APPENDIX M

Uncertainty Model for Orthometric, Tidal, and Hydraulic Datums for use in Risk Assessment Models

M-1. Purpose. This appendix contains excerpted portions from a technical report on datum uncertainty models performed by the Conrad Blucher Institute for Surveying and Science, Texas A&M University (Corpus Christi). The uncertainty study was performed for the USACE Vertical Project Control Delivery Team in 2009. The scope of the study is outlined in paragraph M-2 below. The unedited version of the study report (*Uncertainty Model for Orthometric, Tidal, and Hydraulic Datums for Use in Risk Assessment Models, Phase 2 Final Report, dated 3 Sep 09*) can be obtained at the AGC web site referenced in Chapter 1. References cited in this appendix are listed in Section M-15 (Addendum D to this Appendix).

M-2. Executive Summary. This report is the second in a series requested by the U.S. Army Corps of Engineers (USACE) to assess reference datum accuracy requirements that are currently in place, and to establish whether the USACE is able to perform datum reliable uncertainty analyses to ascertain the risks of project failure. The USACE contracted with the Conrad Blucher Institute for Surveying and Science at Texas A & M University-Corpus Christi to produce these reports under the leadership of Dr. Gary Jeffress, Executive Director.

a. This study phase offers a technical discussion of risk assessment, specifically regarding to relevant orthometric and water level datums and datum conversion for use in protection grade design, and discussion of a suggested approach to integrating vertical uncertainty into future USACE project risk assessments.

b. Findings include an analysis of existing risk assessment guidelines within USACE, as well as a statistical discussion of perceived risk versus actual risk. This statistical discussion goes on to compare and quantify accuracy versus uncertainty. Each datum used by the USACE is analyzed for uncertainty and the accompanying risks, including terrestrial datum and water level datum, and datum conversions, such as converting legacy NGVD29 measurements to NAVD88 elevations.

c. The findings reveal that a very limited analysis of risks associated with converting legacy datums to modern datums has been conducted by the USACE, and that these initial studies reveal the complexities involved in the process, as well as a lack of historical data coverage of significant portions of the United States.

d. Finally, after discussions with engineers in the Corps, the study team created a methodology based upon extended discussions with the USACE and surveyors for investigating and incorporating potential sources of vertical inaccuracy into risk assessment models, and designed a project worksheet and flowcharts to aid in this process. A sample application of this worksheet demonstrating how this could be implemented in future USACE projects is included in this report (see Section M-12--Addendum A to this Appendix). The USACE has adopted a vertical accuracy standard of ± 0.25 feet at the 95% confidence level for the connection of

USACE projects to the National Spatial Reference System (NSRS) maintained by the National Oceanic and Atmospheric Administration. While this standard is very acceptable on a national scale, the standard should be taken under review as changes occur to the NSRS in the future.

M-3. Participants.

Name	Agency	Role
Dr. Gary Jeffress	Texas A&M University-Corpus Christi	Team Leader, Surveyor, and Geodesist
Dr. Edward Jones	Risk Assessment Consultant	Statistics and Risk Assessment
Jennifer Bray	Texas A&M University-Corpus Christi	Technical Writer
Adre Deetlefs	Texas A&M University Corpus Christi	Graduate Research Assistant

M-4. Purpose of Study. From Cooperative Agreement W912HZ-8-0012, "Scope of Work," dated 29 Oct. 2008:

The study team, utilizing statistical data from existing National Oceanic and Atmospheric Administration (NOAA) geospatial databases – Coastal Survey Development Lab/VDatum (CSDL), National Geodetic Survey (NGS)/National Spatial Reference System (NSRS), and Center for Operation Oceanographic Products and Services (CO-OPS) – will develop an uncertainty model for the relevant orthometric, tidal, and hydraulic datums for use in protection grade design and risk assessment models.

Uncertainties in geodetic, topographic, or hydrographic survey measurement systems and dynamic sensor errors are not part of this study since these uncertainties should be available from NOAA, or have been indirectly incorporated into existing products, such as the NSRS.

SECTION 1

A Theoretical Framework for Modeling Elevation Uncertainty

M-5. An Overview of Current Risk Assessment Guidelines within the Corps of Engineers.

a. Overview of EM 1110-2-1619 (Risk-Based Analysis for Flood Damage Reduction Studies). The terms risk and risk assessment are used in many ways. The general public has a definition of risk that can be described as perceived risk. Perceived risk is the public perception of the risk of a specific flooding event. Civil engineers, on the other hand, define risk as a probability determined from flood event related data, such as storm discharge, and from flood risk management measures. The purpose of this report is to integrate expanding knowledge of vertical reference datums and their uncertainty with current engineering approaches to risk assessment.

(1) A formal, or civil engineering, definition of risk is based upon probability and scientific analysis of factors contributing to the flooding event as well as the efficacy of flood risk management measures. Bulletin #17B (1981) *Guidelines for Determining Flood Flow Frequency*, published by the Federal Hydrology Subcommittee states:

> "*…risk is defined as the probability that one or more events will exceed a given flood magnitude within a specified period of years."*

(2) In EM 1110-2-1619 (1996) *Risk-Based Analysis for Flood Damage Reduction Studies* the USACE defines long-term risk in a similar way:

> "*The probability of capacity exceedance during a specified period. For example, 30-year risk refers to the probability of one or more exceedances of the capacity of a measure during a 30-year period*."

(3) This report formalizes this definition using the following notation. If E is a defined flooding event and Y is a specified time period, the risk of one or more flooding event during this period is defined as the conditional probability: $P_Y = P(E > 0 \mid Y)$. If $P_1 = P(E \mid 1)$ is the risk of flooding for a single year and if this is assumed to be independent and unvarying from year to year then it follows that $P_Y = 1 - (1 - P_1)^Y$. Independence of flooding from year to year is typically assumed when little historical data is available.

(4) The same engineering manual goes on to describe the traditional approach to dealing with uncertainty in design by incorporating somewhat arbitrary safety factors into flood risk management plans:

(5) EM 1110-2-1619 also offers a more quantitative approach to assessing risk using quantifiable uncertainty:

"Quantitative risk analysis describes the uncertainties, and permits evaluation of their impact."

b. Statistical Considerations. As described above, there are two definitions of risk: perceived versus actual. This perception is formed based upon recent reporting of the same or similar events. Although perceived risk can have little relationship to more formal risk assessments, it can play an important role in public support of flood risk management.

(1) Actual risk, as defined by engineers, is a probability calculation P_Y. There are many factors that can cause perceived and actual risks to diverge. One potential cause is stating risk as the probability of a flood in a single year, P_1. For example if the probability of a defined flooding event is 1/100, 1 in 100 years, then the probability of one or more floods during a 50-year period is:

$$P_{50} = P(E > 0 \mid 50) = 1 - (1 - 0.01)^{50} = 0.39$$

If this were a flood risk management project with a life expectancy of 50 years, we would say that there is a 39% chance of seeing one or more of these flood events during the life expectancy of this project. Stating that there is only a 1% chance of a flood each year is correct, but understates the risk over the project lifespan.

(2) The relationship between risk and project lifespan is illustrated in Figure M-1 for P_1= 1/100:

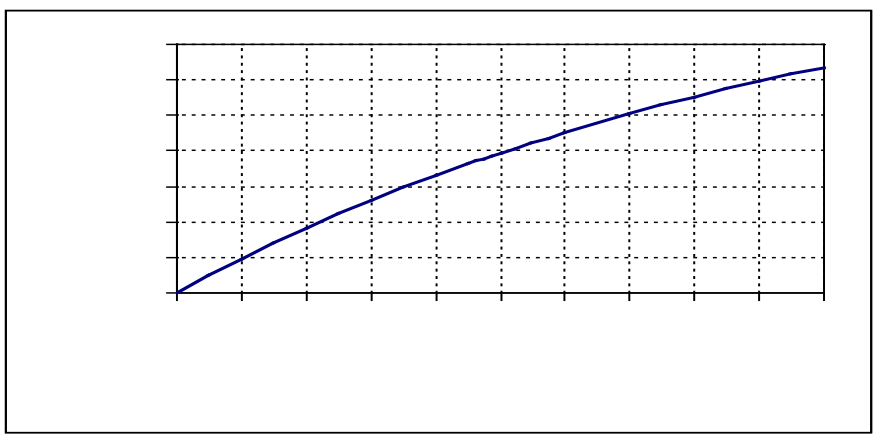

Figure M-1. Risk vs. Project Lifespan for P_1 = 1/100.

This calculation of risk versus project lifespan using the annual probability of flooding can be reversed. The probability of flooding in a single year, P_1, is determined from the distribution of flood events together with the probability that the flood risk management measures control these events. Sometimes it is easier to design a structure using the annual probability of flooding.

(3) The question is what value of P_1, the annual probability of flooding, is needed to provide a stated risk, R over the project lifespan, Y. This is answered by solving for P_1 in the equation $R = 1-(1-P_1)^Y$, yielding the relationship:

$$P_1 = 1 - e^{\left(\ln(1-R)/Y\right)}$$

For example, if we required a risk of less than ten percent for a 50-year project lifespan, the flood risk management project would need to be designed to reduce the probability of flooding in a single year to 2/1000:

$$P_1 = 1 - e^{\left(\ln(1-0.1)/50\right)} = 0.002$$

For small values of R and large values of Y, $R \leq 1/10$ and $Y \geq 50$, this calculation is approximately equal to the ratio R/Y.

c. Quantifying Uncertainty - Accuracy vs. Precision. Uncertainty in vertical measurements arises because of several factors, some involving measurement error and others arising from bias or calibration issues. Measurement error, also referred to as measurement precision, occurs from factors that cause variation in vertical measurements that cannot be entirely controlled. Field surveys, for example, are expected to have some small measurement errors due to instrument inaccuracies as well as small variations in field procedures and environments. Measurements from tidal gages exhibit short term variation from predicted tides due to meteorological changes.

(1) Bias or calibration errors are systematic deviations of the true elevation from the measured elevation. A bench mark, for example, may have been subject to land subsidence making the actual height of the bench mark lower than the bench mark's stated height. Although survey measures using this bench mark might contain only small measurement errors, they will yield heights on newly surveyed points that will all be systematically computed with values higher than their actual height. Similarly, if the realization of a vertical datum in an area is systematically lower or higher than truth, then this causes bias in other marks.

(2) The accuracy of a vertical or horizontal measurement is a function of both measurement bias and precision. Formally, accuracy is defined as the expectation of the square of the difference between the measurement M and the true value T:

$$EMSE = E(M-T)^2 = (E(M)-T)^2 + \sigma^2 = Bias^2 + Var(M).$$

In this statistical formulation, $E(M)$ is the expected value for M, the measurement. The expected deviation of the measurement from its true value, $E(M-T)^2$, is commonly referred to as the expected mean squared error, or EMSE, for the measurement. The squared bias, $(E(M)-T)^2$, is a consequence of calibration issues and systematic differences in the datum

realization. The variance, σ^2, is the measurement error or precision associated with the measurement.

(3) In many cases, the variance or precision of a vertical measurement is much smaller than the bias. In practice, the systematic deviation of a measurement from the reference system is several times larger than the measurement precision. However, risk assessments for some flood risk management projects should include all sources contributing to vertical measurement accuracy over the life expectancy of the project.

M-6. Modeling Elevation Uncertainty--Major Factors Contributing to Elevation Uncertainty. The risk of a flooding event depends upon both the probability of a flood event and the probability that it exceeds the flood risk management measures. Bulletin 17B (1981) sets general guidelines for modeling the flood event distribution using historical gage data. In most flood risk management projects, the probability that a flood event exceeds the flood risk management measures depends upon several vertical measurements. For most flood reduction projects, the accuracy of these measurements is critical. Figure M-2 illustrates a general process for investigating and assessing the impacts of elevation measurement inaccuracy in risk modeling. The major sources of inaccuracy can be organized into three major categories: (1) Terrestrial or Orthometric Elevations, (2) Water Level Elevations, both tidal and non-tidal, and (3) Datum Realizations and Conversions from legacy datum to current project datum.

Figure M-2. Major Sources of Elevation Inaccuracies.

In some flood risk reduction projects, it is necessary to evaluate the elevation inaccuracies arising from all three areas. Other projects may require attention to only one area, such as datum conversion. Any inaccuracy concerns can be further described in terms of a bias and variance

factor, as described above. In most cases, the variance is solely considered, such as for the inaccuracies associated with datum conversions. In some cases, such as land subsidence and rebound, the estimated bias, or offset, over the project lifespan becomes important. Once these inaccuracies are summarized in terms of bias and variance errors, the overall inaccuracy in elevations can be expressed using the expected mean squared error, *EMSE* calculation described above. This in turn should be incorporated into elevations used in engineering risk modeling for a project.

a. Terrestrial Elevations. A terrestrial datum (zero elevation) establishes the standard used for terrestrial leveling such as North American Vertical Datum of 1988 (NAVD88) and its earlier cousin National Geodetic Vertical Datum of 1929 (NGVD29). Onsite vertical measurements are made relative to a fixed point (height of the primary tidal benchmark at Father Point/Rimouski, Quebec, Canada for NAVD88) and tied to local elevation networks as needed. Vertical measurements are subject to measurement errors and bias. In some cases these errors are a result of well established and measured factors, such as leveling measurement precision defined by the quality of the instrument and its correct use, and in others they result from known and difficult to quantify factors such as insufficient coverage of known elevations in the project area.

(1) Subsidence and Rebound. Land subsidence is common along the Gulf coast of the United States, whereas land rebound is common along the coast of Alaska. The combined effects of land subsidence, or isostatic rebound, coupled with sea level changes are referred to as relative sea level rise or fall. This can be a large source of elevation errors. Worse still, relative sea level changes results in elevation bias, bias in which most assumed project elevations are too high or too low. In some cases it is possible to separate land subsidence or rebound from changing sea levels. However, in many cases there are insufficient data to separate the two effects. In engineering risk assessments, subsidence and rebound cause elevations to change relative to the intended datum over the project lifespan. This can be a critical consideration. In many areas, the effects of relative sea level change can be estimated over the life expectancy of the project. In Galveston, Texas, for example, historical data at the Galveston Pier 21 tide gage indicated an average relative sea level rise of approximately 0.21 feet every decade. For a project with a life expectancy of 50 years, this results in a relative sea level rise of approximately one foot.

(2) Elevation Measurements. Elevation measurements can consist of both bias and measurement error. Bias in leveling can occur when established surveying standards are not followed, instruments are not properly calibrated, or when measurements are not properly adjusted for ambient conditions. When chart or topographic elevations are used as project elevations, a bias can occur when the charts are out-of-date. The result is a set of measurements that can be precise, but which are all shifted too high or too low.

(a) Measurement errors in leveling can generally be controlled to small tolerances when established surveying standards are followed. In fact it is common practice to record measurement deviations in closed-loop surveys in the survey log. Closed-loop survey deviations are required to be smaller than the values shown in Table M-1 to ensure the precision of the measurements are within those tolerances. The a priori standard errors of 1 km of single-run

leveling for first-, second-, and third-order leveling used by NGS to incorporate data into the NSRS follow in Table M-1:

Table M-1. Allowable Leveling Misclosures. (from Zilkoski, et al (1992)).

first-order, class 0	*= 0.7 mm*
first-order, class I	*= 1.1 mm*
first-order, class II	*= 1.4 mm*
second-order, class I	*= 2.1 mm*
second-order, class II	*= 2.8 mm*
second-order, class 0	*= 3.0 mm*
third-order	*= 4.2 mm*

The estimates of these standard errors were empirically determined in the late 1970s using the limited amount of data available in computer-readable form at the time the analysis was performed.

(b) It should be noted, however, that survey tolerances used in closed-loop surveys only control measurement error, not measurement bias. In practice, leveling bias is assumed to be small enough to ignore since it would arise from unobserved errors such as relying upon only one faulty monument to adjust the survey observations. If a faulty monument is used, it will bias all recorded vertical elevations by the amount its assumed elevation deviates from its true elevation. This bias is overcome by the USACE requirement to have a minimum of three control monuments for each project, although this requirement will not alleviate broadly occurring subsidence that affects all three monuments.

(c) In most projects, following established surveying standards ensures that measurement error and bias in leveling elevations are small enough to be ignored. Good leveling quality control measures (such as archiving and checking survey log computations) are used to validate these assumptions.

(3) Datum Coverage. Errors in conversion can occur for inadequate or insufficient coverage by one or more of the reference datums. This can result in datum conversion bias on the order of several feet in some extreme cases, for example in some projects involving old legacy datums. In instances when understanding risk and uncertainty in elevation is critical, direct measurements should be used to ensure accurate datum conversion. Conversion from one datum in the project area to another is common. For example this can occur when older elevations, such as NGVD29, are converted to NAVD88 and used in project construction. The accuracy of datum conversions relies on assumed datum accuracy in the project area, and although one datum may be accurate the other may not. Software such as VERTCON and CORPSCON readily supply a conversion from NGVD29 to NAVD88 and vice versa.

(4) National Spatial Reference System Adjustment. In order to ensure consistency between various vertical measurement surveys, the USACE requires all project vertical networks be tied

to the NSRS. This ensures vertical measurement consistency over larger areas and allows planners and engineers to answer larger area flood event questions. These might occur, for example, from unexpected large-scale disasters, such as a dam failure or other, larger than expected, flood events. Conversion of elevations on existing project datums to the current NSRS datum can be inaccurate. Datum conversions, especially vertical datums, are based on models, which may not be reliable. While care is taken to use properly qualified monuments in this conversion, larger projects may have coverage gaps resulting in inaccurate conversions.

b. Water Level Datum. Water level datums can be tidal or non-tidal. A tidal datum consists of lunar-solar tide-affected water level measurements at tide gages such as mean sea level (MSL) or Mean Lower Low Water (MLLW). A non-tidal datum consists of local water level measurements (on bodies of water no measurably affected by lunar-solar tides, like lakes or rivers) such as a low water reference plane (LWRP). Uncertainties in tidal and non-tidal datum realizations can occur from several sources, including gage accuracy and placement. These should also be considered in the total elevation uncertainty budget.

(1) Tidal Elevations. Tidal datums stem from measurements of sea level, and in the case of the Great Lakes, lake levels, at long term tidal gages. Measurements at these gages are averaged over an epoch, a 19 year period, to obtain local mean sea level (LMSL) and other tidal datum at a particular location (see Section M-13--Addendum B to this Appendix). The accuracy of these datums is important to projects near the coasts. The accuracy is influenced by several factors, including gage construction and age, the location of the gage relative to the project area, the historical record from that gage, and any relative sea level change in that area. For short-term station observations (few months to a few years), NOAA uses a method of simultaneous comparison with a National Water Level Observation Network (NWLON) station to determine equivalent 19 National Tidal Datum Epoch (NTDE) values (accuracies are discussed later. See Addendum B to this Appendix at Section M-13.

(a) Sea Level Change. Relative sea level changes are conceptually easy to monitor and estimate. However, data on *absolute* sea level rise or fall are less common. If relative sea level change is the only data available, then its total effect cannot be easily split between absolute sea level change and land subsidence and rebound. However, for assessing the flood damage risks in coastal areas, only the total *relative* sea level change matters. If historical data for relative sea level change is available it should be documented and incorporated into total elevation inaccuracy expressed as a maximum bias and a variance expected over the project lifespan. The bias is an estimate of the total sea level change. The impact of sea level rise is similar to that of land subsidence. The estimated relative sea level rise should be calculated for the project lifespan and entered as a negative bias (-). Any sea level decrease would be expressed as a positive bias (+). The variance of sea level change is an estimate of the uncertainty in the sea level data and the assumption that future changes in sea levels will continue as seen in the historical data. This variance is the variation of sea levels around the sea level trend, and normally would not be expected to change from one epoch to the next. USACE policy for incorporating sea-level change in project planning and design is contained in USACE EC -1165-2-211, 1 July 2009, *Water Resource Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs.*

(b) Gage Uncertainty. Gage uncertainty has been reduced with the installation of newer digital tide gages by NOS. NOAA's National Ocean Service currently uses a digital acoustic Next Generation Water Level Measurement System (NGWLMS). The NGWLMS water level sensors have an accuracy of about 1.0 cm for each sample (*Schultz, et al., 1998*). However, many gages used by the Corps of Engineers are very old and rely on older technology, which is less reliable and less accurate than newer NOS gages. For projects using a tidal datum, it is important to determine the age of the gage and its accuracy. The age of the gage is normally within the records. Identifying the technology used by the gage and the resulting accuracy might take additional investigation. This information can be used to determine the accuracy of datums used from these historic gages. The IPET study revealed several daily staff reading records from USACE tide staff gages near New Orleans with record lengths of several decades. However the metadata records from which to put the readings precisely onto a common vertical reference datum were not located, thus limiting the accuracy for sea level trends analyses. When tracking historical records using NGVD29 as a reference, the time period of the NGVD29 value was missing; knowing the time period and the NGVD29 adjustment date is often critical to application for sea level trends and datum relationships.

(c) Proximity of Gage. The location of the gage is also important. Ideally it should be relatively close to the project area. If not, the heights relative to the tidal datum can be expected to be less accurate in the project area.

(d) Epoch Adjustment. Typically tidal water levels are computed by averaging observations over a 19 year period, referred to as an epoch. Averages computed in this manner represent the water levels at mid-epoch. If water levels are changing over time, either from land subsidence or rebound, or from sea level rise or fall, then current water levels and levels at the end of a project lifespan must be adjusted for this trend. This adjustment is achieved simply by determining the expected relative sea level change over the project lifespan. Sea levels such as MSL, mean sea level, are adjusted for this trend by adding or subtracting the maximum bias expected for the project lifespan. This can significantly impact assumed vertical measurements. In the presence of relative sea level changes, this can introduce significant bias in vertical measurements. According to Zervas, 2001: *"The standard errors of the calculated trends are found to be inversely related to the time span of the data available. An inverse power relationship was derived empirically by fitting a least squares line to a log-log plot of the standard errors for each station versus the year range of the data. This relationship gives an estimated requirement of 50 to 60 years of data for obtaining linear MSL trends having a 1 mm/yr precision with a 95% statistical confidence."*

(e) Gage Historical Record. The historical record for a gage is important. Ideally, a complete record over the epoch period is needed to quantify any trend in relative sea level changes. Incomplete records can cause significant error in trend determination relative to current sea levels. Such historical gaps can arise from unexpected events such vessel collisions and significant storm events.

(2) Non-Tidal Elevations. Non-tidal datums stem from measurements at long term stream gages located in rivers, streams, and reservoirs. The accuracy of these datums is important to projects near these locations. The accuracy is influenced by several factors, including gage

construction and age, the location of the gage relative to the project area, the historical record from that gage and any subsidence or rebound in that area.

(a) Low Water Reference Plane. Low water reference planes (LWRP) are established at local stream gages located in rivers, streams, and reservoirs. Like their coastal cousins, these stream gages can be subject to errors and land subsidence or rebound. These should be considered in the calculating an overall adjustment to elevation uncertainty. Errors in the low water reference plane consist of two components: bias and variance. The bias, or systematic errors, only occurs if the gages used to determine the LWRP are subject to land subsidence or rebound, or if the absolute height of the body of water is raised or lowered by design or some non-random affect in the gage design is biasing all of the measurements. The variance, on the other hand, represents the variation of the LWRP extrapolated into the body of water. If gages in a project area, for example, are located a mile apart then the variation of the LWRP over that mile is represented as a variance, which typically would be small in most cases.

(b) Stream Gage Accuracy. The accuracy of the stream gage, its ability to measure flow rates and stage elevation, used to measure the reference plane should also be considered. In some cases the gage may be older or less well maintained. This uncertainty would be represented as an additional variance.

(c) Stream Gage Proximity. The proximity of the stream gage to the project area should be considered for determining the uncertainty of heights in the project. River or stream flow gages that are critical for a project should be located within the project area.

(d) Pool Elevation Record Length. The historical record for a stream gage is important. Incomplete or inaccurate records can cause significant bias in vertical measurements, relative to current water levels. These too should be indicated with a larger variance component in water level elevations.

c. Datum Conversion. Vertical inaccuracy can be caused by datum confusion and conversion problems. Datum confusion occurs when different datums are used on a project without adequate conversions. For example, an engineer might specify a design elevation of 10 feet using NAVD88. During construction, engineers may confuse datums and, for example, refer to an older datum resulting in a construction height of 10 feet using NGVD29. Different datums, such as NAVD88 and NGVD29 can deviate significantly in assumed elevations in many regions of the country. Deviations of 2-3 feet are not unusual. In some areas of the Gulf coast, for example, FEMA requires construction heights above 10 feet to qualify for federal flood insurance. FEMA does not, however, specify which datum should be used in making these measurements. As a result, most surveyors report elevations using NGVD29, which can be numerically greater than the equivalent NAVD88 elevations, giving the illusion of a higher level of protection. See *Elevation Data for Floodplain Mapping*, 2007 published by the Committee on Floodplain Mapping Technologies. Datum conversions can also cause vertical inaccuracy. Typically this results from insufficient coverage for one or more of the reference datums used in the project. Examples of datum conversion issues are described in the following section. Datum conversions are not exact but rely upon unproven models. This can introduce inaccuracy when converting from one datum to another.

SECTION 2

Practical Implications and Examples

M-7. Overview. In the United States, continental geodetic, tidal, and non-tidal datums (including hydraulic) have been around for about two centuries with our greatest knowledge of these datums appearing towards the end of the 20th century. Much of this knowledge came with the advent of computers, precise measurement technologies, and satellite based measurements. While very few engineering projects cover an entire continent (with the exception of transportation and communication systems), most engineering works need homogeneous spatial vertical reference control to manage the flow of stored water, excessive amounts of water, and general surface water runoff in a local and limited geographic area in concert with the natural drainage system.

a. Transportation systems led the need for more expansive homogeneous leveling networks. First was the need for leveling the tidal regime in New York Bay and Hudson River in 1856-57 for maritime purposes. This was followed by the need for leveling to support the construction of railroads, and later roads, both of which covered the entire North American continent. The first comprehensive vertical control network general adjustment resulted in the Sea Level Datum of 1929, which was renamed the National Geodetic Vertical Datum of 1929 (NGVD29) in 1973. This adjustment was constrained to MSL observed at 26 tide gages (21 in the US and five in Canada). It should be noted that the island state and territories of the United States, including American Samoa, Guam, Hawaii, Northern Marianas, Puerto Rico, and the Virgin Islands were never included in NGVD29 or NAVD88. These areas (except Hawaii) have their own local geodetic reference datums. These include, American Samoa Vertical Datum of 2002 (ASVD02), Guam Vertical Datum of 2004 (GUVD04), Northern Marianas Vertical Datum of 2003 (NMVD03), Puerto Rico Vertical Datum of 2002 (PRVD02) and the Virgin Islands Vertical Datum of 2009 (VIVD09).

b. Knowledge obtained since 1929 showed that the deviation of Local Mean Sea Level from the geoid (e.g. “sea surface topography) at the 26 tide gages used as constraints, introduced distortions in the 1929 general adjustment. Combined with other issues (lack of coverage, lack of good surface gravity data, etc.) it became clear that NGVD29 would need to be superseded eventually. Subsequently a re-adjustment of the vertical network, with vastly increased data sets, was undertaken in 1988 and published in 1991 as the North American Vertical Datum 1988 (NAVD88) (Zilkoski, Richards, and Young, 1992). The new NAVD88 adjustment was constrained to LMSL at one tide gage at Father Point/Rimouski, Quebec, Canada. This new vertical datum remains the current official terrestrial vertical datum used by all civil federal mapping authorities throughout the conterminous United States and Alaska. Over 200 modern digital tide gages operated by CO-OPS as part of the National Water Level Observation Network (NWLON), which computes tidal datums now based on the 1983-2001 National Tidal Datum Epoch (NTDE), complement the NAVD88 vertical datum by supplying local tidal datums and local relative sea level trends tied to NAVD88 through leveling. Complementing the NAVD88 and the 200 tide gages is a vertical transformation software tool called VDatum. VDatum translates geospatial data between 36 different vertical reference systems and removes the most serious impediments to data sharing allowing for the easy transformation of elevation data from

one vertical datum to another (NOAA, 2009). VDatum allows for the transformation between onshore terrestrial vertical datums, tidal datums, topographic vertical data, and hydrographic depth data. The datum relationships among tidal and geodetic datums are designed to match the relationships at tide stations. Using hydrodynamic tidal models and other interpolation software, VDatum is particularly useful in interpolating between tide stations along the shore and interpolating across the water surfaces of bays and estuaries.

M-8. Examples of Risk Resulting from Elevation/Datum Uncertainty.

a. Hurricane Katrina - New Orleans, 2005. In October 2005 Lieutenant General Carl A. Strock, USACE Chief of Engineers formed the Interagency Performance Evaluation Task Force (IPET) to determine the facts concerning the performance of the New Orleans Hurricane Protection System (HPS) during Hurricane Katrina. The details of the study are reported in nine volumes (USACE, 2008). Risk and uncertainty are included in the scope of this study. The Executive Summary of IPET Volume II – Geodetic Vertical and Water Level Datums --dated March 2007 specifically addresses water level and datums:

> *"A spatial and temporal variation was found to exist between the geodetic datums and the water level reference datums used to define elevations for regional hydrodynamic conditions. This 0.2- to 3.0-ft variation is critical in relating measurements of wave heights and water level elevations, high-resolution hydrodynamic conditions, water elevations of hydrostatic forces and loadings at levees and floodwalls, elevations of pump station inverts, and related elevations of flood inundation models deriving drainage volumes or first-floor elevations in residential areas. Flood control structures in this region were authorized, designed, and numerically modeled relative to a water level reference datum (e.g., mean sea level). However, these structures were constructed relative to a geodetic vertical datum that was incorrectly assumed as being equivalent to, or constantly offset from, a water level datum. These varied datums, coupled with redefinitions and periodic readjustments to account for the high subsidence and sea level variations in this region, significantly complicated the process of obtaining a basic reference elevation for hydrodynamic modeling, risk assessment, and design, construction, and maintenance of flood control and hurricane protection systems."*

b. Risk, research, and change are addressed in Volume I, "Executive Summary and Overview" of the IPET study dated June 2008:

> *"RISK: Understanding risk is a powerful tool in helping both individuals and government agencies to make consistent and conscientious decisions concerning natural hazard risk management. The ability to quantify risk for large geographical areas and complex engineered systems is just emerging through the work in New Orleans and central California. Risk provides a much richer body of knowledge to understand and manage vulnerability to hazards as well as providing a clear common picture of the situation to all. Risk methods for regional infrastructure, if fully developed, will not only allow assessment of multiple hazards, but also allow collective consideration of life safety, direct and indirect economics, and social-cultural issues, enabling customization of solutions to*

situations. But the evolution and application of risk to support decision making must be enabled by policy which currently does not exist.

RESEARCH: There is much more to learn. If we as a nation hope to manage risk from the most severe hazards, we need to learn how to work with rather than control nature. Research is needed to better define the actual role of natural environments in managing surge and waves; rules of thumb are just too inaccurate. Given the challenges of continued sea level rise and subsidence and the potential for more intense storms, the art of building and sustaining natural environment is especially important. The vulnerability of natural features to large storms is a particular challenge if we are to rely on them for long-term risk reduction. The fact that there are not enough high quality natural materials to build traditional structures demands that we seek innovative alternatives. The ability to routinely monitor conditions and residual risk on a system- wide and regional basis will require much more effective sensing and analysis, particularly concerning geotechnical issues.

CHANGE: Our current policy and practice does not deal well with change. We must be more anticipatory and adaptive as changes occur in the hazard, the system, or the potential consequences. All of these factors changed dramatically over the life of the hurricane protection projects in New Orleans with little capability for appropriate response. This is another symptom of short term rather than long term sustainable strategies, policies and practices for addressing a major life safety need."

c. Hurricane Ike - East Texas, 2008. Devastating flooding also occurred during Hurricane Ike around Galveston Bay and coastal east Texas in September of 2008. One particular subdivision in LaBelle, Texas suffered about four feet of flooding in houses that have been constructed in the past two decades (see Figure M-3). Most homeowners possessed Elevation Certificates (required by FEMA for flood insurance purposes) showing elevations above the flood stage. A post storm investigation revealed that the original elevation leveling survey (conducted in 1982) to establish elevation control for the subdivision was based on an NGS bench mark with a published elevation that was determined in 1959. A Texas Water Commission study in the 1970s of the area revealed that the area where the NGS bench mark was located was subject to approximately three feet of subsidence. Recent surveys of adjoining bench marks shows up to four feet in subsidence in the same area indicating that the area has experienced another foot of subsidence since the Texas Water Commission report.

Figure M-3. Subdivision flooding during Hurricane Ike in 2008; the house floor level location was measured based on connections to inaccurate survey elevation control due to inaccurate survey elevation control. (The house has since been demolished.)
(Photo courtesy of Caroline Miller.)

M-9. Expected Magnitude and Range of Elevation Uncertainty.

a. Terrestrial Datums.

(1) Elevation Determination. Typically surveying measurement estimation precision, like most scientific measuring techniques, relies on repeatability at a 95 percent confidence level. These tolerances are the result of repeated measurements over time with statistical analysis based on a least squares adjustment methodology, whereas accuracy is an estimation of how close the measurement is to the true value. Table M-2 is from USACE Circular 1110-2-6070 [1], 1 July 2009, "*COMPREHENSIVE EVALUATION OF PROJECT DATUMS - Guidance for a Comprehensive Evaluation of Vertical Datums on Flood risk management, Shore Protection, Hurricane Protection, and Navigation Projects*." These recommended standards show allowable error in establishing survey control in the vertical and horizontal and their respective datums.

---

[1] Interim EC 1110-2-6070 was superseded by and incorporated into this manual.

Table M-2. Nominal or Target Accuracy Standards for Connecting USACE Flood Control Projects to the NSRS Network – Primary Project Control Points.

	NSRS Global Accuracy (95%)	Reference Datum
Vertical	± 0.25 ft (± 8 cm)	NAVD88
Horizontal	± 2 ft (± 60 cm)	NAD83

Accuracies stated are at the 95% confidence level relative to points published by NOAA on the NSRS.

(a) It should be noted that these accuracies are easily achievable with modern surveying equipment operated by educated and experienced field staff. This includes geodetic quality GPS equipment, which offers the additional assurance of supplying much tighter horizontal accuracy. As well, the accuracies stated in Table M-2 refer to tying USACE projects to the NSRS. There is every likelihood that vertical precision within a project (i.e., relative accuracies) will be at a much higher standard.

(b) From discussions with USACE engineers and surveyors, these accuracy standards are suitable for the purpose of tying USACE projects to the NSRS. These accuracies are in line with the desire to standardize USACE projects to a common geodetic vertical datum on a national scale. USACE should re-assess and update these accuracy standards as hydrological and hydraulic modelers adopt or require higher accuracies in the future.

(2) Terrestrial Datums. Since 1929, and hence for most of the modern projects undertaken by the USACE, there have been only two official terrestrial vertical datums: NGVD29 and NAVD88. While there are no data available on the accuracy of these adjustments, there have been extensive comparisons of the two datums, with the assumption that the NAVD88 datum is void of distortions introduced by the 1929 adjustment, which were introduced by constraining the adjustment to fit 26 tide gages, as well as from using less rigorous leveling corrections than used in NAVD88.

(3) The NGVD29 datum, while incorporating distortions on a national scale, was precise in a relative sense over regional areas. As such, the NGVD29 served USACE well for the vast majority of its projects. The move to NAVD88, as directed by Lt. General Carl A. Strock, is encouraged, as the NAVD88 datum represents the most accurate terrestrial orthometric datum available. Figure M-4 shows the differences between NAVD88 and NGVD29 (Zilkoski et al, 1992).

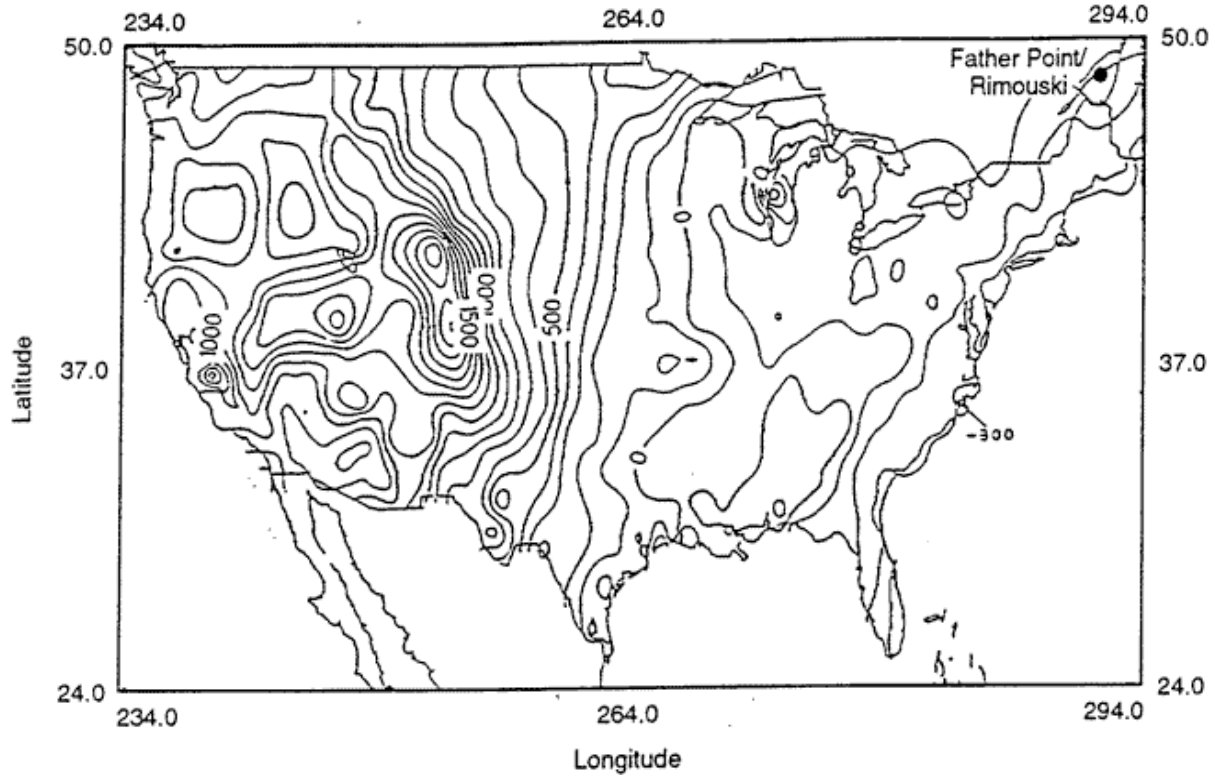

Figure M-4. Contour map depicting height differences between NAVD88 and NGVD29. (units = mm)

(4) Land Subsidence & Isostatic Rebound and Relative Sea Level Change. Surveyors and engineers should pay close attention when determining elevations in areas that are prone to subsidence or isostatic rebound. Examples of each of these geotechnical phenomena can be seen in tide gage records from CO-OPS (see http://www.co-ops.nos.noaa.gov/sltrends/). Figure M-5 shows the relative sea level change due to a combination of rapid land surface rising around Juneau Alaska (due to isostatic rebound) and less rapid global sea level rise. As such, relative to sea level is actually falling in this region at a rate of nearly 13 millimeters per year. In contrast, Figure M-6 shows the relative sea level rate around Galveston, Texas, which is a combination of land sinking (due to subsidence) and global sea level rise. As such, in this region relative sea level rises at the rate of over 6 millimeters per year. Quite often, in practice, NGVD29 and NAVD88 are assumed to be equivalent to present day local MSL. This is an incorrect assumption that often leads to poor planning. The relationships need to be precisely established and used appropriately. More precise rates of vertical land movement are being determined from establishment of the Continuously Operating Reference System (CORS) by NOAA/NGS. A CORS co-located at a tide station, or an episodically re-checked GPS survey at the tide station, will provide more precise magnitude of the local vertical land movement to separate this signal from the rate of local relative sea level change.

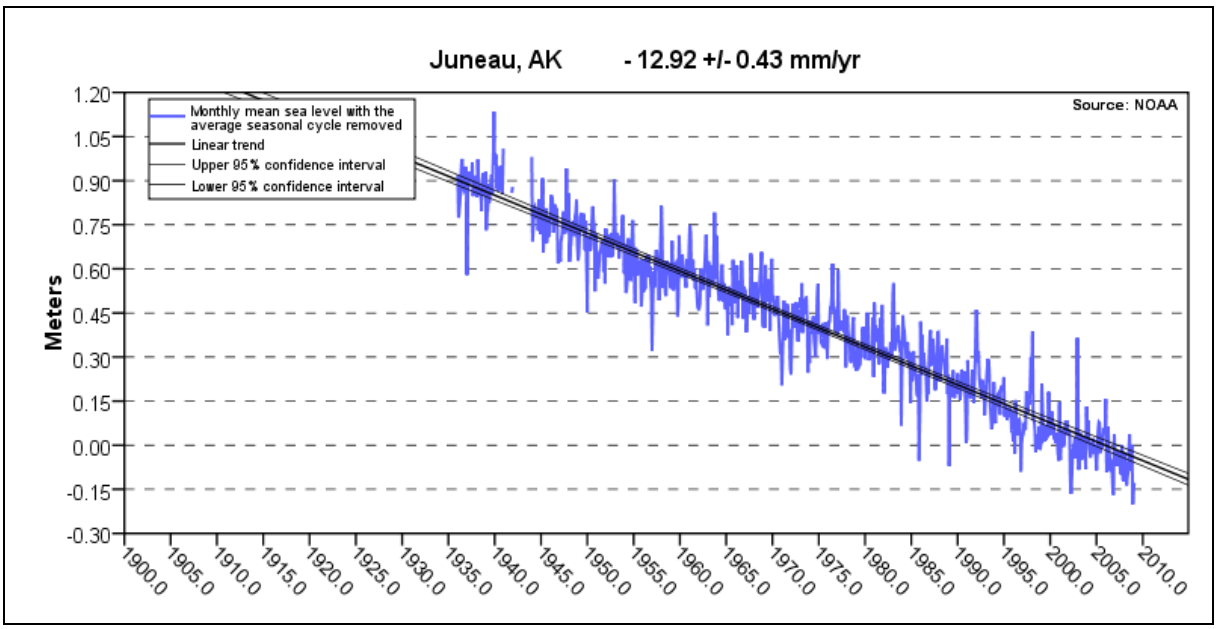

Figure M-5. The mean sea level trend for Juneau, Alaska is -12.92 millimeters/year with a 95% confidence interval of +/- 0.43 mm/yr based on monthly mean sea level data from 1936 to 2006, which is equivalent to a change of -4.24 feet in 100 years.

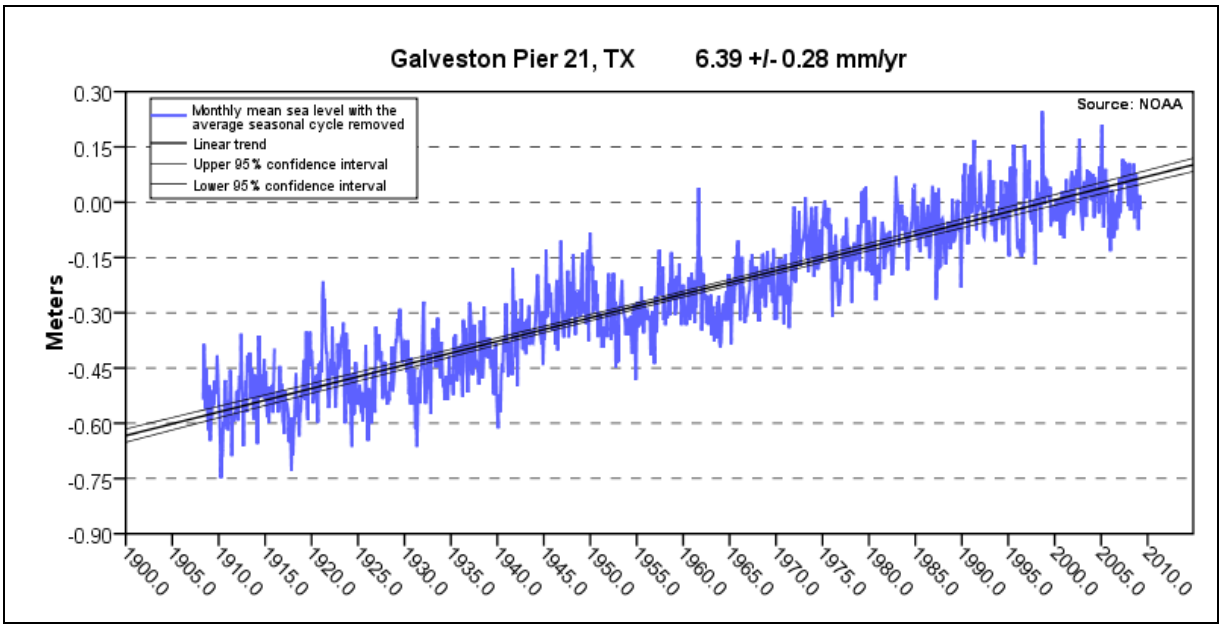

Figure M-6. The mean sea level trend for Galveston, Texas is 6.39 millimeters/year with a 95% confidence interval of +/- 0.28 mm/yr based on monthly mean sea level data from 1908 to 2006, which is equivalent to a change of 2.10 feet in 100 years.

(5) Insufficient or Non-Existing Coverage. Elevation ties to the NAVD88 elevation network should take into account the distance to the nearest recoverable bench marks. In many areas of the continental United States this may prove to be difficult. Figure M-7 shows the national vertical control used in the NAVD88 adjustment and Figure M-8 shows the available first order control in Texas. The maps show an impressive network, however many areas are still without easily accessible bench marks. Tying to the elevation network in many locations can be problematic and/ or expensive.

Figure M-7. Vertical control used in 1988 adjustment.

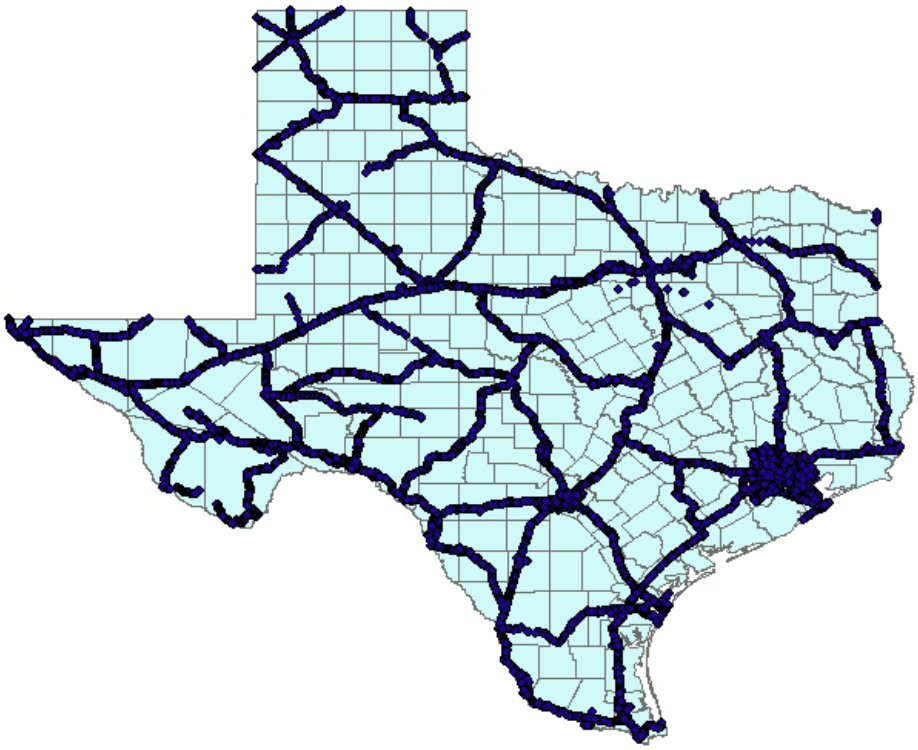

Figure M-8. NGS Database of First-Order Bench Marks in Texas.
(Note the number of counties that show no bench marks.)

b. Water Level Datum.

(1) Tidal Elevations—Gage Uncertainty: Accuracy of a Tidal-Geoid Model of a Navigation Project. The following Table M-3 is from USACE Circular 1110-2-6070, 1 July 2009, "*COMPREHENSIVE EVALUATION OF PROJECT DATUMS - Guidance for a Comprehensive Evaluation of Vertical Datums on Flood Control, Shore Protection, Hurricane Protection, and Navigation Projects*." This table represents the USACE desired accuracy of a navigation project model, considering both the MLLW datum and the geoid.

Table M-3. Recommended Accuracies for Reference Datums on Navigation Project Tidal Models.

	Accuracy (95%)	Reference Datum
Absolute accuracy of tidal-geoid model	± 0.25 ft (± 8 cm)	MLLW
Relative accuracy of tidal-geoid model	± 0.1 ft (± 3 cm)	MLLW
Tidal-geoid model resolution	0.01 ft	
Linear density along navigation channel	100 to 500 ft (varies with magnitude of tidal range)	
Geoid model	use latest available at time of study (currently Geoid03)	
Accuracy of predicted geoid model	< 5 cm	
Accuracy of predicted MLLW datums In offshore entrance channels	< 5 cm	
Tidal-geoid model format	1D or 2D (typically 1D for linear navigation channels)	

NOTE: The above standards are believed representative for most CONUS navigation projects. Exceptions may exist in extreme tide ranges or in parts of Alaska.

(2) From discussions with USACE engineers and surveyors, these proposed accuracy standards are suitable for the purpose of tying USACE projects to the NSRS and the NOS tidal datums computed for the latest tidal epoch. These accuracies are in line with the desire to standardize USACE projects to a common geodetic vertical datum on a national scale. USACE should re-assess and update these accuracy standards as NOAA adopts changes to the NSRS in the future.

(3) Tidal Elevations—Proximity of Gage. Presently the NWLON comprises some 200 tide gages. While most of these gages are located adjacent to major population centers and ports, there are coastal areas that are not covered adequately to supply accurate water level and tidal datums. Recently, CO-OPS conducted a comprehensive gap analysis of adequate tidal data coverage. This study is now published as NOAA Technical Memorandum NOS CO-OPS 0048

entitled, "*A Network Gaps Analysis for the National Water Level Observation Network*" by Stephen K. Gill and Kathleen M. Fisher, March 2008. NOS states:

> *"A deterministic approach to estimating the areas of NWLON coverage for datum determination at nearby subordinate tide stations has been developed. The approach uses the basic error analyses of Swanson (1974) and the regression error analyses of Bodnar (1981) to estimate regions of coverage for each individual NWLON station. Using GIS tools, the information is displayed on maps of coverage polygons. The GIS output is then used to identify geographic areas that represent gaps in the NWLON. The datum error polygons can be used for multiple purposes for short-term and long-term management of the NWLP. This analysis is being used for strategic planning and prioritization of locations to establish new NWLON stations as the network grows towards the optimum number of stations. It is being used to make decisions regarding utilization of resources for the importance of bringing an NWLON station back on line immediately or if a nearby station can be used effectively as a back-up until reconstruction can take place. The analysis results identified approximately 113 gaps in NWLON coverage beyond the 200 station deployed as of FY2007. Forty-three (43) gaps are located along the east coast, 33 in the gulf coast, 6 gaps on the west coast, 29 gaps in Alaska, and 2 in Hawaii."*

(4) Figure M-9 shows the water level observation gap analysis for the Gulf of Mexico along the Texas coast.

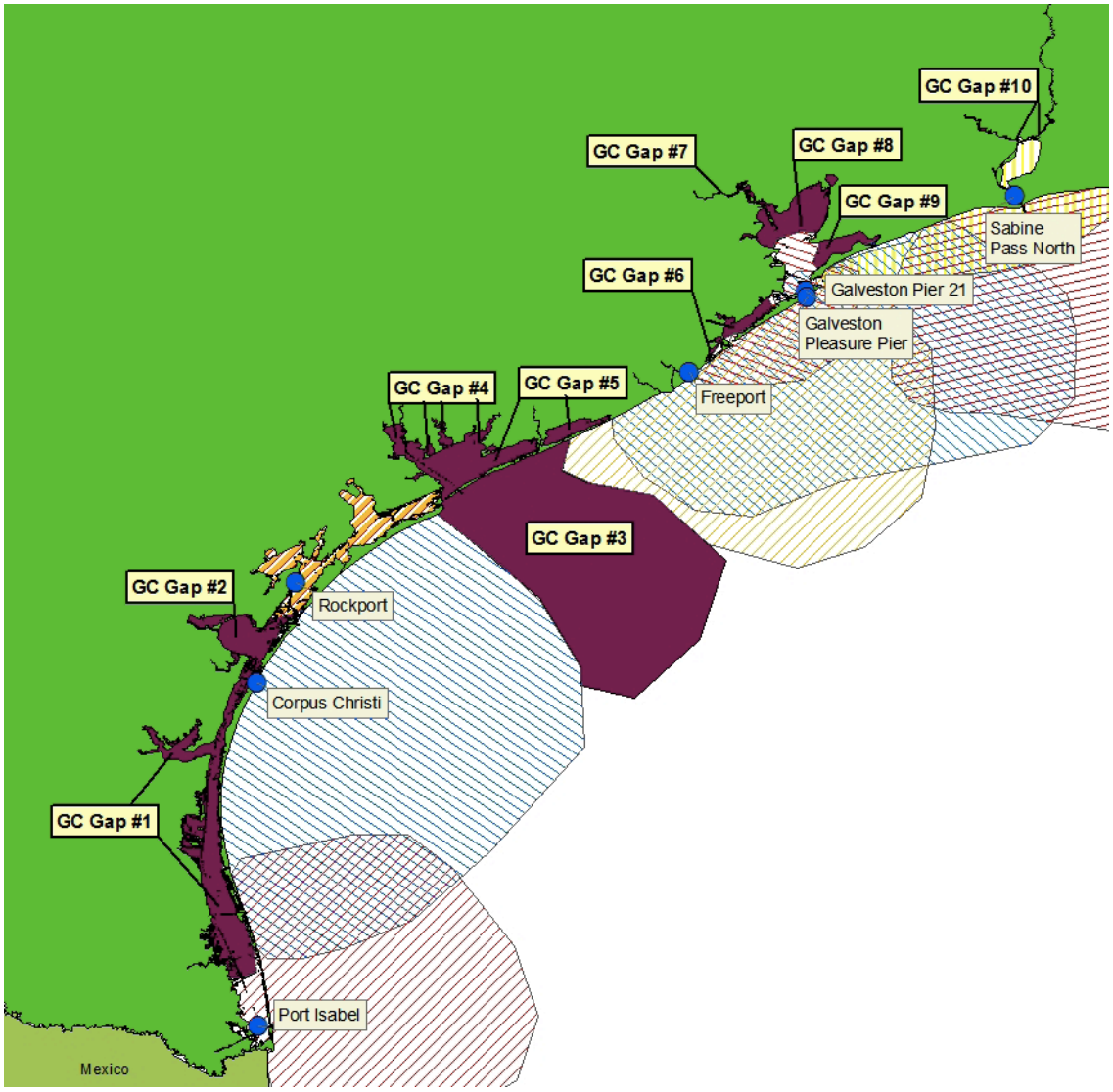

Figure M-9. NWLON gaps analysis for Texas.

(5) Tidal Elevations—Gage Historical Record (time span). In order to compute tidal datums, a water level measurement station needs to collect data for at least 19 years and preferably during the 19 years selected for the National Tidal Datum Epoch (NTDE). The longer the water level station collects data, the greater reliability of observing long-term sea level changes. Tidal datums are computed using monthly means for high and low tides over the 19-year epoch. Monthly means cannot be computed if a more than 72 hour gap exists in the record. Therefore, it is imperative that a continuous record for the data series be maintained for the duration of the epoch and well beyond the 19 years if long-term trends are to be computed. The following is taken from NOAA Special Publication NOS CO-OPS 1, "*Tidal Datums and Their Applications*," Silver Spring, Maryland, June 2000. This special publication was prepared under the editorship of Stephen K. Gill and John R. Schultz; Contributors were Wolfgang Scherer, William M. Stoney, Thomas N. Mero, Michael O'Hargan, William Michael Gibson, James R.

Hubbard, Michael I. Weiss, Ole Varmer, Brenda Via, Daphne M. Frilot, and Kristen A. Tronvig. The following excerpts from this publication describe the definitions of the NTDE and the tidal datums computed:

"First-Reduction Tidal Datum Computations.

The National Tidal Datum Epoch (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 1983 through 2001. 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 benchmarks.

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 40 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.

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. "

---

(6) Tidal Elevations—Tidal Datum Accuracy. Tidal datums for each water level observation station vary in their accuracies depending on the type of tide (diurnal, semi-diurnal,

or mixed); the range of tide; the coastal hydraulics; and the weather effects of wind speed, wind direction, and barometric pressure. The standard deviation of the computed datums is computed and is available from the NOS. The accuracy of tidal datums is discussed in the following, which is taken from NOAA Special Publication NOS CO-OPS 1:

"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 below. 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 the table. That is, the values in the table are the confidence intervals for the tidal datums based on the standard deviation.

Generalized accuracy of tidal datums for East, Gulf, and West Coasts when determined from short series of record and based on +/- sigma. From NOS CO-OPS 1, Swanson (1974).

Series Length (months)	*East Coast*		*Gulf Coast*		*West Coast*	
	(cm)	*(ft.)*	*(cm)*	*(ft.)*	*(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). The table below 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.

Error in position of marine boundary as a function of the slope of the land (From NOS CO-OPS 1).

% 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*

---

(7) NOAA has recently updated the above information. See "*Water Level Station Specifications and Deliverables for Shoreline Mapping Projects*," May 2009; Center for Operational Oceanographic Products and Services; National Ocean Service; National Oceanic and Atmospheric Administration.

(8) In practice, NOAA considers the accuracies found in the above table to be maximum values, as they are based on comparisons of NWLON station pairs. Most of which are a considerable distance from each other (both in miles and in tidal differences). NOAA now uses a set of equations developed through a multiple correlation analysis of the Swanson results by Bodnar (1981) to determine higher resolution accuracy estimates for individual stations rather than a regional approach. Errors in the estimation of 19 NTDE datums at short term stations are a function of the geographic distance from the short-term station to the control station; the difference in the time of tide between the stations; and, the ratio of the range of tide between the short-term and control. Having a stronger, denser NWLON control network is one way NOAA is minimizing these dependencies. The other obvious way to minimize datum errors, in practice, is to leave short-term stations in operation for at least one-year for a more accurate datum computation (the standard deviations for the errors in the above table for a one-year station are only ½ of what they are for a one-month station).

(9) Non-Tidal Elevations: Low Water Reference Plane. Low Water Reference Plane (LWRP) is a hydraulic reference plane, established from long-term observations of the river's stage, discharge rates, and flow duration periods. The low water profile is developed about the 97-percent flow duration line (USACE EM 1110-1-1005). For example, a low water profile was taken throughout the Memphis district from August 15 through 23 in 2005. This profile was used to shape the proposed 2007 LWRP between the five key stations. The August 2005 profile is considered representative of the low water slope that would occur as a result of the 97 percent

exceedance discharge. The stages that occurred on the survey dates were within 0.0-0.7 feet of the computed LWRP stages at the five key gage locations; stages for survey data at four of the five locations were within 0.5 feet (from Memphis District, USACE, 2007).

(10) Non-Tidal Elevations: Stream Gage Accuracy. Stream gages are designed to give hydraulics engineers data on the discharge flow of water at that point in a stream. The discharge flow is the product of the velocity and the area (i.e., *discharge = area × velocity*). The stream gage measures the stage of the river, which is then used as an observable on a stage vs. discharge logarithmic graph. As such, the water surface stage elevation is a component of the final discharge value. Olean and Norris report the accuracy of stream gages used by the US Geological Survey as "S*tream gages operated by the US Geological Survey provide stage measurements that are accurate to the nearest 0.01 foot, or 0.2 percent of stage, whichever is greater*" (Olson and Norris, 2006). Most U.S. Geological Survey stream gages used by the USACE are tied to NGVD29 datum. Updating these values to NAVD88 will assist the modeling of stream and river hydraulics as more sophisticated models allow the management of entire river catchment areas.

c. VDatum.

(1) The tidal hydraulic forcing of the VDatum model relies on existing water level observation stations. The model interprets water levels over time between these existing stations. The uncertainty with these models increases with distance from the water level observation stations and areas that are more remote from tide stations, such as South Bay in San Francisco, show higher variances in the estimation of tidal datums. VDatum is a useful tool for converting elevations from one datum to another (and along the coast this would include tidal datums); however, the software is interpretive of various data sets and models and does have uncertainty depending on the quality and quantity of the underlying data sets. Additionally, VDatum is still under development as of this writing. Changes and adjustments to the algorithms are ongoing. The following timeline is an indication of the current rate of change to the software taken from http://vdatum.noaa.gov/about/currentevents.html:

March 27, 2009
VDatum version 2.2.4 Released!

August 07, 2008
VDatum version 2.2.3 Released!
- Added GEOID 06 model: supporting elevation conversions in Alaska with the newest Geoid transformation grids.

July 11, 2008
VDatum version 2.1.3 Released!
- Added transformation filters for conversion from tidal datums to IGLD 85 and vice versa. The conversions between tidal datums and IGLD85 are prohibited.

July 2, 2008
VDatum version 2.1.2 Released!
- Fixed sign problem with sounding data

June 23, 2008
VDatum version 2.1.1 Released
- Added HPGN transformation grids which supporting horizontal transformation from NAD 27 to NAD83 (HARN). Fixed problem with IGLD85 grids. Fixed problem with 3-D transformation based on HPGN v2.9 model. Input and output time are set to January 1st of the current year. Minor tweaks and GUI improvements.

October 01, 2007
VDatum version 2.0.0 Release!
VDatum 2.0.0 has been released. This version contains significant enhancements and new features, including a new user-friendly interface and productivity features.

(2) The NOAA VDatum team is conducting a detailed error analysis on the use of VDatum for each of its regional applications. Some of the analyses completed for certain regional can currently be found on the VDatum website. This error analysis reveals how complex a task assessing the accuracies associated with VDatum conversions can be. These complexities, coupled with the previously mentioned ongoing development of VDatum, present challenges in trying to assess the risk and uncertainty of using VDatum transformation values.

SECTION 3

Recommendations & Conclusions

M-10. Datum Uncertainties. Most risk assessments for flooding depend upon accurate vertical measurements and the accuracy of these measurements depends upon several factors. These can be divided into two categories: factors related to measurement errors, such as leveling, and factors related to measurement bias, such as the use of a faulty monument. It is important to review these factors with surveyors and others who are knowledgeable about the local issues and conditions that impact vertical measurement accuracy.

a. The terrestrial datum can be subject to problems related to leveling control, datum confusion, datum coverage, and relative sea level changes. In addition they should be tied into the NSRS to allow for comparisons among projects and for analysis of larger flooding events and unexpected disasters. Engineers involved in hydrological risk assessments should discuss the effects of these issues with local experts knowledgeable in these factors. In some cases, this might require resurveying elevations in the project area, as well as a detailed analysis of various datums used in that area.

b. Surveyors and others responsible for establishing and maintaining reference elevations for a project should ensure that standard surveying practices are followed when establishing elevations. This should include good quality control of surveys. Quality control, at a minimum, should include keeping long-term archives of survey logs and checking individual logs to assess leveling precision to determine whether or not any bias was introduced from using insufficient or inaccurate monuments.

c. Projects on the coast that rely on tidal datums are subject to possible inaccuracies due to variations of the tidal gages in the project area, proximity of tidal gages to the project site, and incomplete historical records or tidal gage readings. In addition, relative sea level changes in the area should be assessed, including both the general rate of change and the length of time from the middle of the epoch used to establish the tidal datum. Again, it is generally useful to discuss these issues with local experts, surveyors and others responsible for maintaining these gages and to review a trend analysis for these data to plan for elevation changes during the estimated project life expectancy.

d. A general approach to incorporating these datum issues into risk assessments is outlined in Table M-4. This table also appears as a worksheet in Addendum B to this Appendix, together with supporting flowcharts summarizing how the elevation uncertainty worksheet is used to compute an elevation uncertainty budget. Estimates of potential vertical measurement bias and variance should be evaluated in conjunction with local experts familiar with these measurements, surveyors and mapping experts for the project region. This table provides general groupings for sources of vertical uncertainty that includes terrestrial, water levels, and datum conversion issues.

Table M-4. Worksheet for Determining Elevation Uncertainty for Project Risk Assessments.

SOURCES OF VERTICAL UNCERTAINTY	Average Bias(ft)	Average Variance(ft^2)
TERRESTRIAL		
Subsidence(-)/Rebound(+)		
Measurement Uncertainty		
Datum Coverage		
National Spatial Reference System		
Other Sources of Uncertainty		
Total Terrestrial Adjustment		
WATER LEVELS		
TIDAL		
Sea Level Change		
Gage Accuracy		
Gage Proximity		
Project Epoch Adjustment		
Gage Historical Record		
Other Sources of Vertical Uncertainty		
Total Tidal Adjustment		
NON-TIDAL		
Low Water Reference Plane		
Gage Accuracy		
Gage Proximity		
Pool Elevation Record (length)		
Other		
Total Non-Tidal Adjustment		
DATUM CONVERSIONS		
NGVD29 to NAVD88		
NAD83 Ellipsoid to NAVD88		
Geoid Model Uncertainty		
Legacy Datum to NAVD88		
VDatum conversions		
Other		
Total Datum Conversion Adjustment		
OVERALL UNCERTAINTY		

(1) The first column contains the potential sources described in this report organized by terrestrial elevations, water levels, and datum conversions. Depending upon the project, one or all of these categories would be used to calculate the elevation uncertainty. The elevations assumed in risk modeling should be raised or lowered by the *overall uncertainty*, the last line of

Table M-4. Overall uncertainty is added to the assumed elevations. To account for a 95% one-sided confidence interval in variances, 1.645σ is also added or subtracted from the assumed elevations. This calculation is added in cases where higher elevations produce higher risks, and is subtracted in cases where lower elevations produce higher risks.

(2) The second column is used to record the magnitude of potential bias or deviation between the project elevation measurements at the time the project was designed and true elevations over the design life of the project. In some cases the sign of the bias (+ or -) may be known. Historical records in Galveston, for example, indicate that relative sea level change is rising, creating a negative bias. At present, relative sea level change in Galveston is approximately 2.1 ft/100 years.

(3) Measurement errors, expressed as a variance, are recorded in the third column. In some cases these can be expressed precisely. Leveling variance, for example, is often controlled to a very small tolerance, typically $\sigma^2 = 0.01^2$ for a project. On the other hand, although information is generally available for estimating the variances associated with datum conversions and coverage, they are generally less precise.

e. In an ideal state in which elevations are known exactly and are not expected to change over the project lifespan, the elevation budget, or adjustment, would be zero. Recorded elevations would be used as input into the risk assessment calculations relating flood stage to the probability of flooding. For most projects, however, elevation adjustments are necessary. This worksheet is designed as an aide in that process.

f. If elevations are not expected to change over time, and if measured elevations are unbiased, then only variances are recorded in the worksheet. These are recorded by source as a variance with units (ft^2) since the final adjustment for individual variances is calculated using the formula for the total standard deviation (σ_T):

$$\sigma_T = \sqrt{\sigma_1^2 + \sigma_2^2 + \cdots + \sigma_{1k}^2}$$

where σ_1^2, σ_2^2,…, σ_{1k}^2 are the k non-zero variances recorded in the Elevation Uncertainty Worksheet, assuming they are all uncorrelated.

g. If elevations might change over the project lifespan, or if epoch adjustments are necessary, then the total bias is calculated by simply summing the individual bias adjustments expected in the elevations.

h. Some bias values may be expressed as plus and minus, +/-. This can occur because of spatial variation and uncertainty of historical data. The worst case scenario for a bias value will be either positive or negative depending upon the nature of the project. A conservative approach would dictate that the overall bias calculation is computed using only the worst case scenarios for a particular project.

i. For example, levee height is directly related to the risk of a flooding event causing a levee breach. In this case, a negative bias is worse than positive since a negative bias would result in true levee height being lower than the design height needed for that risk level. Dredging projects, on the other hand, might be concerned about a vertical bias in either direction. If a positive bias is not accounted for the design depth, then channels would be dredged deeper than required, and a negative bias would result in channels that are shallower than required.

M-11. Example Computation for a Coastal Protection Project. As an example, consider a coastal protection project such as levees in Galveston with a 50-year design life. The project levees are designed using LMSL wherein some of the measurements require conversion of historical elevations measured in NGVD29 and the final values are expressed using NAVD88. Table M-5 contains representative entries for this hypothetical example.

a. Leveling is conducted using accepted standard surveying practices. This requires all measurements be closed-loop measurements to ensure the measurement variance is no larger than 0.01^2 ft. Bias for these measurements is zero if these measurements are tied to two or more reliable monuments. In addition, quality control practice would archive project log books and check the closed-loop calculations to ensure the measurement variance meets measurement standards.

Table M-5. An Example Application of Vertical Inaccuracy Analysis for a Hypothetical Coastal Protection Project in Galveston, TX.

SOURCES OF VERTICAL UNCERTAINTY	Average Bias(ft)	Average Variance(ft^2)
TERRESTRIAL		
Subsidence(-)/Rebound(+)	-0.70	0.01^2
Measurement Uncertainty	na	0.01^2
Datum Coverage	na	0.00
National Spatial Reference System	na	0.20^2
Other Sources of Uncertainty		
Total Terrestrial Adjustment	-0.70	0.0402
WATER LEVELS		
TIDAL		
Sea Level Change	-0.35	0.01^2
Gage Accuracy	na	0.01^2
Gage Proximity	na	0.01^2
Project Epoch Adjustment	-0.06	0.00
Gage Historical Record	na	0.00
Other Sources of Vertical Uncertainty	na	
Total Tidal Adjustment	-0.41	0.0003
NON-TIDAL		
Low Water Reference Plane		
Gage Accuracy	na	
Gage Proximity	na	
Pool Elevation Record (length)	na	
Other		
Total Non-Tidal Adjustment		
DATUM CONVERSIONS		
NGVD29 to NAVD88	na	0.01^2
Ellipsoid to NAVD88	na	
Ellipsoid to Geoid	na	
Legacy Datum to NAVD88	na	
VDatum conversions	na	
Other	na	
Total Datum Conversion Adjustment	na	0.0001
OVERALL UNCERTAINTY	-1.11 (ft)	0.20 (ft)

Table M-5 (Continued). An Example Application of Vertical Inaccuracy Analysis for a Hypothetical Coastal Protection Project in Galveston, TX.

Notes on Table:
Bias Calculations: Since heights lower than designed are a concern, the total adjustment for worst case bias is: -0.70 –0.41 = -1.11 ft for the combined effects of terrestrial, and water level elevation bias.

Variance Calculations: The total adjustment for variance is the variance for the terrestrial elevations, the tidal datum, and the datum conversions. The overall standard deviation is $\sigma_T = \sqrt{0.0406} = 0.20'$.

b. Since some of the measurements will rely upon NGVD29 datum, some uncertainty can be expected from converting these values to NAVD88 datum required for the design heights. In the region covered by this project, this conversion is assumed to have a variance of 0.01^2 (ft^2), which is added to the overall variance used to compute the overall standard deviation.

c. The largest potential source of vertical inaccuracy in this project is relative sea level change. In Galveston, the tidal gage used for this project indicates a relative sea level increase of 2.1 ft/100 years, or 0.021 ft/yr. Since the assumed design life of this project is 50 years, the total bias expected over the life expectancy of this project is minus (-) 1.11ft.

d. The final potential source of vertical inaccuracy for the terrestrial datum in this project is conversion to the NSRS. Discussion with local experts indicates that this conversion has a variance of 0.20^2 (ft^2).

e. As previously described, risk assessments are currently conducted following the model and process described EM 1110-2-1619, "*Risk Based Analysis for Flood Damage Reduction Studies*" (August 1996). This is a general process that can be tailored to accommodate most flood risk management projects designed by the Corps of Engineers. However, the assumptions and inputs to this assessment are critical to obtaining accurate risk estimates. Vertical inaccuracy is typically a key input to a risk assessment. The risk of a flooding event is typically directly tied to the design height of flood risk management measures.

f. The overall bias and standard error of measurement can be used to set conservative design heights or depths in a project. The concern is that the design height be conservative enough to provide adequate protection over the project lifespan. If D represents the design height, the goal is to ensure that $D \geq D_{min}$, where D_{min} is the minimum design height needed to ensure the risk of flooding is less than a targeted level. If *B* is the overall bias calculated in Table M-5, which can be negative or positive, then in order to ensure that $D \geq D_{min}$ over the project lifespan with 95% confidence, calculate D using $D = D_{min} + B - 1.645\sigma_T$, where σ_T is the total standard deviation from Table M-5.

g. For example, in the Galveston coastal protection project described above, the overall bias and standard deviation were -1.11' and 0.20', respectively. Hence risk assessment should be calculated using heights calculated by $D = D_{\min} - 1.21 - 1.645 \cdot 0.20 = D_{\min} - 1.54'$. In other words, at the end of design life of this hypothetical project, the terrestrial heights are estimated to be as much as 1.54' lower than originally designed. Estimated risks could be reported as a range using the value determined at the design height and a higher risk calculated using heights 1.54' lower.

h. Dredging and other projects where the goal is to ensure that the depth D is equal to or greater than a target depth are treated similarly but with an important change. The dredging depths need to be adjusted over time to account for trends in subsidence, rebound, or sea level change. The goal is still to ensure that $D_T \geq D_{min}$, i.e. where D_T is the dredge depth at time T and D_{min} is the minimum target depth. In this case, Table M-5 is calculated relative to time=T. The bias corrections for subsidence and rebound as well as the sea level change are calculated for time=T rather than using the minimum or maximum bias expected over the project lifespan.

i. In summary, heights are not static and in some cases can be inaccurate. Over the design life of a project relative sea level changes can increase or decrease the original design heights or depths for a project. Measurement error can also arise from datum conversions and inadequate coverage. These factors combine to cause uncertainty in vertical measurements assumed for an engineering project.

j. It is important to consider all factors and to attempt to estimate the magnitude of these factors by consulting local surveying and mapping experts. In some regions, this may require additional resources to accurately establish the magnitude of these effects. Existing reference monuments may need to be resurveyed, and in some cases new monuments in the project area may be needed.

M-12. Addendum A: Uncertainty Worksheet and Terms.

a. Project Risk Assessment: Vertical Uncertainty Worksheet. The following worksheet may be used for investigating and incorporating potential sources of vertical uncertainty in project risk assessments.

SOURCES OF VERTICAL UNCERTAINTY	Average Bias(ft)	Average Variance(ft^2)
TERRESTRIAL		
Subsidence(-)/Rebound(+)		
Measurement Uncertainty	na	
Datum Coverage	na	
National Spatial Reference System	na	
Other Sources of Uncertainty		
Total Terrestrial Adjustment		
WATER LEVELS		
TIDAL		
Sea Level Change		
Gage Accuracy	na	
Gage Proximity	na	
Project Epoch Adjustment		
Gage Historical Record	na	
Other Sources of Vertical Uncertainty	na	
Total Tidal Adjustment		
NON-TIDAL		
Low Water Reference Plane		
Gage Accuracy	na	
Gage Proximity	na	
Pool Elevation Record (length)	na	
Other		
Total Non-Tidal Adjustment		
DATUM CONVERSIONS		
NGVD29 to NAVD88	na	
NAD83 Ellipsoid to NAVD88	na	
Geoid Model Uncertainty	na	
Legacy Datum to NAVD88	na	
VDatum conversions	na	
Other	na	
Total Datum Conversion Adjustment	na	
OVERALL ADJUSTMENT		

b. Terms Defined.

(1) Subsidence (-)/Rebound (+). Measurements of subsidence and rebound can be determined using long-term accurate GPS observations as undertaken by the National Geodetic Survey's Continuous Operated Reference Stations (CORS) or through episodic re-surveying of a mark through Global Navigation Satellite System (GNSS).

(2) Measurement Uncertainty. The actual elevation measurement variance is known from long-term use of various leveling technologies. These include observations made using optical levels, digital levels, trigonometric techniques, and precise geodetic GPS observations. These include both orthometric elevation and ellipsoid elevation observations.

(3) Datum Coverage. Proximity to established NSRS control can affect the accuracy of elevation measurements. The distance between NSRS control, be it a benchmark or a CORS site, can add to the uncertainty of the observation.

(4) National Spatial Reference System. The current NSRS vertical datum is the NAVD88 datum. The adjustment that produced the published elevations of benchmarks included in the network vary across the United States. It is generally accepted that the adjustment had a vertical accuracy of five centimeters at the time of the adjustment.

(5) Other Sources of Inaccuracy. Unique field measurements may cause additional sources of uncertainty, which can be accounted for within this component of the computation.

(6) Sea Level Change. Sea level change is measured using long-term coastal water level observations and long-term satellite altimeter observations. Current data estimates the rate of change to be + 2-3 millimeters per year on a global basis.

(7) Gage Accuracy. Modern water level gages have a single observation resolution of 0.01 ft. Older float gages will have lower resolutions depending on age and model. Water level observations are designed to reduce the effects of high frequency wave energy and the result of the mean of a series of observations with a computed standard deviation. These observed variances can be used to compute overall uncertainty.

(8) Gage Proximity. Water level observations at a gage are accurate for the specific location of the gage. Using a gage to establish water levels some distance from the gage will introduce uncertainty. Uncertainty from gage proximity to the project should be ascertained.

(9) Project Epoch Adjustment. Tidal water level datums are computed using water level data observed over a 19-year epoch. Approximately every 25 years the National Ocean Service is instructed by Congress to update the tidal datums to a new epoch. Changes in datum elevation caused by updated epoch computation should be noted.

(10) Gage Historical Record. Gages used to compute tidal datums ideally use a complete record series of data. Tidal datums can be computed for gages with an incomplete data record by

using a nearby gage with similar tidal characteristics as a control. Gages with incomplete records will have unique variances, which should be noted.

(11) Low Water Reference Plane (LWRP). Non-tidal LWRP's are associated with stream gaging, the computation of stream profiles, stream stage, and discharge rates. The combination of vertical measurements for projects requiring vertical positioning relative to stream staging should be estimated using this component.

(12) Gage Accuracy. Stream gages vary with age and technology. A suitable accuracy for each stream gage should be assessed for this component.

(13) Gage Proximity. The proximity of a stream gage relative to a project site will dictate a higher uncertainty for determining elevations relative to the stream stage. For major projects, establishing a modern stream gage at the site of the project can reduce this uncertainty.

(14) Pool Elevation Record Length. Water storage reservoir, lakes, and pools, which fluctuate due to rainfall and seasonal effects, are subject to the length of record series. The computation of average stage elevation or similar may have uncertainty based on the length of the records.

(15) NGVD29 to NAVD88. Conversion of elevation from NGVD29 to NAVD88 is usually carried out using conversion software, namely VERTCON or CORPSCON or VDATUM (which incorporates VERTCON). These software programs are based on a national generalized model based on comparisons of known points in the NSRS. Uncertainty arises when a conversion is performed at a distant location, which is not in the adjacent vicinity to known points. These uncertainties should be assessed.

(16) NAD83 Ellipsoid to NAVD88. The following is from "*Converting GPS Height into NAVD88 Elevation with the GEOID96 Geoid Height Model*" by Dennis G. Milbert, Ph.D. and Dru A. Smith, Ph.D., National Geodetic Survey: "*Gravimetric geoid models show systematic departures from NAD83 GPS derived ellipsoidal heights at leveled benchmarks with NAVD88 orthometric heights. These departures are dominated by datum definition and datum realization problems. It is possible to fit these departures into a very smooth conversion surface, and add this surface to a gravimetric geoid model. For example, the GEOID96 geoid height model, which incorporates such a conversion surface, displays about 2.5 cm of accuracy (one sigma) between points spaced at 50 km or greater. GPS ellipsoidal height error of about 6 cm was observed after the computations.*" (Milbert and Smith, 1996)

(17) Geoid Model Uncertainty. The geoid is the equipotential surface of the Earth's gravity field, which best fits, in a least squares sense, global mean sea level. Several versions of the Geoid have been computed over the last three decades. Estimates of the accuracy of the Geoid vary due to the source and density of gravity data used to compute the Geoid. Current estimates show the Geoid accuracy to be approximately 20-30 centimeters for worst cases areas derived from sparse data sets. For details see http://www.ngs.noaa.gov/GEOID/geolib.html

(18) Legacy Datum to NAVD88. Due to the age and lack of documentation of legacy datums used by USACE, a conservative estimate should be used for this estimate of uncertainty. Local knowledge or professional judgment may be used to ascertain an appropriate level of uncertainty for the conversion of legacy datums.

(19) VDatum Conversions. See NOAA VDatum web site.

c. Flow Charts for Use in Assessing Risk Uncertainty.

(1) Flowchart for identifying terrestrial elevation inaccuracies.

(2) Flowchart for identifying tidal datum inaccuracies.

(3) Flowchart for identifying non-tidal datum inaccuracies.

(4) Flowchart for identifying datum conversion inaccuracies.

M-13. Addendum B: Definitions of Tidal Datums, Geodetic Vertical Datums, and the Relationship between Tidal and Geodetic Vertical Datums.
(From http://tidesandcurrents.noaa.gov/datum_options.html).

a. Tidal datums.

In general, a datum is a base elevation used as a reference from which to reckon heights or depths. A tidal datum is a standard elevation defined by a certain phase of the tide. Tidal datums are used as references to measure local water levels and should not be extended into areas having differing oceanographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as benchmarks. Tidal datums are also the basis for establishing privately owned land, state owned land, territorial sea, exclusive economic zone, and high seas boundaries. Below are definitions of tidal datums maintained by the Center for Operational Oceanographic Products and Services.

MHHW* Mean Higher High Water	The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch.
MHW Mean High Water	The average of all the high water heights observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch.
DTL Diurnal Tide Level	The arithmetic mean of mean higher high water and mean lower low water.
MTL Mean Tide Level	The arithmetic mean of mean high water and mean low water.
MSL Mean Sea Level	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.
MLW Mean Low Water	The average of all the low water heights observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch.
MLLW* Mean Lower Low Water	The average of the lower low water height of each tidal day observed over the National

	Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch.
GT Great Diurnal Range	The difference in height between mean higher high water and mean lower low water.
MN Mean Range of Tide	The difference in height between mean high water and mean low water.
DHQ Mean Diurnal High Water Inequality	The difference in height of the two high waters of each tidal day for a mixed or semidiurnal tide.
DLQ Mean Diurnal Low Water Inequality	The difference in height of the two low waters of each tidal day for a mixed or semidiurnal tide.
HWI Greenwich High Water Interval	The average interval (in hours) between the moon's transit over the Greenwich meridian and the following high water at a location.
LWI Greenwich Low Water Interval	The average interval (in hours) between the moon's transit over the Greenwich meridian and the following low water at a location.
Station Datum	A fixed base elevation at a tide station to which all water level 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 benchmark at the station and is held constant regardless of changes to the water level gage or tide staff. The datum of tabulation is most often at the zero of the first tide staff installed.
National Tidal Datum Epoch	The specific 19-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 NTDE is 1983 through 2001 and is actively considered for revision every 20-25 years. Tidal datums in certain regions with anomalous sea level changes (Alaska, Gulf of Mexico) are calculated on a Modified 5-Year Epoch.

*NOTE: Some locations have diurnal tides--one high tide and one low tide per day. At most locations, there are semidiurnal tides--the tide cycles through a high and low twice each day, with one of the two high tides being higher than the other and one of the two low tides being lower than the other.

b. Geodetic vertical datums.

The National Geodetic Survey (NGS) defines a geodetic datum as: 1. "A set of constants used for calculating the coordinates of points on the Earth." Generally a datum is a reference from which measurements are made. In surveying and geodesy a datum is a reference point on the earth's surface against which position measurements are made and an associated model of the shape of the earth for computing positions. Horizontal datums are used for describing a point on the earth's surface in latitude and longitude. Vertical datums are used to measure elevations or underwater depths.	
North American Vertical Datum of 1988 (NAVD88)	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. NAVD88 and IGLD 85 are identical. However, NAVD88 benchmark 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. NAVD88 should not be used as Mean Sea Level.
National Geodetic Vertical Datum of 1929 (NGVD29)	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 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. See North American Vertical Datum of 1988 (NAVD88). NGVD29 should not be used as Mean Sea Level. NGVD29 is no longer supported by NGS.

M-14. Addendum C: Estimation of Vertical Uncertainties in VDatum.

[This report section has been withdrawn from this Appendix M. It is a copy of a NOAA report (*Estimation of Vertical Uncertainties in VDatum*) found at http://vdatum.noaa.gov/docs/est_uncertainties.html, which was created in March 2009 and last revised in July 2009. This report section may also be viewed at the AGC web site http://www.agc.army.mil/ndsp--(*Uncertainty Model for Orthometric, Tidal, and Hydraulic Datums for Use in Risk Assessment Models, Phase 2 Final Report, dated 3 Sep 09*)]

M-15. Addendum D: References.

Carlson, E., D. Doyle, and D. Smith, 2009. Development of Comprehensive Geodetic Vertical Datums for the United States Pacific Territories of American Samoa, Guam, and the Northern Marianas. Surveying and Land Information Systems, Vol. 69(1), pp 5-17.

Committee on Floodplain Mapping Technologies, 2007. *Elevation Data for Floodplain Mapping*. Published by the NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES.

Gill, Stephen K., Kathleen and M. Fisher, NOAA Technical Memorandum NOS CO-OPS 0048, "A Network Gaps Analysis for the National Water Level Observation Network," March 2008.

Mader, G. L., N. D. Weston, M. L. Morrison, and D. G. Milbert, 2003. NGS Geodetic Tool Kit, Part II: The On-Line Positioning User Service (OPUS). See: http://www.ngs.noaa.gov/TOOLS/Professional_Surveyor_Articles/OPUS.pdf. 6 pp.

Mulcare, D.M., 2004. NGS Toolkit, Part 9: The National Geodetic Survey VERTCON Tool. See: http://www.ngs.noaa.gov/TOOLS/Professional_Surveyor_Articles/VERTCON.pdf

NOAA Special Publication NOS CO-OPS 1, "TIDAL DATUMS AND THEIR APPLICATIONS," Silver Spring, Maryland, June 2000. See: http://tidesandcurrents.noaa.gov/publications/tidal_datums_and_their_applications.pdf.

NOAA Vertical Transformation , 2009. http://vdatum.noaa.gov/above.html.

Olson, Scott A. and J. Michael Norris, "U.S. Geological Survey Streamgaging…from the National Streamflow Information Program," 2006 . http://pubs.usgs.gov/fs/2005/3131/FS2005-3131.pdf.

Pursell, D., 2007. National Readjustment. See: http://www.ngs.noaa.gov/NationalReadjustment/Library/FGCS.2.14.07.presentation.ppt.

Roman, D. R., Y. M. Wang, W. Henning, and J. Hamilton, 2004. Assessment of the new national geoid height model, GEOID03.2004 ACSM/TAPS Conference and Technology Exhibition, Nashville, TN. 14 pp. See: http://www.ngs.noaa.gov/GEOID/geolib.html.

Schultz, J.R., W.D. Scherer, and M.D. Earle, Documentation of National Ocean Service Data Quality Assurance Procedures: Phase 1, NOAA Technical Report NOS CS 2, Oceanographic Products and Services Division, Silver Spring, MD, 1998. See: http://tidesandcurrents.noaa.gov/publications/tidal_datums_and_their_applications.pdf

USACE, 1996. EM 1110-2-1619 U.S. Army Corps of Engineers CECW-EH-Y Washington, DC 20314-1000; Manual No. 1110-2-1619; 1 August 1996. Title:
Engineering and Design
RISK-BASED ANALYSIS FOR FLOOD DAMAGE REDUCTION STUDIES
http://140.194.76.129/publications/eng-manuals/em1110-2-1619/entire.pdf

USACE, 2007. MEMPHIS DISTRICT, LOW WATER REFERENCE PLANE MISSISSIPPI RIVER - LWRP TABULATED FOR EACH ONE-TENTH RIVER MILE, 2007. From THE DISTRICT ENGINEER.

USACE, 2007. USACE Publication Number: EM 1110-1-1005 Jan 2007. Title: Engineering and Design - Control and Topographic Surveying.
http://140.194.76.129/publications//eng-manuals/em1110-1-1005/.

USACE, 2009. USACE Publication Number: EC 1165-2-211 1 July 2009. Title: Water Resource Policies and Authorities Incorporating Sea-Level Change Considerations I Civil Works Programs.
http://140.194.76.129/publications/eng-circulars/ec1165-2-211/ec1165-2-211.pdf

USACE, 2009. USACE Circular 1110-2-6070, 1 July 2009, "Engineering and Design COMPREHENSIVE EVALUATION OF PROJECT DATUMS - Guidance for a Comprehensive Evaluation of Vertical Datums on Flood Control, Shore Protection, Hurricane Protection, and Navigation Projects".
http://140.194.76.129/publications/eng-circulars/ec1110-2-6070/entire.pdf

Zervas, C., 2001, Sea Level Variations of the United States 1854-1999, NOAA Technical Report NOS CO-OPS 36, 201 p.
http://tidesandcurrents.noaa.gov/publications/techrpt36doc.pdf

Zilkoski, D. B., J. H. Richards, and G. M. Young, 1992. Results of the general adjustment of the North American vertical Datum of 1998. Surveying and Land Information Systems, Vol. 52(3), pp 133-149. See: http://www.ngs.noaa.gov/PUBS_LIB/NAVD88/navd88report.htm.

Zilkoski, D. B., J. D. D'Onofrio, and S. J. Frakes, 1997. Guidelines for establishing GPS-derived ellipsoid heights. NOAA Technical Report NOS NGS 58. 23 pp. See
http://www.ngs.noaa.gov/PUBS_LIB/NGS-58.pdf