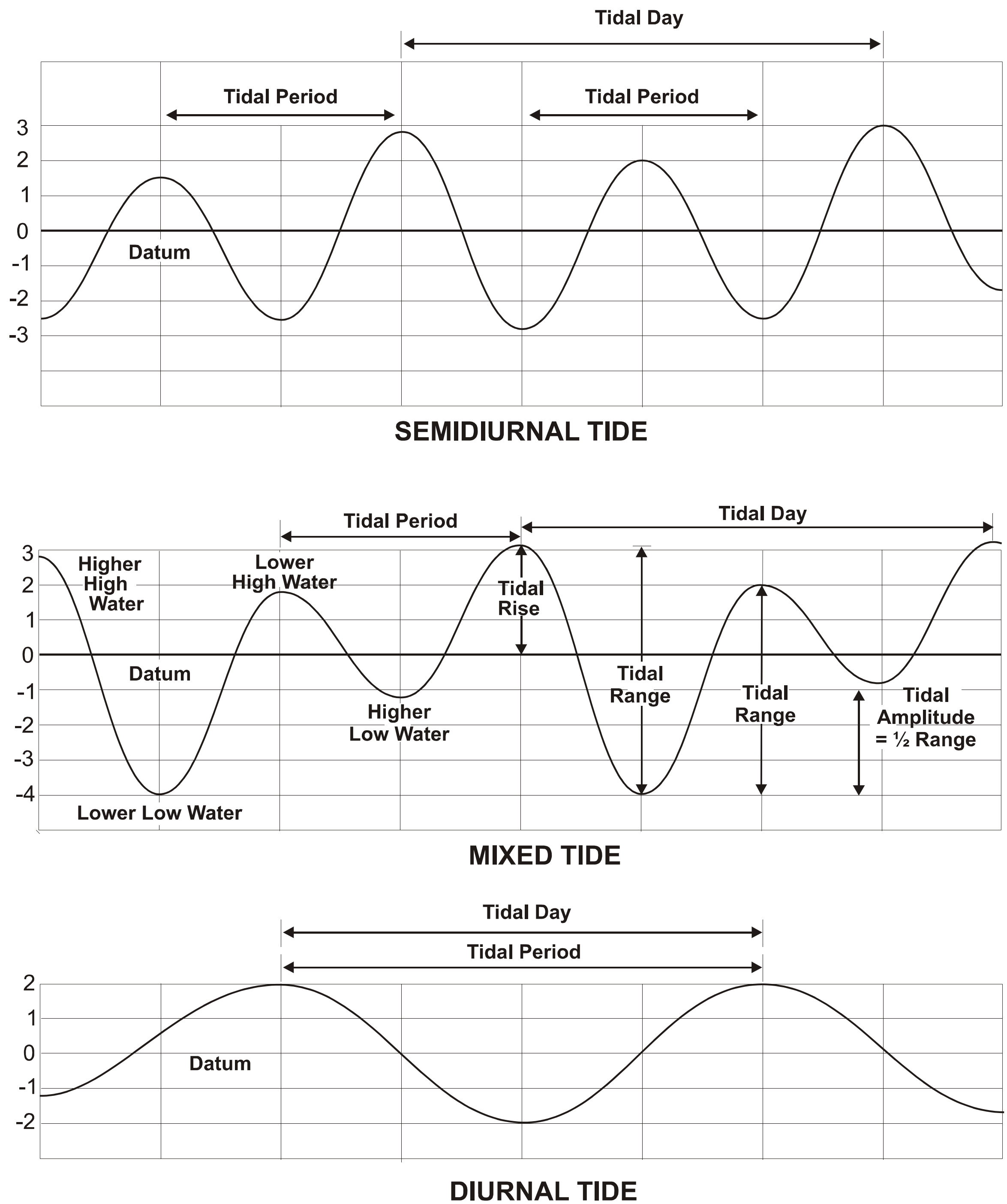
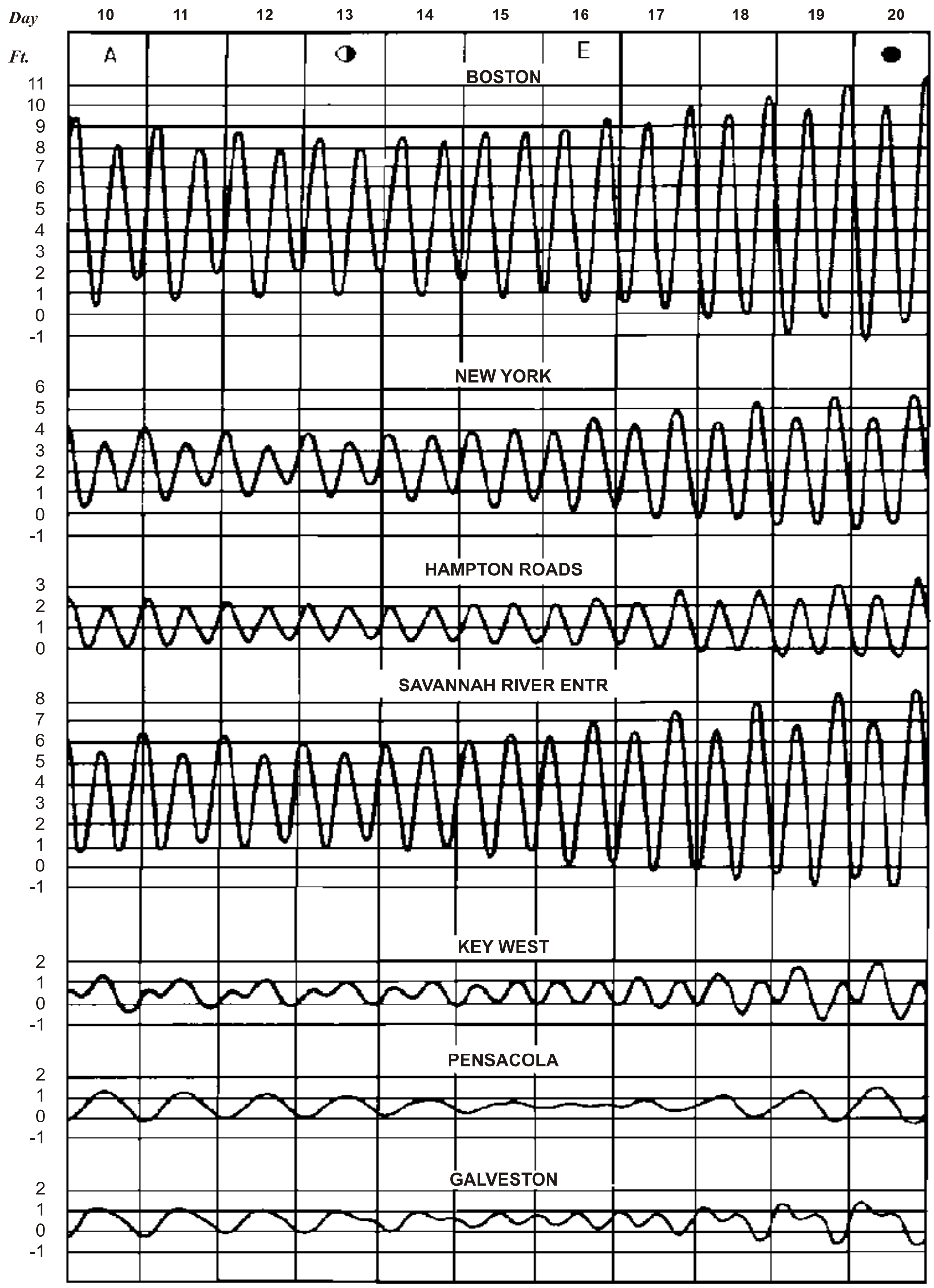


Figure 1. A depiction of the three primary kinds of tides. From the top panel downward they are semidiurnal, mixed, and diurnal. Standard tidal terminology is used to describe the various aspects of the tides. The zero on these graphs is illustrative of the relationship of the tides to Mean Sea Level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

TYPICAL TIDE CURVE FOR UNITED STATES PORTS



A discussion of these curves is given on the preceding page.

Lunar data:

- A - Moon in apogee
- ◑ - last quarter
- E - Moon on Equater
- ● - new Moon

Figure 2. Characteristic tide curves near port facilities along the U.S. East and Gulf Coasts. The tides depicted are primarily semidiurnal along the East Coast. The tides at Pensacola are primarily diurnal. The effects of the phases of the moon are also illustrated. The elevations in feet of the tide are referenced to the tidal datum mean lower low water.

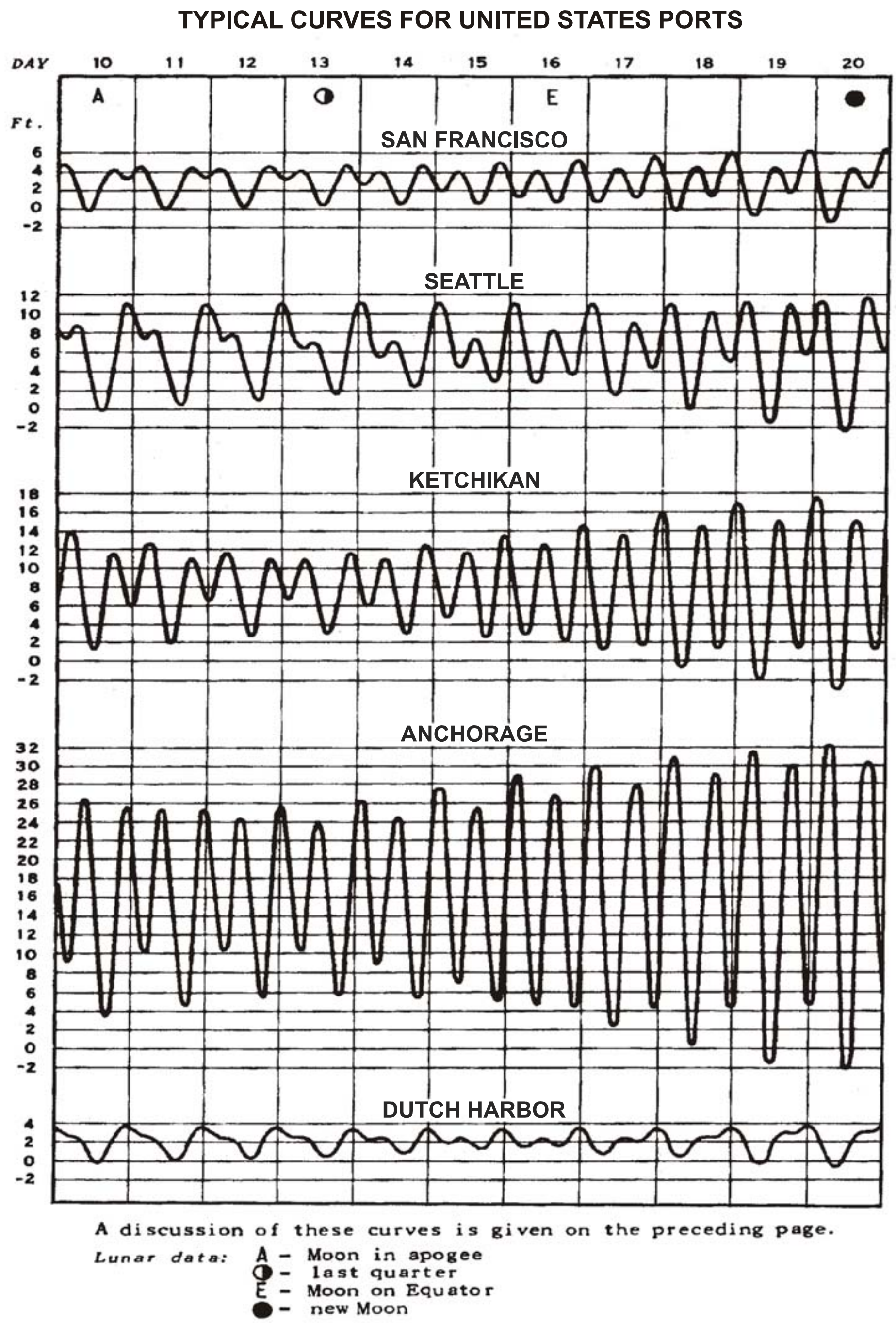


Figure 3. Characteristic tide curves for the West Coast. The tides depicted are primarily mixed. The tidal range at Anchorage is relatively large. The effects of the phases of the moon are also illustrated. The elevations in feet of the tide are referenced to the tidal datum, mean lower low water.

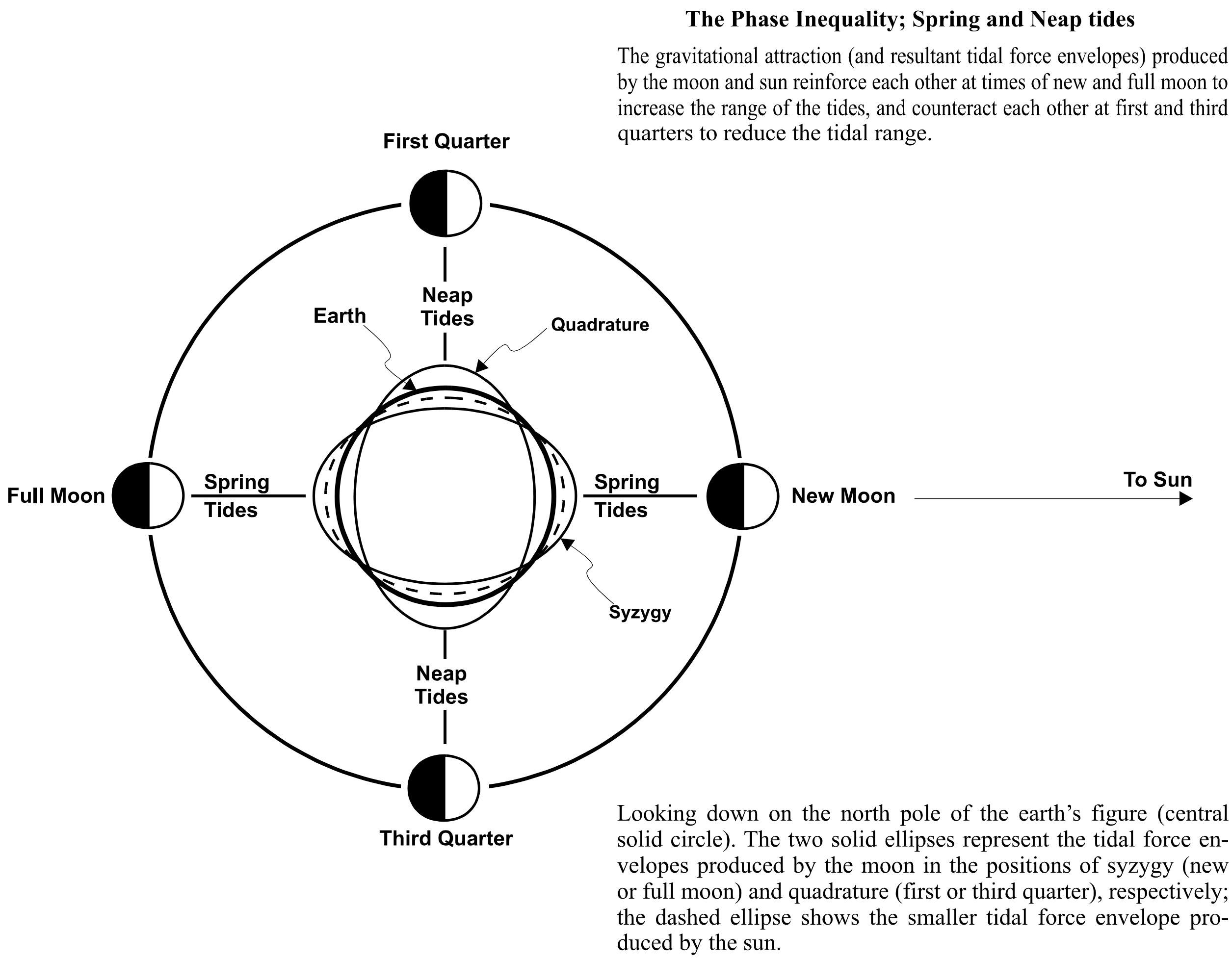
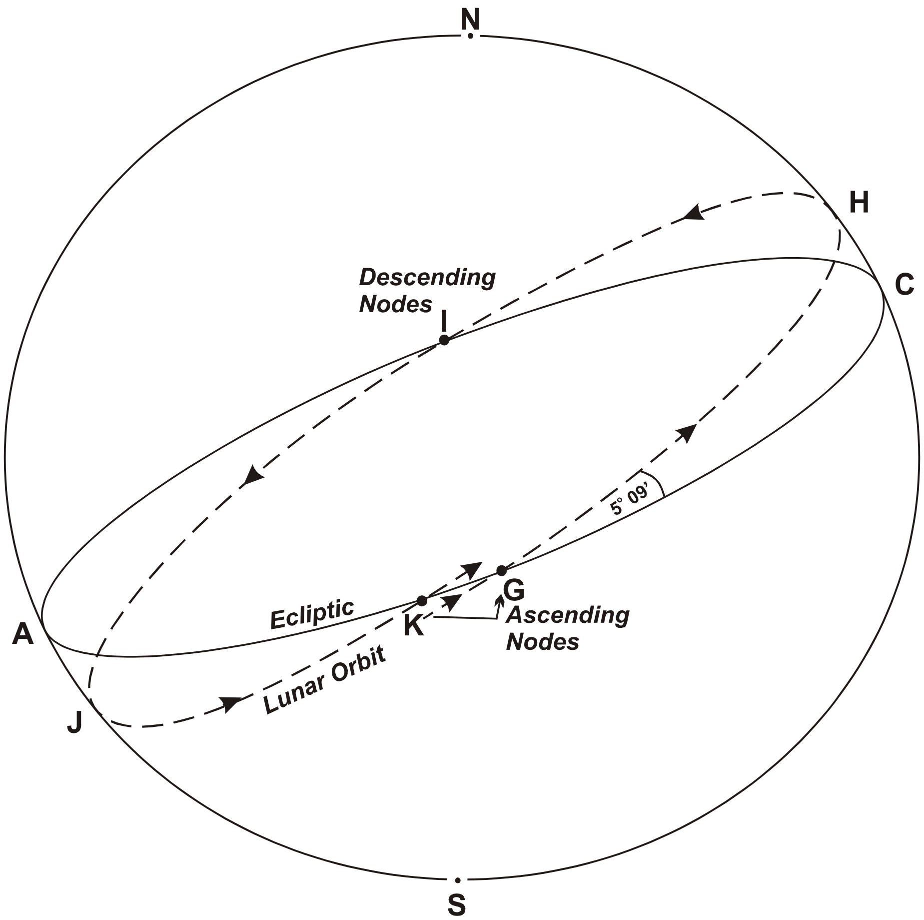


Figure 4. An illustration of solar and lunar tide producing forces. The largest tides, spring tides, are produced at new and full moon. The smallest tides, neap tides, occur during the first and third quarters of the moon.



Motion of the moon's nodes. The points where the moon's path crosses the ecliptic are called nodes; the point where the moon crosses the ecliptic from south to north at *G* is called the ascending node, while *I* is called the descending node. The moon's orbit from the ascending node *G* to the next ascending node K takes *27.2122* mean solar days (the Draconitic Period). Measured relative to a fixed star the moon takes *27.3216* mean solar days to complete its orbit (the Sidereal Period). The movement of the nodes westwards along the ecliptic is called the regression of the nodes; it is analogous to the precession of the equinoxes along the equator but is much faster, having a period of *18.61* years. This is equivalent to *27.3216-27.2122=0.1094* days per orbit; in the diagram it is represented by the distance *KG*.

Figure 5. A diagram illustrating the regression of the moon's nodes.

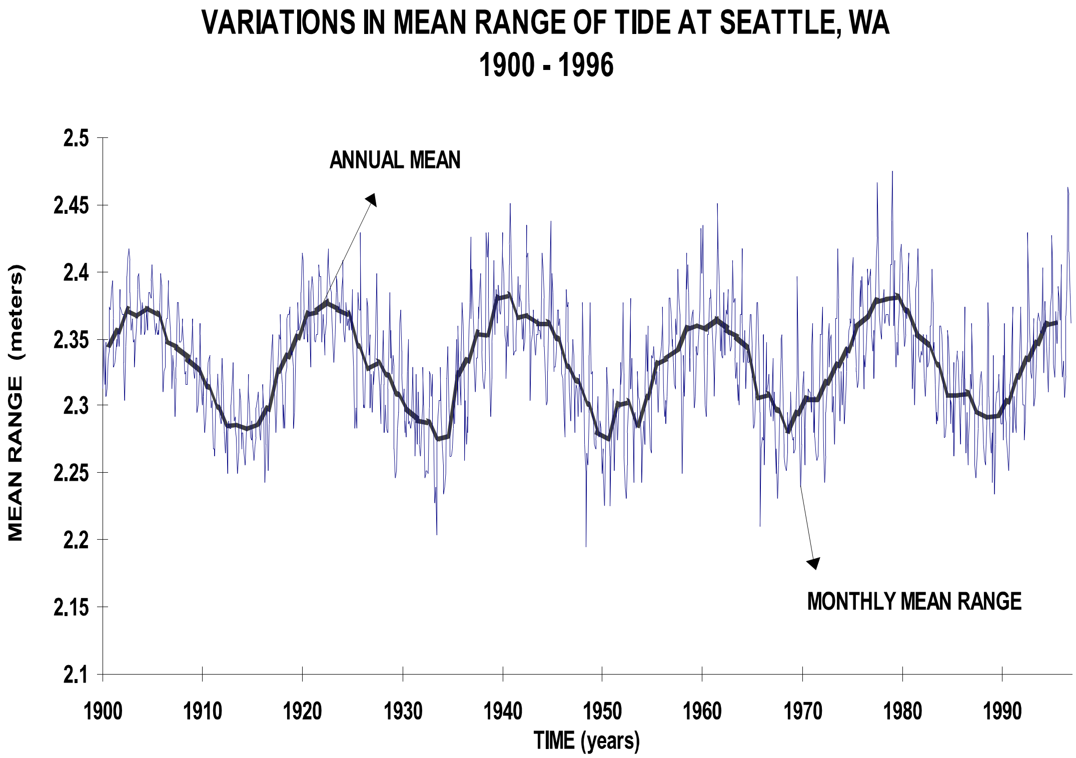


Figure 6. An illustration of the effect of the regression of the moon's nodes on the water levels at Puget Sound, WA. The heavy black curve is the annual mean range, or the difference in height between mean high water and mean low water. The time elapsed between trough to trough, or peak to peak, is the period of oscillation of the regression, and is about 18.6 years.

Tidal Analysis and Predictions

The routine prediction of tides is based upon a simple principle that for a linear system whose forcing can be decomposed into a sum of harmonic terms of known frequency (or period), the response can also be represented by a sum of harmonics having the same frequencies (or periods) but with different amplitudes and phases from the forcing. The tides are basically such a system (*e.g., Schureman, 1941*), due to their astronomical cycles imposed by the motions of the earth, sun, and moon. However, the system is not truly linear, and, in making tidal predictions, sums, differences, and harmonics of forcing frequencies are considered to approximately incorporate nonlinear effects (e.g., *Schureman, 1941*). For the open coastal regions, the tidal prediction capability requires only prior observations of the tides at the location of interest over a suitable period of time from which the amplitudes and phases of the major harmonic constituents can be ascertained by tidal analysis. For tide prediction reference stations, NOS generally uses a minimum one year of hourly water level observations to compute the semi-diurnal and diurnal tidal frequencies and a separate analysis of several years of monthly mean sea levels to compute the solar annual and solar semiannual, S_a and S_{sa}, terms. Resolving S_a and S_{sa} may require on the order of 10 years of water level data (*Scherer, 1990*). Typically, NOS uses up to 37 amplitudes and phases for important periods (period= 1/frequency) required to reconstitute a tidal signal.

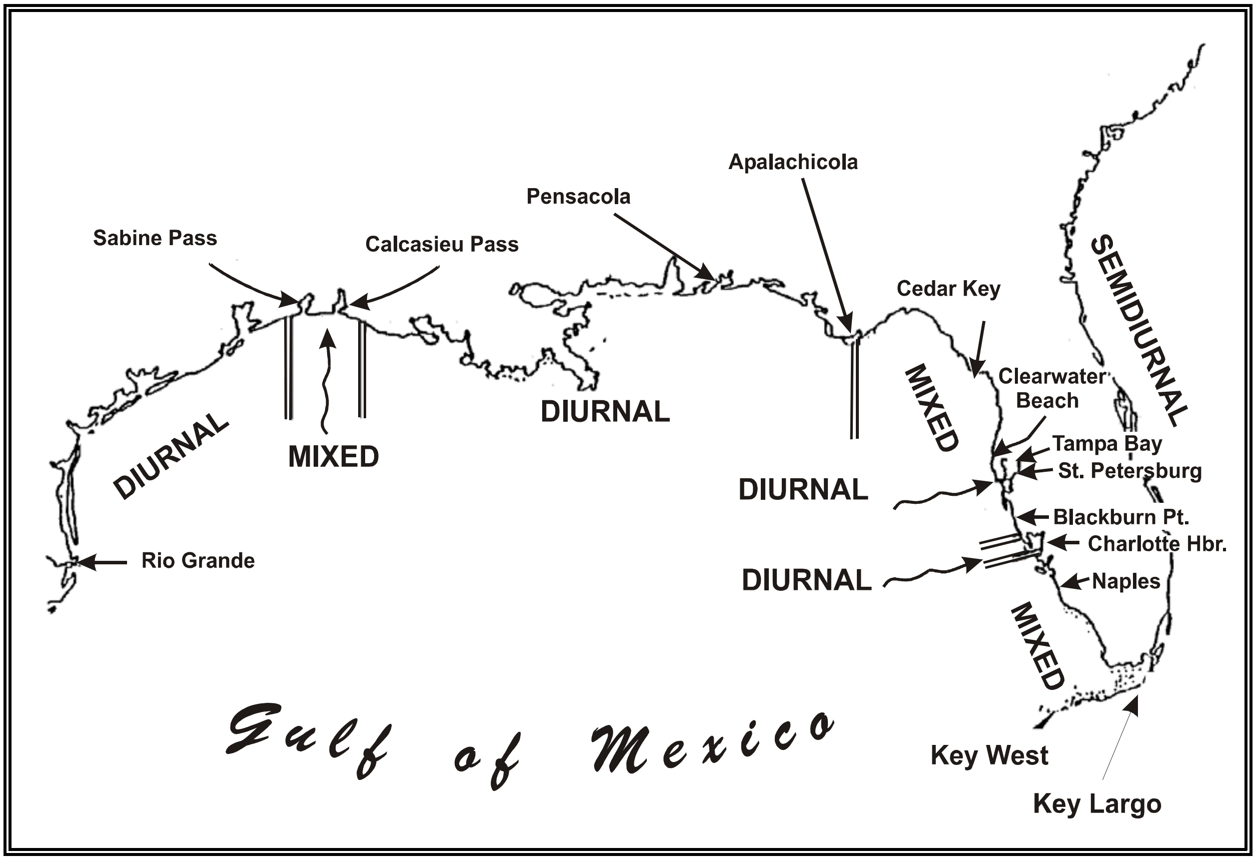


Figure 7. An illustration of the spatial variability of the type of tide in the Gulf of Mexico.

Harmonic Constituents

The component tides are usually referred to as harmonic constituents. The principal harmonic constituents of the tide (*e.g., Schureman, 1941*) are illustrated in Table 1.

Table 1. Principle harmonic constituents of the tides.

Species and name	**Symbol**	**Period Solar hours**	**Relative Size**
Semi-diurnal:			
Principal lunar	M_2	12.42	100
Principal solar	S_2	12.00	47
Larger lunar elliptic	N_2	12.66	19
Luni-solar semi-diurnal	K_2	11.97	13
Diurnal:			
Luni-solar diurnal	K_1	23.93	58
Principle lunar diurnal	O_1	25.82	42
Principle solar diurnal	P_1	24.07	19
Larger lunar elliptic	Q_1	26.87	8
Long period:			
Lunar fortnightly	M_f	327.9	17
Lunar monthly	M_m	661.3	9
Solar semi-annual	S_{sa}	4383	8
Solar annual	S_a	8766	1

The "relative size" column in Table 1 represents values from equilibrium theory presented by *Schureman* (1941) in his Table 2, expressed as a percent of M_2. Equilibrium theory assumes that the earth is totally water covered and does not consider frictional effects on tidal water motions. It is a simplified method to describe mass tidal characteristics. In addition, *Schureman's* Table 14 presents information on the effect of the longitude of the moon's node. His Table 14 shows that each of the above coefficients are gradually modulated over an 18.6 year cycle, and provides a coefficient which is a function of the year and multiplies the above coefficients to account for the regression of the nodes. The use of the constituents $(M, S, N, K)_2$, $(K,O,P)_1$, qualitatively illustrated in Figure 8, will generally be sufficient to predict the astronomical tide signal to about 90% at tide stations exposed to open ocean conditions. The difference between the astronomical tide signal and the water level measurements is generally attributable to the effects of local meteorological conditions. However, at different locations different constituents dominate, each site is different, and the relative size values from Table 1 above should not be used indiscriminately.

TIDAL PREDICTIONS

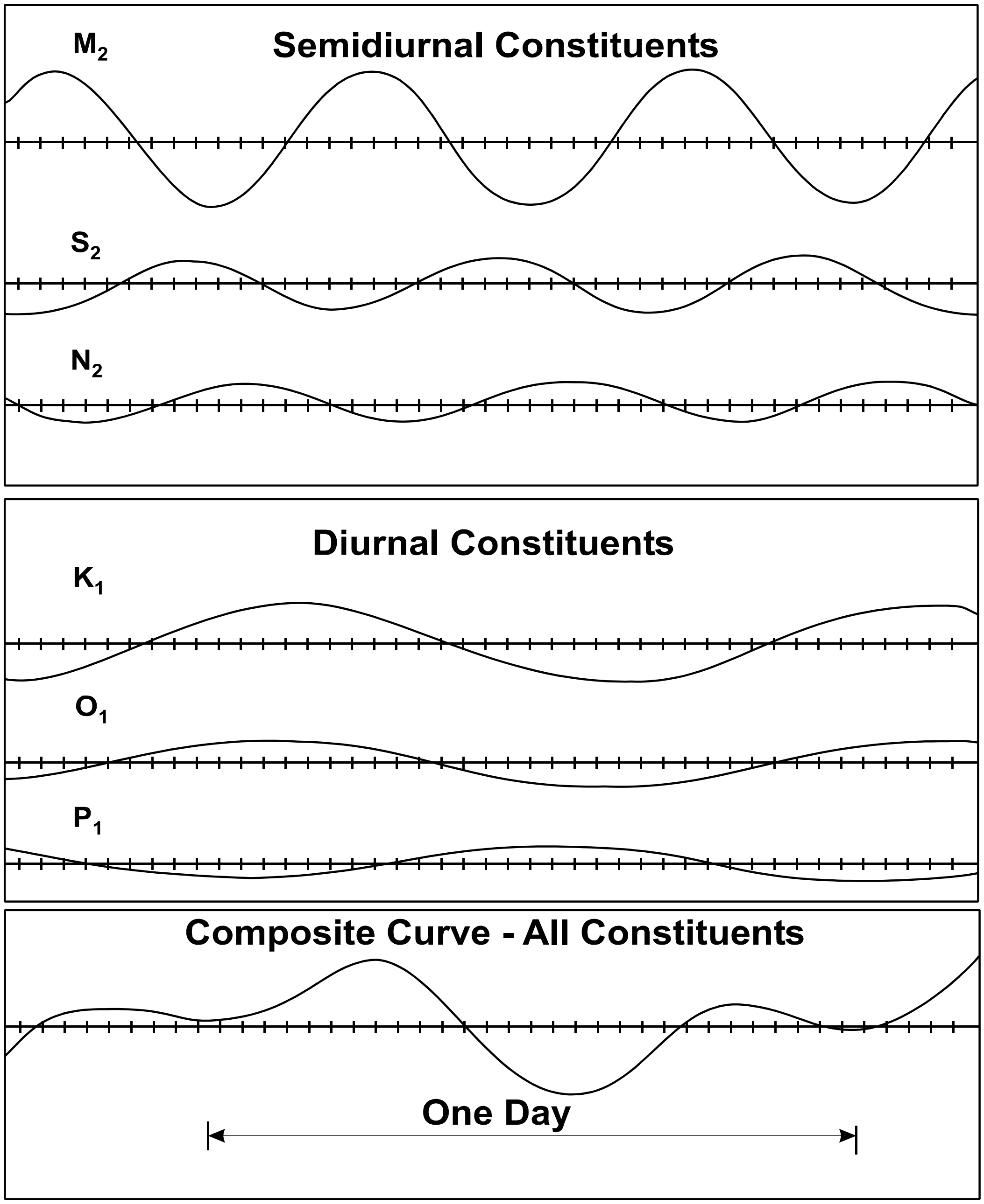


Figure 8. An illustration of the principle harmonic constituents of the tides. The periods and relative sizes of the constituents from Table 1 are suggested. The bottom panel qualitatively illustrates the result of summing the constituents to reconstruct the astronomical tidal component of water level measurements.

Other Signals in Water Level Measurements

Tides are not the only factor causing the sea surface height to change. Additional factors include waves and wind 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 and seiche - 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).

Oceanographers, when determining tidal datums, use averaging techniques over a specific time period, the *tidal epoch* of 19 years. As mentioned, 19 years is used because it is the closest full year to the 18.6-year node cycle, the period required for the regression of the moon's nodes to complete a circuit of 360° of longitude (*Schureman, 1941*). Referring to Figure 1, the average of all the observed higher high waters over a specific 19 year period (i.e., a NDTE) is defined as the tidal datum *mean higher high water(MHHW)*. As suggested in Figure 1, MHHW will have a specific height, which is not necessarily equal to any higher high water observed during a given tidal day. The averaging technique defines a reference plane from which all the fluctuations in the sea level discussed here, except for global sea level change, have been removed. Thus, the policy of NOS is to consider a new tidal datum epoch every 20 to 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).

3. TIDAL DATUMS

A. Chronology from the 1800s to the Present

The NOS has had many names in the past. The organization was known as: The Survey of the Coast from its founding in 1807 to 1836, Coast Survey from 1836 to 1878, Coast and Geodetic Survey (USC&GS) from 1878 to 1970, National Ocean Survey from 1970 to 1982, and in 1982, it was named National Ocean Service. From 1965 to 1970, the Coast and Geodetic Survey was a component of the Environmental Science Services Administration (ESSA). The NOS is a component of the NOAA which became the successor to ESSA in 1970. The NOAA is a component of the U.S. Department of Commerce. See Appendix A, Table A1 for a detailed chronology of the significant events in the development of the products and instrumentation related to the analysis of tides and tidal datums by the NOS.

B. Legal History of Tidal Datums

Congress has conferred statutory responsibility to NOS. Congress legislated the task to survey the coast of the U.S. to predecessor agencies of NOS with subsequent legislation defining missions and responsibilities.

Other Federal agencies, such as the Department of Energy (DOE), the Environmental Protection Agency (EPA), the U.S. Army Corps of Engineers (USACE), the Department of the Interior's Minerals Management Service (MMS) and the Geological Survey (USGS), and NOAA's National Weather Service (NWS), recognize NOS' expertise in the computation of tidal datums and currently have or have had cooperative agreements with NOS to provide tidal datums. USACE and USGS also operate extensive water level observation networks, however, these agencies rely on NOS' expertise in tidal areas.

The pertinent legislation and statutory authority of NOS have evolved under these following key federal statutes in determining the federal role in regulatory, jurisdiction, and management functions in the coastal zone (*U.S. Department of Commerce Year of the Ocean Discussion Papers, 1998*). The Supreme Court rules on admiralty law cases in Territorial Seas, and also provides rulings on riparian rights, navigability, and the public trust doctrine. The Supreme Court has clarified legal terminology such as *ordinary mean high water* to have a precise scientific definition as a tidal datum (*Slade et al., 1997*). In addition, key federal authorities, treaties, and international agreements are summarized below (*Shalowitz, 1962, Graber, 1981; U.S. Department of State Dispatch Supplement, 1995; Slade et al., 1997; U.S. Department of Commerce Year of the Ocean Discussion Papers, 1998*).

C. Congressional Acts

Laws Relating to NOS Organic Authority

The following is a brief listing of laws which relate to NOS organic authority to measure tidal datums. The list is selective and is not intended to be comprehensive.

- **The Organic Act of Feb. 10, 1807 (2 Stat, 413)**

This act covered the founding of the Survey of the Coasts, in order "to cause a survey to be taken of the coast . . . for completing an accurate chart of every part of the coasts."

- **Appropriations Act of 1841**

This act included a "hydrographical survey of the northern and northwestern lakes. . . . ," now known as the Great Lakes.

- **Coast and Geodetic Survey Act, as amended, 33 U.S.C. §§ 883 a-k**

NOS is statutorily authorized, among other things, to collect, analyze and disseminate data on tides and water levels pursuant to 33 U.S.C. This act established the following NOS statutory authority :

33 U.S.C. 883a - Authorizes NOS to conduct hydrographic surveys; tide and current observations; and geomagnetic, seismological, gravity, and related geophysical measurements and investigations, and observations for the determination of latitude and longitude.

33 U.S.C. 883b - In order that full public benefit may be derived from the operations of NOS by the dissemination of data resulting from its authorized activities and of related data from other sources, Section 883b authorizes NOS to analyze and predict tide and current data; and process and publish data, information, compilations, and reports.

33 USC 883d - Authorizes NOS to conduct investigations and research in geophysical sciences, including oceanography, geodesy, seismology, and geomagnetism, to improve the efficiency of NOS and to increase engineering and scientific knowledge.

33 U.S.C. 883e - Authorizes NOS to enter into agreements with states for surveying and mapping.

- **Under the Submerged Lands Act of 1953 (43 U.S.C. §§ 1301 <u>et seq</u>.)**

Establishes title of the states to land beneath navigable waters up to but not above the line of Mean High Water and a distance seaward from the coast line of three nautical miles.

- **Outer Continental Shelf Lands Act of 1953 (43 U.S.C. §§ 1331 <u>et seq</u>.)**

To provide for the jurisdiction of the U.S. over submerged lands of the outer continental shelf. This act provides that the Secretary of the Interior shall administer the leases of mineral rights on the outer continental shelf.

- **Act of April 5, 1960 (74 Stat. 16)**

Amends Act of August 6, 1947 to remove geographical limitations on the activities of the Coast and Geodetic Survey, the predecessor organization to NOS.

- **Public Law 105-384 November 13, 1998 (112 Stat. 3451)**

Title III - NOAA Hydrographic Services Improvement Act of 1998 most recently addresses NOAA's role in acquiring tide and current observations in the context of providing hydrographic services to the nation and specifically authorizes appropriations: "is authorized for each fiscal year to implement and operate a national quality control system for real-time tide and current and maintain the national tide network, and . . . is authorized for each fiscal year to design and install real-time tide and current data measurement systems under Section 303(b)(4)."

Laws Relating to Present Regulatory Context

The following laws are important in the present regulatory context in which tidal datums control the jurisdiction of the act. The list is not intended to be comprehensive.

- **Rivers and Harbors Act of 1899 (33 U.S.C. §§ 401 et seq.)**

In the navigable waters of the U.S., coastal construction, excavation, and filling must be proceeded by a permit from the U.S. Army Corps of Engineers. The act also prohibits the dumping of garbage and other substances into navigable waters.

- **Bridges over Navigable Waters (33 U.S.C. §§ 491 - 535)**

Bridges, dams, dikes or other forms of coastal construction are not allowed to interfere with navigable waters, except by permission from the Commandant of the Coast Guard.

- **Suits in Admiralty Act of 1920 (46 U.S.C. §§741-752)**

Under this act, the maritime public can sue the government for damages if negligence occurred during the preparation of charts and tables.

- **National Environmental Policy Act of 1969 (NEPA)**

This act is administered by the Environmental Protection Agency (EPA). This statute requires an environmental impact statement to be developed for "major Federal actions significantly affecting the quality of the human environment." The statements are to cover "(i) the environmental impact of the proposed action, (ii) any adverse environmental effects which cannot be avoided should the proposal be implemented, and (iii) alternatives to the proposed action . . . "

- **Ports and Waterways Safety Act of 1972, as amended, (33 U.S.C. §§ 1221-1236)**

This act grants the Coast Guard regulatory authority over the movements of ships in hazardous areas or with hazardous cargoes, or in cases where adverse weather, poor visibility, and heavy vessel traffic affect the safety of operations. It also directs the Secretary of Transportation regulatory authority over ship design and maintenance for the purpose of protecting the marine environment.

- **Federal Water Pollution Control Act Amendments of 1972 (33 U.S.C. §§ 1251 et seq.)**

This act authorized the USACE to control the discharge of dredged materials in the coastal ocean. It prohibits the discharge of pollutants in either onshore or offshore vessels or facilities. It applies to the territorial sea and contiguous zone.

- **Marine Protection, Research and Sanctuaries Act of 1972, as amended, (16 U.S.C. §§ 1447 a-f)**

This act requires that a permit be issued prior to the dumping of any material in the territorial sea or contiguous zone. Depending upon the type of material, permits are either obtained from the Secretary of the Army or the Environmental Protection Agency.

- **Coastal Zone Management Act of 1972 (16 U.S.C. §§ 1451 et seq.)**

Under this act, states are given an incentive to develop Coastal Zone Management Programs. The Office of Coastal Zone Management within NOAA administers the act. The act requires that policy be established on energy facilities, shoreline erosion, and beach access. In addition, the act specifies that states must catalog the coastal zones to be managed under the act, inventory the natural resources in these areas, and designate priorities for land and water use, and it places control on water use.

- **Deepwater Port Act of 1974 (33 U.S.C. §§ 1501 et seq.)**

A deepwater port is defined as "any fixed or floating manmade structures other than a vessel...located beyond the territorial sea of the U.S. and off the coast of the United States and which are used or intended for use as a port or terminal for loading or unloading and further handling of oil for transportation to any State..." The act prohibits the discharge of oil from a vessel within a safety zone established around a deepwater port, from a vessel that has received oil from another vessel at a deepwater port, or from a deepwater port. It imposes penalties and liability for violations.

- **Magnuson-Stevens Fisheries Conservation and Management Act of 1976 (16 U.S.C. §§ 1801-1883)**

Establishes a fisheries conservation zone (200 nautical miles) within which the United States assumes exclusive fisheries management authority. Measured from the low water line on largest scale chart. The law provides that fishing by a non-US vessel will not be authorized within the fishery conservation zone or for anadromous species or continental shelf fishery resources beyond that zone except under international fishery agreements and permits.

- **National Marine Sanctuaries Act (16 U.S.C. §§ 1431 et seq.)**

The Act establishes that the Secretary of Commerce may designate nationally significant areas as national marine sanctuaries. The national areas are selected on the basis of protection of national marine resources and habitats, scientific research and education of the public, tourism, and commercial and recreational fishing.

D. Supreme Court Decisions

The Supreme Court has shaped the legal context of the marine environment by its many decisions on navigable waters, marine boundaries, and the public trust doctrine. One of the most important decisions occurred in the 1936 case of *Borax, Ltd v. City of Los Angeles (Slade et al., 1997).* In this case, the Supreme Court recognized the importance of the averaging of all the high tides during the 19-year tidal datum epoch when determining the mean high tide line. Hence, the primary or first reduction datums computed by NOS must be computed for a specific 19-year lunar epoch. Similarly, the other principal tidal datums described later in this report must all be calculated over the specific tidal epoch.

E. National Agreement

National Tidal Datum Convention of 1980

The National Tidal Datum Convention of 1980 (*Federal Register, 1980; Hicks, 1980*), among other things, established a uniform system of tidal datums for all tidal waters in the U.S., its territories and trusts; and authorized the NOS definitions of mean high water, mean higher high water, mean low water, and mean lower low water as the official policy of the U.S. Government.

F. International Agreements

Boundary Waters Treaty of 1909

This act established the International Joint Commission (IJC) to manage and control the Great Lakes.

Convention on the Continental Shelf

In this convention, the phrase “continental shelf” is defined as “the seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200m, or, beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources of the said areas, to the seabed and subsoil of similar submarine areas adjacent to the coasts of islands.”

The convention gives the coastal nation exclusive sovereign rights over the continental shelf, subject to certain provisions to protect navigation, fishing and the conservation of living resources of the sea, “for the purpose of exploring it and exploiting its natural resources.”

Convention on the Territorial Sea and the Contiguous Zone

This convention was adopted by the United Nations conference at Geneva 1958, establishing the sovereignty of the state beyond its land territory and internal waters “the normal baseline for measuring the breadth of the territorial sea is the low water line.” The low water line according to U.S. policy is equivalent to the intersection of the tidal datum *mean low water* (MLW) with the coast (U.S. Department of State Dispatch, 1995). However, the Department of State’s term “mean low water” refers to the NOS term Mean Lower Low Water. These conventions which are a part of the larger United Nations Law of the Sea Convention (U.S. Department of State Dispatch, 1995), will increasingly be relied upon as a legal framework for international treaties which concern sovereignty, rights of passage and anchorage, seabed mining and exploration, fisheries management and conservation, and scientific research and exploration.

4. THE NATIONAL WATER LEVEL PROGRAM STANDARDS AND PROCEDURES

A. Water Level Stations

The 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. The instrumentation of the NWLP consists of tide stations in a network called the National Water Level Observation Network (NWLON) and any short-term stations operating for special projects such as hydrographic surveys, photogrammetry, and USACE dredging activities. The NWLON is composed (as of 2000) of approximately 189 long-term stations distributed around the country and the world. Due to resource constraints and storm damage, not all stations are always operational. Alaska has 16 stations; Hawaii and Pacific Islands have 12 stations; the West Coast has 26 stations; the Gulf Coast and Caribbean have 31 stations; the East Coast has 55 stations; the Great Lakes have 49 stations (Figure 9).

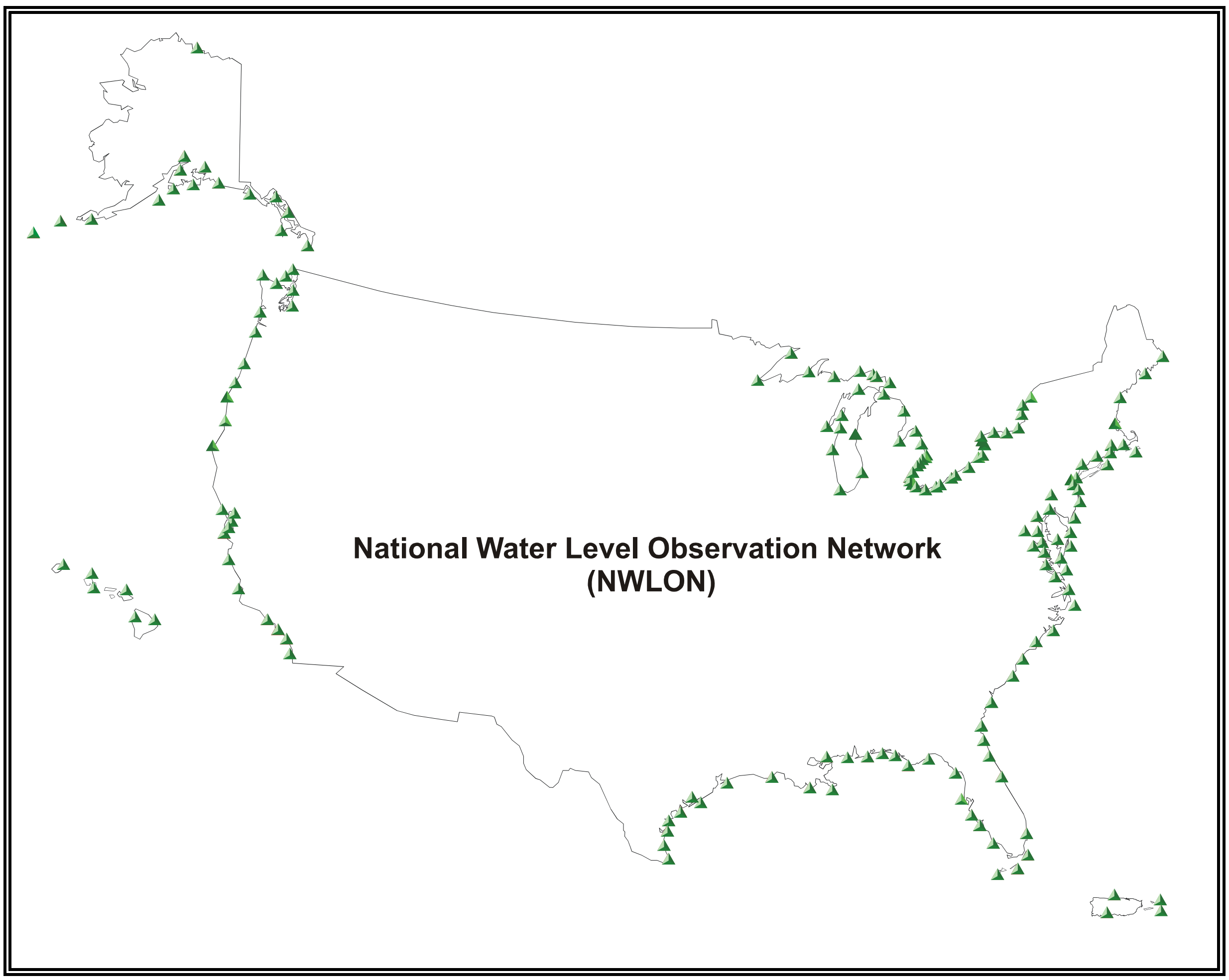


Figure 9. Locations of U.S. NWLON tide stations.

The programs supported by the NWLON include: real-time navigation safety, nautical charting, hydrography, photogrammetry, boundary determination, navigation products, channel dredging and harbor improvements, tsunami and storm surge warnings, tide predictions, environmental monitoring, global climate change, international lake level regulation, international treaty compliance, and international datum determination.

Additionally, the water level and geophysical data collected at these sites are frequently used to study the coastal environment, perform scientific studies of the dynamics of sea-level, and validate models of the geoid, tides, circulation, and satellite altimeter derived sea-surface height fields.

The locations of tide stations are organized into a hierarchy (Figure 10). Control (or primary) tide stations provide a continuously operating nationwide coarse network which is supplemented by denser networks of short-term operating secondary and tertiary networks necessary to provide total tidal datum coverage.

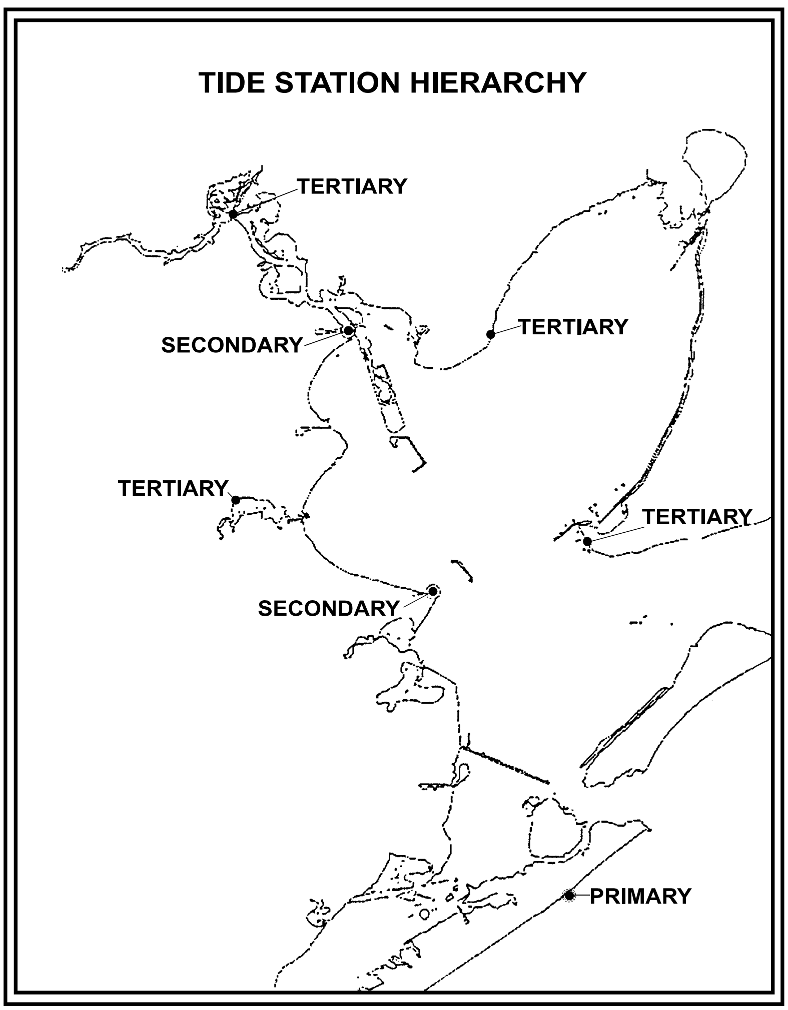


Figure 10. Illustration of tide station hierarchy.

Primary 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. As the records from such a station constitute basic water level data for present and future use, the aim is to install and maintain the stations to obtain the highest degree of reliability and precision that is practical. This justifies detailed planning and site selection. The essential equipment of a control tide station includes an automatic water level sensor, protective well or sump well (as for Great Lakes stations), shelter, back-up water level sensor, ancillary geophysical instruments, and a system of bench marks.

Secondary water level stations are those which are operated for less than 19 years but for at least 1 year, and have a planned finite lifetime. Secondary tide stations are established for the purpose of obtaining general tidal information for a locality and also to obtain specific data for the reduction of soundings in connection with hydrographic surveys. Secondary stations also provide control in bays and estuaries where localized 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 datum, 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, tertiary, and seasonal) may have their data reduced to equivalent 19 year means 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 simultaneously compared to adjacent stations for datum determination in harbors.

The site selection criteria for tide stations include geographical and time-varying knowledge of the changes in Mean Tide Level (MTL) or MSL, changes in Mean Range of tide (Mn), and changes in time of tide. Additional factors are 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. Figure 11 is an example of the coverage of Chesapeake Bay, MD, where the tidal characteristics change rapidly. A control water level station is sited to provide datum control for national applications, and are sited in as many places as needed for datum control.

Site reconnaissance is performed prior to the installation of a new station. Field site visits are done to aid in the design, make measurements, and render technical drawings; to recover bench marks and/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 bench mark locations, adequate water depth, special materials that might be needed to prevent marine fouling and/or corrosion, availability of telephone and electrical service, site security, and lightening protection.

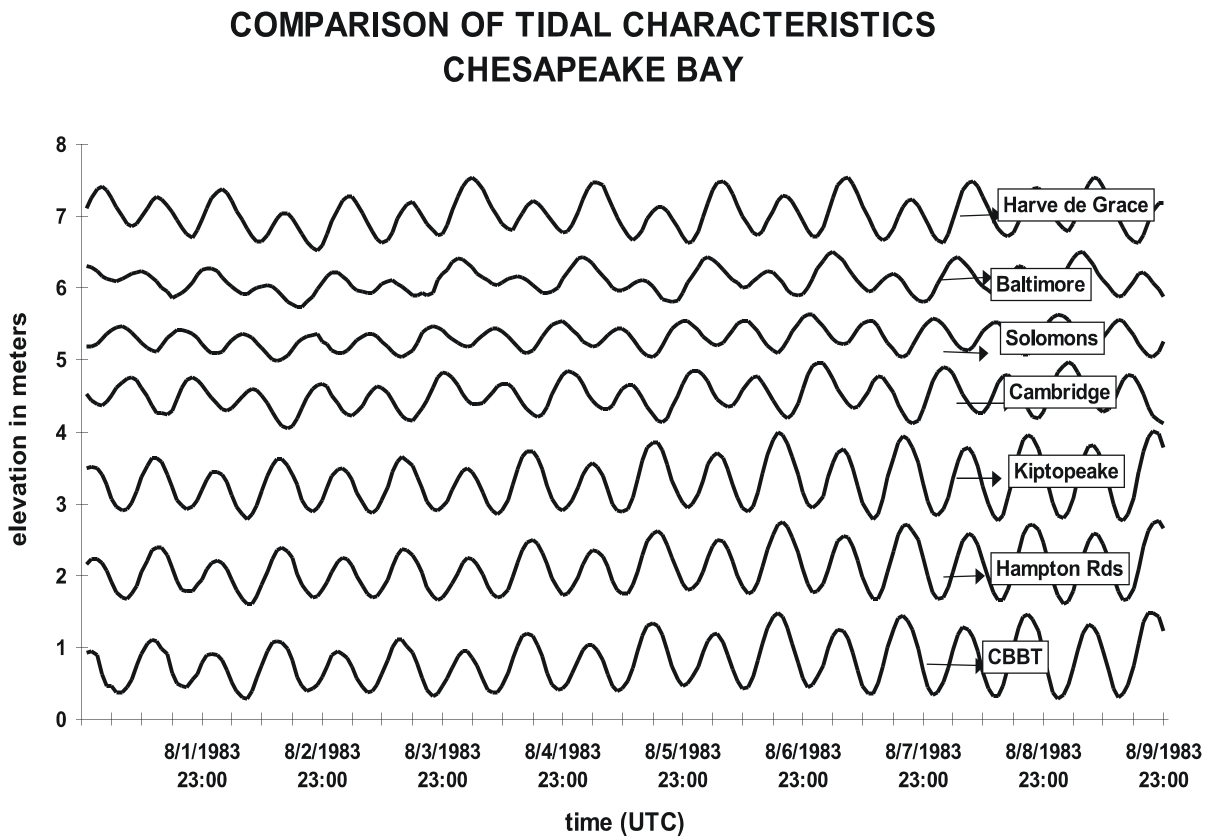


Figure 11. An illustration of the change in tidal characteristics as a function of location in Chesapeake Bay, MD.

B. Bench Marks and Differential Leveling

A bench mark is a fixed physical object or mark used as a reference for a vertical datum (Figure 12). A tidal bench mark is a mark near a tide station to which the tidal datums are referenced. A network of bench marks is an integral part of every water level measurement station. Since gauge measurements are related to the bench marks, it follows that the overall quality of datums is 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 set atop stainless steel rods driven to substantial resistance.

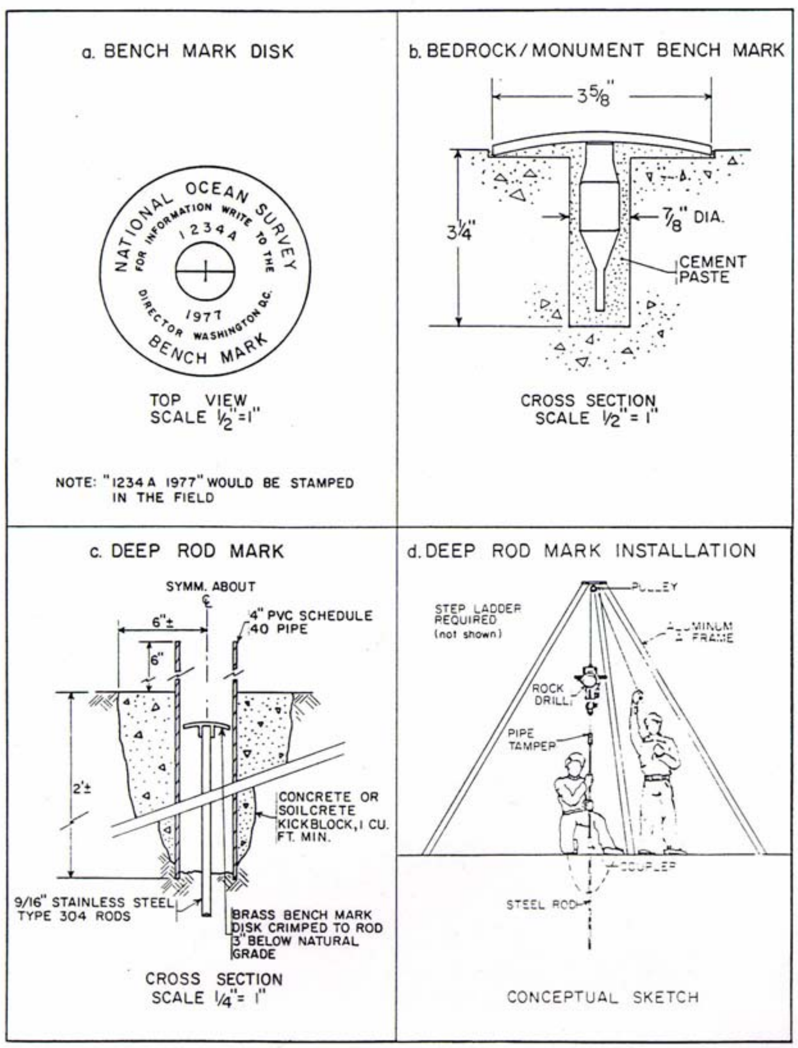


Figure 12. An illustration of an NOS bench mark and various installation methods.

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 10 bench marks is installed in the vicinity of the station. Five bench marks are installed at secondary (1 year to less than 19 years) and tertiary (30 days to less than 1 year) stations. At least 3 bench marks are installed at short-term (less than 30 days) stations.

Differential levels (Figure 13) 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.

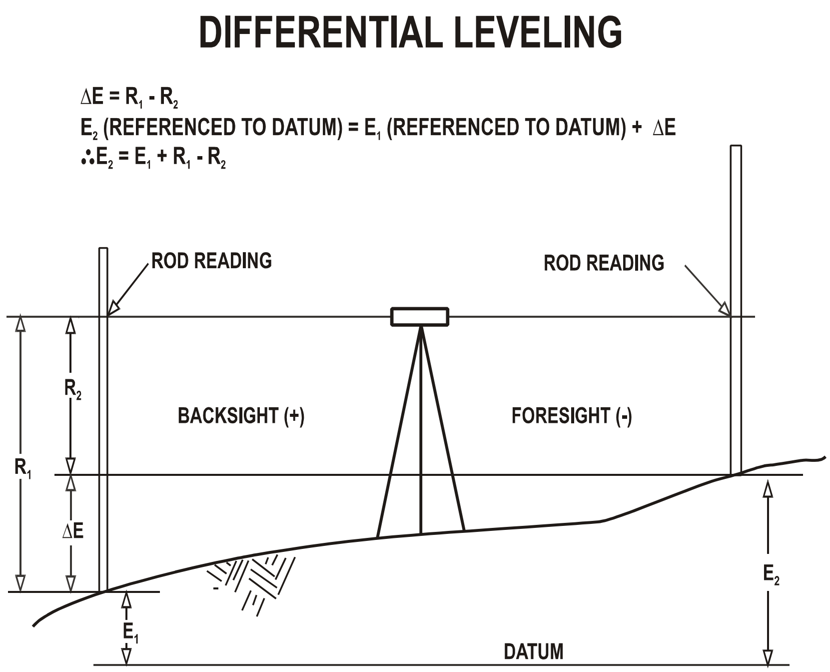


Figure 13. A schematic diagram of extending vertical control inland from the tidal datum by the method of differential leveling.

The User's Guide for the Installation of Bench Marks and Leveling Requirements for Water Level Stations (*Hicks et al., 1987*) provides 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. There are approximately 3000 along the U.S. East Coast, 500 installed on the Gulf Coast, 1000 along the West Coast, 1200 in Alaska, 150 in the Pacific Islands, and 177 around the Great Lakes. Bench mark elevations may become invalid due to vertical movement of the structure or substrate or movement due to local construction. The established elevation of bench marks relative to tidal datums 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 published values for bench mark elevations. An example of the bench mark elevation portion of a published bench mark sheet is shown in Figure 14.

PUBLICATION DATE: 11/02/1999 Page 5

ALASKA 945 5760

NIKISKI, COOK INLET

Tidal datums at NIKISKI, COOK INLET are based on the following:

LENGTH OF SERIES	= 2 YEARS
TIME PERIOD	= January 1997 - December 1998
TIDAL EPOCH	= 1960-1978
CONTROL TIDE STATION	= SELDOVIA, COOK INLET (945 5500)

Elevations of tidal datums referred to mean lower low water (MLLW) are as follows:

HIGHEST OBSERVED WATER LEVEL (12/26/1976)	= 8.513 METERS
MEAN HIGHER HIGH WATER (MHHW)	= 6.239 METERS
MEAN HIGH WATER (MHW)	= 6.026 METERS
MEAN SEA LEVEL (MSL)	= 3.427 METERS
MEAN TIDE LEVEL (MTL)	= 3.330 METERS
*NORTH AMERICAN VERTICAL DATUM-1988 (NAVD)	= 2.088 METERS
MEAN LOW WATER (MLW)	= 0.634 METERS
MEAN LOWER LOW WATER (MLLW)	= 0.000 METERS
LOWEST OBSERVED WATER LEVEL (01/29/1979)	= -1.545 METERS

Bench mark elevation information:

	ELEVATION IN METERS ABOVE:	
BENCH MARK STAMP/DESIGNATION	MLLW	MHW
5760 K 1978	12.583	6.557
5760 L 1983	12.695	6.669
5760 M 1983	13.049	7.023
5760 N 1983	26.212	20.186
NIK 1964	11.090	5.064
NIKISKI 2	15.574	9.548
NIKISKI 3	34.642	28.616
NO 7 1973	35.746	29.720
NO 8 1973	33.451	27.425
NO 9 1973	35.736	29.710

PUBLICATION DATE: 05/21/1996 Page 3 of 5

Figure14. A sample of a page from a published bench mark sheet for Nikiski, AK. This page illustrates information pertaining to tidal datums and vertical control. Note that for this station, the tidal datums were computed from a secondary reduction, the control station is indicated, and elevations of the tidal datums are relative to MLLW.

Bench marks are leveled by either a compensator leveling instrument 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. 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.

The Global Positioning System (GPS) is emerging as a global vertical measurement system (*Milbert, 1995*). The NOS National Geodetic Survey (NGS) is implementing GPS into operations and is developing a nationwide Continuously Operating Reference System (CORS). GPS is being used to measure vertical crustal motion at water level stations at certain test sites. Differential GPS connection of bench marks (i.e., determination of ellipsoidal height of bench marks) enables the seamless integration of tidal datums with geodetic heights measured by GPS (*e.g., DeLoach, 1995; Wells et al., 1996; Defense Hydrographic Initiative, 1996*). Presently, work is underway to investigate using GPS to minimize the number of bench marks at each station, to provide tidal datums relative to the ellipsoid to facilitate standardization with a future "global" datum, and to better assess localized land movement as opposed to bench mark instability. These efforts will also facilitate understanding of the slopes or differences between tidal datums in different locations. NOS is also investigating the use of Real-Time Kinematic (RTK) GPS in hydrographic surveying, assuming that the relationship between Chart Datum (MLLW) and the ellipsoid is known.

C. Collection of Observations

Due to physical and environmental complexities, including spatial and temporal variability and severe environments in coastal zones, sophisticated instruments are necessary to measure instantaneous water levels, tides, storm surges, tsunamis, and long-term sea level trends. These instrument suites must be very accurate and reliable.

In past years, water levels were measured using float and wire sensors housed in stilling wells, first with analog strip chart mechanical gauges and later with punched-paper-tape to analog digital recorder (ADR) conventional tide gauges (*e.g., Schureman, 1941)*. Tide observers and tide staffs were used to connect the measurements to the local bench mark networks. This technology was suitable for most traditional monitoring requirements for surveying and mapping, however present instrumentation and computer technologies used by NOS enable more accurate, flexible, and automated tide gauge systems to be applied towards eliminating the sources of uncertainty in measurement that the older systems exhibited and towards the emerging programmatic real-time automated needs of NOAA programs (NRC, 1986). A more accurate system of measurement also supports the requirement of the long term measurements to estimate relative sea level trends with amplitudes of a few millimeters.

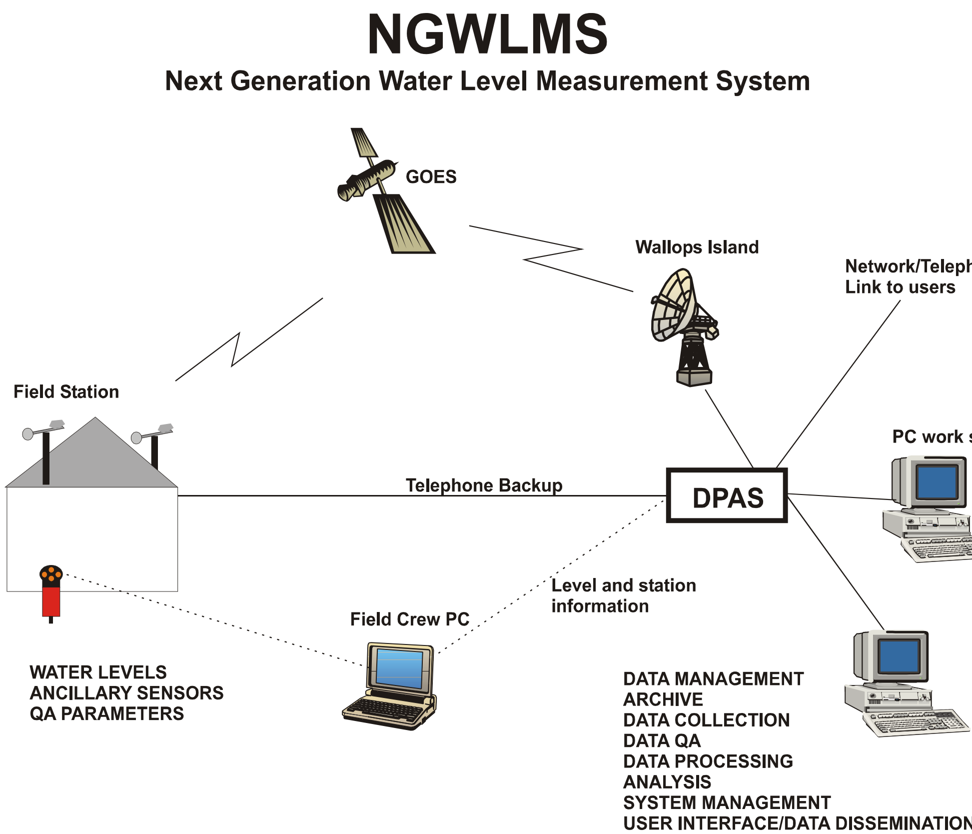


Figure 15. A schematic diagram of the main systems associated with NGWLMS.

The NWLON Station and Its Equipment

Present water level stations use modern sensor technology (*NRC, 1986*), improved instruments, digital recording, satellite communication, modern database programming and management techniques, and additional geophysical instruments (Figure 15). Many stations also measure wind speed and direction, barometric pressure, air and water temperature. These are used to interpret the sea level records, perform scientific analyses of the natural phenomena in the coastal zone, and when disseminated to mariners through the Physical Oceanographic Real-Time Systems (PORTS^{TM}), provide real-time environmental conditions suitable for navigational decision making (*NRC, 1986; 1996*).

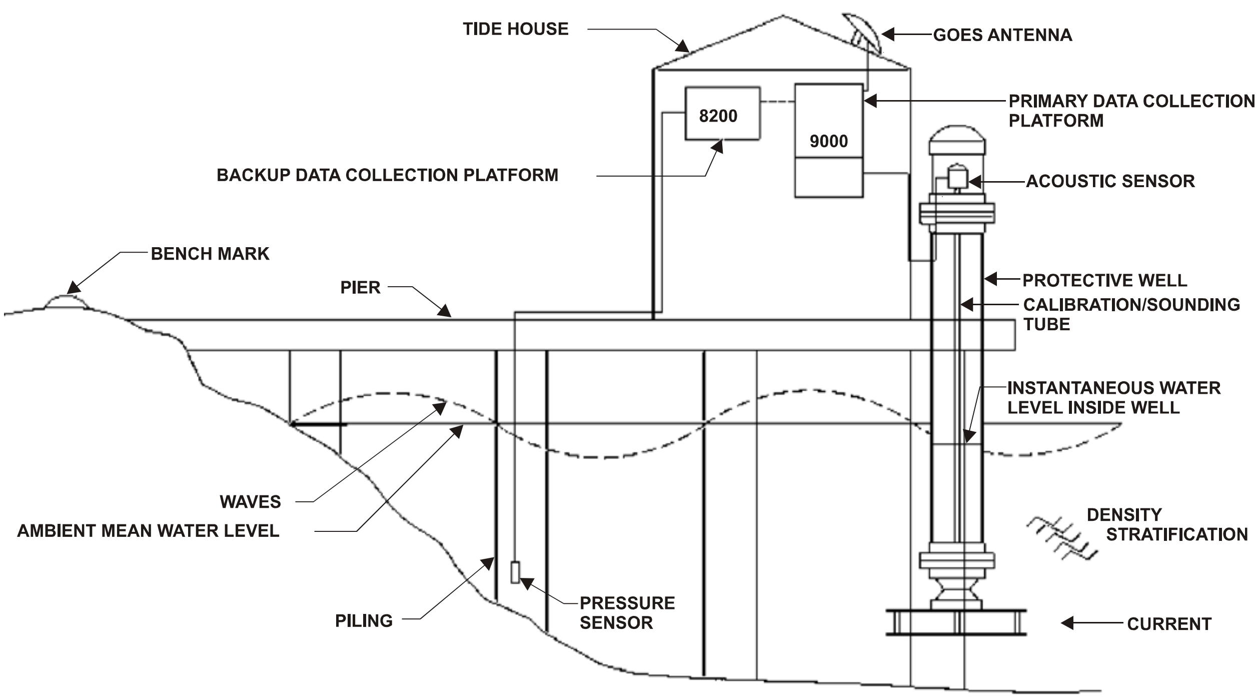
The system that accomplishes these tasks is known as the Next Generation Water Level Measurement System (NGWLMS). The NGWLMS equipment was developed by NOS to modernize the NWLON (*e.g., Scherer, 1986; Mero and Stoney, 1988*). A NGWLMS is a stand alone system that acquires, stores and transmits water level, weather and other data from the field unit (*Edwing, 1991*). The main requirement for the unit is to accurately measure water level information with low power consumption, high reliability, and defined accuracy. The goal is to monitor waters levels with an accuracy of better than 1.0 cm, as the present global estimate of sea level rise is 0.15 cm per year. Considering all the variability in water level measurements, resulting from the contributions noted earlier, this level of accuracy presents a challenge for instrumentation and research. The NGWLMS water level sensors have an accuracy of about 1.0 cm for each sample (*Schultz, et al., 1998*).

Instruments

The NGWLMS field unit is a fully automated, data acquisition and transmission system. It was developed and procured from off the shelf components in the mid-1980s, and underwent extensive evaluation prior to delivering data from which operational products are calculated. In addition, the internal firmware and some of the internal modules of the field unit have received periodic upgrades to maintain or enhance capabilities.

The data collection platform (DCP) (Figure 16) consists of a Sutron 9000 Remote Terminal Unit (RTU). This is a modular unit that contains power supply, communications controller, Geostationary Operational Environmental Satellite (GOES) satellite transmitter, central processor unit, memory expansion module, telephone modem, general purpose Input/Output (I/O) module, and an Aquatrak water level sensor controller manufactured by Bartex. The unit receives data from the sensors which measure the water level and geophysical parameters (*Edwing, 1991*). This measurement sub-system accommodates up to eleven additional instrument channels. The field unit is fully automated for remote installations. The unit's design and satellite data transmission streamlines the digital data relay and processing.

The NGWLMS field unit is a multi-tasking, programmable computer. The unit is fully automated, password protected, and is easily sited. The Sutron 9000 accommodates two water level



NEXT GENERATION WATER LEVEL MEASUREMENT SYSTEM

Figure 16. A schematic diagram illustrating the design of a standard NGWLMS.

instruments with the option of installing eleven additional instruments. The unit's telemetry capability includes satellite, radio, telephone and direct access for the dissemination of near real-time and real-time data, complete data custody, and recovery from system or communications malfunction. The Aquatrak is a downward-looking acoustic water level measurement sensor that returns data that can be directly referenced to the station datum at the site. (*Edwing, 1991*). Provisions are made within the data base processing system to convert water level data to local tidal datum references.

The instruments typically installed at an NWLON station are: the primary water level sensor (a Bartex "Aquatrak" acoustic sensor); a strain-gauge pressure transducer for back-up water level measurements; an R.M. Young anemometer for measuring wind speed, direction and maximum hourly gusts; a Yellow Springs Instruments Corporation (YSI) thermistor for measuring air or water temperature; a Seabird or Falmouth water conductivity instrument; and a Setra or Visalla barometer for measuring atmospheric pressure (*Edwing, 1991*). Since technology is constantly evolving, the mix of computers and sensors is subject to change in the future. The environment at the stations in the Great Lakes is such that shaft angle encoders and float/wire sensors are used instead of the acoustic sensors. NOS is also investigating new sensor technologies, such as laser and microwave sensors, to replace the acoustic sensor since it still requires a protective well.

Measurement of Water Levels

The primary requirement of a water level station is to accurately and reliably measure time varying water levels in often hostile conditions. The primary water level sensor is a non-contact sensor, i.e., the sensor consists of an acoustic transducer head connected to a ½ -inch diameter vertical PVC tube open at the lower end, which is in the water.

The water level in the tube moves up and down with the tide. The tube, and the sturdy environmental protective well housing which surrounds the tube, provide a limited damping effect. The protective well is a 6 inch diameter PVC well with and a 2 inch inverted cone orifice in the water. Typically, 12 inch diameter parallel plates at the orifice are also installed. This design reduces the unwanted filtering effects of a true stilling well while permitting the field unit to be sited in dynamic environments with wave action and high velocity currents and also reduces the errors due to wave motion and stream flow associated with currents on the internal water level. This arrangement, as far as possible, gives a linear response to exterior changes in sea level (*Scherer, et al., 1981*).

The acoustic head emits a sound pulse, which travels from the top of the tube to the water surface in the tube, and is then reflected up the tube. The reflected pulse is received by the transducer, and the Aquatrak controller, or water level sensor module. The Sutron 9000 unit then calculates the distance to the water level using the travel time of the sound pulse (*Sutron, 1988*) with corrections for air temperature and density effects (*Edwing, 1991*).

As well as the reflected pulse from the water level, there is also a reflection from a hole in the side of the sounding tube at an accurately known distance from the transducer head. This measured reflection is used by the Aquatrak controller to continually self-calibrate the measuring system. Temperature gradients in the protective well can introduce a source of systematic error. Two temperature thermistors are installed at two locations in the sounding tube and a correction factor can be applied as required (*Edwing, 1991*). As mentioned, a system of tidal bench marks is in place to ensure the stability and continuity of the measurements and to recover the tidal datums (*Edwing, 1991; Mero and Stoney, 1988*).

Backup Water Level System

Each NGWLMS field unit has a backup system. This contains a stand alone backup data recorder which measures and stores water level data from a pressure transducer installed in a gas-purged/orifice configuration.

The backup water level readings are logged every six minutes into the memory of the Sutron RTU 8200 data recorder and are passed to the Sutron 9000 unit, via an optically isolated serial communication link. The 8200 is a fully-automated, multipurpose, programmable DCP that supports multiple sensors and satellite telemetry.

The memory of the Sutron 8200 can hold about two months of data (*Mero and Stoney, 1988*). Should there be problems with the primary data system, the data from the 8200 can be retrieved during an on-site visit. This backup system uses battery power with solar recharge and can operate unattended for over a year (*Mero and Stoney, 1988*).

Powering the NGWLMS Unit

The NGWLMS unit can use a variety of power sources, including electrical power, solar panels or batteries. Batteries provide about seven days of reserve operating power in case of loss of primary power. For installations where electrical power is not available, the system will run on batteries which are charged by solar panels (*Mero and Stoney, 1988*).

Data Sampling Rate

The sampling rate for the primary and backup water level measurements is 1 sample per second. However not all of these data are stored. The water level measurements are averaged over a three-minute period (*Scherer, et al., 1981*) and are stored in the memory at 6-minute intervals. Each weather parameter is stored hourly, and is the average of 2 minutes of sampling on the hour. The memory of the 9000 has a "rolling log" which retains the last 30 days of data (*Mero and Stoney, 1988*).

For primary water levels, an average of 181 samples is computed, 1 sample per second over three minutes. The standard deviation is then calculated, and any sample readings greater than 3 standard deviations from the mean are identified and termed outliers. The mean and standard deviation are then recalculated from the remaining samples after outliers are removed, and the values of the recalculated mean, the standard deviation, and the number of outliers are stored in the Sutron 9000 or 8200.

The NGWLMS station has the capacity to operate with various, site-specific combinations of sensors, averaging and sampling intervals. These combinations can be adjusted by using a personal computer connected to a communication port in the unit, either directly at the site, or remotely with a "modem" through the normal public telephone network. Another feature of the 9000 field unit is that the system software can be modified remotely via telephone. This capability has proven to be useful during early system development and for software upgrades.

Data Retrieval

Data can be retrieved from the Sutron 9000 unit by (a) on-site retrieval, using a personal computer communication program, and (b) remote retrieval, where data is retrieved by automated modem dial-up or by automatic satellite transmissions every hour via the NOAA's Geostationary Operational Environmental Satellite (GOES) (*Mero and Stoney, 1988; Gill, 1997*).

Other Primary Sensors

NOS uses other sensor technologies as primary sensors where the acoustic system configurations cannot physically be installed or the acoustic systems are not appropriate due to operating conditions. Examples are in areas of Alaska and in the Great Lakes where seasonal ice conditions prohibit installation of protective wells and where acoustic sounding tube temperature gradients cannot be controlled. In Alaska, a dual orifice digital bubbler water level sensor system is employed configured with Paroscientific pressure transducers vented to the atmosphere. In the Great Lakes, float driven shaft angle encoder sensor systems are installed in sump wells that have underground horizontal pipe assemblies out to the water low enough to be unaffected by the ice.

D. Quality Assurance of Water Level Data

NOS has written Standard Operating Procedures (SOPs) for station instrumentation. The primary documentation is the "NGWLMS Site Design, Preparation, and Installation Manual" (*Edwing, 1991*). This document defines support for NGWLMS field unit deployment and operation, and includes system configuration and annual inspection procedures. Field Engineering Notes are issued as needed to provide updated field unit maintenance procedures. Project Instructions are issued annually and amended as required to provide specific station maintenance requirements.

The SOP for bench marks and leveling is entitled, "Users Guide for the Installation of Bench Marks and Leveling Requirements for Water Level Stations" (*Hicks et al., 1987*). This document presents SOPs for second order and third order leveling of the tide station bench marks.

The use of standardized documentation and procedures is a requirement for delivering data of known quality. The above documents define the procedures for facility maintenance, instrument maintenance, data quality monitoring, and stability monitoring.

Specific procedures are defined for inspecting and repairing water level station structures, inspecting and repairing utilities, maintaining underwater components, and cleaning marine growth (*Edwing, 1991*). There are specific procedures for calibration, inspection, and acceptance testing of system-wide components. These procedures include field verification of instruments and hardware, preventive maintenance and corrective maintenance procedures, how to modify and upgrade components, and how to install, test, and retrieve data collected from the back-up system (Edwing, 1991).

Field crews responsible for station installation and maintenance have software that enables them to run diagnostic tests on the system while on-site. In addition, each day CO-OPS obtains a preliminary daily review of the status of instruments from the GOES Daily Telemetry Status Report. Data tracking also occurs through the data base management system which performs a variety of data quality checks and can record flags for each point of data processed. Data are also reviewed by the Continuously Operating real-Time Monitoring System (CORMS) program on a 24 hour by 7 day basis.

The SOPs for bench marks and leveling instruct field parties in the installation and maintenance of bench marks to be used for tidal datum references. There are also detailed instructions on how to conduct differential leveling to monitor vertical stability of gauges and how to define a primary bench mark (*Smith, 1997*).

The documentation produced by the field parties are maintained in a site package filed at CO-OPS for each tide station. The report includes a nautical chart section of the area around the tide station, a bench mark sketch, directions on how to find the station and bench marks, bench mark descriptions and recovery notes, photographs of station components, bench mark settings, bench mark leveling records and abstracts, station installation and maintenance reports, and miscellaneous notes applicable to the station.

5. DATA PROCESSING AND TIDAL DATUM COMPUTATIONAL METHODOLOGIES

A. Data Processing and Analysis Subsystem (DPAS)

The Data Processing and Analysis Subsystem (DPAS) is the NOS database management system which receives water level and geophysical data from the water level station instrumentation, performs automated quality control, facilitates the processing and analysis of the data, generates resulting products to be disseminated to the public, maintains control over the data collection activities of the field units, provides mechanisms for the timely release of data, and archives the data.

DPAS Data Flow

Data from remote NGWLMS field units can be transmitted to DPAS by satellite, telephone, or diskette (*Gill et al., 1997*). The primary mode of data telemetry is by GOES satellite. Each field unit transmits data collected during the previous hour period once every hour. For water level from the primary water level sensor only, redundant data (i.e., several hours prior to the present period) are also sent in the satellite message. Quality control parameters such as standard deviations and outliers are also sent in the satellite message for the present time period, but not for the redundant data. The GOES satellite message includes 6-minute water level data, half-hour backup water level data, and hourly geophysical data. The satellite messages are sent to NOAA's National Environmental Satellite, Data and Information Service (NESDIS) downlink facility at Wallops Island, VA. DPAS automatically calls the NESDIS downlink facility once every hour to download new satellite messages. The satellite messages are decoded from pseudo-binary format into ASCII files, and the ASCII files are copied into the DPAS database. Automated Quality Control (QC) procedures are performed, and each time a QC flag is set, it is stored in the database. For example, a QC check is performed to test the water level against maximum and minimum physically-reasonable values. If the water level fails this check, the QC flag indicating a failed maximum-minimum range-test is set. Additional QC checks include a test to see if several consecutive values of the water level are the same; if this is true, the implication is that the sensor is not responding. A third difference check is done to detect discontinuities in the data. Checks are made of the two thermistor values that are installed within the protective well to ensure they do not exceed tolerances. Sensor and datum offset checks are compared against accepted values of these coefficients in the DPAS database. If discrepancies exist, the flags are set. For the geophysical data, only maximum and minimum checks are performed. Tolerance limits are individually set for each station and parameter.

Data acquisition by telephone call is the backup mode of data telemetry. Only a few stations do not have telephone connections. Phone calls to the field units may be made on demand or programmed into DPAS. In any event, DPAS makes automatic phone calls about every 2 weeks to test the phone connection. Data collected by phone undergo the same QC checking outlined above. When all else fails, the third mode of data recovery is to download the data from the Sutron 9000 by diskette. Depending upon the type of data collected, up to thirty days of data may be stored, which provides adequate time for data recovery by this means. This data is also edited and quality controlled in the manner outlined above.

A number of reports are generated by DPAS to document the data quality. The preliminary Data Quality Assurance Report summarizes the number of tolerance failures for each station for a user-specified period of time. The Satellite Transmission Report provides a listing of all transmissions received at CO-OPS via NESDIS within the last 24 hours. The Sensor and Datum Offset Report lists all sensor and datum offsets used to process the data. This includes the offsets recorded at the field unit, telemetered to DPAS, and manually entered into DPAS. The Daily Telemetry Status Report is generated every 24 hours for all stations that were expected to transmit data. This is reviewed every day for flags which are indicative of malfunctioning sensors. The GOES Monthly Summary Report identifies problems that occur because of the satellite for NWLON stations. This report also includes the random reports produced from stations that were modified for either the Tsunami Warning Program and the Storm Surge Warning Program.

Processing and analyses of data within CO-OPS are done according to a set of SOPs which control human error by prescribing a step-by-step approach and operate on a defined set of inputs with a defined set of output products.

The SOP entitled "NGWLMS Preliminary Data Quality Review" (*Gill, 1994*) takes as input the unedited NGWLMS water level and geophysical data that has gone through the automated QC outlined above. Produced as an output is a preliminary data quality review with feedback to appropriate engineering personnel on instrument operation. This SOP is performed on a monthly basis during the last week of each month for that month's data. Data quality reviews occur more frequently for special projects such as hydrographic surveys, other short-term deployments, or NGWLMS stations that have chronic problems. The procedure of preliminary review consists of checking the data, relevant comparisons, scanning the DPAS Acquisition Report, checking outliers, and flags that have been set, and forwarding copies of the documented problems to engineering personnel.

A second SOP *(Gill, 1995),* operates on the raw unedited data and is entitled, "Processing of 6-minute Data for Hourly Heights, High and Low Waters, and Monthly Means." The input is the raw, QC-flagged water level data, standard deviations and outliers, sensor and datum offset information, and the inventories of time series in DPAS. Outputs of this procedure are the final edited versions of the 6-minute water level time series data, tabulation of the hourly heights, high and low waters, and monthly means referenced to a site-specific, arbitrary, station datum. This processing includes QC, editing, gap filling, and tabulation. This procedure first checks that all of the parameters for a station were entered into DPAS correctly. Inventories of the data are all checked. Normally, DPAS automatically loads the previous month's data around the third of each month. However, if there are gaps in the primary sensor data, this is performed manually. Data are plotted to examine the data quality and determine what kind of gap filling, if any, is required. If gaps are small, then linear interpolation is usually adequate. If gaps are up to 3 days, then the gaps may be filled with backup water level data, with predictions, or by comparison of data with a nearby station after amplitude and phase offsets are computed. Once the gaps are filled, and depending upon the type of station, several parameters may then be computed including generation of hourly heights, generation of high and low tides, and selection of higher highs and lower lows. Several diagnostic QC checks are defined for each step of the process. After this, the monthly means are produced. The time series data, hourly heights, high and low waters, higher highs and lower lows are marked complete, and subsequently marked verified after review by a senior analyst.

Tidal datums and associated tidal products are also computed using DPAS *(Smith, 1997)*. The procedure controlling the analysis is defined in "SOP for the Computation and Acceptance of Tidal Datums for NOS Tidal Stations Using DPAS." Tidal datums at control stations are computed by the first reduction or arithmetic mean method for a specific length of record, generally a tidal epoch *(Smith, 1997)*. The input for the procedure requires the monthly mean values for a tidal epoch. The current tidal epoch is defined to be from 1960-1978. Tidal datums at secondary stations are generally computed by comparison of monthly means between subordinate and control stations *(Smith, 1997)*. Tidal datums at tertiary stations are computed by comparison of monthly means or comparison of simultaneous high and low waters (if no calendar month of data) between the tertiary station and a control, or with an acceptable secondary station (*Smith, 1997*). The input for this procedure is the simultaneous means from the control and subordinate station in a region of similar tidal characteristics to produce an equivalent datum at the subordinate station with an adjustment to 19-year values. This SOP results in accepted values which consist of 1960-1978 epoch datums relative to the station datum and associated values of Greenwich High Water Interval (HWI), and Greenwich Low Water Interval (LWI), Mean Range (Mn), Great Diurnal Range (GT), Diurnal High Water Inequality (DHQ), and Diurnal Low Water Inequality (DLQ) (*Hicks, 1989*).

The tidal datum computation process involves QC of the data, review of preliminary datum tabulations and datum reference, benchmark and station stability, and computation of the standard tidal datums. Procedures include detailed instructions for publishing a bench mark sheet *(Smith, 1997)*. The elevation of the primary bench marks relative to the station datum, the elevation differences between the primary bench mark and the other benchmarks, bench mark descriptions, and bench mark locations are documented. Corrections pertaining to the bench marks are entered at this point. The output is an accepted set of tidal datums and published bench mark sheets for each station.

The SOP, "Formal Year-End Reviews of Tide Station Data" *(Gill, 1997)* provides a further level of data quality assurance. The input of the procedure is the most recent year of data from operating NGWLMS stations, tabulation packages for each station, copies of the data inventories of the digital data on DPAS, DPAS sensor and datum offset reports, and site packages. Reviews of the data occur after the December preliminary data quality review. The output from the procedure is the completed, documented, calender year-end review for all NWLON and special project stations. The data and products are reviewed for consistency, anomalous values, completeness, and documentation. Also reviewed are the water level time series, datums, harmonic constituents, and benchmark and leveling information.

B. First-Reduction Tidal Datum Computations

The attention to detail in the data quality assurance, mentioned in the previous sections on instrumentation and standard operating procedures, leads to water level data sets that are used to produce tidal datums. In this section, the standard tidal datums are defined.

The NTDE is defined as the specific 19-year cycle adopted by the NOS as the official time segment over which water level observations are taken and reduced to obtain mean values (e.g., mean lower low water) for tidal datums. Adoption of the NTDE averages out long-term seasonal meteorological, hydrologic, and oceanographic fluctuations. It provides a nationally consistent tidal datum network by accounting for seasonal and secular trends in sea level that affect the adequacy of the tidal datums (*Marmer, 1951*). NOS operates the NWLON to provide the data required to maintain the epoch and to make primary and secondary determinations of the tidal datums. The present NTDE is 1960 through 1978. It is reviewed for revision at least every 20 to 25 years and implementation of a new NTDE is currently under consideration by NOS.

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.

A primary determination of a 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 (*Marmer, 1951*).

Mean Higher High Water (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 NTDE). Only the higher high water of each pair of high waters of a tidal day is included in the mean. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent of a 19-year value (*Marmer, 1951*).

Mean High Water (MHW) is defined as the arithmetic mean of the high water heights observed over a specific 19-year Metonic cycle (the NTDE). For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent of a 19-year value (*Marmer, 1951*). Use of the synonymous term, mean high tide, is discouraged.

Mean Low Water (MLW) is defined as the arithmetic mean of the low water heights observed over a specific 19-year Metonic cycle (the NTDE). For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent of a 19-year value (*Marmer, 1951*). Use of the synonymous term, mean low tide, is discouraged.

Mean Lower Low Water (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, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent of a 19-year value (*Marmer, 1951*).

In addition, Mean Tide Level (MTL), Mean Range (Mn), Diurnal High Water Inequality (DHQ), Diurnal Low Water Inequality (DLQ), Great Diurnal Range (Gt), Diurnal Tide Level (DTL), and Mean Sea Level (MSL) have the following definitions: MTL is the average of MHW and MLW; Mn is the difference between MHW and MLW; DHQ is the difference between MHHW and MHW; DLQ is the difference between MLW and MLLW; Gt is the difference between MHHW and MLLW; DTL is a tidal datum which defines the midpoint between MHHW and MLLW; and MSL is defined as the arithmetic mean of hourly heights observed over a specific 19-year Metonic cycle (the NTDE). Shorter series, such as monthly mean sea level and yearly mean sea level, are specified in the name (*Marmer, 1951; Hicks, 1985*). The Glossary of this document contains the definitions of additional tidal datums.

C. Equivalent Short-Term Datums

Due to time and resource constraints, primary determinations of tidal datums 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 by means of observations covering much shorter periods than 19 years if the results are corrected to an equivalent mean value by comparison with a suitable primary control tide station (*Marmer, 1951*).

A primary control station is one (*Marmer, 1951*) at which continuous observations have been made over a minimum of 19 years spanning the NTDE. The data series from this station serves as a primary control for the reduction of relatively short series from subordinate stations through the method of comparison of simultaneous observations and for monitoring long-period sea level trends and variations.

A secondary control tide station is a subordinate tide station at which continuous observations have been made over a minimum of one year but less than 19 years. The data series is reduced to equivalent 19-year tidal datums by comparison with simultaneous observations from a suitable primary control observation.

A tertiary control tide station is a subordinate tide station at which continuous observations have been made over a minimum of 30 days but less than 1 year. The data series is reduced to equivalent 19 year tidal datums by comparison with simultaneous observations from a suitable secondary or primary control tide station. NOS uses the following methods to perform comparisons of simultaneous observations for secondary (i.e., short-term) determinations of tidal datums.

Standard Method. This method is generally used for the West Coast, and Pacific Island stations. Values needed are MTL, MSL, Mn, DHQ, and DLQ as determined by comparison with an appropriate control. From those, the following are computed:

MLW = MTL - (0.5*Mn)

MHW = MLW + Mn

MLLW= MLW - DLQ

MHHW = MHW + DHQ

DTL = 0.5*(MHHW + MLLW)

GT = MHHW - MLLW

Modified-Range Ratio Method. This method is generally used for the East Coast, Gulf Coast, and Carribbean Island Stations. Values needed are MTL, DTL, MSL, Mn, and GT as determined by comparison with an appropriate control. From those, the following are computed:

MLW = MTL - (0.5*Mn)	MHHW = MLLW + GT
MHW = MLW + Mn	DHQ = MHHW - MHW
MLLW= DTL - 0.5*GT	DLQ = MLW - MLLW

Direct Method. Datums are determined directly by comparison with an appropriate control for the available part of the tidal cycle. It is usually used only when a full range of tidal values are not available. For example: Direct Mean High Water, when low waters are not recorded.

Figure 17 is an illustration of how these tidal datums are related to a typical beach profile and also illustrates how the various tidal datums are applied to marine boundary issues.

DATUMS

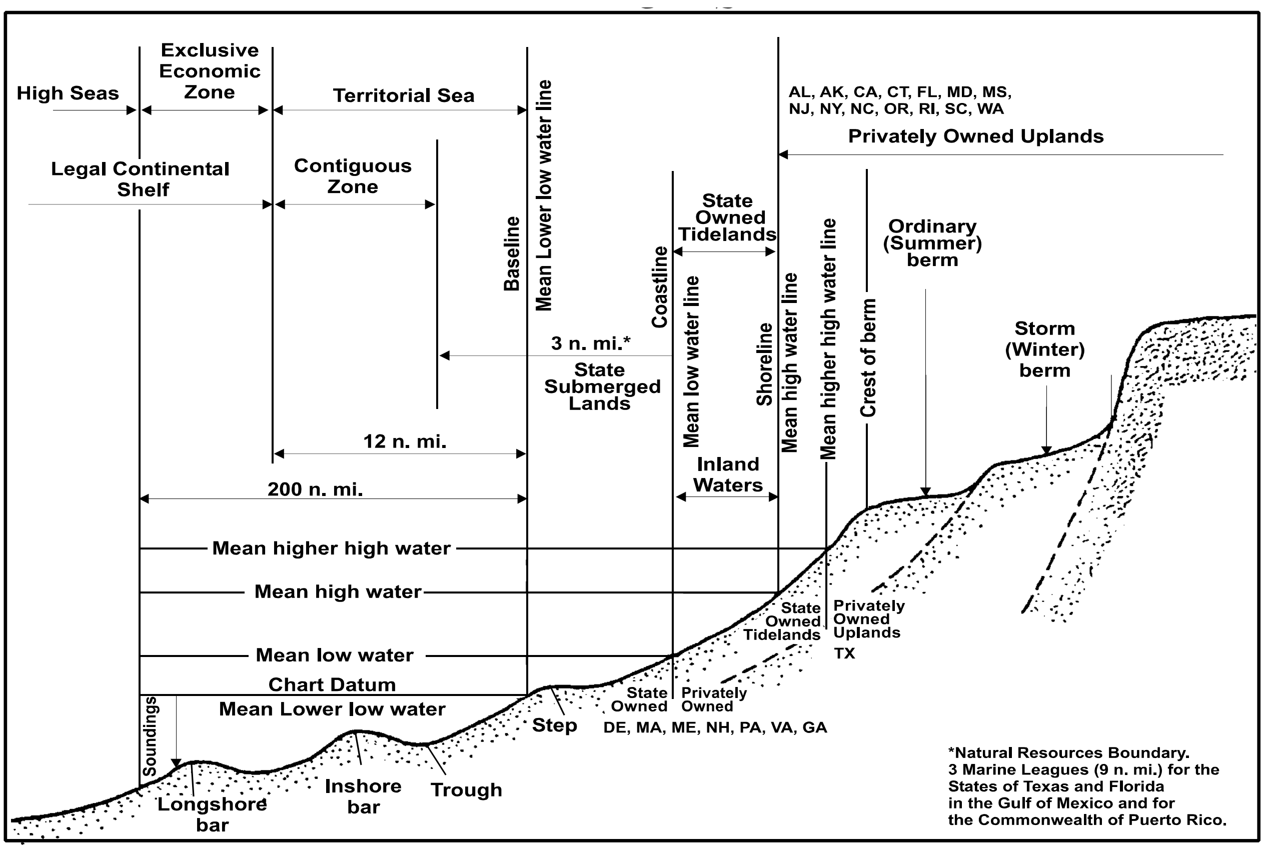


Figure 17. The principal tidal datums related to a beach profile. The intersection of the tidal datum with land determines the landward edge of a marine boundary.

D. Accuracy

Generalized accuracies *(Swanson, 1974)* for datums computed at secondary or tertiary stations based on the standard deviation error for the length of the record are summarized in Table 2. These values were calculated using control stations in the NWLON. The accuracies of the secondary and tertiary datums can be interpreted as known to within plus or minus the appropriate value in Table 2. That is, the values in Table 2 are the confidence intervals for the tidal datums based on the standard deviation.

Table 2. Generalized accuracy of tidal datums for East, Gulf, and West Coasts when determined from short series of record and based on +/- sigma. From Swanson (1974).

Series Length (months)	East Coast (cm)	(ft.)	Gulf Coast (cm)	(ft.)	West Coast (cm)	(ft.)
1	4.26	0.13	5.91	0.18	4.26	0.13
3	3.28	0.10	4.92	0.15	3.61	0.11
6	2.30	0.07	3.94	0.12	2.62	0.08
12	1.64	0.05	2.95	0.09	1.97	0.06

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 3 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. In this table, the error is defined as (0.03 m)x[cotangent(slope)]. The greatest errors in the determination of the marine boundary occur for relatively flat terrain, which is characteristic of broad sections of the Atlantic and Gulf Coasts.

Table 3. Error in position of marine boundary as a function of the slope of the land.

% 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	0.6	3.0
2.0	1	1.5
5.0	3	0.61
10.0	6	0.30
15.0	9	0.18
20.0	11	0.15
30.0	17	0.09
50.0	27	0.06
100.0	45	0.03

6. TIDE AND WATER LEVEL PRODUCTS

A. Types

An extensive amount of tidal data is available from NOS. These data can be obtained in a variety of ways, such as historical data in either hard copy or digital formats; near-real-time data obtained through radio, telephone, or satellite link; and near-real-time and historic data obtained over the Internet. The acquisition of NOS-held historic data and data available over the Internet is discussed in the following sections.

B. Historic

A large volume of historic tide and water level data have been archived by NOS. Much of this information can be obtained in hard copy and electronic formats, as well as over the Internet. Recent efforts at digitizing historical hourly heights and monthly means form all NWLON stations is resulting in digital long term time series available to the user in digital form for the first time. General digital and hard copy data and information include raw and verified data, (tidal, oceanographic and meteorological), standard NOS publications, customized data, atlases, charts, reports, and memorandums. Listings of data availability and indices of water level stations are available from CO-OPS web pages and hard copies are available on request.

CO-OPS also provides expert consultation, including certification of observed and predicted water level data for court evidence and legal documents as requested. Special services include the preparation of customized tide and tidal current predictions; generating plots of hourly or 6-minute tidal heights; plots of daily, monthly, or yearly mean sea level; plots of daily mean observed versus predicted water level; and providing simultaneous plots of two stations or plots of observed water levels versus predicted tidal heights. Special services also include development of long-term tidal means and extreme water level data analysis; computation of long-term relative sea level trends; documentation of elevation of primary bench marks above summary datums; establishing tidal datums for previous time periods; tidal zoning; and providing technical advice on methods for conducting tidal surveys.

Other divisions of NOS also distribute products and services that contain tide and water level information provided by CO-OPS. The most well known of these are the nautical charts for the U.S. and its territories from the Office of Coast Survey (OCS). These charts are fundamental navigational tools required for safe passage of waterborne commerce. They can also serve as base maps for resource management, shoreline development planning, and other applications. Charts depict the location of the shoreline, minimum water depths referenced to tidal datums, aids to navigation, hazards to navigation, sediment notations, and other supplemental information. One valuable technique to estimate historic marine boundaries uses historic nautical charts of NOS. Historic NOS charts help to identify the geomorphology of the coast dating to 1834 at some locations.

Since the 1930s, precision aerial photography has been a primary source material for coastal survey maps. The main aerial photographic product produced by the NGS is a 9x9 inch color photograph, usually exposed at scales from 1:10,000 to 1:50,000. Aerial photography is also a valuable technique to estimate historic marine boundaries and the photogrammetric surveys themselves are either tide-controlled to produce depictions of MHW or are taken at known stages of the tide.

Products available from NGS include coastal survey maps, also known as T-sheets. These maps are special use planimetric or topographic maps that accurately depict the shoreline and alongshore natural and manmade features, such as rocks, bulkheads, jetties, piers, and ramps. These maps range in scale from 1:5,000 to 1:40,000. Carefully controlled for tide variations (standardized to Mean Low Water), these maps represent the most accurate delineation of shoreline in the Nation.

NGS also maintains the National Spatial Reference System (NSRS) which is a consistent national coordinate system that defines latitude, longitude, elevation, scale, gravity, and orientation throughout the Nation, as well as how these values change with time. There are over 800,000 geodetic control survey points in the U.S. Approximately 3,700 of these form the highest accuracy core of the system. They include the Federal Based Network (FBN), Cooperative Based Network (CBN), and CORS sites covering the U.S. and its territories. Individual data sheets for all FBN, CBN, and CORS points are available from the NGS web site, http://www.ngs.noaa.gov. The NGS and CO-OPS bench mark databases have a dynamic linkage whereby the user can cross reference common geodetic bench marks with tidal bench marks.

C. Operational Support to Other Programs

Physical Oceanographic Real-Time System

Water level measurements and additional geophysical data from selected NWLON stations are used to support the CO-OPS managed PORTS™ program; an integrated real-time navigation system, delivering to the mariner in near-real remote data displays which range from simple numeric to graphics. Present technology enhancements include real-time water level data access, tabular or graphic display, and tide and tidal current prediction comparison. The real-time data can be obtained by the local user by interrogating the PORTS™ local data acquisition systems by telephone (*Bethem and Frey, 1991*). The water levels and additional geophysical data disseminated by PORTS™ and at other key installations are monitored by CORMS, a monitoring system that operates on a 24 hour, seven day per week basis. The purpose of the monitoring is to provide quality control of the data, stop dissemination of questionable data, and to provide for the prompt repair of key sensors in critical harbor locations (*Gill et al, 1997; Reilly et al, 1998*).

Tsunami Warning System

Data for tsunami warning and research is delivered by random transmissions, triggered by the water level measurements. The GOES satellite has an emergency report mode of operation, and the Sutron 9000 has been configured for this mode. This modification augments NGWLMS capabilities to meet the NWS Tsunami Warning Program needs and NOAA's Office of Oceanic and Atmospheric Research (OAR) Pacific Marine Environmental Laboratory (PMEL) Tsunami Research program needs. The NWS/PMEL cooperative program receives emergency reporting of water level data by the GOES event-triggered, random report capability. The trigger is water level rate of change in excess of a threshold value. The modifications include on site storage in the NGWLMS primary system of more than 20 days of 1 minute water level data, accessible by telephone. Further on site storage is provided in the NGWLMS backup system for more than 5 days of 15 second water level data on removable RAM-Pack. These modifications are installed at 40 sites.

Storm Surge Warnings

Similar modifications used by the Tsunami Warning System have been made to the field unit to support the NWS Storm Surge Warning Program, especially on the east coast. Random satellite messages can be either manually triggered via phone call or automatically triggered by pre-configured limits and rate-of-changes being exceeded when a storm approaches the coast. The random messages are received in headquarters and the near real-time high rate data decoded, and predicted verses observed data become part of the NWS AFOS/AWIPS bulletins and are also disseminated using a Web site named "Tides Online" *(Burton, 2000)*

D. Internet

NOS maintains a World Wide Web site , http://nos.noaa.gov, which allows users to have direct access to NOS database holdings, as well as the ability to order selected specific products available from NOS. CO-OPS also maintains a web site, http://co-ops.nos.noaa.gov, where much of the historic and near-real-time data collected, analyzed, and disseminated by CO-OPS are made available. The CO-OPS home page provides direct access to the CO-OPS database and gives external users a wide range of choices of water level and environmental data. For example, data from CO-OPS water level stations are available directly from the web site. Historic monthly means, hourly heights, highs and lows, six minute water level data, six months of tide predictions for primary stations, and tidal datum information for NOS water level stations are available. Oceanographic and meteorological data such as wind speed, directions and gust, air and water temperature, and barometric pressure are available for selected sites. The web site also allows users to access and download bench mark descriptions and elevations for over 1700 NOS water level stations from all U.S. coastal states, view and/or download a list of stations for which data are available, access some CO-OPS documents and reports, and submit comments. An additional feature of the CO-OPS web site is the Tides Online feature which provides high rate near-real-time predicted and observed tidal information and meteorological data during storm events for those stations triggered by the event.

Also featured on the CO-OPS web site are selected data and plots from the PORTS™ program. PORTS™ provides data such as water levels, currents, and other oceanographic and meteorological data from bays and harbors through the Internet, as well as by telephone. Data are available for the following PORTS sites: Tampa Bay, San Francisco Bay, New York/New Jersey Harbor, Houston/Galveston, and Chesapeake Bay.

NOS also maintains the MapFinder which is a one-stop web site that provides direct Internet access to primary NOS imagery and data holdings for coastal photography, nautical charts, coastal survey maps, environmental sensitivity index maps, hydrographic surveys, water level stations, and geodetic control points. NOS MapFinder provides a spatial index that allows users to identify specific NOS products. Many of these are online as directly usable products that can be ordered from NOS. Water Level Station information from NWLON is also available through the MapFinder. As mentioned earlier, water level data are also available on the CO-OPS section of the web site. Descriptions of the entire active continuous network of stations are available from the MapFinder.

7. APPLICATIONS OF TIDAL DATUMS

Significance of Datums in Modern Applications

For marine applications, tidal datums are the reference planes from which measurements of height and depth are made (*Hicks, 1985*), and from which marine boundaries are determined. However, since the sea surface moves up and down in time intervals from seconds to geological time, and in height from less than a millimeter to over 100 meters, this reference surface must be mathematically defined. When the sea surface is mathematically defined by a statistical averaging of the observed values of a particular phase of the tidal cycle (e.g., MLLW), it is called a tidal datum.

As discussed in Chapter 4, these tidal datums are based on water level observations from a water level measurement system, and transferred to land by differential leveling between the tide measurement system and local bench marks. The bench marks serve to preserve the tidal datum elevations in case the measurement systems are removed, to maintain the station reference "zero" for NWLON stations, and to be used by surveyors and engineers as vertical reference points. The following is a discussion of traditional and emerging applications of tidal datums.

A. Application to Hydrographic Surveys and Mapping Programs

Depths on Nautical Charts

The depths on nautical charts in U.S. coastal waters are referenced to MLLW. On a nautical chart, MLLW is called chart datum. The reference base of the heights of structures on nautical charts (e.g, bridge clearances) is MHW. Wrecks, obstructions, and navigational hazards are charted in depths below MLLW (see figure 18).

MLLW, the lowest tidal datum computed by NOS from observed values, is used as the reference plane to refer depths because of the practical advantages afforded to pilots (e.g., *Shalowitz, 1962; NOS Hydrographic Manual, 1976*). Using MLLW provides pilots with a margin of safety consistent with average meteorological conditions. At the lower low water phase of the tidal cycle, the depths in a navigation channel are at a minimum. Thus, at lower low water, the pilot is able to ascertain if the draft of the vessel approaches the minimum depth in a navigation channel. Using MLLW complements the dredging operations used by the USACE to maintain and chart the navigation channels.

Hydrographic Surveys

The purpose of a hydrographic survey is to determine the topography of the ocean floor and to locate and describe all hazards and aids to navigation. Horizontally, surveys are referenced to the North American Datum of 1983 (NAD 83) via measurements from GPS. Vertically, they are referenced to a tidal datum. Note that while GPS is based on the Department of Defense (DOD) adopted standard of the World Geodetic System (WGS 84), NAD 83 is the official horizontal datum of the United States.

TIDES-SUPPORT TO NAUTICAL CHARTING HYDROGRAPHY APPLICATIONS

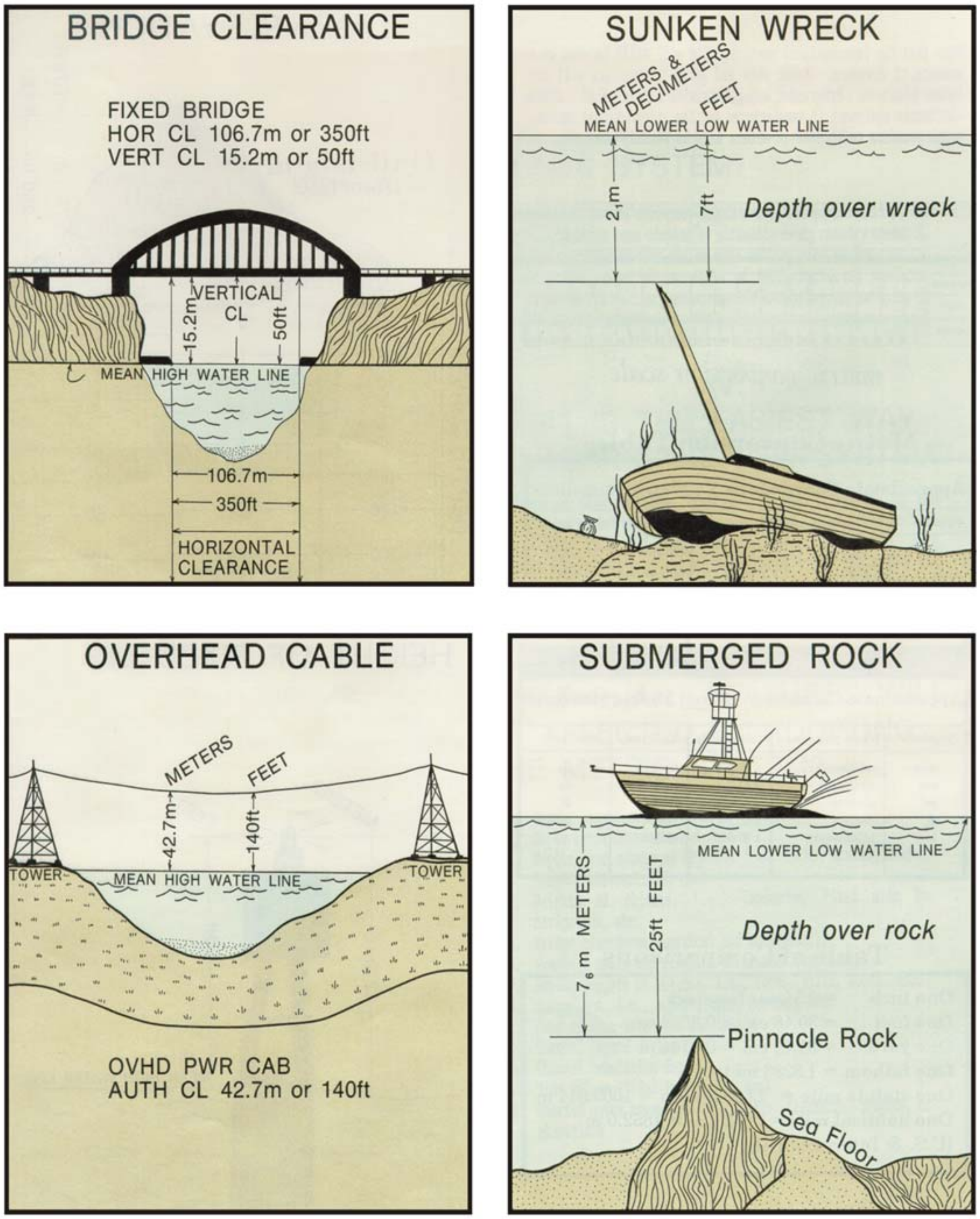


Figure 18. Applications of tidal datum references to nautical charting.

In hydrographic survey operations, *in situ* water level observations are required to reduce the soundings to chart datum, MLLW. Each sounding that the ship makes is corrected for its vertical and horizontal position at the time of the measurement. Corrected depths are depths of the water relative to chart datum (*NOS Hydrographic Manual, 1976*). Detailed specifications and deliverables for tides and water levels are found in the NOS Hydrographic Surveys Specifications and Deliverables (*NOAA, 2000*) document. The document expresses hydrographic sounding error budget considerations for the estimated allowable error contribution from all sources, including water level measurement error, tidal datum computation error, and error in the application of tidal zoning. The accurate computation of tidal datums at short-term stations installed during hydrographic surveys is a key ingredient to applying accurate tide reducers to each sounding.

Tidal zoning is the interpolation or extrapolation of a tide curve relative to MLLW away from a known observational point on the shore. NOS presently uses discrete geographical zones using MapInfo Geographical Information System (GIS) to estimate tides in the middle of estuaries or offshore on the continental shelf for hydrographic survey applications. NOS is conducting applied research into new methodologies for the necessary tide corrections using interpolation of tidal constituent amplitudes and phases and interpolation of residuals (*Hess et al, 1999*).

NOS is also investigating the use of RTK GPS for providing vertical control and reduction of soundings to chart datum during hydrographic survey operations. USACE has also started implementing the use of GPS for vertical control in their dredging operations and hydrographic surveys of dredged channels (*Deloach, 1995*).

Shoreline Mapping

Tidal datums are required by NOS for conducting shoreline mapping. MHW is the NOS defined shoreline on nautical charts (*Hicks, 1981*). However, given the uncertainty of this shoreline determination, NOS nautical charts should not be used for resolving property disputes. Aerial photography taken at the stages of MHW and MLLW are used to delineate the shoreline at these stages on nautical charts (see figure 19). The photographs taken at MLLW are used to delineate the State Submerged Lands, Territorial Sea, and Exclusive Economic Zone on NOS charts, T-sheets, and other output products. The delineation of marine wrecks and other navigational hazards are made at MLLW. The majority of these aerial surveys use predicted tide heights. However, in some surveys, the actual water level is used at the time of the photograph.

Two acts, the Rivers and Harbors Act and the Federal Water Pollution Control Act, give USACE and EPA jurisdiction in the Coastal Zone, respectively. Tidal datums are used to determine each agency's area of regulation, enforcement, and jurisdiction.

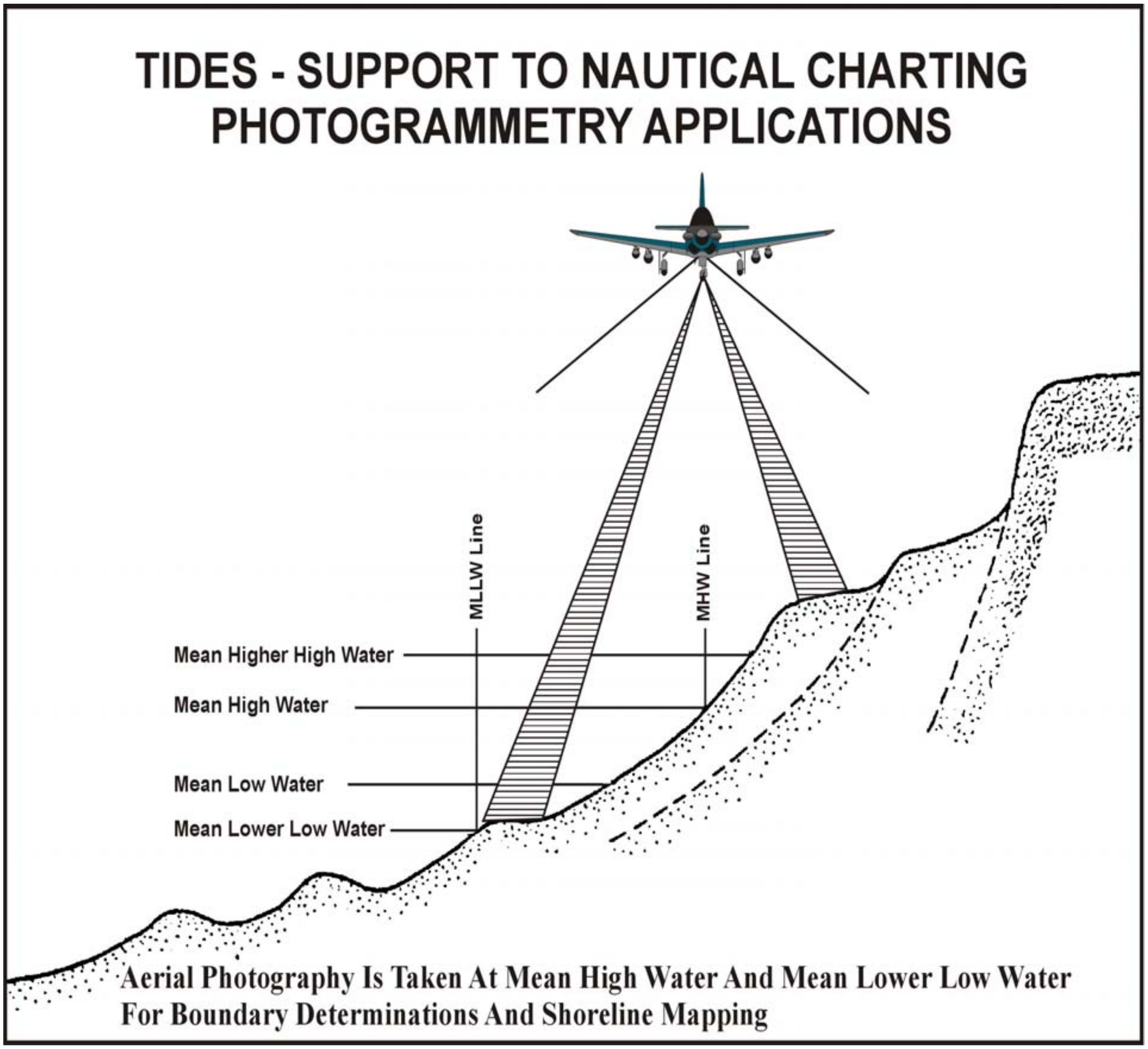


Figure 19. Applications of tidal datums to remote sensing for shoreline mapping.

B. Navigation

Mariners navigating coastal waters are expected to consider local tide and tidal current predictions, sea-state, and predictions of marine weather. Scheduling of the vessel may be adjusted so that the estimated time of arrival coincides with the most favorable conditions. Information may be obtained from commercial publications based on NOS tide prediction products.

NOS publishes nautical charts of the waters of the U.S. and its territories (*Coastal Mapping Handbook, 1978*). The charts are produced by taking into account the basic hydrographic and water level data produced by NOS. In addition, nautical charts are the principle means by which data from other agencies are organized and disseminated to the mariner in a relevant manner. The full benefit of aids to navigation including improved channels and harbors, traffic separation schemes, and navigation regulations are obtained when organized on a nautical chart.

Nautical charts, in areas with slowly changing bathymetry, are revised every 4-12 years. More active areas may be revised every 2-3 years, and the most active areas, may be revised every 6 months. Charts are revised because of new aerial photographs of the region, field generated data on shoaling, dredging in channels, changes to visual or electronic aids to navigation, and natural or manmade changes to the shoreline or coastal structures.

The local nautical chart is the basis of decision-making in navigating a coastal region. On the nautical chart are printed the depths, tidal ranges, location of the dredged channels, obstructions and aids to navigation, and landmarks, which provide the visual information necessary for safe navigation and to determine location.

The predicted heights of the tides from the tide tables are referenced to chart datum on the local nautical charts, i.e., MLLW for U.S. Coastal waters. For foreign coasts, a datum approximating mean low water springs, Indian spring low water, or the lowest possible low water is generally used. In many countries, these datums are based on astronomical tide predictions, not observed water levels as is the practice of the U.S. The depression of the foreign datum below MSL is included in the Tide Tables. A new international chart datum has been proposed to be Lowest Astronomical Tide (LAT) which is defined as the elevation of the lowest predicted tide to occur over a 19-year period.

Since the depth of water on the nautical charts is referenced to MLLW, mariners use the height of the predicted tide is added to the depth shown on the chart to determine the predicted total water depth. If the sign of the predicted height is positive, it should be added to the charted depth; if the sign of the predicted height is negative, it should be subtracted from the charted depth. Use of MLLW in the U.S. is a conservative local reference plane at the lower low water phase of the tide to ensure that the depth of the water will at least approximately be the depth printed on the nautical chart.

Changes in sea level in the coastal zone are due not only to tides, but also to winds, barometric pressure, and freshets from river outflow. Onshore winds or low barometric pressure will cause the water level to be higher than the predicted tide, while offshore winds or high barometric pressure depresses sea level relative to the predicted tides. Freshets or drought conditions may cause height variations of more than plus or minus a foot, respectively, compared to the predicted tides.

The PORTS™ is an NOS program that provides real-time water level, wind speed and direction, current, water and air temperature data to vessels in the estuaries or harbors of San Francisco, New York/New Jersey, Houston/Galveston, Tampa Bay, and Chesapeake Bay. These variables provide detailed and local environmental conditions. Data quality assurance and control are exerted on the environmental sensors in PORTS™ (*Mero, 1998*). The CO-OPS program, CORMS, is a mechanism to monitor real-time data disseminated to the public on a 24 hour per day basis. If the data is valid as determined by CORMS personnel, it is disseminated to the public via the Internet (*Reilly et al, 1998*). Otherwise, data is withheld, and if necessary, sensor maintenance is performed (*e.g., Gill* *et al., 1997)*. A key to the correct application of real-time data is the knowledge of the MLLW reference. Without accurate knowledge of the tidal datum, the real-time water levels would have no practical meaning for real-time navigation users. As in traditional NOS tide prediction products, all PORTS™ water level information is disseminated (Internet text or graphic, or voice) referenced to MLLW.

Amphibious landings and exercises, as well as other coastal operations conducted by the military, require similar tidal information. NOS bathymetric data, nautical charts, and tidal predictions are utilized by the U.S. Army, Marine Corps, Navy and the U.S. Coast Guard (USCG) for planning and conducting these operations. NOS bathymetry and tidal predictions (or tidal constituents from which predictions are made) referenced to tidal datums, are incorporated into several military guides and decision aids. Applications include: determining clearances for landing craft, determining beach widths, operating wave and surf models that consider tidal effects on these important parameters, and taking advantage of total knowledge for efficient supply transfer from ships offshore over the beach.

C. Marine Boundaries

Although NOS is not responsible for the establishment of marine and coastal boundaries, it is required to provide the tidal datums necessary to support these boundaries *(Hull and Thurlow*). Chart datum, MLLW, is the elevation of the baseline for many marine boundaries, including most which are recognized by the United Nations Convention on the Law of the Sea (*U.S. Department of State Dispatch, 1995*). However, baselines may differ in position for the purposes of different statutes. The baselines (see Figure 17) usually consist of points or line segments on these tidal datum lines from which the marine boundaries are measured and constructed (e.g., *Shalowitz, 1962; Hull and Thurlow*).

The marine boundaries of the U.S. are:

1. Private U.S. property exists in most cases landward of MHW.

2. State-owned Tidelands exist between MHW and MLW in most cases. Refer to Fig. 18 for individual cases. U.S. Inland Waters are concurrently defined to exist between MHW and MLW for the purpose of marine navigation.

3. The State's Submerged Lands Boundary extends seaward 3 nautical miles from MLW, except for Texas and the Gulf coast of Florida where it terminates at 9 nautical miles. In this band, plus the state-owned tidelands, the states exercise the Public Trust Doctrine, subject to federal supremacy (*Putting the Public Trust Doctrine to Work, 1997*).

4. The Territorial Sea Boundary extends 12 nautical miles seaward of MLLW. It is also known as the Marginal Sea, Marine Belt, Maritime Belt, 12-Mile Limit, and Adjacent Sea Boundary. Historically, this boundary was 3 nautical miles; it was changed to its present 12 mile limit in 1988 (*U.S. Department of State Dispatch, 1995*). In the Territorial Sea, the sovereignty of the nation extends to the airspace above, the subsoil, the water, and the resources.

5. The Contiguous Zone Boundary occurs at 12 nautical miles from MLLW. In the U.S., the Territorial Sea and Contiguous Zone are coterminous (*U.S. Department of State Dispatch, 1995*). In the contiguous zone, the nation may exercise rights to protect its interests, but does not exert sovereign control. The main purpose of the contiguous zone is to exert control over shipping near a nation's coast. Referring to Fig. 20, under the United Nations Convention on the Law of the Sea, a coastal nation may declare a Contiguous Zone between 12 and 24 nautical miles.

6. The 200-mile Fishery Conservation Zone extends seaward from MLLW (*Hull and Thurlow*).

7. The Presidential Proclamation 5030 of March 1983, established the (EEZ), which claimed rights to living and mineral resources and jurisdiction of approximately 3.9 billion acres. The baseline for demarcation of the EEZ is the MLLW boundary of the Territorial Sea and extends 200 nautical miles. It should be noted that different coastal nations have different definitions of their ordinary low water. These definitions are not usually consistent with NOS definitions.

The Mean High Water Line (MHWL) is the coastal boundary between private and state property with the following exceptions (e.g.*, Shalowitz, 1962; Maloney and Ausness, 1974*):

1. Maine, New Hampshire, Massachusetts, Pennsylvania, Delaware, Virginia, and Georgia use the Mean Low Water Line (MLWL).

2. Texas uses the Mean Higher High Water Line (MHHWL) when Spanish or Mexican grants are involved.

3. Louisiana has adopted the civil law boundary of the line of highest winter tide.

4. In Hawaii, the upland owner has title to the upper reaches of the wash of the waves.

Figure 20 illustrates the marine boundaries that are allowed by the United Nations Convention on the Law of the Sea (*U.S. Department of State Dispatch, 1995*). Figure 17 illustrates the application of the federal and state boundaries to the coastlines of the United States.

In order to map tidal boundaries such as MHWL or MLWL (e.g., *Shalowitz, 1962; Hull and Thurlow, 1981*), and determine the latitude and longitude coordinates of their intersection with the coast, the surveyor performs the following basic procedures:

1. Obtain the published bench mark information at or near the location.

2. Find the tidal bench marks and run a closed line or loop of differential levels from the bench marks to that part of the shore where the boundary is to be located, run levels along the shoreline, and mark or stake points at intervals along the shore in such a manner that the ground at each point is at the elevation of the tidal datum.

3. If the boundary is to be mapped, the horizontal distances and directions, or bearings, between each of these points and between those points or features in the area, and between the points and the horizontal control stations are measured so that the boundary may be plotted on a plat or map to the exact scale ratio and in true relation to other boundaries.

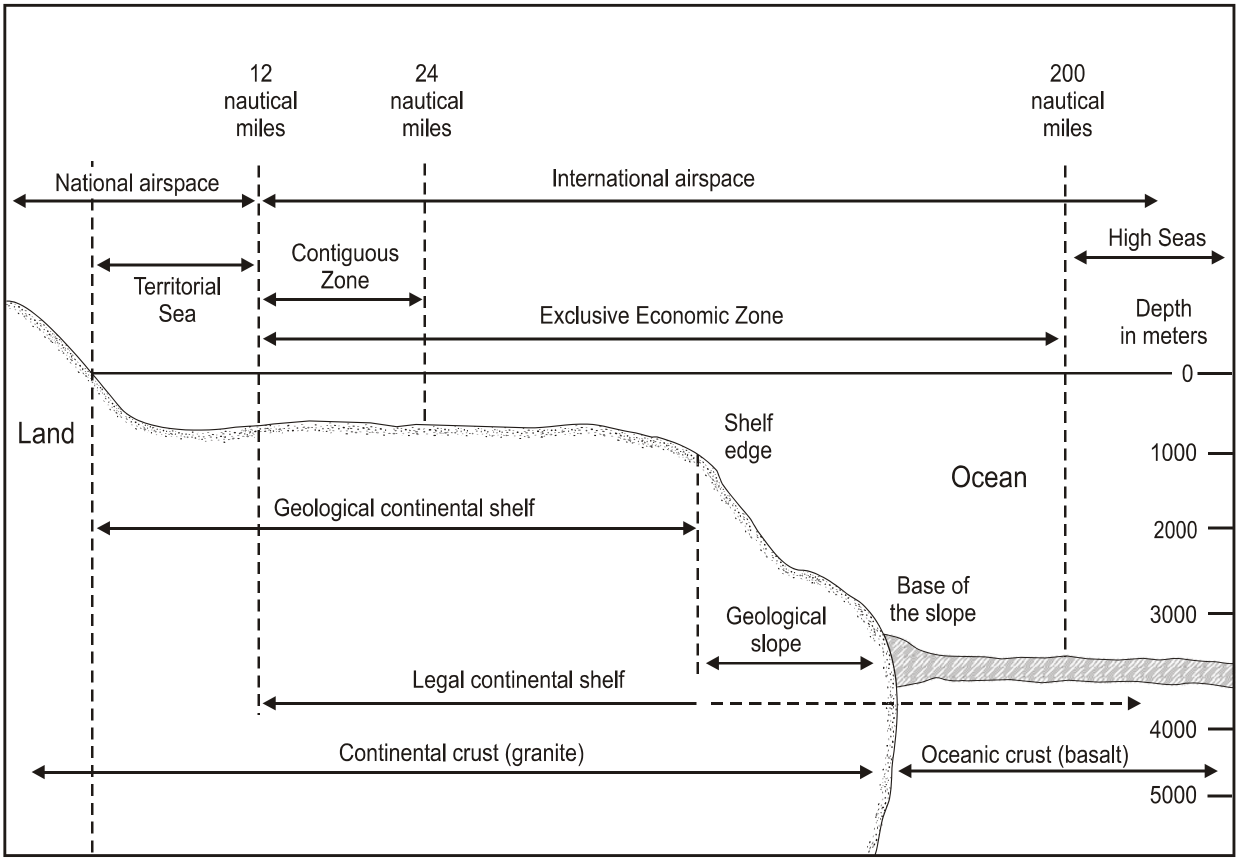


Figure 20. The marine boundaries allowed under the united Nations convention on the law of the Sea. The landward edge of the Territorial sea in the U.S. is the MLLW line (0 depth).

D. Sea Level

Estimates of Sea Level Change

The relative secular sea level change is readily seen (Figure 21) when the yearly mean sea level is plotted against time. For datum computation, the NTDE is used as the fixed period of time for determining 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 (Figures 22 and 23). Thus, a new NTDE must be considered periodically (*Hicks, 1980*). NOS is reviewing the long-term sea level changes and potential elevation changes to tidal datums across the NWLON and will soon be updating to a new NTDE (*Gill, 1998*).

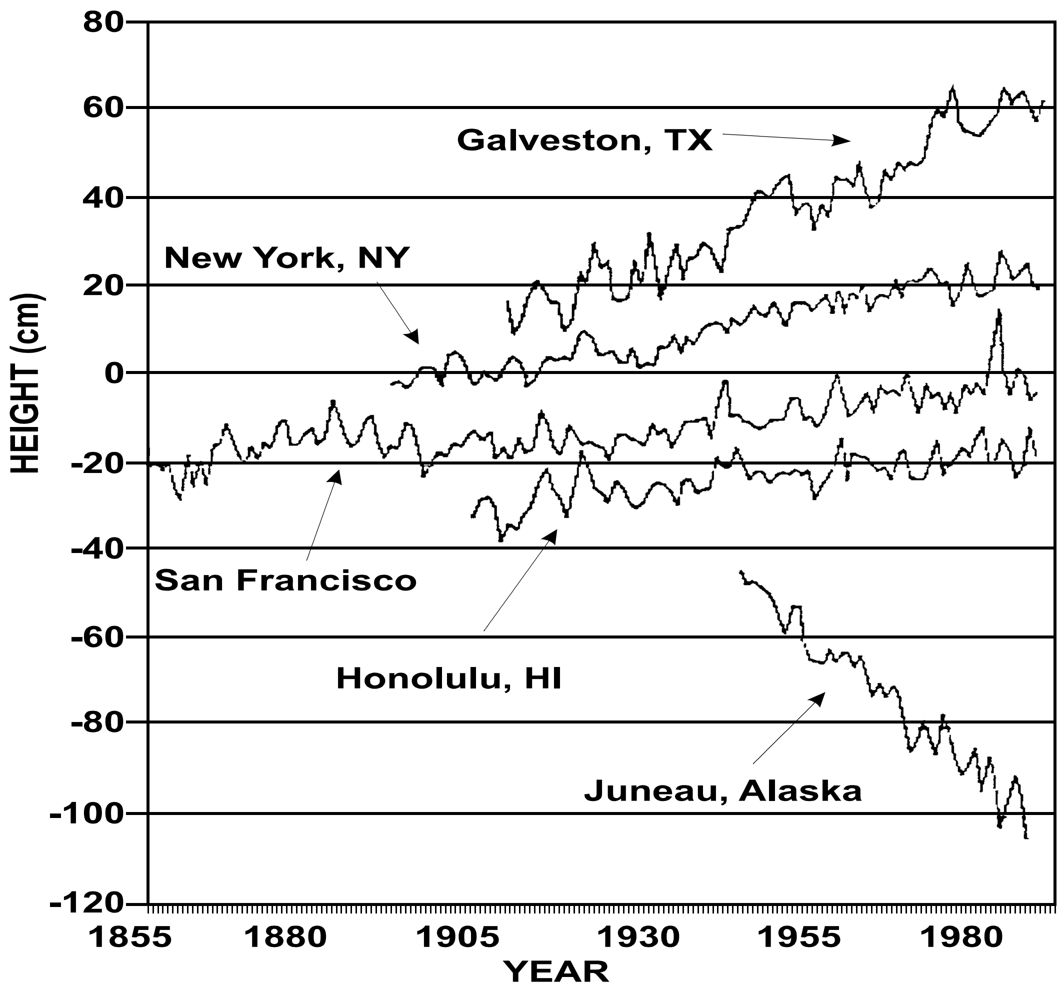


Figure 21. Relative sea level change at several locations in the U.S.

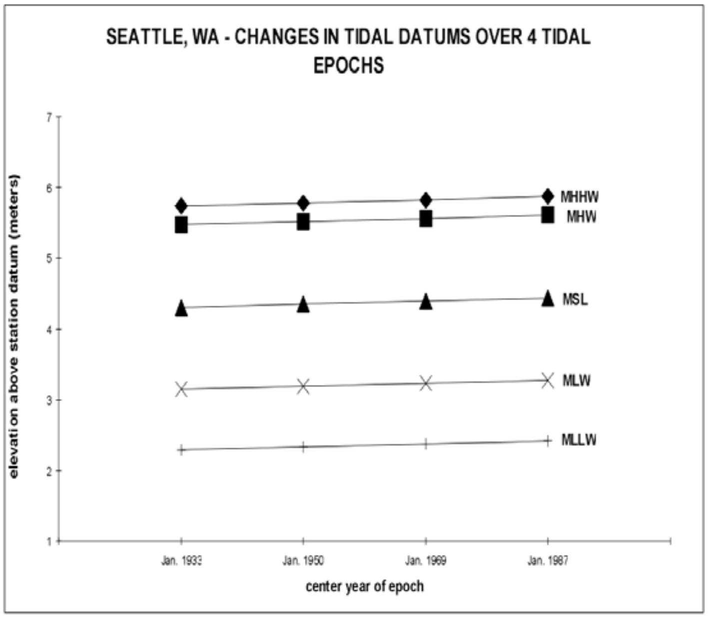


Figure 22. The change in the values of the principle tidal datums over four epochs at Seattle, WA. This represents a case where isostatic rebound nearly balances relative sea level rise.

NOS publishes relative sea level trends from stations in the NWLON (see http//co-ops.nos.noaa.gov under "publications") for both the entire series lengths and for a common period 1950-1993 for comparative purposes (see also *Lyles et al, 1988*). These sea level trends estimate the rate of change in sea level relative to the local land at each tide station. They are "relative" trends and are made possible by the routine quality assurance of the data, the careful routine surveying of the tide gauges to the local bench mark networks, and the monitoring of the vertical stability of individual bench marks and the tide gauge structures. By themselves, the trends provide no information as to what causes their magnitudes.

Relative secular sea level changes are composed primarily of two components; one is vertical land movement, the second is changes in the global water balance. Vertical land movement may be due to earthquakes, subsidence (downward) caused by the removal of oil or water or marsh compaction, glacial isostatic rebound (upward) caused by the melting of the glaciers from the last ice age of approximately 11,000 years ago, or by plate tectonics. The global water balance is influenced to the degree that water is either stored in or melting from polar ice caps, the Greenland ice sheet, and glaciers; stored in groundwater aquifers, lakes, and reservoirs; or changing in volume due to ocean thermohaline changes. In addition, there are long-term effects of the changes in the sizes of the ocean basins themselves due to crustal deformation. (*NRC, 1990*).

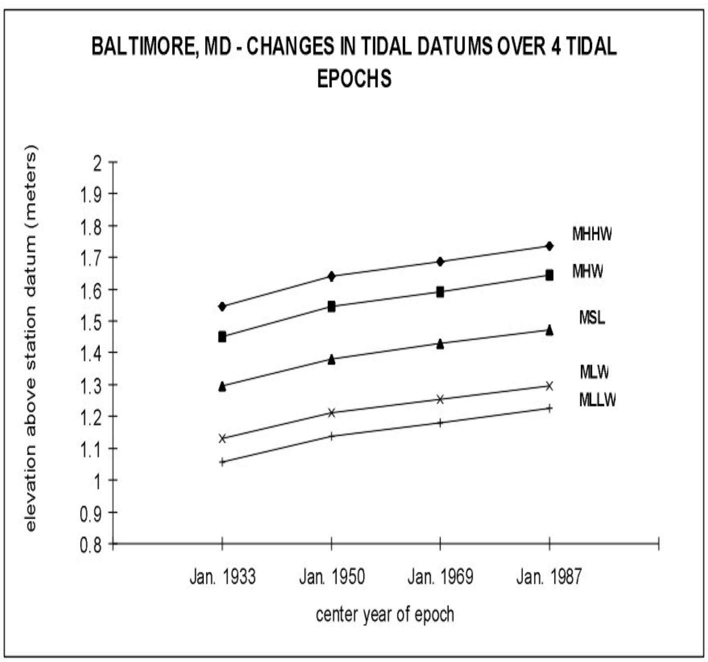


Figure 23. The change in the values of the principle tidal datums over four epochs at Baltimore. This represents a case where subsidence and relative sea level change require re-calculation of the tidal datums for the most recent epoch.

The vertical land movement component is known to dominate the relative sea level variations at many locations. For instance, at Skagway, Alaska, relative sea level is falling approximately 160 cm per century due to post glacial rebound of the land. At Grand Isle, Louisiana, relative sea level is rising at approximately 110 cm per century due to compaction of sediments and oil withdrawal in the Mississippi River delta region. Similarly, in the Galveston Bay, Texas region, the tide station record at Galveston indicates the relative sea level is rising at 75 cm per century.

Much of the active research in sea level analyses has been focused on the worldwide long- term tide gauge records and trying to determine what they can tell us about global sea level change. Various selection criteria and the use of post-glacial rebound models have been applied to the tide station data to attempt to take out the record the vertical land movement component so that the remaining signal would indicate true changes in global water balance (*Douglas, 1991 and 1992*). Current estimates of global sea level rise are between 10 cm and 20 cm per century (*Douglas, 1991 and 1992; Pilkey, 1981; NRC, 1990*).

The long-term effects of sea level rise are difficult to assess. For example, the present rate of 20 cm per century sea level change could result in a horizontal retreat of the shoreline of 500 to 1500 ft in the next 100 years over some stretches of the U.S. Coast. On East and Gulf Coast beaches, relative sea level rise is accompanied by lateral shoreline retreat orders of magnitude greater than the vertical rise in sea level because of the gentle slope of the coastal plain's surface. The extent to which shoreline retreat occurs is a function of the slope of the shore in low-lying areas. Cliffed shorelines retreat in catastrophic jumps. The evolution of coastal geomorphology is evident in the historical nautical charts of NOS, suggesting the erosional character of much of the U.S. shoreline, although the nautical charts should not be solely relied upon as proof.

E. Coastal Engineering

High water datums (such as MHW, MHHW) are applied to engineering design and construction of coastal structures such as seaports, harbors, navigation channels, turning basins, docking areas, bulkheads, sea walls, revetments, beach nourishment, breakwaters, offshore islands and platforms.

Carefully formulated design considerations, methodologies, and example problems are provided in the *U.S. Army Coastal Engineering Research Center Shore Protection Manual Vols. I-III (1998)*. The USACE also maintains a library of computer programs to assist in designing structures in the ocean environment, and distributes scientific and engineering guidance in *Coastal Engineering Technical Notes (1979-present)*. The USACE has historically contributed to applies research for the application of tidal datums to coastal engineering (see *Harris, 1981 and Harris, 1966*).

Coastal engineering begins with a thorough description and understanding of the marine environment at the site of the proposed construction. The physical environment requires detailed knowledge of the site location and conditions, bathymetry, and knowledge of water levels and currents. Wave conditions generated locally by the wind and swell, as well as the modification of waves by shoaling and refraction are considered. These shallow water wave modifications are often based on NOS bathymetric data and charts with consideration of tidal variations. Waves generated by extreme events such as hurricanes or tsunamis are often of importance. When currents are determined, such as for sediment transport calculations or to calculate current forces on structures, NOS bathymetric data, charts, and tidal characteristics may be considered, especially if numerical circulation models are used. The design height of most coastal and ocean structures requires knowledge of the height of MLLW combined with the height of the astronomical tide, storm surge, and waves. The height of the highest and lowest observed tides relative to the engineering project datum are also valuable parameters.

The change in relative mean sea level may require that coastal engineers factor in effects of long-term sea level rise. Sea level change generally leads to increased erosion and wave-overtopping, both factors contributing to failure of a structure. Sea level change may be accounted for in two ways. The first is to build the structure with the projected sea level change as a design consideration. The second is to build the structure less expensively, and to factor in the future cost of structure modification as required (*NRC, 1987*).

F. Warnings and Hazard Mitigation

Tsunamis

Many stations in the NWLON in the Pacific are part of the Tsunami Warning Program (*NOS, 1983*). A tsunami wave is an ocean wave caused by an underwater earthquake, submarine landslide, or underwater volcano. In the open ocean a tsunami wave is about 100 miles long, a few feet high, and travels about 600 miles per hour. The speed of a tsunami is related to the depth of the ocean. When it approaches the shore, a tsunami's speed decreases, its length decreases, and its height increases. High tsunamis threaten lives and property in the coastal zone. A tsunami alert is first established through the seismographic network, mainly operated by the USGS. If an event is detected which could cause a tsunami, the tide gauges of the NWLON are monitored. Since tsunamis travel at predictable speeds, arrival times can be determined throughout the Pacific.

Tsunamis affect the entire Pacific Ocean. Tsunamis may also effect the Atlantic, however, the generally greater tectonic activity of the Pacific Basin makes the occurrence of tsunamis greater in the Pacific. According to the Alaska Tsunami Warning Center (ATWC) web site, http://www.alaska.net/~atwc/, tsunamis can travel across the Pacific in less than a day. A tsunami propagating from a nearby generation area may rise to height of over 30 m (100 ft), whereas a tsunami propagating from a distant generation area may rise to a height of 15 m (50 ft). Tsunamis of local origin may give communities only a few minutes to respond. More distant tsunamis increase the length of the warning time, but also increase the probability of a costly false alarm. The height of the tide may affect the severity of the tsunami.

Responding to the potential for natural disaster posed by tsunamis has caused elaborate interagency and international cooperative agreements. In the U.S., the interagency coordination includes NOAA's NOS and NWS, the USGS, and the Federal Emergency Management Agency (FEMA). NOS provides the water level data and tidal datums to measure the inundation parameters. NWS disseminates the warnings. USGS provides the seismic network to detect the tectonic disturbance. FEMA responds to the natural disasters caused by the flooding. On an international level, the International Tsunami Information Center (ITIC), located in Honolulu, Hawaii, coordinates dissemination of warnings and humanitarian aid. The 25 member nations are: Australia, Canada, Chile, China, Columbia, Cook Islands, Costa Rica, Democratic People's Republic of Korea, Ecuador, Fiji, France, Guatemala, Indonesia, Japan, Mexico, New Zealand, Nicaragua, Peru, Phillippines, Republic of Korea, Russian Federation, Singapore, Thailand, United States, and Western Samoa.

For the U.S., chart datum, MLLW, is the reference level to which the runup of the tsunami is measured, http://www.alaska.net/~atwc. Runup is defined as the maximum *height* of the water onshore observed above a reference sea level, usually measured at the horizontal inundation limit. The horizontal inundation limit is defined as the inland limit of wetting measured horizontally from the edge of the coast defined by mean sea level. In contrast, the horizontal inundation distance is defined as the distance that a tsunami wave penetrates onto the shore, measured horizontally from the mean sea level position of the water's edge. This distance is usually measured as the maximum distance for a particular segment of the coast. Inundation is defined as the depth, relative to a stated reference level, to which a particular location is covered by water.

Storm Surges

A storm surge (Figures 24 and 25) results from winds and reduced pressure in a hurricane, or a severe extra-tropical storm, (i.e., low-pressure system) traveling near the coast. By the inverse barometer effect, the elevation of the sea surface is raised by about one or two feet, and measures about 50 miles across (*e.g., Frazier, 1979*). Like the tsunami, as this dome of water approaches the shallow water of the coast, its amplitude increases. Added to the storm surge are the waves due to the onshore winds of the hurricane, plus the astronomical tides. During a storm surge event, the surge and high waves cause injury and death, property damage, damage to structures, avulsion, and erosion. In fact, during powerful northeasters, the NWLON stations, their instruments, stilling wells, protective wells, and piers may suffer varying degrees of damage. The surge may also propagate into estuaries and rivers, causing high waters and associated flooding inland.

One hundred and fifty-six NWLON stations are connected to the NWS' local forecast offices. Data are transmitted from the platform over the GOES satellite and then disseminated to NWS regional offices via the NWS Automation of Field Operations and Services (AFOS). In a non-storm event mode, data from all 156 stations are transmitted every hour. A new feature allows Internet access of event-triggered high rate GOES satellite data during storm events. NWS and CO-OPS web site users can obtain real-time graphical data of predicted and preliminary observed tides and meteorological parameters from stations where they are installed. CO-OPS provides a suite of automated products to NWS from the NWLON and from PORTS™ (*Burton, 2000).*

For simplicity, storm surge can be defined as the difference between the measured water levels and the elevation of the astronomically predicted tide. In most tidal areas, the maximum height reached by the storm surge is affected by the phase of the tide at the time of the surge and the stand of local mean sea level for that time of year. Spring tides may contribute to the overall damage and flooding effects of storms, while neap tides generally, though not always, tend to reduce the severeness. NOS publishes technical reports of damaging storms. Examples are given by *Deitemyer (1993)* and *Zervas et al , 2000.* The information included is date, time, and height of the maximum available water level above MLLW, MHHW, and National Geodetic Vertical Datum (NGVD 1929); the date and height of the maximum historical water above MLLW. These datums are referenced to the 1960-1978 epoch. About 5 hurricanes strike the United States coastline every 3 years. On average, of these five, two are major hurricanes measuring a category 3 or higher (defined as having winds above 111 miles per hour) on the Saffir-Simpson Scale. These storms may cause billions of dollars in damages because of the construction of hotels, marinas, piers, homes, roads, bridges, and other forms of infrastructure, at elevation levels 10-15 ft above MSL.

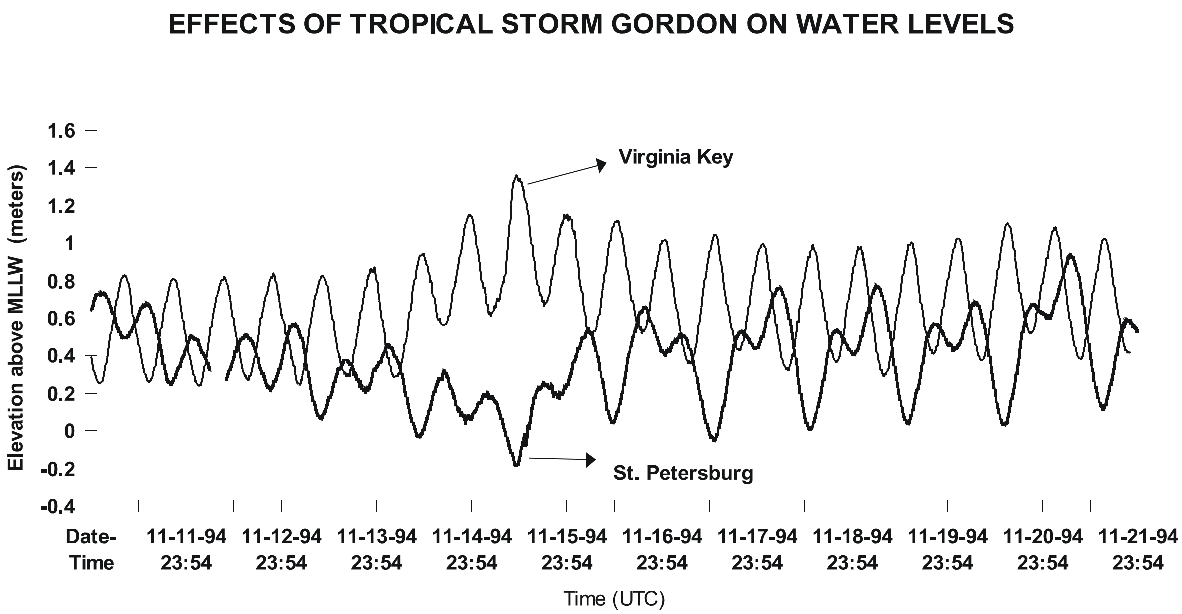


Figure 24. Elevated water levels due to the storm surge of tropical storm Gordon. In comparison to water levels at St. Petersburg, more pronounced effects are evident at Virginia Key.

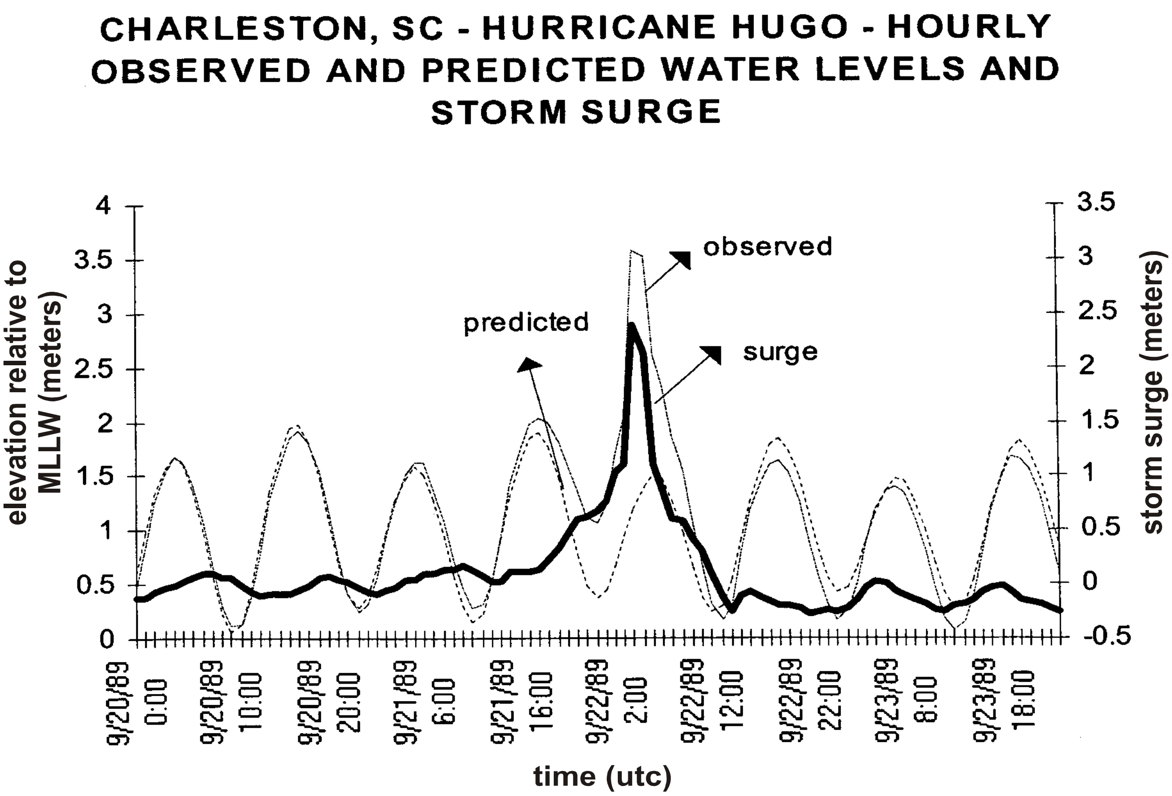


Figure 25. Observed, predicted, ans storm surge at Charleston, SC during hurricane Hugo.

Emergency Management

The warnings of natural disasters due to extreme oceanographic and meteorological events are the responsibility of NOAA's National Weather Service (NWS). The Internet address for near-real-time warnings is http://iwin.nws.noaa.gov/iwin/nationalwarnings.html. Hurricane, flood, special marine, winter storm, severe thunderstorm, flash flood, and tornado warnings are updated every minute. The web site provides nationwide coverage of all warnings applicable to the U.S.

Planning for and responding to natural disasters is mainly the responsibility of the FEMA. FEMA's National Flood Insurance Program (NFIP) has played a critical role in fostering and accelerating the principles of coastal flood management. Flood insurance is available to flood-prone communities through the NFIP, which is administered by FEMA. Prior to the NFIP, flood insurance was generally unavailable from the private sector and most states and local communities did not regulate flood plain development. Instead dependence was placed on the construction of flood control projects such as breakwaters and seawalls to reduce flood damage. Despite the expenditures of billions of dollars for these flood control projects, annual flood damages and disaster assistance costs were increasing at a rapid pace. In response to this worsening situation, Congress created the NFIP in 1968 to reduce flood losses and disaster relief cost by guiding future development away from flood hazard areas where practicable, requiring flood resistant design and construction, and transferring costs of losses to coastal occupants through flood insurance premiums.

According to FEMA, communities can reduce their vulnerability to hurricanes through the adoption and enforcement of wind- and flood-resistant building codes. Sound land-use planning can also ensure that structures are not built in the highest hazard areas. Simple construction techniques may also help. For example, coastal homes and businesses can be elevated to permit storm surges to pass under living and working spaces. The height of the structure should be above the base flood height (a flood height having a certain percent chance of being equaled or exceeded in a given year). The base flood is defined as the 100-year flood, and is the national basis of flood plain management and flood insurance (*FEMA, 1995*). Flood Insurance Studies (FIS) are studies to determine the risk of flood in a community. An FIS for a community may combine information from hydrologic and hydraulic studies, flood plain topographic surveys, information from flooded communities themselves, and statistical records of river, tsunami, and storm surge floods *(FEMA, 1996*). On the basis of the FIS, a Flood Insurance Rate Map (FIRM) is developed to outline on a USGS 7.5-minute quadrangle the spatial extent of flooded areas in the event of a base flood. These areas are called Special Flood Hazard Areas (SFHAs) (*FEMA, 1995*). The SFHAs are identified on the FIRM by the codes A, AE, AH, AO, AR, A1-30, A99, V, VE, and V1-30 (*FEMA, 1996*). The glossary that defines the significance of the these codes is found in *FEMA (1995)*. The horizontal datums that define FIRMS may be North American Datum (NAD 27), NAD 83, Puerto Rico, Old Hawaiian, or local. The vertical datum may be NGVD 29, North American Vertical Datum (NAVD 88), or local mean sea level.

Because of the inherent horizontal and vertical uncertainties associated with maps, FEMA urges that these FIRMS not be used for engineering studies, or for giving exact boundaries of SFHAs. FEMA (http://www.fema.gov) delivers a caveat that "users must apply considerable care and judgement in applying this product."

G. Modeling

Water levels, tides, storm surges, tsunamis, currents, temperature and salinity, and other physical, chemical and biological properties of the ocean-atmosphere-terrestrial system may be predicted by advanced hydrodynamical numerical models (*e.g., Hsueh, et al., 1997*). When hydrodynamical models are used to predict either tides, water levels, tsunamis or storm surges, the accuracy of their sea surface height fields are evaluated and calibrated by data obtained from NWLON stations and their international counterparts (*Schultz and Aikman, 1998; Le Provost et al., 1995; Gerritsen et al., 1995*). NOS bathymetric data and charts, referenced to tidal datums, also provide bottom depth and coastline boundaries for these models. Estuarine models have operational application to the navigation community especially in areas of low range of tide and significant contribution to water level variations due to weather. The models are capable of providing more accurate information on the forecasting of the actual water levels than traditional astronomical tide prediction products alone (*Bosley and Hess, 1997).*

NOAA's NWS is the lead civilian agency to develop and disseminate operational forecasts of marine weather. For the mariner, weather forecasts are essential. The chief variables are water level, current speed, water temperature and salinity, wind speed and direction, significant wave height, period and direction, air temperature, and visibility. In addition, special marine weather or severe oceanographic conditions due to hurricanes, storm surges and tsunamis are also publicly available. Forecasts for hurricanes or high seas are available over the Internet at http://www.nhc.noaa.gov. More standard marine forecasts including weather suitable for aviators are available from http://www.ncep.noaa.gov.

Emerging model areas for which vertical tidal and geodetic datums are important is in the topographic/bathymetric programs in numerical hydrodynamic models are run relative to specific tidal datums and geodetic datums. Important GIS applications for flooding, storm surge and other studies would result.

H. Other Vertical Datums and Their Relationship to Tidal Datums

When a position on the face of the earth is described accurately, it must be referenced in terms of latitude, longitude, and height, or three-dimensionally. This is accomplished by referencing positions in terms of vertical and horizontal datums. A geodetic or horizontal datum is a set of parameters defining a coordinate system, and a set of control points whose geometric relationships are known, either through measurement or calculation. Modern geodetic datums are defined with respect to the center of the Earth, while historical geodetic datums are defined with respect to fundamental points of the surface of the Earth.

Vertical datums allow determination of elevation or height. The zero surface to which elevations or heights are referred is called a vertical datum. Traditionally, surveyors and map makers have tried to simplify the task of determining elevation or height by using the average (or mean) sea level as the definition of zero elevation because the sea surface is available worldwide. However, for a local or regional area, there may be no tangible surface of the ocean from which to measure height. Therefore, some other reference must be used.

MSL is a close approximation to another surface, defined by gravity, called the geoid (Marmer, 1951). The geoid is the most accurate representation of the Earth's shape and the true zero surface for measuring elevations, just as geodetic datums are the true references used for determining latitude and longitude. The geoid is the shape the ocean surface would have if it were not in motion and only influenced by gravity. To actually measure the heights above or below the geoid surface is difficult. Where this surface is located is inferred by making gravity measurements and by modeling it mathematically. The geoid is not the same as MSL; however, for practical purposes, one assumes that at the coastline the geoid and the MSL surfaces are essentially the same (Marmer, 1951). Gravity varies because the mass of the Earth varies due to differences in topography and the density of underlying materials.

Mariners use a variety of techniques and equipment to measure heights. Because assumptions are made, there is no guarantee that each technique will produce the same height measurement. Although a map or chart may state that heights are referenced to MSL, height measurement systems may not give exactly equivalent results. Different applications need heights and elevations with respect to different zero surfaces.

In order to understand the differences in vertical measurements and their representation on maps and charts or on the display of a piece of equipment, it is necessary to understand the differences between the topographic surface, ellipsoidal surface, and the geoid. The topographic surface is simply the actual visible surface of the Earth. A flattened sphere, which is called a spheroid or an ellipsoid, is used to represent the geometric model of the Earth. The reference ellipsoid is a mathematical model which approximates the irregular shape of the geoid. As mentioned earlier, the geoid, which is approximated by MSL, is the zero surface as defined by the Earth's gravity. Many reference ellipsoids are in use which minimize differences between the geoid and the ellipsoid for individual countries or continents. The most accurate global ellipsoid is the World Geodetic System (WGS 84). The geoid deviates slightly from the simpler WGS 84 reference ellipsoid due to local variations in topography and density of the Earth. For most of the Earth, the deviation between the mean sea level, geoid and the WGS84 Datum is within ± 40 meters. As mentioned earlier, locations on the Earth's surface must be defined in terms of horizontal position and vertical elevation. Presently, positions shown on some USGS topographic quadrangle maps are specified relative to the NAD83, which was based on the global WGS 84 ellipsoid.

MSL, as defined by NOS, is the local mean sea level determined over a specific NDTE and should not be confused with the fixed datums of the National Geodetic Reference System, the NGVD 1929 (previously referred to as the Sea Level Datum of 1929), or the NAVD 88.

NGVD 1929 is a fixed datum adopted as a standard geodetic reference for heights. It was derived from a general adjustment of the first order leveling nets of the U.S. and Canada, in which MSL was held fixed based on observations at 26 stations in the U.S. and Canada. Numerous adjustments have been made to these leveling nets since originally established in 1929. NGVD 1929 is no longer maintained by NGS as the official geodetic reference datum for the U.S. and has been superceded by NAVD88.

The official vertical reference datum, NAVD 88, and International Great Lakes Datum of 1985 (IGLD 85) are both based upon a simultaneous, least-squares, minimum constraint adjustment of the Canadian-Mexican-U.S. leveling observations. The height above local mean sea level for the primary bench mark at Father Point/Rimouski, Quebec, Canada was held fixed as the single constraint.

These fixed geodetic datums (e.g., NGVD 1929 and NAVD 88) do not take into account the changing stands of sea level and because they represent a "best" fit over a broad area, their

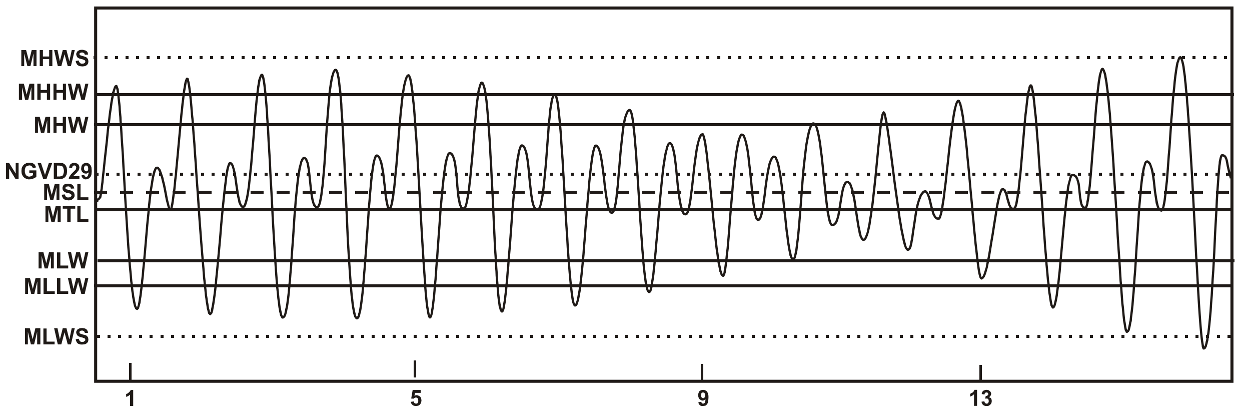


Figure 26. An illustration of the principal tidal datums and their relationship to the geodetic datum NGVD 1929 for a typical mixed tide curve.

relationship to local mean sea level differs from one location to another. Figure 26 illustrates the tidal datums with respect to a typical mixed tide curve. Mean High Water Springs (MHWS) is a tidal datum defined as the arithmetic mean of the high water heights occurring at the time of the spring tides during the NTDE. Mean Low Water Springs (MLWS) is a tidal datum defined as the arithmetic mean of the low water heights occurring at the time of the spring tides during the NTDE. Figure 27 illustrates how the elevation of the tidal datums change in relationship to the geodetic datums proceeding up a tidal river. The slopes of the changes in tidal datums relative to NAVD88, in this example, are highly dependent on changes in Mn. The illustration shows why tidal datums elevations, as well as their relationships to geodetic datums, should not be extrapolated too far from known locations without knowledge of the tidal characteristics of the estuary, bay, or river.

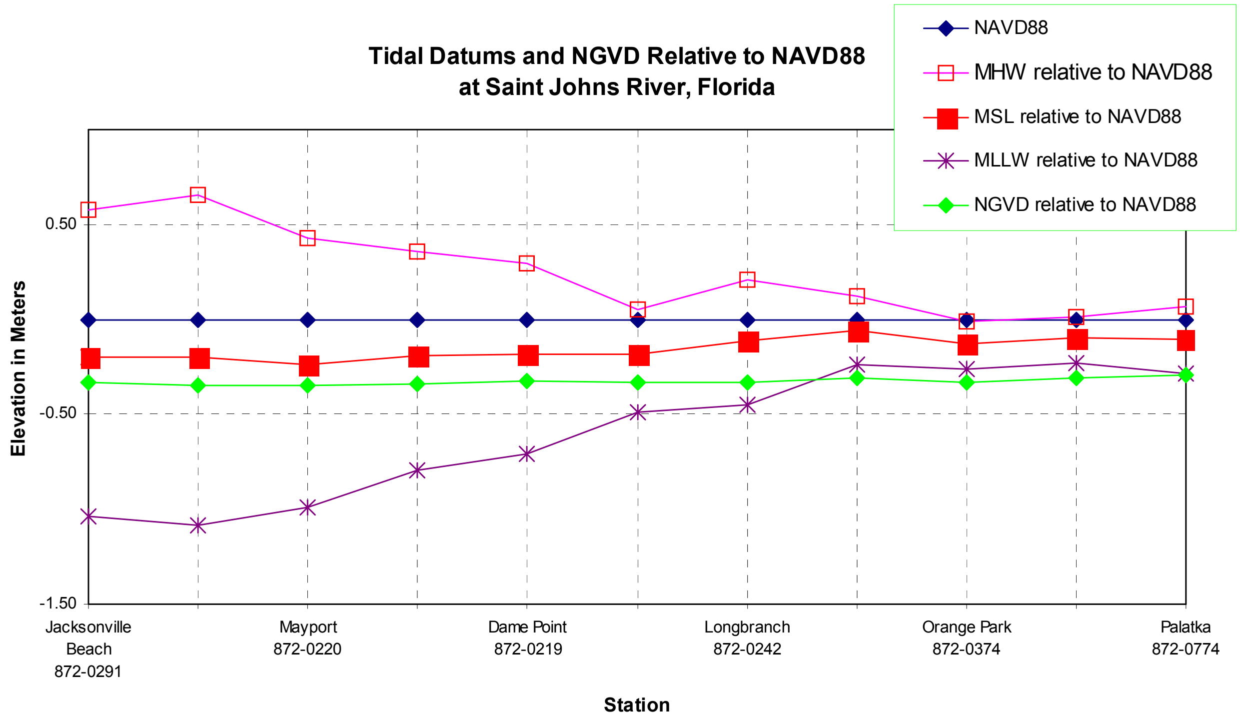


Figure 27. Tidal datums and geodetic datums for the St. Johns River**.**

Topographic Quadrangle Maps

The USGS is the lead civilian agency in data acquisition for elevation data of the land. This data is widely disseminated on USGS topographic maps. According to the USGS Web site, http://mapping.usgs.gov, the shoreline on USGS 7.5-minute quadrangle maps, and 7.5-minute Digital Electronic Models (DEMs) is defined as MHW. Typically, land elevations on USGS maps are referenced to NGVD 1929. Usually, NGVD 1929 is defined as the zero contour for elevations at MSL.

The 7.5-minute DEM is cast on a Universal Transverse Mercator (UTM) projection. These maps have a scale of 1:24,000. This means that 1 inch represents about 2000 ft, or 1 cm represents about 240 m. These elevation products have a root mean squared error (rmse) of 7 m as the desired vertical accuracy. The maximum error permitted is 15 m. According to USGS, an error due to a blunder of 50 m would be the absolute error tolerance in the vertical. On a 7.5-minute quadrangle, the purpose of the contours is primarily to indicate relief, and the contour interval is selected primarily to indicate spatial gradients in the vertical. Hence, accuracy is related to one-half of the contour interval. In the horizontal, 7.5-minute DEMs have a horizontal accuracy of 12.2 m (40 ft) for 90% of all horizontal points tested by USGS (*USGS Fact Sheet 078-96, 1997*). Accuracy testing occurs at several well-defined points in the 7.5-minute quadrangle, such as at the intersection of two roads, or a hill top. Since accuracy testing occurs throughout the quadrangle, this ensures that the elevation contours are internally consistent. The National Imagery and Mapping Agency (NIMA) provides as a rule-of-thumb that maps of this scale may have a horizontal error as large as 50 m (*NIMA, 1998*).

On a USGS topographic map, a water body is assigned a constant elevation (*USGS, Standards for Digital Elevation Models, 1997*). Oceans or estuaries at "mean sea level," are typically assigned an elevation value of zero (i.e., NGVD 1929). However, the geometry of the mapped water body is, in part, a function of the aerial photogrammetry at the time of the survey. In low-lying coastal areas of gentle slopes, water bodies have different sizes, depending on Mn and the time of the survey relative to the tidal phase. Water bodies that do not have a published elevation are assigned an interpolated elevation which does not exceed the highest contour that approximates the shoreline of the water body. Swamps and marshes that join major water bodies at a particular elevation are forced to the elevation of the water body. Note that NGVD 1929 is not equal to MSL, MHW, or nautical chart datum, MLLW. All other inland water bodies are assigned an elevation referenced to NGVD 1929.

I. Tidal Datums and GPS

The impact of GPS technology on geodetic control surveys has been immense (Leick, 1990). The heights obtained from GPS are in a different height system than those historically obtained with traditional geodetic leveling. In the past, line-of-sight instrumentation was relied on to develop horizontal and vertical coordinates. With GPS, ground station intervisibility is no longer required, and surveys can be performed with much longer lines. Also, different instruments and survey techniques were used to measure horizontal and vertical coordinates, leading to two different networks with little overlap. GPS, on the other hand, is a three-dimensional system.

Implementing the use of differential GPS (DGPS) technology and procedures has great potential for application to marine surveying and mapping and has strong linkages to tidal datums and their operational application (*Martin, 1999*). There are several distinct applications for using DGPS: 1) to support the development of a seamless, geocentric reference system for the acquisition, management, and archiving of NOS water level data which will provide a nationally and globally consistent digital database which will comply with the minimum geospatial metadata standards of the National Spatial Data Infrastructure and connect the NOS water level database to the NGS NSRS; 2) to establish transformation functions between chart datum (MLLW) and the geocentric reference system to support NOS 3-dimensional hydrographic surveys and the implementation of Electronic Chart Display and Information Systems (ECDIS). Integration of DGPS procedures into CO-OPS PORTS™ operations will ensure safe and efficient navigation and cost-effective water-bourne commerce; 3) to use DGPS-derived orthometric heights to support water level datum transfers; and 4) to use DGPS at NWLON stations to monitor crustal motions (horizontal and vertical) in support of global climate change investigations.

To meet the requirements of these applications, NOS is establishing field requirements for the following: 1) conducting static DGPS surveys on a minimum of one bench mark at all NWLON stations and connecting additional GPS-observable marks during the static survey using rapid static GPS procedures to verify bench mark stability with priority will be given to connecting to NSRS, particularly NAVD 88 bench marks; 2) conducting static DGPS surveys on a minimum of one bench mark at subordinate water level stations with an accepted MLLW value (on current official NTDE) and connect additional GPS-observable marks during the static survey using rapid static GPS procedures to verify bench mark stability with priority given to connecting to NSRS, particularly NAVD 88 bench marks; 3) conducting static DGPS surveys on a minimum of one bench mark at new temporary water level stations upon installation and connecting additional GPS-observable marks during the static survey using rapid static GPS procedures to verify bench mark stability with priority given to connecting to NSRS, particularly NAVD 88 bench marks; and 4) conducting static DGPS surveys at water level stations concurrently with the occupation of NAVD 88 marks to accomplish water level datum transfers using GPS-derived orthometric heights (*NGS 1997*).

GPS-derived orthometric heights can be accurately determined and used for water level datum transfers when following the established guidelines for 3-D precise relative positioning to measure ellipsoid heights, properly connecting to several NAVD 88 bench marks, and using the latest high-resolution modeled geoid heights for the area of interest. In many remote locations, the use of GPS-derived orthometric heights for datum transfer will be more efficient (timely) and more cost-effective than the use of conventional differential surveying techniques and may, under certain circumstances, preclude the installation of additional water level stations to establish a datum.

An ellipsoid height (h) is the distance from a point on the Earth's surface measured along a line perpendicular to a mathematically-defined reference ellipsoid. GPS is used to measure the ellipsoid height of a point relative to the reference ellipsoid, which presently is WGS84. WGS 84 is an earth-centered, earth-fixed coordinate system. See the Defense Mapping Agency (DMA) Technical Report, Department of Defense World Geodetic System 1984, DMA TR 8350.2 for a definition of WGS 84 and relationships with other geodetic systems. For the purpose of determining GPS-derived orthometric heights, WGS 84 and the NAD 83 are essentially the same datum. This is important to understand when choosing a geoid model for the orthometric height computation. An orthometric height (H) is the distance from a point on the Earth's surface measured along a line perpendicular to a reference geoid. The difference between the ellipsoid height and the orthometric height is the geoid height (N). The following simple relationship is used to determine GPS-derived orthometric heights:

$$H_{GPS} = h - N$$

where H_{GPS} is the GPS-derived orthometric height, h is the ellipsoid height measured with GPS, and N is a modeled geoid height using the latest high resolution geoid model, which currently is GEOID96. GEOID96 supports the direct conversion of NAD 83 ellipsoid heights to NAVD 88 orthometric heights. Access the NGS Web site, http://www.ngs.noaa.gov, to obtain and download available information on geoid models.

J. Environmental Applications: Wetlands, Marine Sanctuaries, NOAA's Trust Resources

Wetlands

Wenzel and Scavia (1993) point out that coastal wetlands, among the Earth's most productive ecosystems, are often filled, drained, dredged, or polluted. Wetlands are also lost because of the construction of canals, waterways, and diversion of sediment to the offshore region. They are nurseries for fish, mollusks, and shrimp, and are homes to many species of birds and other animals. Wetlands are generally marshes, swamps, and mangrove forests. These are generally classified as back-barrier marshes, estuarine marshes, and tidal-freshwater marshes. Wetlands are a natural part of coastal recreation, serve to protect water quality, and help to prevent beach erosion. Wetlands account for most of the land within 1 m above MHW (*NRC, 1987*).

Ecological conditions in wetlands range from marine to terrestrial. The controlling factors are generally light, temperature, salinity, oxygen, geological/geomorphic processes, tidal and wave energy. A rise in sea level may cause a landward progression of biota, among other things. However, the ecological response may involve a complex set of interrelationships, depending upon the type of marsh (*NRC, 1987*).

In response to the loss of wetlands, several Federal agencies are involved in their scientific observation and mapping, as well as in the regulatory process. For example, NOAA is engaged in a nation-wide effort to map wetlands and perform habitat change analysis *Wenzel and Scavia* (1993). Section 10 of the Federal River and Harbors Act, Section 404 of the Federal Clean Water Act, and Executive Order 11988 on flood-plain management (*NRC, 1987*) establish permit requirements for actions that affect waterways and wetlands. In general, the philosophy of USACE and EPA is to discourage the issuance of a permit if the activity will alter wetlands, or to negotiate so that there is no net loss of wetlands. The Coastal Zone Management (CZM) Program is a voluntary partnership between the federal agencies and state governments. According to the Office of Ocean and Coastal Resource Management (OCRM), a total of 27 coastal states and five island territories have developed CZM programs, which protect more than 99% of the nations 95,000 miles of oceanic and Great Lakes coastline. Tidal datum information in NOS products and archives may be used to help delineate CZM boundaries and jurisdictions. A summary of ongoing NOAA applied research efforts to monitor coastal wetland loss due to increase in sea level in the Chesapeake Bay using tide gauge data and DGPS data are found in Nerem et al, 1998.

On nautical charts, NOS generally does not provide the MHWL on the ground in marsh areas. In wetlands, the MHWL is generally obscured. The MHWL in a wetlands will meander, be difficult to locate by an aerial photograph, and require a ground survey to map the tidal datums onto the land. In general, NOS surveys are made for nautical charts, and on the charts, the seaward edge of the wetlands is shown as the shoreline (*Hull and Thurlow*). This procedure is adequate for navigational purposes, but is not a shoreline for boundary purposes in wetlands.

Recent emerging applications of tidal datums and geodetic datums is exemplified by the Hamilton Marsh Restoration Project (USACE, 1999) in which CO-OPS and NGS are supporting the NOS ORR, the USACE, and local constituencies in the San Francisco Bay Area in restoring the Hamilton marsh by providing geodetic elevation maps using DGPS surveys and tidal datum and tidal prism information tied to geodetic datums. Knowing the elevations of the vertical reference datums are critical to a successful restoration process.

Additionally, the use of long term continuously operating GPS measurements co-located with long term sea level measurements has been initiated in the Chesapeake Bay to support further understanding and prediction of the roles of relative sea level rise and land subsidence on coastal wetland loss (Nerem et al 1998).

Marine Sanctuaries

The Marine Sanctuaries Act, U.S. Code 16, Conservation, Chapter 32, Marine Sanctuaries, extends Federal regulation into the ocean realm. The Marine Sanctuaries Act extends federal regulatory jurisdiction to the EEZ boundary, determined by MLLW. Maps depicting the boundaries of Marine Sanctuaries are drawn by using the tidal datums (e.g., MLLW) as the primary reference line. The act defines the term "marine environment," to be "those areas of coastal and ocean waters, the Great Lakes and their connecting waters, and submerged lands over which the United States exercises jurisdiction, including the exclusive economic zone, consistent with international law." Within this zone, the Secretary of the Department of Commerce may, "provide a coordinated and comprehensive approach to the conservation and management of special areas of the marine environment." The Secretary, among other things, must consider "the present and potential activities that may adversely affect the sanctuary"; the Secretary must work within a framework of "existing State and Federal regulatory and management authorities applicable to the area and the adequacy of those authorities"; consider the manageability of the area, including such factors as its size, its ability to be identified as a discrete ecological unit with definable boundaries, its accessibility, and its suitability for monitoring and enforcement activities"; assess " . . . the public benefits to be derived from sanctuary status, with emphasis on the benefits of long-term protection of nationally significant resources, vital habitats, and resources which generate tourism"; evaluate " . . . the negative impacts produced by management restrictions on income-generating activities such as living and nonliving resources development."

According to the Marine Sanctuaries Act, in the case that a "national marine sanctuary . . . is located partially or entirely within the seaward boundary of any State, the Governor affected may attest "to the Secretary that the designation of any of its terms is unacceptable, in which case the designation or the unacceptable term shall not take effect in the area of the sanctuary lying within the seaward boundary of the State." See the earlier section on state marine boundaries in this report. The Secretary may issue special use permits which "establish conditions of access to and use of any sanctuary resource," provided that "an activity . . . is compatible with the purposes for which the sanctuary is designated and with protection of sanctuary resources."

NOAA's Trust Resources

The NOS Office of Response and Restoration (ORR) has the primary responsibility within NOAA to implement these Marine Sanctuary regulations and those which follow from the Endangered Species Act and the Marine Mammal Protection Act. ORR provides decision makers with comprehensive scientific information on the resources of the nation's coastal areas, estuaries, and oceans.

The Damage Assessment Division (DAD) is an essential part of NOAA's effort to meet natural resource trustee responsibilities delegated to the agency by the Secretary of Commerce. Under the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund), the Clean Water Act, the Oil Pollution Act of 1990, and the National Marine Sanctuaries Act, NOAA serves as the primary federal trustee for coastal and marine resources. Trust resources include commercial and recreational fishery resources; anadromous species; endangered and threatened marine species and their habitats; marine mammals, coastal habitats, and resources associated with marine sanctuaries and national estuarine research reserves. The Director ORR is the delegated authority to act as the "designated official" (i.e., the trustee) in executing natural resource authorities.

The DAD mission is to restore coastal and marine resources that sustain injury from oil spills or hazardous material releases. DAD pursues this specific, results-oriented mission to reverse human impacts on coastal systems through the following approach: 1) assesses injury to NOAA trust resources caused by spills and chronic releases of hazardous materials or oil; 2) develops plans for restoring injured resources and replacing lost natural resource services–these plans serve as the basis for damage claims; and 3) recovers restoration funds from polluters through negotiation or legal action. No other federal agency is a trustee for these natural resources and, therefore, only NOAA would pursue damage actions to restore coastal resources.

Damage assessment actions fill a unique niche in NOAA's stewardship portfolio by directly restoring injured coastal resources using funds recovered from those responsible for causing the injury. Since its inception in 1990, NOAA's Damage Assessment and Restoration Program has recovered more than $150 million for the restoration of NOAA trust resources. These funds are now being used to implement approximately 20 restoration projects around the country.

The Hazardous Materials Response and Assessment (HAZMAT) Division also conducts state-of-the-art science, and directly applies the results for injury assessment and restoration planning. HAZMAT provides an incentive for industry to follow environmentally-responsible business practices, thus avoids the risk of natural resource liability and helps state and federal trustee agencies develop more effective programs for restoring natural resources.

A primary tool for the biological description of coastal zones and marine sanctuaries is the Environmental Sensitivity Index (ESI) maps. According to HAZMAT, http://response.restoration.noaa.gov/esi/esiintro.html, three primary kinds of information are displayed: shoreline rankings, biological resources, and human-use resources. The classification scheme is described in *Environmental Sensitivity Index Guidelines. Version 2.0 (NOAA, 1997).* Briefly, the shoreline classification is ranked on a scale of one through ten based on the natural persistence of oil and its ease of cleanup. A shoreline classified as "one" would typically be exposed to high wave and tidal current energy, have a steep slope, be composed of bedrock, and have biological resources in low-concentrations of individuals. A shoreline ranked as "ten" would be nearly devoid of tidal energy, would have a flat slope, be composed of mud, and have high biological value. Biological resources are mapped according to species. For each species, the spatial boundaries of their ecological niches are mapped. A brief listing is provided below (the interested reader should consult the documentation for more details):

- Marine Mammals – concentration areas, migratory areas.
- Terrestrial Mammals – concentration areas, intertidal feeding, endangered species.
- Birds – concentration areas, rookeries, migratory patterns, endangered species.
- Reptiles and Amphibians – concentration areas, nesting beaches, endangered species.
- Fish – concentration areas, spawning grounds, nurseries, endangered species.
- Invertebrates – concentration areas, harvest areas, endangered species.
- Habitats and Plants – concentration areas, sub-tidal, intertidal, wetland, and upland species.

Shoreline habitats are indicated by a color-coded ranking scheme. The designation of coastal habitats are indicated by a color line with no dimension. The maps handle gentle-sloping coastal areas with large tidal ranges, and hence wide intertidal zones, by filling in the entire area from low-water to high-water with the habitat classification color. If wetland data is available, the entire extent of the wetland is filled with a color code. Both the seaward edge and the landward edge are indicated.

Lastly, the boundaries of recreational and management areas, resource extraction sites, and cultural resources are delineated on ESI maps. The management areas include, among other things, marine sanctuaries, national wildlife refuges, national and state parks, and reserves and preserves set up by various agencies and organizations.

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9. GLOSSARY

A

absolute mean sea level change.
A eustatic change in mean sea level relative to the geographic center of the Earth.

accepted values
Tidal datums, tidal ranges and Greenwich high and low water intervals obtained through primary determination or through secondary determination through simultaneous observational comparisons made with a primary control tide station in order to derive the equivalent of a 19-year value.

ADR gauge
Analog to Digital Recorder. A float or pressure actuated water level gauge that records the heights at regular time intervals in digital format. The NOS gauges typically output 6-minute interval data onto punched-paper-tape.

air acoustic ranging sensor
A pulsed, acoustic ranging device using the air column in a tube as the acoustic sound path. The fundamental measurement is the time it takes for the acoustic signal to travel from a transmitter to the water surface and then back to the receiver. The distance from a reference point to the water surface is derived from the travel time. A calibration point is set at a fixed distance from the acoustic transducer and is used to correct the measured distance using the calibrated sound velocity in the tube.

air temperature sensors
Thermistors located in the protective well of a NGWLMS for the purpose of verifying uniformity of temperature for measurements taken by the air acoustic ranging sensor.

apogean tides or apogean tidal currents
Tides of decreased range or currents of decreased speed occurring monthly as the result of the Moon being in apogee. The apogean range (An) of the tide is the average range occurring at the time of apogean tides and is most conveniently computed from the harmonic constants. It is smaller than the mean range, where the type of tide is either semidiurnal or mixed, and is of no practical significance where the type of tide is predominantly diurnal.

apogee
The point in the orbit of the Moon or man-made satellite farthest from the Earth. The point in the orbit of a satellite farthest from its companion body.

apparent secular trend
The nonperiodic tendency of sea level to rise, fall, or remain stationary with time. Technically, it is frequently defined as the slope of a least-squares line of regression through a relatively long series of yearly mean sea-level values. The word "apparent" is used since it is often not possible to know whether

a trend is truly nonperiodic or merely a segment of a very long (relative to the length of the series) oscillation.

automatic tide gauge
An instrument that automatically registers the rise and fall of the tide. In some instruments, the registration is accomplished by recording the heights at regular time intervals in digital format; in others, by a continuous graph of height against time. The automatic gauges used in the past by the National Ocean Service were of both types.

B

bench mark (BM)
A fixed physical object or mark used as reference for a vertical datum. A tidal bench mark is one near a tide station to which a tide staff and tidal datums are referred. A primary bench mark is the principal (or only) mark of a group of tidal bench marks to which the tide gauge measurements and tidal datums are referred. The standard tidal bench mark of the National Ocean Service is a brass, bronze, or aluminum alloy disk 3-½ inches in diameter containing the inscription NATIONAL OCEAN SERVICE together with other individual identifying information. A vertical geodetic bench mark identifies a surveyed point in the National Geodetic Vertical Network. Most geodetic bench mark disks contain the inscription VERTICAL CONTROL MARK NATIONAL GEODETIC SURVEY with other individual identifying information. Bench mark disks may also be horizontal control pojnts and are so designated on their stampings. Bench mark disks of either type may, on occasion, serve simultaneously to reference both tidal and geodetic datums. Numerous bench marks of predecessor organizations to NOS, or parts of other organizations absorbed into NOS, still bear the inscriptions: U.S. COAST & GEODETIC SURVEY, NATIONAL OCEAN SURVEY, U.S. LAKE SURVEY, CORPS OF ENGINEERS, and U.S. ENGINEER OFFICE.

bubbler tide gauge
NOS has used this type of gas-purged pressure water level gauge in various configurations over time and is typically configure with a brass cylindrical orifice below the water linked through a length of neoprene rubber tubing to a bellows mechanism (historically) or a strain-gauge or crystal oscillator pressure transducer (present) to measure the water level elevation above the orifice. NOS systems use nitrogen gas supplied from a supply tank at the station. Because the bellows or the transducers are vented to the atmosphere, barometric pressure corrections to obtain water level relative to the land are not required.

C

chart datum
The datum to which soundings on a chart are referred. It is usually taken to correspond to a low-water elevation. Since 1989, chart datum has been implemented to mean lower low water for all marine waters of the United States, its territories, Commonwealth of Puerto Rico, and Trust Territory of the Pacific Islands. See datum and National Tidal Datum Convention of 1980.

Coast and Geodetic Survey
A former name of the National Ocean Service. The organization was known as: The Survey of the Coast from its founding in 1807 to 1836, Coast Survey from 1836 to 1878, Coast and Geodetic Survey from 1878 to 1970, and National Ocean Survey from 1970 to 1982. In 1982 it was named National Ocean Service. From 1965 to 1970, the Coast and Geodetic Survey was a component of the Environmental Science Services Administration (ESSA). The National Ocean Survey was a component of the National Oceanic and Atmospheric Administration (NOAA). NOAA became the successor to ESSA in 1970. The National Ocean Service is a component of NOAA, U.S. Department of Commerce.

coast line
The low water datum line for purposes of the Submerged Lands Act (Public Law 31). See shoreline.

coastal boundary
The mean high water line (MHWL) or mean higher high water line (MHHWL) when tidal lines are used as the coastal boundary. Also, lines used as boundaries inland of and measured from (or points thereon) the MHWL or MHHWL. See marine boundary.

coastal zone (legal definition for coastal zone management)
The term coastal zone means the coastal waters (including the lands therein and thereunder) and the adjacent shorelands (including the waters therein and thereunder), strongly influenced by each and in proximity to the shorelines of the several coastal states, and includes islands, transitional and inter-tidal areas, salt marshes, wetlands, and beaches. The zone extends, in Great Lakes waters, to the international boundary between the Unites States and Canada and in other areas seaward to the outer limit of the United States territorial sea. The zone extends inland from the shorelines only to the extent necessary to control shorelands, the uses of which have a direct and significant impact on the coastal waters. Excluded from the coastal zone are lands the use of which is by law subject solely to the discretion of or which is held in trust by the Federal Government, its officers, or agents.

comparison of simultaneous observations
A tidal datum reduction process in which a short series of tide or tidal current observations at any place is compared with simultaneous observations at a control station where tidal or tidal current constants have previously been determined from a long series of observations. For tides, it is usually used to adjust constants from a subordinate station to the equivalent of that which would be obtained from a l9-year series.

constituent
One of the harmonic elements in a mathematical expression for the tide-producing force and in corresponding formulas for the tide or tidal current. Each constituent represents a periodic change or variation in the relative positions of the Earth, Moon, and Sun. A single constituent is usually written in the form $y = A \cos(at + \alpha)$, in which y is a function of time as expressed by the symbol t and is reckoned from a specific origin. The coefficient A is called the amplitude of the constituent and is a measure of its relative importance. The angle $(at + \alpha)$ changes uniformly and its value at any time is called the phase of the constituent. The speed of the constituent is the rate of change in its phase and is represented by the symbol a in the formula. The quantity a is the phase of the constituent at the initial instant from which

the time is reckoned. The period of the constituent is the time required for the phase to change through 360° and is the cycle of the astronomical condition represented by the constituent.

control station
See primary control tide station, secondary control tide station, and control current station.

data collection platform (DCP)
A microprocessor based system that collects data from sensors, processes the data, stores the data in random access memory (RAM), and provides communication links for the retrieval or transmission of the data.

D

datum of tabulation
A permanent base elevation at a tide station to which all tide gauge measurements are referred. The datum is unique to each station and is established at a lower elevation than the water is ever expected to reach. It is referenced to the primary bench mark at the station and is held constant regardless if changes to the tide gauge or tide staff. The datum of tabulation is most often at the zero of the first tide staff installed.

datum (vertical)
For marine applications, a base elevation used as a reference from which to reckon heights or depths. It is called a tidal datum when defined in terms of a certain phase of the tide. 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. See chart datum.

diurnal
Having a period or cycle of approximately one tidal day. Thus, the tide is said to be diurnal when only one high water and one low water occur during a tidal day, and the tidal current is said to be diurnal when there is a single flood and a single ebb period of a reversing current in the tidal day. A rotary current is diurnal if it changes its direction through all points of the compass once each tidal day. A diurnal constituent is one which has a single period in the constituent day. The symbol for such a constituent is the subscript 1. See stationary wave theory and type of tide.

diurnal inequality
The difference in height of the two high waters or of the two low waters of each tidal day; also, the difference in speed between the two flood tidal currents or the two ebb currents of each tidal day. The difference changes with the declination of the Moon and, to a lesser extent, with the declination of the Sun. In general, the inequality tends to increase with increasing declination, either north or south, and to diminish as the Moon approaches the Equator. Mean diurnal high water inequality (DHQ) is one-half the average difference between the two high waters of each tidal day observed over the National Tidal Datum Epoch. It is obtained by subtracting the mean of all the high waters from the mean of the higher high waters. Mean diurnal low water inequality (DLQ) is one-half the average difference between the

two low waters of each tidal day observed over the National Tidal Datum Epoch. It is obtained by subtracting the mean of the lower low waters from the mean of all the low waters. Tropic high water inequality (HWQ) is the average difference between the two high waters of each tidal day at the times of tropic tides. Tropic low water inequality (LWQ) is the average difference between the two low waters of each tidal day at the times of tropic tides. Mean and tropic inequalities, as defined above, are applicable only when the type of tide is either semidiurnal or mixed. Diurnal inequality is sometimes called declinational inequality.

diurnal range
Same as great diurnal range.

diurnal tide level
A tidal datum midway between mean higher high water and mean lower low water.

duration of rise and duration of fall
Duration of rise is the interval from low water to high water, and duration of fall is the interval from high water to low water. Together they cover, on an average, a period of 12.42 hours for a semidiurnal tide or a period of 24.84 hours for a diurnal tide. In a normal semidiurnal tide, duration of rise and duration of fall each will be approximately equal to 6.21 hours, but in shallow waters and in rivers there is a tendency for a decrease in duration of rise and a corresponding increase in duration of fall.

E

earth tide
Periodic movement of the Earth's crust caused by gravitational interactions between the Sun, Moon, and Earth.

ecliptic
The intersection of the plane of the Earth's orbit with celestial sphere.

epoch
(1) Also known as phase lag. Angular retardation of the maximum of a constituent of the observed tide (or tidal current) behind the corresponding maximum of the same constituent of the theoretical equilibrium tide. It may also be defined as the phase difference between a tidal constituent and its equilibrium argument. As referred to the local equilibrium argument, its symbol is k. When referred to the corresponding Greenwich equilibrium argument, it is called the Greenwich epoch that has been modified to adjust to a particular time meridian for convenience in the prediction of tides is represented by g or by k'. The relations between these epochs may be expressed by the following formula:
$G = k + pL$
$g = k' = G - aS / 15$
in which L is the longitude of the place and S is the longitude of the time meridian, these being taken as positive for west longitude and negative for east longitude; p is the number of constituent periods in the constituent day and is equal to 0 for all long-period constituents, 1 for diurnal constituents, 2 for semidiurnal constituents, and so forth; and a is the hourly speed of the constituent, all angular

measurements being expressed in degrees. (2) As used in tidal datum determination, it is 19-year cycle over which tidal height observations are averaged in order to establish the various datums. As there are periodic and apparent secular trends in sea level, a specific 19-year cycle (the National Tidal Datum Epoch) is selected so that all tidal datum determinations throughout the United States, its territories, Commonwealth of Puerto Rico, and Trust Territory of the Pacific Islands, will have a common reference. See National Tidal Datum Epoch.

equatorial tides
Tides occurring semimonthly as a result of the Moon being over the Equator. At these times the tendency of the Moon to produce a diurnal inequality in the tide is at a minimum.

equilibrium argument
The theoretical phase of a constituent of the equilibrium tide. It is usually represented by the expression (V + u), in which V is a uniformly changing angular quantity involving multiples of the hour angle of the mean Sun, the mean longitudes of the Moon and Sun, and the mean longitude of lunar or solar perigee; and u is a slowly changing angle depending upon the longitude of the Moon's node. When pertaining to an initial instant of time, such as the beginning of a series of observations, it is expressed by (V_o + u).

equilibrium theory
A model under which it is assumed that the waters covering the face of the Earth instantly respond to the tide-producing forces of the Moon and Sun to form a surface of equilibrium under the action of these forces. The model disregards friction, inertia, and the irregular distribution of the land masses of the Earth. The theoretical tide formed under these conditions is known as the equilibrium tide.

equilibrium tide
Hypothetical tide due to the tide producing forces under the equilibrium theory. Also known as gravitational tide.

equinoctial tides
Tides occurring near the times of the equinoxes.

equinoxes
The two points in the celestial sphere where the celestial equator intersects the ecliptic; also, the times when the Sun crosses the equator at these points. The vernal equinox is the point where the Sun crosses the Equator from south to north and it occurs about March 21. Celestial longitude is reckoned eastward from the vernal equinox. The autumnal equinox is the point where the Sun crosses the Equator from north to south and it occurs about September 23.

equipotential surface
Same as geopotential surface.

estuary
An embayment of the coast in which fresh river water entering at its head mixes with the relatively saline ocean water. When tidal action is the dominant mixing agent it is usually termed a tidal estuary. Also,

the lower reaches and mouth of a river emptying directly into the sea where tidal mixing takes place. The latter is sometimes called a river estuary.

eustatic sea level rate
The worldwide change of sea level elevation with time. The changes are due to such causes as glacial melting or formation, thermal expansion or contraction of sea water, etc.

extreme high water
The highest elevation reached by the sea as recorded by a tide gauge during a given period. The National Ocean Service routinely documents monthly and yearly extreme high waters for its control stations.

extreme low water
The lowest elevation reached by the sea as recorded by a tide gauge during a given period. The National Ocean Service routinely documents monthly and yearly extreme low water for its control stations.

F

first reduction
A method of determining high and low water heights, time intervals, and ranges from an arithmetic mean without adjustment to a long-term series through simultaneous observational comparisons.

float well
A stilling well in which the float of a float-actuated gauge operates. See stilling well.

forced wave
A wave generated and maintained by a continuous force. See gravity wave.

Fourier series
A series proposed by the French mathematician Fourier about the year 1807. The series involves the sines and cosines of whole multiples of a varying angle and is usually written in the following form:
$y = A_o + A_1 \sin x + A_2 \sin 2x + A_3 \sin 3x + \ldots B_1 \cos x + B_2 \cos 2x + B_3 \cos 3x + \ldots$
By taking a sufficient number of terms the series may be made to represent any periodic function of x.

free wave
A wave that continues to exist after the generating force has ceased to act.

G

geodetic datum
See National Geodetic Vertical Datum of 1929 and North American Vertical Datum of 1988.

geopotential

The unit of geopotential difference, equal to the gravity potential of 1 meter squared per second squared, m^2 / s^2, or 1 joule per kilogram, J / kg.

geopotential anomaly (delta D)
The excess in geopotential difference over the standard geopotential difference [at a standard specific volume at 35 parts per thousand (°/oo) and 0 degrees C] between isobaric surfaces. See geopotential and geopotential topography.

great diurnal range (Gt)
The difference in height between mean higher high water and mean lower low water. The expression may also be used in its contracted form, diurnal range.

great tropic range (Gc)
The difference in height between tropic higher high water and tropic lower low water. The expression may also be used in its contracted form, tropic range.

Greenwich argument
Equilibrium argument computed for the meridian of Greenwich.

Gulf Coast Low Water Datum (GCLWD)
A tidal datum. Used as chart datum from November 14, 1977, to November 27, 1980, for the coastal waters of the Gulf coast of the United States. GCLWD is defined as mean lower low water when the type of tide is mixed and mean low water (now mean lower low water) when the type of tide is diurnal. See National Tidal Datum Convention of 1980.

geopotential difference
The work per unit mass gained or required in moving a unit mass vertically from one geopotential surface to another. See geopotential, geopotential anomaly, and geopotential topography.

geopotential (equipotential) surface
A surface that is everywhere normal to the acceleration of gravity.

geopotential topography
The topography of an equiscalar (usually isobaric) surface in terms of geopotential difference. As depicted on maps, isopleths are formed by the intersection of the isobaric surface with a series of geopotential surfaces. Thus, the field of isopleths represents variations in the geopotential anomaly of the isobaric surface above a chosen reference isobaric surface (such as a level of no motion).

H

half-tide level
A tidal datum. The arithmetic mean of mean high water and mean low water. Same as mean tide level.

harmonic analysis

The mathematical process by which the observed tide or tidal current at any place is separated into basic harmonic constituents.

harmonic constants
The amplitudes and epochs of the harmonic constituents of the tide or tidal current at any place.

harmonic prediction
Method of predicting tides and tidal currents by combining the harmonic constituents into a single tide curve. The work is usually performed by electronic digital computer.

head of tide
The inland or upstream limit of water affected by the tide. For practical application in the tabulation for computation of tidal datums, head of tide is the inland or upstream point where the mean range becomes less than 0.2 foot. Tidal datums (except for mean water level) are not computed beyond

high tide
Same as high water.

high water (HW)
The maximum height reached by a rising tide. The high water is due to the periodic tidal forces and the effects of meteorological, hydrologic, and/or oceanographic conditions. For tidal datum computational purposes, the maximum height is not considered a high water unless it contains a tidal high water.

high water line
The intersection of the land with the water surface at an elevation of high water.

high water mark
A line or mark left upon tide flats, beach, or along shore objects indicating the elevation of the intrusion of high water. The mark may be a line of oil or scum on along shore objects, or a more or less continuous deposit of fine shell or debris on the fore shore or berm. This mark is physical evidence of the general height reached by wave run up at recent high waters. It should not be confused with the mean high water line or mean higher high water line.

higher high water (HHW)
The highest of the high waters (or single high water) of any specified tidal day due to the declination Al effects of the Moon and Sun.

higher low water (HLW)
The highest of the low waters of any specified tidal day due to the declination Al effects of the Moon and Sun.

hydrographic datum
A datum used for referencing depths of water and the heights of predicted tides or water level observations. Same as chart datum. See datum.

I

Indian spring low water
A datum originated by Professor G. H. Darwin when investigating the tides of India. It is an elevation depressed below mean sea level by an amount equal to the sum of the amplitudes of he harmonic constituents M_2, S_2, K_1, and O_1.

Indian tide plane
Same as Indian spring low water.

International Great Lakes Datum (1955) [IGLD (1955)]
Mean water level at Pointe-au-Pere, Quebec, on the Gulf of St. Lawrence over the period 1941 through 1956, from which geopotential elevations (geopotential differences) throughout the Great Lakes region are measured. The term is often used to mean the entire system of geopotential elevations rather than just the referenced water level. See low water datum (1).

International Hydrographic Organization (formerly Bureau)
An institution consisting of representatives of a number of nations organized for the purpose of coordinating the hydrographic work of the participating governments. It had its origin in the International Hydrographic Conference in London in 1919. It has permanent headquarters in the Principality of Monaco and is supported by funds provided by the member nations. Its principal publications include the Hydrographic Review and special publications on technical subjects.

international low water
A hydrographic datum originally suggested for international use at the International Hydrographic Conference in London in 1919, and later discussed at the Monaco Conference in 1926. The proposed datum, which has not yet been generally adopted, was to be "a plane so low that the tide will but seldom fall below it." This datum was the subject of the International Hydrographic Bureau's Special Publication No. 5 (March 1925) and No. 10 (January 1926), reproduced in the Hydrographic Review for May 1925 and July 1926.

intertidal zone (technical definition)
The zone between the mean higher high water and mean lower low water lines.

inverse barometer effect
The inverse response of sea level to changes in atmospheric pressure. A static reduction of 1.005 mb in atmospheric pressure will cause a stationary rise of 1 cm in sea level.

K

K_1
Lunisolar diurnal constituent. This constituent, with O_1, expresses the effect of the Moon's declination. They account for diurnal inequality and, at extremes, diurnal tides. With P_1, it expresses the effect of the Sun's declination. Speed = 15.041,068,6° per solar hour.

K_2
Lunisolar semi diurnal constituent. This constituent modulates the amplitude and frequency of M_2 and S_2 for the declination Al effect of the Moon and Sun, respectively. Speed = 30.082,137,3˚ per solar hour.

kappa (κ)
Name of Greek letter used as the symbol for a constituent phase lag or epoch when referred to the local equilibrium argument and frequently taken to mean the same as local epoch. See epoch (1).

kappa prime (κ´)
Name of Greek letter (with prime mark) used as the symbol for a constituent phase lag or epoch when the Greenwich equilibrium argument (G) has been modified to a particular time meridian. Same as g. See kappa (κ) and epoch (1).

L

L_2
Smaller lunar elliptic semi diurnal constituent. This constituent, with N_2, modulates the amplitude and frequency of M_2 for the effect of variation in the Moon's orbital speed due to its elliptical orbit. Speed = 29.528,478,9˚ per solar hour.

lagging of tide
The periodic retardation in the time of occurrence of high and low water due to changes in the relative positions of the Moon and Sun.

lambda
Smaller lunar evectional constituent. This constituent, with ν_2, μ_2, and (S_2), modulates the amplitude and frequency of M_2 for the effects of variation in solar attraction of the Moon. This attraction results in a slight pear-shaped lunar ellipse and a difference in lunar orbital speed between motion toward and away from the Sun. Although (S_2) has the same speed as S_2, its amplitude is extremely small. Speed = 29.455,625,3˚ per solar hour.

latitude
The angular distance between a terrestrial position and the equator measured northward or southward from the equator along a meridian of longitude.

level of no motion
A level (or layer) at which it is assumed that an isobaric surface coincides with a geopotential surface. A level (or layer) at which there is no horizontal pressure gradient force.

level surface
See geopotential surface as preferred term.

littoral zone

In coastal engineering, the area from the shoreline to just beyond the breaker zone. In biological oceanography, it is that part of the benthic division extending from the high water line out to a depth of about 200 meters. The littoral system is divided into a eulittoral and sublittoral zone, separated at a depth of about 50 meters. Also, frequently used interchangeably with intertidal zone.

long period waves (long waves)
Forced or free waves whose lengths are much longer than the water depth. See tidal wave and tsunami.

longitude
Angular distance in a great circle of reference reckoned from an accepted origin to the projection of any point on that circle. Longitude on the Earth's surface is measured on the Equator east and west of the meridian of Greenwich and may be expressed either in degrees or in hours, the hour being taken as the equivalent of 15° of longitude. Celestial longitude is measured in the ecliptic eastward from the vernal equinox. The mean longitude of a celestial body moving in an orbit is the longitude that would be attained by a point moving uniformly in the circle of reference at the same average angular velocity as that of the body, with the initial position of the point so taken that its longitude would be the same as that of the body at a certain specified position in its orbit. With a common initial point, the mean longitude of a body will be the same in whatever circle it may be reckoned.

low tide
Same as low water.

low water (LW)
The minimum height reached by a falling tide. The low water is due to the periodic tidal forces and the effects of meteorological, hydrologic, and/or oceanographic conditions. For tidal datum computational purposes, the minimum height is not considered a low water unless it contains a tidal low water.

low water datum (LWD)
(1) The geopotential elevation (geopotential difference) for each of the Great Lakes and Lake St. Clair and the corresponding sloping surfaces of the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence Rivers to which are referred the depths shown on the navigational charts and the authorized depths for navigation improvement projects. Elevations of these planes are referred to IGLD (1955) and are Lake Superior 600.0 feet, Lakes Michigan and Huron 576.8 feet, Lake St. Clair 571.7 feet, Lake Erie 568.6 feet, and Lake Ontario 242.8 feet. (2) An approximation of mean low water that has been adopted as a standard reference for a limited area and is retained for an indefinite period regardless of the fact that it may differ slightly from a better determination of mean low water from a subsequent series of observations. Used primarily for river and harbor engineering purposes. Boston low water datum is an example.

low water equinoctial springs
Low water springs near the times of the equinoxes. Expressed in terms of the harmonic constants, it is an elevation depressed below mean sea level by an amount equal to the sum of the amplitudes of the constituents M_2, S_2, and K_2.

low water line

The intersection of the land with the water surface at an elevation of low water.

lower high water (LHW)
The lowest of the high waters of any specified tidal day due to the declination Al effects of the Moon and Sun.

lower low water (LLW)
The lowest of the low waters (or single low water) of any specified tidal day due to the declination effects of the Moon and Sun.

lower low water datum (LLWD)
An approximation of mean lower low water that has been adopted as a standard reference for a limited area and is retained for an indefinite period regardless of the fact that it may differ slightly from a better determination of mean lower low water from a subsequent series of observations. Used primarily for river and harbor engineering purposes. Columbia River lower low water datum is an example.

lunar day
The time of the rotation of the Earth with respect to the Moon, or the interval between two successive upper transits of the Moon over the meridian of a place. The mean lunar day is approximately 24.84 solar hours in length, or 1.035 times as great as the mean solar day.

lunar tide
That part of the tide on the Earth due solely to the Moon as distinguished from that part due to the Sun.

lunisolar tides
Harmonic tidal constituents K_1, and K_2, which are derived partly from the development of the lunar tide and partly from the solar tide, the constituent speeds being the same in both cases. Also, the lunisolar synodic fort nightly constituent MSf.

lunitidal interval
The interval between the Moon's transit (upper or lower) 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 known as mean high water lunitidal interval and is abbreviated to high water interval (HWI). Similarly, mean low water lunitidal interval is abbreviated to low water interval (LWI). The interval is described as local or Greenwich according to whether the reference is to the transit over the local or Greenwich meridian. When not otherwise specified, the reference is assumed to be local. When there is considerable diurnal inequality in the tide, separate intervals may be obtained for the higher high waters, lower high waters, higher low waters, and lower low waters. These are designated respectively as higher high water interval (HHWI), lower high water interval (LHWI), higher low water interval (HLWI), and lower low water interval (LLWI). In such cases, and also when the tide is diurnal, it is necessary to distinguish between the upper and lower transit of the Moon with reference to its declination. Intervals referred to the Moon's upper transit at the time of its north declination or the lower transit at the time of south declination are marked a. Intervals referred to the Moon's lower transit at the time of its north declination or to the upper transit at the time of south declination are marked b.

M

M_1
Smaller lunar elliptic diurnal constituent. This constituent, with J_1, modulates the amplitude of the declinational K_1, for the effect of the Moon's elliptical orbit. A slightly slower constituent, designated (M_1), with Q_1, modulates the amplitude and frequency of the declinational O_1, for the same effect. Speed = 14.496,693,9˚ per solar hour.

M_2
Principal lunar semidiurnal constituent. This constituent represents the rotation of the Earth with respect to the Moon. Speed = 28.984,104,2˚ per solar hour.

M_3
Lunar terdiurnal constituent. A shallow water compound constituent. See shallow water constituent. Speed = 43.476,156,3˚ per solar hour.

M_4, M_6, M_8
Shallow water overtides of principal lunar constituent. See shallow water constituent.
Speed of M_4 = 57.968,208,4˚ per solar hour.
Speed of M_6 = 86.952,312,7˚ per solar hour.
Speed of M_8 = 115.936,416,9˚ per solar hour.

marigram
A graphic record of the rise and fall of the water. The record is in the form of a curve in which time is generally represented on the abscissa and the height of the tide on the ordinate. See tide curve.

marine boundary
The mean lower low water line (MLLWL) when used as a boundary. Also, lines used as boundaries seaward of and measured from (or points thereon) the MLLWL. See coastal boundary.

mean diurnal tide level (MDTL)
A tidal datum. The arithmetic mean of mean higher high water and mean lower low water.

mean high water (MHW)
A tidal datum. The average of all the high water heights observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch.

mean high water line (MHWL)
The line on a chart or map which represents the intersection of the land with the water surface at the elevation of mean high water. See shoreline.

mean higher high water (MHHW)

A tidal datum. The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch.

mean higher high water line (MHHWL)
The line on a chart or map which represents the intersection of the land with the water surface at the elevation of mean higher high water.

mean low water (MLW)
A tidal datum. The average of all the low water heights observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch.

mean low water line (MLWL)
The line on a chart or map which represents the intersection of the land with the water surface at the elevation of mean low water.

mean low water springs (MLWS)
A tidal datum. Frequently abbreviated spring low water. The arithmetic mean of the low water heights occurring at the time of spring tides observed over the National Tidal Datum Epoch. It is usually derived by taking an elevation depressed below the half-tide level by an amount equal to one-half the spring range of tide, necessary corrections being applied to reduce the result to a mean value. This datum is used, to a considerable extent, for hydrographic work outside of the United States and is the level of reference for the Pacific approaches to the Panama Canal.

mean lower low water (MLLW)
A tidal datum. The average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch.

mean lower low water line (MLLWL)
The line on a chart or map which represents the intersection of the land with the water surface at the elevation of mean lower low water.

mean range of tide (Mn)
The difference in height between mean high water and mean low water.

mean rise
The height of mean high water above the elevation of chart datum.

mean rise interval (MRI)
The average interval between the transit of the Moon and the middle of the period of the rise of the tide. It may be computed by adding half the duration of rise to the mean low water interval, rejecting the semidiurnal tidal period of 12.42 hours when greater than this amount. The mean rise interval may be either local or Greenwich according to whether it is referred to the local or Greenwich transit.

mean river level
A tidal datum. The average height of the surface of a tidal river at any point for all stages of the tide observed over the National Tidal Datum Epoch. It is usually determined from hourly height readings. In rivers subject to occasional freshets, the river level may undergo wide variations and, for practical purposes, certain months of the year may be excluded in the determination of the tidal datum. For charting purposes, tidal datums for rivers are usually based on observations during selected periods when the river is at or near a low water stage.

mean sea level (MSL)
A tidal datum. The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch. Shorter series are specified in the name; e.g., monthly mean sea level and yearly mean sea level.

mean tide level (MTL)
Same as half-tide level.

mean water level (MWL)
A datum. The mean surface elevation as determined by averaging the heights of the water at equal intervals of time, usually hourly. Mean water level is used in areas of little or no range in tide.

mean water level line (MWLL)
The line on a chart or map which represents the intersection of the land with the water surface at the elevation of mean water level.

meteorological tides
Tidal constituents having their origin in the daily or seasonal variations in weather conditions which may occur with some degree of periodicity. The principal meteorological constituents recognized in the tides are Sa, Ssa, and S_1. See storm surge.

Metonic cycle
A period of almost 19 years or 235 lunations. Devised by Meton, an Athenian astronomer who lived in the fifth century B.C., for the purpose of obtaining a period in which new and full Moon would recur on the same day of the year. Taking the Julian year of 365.25 days and the synodic month as 29.530,588 days, we have the l9-year period of 6,939.75 days as compared with the 235 lunations of 6,939.69 days, a difference of only 0.06 day.

Mf
Lunar fort nightly constituent. This constituent expresses the effect of departure from a sinusoidal declination Al motion. Speed = 1.098,033,1˚ per solar hour.

mixed (tide)
Type of tide characterized by a conspicuous diurnal inequality in the higher high and lower high waters and/or higher low and lower low waters. See type of tide.

Mm
Lunar monthly constituent. This constituent expresses the effect of irregularities in the Moon's rate of change of distance and speed in orbit. Speed = 0.544,374,7˚ per solar hour.

modified epoch
See kappa prime and epoch (1).

MSf
Lunisolar synodic fort nightly constituent. Speed = 1.015,895,8˚ per solar hour.

mu (μ_2)
Variational constituent. See lambda. Speed = 27.968,208,4˚ per solar hour.

N

N
Rate of change (as of January 1, 1900) in mean longitude of the Moon's node. N = 0.002,206,41˚ per solar hour.

N_2
Larger lunar elliptic semi diurnal constituent. See L_2 Speed = 28.439,729,5˚ per solar hour.

$2N_2$
Lunar elliptic semi diurnal second-order constituent. Speed = 27.895,354,8˚ per solar hour.

National Geodetic Vertical Datum of 1929 [NGVD (1929)]
A fixed reference adopted as a standard geodetic datum for elevations determined by leveling. The datum was derived for surveys from a general adjustment of the first-order leveling nets of both the United States and Canada. In the adjustment, mean sea level was held fixed as observed at 21 tide stations in the United States and 5 in Canada. The geodetic datum now in use in the United States is the National Geodetic Vertical Datum. The year indicates the time of the general adjustment. A synonym for Sea-level Datum of 1929. The geodetic datum is fixed and does not take into account the changing stands of sea level. Because there are many variables affecting sea level, and because the geodetic datum represents a best fit over a broad area, the relationship between the geodetic datum and local mean sea level is not consistent from one location to another in either time or space. For this reason, the National Geodetic Vertical Datum should not be confused with mean sea level. NGVD(1929) has been superceded for use by NAVD88.

National Tidal Datum Convention of 1980
Effective November 28, 1980, the Convention: (1) establishes one uniform, continuous tidal datum system for all marine waters of the United States, its territories, Commonwealth of Puerto Rico, and Trust Territory of the Pacific Islands, for the first time in its history; (2) provides a tidal datum system independent of computations based on type of tide; (3) lowers chart datum from mean low water to mean lower low water along the Atlantic coast of the United States; (4) updates the National Tidal Datum

Epoch from 1941 through 1959, to 1960 through 1978; (5) changes the name Gulf Coast Low Water Datum to mean lower low water; (6) introduces the tidal datum of mean higher high water in areas of predominantly diurnal tides; and (7) lowers mean high water in areas of predominantly diurnal tides. See chart datum.

National Tidal Datum Epoch
The specific l9-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level. The present National Tidal Datum Epoch is 1960 through 1978. It is reviewed annually for possible revision and must be actively considered for revision every 25 years.

National Water Level Observation Network (NWLON)
The network of tide and water level stations operated by the National Ocean Service along the marine and Great Lakes coasts and islands of the United States. The NWLON is composed of the primary and secondary control tide stations of the National Ocean Service. Distributed along the coasts of the United States, this Network provides the basic tidal datums for coastal and marine boundaries and for chart datum of the United States. Tide observations at a secondary control tide station or tertiary tide station are reduced to equivalent l9-year tidal datums through the comparison of simultaneous observations with a primary control tide station. In addition to hydrography and nautical charting, and to coastal and marine boundaries, the Network is used for coastal processes and tectonic studies, tsunami and storm surge warnings, and climate monitoring. The National Water Level Observation Network also includes stations operated throughout the Great Lakes Basin. The primary network is composed of 54 sites with 139 seasonal gauge sites selectively operated 4 months annually for the maintenance of IGLD. The network supports regulation, navigation and charting, river and harbor improvement, power generation, various scientific activities, and the adjustment for vertical movement of the Earth's crust in the Great Lakes Basin.

neap range
See neap tides.

neap tides or tidal currents
Tides of decreased range or tidal currents of decreased speed occurring semimonthly as the result of the Moon being in quadrature. The neap range (Np) of the tide is the average range occurring at the time of neap tides and is most conveniently computed from the harmonic constants. It is smaller than the mean range where the type of tide is either semi diurnal or mixed and is of no practical significance where the type of tide is predominantly diurnal. The average height of the high waters of the neap tide is called neap high water or high water neaps (MHWN) and the average height of the corresponding low waters is called neap low water or low water neaps (MLWN).

Next Generation Water Level Measurement System (NGWLMS)
A fully integrated system encompassing new technology sensors and recording equipment, multiple data transmission options, and an integrated data processing, analysis, and dissemination subsystem.

node cycle

Period of approximately 18.61 Julian years required for the regression of the Moon's nodes to complete a circuit of 360° of longitude. It is accompanied by a corresponding cycle of changing inclination of the Moon's orbit relative to the plane of the Earth's Equator, with resulting inequalities in the rise and fall of the tide and speed of the tidal current.

North American Vertical Datum of 1988 (NAVD 88)
A fixed reference for elevations determined by geodetic leveling. The datum was derived from a general adjustment of the first-order terrestrial leveling nets of the United States, Canada, and Mexico. In the adjustment, only the height of the primary tidal bench mark, referenced to the International Great Lakes Datum of 1985 (IGLD 85) Local mean sea level height value, at Father Point, Rimouski, Quebec, Canada was held fixed, thus providing minimum constraint. NAVD 88 and IGLD 85 are identical. However, NAVD 88 bench mark values are given in Helmert orthometric height units while IGLD 85 values are in dynamic heights. See International Great Lakes Datum of 1985, National Geodetic Vertical Datum of 1929, and geopotential difference.

nu (ν_2)
Larger lunar evectional constituent. See lambda. Speed = 28.512,583,1° per solar hour.

O

O_1
Lunar diurnal constituent. See K_1. Speed = 13.943,035,6° per solar hour.

oceanography
Oceanography is the science of all aspects of the oceans, in spite of its etymology. The term, oceanography, however, implies the interrelationships of the various marine sciences of which it is composed. This connotation has arisen through the historical development of marine research in which it has been found that a true understanding of the oceans is best achieved through investigations based on the realization that water, its organic and inorganic contents, motions, and boundaries are mutually related and interdependent.

OO_1
Lunar diurnal, second-order, constituent. Speed = 16.139,101,7° per solar hour.

overtide
A harmonic tidal (or tidal current) constituent with a speed that is an exact multiple of the speed of one of the fundamental constituents derived from the development of the tide-producing force. The presence of overtides is usually attributed to shallow water conditions. The overtides usually considered in tidal work are the harmonics of the principal lunar and solar semi diurnal constituents M_2 and S_2, and are designated by the symbols M_4, M_6, M_8, S_4, S_6, etc. The magnitudes of these harmonics relative to those of the fundamental constituents are usually greater in the tidal current than in the tide.

P

p
Rate of change (as of January 1, 1900) in mean longitude of lunar perigee. p = 0.004,641,83˚ per solar hour.

p_1
Rate of change (as of January 1, 1900) in mean longitude of solar perigee. p_1 = 0.000,001,96˚ per solar hour.

P_1
Solar diurnal constituent. See K_1. Speed = 14.958,931,4˚ per solar hour.

parallel plate intake
Intake of a stilling or protective well with two parallel plates attached below. The plates are typically three times the diameter of the well and are spaced three inches apart. The plates are used to minimize current-induced draw-down (Bernoulli effect) error in water level measurements.

perigean tides or tidal currents
Tides of increased range or tidal currents of increased speed occurring monthly as the result of the Moon being in perigee. The perigean range (Pn) of tide is the average range occurring at the time of perigean tides and is most conveniently computed from the harmonic constants. It is larger than the mean range where the type of tide is either semi diurnal or mixed, and is of no practical significance where the type of tide is predominantly diurnal.

perigee
The point in the orbit of the Moon or man-made satellite nearest to the Earth. The point in the orbit of a satellite nearest to its companion body.

perihelion
The point in the orbit of the Earth (or other planet, etc.) nearest to the Sun.

period
Interval required for the completion of a recurring event, such as the revolution of a celestial body or the time between two consecutive like phases of the tide or tidal current. A period may be expressed in A angular measure and is then taken as 360˚. The word also is used to express any specified duration of time.

phase
(1) Any recurring aspect of a periodic phenomenon, such as new Moon, high water, flood strength, etc. (2) A particular instant of a periodic function expressed in angular measure and reckoned from the time of its maximum value, the entire period of the function being taken as 360˚. The maximum and minimum of a harmonic constituent have phase values of 0˚ and 180˚, respectively.

phase inequality
Variations in the tides or tidal currents due to changes in the phase of the Moon. At the times of new and full Moon the tide-producing forces of the Moon and Sun act in conjunction, causing the range of tide

and speed of the tidal current to be greater than the average, the tides at these times being known as spring tides. At the times of the quadratures of the Moon these forces are opposed to each other, causing neap tides with diminished range and current speed.

PORTS™
Physical Oceanographic Real Time System. A system of current, water level, and meteorological stations telemetering their data to a central location for storage, processing, and dissemination. Available to pilots, mariners, the U.S. Coast Guard, and other marine interests in voice or digital real-time form. First introduced in Tampa Bay.

potential, tide-producing
Tendency for particles on the Earth to change their positions as a. result of the gravitational interactions between the Sun, Moon, and Earth. Although the gravitational attraction varies inversely as the square of the distance of the tide producing body, the resulting potential varies inversely as the cube of the distance.

pressure sensor
A pressure transducer sensing device for water level measurement. A relative transducer is vented to the atmosphere and pressure readings are made relative to atmospheric pressure. An absolute transducer measures the pressure at its location. The readings are then corrected for barometric pressure taken at the surface.

primary control tide station
A tide station at which continuous observations have been made over a minimum of 19 years. Its purpose is to provide data for computing accepted values of the harmonic and non harmonic constants essential to tide predictions and to the determination of tidal datums for charting and for coastal and marine boundaries. The data series from this station serves as a primary control for the reduction of relatively short series from subordinate tide stations through the method of comparison of simultaneous observations and for monitoring long-period sea level trends and variations. See tide station, secondary control tide station, tertiary tide station, and subordinate tide station (1).

protective well
A vertical pipe with a relatively large opening (intake) in the bottom. It is used with the air acoustic ranging sensor and electronic processing (filtering) technique to minimize the nonlinear characteristics of the stilling well. Its purpose is also to shield the sensing element from physical damage and harsh environment. Unlike a stilling well, damping of high frequency waves is not a critical requirement. See stilling well.

Q

Q_1
Larger lunar elliptic diurnal constituent. See M_1. Speed = 13.398,660,9° per solar hour.2Q_1 Lunar elliptic diurnal, second order, constituent. Speed = 12.854,286,2° per solar hour.

quadrature of Moon
Position of the Moon when its longitude differs by 90 deg from the longitude of the Sun. The corresponding phases are known as first quarter and last quarter.

R

R_2
Smaller solar elliptic constituent. This constituent, with $_{T2}$, modulates the amplitude and frequency of S_2 for the effect of variation in the Earth's orbital speed due to its elliptical orbit. Speed = 30.041,066,7° per solar hour.

radiational tide
Periodic variations in sea level primarily related to meteorological changes such as the semidaily (solar) cycle in barometric pressure, daily (solar) land and sea breezes, and seasonal (annual) changes in temperature. Other changes in sea level due to meteorological changes that are random in phase are not considered radiation Al tides.

range of tide
The difference in height between consecutive high and low waters. The mean range is the difference in height between mean high water and mean low water. The great diurnal range or diurnal range is the difference in height between mean higher high water and mean lower low water. For other ranges see spring, neap, perigean, apogean, and tropic tides; and tropic ranges.

real-time
Pertains to a data collecting system that controls an on-going process and delivers its outputs (or controls its inputs) not later than the time when these are needed for effective control.

red tide (water)
The term applied to toxic algal blooms caused by several genera of dinoflagellates (Gymnodinium and Gonyaulax) which turn the sea red and are frequently associated with a deterioration in water quality. The color occurs as a result of the reaction of a red pigment, peridinin, to light during photosynthesis. These toxic algal blooms pose a serious threat to marine life and are potentially harmful to humans. The term has no connection with astronomic tides. However, its association with the word "tide" is from popular observations of its movements with tidal currents in estuarine waters.

reduction of tides or tidal currents
A processing of observed tide or tidal current data to obtain mean values for tidal or tidal current constants.

reference station
A tide or current station for which independent daily predictions are given in the "Tide Tables" and "Tidal Current Tables," and from which corresponding predictions are obtained for subordinate stations by means of differences and ratios. See subordinate tide station (2) and subordinate current station (2).

relative mean sea level change
A local change in mean sea level relative to a network of bench marks established in the most stable and permanent material available (bedrock, if possible) on the land adjacent to the tide station location. A change in relative mean sea level may be composed of both an absolute mean sea level change component and a vertical land movement change component, together.

river current
The gravity-induced seaward flow of fresh water originating from the drainage basin of a river. In the fresh water portion of the river below head of tide, the river current is alternately increased and decreased by the effect of the tidal current. After entering a tidal estuary, river current is the depth averaged mean flow through any cross-section and finally, into the ocean. See head of tide and estuary.

S

s
Rate of change (as of January 1, 1900) in mean longitude of Moon. s = 0.549,016,53˚ per solar hour.

S_1
Solar diurnal constituent. Speed = 15.000,000,0˚ per solar hour.

S_2
Principal solar semi diurnal constituent. This constituent represents the rotation of the Earth with respect to the Sun. Speed = 30.000,000,0˚ per solar hour.

S_4, S_6
Shallow water overtides of the principal solar constituent.
Speed of S_4 = 60.000,000,0˚ per solar hour.
Speed of S_6 = 90.000,000,0˚ per solar hour.

Sa
Solar annual constituent. This constituent, with Ssa, accounts for the nonuniform changes in the Sun's declination and distance. In actuality, they mostly reflect yearly meteorological variations influencing sea level. Speed = 0.041,068,64˚ per solar hour.

Ssa
Solar semiannual constituent. See Sa. Speed = 0.082,137,3˚ per solar hour.

salinity (S)
The total amount of solid material in grams contained in 1 kilogram of sea water when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized. S(˚/oo) = 1.806,55 x Cl (˚/oo) Where Cl(˚/oo) is chlorinity in parts per thousand. See chlorinity.

secondary control tide station

A tide station at which continuous observations have been made over a minimum period of 1 year but less than 19 years. The series is reduced by comparison with simultaneous observations from a primary control tide station. This station provides for a 365-day harmonic analysis including the seasonal fluctuation of sea level. See tide station, primary control tide station, tertiary tide station, and subordinate tide station (1).

secular trend
See apparent secular trend as preferred term.

seiche
A stationary wave usually caused by strong winds and/or changes in barometric pressure. It is found in lakes, semi enclosed bodies of water, and in areas of the open ocean. The period of a seiche in an enclosed rectangular body of water is usually represented by the formula:
Period $(T) = 2L / \sqrt{gd}$
in which L is the length, d the average depth of the body of water, and g the acceleration of gravity. See standing wave.

seismic sea wave
Same as tsunami.

semidiurnal
Having a period or cycle of approximately one-half of a tidal day. The predominant type of tide throughout the world is semi diurnal, with two high waters and two low waters each tidal day. The tidal current is said to be semi diurnal when there are two flood and two ebb periods each day. A semi diurnal constituent has two maxima and two minima each constituent day, and its symbol is the subscript 2. See type of tide.

semidiurnal tide
A tide with two high and two low waters in a tidal day with comparatively little diurnal tide inequality.

sequence of tide
The order in which the four tides of a day occur, with special reference as to whether the higher high water immediately precedes or follows the lower low water.

shallow water constituent
A short-period harmonic term introduced into the formula of tidal (or tidal current) constituents to take account of the change in the form of a tide wave resulting from shallow water conditions. Shallow water constituents include the overtides and compound tides.

shallow water wave
A wave is classified as a shallow water wave whenever the ratio of the depth (the vertical distance of the still water level from the bottom) to the wave length (the horizontal distance between crests) is less than 0.04. Such waves propagate according to the formula:
$C = \sqrt{gd}$

where C is the wave speed, g the acceleration of gravity, and d the depth. Tidal waves are shallow water waves.

shoreline (coastline)
The intersection of the land with the water surface. The shoreline shown on charts represents the line of contact between the land and a selected water elevation. In areas affected by tidal fluctuations, this line of contact is the mean high water line. In confined coastal waters of diminished tidal influence, the mean water level line may be used. The shoreline is defined as MHW.

sidereal day
The time of the rotation of the Earth with respect to the vernal equinox. It equals approximately 0.997,27 of a mean solar day. Because of the precession of the equinoxes, the sidereal day thus defined is slightly less than the period of rotation with respect to the fixed stars, but the difference is less than the hundredth part of a second.

small diurnal range (Sl)
Difference in height between mean lower high water and mean higher low water.

small tropic range (Sc)
Difference in height between tropic lower high water and tropic higher low water.

solar day
The period of the rotation of the Earth with respect to the Sun. The mean solar day is the time of the rotation with respect to the mean Sun. The solar day commencing at midnight is called a civil or calendar day, but if the day is reckoned from noon it is known as an astronomical day because of its former use in astronomical calculation.

solar tide
(1) The part of the tide that is due to the tide-producing force of the Sun. (2) The observed tide in areas where the solar tide is dominant. This condition provides for phase repetition at about the same time each solar day.

solstices
The two points in the ecliptic where the Sun reaches its maximum and minimum declinations; also the times when the Sun reaches these points. The maximum north declination occurs on or near June 21, marking the beginning of summer in the Northern Hemisphere and the beginning of winter in the Southern. The maximum south declination occurs on or near December 22, marking the beginning of winter in the Northern Hemisphere and the beginning of summer in the Southern.

solstitial tides
Tides occurring near the times of the solstices. The tropic range may be expected to be especially large at these times.

species of constituent

A classification depending upon the period of a constituent. The principal species are semidiurnal, diurnal, and long-period.

spring high water
Same as mean high water springs (MHWS). See spring tides.

spring low water
Same as mean low water springs (MLWS). See spring tides and mean low water springs.

spring range (Sg)
See spring tides.

spring tides or tidal currents
Tides of increased range or tidal currents of increased speed occurring semimonthly as the result of the Moon being new or full. The spring range (Sg) of tide is the average range occurring at the time of spring tides and is most conveniently computed from the harmonic constants. It is larger than the mean range where the type of tide is either semi diurnal or mixed, and is of no practical significance where the type of tide is predominantly diurnal. The average height of the high waters of the spring tides is called spring high water or mean high water springs (MHWS) and the average height of the corresponding low waters is called spring low water or mean low water springs (MLWS).

stand of tide
Sometimes called a platform tide. An interval at high or low water when there is no sensible change in the height of the tide. The water level is stationary at high and low water for only an instant, but the change in level near these times is so slow that it is not usually perceptible. In general, the duration of the apparent stand will depend upon the range of tide, being longer for a small range than for a large range, but where there is a tendency for a double tide the stand may last for several hours even with a large range of tide.

stationary wave theory
An assumption that the basic tidal movement in the open ocean consists of a system of stationary wave oscillations, any progressive wave movement being of secondary importance except as the tide advances into tributary waters. The continental masses divide the sea into irregular basins, which, although not completely enclosed, are capable of sustaining oscillations which are more or less independent. The tide-producing force consists principally of two parts, a semi diurnal force with a period approximately the half-day and a diurnal force with a period of a whole day. Insofar as the free period of oscillation of any part of the ocean, as determined by its dimensions and depth, is in accord with the semi-diurnal or diurnal tide-producing forces, there will be built up corresponding oscillations of considerable amplitude which will be manifested in the rise and fall of the tide. The diurnal oscillations, superimposed upon the semi diurnal oscillations, cause the inequalities in the heights of the two high and the two low waters of each day. Although the tidal movement as a whole is somewhat complicated by the overlapping of oscillating areas, the theory is consistent with observational data.

stilling well

A vertical pipe with a relatively small opening (intake) in the bottom. It is used in a gauge installation to dampen short period surface waves while freely admitting the tide, other long period waves, and sea level variations; which can then be measured by a tide gauge senor inside. See float well and protective well.

storm surge
The local change in the elevation of the ocean along a shore due to a storm. The storm surge is measured by subtracting the astronomic tidal elevation from the total elevation. It typically has a duration of a few hours. Since wind generated waves ride on top of the storm surge (and are not included in the definition), the total instantaneous elevation may greatly exceed the predicted storm surge plus astronomic tide. It is potentially catastrophic, especially on low lying coasts with gently sloping offshore topography. See storm tide.

storm tide
As used by the National Weather Service, NOAA, the sum of the storm surge and astronomic tide. See storm surge.

submerged lands
Lands covered by water at any stage of the tide. See tidelands.

subordinate tide station
(1) A tide station from which a relatively short series of observations is reduced by comparison with simultaneous observations from a tide station with a relatively long series of observations. See tide station, primary control tide station, secondary control tide station, and tertiary tide station. (2) A station listed in the Tide Tables from which predictions are to be obtained by means of differences and ratios applied to the full predictions at a reference station. See reference station.

T

T
Rate of change of hour angle of mean Sun at place of observation. T = 15˚ per mean solar hour.

T_2
Larger solar elliptic constituent. See R_2.
Speed = 29.958,933,3˚ per solar hour.

telemetry
The capability of transmitting or retrieving data over long distance communication links, such as satellite or telephone.

terdiurnal
Having three periods in a constituent day. The symbol of a terdiurnal constituent is the subscript 3.

tertiary tide station

A tide station at which continuous observations have been made over a minimum period of 30 days but less than 1 year. The series is reduced by comparison with simultaneous observations from a secondary control tide station. This station provides for a 29-day harmonic analysis. See tide station, primary control tide station, secondary control tide station, and subordinate tide station (1).

tidal bench mark description
A published, concise description of the location, stamped number or designation, date established, and elevation (referred to a tidal datum) of a specific bench mark.

tidal characteristics
Principally, those features relating to the time, range, and type of tide.

tidal constants
Tidal relations that remain practically constant for any particular locality. Tidal constants are classified as harmonic and non harmonic. The harmonic constants consist of the amplitudes and epochs of the harmonic constituents, and the non harmonic constants include the ranges and intervals derived directly from the high and low water observations.

tidal datum
See datum.

Tidal day
The time of the rotation of the earth with respect to the moon, approximately 24 hours and 50 minutes. Same as lunar day.

tidal difference
Difference in time or height between a high or low water at a subordinate station and a reference station for which predictions are given in the Tide Tables. The difference, when applied according to sign to the prediction at the reference station, gives the corresponding time or height for the subordinate station.

tidal epoch
See National Tidal Datum Epoch and epoch.

tidal estuary
See estuary.

tidal range
The difference in height between consecutive high and low (or higher high and lower low) waters.

tidal wave
A shallow water wave caused by the gravitational interactions between the Sun, Moon, and Earth. Essentially, high water is the crest of a tidal wave and low water, the trough. Tidal current is the horizontal component of the particulate motion, while tide is manifested by the vertical component. The observed tide and tidal current can be considered the result of the combination of several tidal waves,

each of which may vary from nearly pure progressive to nearly pure standing and with differing periods, heights, phase relationships, and direction.

tidal zoning
The practice of dividing a hydrographic survey area into discrete zones or sections, each one possessing similar tidal characteristics. One set of tide reducers is assigned to each zone. Tide reducers are used to adjust the soundings in that zone to chart datum (MLLW). Tidal zoning is necessary in order to correct for differing water level heights occurring throughout the survey area at any given time. Each zone of the survey area is geographically delineated such that the differences in time and range do not exceed certain limits, generally 0.2 hours and 0.2 feet respectively; however, these limits are subject to change depending upon type of survey, location, and tidal characteristics. The tide reducers are derived from the water levels recorded at an appropriate tide station, usually nearby. Tide reducers are used to correct the soundings throughout the hydrographic survey area to a common, uniform, uninterrupted chart datum. See tide reducers.

tide
The periodic rise and fall of the water resulting from gravitational interactions between Sun, Moon, and Earth. The vertical component of the particulate motion of a tidal wave. Although the accompanying horizontal movement of the water is part of the same phenomenon, it is preferable to designate this motion as tidal current. See tidal wave.

tide curve
A graphic representation of the rise and fall of the tide in which time is usually represented by the abscissa and height by the ordinate. For a semidiurnal tide with little diurnal inequality, the graphic representation approximates a cosine curve. See marigram.

tide (water level) gauge
An instrument for measuring the rise and fall of the tide (water level). See ADR gauge, automatic tide gauge, Next Generation Water Level Measurement System, gas purged pressure gauge, electric tape gauge, pressure gauge, and tide staff.

tide-producing force
That part of the gravitational attraction of the Moon and Sun which is effective in producing the tides on the Earth. The force varies approximately as the mass of the attracting body and inversely as the cube of its distance. The tide-producing force exerted by the Sun is a little less than one-half as great as that of the Moon. A mathematical development of the vertical and horizontal components of the tide-producing forces of the Moon and Sun will be found in Coast and Geodetic Survey Special Publication No. 98.

tide reducers
Height corrections for reducing soundings to chart datum (MLLW). A tide reducer represents the height of the water level at a given place and time relative to chart datum. Tide reducers are obtained from one or more tide stations within or nearby the survey area. Often, due to differing tidal characteristics over the survey area, the tide reducers obtained directly from a tide station must be corrected to adjust for time and range of tide differences in the various zones of the hydrographic survey area. See tidal zoning.

tide staff
A tide gauge consisting of a vertical graduated staff from which the height of the tide can be read directly. It is called a fixed staff when secured in place so that it cannot be easily removed. A portable staff is one that is designed for removal from the water when not in use. For such a staff a fixed support is provided The support has a metal stop secured to it so that the staff will always have the same elevation when installed for use. See electric tape gauge.

tide (water level) station
The geographic location at which tidal observations are conducted. Also, the facilities used to make tidal observations. These may include a tide house, tide gauge, tide staff, and tidal bench marks. See primary control tide station, secondary control tide station, tertiary tide station, and subordinate tide station (1).

Tide Tables
Tables which give daily predictions of the times and heights of high and low waters. These predictions are usually supplemented by tidal differences and constants through which predictions can be obtained for numerous other locations.

tidelands
The zone between the mean high water and mean low water lines. It is identical with intertidal zone (technical definition) when the type of tide is semi diurnal or diurnal.

tidewater
Water activated by the tide generating forces and/or water affected by the resulting tide, especially in coastal and estuarine areas. Also, a general term often applied to the land and water of estuarine areas formed by postglacial drowning of coastal plain rivers.

time, kinds
Time is measured by the rotation of the Earth with respect to some point in the celestial sphere and may be designated as sidereal, solar, or lunar, according to whether the measurement is taken in reference to the vernal equinox, the Sun, or the Moon. Solar time may be apparent or mean, according to whether the reference is to the actual Sun or the mean Sun. Mean solar time may be local or standard, according to whether it is based upon the transit of the Sun over the local meridian or a selected meridian adopted as a standard over a considerable area. Greenwich time is standard time based upon the meridian of Greenwich. In civil time the day commences at midnight, while in astronomical time, as used prior to 1925, the beginning of the day was reckoned from noon of the civil day of the same date. The name universal time is now applied to Greenwich mean civil time.

time meridian
A meridian used as a reference for time.

tractive force
The horizontal component of a tide producing force vector (directed parallel with level surfaces at that geographic location).

transit

The passage of a celestial body over a specified meridian. The passage is designated as upper transit or lower transit according to whether it is over that part of the meridian lying above or below the polar axis.

tropic inequalities
Tropic high water inequality (HWQ) is the average difference between the two high waters of the day at the times of tropic tides. Tropic low water inequality (LWQ) is the average difference between the two low waters of the day at the times of tropic tides. These terms are applicable only when the type of tide is semi diurnal or mixed. See tropic tides.

tropic intervals
Tropic higher high water interval (TcHHWI) is the lunitidal interval pertaining to the higher high waters at the time of the tropic tides. Tropic lower low water interval (TcLLWI) is the lunitidal interval pertaining to the lower low waters at the time of the tropic tides. Tropic intervals are marked a when reference is made to the upper transit of the Moon at its north declination or to the lower transit at the time of south declination, and are marked b when the reference is to the lower transit at the north declination or to the upper transit at the south declination. See tropic tides.

tropic ranges
The great tropic range (Go), or tropic range, is the difference in height between tropic higher high water and tropic lower low water. The small tropic range (Sc) is the difference in height between tropic lower high water and tropic higher low water. The mean tropic range (Mc) is the mean between the great tropic and the small tropic range. Tropic ranges are most conveniently computed from the harmonic constants. See tropic tides.

tropic tides
Tides occurring semimonthly when the effect of the Moon's maximum declination is greatest. At these times there is a tendency for an increase in the diurnal range. The tidal datums pertaining to the tropic tides are designated as tropic higher high water (TcHHW), tropic lower high water (TcLHW), tropic higher low water (TcHLW), and tropic lower low water (TcLLW).

tropical year
The average period of the revolution of the Earth around the Sun with respect to the vernal equinox. Its length is approximately 365.242,2 days. The tropical year determines the cycle of changes in the seasons, and is the unit to which the calendar year is adjusted through the occasional introduction of the extra day on leap years.

trough
The lowest point in a propagating or standing wave. See low water and tidal wave.

tsunami
A shallow water progressive wave, potentially catastrophic, caused by an underwater earthquake or volcano.

type of tide

A classification based on characteristic forms of a tide curve. Qualitatively, when the two high waters and two low waters of each tidal day are approximately equal in height, the tide is said to be semidiurnal; when there is a relatively large diurnal inequality in the high or low waters or both, it is said to be mixed; and when there is only one high water and one low water in each tidal day, it is said to be diurnal. Quantitatively (after Dietrich), where the ratio of $K_1 + O_1$ to $M_2 + S_2$ is less than 0.25, the tide is classified as semidiurnal; where the ratio is from 0.25 to 1.5, the tide is mixed, mainly semidiurnal; where the ratio is from 1.5 to 3.0, the tide is mixed, mainly diurnal; and where greater than 3.0, diurnal.

U

universal time (UT)
Same as Greenwich mean time (GMT).

uplands
Land above the mean high water line (shoreline) and subject to private ownership, as distinguished from tidelands, the ownership of which is prima facie in the state but also subject to divestment under state statutes. See tidelands.

V

vanishing tide
In a predominantly mixed tide with very large diurnal inequality, the lower high water (or higher low water) becomes indistinct (or vanishes) at times of extreme declinations.

W

wave height
The vertical distance between crest and trough. See range of tide.

Z

Z_0
Symbol recommended by the International Hydrographic Organization to represent the elevation of mean sea level above chart datum.

Appendix A: Chronology of Significant Events in the Analysis of Tides and Tidal Datums

Table A1. Chronology of Significant Events:

1807 — The Survey of the Coast established.
1830 — Tide predictions for United States began. Published in The American Almanac. High water time predictions (one per day) for Boston, New York, and Charleston. Time differences for 96 other stations. Spring range predictions for 84 stations.
1836 — The Survey of the Coast became Coast Survey.
1844 — Tide notes (including lunitidal intervals) on nautical charts began.
1853 — Tables for obtaining tide predictions by the nonharmonic lunitidal interval method first published in the appendix to the Annual Report.
1864 — Last year of tables for lunitidal interval method. One thousand copies provided to Union naval forces.
1867 — First Tide Tables published.
1868 — Low water predictions began for west coast of Florida and Pacific coast.
1878 — Coast Survey became Coast and Geodetic Survey.
1885 — William Ferrel's Maxima and Minima Tide Predictor introduced.
1887 — Low water predictions included for all stations.
1890 — Tidal current predictions began (New York Harbor and vicinity).
1896 — Extension of tables to include numerous ports throughout the world.
1912 — Harris-Fischer Tide Predicting Machine introduced.
1914 — Last year Ferrel's Maxima and Minima Tide Predictor used.
1923 — Tidal Current Tables first published separately from Tide Tables (two volumes, Atlantic Coast and Pacific Coast, North America).
1928 — Single port miniature tables introduced.
1932 — Last year of single port miniature tables (revived from 1940 through 1944 for New York Harbor and vicinity only).
1940 — Special restricted tables for war effort began.
1951 — Last year of special wartime and occupation tables.
1955 — Special Tide Tables for selected places in Greenland, Canada, and Alaska began.
1959 — Tide predictions added to Small Craft Chart series.
1961 — Motor drive and automatic readout installed on Harris-Fischer machine.
— Last year of special Tide Tables for selected places in Greenland, Canada, and Alaska.
1965 — Last year Harris-Fischer Tide Predicting Machine used.
— Analog-to-digital recorder (ADR) tide gauges and computer processing introduced.
1966 — Electronic digital computer introduced for predictions.
1967 — Established Estuarine Flushing and Nontidal Current Prediction Service.
— International Symposium on Mean Sea Level, IAPO and UNESCO.
— Electronic digital computer introduced for harmonic analysis of tides.
1970 — Coast and Geodetic Survey became National Ocean Survey.
1973 — Established National Tidal Datum Epoch.
— Telemetered water level measurements introduced for Great Lakes.
1977 — Gulf Coast Low Water Datum adopted.
1978 — Water Level Telemetry System introduced for marine coasts.
1980 — National Tidal Datum Convention of 1980 adopted.
1982 — National Ocean Survey became National Ocean Service.
— Personal computer software introduced for local user access to water level telemetry stations.
1987 — Tidal Circulation and Water Level Forecast Atlas introduced.
— Operational RADS current meter system introduced.
1988 — International Conference on Tidal Hydrodynamics.
— Personal computer software introduced for local user access to current telemetry stations.
— Operational NGWLMS field units introduced using an air acoustic ranging sensor and satellite telemetry.
1995 — Operational NGWLMS field units become standard. Last year ADR gauges used.
1996 — NGWLMS Data processing and analysis system becomes operational.
1997 — Internet and Web access implemented for products.