CHAPTER 9

Checklist for Assessing Project Datums and Elevation Uncertainties through Project Phases

9-1. Purpose. This chapter provides guidance for evaluating the adequacy of elevation grades and reference datums through the life cycle of a project. This includes evaluations or assessments to ensure the project is referenced to the current NSRS and/or NWLON framework. Procedures for estimating project grade or depth measurement uncertainties are also outlined.

9-2. Planning and PED Phases—Reference Datum Checklist. During the planning and/or detailed design phases (e.g., PED), water level datums, geodetic datums, and topographic elevation references shall be clearly defined and established throughout the project area. This entails setting Primary Project Control Points (PPCPs) at a spacing sufficient to densify supplemental (local) control for subsequent engineering and construction surveys, as outlined in previous chapters of this manual. All PPCPs must be published in the NSRS. The project area includes not only the planned location of a flood protection structure but also related flood plain mapping on the protected side of the control structure and perhaps hydrographic surveys on the flood side. Navigation projects may include external confined disposal and beach renourishment sites. These design reference surfaces must be established prior to performing basic site plan mapping, aerial mapping, LIDAR elevation mapping, hydrographic surveys, geotechnical investigations, and related preliminary design requirements. The main issues to be evaluated and resolved during the preliminary planning and/or design phases are listed in Table 9-1.

Table 9-1. Reference Datum Checklist—Planning and PED Phases (Navigation, Flood Risk Management, and HSPP Projects).

PROJECT ELEMENT	ACTION
Establish Primary Project Control PBMs	Use existing (published) NSRS PBM or survey new PBM and submit/publish in NSRS—see Chapter 3
Reference datums	NAD83, NAVD88, & hydraulic/tidal
Accuracy required	see nominal standards in Table 3-1
Density of Primary Control PBMs	see Chapter 6 (Inland projects)
Recommended survey procedures	see Chapter 3
PPCP satellite visibility	Verify horizon clearances

Table 9-1 (Continued). Reference Datum Checklist—Planning and PED Phases (Navigation, Flood Risk Management, and HSPP Projects).

PROJECT ELEMENT	ACTION
Local construction reference PBMs (LPCP)	Survey connections made directly from PPCP PBMs
Datum	NAD83, NAVD88, & hydraulic/tidal
Local construction datum	Note relationship to NSRS (NAVD88)
Density of LPCPs	Ensure spacing within leveling or RTK ranges to project
Local relative accuracy	see Chapter 3
PBMs indicated in contract documents	minimum of three required for construction plans & specs
Legacy Datums	Document reference to NSRS (NAVD88)
Protection Grade Elevation References	Ensure referenced to NSRS (NAVD88) from PPCP/LPCP ties
Subsurface investigation boring reference elevation	NSRS/NAVD88—connected from PPCPs or local PBMs
Site plan mapping reference datums	NAD83 and NAVD88 (current adjustments and epochs) and Local Station-Offset system
Detailed topographic site plan accuracies (hard features, ground shots, etc)	See Chapter 3 (total station or RTK methods relative to PBMs)
Hydraulic/tidal gage reference PBMs	Directly referenced to river/tidal gage reference datum
Minimum number of gage reference PBMs	3 (one PBM must be connected to/published in NSRS)

Table 9-1 (Concluded). Reference Datum Checklist—Planning and PED Phases (Navigation, Flood Risk Management, and HSPP Projects).

PROJECT ELEMENT	ACTION
Navigation MLLW datum modeling	VDatum or spatially interpolated—document model
Navigation RTK base station	Documented in plans and published in NSRS
Navigation tidal PBM calibration points	Documented in plans and connected to CO-OPS network
Metadata	Design memorandums, project drawings, CADD files, studies, reports, flood profile diagrams and related framework documents contain full and complete metadata on the reference elevation datum, primary project control PBMs, and local construction control PBMs; including the relationships and estimated accuracies of legacy reference datums, bench marks, and designed protective elevations.

9-3. Construction Phase Checklist.

a. Minimum construction stakeout criteria. Local horizontal alignment and vertical control PBMs established during the detailed design phase and shown on the contract plans shall be thoroughly verified during the initial construction stakeout. This verification entails checks to a minimum of three PBMs shown on the contract drawings. Checks between the local reference points should generally agree to within ±0.05 ft. Checks on horizontal alignment control points or bench marks exceeding these tolerances shall be thoroughly investigated and resolved prior to construction stake out. The government construction inspector shall review in progress (on site) initial construction stakeout work and shall thoroughly review the contractor's stake out notes for both the basic control check and the site stake out.

b. Machine control system calibration. Machine control positioning systems on graders and bulldozers must be verified on site to ensure horizontal and vertical grading references check with fixed project control bench marks. Machine control RTK networks must also be adequately "site calibrated" prior to excavation or grading, ensuring fixed calibration bench marks surround the construction site.

c. Verification of as-built floodwall cap elevations. Post-construction profile or topographic surveys of floodwalls shall be made to verify as-built controlling elevations and horizontal location. These surveys may be performed using total stations, levels, or RTK methods. Surveys must originate from the reference control PBMs shown in the contract plans. Elevations of sheet pile or floodwall caps should be recorded to the nearest 0.1 ft.

d. Navigation project control verification. RTK or RTN horizontal positioning calibration shall be checked or site calibrated at independent PBMs. RTK/RTN water surface elevation measurements shall be calibrated to the local river or tide gages. In tidal areas verify the latest MLLW gradient model is being used. Levels should be run between tidal reference PBMs to verify stability. Staff gages should be set by leveling to a minimum of two reference PBMs.

9-4. Post-Construction (Operation and Maintenance) Phase—Periodic Reassessments or Evaluations of Controlling Reference Elevations. Periodic reevaluations of project reference elevations and related datums shall be included as an integral component in the various civil works inspection programs of completed projects. The frequency that these periodic reevaluations will be needed is a function of estimated magnitude of geophysical changes that could impact designed protection grades. Most USACE projects are in relatively stable areas and can be evaluated at less frequent intervals. Some criteria for determining resurvey frequencies might include: (1) protected population areas, (2) known insufficient datums, (3) known settlement problems, (4) known subsidence or crustal uplift, (5) District or sponsor priority, (6) type for flood protection structure, or (7) structure height. Navigation project grades or flood protection elevations that are referenced to tidal datums will have to be periodically coordinated with and/or reviewed by NOAA CO-OPS to ensure the latest tidal hydraulic effects are incorporated and that the project is reliably connected with the NSRS. For dams, levees, and related structures, a complete reevaluation of the vertical datums should be conducted at the frequency specified in the O&M Manual for the project; typically ranging from 2 to 5 years in high subsidence areas to 10 or more years in stable areas. Any uncertainties in protection levels that are identified during the inspection should be incorporated into any applicable risk/reliability models developed for the project. Technical guidance on periodic inspection monitoring surveys is found in EM 1110-2-1009 (*Structural Deformation Surveying*).

a. Reference bench mark verification. Periodic resurveys shall be performed relative to the PPCPs established for the project. The NSRS datasheet shall be reviewed to determine if NGS has revised the elevation for the primary mark. The stability of the PPCPs shall be verified by GPS observations or differential level runs to adjacent NSRS reference bench marks. Checks to ± 0.1 ft would be a reasonable tolerance. The PPCP should normally be used as the base station when GPS RTK surveys are performed at the project site.

b. Topographic survey methods. Topographic surveys of floodwall caps, levee or floodwall profiles, inverts, pump stations, etc. should generally meet the tolerances indicated in Chapter 3, which are relative to the LPCPs and/or indirectly to the NSRS PPCPs. Differential leveling (spirit or digital), GPS RTK, or total station methods should yield ± 0.1 ft relative accuracies on surveyed points relative to LPCPs. Reference also topographic surveying methods in EM 1110-1-1005 (*Control and Topographic Surveying*).

c. Profile surveys of levee grades and floodwall caps. Periodic topographic surveys of levee and floodwall elevations shall be performed to verify the current protection elevations. Either differential leveling or GPS RTK methods may be used—RTK normally being the most efficient method given 3D coordinates are directly observed at each point. Shot points are taken at 50-ft or 100-ft intervals along the structure, breaks in grade, gate structures, monoliths, and at other features as designated.

d. Topographic sections on protected or flood sides of floodwalls. Floodwalls set atop or around bridges, levees, pump stations, and other facilities may require periodic topographic surveys of the surrounding berms, revetments, chords, or water depths. Subsurface hydrographic surveys may be required in adjacent canals or rivers to check for scour into the levee revetment or floodwall base. The density of such surveys will depend on the potential scour or settlement being monitored. Typically, 50- to 100-ft sections will be surveyed using standard topographic survey methods, such as GPS RTK.

(1) Hydrographic surveys of deeper water on the flood side can be performed following the techniques outlined in EM 1110-2-1003 (*Hydrographic Surveying*). In shallow river or canal areas (i.e., < 15 ft water depth), standard leveling or total station topographic survey methods may be used with a 25-ft expandable level rod. Typical cross-section spacing is 50 ft or 100 ft c/c.

(2) Acoustic depths may be taken from a boat using inexpensive single-beam survey methods. If 100% bottom coverage is required to evaluate scour or other anomalies in a floodwall or levee footing, then either multi-transducer or multibeam survey systems may be employed, depending on water depth and other factors. Other high-definition acoustic devices may also be used.

e. Deformation and deflection measurements. Many of the precise survey procedures used for large dams outlined in EM 1110-2-1009 (*Structural Deformation Surveying*) may be applied to levees and floodwalls—on an isolated basis given the large geographical extent of floodwalls as compared to dams. This would include precise differential leveling to monitor regional subsidence and settlement, and crack or monolith lateral movement using micrometers. A number of options exist to monitor relative (internal) horizontal deflections of individual floodwall sections. Overall (global) lateral deformation or translation requires monitoring from undisturbed permanent reference points.

f. Navigation and coastal shore protection structures. Coastal navigation, shore protection, and hurricane protection projects need to be periodically evaluated to check for updates to the reference sea level datum. This is normally performed during the development of maintenance dredging plans & specifications.

(1) A periodic assessment of these projects is intended to verify (1) that the design/constructed sea level reference datum is current (i.e., latest tidal datum epoch and model) and (2) that the local project control has been connected with the latest NSRS (NAVD88) adjustment.

(2) Many shore protection projects were originally designed to sea level datums based on interpolated or extrapolated references from gages. Depending on the type of gage, tidal range, and the distance from the gage, this interpolation or extrapolation may no longer be valid or sufficiently accurate—i.e., generally within ± 0.25 ft of the reference water level datum. With sea level rise, the crest elevation of structures may be below that originally designed. However, the original design documents should be checked to verify that allowance for sea level rise was considered in the design elevation and is consistent with the current condition.

g. Coastal navigation project reference datums. Reference tide gages should be checked for periodic datum updates or corrections by NOAA CO-OPS. Updates to VDatum models should also be checked to make sure the latest revisions are accounted for in the model.

h. Checklist. Table 9-2 summarizes some of the items that should be evaluated during periodic inspections or resurveys of levees and floodwalls.

Table 9-2. Summary of Requirements for Referencing Levee and Floodwall Elevations during Post-Construction Maintenance (Periodic Evaluation) Phase.

Post-construction Operation & Maintenance	Periodic inspection and verification of reference hydraulic/tidal and geodetic NSRS datums, subsidence, and sea level changes
Verification of Primary/local PBM relative to NSRS regional network	Check tolerance: ± 0.1 ft (3D)—see criteria in Chapter 3
Topographic inspection survey density:	
Floodwall cap profile surveys	25 to 100 ft shot points (typical) plus breaks in grade
Cross-section topo/hydro surveys	50 or 100 ft c/c typical
Resolution	± 0.1 ft (3D) typical

9-5. Sample PED Evaluation Report on a Hurricane Protection Project's Reference Datums. The following example report contains excerpts from an evaluation of reference datum connections in a New Orleans District Design Report. This evaluation checklist and report reviewed the reference datums used for various engineering disciplines covered in the report. The initial checklist indicates areas that will require additional field survey or design review effort.

Comprehensive Evaluation of Project Datum--Quality Control Checklist (New Orleans District)

Title: LPV-12.2, Hurricane Protection Project, Jefferson Lakefront, Fronting Protection, Duncan Pumping Station, Jefferson Parish, Louisiana - Design Report

Prepared by: *mh*
Checked By: *rmf*
Date: *31-May-07*

General Checklist

[No] *Gages Referenced To both NAVD88 and Latest Epoch Tidal Datum (MLLW, LMSL)*
[???] *Gage Inspection Current*
[No] *Do Plans Document 3 PBMs*
[No] *Is A PBM Tied To NAVD88 and Tidal Datum*
[N/A] *Is Navigation Project Tied To MLLW*
[???] *Has Subsidence and Sea Level Rise Been Considered*
[Yes] *Are Units Specified (US Survey Foot)*
[Yes] *State Plane Zone Specified*
[No] *Do Project PBMs Indicate Epoch, Datum, Description, Elevation*

Comments [Excerpted]:

Executive Summary

3.0 Site Survey Plan
This is very good. It makes it clear which horizontal and vertical systems were used in the preparation of the topographic survey and also makes it clear that older pump station plans are referenced to Cairo 1910 and incorporated into the report for "informational purposes only."

Design Report

3.0 Site Survey Plan
Good. Includes additional information that confirms Geoid03 (revised for South Louisiana in Oct '05) was used in GPS processing. Refer to Appendix C below for more detail.

10.0 Preliminary Cost Estimate
Drawings in 10.2 Demolition indicate "NGVD" in margin. Should be NAVD88 (2004.65)

Appendix A - Scope of Work

7. Site Surveys and Mapping
All federally funded Hurricane Protection, Flood Control, Shore Protection, and Navigation projects require documentation of the following:
1) Reference to accurate and current hydraulic/tidal datum (e.g., LWRP, LMSL, MLLW) based upon an adequate gage network with ties to NOAA using latest tidal epoch.

2) Three bench marks at each gage relative to NAVD88 (latest adjustment/epoch with at least one PBM directly tied to the NSRS) and from which rigorous gage inspections are performed and documented (bench mark ties to 3rd order)

3) Reference/relationship from latest epoch of NAVD88 to construction/design datum if other than NAVD88 or current hydraulic/tidal datum (e.g., relationship from NAVD88 to MLG, NGVD29, Cairo, etc.).

A total of three bench marks needs to be identified or established at the project site in accordance with CEMVN-ED-SS-06-01, "USACE New Orleans District Guide for Minimum Survey Standards for Performing Hydrographic, Topographic, and Geodetic Surveys" and the location, identification and elevation of these bench marks needs to be shown on all relevant project sheets/drawings (see Appendix C note below).

8. Geotechnical Explorations, Test, and Analysis
Soil Borings and Cone Penetrometer test to be tied to baseline with station and offset and X/Y and elevation given with respect to project reference systems (see Appendix D note below).

Appendix B - Plates

Plate #4 - Confirm survey baseline referenced to Geodetic North Azimuth and add stationing, PI Coordinates, source, ID, etc. or remove completely.

Plate #27
" Existing elevations are per the design drawings.*
Actual as-built elevations are +/-0.8' lower"
This is a very good and helpful note.

Appendix C - Site Survey Plan

Need to show site map and data sheets for control points "082806GD" and NGS "BUICK" (pictures, description, location, references, elevation, etc.) and establish a third bench mark with all of this information.

Appendix D - Geotechnical Investigation

Only two soil boring logs shown (of eight proposed). Ground elevations for two soil boring locations shown on log, margin info indicates NGVD (confusing/ambiguous).

Station/offset info for proposed soil boring and CPT test sites unclear. Need coordinates and elevations of all soil boring and CPT sites.

General - Include statement: All surveys shall be conducted in accordance with CEMVN-ED-SS-06-01, "USACE New Orleans District Guide for Minimum Survey Standards for Performing Hydrographic, Topographic, and Geodetic Surveys" and shall be submitted to ED-SS. The guidance is available at http://www.mvn.usace.army.mil/ed/edss/surveyingguidelines.asp

9-6. Elevation Uncertainty Estimates of Reference Grades. The surveyed elevation of a flood protection structure or navigation grade has an uncertainty due to the propagated errors of all the uncertainties in the components that derived the elevation. These include the regional geodetic PPCP datum uncertainties, hydraulic or tidal datum uncertainties, water level gage references, local LPCP datum uncertainties, topographic/hydrographic survey errors, feature irregularities, etc.

a. For example, if the PPCP for a levee project has an estimated NSRS accuracy of ± 0.2 ft, and topographic surveys or the levee profile are performed through local LPCPs on the levee, then the resultant NSRS accuracy of a ground shot atop the levee (or a first-floor elevation in the flood plain) could propagate to as much as ± 0.5 ft. Likewise, the resultant elevation accuracy of a navigation project grade or HSPP structure elevation depends on reliability of the tidal datum, sea level change estimates, and the depth measurement process.

b. Uncertainties in navigation depths will normally range between ± 0.5 ft and ± 1 ft, or larger in some projects. These propagated uncertainties must be estimated for each project and factored in to the risk analysis or design of a protection grade or navigation channel design grade—see EM 1110-2-1619 (*Risk-Based Analysis for Flood Damage Reduction Studies*). Table 9-3 lists typical elevation uncertainty estimates for inland and coastal projects.

Table 9-3. Typical Elevation Uncertainty Estimates of Gages and Project Features Relative to NSRS.

Feature	Elevation Uncertainty Project (Standard Deviation 95%)
River Gages	
Gages directly connected to NSRS based on direct leveling or DGPS satellite observations	± 0.05 ft to ± 0.2 ft
Gages on legacy datums with firm (published NSRS) relationships	± 0.15 ft to ± 0.4 ft
Gages on legacy datums without firm (or unknown) connections to national vertical network	± 0.5 ft to ± 2.0 ft

Table 9-3 (Concluded). Typical Elevation Uncertainty Estimates of Gages and Project Features Relative to NSRS.

Feature	Elevation Uncertainty Project (Standard Deviation 95%)
Topographic Feature Elevations (Propagated Errors)	
Levee/floodplain/first-floor elevations based on direct connections with current NSRS bench marks	± 0.2 ft to ± 0.3 ft
Levee/floodplain/first-floor elevations based on legacy datums and uncertain PBM origins	± 0.5 ft to ± 1 ft
Levee/floodplain/first-floor elevations based on legacy datums but firmly related to current NSRS vertical network	± 0.3 ft
Coastal Project Grades	
Tide Gages (function of period of record, epoch, etc.—see Chapter 4)	± 0.2 ft to ± 0.5 ft
Tidal model at project site hydrodynamically modeled to local NOAA LMSL datum	± 0.1 ft
Tidal model at project site estimated based on unknown or outdated tidal datum (uncertainty function of tide range and distance from original gage)	± 0.2 ft to ± 0.5 ft
Navigation channel depth or HSPP grade (propagated error)	± 0.5 ft to ± 1.0 ft

c. Appendix M *(Uncertainty Model for Orthometric, Tidal, and Hydraulic Datums for use in Risk Assessment Models)* discusses methods for estimating overall datum and survey uncertainties on USACE project grades, and the statistical factors that should be considered in arriving at risk assessments associated with datum uncertainties. This appendix contains practical examples of the factors (such as those in Table 9-3) that must be incorporated in datum uncertainty computations.

9-7. Computing Elevation Uncertainties in the Design of Flood Protection and HSPP Structures. Uncertainty is defined as the result of imperfect knowledge concerning the present or future state of a system, event, situation, or (sub) population under consideration. Datum and resultant elevation uncertainties of reference PBMs and gages must be factored in the design of protection elevations on inland or coastal flood protection structures. Uncertainty "allowances" also factor in to risk-based design of protection elevations, which involves estimating the probability and

severity of undesirable consequences of a failure, e.g., loss of life, threat to public safety, environmental and economic damages. Risks associated with datum and subsidence uncertainties would involve potential overtopping during flood stages. General guidance on these design considerations is summarized below.

> *Loss of protection due to lowering of the top of flood barrier relative to design water levels shall be accounted for in any flood risk management project with site geology that is undergoing long term regional settlement [subsidence] and/or on coastlines where future sea level rise is occurring. For the system to be reliable, the top of the flood protection must be able to provide the required design height over the service life of the project. In areas where subsidence is a concern, a comparative analysis shall be performed ...To ensure reliability of the system, and to account for local settlement caused by the weight of levees, or from general lowering of an area relative the water level due to regional subsidence and/or sea level rise, flood risk management projects shall be initially constructed to a height sufficient to maintain the required height for all future conditions. Flood risk management projects shall also be constructed to the design level for current conditions with allowance for raising in the future to meet design heights as settlement and/or subsidence occurs.*

a. An additional freeboard allowance can be estimated that will account for geodetic datum uncertainties and long-term subsidence. The floodwall depicted in Figure 9-1 depicts freeboard allowances for uncertainties in the regional geodetic datum and regional subsidence. These allowances may be estimated from the ranges shown in Table 9-3 and from the uncertainty estimates listed in Table 9-4 in the following section.

b. Application of these uncertainty allowances are outlined in EM 1110-2-1619 *(Risk-Based Analysis for Flood Damage Reduction Studies*). .

Figure 9-1. Allowances for geodetic datum and subsidence in risk-based design.

9-8. Site Information Classifications and Requirements. Table 9-4 provides general site information classifications for reference datums, based on various levels of potential adverse site conditions. These classifications apply to the design of new protection structures or an evaluation of existing projects. "Well-Defined" or "Ordinary" classifications are considered acceptable. "Limited" site information will require additional field survey data. Datum or subsidence uncertainty estimates shown in the table should be factored into design risk assessment models and floodwall height overbuild computations.

Table 9-4. Site Information Classifications and Uncertainty Estimates (95% Confidence Levels) of the Primary Project Control Point (PPCP).

Condition	Well-Defined	Ordinary	Limited
Connection to existing NSRS PBM	1st Order PBM in NSRS	2nd Order NSRS PBM	3rd or 4th NSRS PBM
Surveyed connection method with NSRS	1st/2nd Order differential levels	2/5 cm NGS GPS standards 3rd Order levels GPS CORS/OPUS	GPS RTK or unknown method
Reference orthometric datum	NAVD88	NAVD88	NGVD29
Published in NSRS	Yes	Yes	No
Estimated network orthometric datum accuracy relative to NSRS	± 0.02 ft to < ± 0.10 ft	> ± 0.10 ft to < ± 0.25 ft	> ± 0.25 ft
Estimated regional hydraulic/tidal water level datum accuracy at gage reference PBM	± 0.05 ft to < ± 0.10 ft	> ± 0.10 ft to < ± 0.25 ft	> ± 0.25 ft
Uncertainty in 50-year subsidence forecast predictions (95%) in high subsidence areas	< ± 0.1 ft	> ± 0.1 ft to < ± 0.5 ft	> ± 0.5 ft
Uncertainty in 50-year sea level forecast predictions (95%)	< ± 0.1 ft	> ± 0.1 ft to < ± 0.5 ft	> ± 0.5 ft

9-9. Estimating Uncertainties on Coastal Navigation Project Grades. The design navigation grade or required dredging template needs to contain an allowance for uncertainties in the reference datum, tidal models, and survey accuracies. This allowance is dependent on a statistical analysis of the "total propagated uncertainty" (TPU) of individual depth measurements made by the acoustic measurement system, along with estimated hydrodynamic, meteorological, and environmental conditions occurring at a specific project site. Statistical uncertainties in the overall depth measurement process at a specific project site should be reviewed and evaluated during the PED phase. These will include local system variables (e.g., positional uncertainties, acoustic calibration precisions, vessel motion correction, acoustic depth resolution, sound

velocity and outer beam refraction, etc.) and other systematic biases (tidal phase variations, tidal MLLW modeling variations, etc.) that may be present in the propagated depth error budget—TPU.

a. Indeterminate biases. Indeterminate biases include biases in tidal models, tidal epoch latencies, reference datum biases, tidal bench mark settlement, sea level change, acoustic bottom reflectivity, reference datum adjustments, geoid readjustments, and other largely indeterminate factors. These are biases that are difficult or nearly impossible to measure or correct for. They are generally not factored in dredge clearance assessment. This is because these biases are present in all repeated surveys over the project, assuming the same vertical reference tidal bench mark is used on a given project. They do, however, enter into the estimated uncertainty of a reported channel clearance to the public and cost estimates for dredging.

(1) For example, sea level rise occurring between tidal epoch updates could be as much as 0.2 ft. Thus, the MLLW datum at the reference bench mark would have a constant bias of 0.2 ft and the reported channel clearance constantly off by that same amount. This equates to overdredging the project by a constant 0.2 ft, which may have significant budget impacts.

(2) The use of outdated or undefined local reference datums will also cause systematic biases in the maintained or reported project depth. Datum biases of upwards of 2 ft have been known to occur, resulting in incorrectly reported or interpreted channel clearance depths.

(3) Tidal bench mark elevations used to reference measurement, payment, and clearance surveys at a project are also subject to uncertainties. The stability of the bench mark could be subject to regional settlement or uplift. The MLLW datum has an uncertainty dependent on the length of the time the gage was in place, the distance from a primary gage, and other factors. The uncertainty of the computed MLLW datum at a gage site can range from ± 0.1 ft to as much as ± 0.25 ft—see Chapter 4. It is also assumed that a primary reference bench mark is used to control all surveys performed at a given project site. If different bench marks are used, and inconsistencies between these bench marks exist (height or MLLW datum), then these errors would be propagated into the TPU estimates. An example would be uncertainties in a tidal zoning model.

(4) Tidal datum variations over a project may be subject to uncertainties if not minimized by some form of hydrodynamic modeling, such as those used in developing VDatum tidal datum fields.

(5) Geoid undulations occurring over a project must be modeled if RTK methods are used to measure the water surface elevation. Geoid model uncertainties in coastal areas are typically at the 1 to 3 cm range, with predicted uncertainties slightly larger (5 cm) in offshore entrance channels. There are no practical methods of refining the model in offshore models; however, since these errors are systematic to all users of the same model, survey repeatability (or more importantly, reproducibility) is not impacted.

(6) The accumulation of these global uncertainties can range from 0.1 to 0.5 ft. The addition of these global uncertainties can propagate to an overall uncertainty in the reported

project clearance. For example, a project with an estimated local survey confidence of ± 0.25 ft relative to a fixed bench mark/gage and an estimated global uncertainty of ± 0.25 ft would have an overall uncertainty of nearly ±0.4 ft. Given these uncertainties, reporting project clearances to an implied 0.1 ft confidence level is problematic.

b. Water surface correction uncertainty due to unmodeled tidal phase lags. Aside from vessel motion corrections (roll, pitch, yaw, heave), the largest portion of the depth error budget (TPU) is attributable to unmodeled tidal phase lags—i.e., surface slope gradients between the reference gage and the project site. This error is significant is tidal estuaries, rivers, or when inshore gage readings are extrapolated out into a coastal entrance channel—see Chapter 4. If RTK-derived water surface elevations are measured, coupled with GPS-aided IMU systems to correct vessel motions (e.g., POS/MV), then the uncertainty of the water surface elevation measurement at the project site may be estimated.

c. General measurement uncertainties. Uncertainty estimates in the design and maintenance of navigation grades in a typical navigation project of limited geographical extent are summarized in Table 9-5. This table differentiates between the survey procedures used to measure the water surface at the offshore project site—(1) unmodeled surface elevation extrapolation from a shore-based tide gage or (2) direct RTK surface elevation measurement at the project site. This table is not inclusive of all the measurement factors that make up a depth measurement—see the TPU factors in Figure 9-3.

Table 9-5. Estimated Uncertainties in Measuring Navigation Project Grades in a Typical Navigation Project.

Measurement Factor	Uncertainty Range
Tidal gage MLLW datum accuracy	0.1 - 0.2 ft
Tidal epoch latency (update lag during 19-year period)	0.05 - 0.1 ft
Projected gage/tidal PBM elevation (RTK):	
RTK geoid prediction	0.1 - 0.2 ft
RTK accuracy	0.1 - 0.15 ft
Projected gage/tidal PBM elevation: (extrapolated from gage to work site)	
MLLW range gradient (unmodeled/estimated)	0.1 - 0.3 ft
Tidal phase lag (gage to work site)	0.2 - 2 ft +
Acoustic depth measurement uncertainties:	
Depths < 15 ft	0.05 – 0.1 ft
Depths 15 ft to 40 ft	0.1 – 0.3 ft
Depths > 40 ft	0.3 – 0.5 ft

(1) The applicable uncertainties in Table 9-5 are statistically propagated to determine the resultant uncertainty of a depth measurement and uncertainty in the dredged clearance estimate.

(2) As an example, given a Gulf Coast 45-ft deep-draft navigation project located 5 miles distant from the reference tide gage. The reference gage datum computation was based on 90 days of observations 30 years ago. The tide readings at the gage are extrapolated out to the project site without any tide range or phase correction. The mean tide range is 8 ft at the offshore project site and 6 ft at the gage. The phase lag between the project site and gage is estimated at 45 minutes. The TPU of the measured grade would be estimated as follows:

Estimated Uncertainty Factor in TPU	Uncertainty in ± ft (95%)	
Tidal gage MLLW datum accuracy	0.3 ft	(Chapter 4)
Tidal epoch latency (update lag)	0.05 ft	(1993 to 2009)
Extrapolated (projected) surface from gage		
MLLW range gradient	0.2 ft	(unmodeled MLLW reference)
Tidal phase lag (average ebb/flood)	0.7 ft	(average random deviations)
Acoustic depth measurement	0.3 ft	(from above table)
Total Propagated Uncertainty:	0.8 ft	RMS (95%)

d. This implies that the uncertainty of the measured or cleared navigation grade is uncertain at the ± 0.8 ft (95%) confidence level. This uncertainty allowance should be factored in the tolerances used in the original studies that determine the authorized navigation depth for a project—see EM 1110-2-1613 (*Hydraulic Design of Deep-Draft Navigation Projects*). This uncertainty allowance (or tolerance) can also play in the evaluation of dredge clearance survey data and in the significant figure (rounding) resolution of recorded depths and clear grades. Figure 9-2 illustrates the uncertainty allowance estimate relative to (i.e., above and below) a nominal or required clearance grade. This uncertainty may or may not be significant on soft bottom maintenance dredging projects; however, on new work or rock-cut channels, this allowance may need to be applied to the overdepth allowance to provide additional confidence that the final channel clearance is to grade.

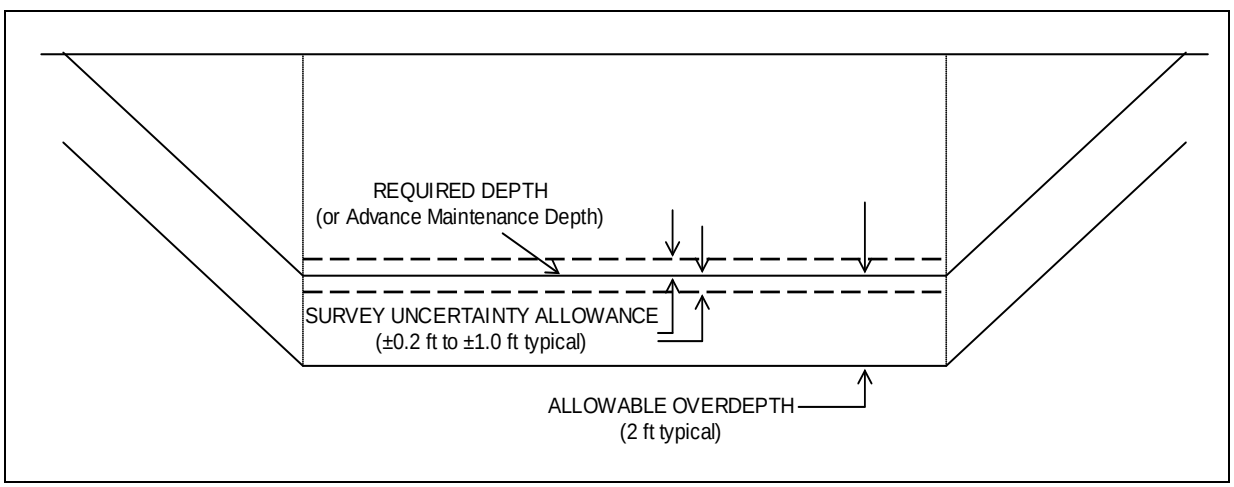

Figure 9-2. Propagated uncertainty allowance on a typical maintenance dredging template.

e. Approximate estimates of TPU in deep-draft navigation projects. Table 9-6 provides another example of general estimates for survey TPUs under nominal deep-draft project conditions, accounting for various measurement conditions largely dependent on the water surface measurement correction. These ranges may be used to estimate the TPU for a specific navigation project. Given the main variable in the table is dependent on the gage location relative to the project site (non-RTK measurements) the magnitude of this error needs to be estimated based on actual tidal range and phase conditions.

Table 9-6. Estimated TPU Allowances for Deep-Draft Navigation Projects.

Typical TPU	Water Surface Elevation Measurement Procedure	Tidal regime hydrodynamically modeled
Hard Bottom Materials		
± 0.20 foot	Determined from carrier phase GPS (RTK)	Yes
± 0.25 foot	Determined from carrier phase GPS (RTK)	No
± 0.20 foot	Estimated from gage less than 1 mile from project site	Yes
± 0.25 foot to ± 0.50 foot	Estimated from gage 1 to 5 miles from project site	No
± 0.50 foot to ± 1.0 foot	Estimated from gage > 5 miles from project site	No
± 0.50 foot to ± 2.0 foot	Estimated from gage > 10 miles from project site	No
Soft Bottom Materials (Maintenance Dredging)		
± 0.25 foot	Determined from carrier phase GPS (RTK)	Yes
± 0.25 foot to ± 1.0 foot	Estimated from gage 1 to 10 miles from project site	No
± 0.50 foot to ± 2.0 foot	Highly variable acoustic reflectivity due to suspended sediment, fluff, dense bottom vegetation, etc.	Yes

f. Methods for directly computing TPU of depth measurements. A more refined estimate of the TPU in measured depths (and clearance grades) in a navigation project may be computed using algorithms developed by the Canadian Hydrographic Service (CHS) for the US Naval Oceanographic Office—see "*Error Budget Analysis for US Naval Oceanographic Office (NAVOCEANO) Hydrographic Survey Systems: Final Report for Task 2, FY 01*" (NAVOCEANO/Hare 2001). A screen capture of a TPU calculator using these algorithms is shown in Figure 9-3. This TPU calculator provides user input of the estimated accuracies of over 50 parameters making up the total (propagated) depth error budget. It is applicable to either multibeam or single-beam hydrographic systems. This calculator compares the resultant TPU with both USACE EM 1110-2-1003 (*Hydrographic Surveying*) accuracy standards and International Hydrographic Organization "*Special Publication S-44*" (IHO 1998) accuracy standards. In addition, positional errors and target detection resolutions are estimated, as shown in the figure.

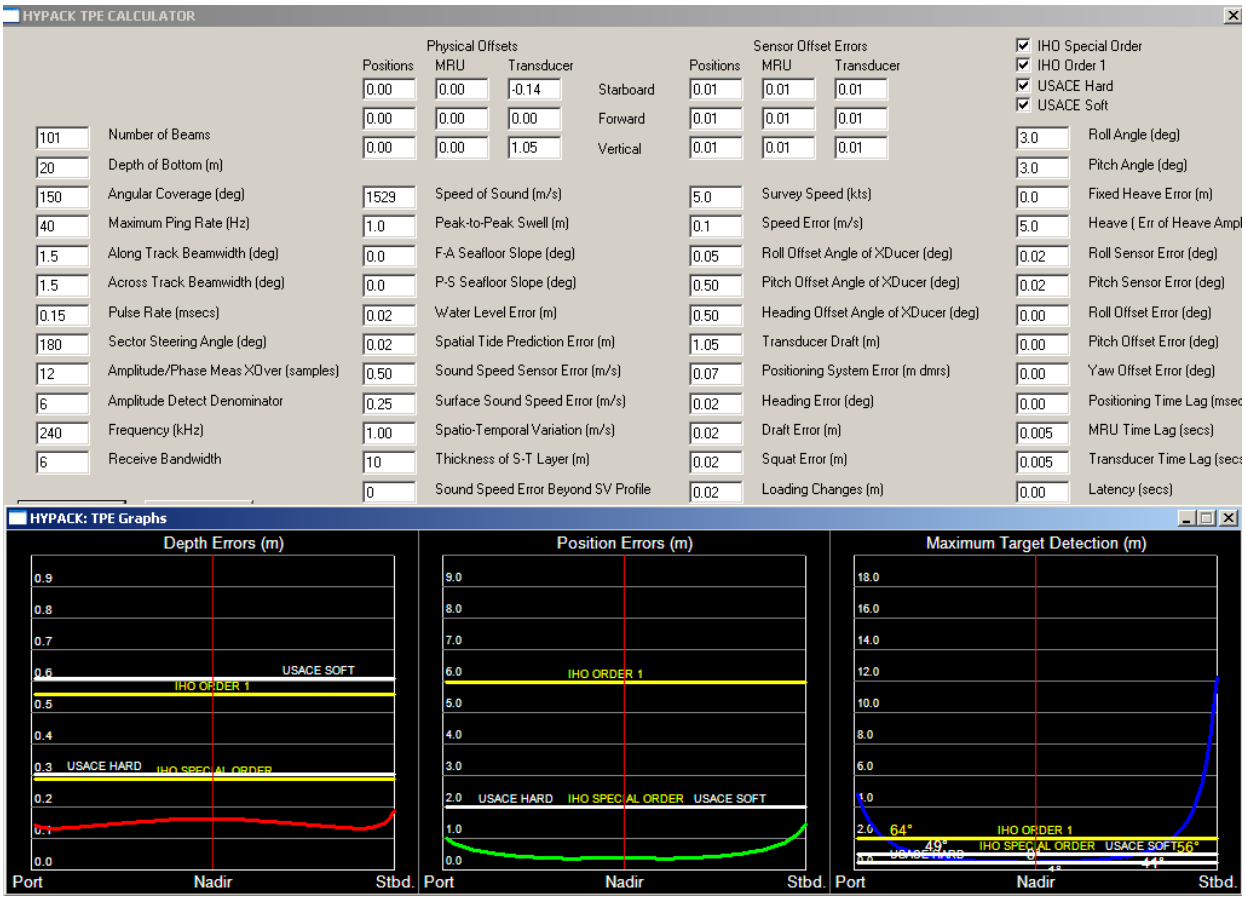

Figure 9-3. Total Propagated Uncertainty calculator for depth, position, and object detection. Values shown are for example only—users must insert estimated uncertainties for each parameter specific to their survey systems, procedures, and project. (HYPACK, Inc.)