APPENDIX E

Tidal Modeling Procedures for Coastal Navigation Projects

E-1. Purpose. This appendix provides supplemental guidance to Chapter 4. It contains technical guidance and examples of interpolated tidal modeling procedures for USACE coastal navigation projects. It is primarily applicable in those regions where NOAA VDatum model coverage is not complete (as of 2009) or does not exist, such as in intracoastal waterways and sounds.

E-2. Requirements for Accurately Modeled Tidal Reference Datums. Tidal reference datums vary both spatially and temporally. Thus, the water surface elevation at a shore-based gage is adequate only for that specific location and time. The height of the water level will be significantly different between two points around an inlet, due to varying times and weather conditions—see Figure E-1. Likewise the MLLW datum will vary with the tidal range variations, which are modified by the topography of an inlet or coastal region. The MLLW datum elevation at a reference gage should not be extrapolated to another location without some modeled correction. It is also subject to long-term variation due to sea level change, subsidence, or other factors. This requires periodic updating of tidal datums based on NOAA's latest NTDE, which is currently 1983-2001 for most areas.

a. Tidal datum models. Lack of accurately modeled tidal datums can have significant impacts on navigation project construction and maintenance costs. Navigation projects that are not adequately referenced to an established tide gage and modeled MLLW datum plane, or have not been updated for sea level change, can result in overdredging or underdredging, along with increased construction disputes and claims. The primary factors that need to be considered in evaluating the adequacy of depth grade determination on a navigation project include the following:

(1) Tidal range variations over the project reach. Geospatial variation of MLLW dredging datum relative to the orthometric and ellipsoid datums used to reference acoustic depth measurements.

(2) Tidal phase variations over the project reach. Real-time survey techniques used to measure the elevation of the water surface at the construction site that corrects tidal phase variations observed at a reference tide gage.

(3) Tidal epoch adjustments for sea level or land subsidence changes. Involves monitoring NOAA tide gage records for changes to tidal epochs, tidal PBM adjustments, etc.

(4) Quality of reference tidal datum determinations. Awareness of the uncertainties in tidal gage datums and any models derived therefrom—i.e., VDatum.

b. Tide gage extrapolations. The long-established practice for dredging and related payment surveys of navigation projects involves extrapolation of a water (tide) level gage to the

offshore construction site—i.e., extrapolating the tide level at the gage to the offshore point. This assumes both the water surface level and reference datum range are constant over the extrapolated distance—i.e., assumes no tidal phase or range variations exist. This distance may range from a few hundred feet to over 10 miles. These assumptions of linearity in water surface levels and datum degrade with distance from the reference gage. At low tidal ranges, longer extrapolations may be possible. At higher ranges (> 2 ft), extrapolations greater than a half-mile to 1 mile may be invalid and inaccurate. In addition, local weather conditions may further degrade the distance that a tide reading can be reliably extrapolated from a gage. Sea surface setup due to strong winds can significantly alter the surface model. Approximate methods for estimating tide phase differences ("tidal zoning") are used in some Districts, with mixed accuracy results as these methods do not account for local weather conditions.

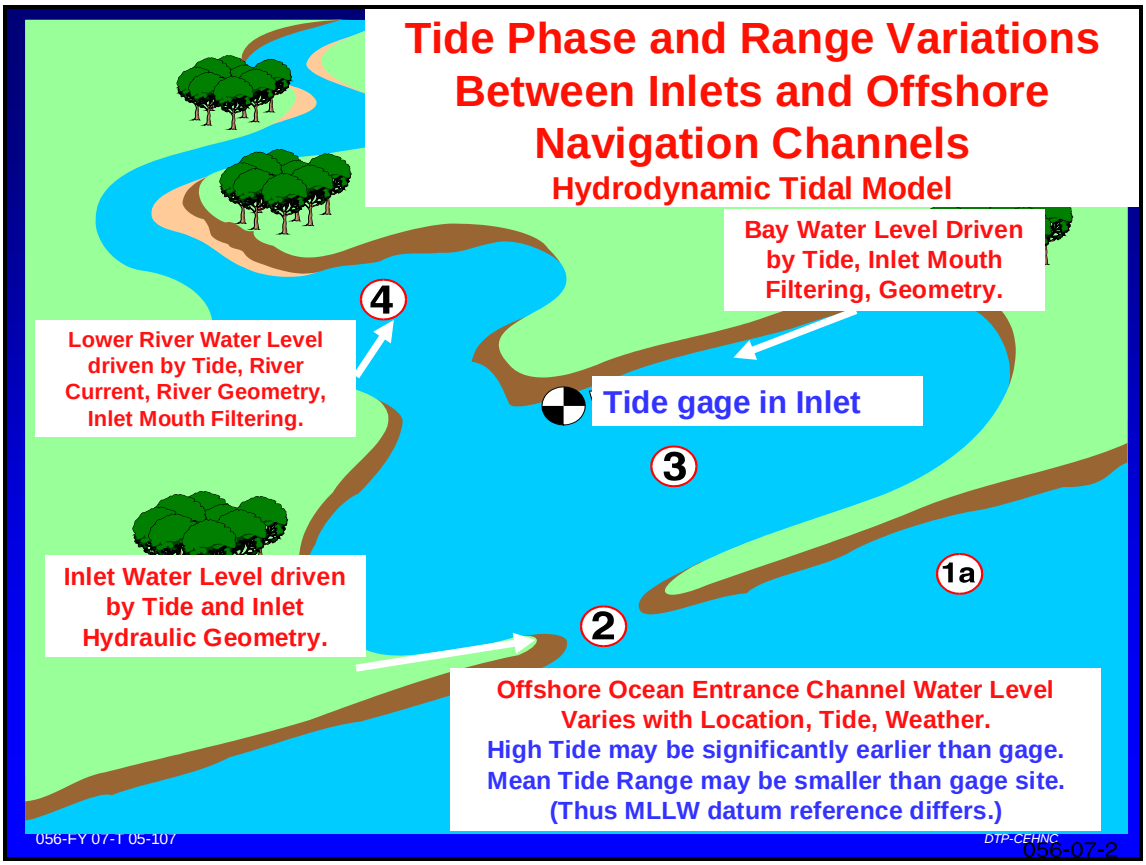

Figure E-1. Tide phase and range variations at an inlet.

c. Hydrodynamic conditions at tidal inlets. The overall effect of adverse conditions encountered at typical USACE coastal inlets is best summarized in the following excerpt from Part II of EM 1110-2-1100 (*Coastal Engineering Manual*).

"Hydrodynamic conditions at tidal inlets can vary from a relatively simple ebb-and-flood tidal system to a very complex one in which tide, wind stress, freshwater influx, and wind

waves (4- to 25-sec periods) have significant forcing effects on the system … Flow enters the bay (or lagoon) through a constricted entrance, which is a relatively deep notch (usually 4 to 20 m at the deepest point). Entrance occurs after flow has traversed over a shallow shoal region where the flow pattern may be very complex due to the combined interaction of the tidal-generated current, currents due to waves breaking on the shallow shoal areas, wind-stress currents, and currents approaching the inlet due to wave breaking on adjacent beaches …. Particularly during stormy conditions with strong winds, flow patterns may be highly complex. Also, the complicated two-dimensional flow pattern is further confounded because currents transverse to the coast tend to influence the propagation of waves, in some cases blocking them and causing them to break … Final complications are structures such as jetties, which cause wave diffraction patterns and reflections. In inlets with large open bays and small tidal amplitudes, flows can be dominated by wind stress. In such cases, ebb conditions can last for days when winds pile up water near the bay side of the inlet, or long floods can occur when winds force bay water away from the inlet. Most inlet bays, however, are small and some are highly vegetated, so wind stress is not a dominant feature, except under storm conditions ... Although many bays do not receive much fresh water relative to the volume of tidal flow, substantial freshwater input due to river flow can sometimes create vertically stratified flows through a tidal inlet. Typically, however, well-mixed conditions exist for most inlets."

E-3. Modeling the MLLW Dredging Datum on USACE Navigation Projects. Most often, linear or surface interpolations between gages will be used. On projects with larger tide ranges where the uncertainty of a linear model between gages increases beyond the allowable tolerance, a more sophisticated hydrodynamic model may be required to best define the MLLW datum. This presumes adequate gage records exist from which to calibrate the tidal model in an area. On some projects, a single gage may be adequate. Others may require additional gages to define and verify the model. If these additional gages do not exist, then a gaging program will have to be programmed. In addition, topographic and bathymetric models of the project may have to be generated if they do not exist. A firm connection to the orthometric datum (NAVD88) may also be required. Thus, a number of project-specific technical factors will govern the overall effort required to model the MLLW datum plane of a project. This will also include the experience of those assessing the tidal model relative to the required relative accuracy of the tidal model.

a. Tidal error budget. One must not lose sight of the overall error budget in evaluating the effort required to model the MLLW datum on a project. Relative to removing large phase and wind setup errors with RTK measurements, these MLLW datum modeling errors are often insignificant. Thus, before embarking on any extensive and costly gaging program, the significance or sensitivity of these added gage observations on the overall tidal model must be substantiated. Likewise, the difference between a simple linear interpolation and a hydrodynamically modeled interpolation must be evaluated for significance relative to the intended tolerance. In addition, there is no point in performing elaborate MLLW datum tidal modeling unless RTK surface elevation measurements are mandated for the completed project. Having a MLLW tidal model accurate to ±0.1 ft with a ±1 ft phase error due to extrapolated gage readings five miles offshore would obviously be an inconsistent use of resources.

b. Tidal model accuracy. An evaluation of the errors in a tidal model is necessary to evaluate uncertainties between tide stations. The primary factors that need to be considered in modeling a reference tidal datum around a coastal protection structure include the following:

(1) Tidal phase variations over the project reach.

(2) Tidal range variations over the project reach.

(3) Tidal epoch adjustments for sea level or land subsidence changes.

(4) Quality of reference tidal gage datum determinations

(5) Seasonal variations in LMSL (i.e., biased sea level rise during hurricane season).

(6) Need for short-term (i.e., 5-year) tidal epochs in high subsidence or uplift areas.

c. Modeling tide range or MLLW variations over a navigation project. Variations in tidal range (i.e., undulations in MLLW datum relative to MSL or to the local geodetic/orthometric datum) within a project must be accounted for. This requires developing some model of the tidal hydrodynamic characteristics throughout the project. Figure E-2 illustrates this MLLW variation over a Jacksonville District deep-draft coastal inlet project (St Johns River—Ocean to Jacksonville, FL). The MLLW datum relative to MSL varies from the ocean through the entrance jetties and up river some 20 miles to the termination of the deep-draft project past the gage at Longbranch, and further upstream in the shallow-draft project to Palatka, FL. The MSL reference plane also varies relative to NAVD88, generally rising upstream. Figure E-2 also depicts that NGVD29 and NAVD88 are not parallel datums. The MSL-MLLW datum variation may also be impacted by fresh water flow into the tidal area.

(1) Modeling the MLLW datum through a navigation project requires an adequate density of tide gages from which the model can be calibrated, and intermediate datum variations between the gages can be modeled. In Figure E-2, the roughly 5.6 ft tide range at the ocean narrows down to 1.6 ft over a 25-mile navigation project. Although the gages shown in Figure E-2 are spaced at about every 5 to 10 miles, they should be of sufficient density to calibrate a hydrodynamic tidal model for this project. The interpolations between the gages shown on Figure E-2 represent only a crude tidal model of the MLLW reference plane—a full hydrodynamic tidal model such as VDatum would be represented by a smooth curve. In many cases with small tidal range variations, or with a dense gage network, a linearly interpolated model may prove adequate. That may be the case for portions of the above project where the variation between gages is not large.

(2) Figure E-3 illustrates the tidal range variation over seven miles of a Norfolk District shallow draft project on the Atlantic east coast in Virginia. There would appear to be a sufficient density of gage data to model the MLLW datum plane for this project—updating the older MLW datum. The NGVD29 orthometric datum reference on this project needs to be updated to NAVD88 along with a NAD83/GRS80 ellipsoid reference. Note that the relationship to the legacy datum (Corps of Engineers Low Water— C.E.L.W.) is shown on the figure.

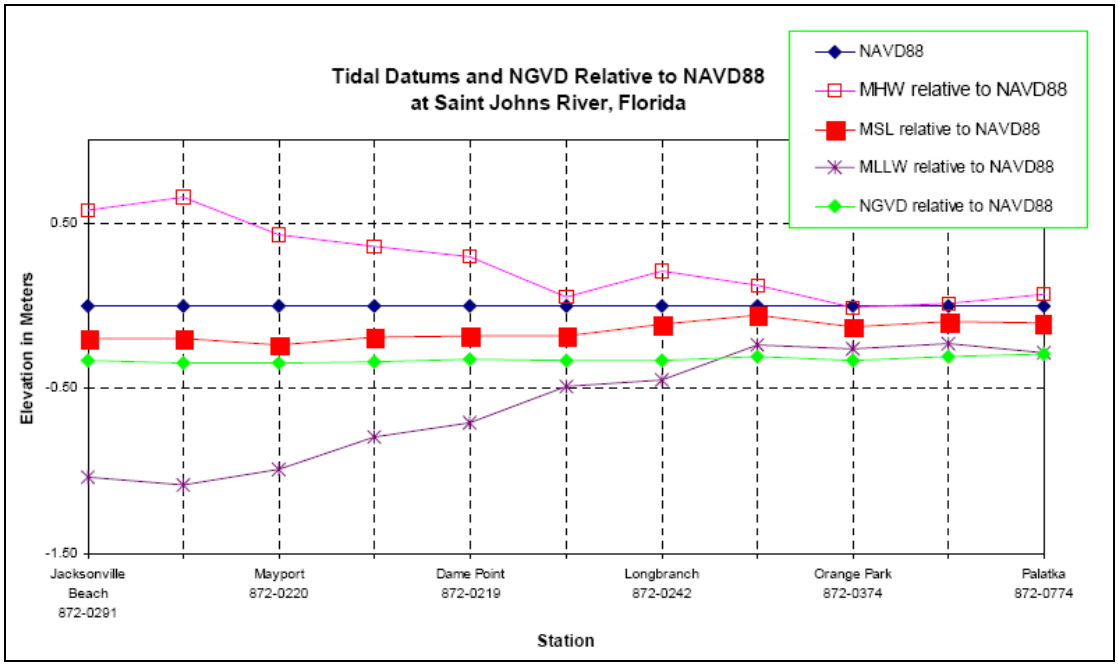

Figure E-2. Tidal range variation at a coastal inlet.

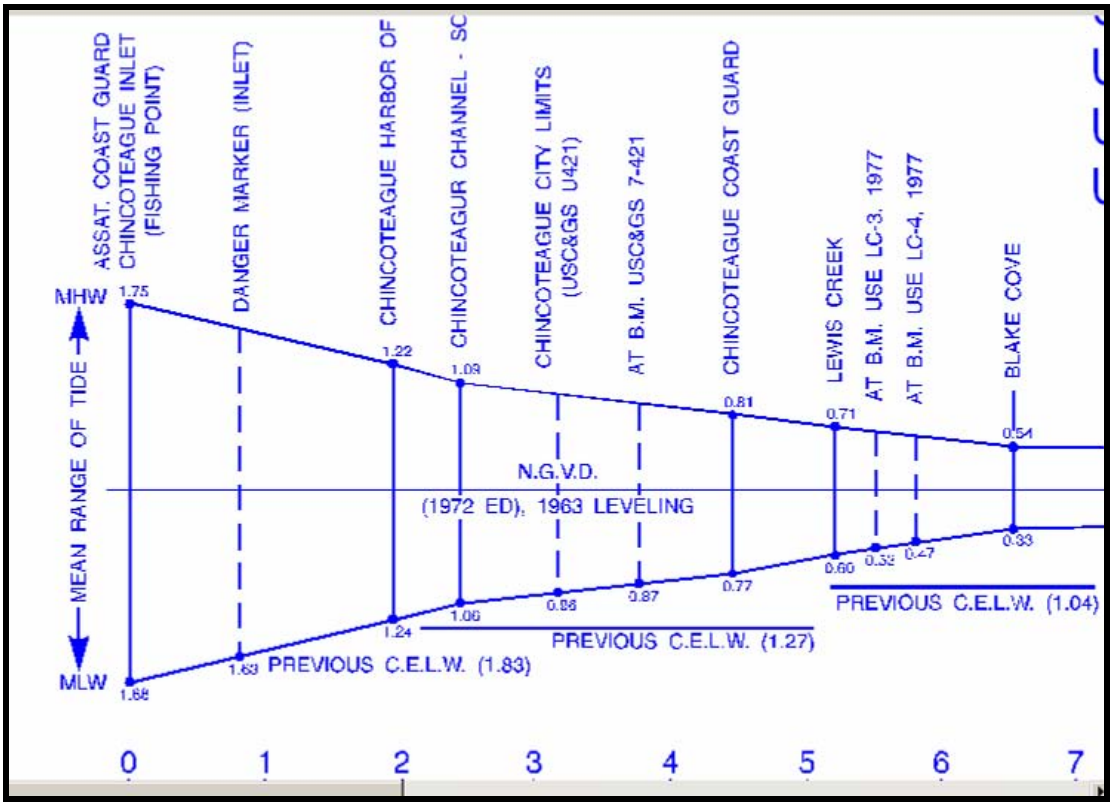

Figure E-3. Tidal range variation at Chincoteague Inlet, VA.

E-4. Procedures for Estimating Navigation Project MLLW Datum Models using Spatial Interpolation Techniques.

a. Tidal model updating actions. A number of options exist to update a tidal model for coastal navigation projects that require upgrading to the current NOAA tidal reference. Updating the tidal model requires the following basic actions: (1) ensure tidal datum reference planes (MLLW) are defined relative to published NOAA gages and tidal bench marks, (2) ensure the latest NTDE adjusted by NOAA is used, (3) model the MLLW reference plane relative to NAVD88 throughout the length of the project, (4) publish and disseminate the NAVD88-MLLW model for users, (5) optionally develop the NAVD88-MLLW datum relationship at tidal bench marks if these marks are used as RTK base stations, and (6) submit any USACE hydrodynamic tidal modeling data to NOAA for their use in expanding the nationwide VDatum.

b. Tidal gaging options. Items (1) and (2) above are easily achieved as long as an existing or historical gage exists at the navigation project. This will likely be the case for the majority of the Corps' deep-draft navigation projects. If not, then a standard gaging program will have to be developed in order to establish a tidal datum at a project—see "*Computational Techniques for Tidal Datums Handbook*" (NOAA 2003). Any such effort must be coordinated with NOAA in order to ensure the project becomes included in NOAA's NWLON inventory. Time and cost estimates for performing the gaging can be obtained from NOAA. Project modeling—Items (3) through (6) above—will require close coordination with District H&H elements, ERDC/CHL, and/or NOAA. In small tide ranges either between gages or in the overall area, linear interpolation of the MLLW model will often be sufficiently accurate and economically developed. These models may already have been developed for some projects, and may currently need only to be adjusted for tidal epoch updates and geoid models.

c. Example of model vs. interpolation decisions--Miami Harbor (Jacksonville District). Figure E-4 depicts a navigation project (Miami Harbor) where a simple straight-line interpolation of the tidal datum might be warranted in lieu of performing a full hydrodynamic model study. Initial estimates of changes in time and range of tide for any survey area can be obtained from a review of the NOAA tide prediction "Table 2" information found on the NOAA CO-OPS web site. (This web site also provides links to NGS bench mark datasheets). The NOAA tide table values should be used with caution as the data summaries are from observations of varying lengths and various time periods and may be out of date and no longer reflective of current conditions. The tide tables list mean ranges of tide (MHW – MLW), Spring Ranges of Tide (Range of tide at New and Full moons), and the elevation of Mean Tide Level (MTL) above Chart Datum (MLLW). NOAA tide prediction data for the Miami Harbor area is shown below (in feet).

	Lat	*Long*	*Mn Rge*	*Spg Rge*	*MTL*
Miami Harbor Entrance	*25° 46.1'*	*80° 07.9'*	*2.46*	*2.93*	*1.39*
Government Cut, Miami Harbor Entrance	*25° 45.8'*	*80° 07.8'*	*2.32*	*2.83*	*1.32*
Biscayne Bay					
San Marino Island	*25° 47.6'*	*80° 09.8'*	*2.14*	*2.57*	*1.21*
Miami, Marina	*25° 46.7'*	*80° 11.1'*	*2.18*	*2.59*	*1.22*
Dodge Island, Fishermans Channel	*25° 46.2'*	*80° 10.1'*	*2.10*	*2.52*	*1.19*
Dinner Key Marina	*25° 43.6'*	*80° 14.2'*	*1.94*	*2.33*	*1.10*

This navigation project has an adequate density of NOAA tide data and has a relatively small tidal range—around 2.5 ft at the ocean entrance. The mean range of tide decreases by 0.16 ft between the Miami Beach Government Cut and inside near the Port of Miami turning basin. Similarly, the 0.14 ft range decrease is small between outside on Miami Beach and Miami Beach Government Cut. The regionally modeled tidal range at a point 3 miles offshore in open ocean could be compared with the range at the Miami Beach pier to see if there is a significant difference. The slope of MLLW can be estimated by looking at the changes in the elevation of MTL relative to MLLW. On the outside, the MTL-MLLW difference is approximately 1.4 ft and decreases to approximate 1.2 ft. inside at the Miami Marina (see Figure E-4). Given the small tide range, and the relatively small tidal range variations between outside and inside channels, the complexity of the variations is not sufficient to warrant a development of a hydrodynamic model. Thus, a straight-line interpolation of the model between observation locations would be acceptable. A regional ocean tidal model (e.g., the ADCIRC 2001 East Coast Model) would be considered in assigning a range value to the model for the outer offshore end of the entrance channel.

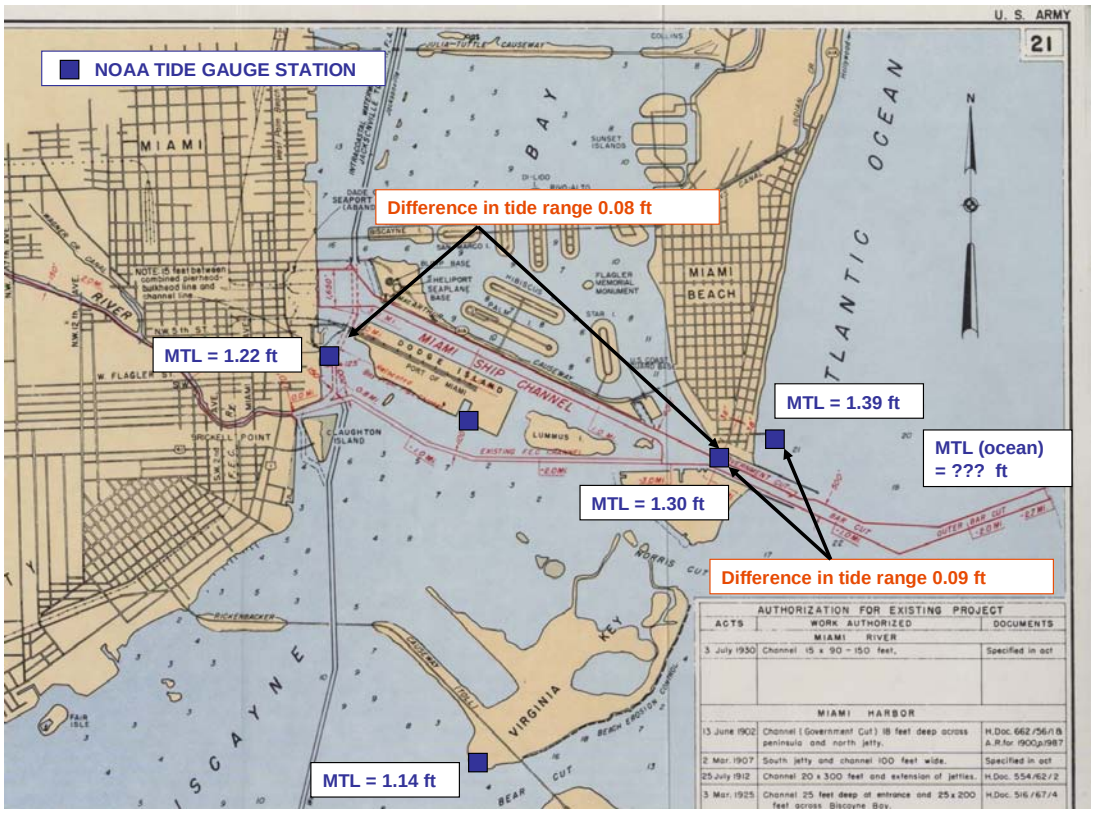

Figure E-4. Tidal Model calibrations at Miami Harbor.

d. Example: Yaquina River (Portland District). A similar analysis can be made for a West Coast project with a larger tide range—Yaquina River, OR (Portland District). The authorized depth varies from 40-ft at the bar, to 18 ft at Yaquina, then 10-ft to Toledo. The estimated mean range of tide and the MTL-MLLW elevation differences from the NOAA tide tables are shown below (in feet):

Yaquina Bay and River	*Lat*	*Long*	*Mn Rge*	*Spg Rge*	*MTL*
Bar at entrance	*44° 37'*	*124° 05'*	*5.9*	*7.9*	*4.2*
Newport	*44° 38'*	*124° 03'*	*6.0*	*8.0*	*4.3*
Southbeach	*44° 37.5'*	*124° 02.6'*	*6.37*	*8.34*	*4.51*
Yaquina	*44° 36'*	*124° 01'*	*6.2*	*8.2*	*4.4*
Winant	*44° 35'*	*124° 00'*	*6.3*	*8.2*	*4.3*
Toledo	*44° 37'*	*123° 56'*	*6.3*	*8.1*	*4.2*

However, a check of the latest NOAA tide station published bench mark information shows that the tide table values are out-of-date and should not be used. In general, if the latitude/longitude files have values only to the nearest degree, as opposed to a tenth of a degree, then the data are from pre-1960 observations. Using the latest information collected in the 1980's by CO-OPS, the table becomes (in feet):

Yaquina Bay and River	*Lat*	*Lon*	*Mn Rge*	*MTL*
Bar at entrance	*44 37*	*124 05*	*5.9*	*4.2*
Newport	*44 36.6*	*124 03.3*	*6.21*	*4.49*
Southbeach	*44 37.5*	*124 02.6*	*6.26*	*4.51*
Weiser Point	*44 35.6*	*124 00.5*	*6.46*	*4.57*
Toledo	*44 37.0*	*123 56.2*	*6.87*	*4.71*

Thus the older results show much less variability in the tide range than the updated, more recent data. The table and Figure E-5 shows that the range of tide increases by almost 1.0 ft. from outside to upriver at Toledo, and there is a 0.50 ft. slope in MLLW relative to MTL. This may be an area where a hydrodynamic model may prove useful to account for the non-linear changes in the tide going upriver.

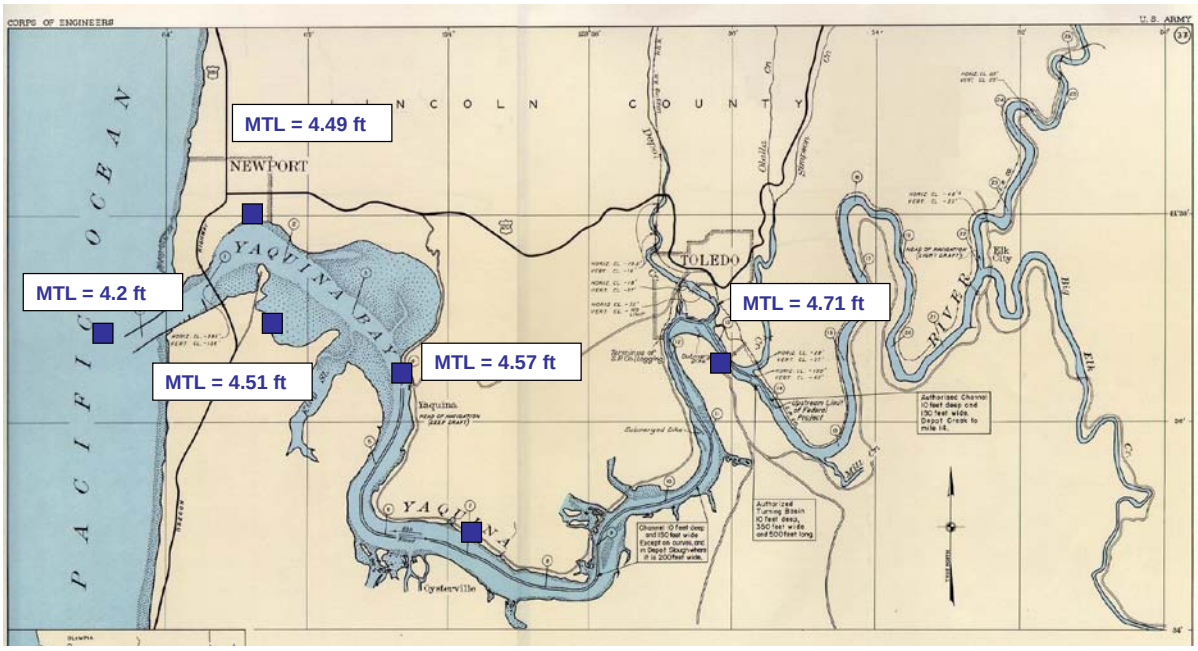

Figure E-5. Tidal Model calibrations at Yaquina River, OR.

e. Example: Portsmouth, NH (New England District). The following New England District project (Portsmouth, NH) is typical of a large tidal range variance—approximately 8 ft. MTL variations at various points are shown in Figure E-6. Predicted tide ranges are shown below.

Portsmouth Harbour	*Lat*	*Long*	*Mn Rge*	*Spg Rge*	*MTL*
Jaffrey Point	*43° 03.4'*	*70° 43.9'*	*8.7*	*10.0*	*4.7*
Gerrish Island	*43° 04.0'*	*70° 41.7'*	*8.7*	*10.0*	*4.7*
Fort Point	*43° 04.3'*	*70° 42.7'*	*8.6*	*9.9*	*4.6*
Kittery Point	*43° 04.9'*	*70° 42.2'*	*8.7*	*10.0*	*4.7*
Seavey Island	*43° 05'*	*70° 45'*	*8.1*	*9.4*	*4.4*
Portsmouth	*43° 04.7'*	*70° 45.1'*	*7.8*	*9.0*	*4.2*

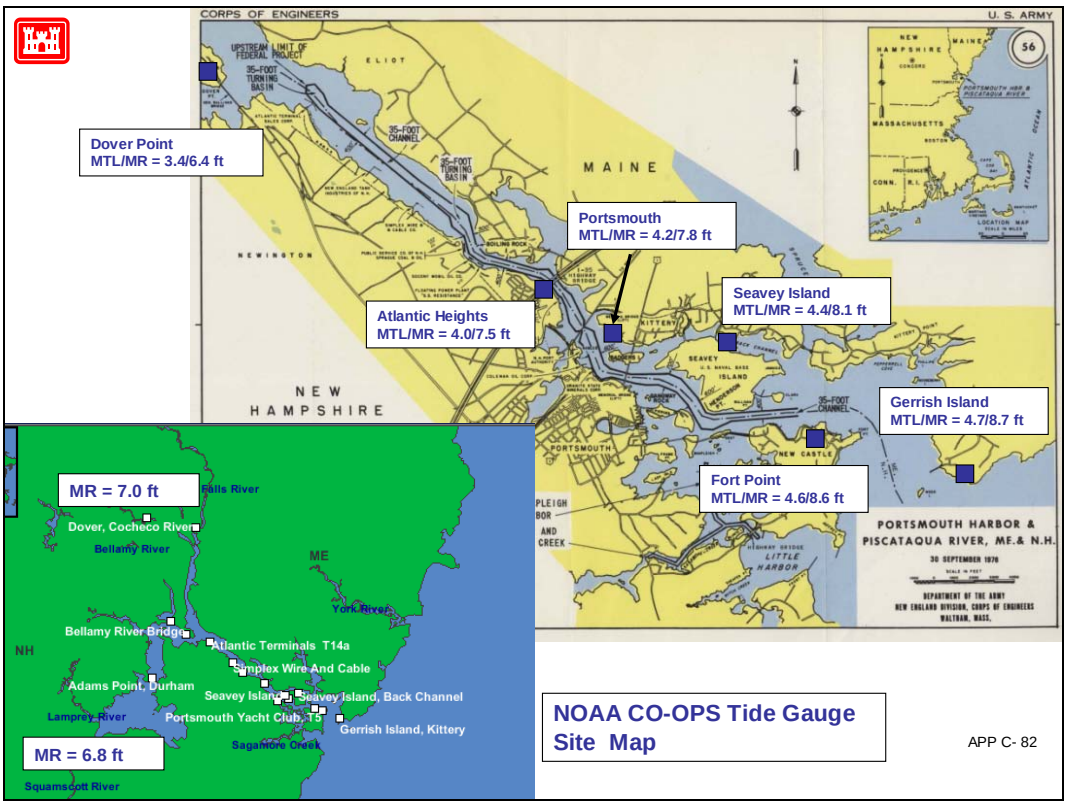

Figure E-6. Tidal Model calibrations at Portsmouth, NH.

E-5. Tidal Zoning Models. Discrete tidal zones are constructed based on knowledge of the tide at shore-based historical stations and estimated positions of co-tidal lines for range and time of tide. For most NOAA applications the resolution of the zoning has been to construct a zone polygon for every 0.2-foot change in range and every 0.3-hour change in time of tide. For many tidally complex areas (such as around Key West for instance) tide zones with higher resolution are used. Tidal zoning errors are considered random errors although they have a certain periodic nature and not a normal statistical distribution. Zoning errors also are characterized by two components: a time correction and a range ratio correction to observations from a nearby tide station. Maximum zoning errors for each project are estimated by simultaneously comparing tide curves constructed from time and range corrections to historical tide station observations. Statistics of the residuals are then analyzed to estimate the error in the zoning for the entire project.

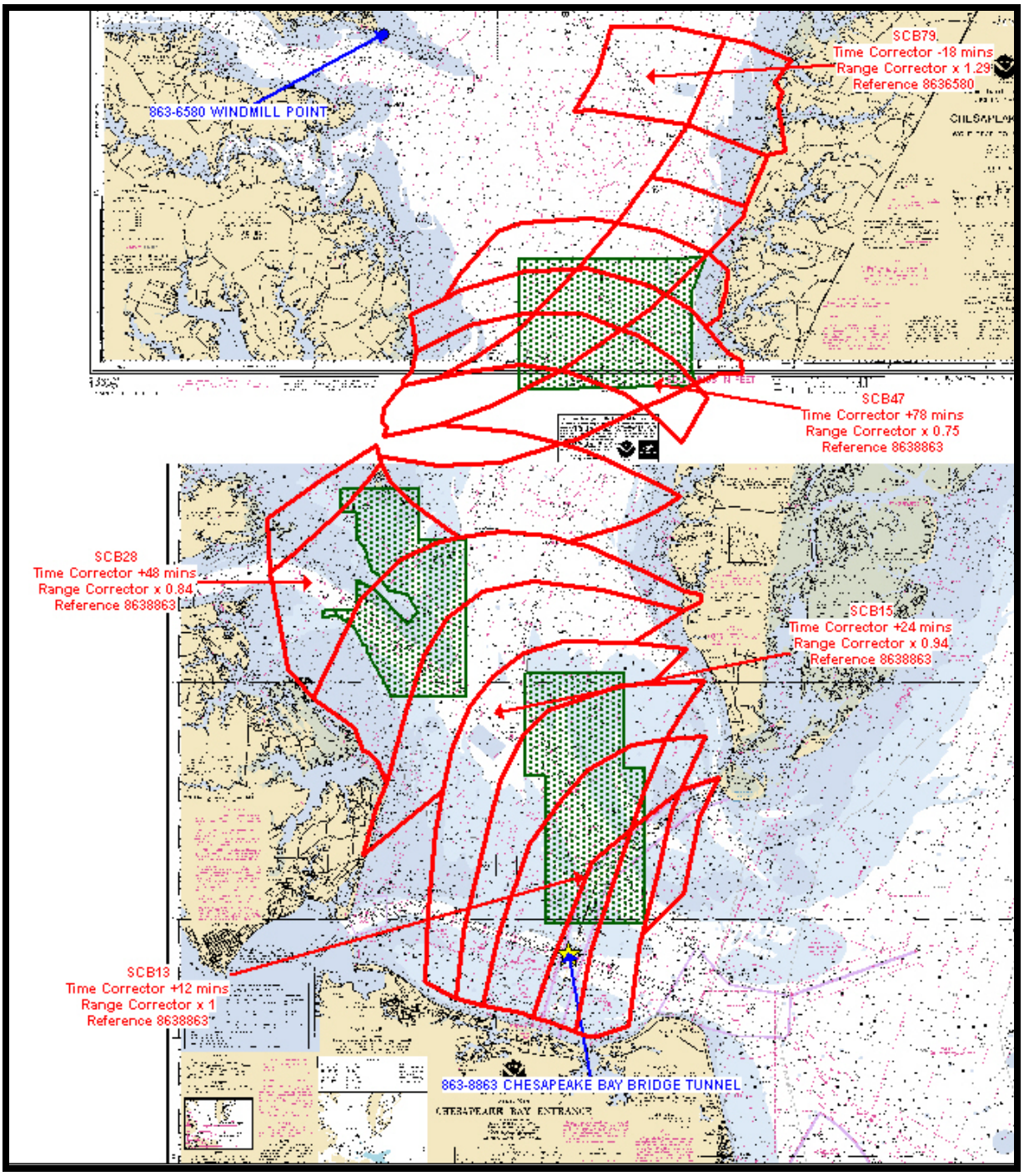

Figure E-7. The discrete tidal zones constructed from the co-tidal lines and the survey areas in lower Chesapeake Bay.

a. Tidal zoning errors. There are inherent errors in the application of discrete tidal zoning: 1) discontinuities at the edge of the zones; 2) resolution in areas of complex tidal characteristics, where the location and number of zones is not adequate to describe the changes in the tide over the survey area; 3) where large time corrections and large range ratios are required; and 4) the

fact that placement of the zones becomes subjective when the co-tidal lines are based upon inconsistent or inadequate source data. Figure E-7 illustrates an application for tidal zoning in Chesapeake Bay—in particular for areas in the middle of the bay where no RTK or RTN coverage is available. Where RTK/RTN coverage is available only the co-range model would have application.

b. Discussion of applications. The major contributors to the tides error budget are the datum error, which contributes as a systematic bias, and the tidal zoning error, which contributes as a random error. In practice the datum error is reduced with longer data series. Errors can be very significant if less than 30-days of data are observed. Substantial reductions in error from those of a 30-day series are not realized until one-year of data are collected. For tidal modeling purposes, NOAA gage datums, (or acceptable datums from another agency's long-term gages) will be assumed as absolute—no effort will be considered in improving the accuracy of existing datums by extending gage periods. The tidal zoning error can be reduced by lessening the amount of time and range correction needed by establishing more tide stations for use in direct control of the survey.

c. TCARI. Use of NOAA's "Tidal Constituent and Residual Interpolation" (TCARI) procedures can also reduce tidal zoning errors. Project planning an implementation are focused on finding the practical balance between the number of tide stations required and the amount of tidal zoning required. This in turn depends upon the complexities of the tidal characteristics in the area along with the resources and logistics required to establish and maintain tide stations. Calibrated tide gages that are configured and installed to minimize dynamic errors result in the measurement errors usually being minor contributors to the tides error budget. The estimated total tides error can then be root-summed-squared with all of the other hydrographic survey error sources to estimate the total survey error budget.

d. Example tidal zoning project. Even in these larger tidal ranges the gage density appears sufficient to model the MLLW datum variation by interpolation throughout the deep draft portion of the project. Figure E-8 is a graphic showing the CO-OPS discrete tidal zoning scheme for Porthmouth, NH. If RTK procedures were not employed at this project site, time and range correctors for each zone would be applied to an appropriate tide station installed in the harbor to account for time and range changes in the project area. The closest NOAA operating NWLON stations are Boston, MA and Portland, ME.

E-6. Hydrodynamic Tidal Modeling of Navigation Projects.

a. From the above, it would appear that many USACE deep-draft navigations will have a sufficient density of NOAA CO-OPS tidal data such that spatially interpolated models will be adequate. Interpolated models can be:

(1) a linear interpolation of elevation relationships over relatively short distances.

(2) a discrete tidal zoning interpolation based on changes in cotidal lines over the survey area.

(3) a continuous tidal zoning interpolation model such as TCARI.

Where this is not the case, then a hydrodynamic tidal model may have to be generated to define the MLLW datum plane throughout a project.

b. The technical process of developing a hydrodynamic tidal model of a typical coastal inlet, and calibrating that model to one or more fixed gages, is relatively straightforward and models for performing this are well documented in part II of EM 1110-2-1100 (*Coastal Engineering Manual*) and other sources. Many USACE navigation projects have been extensively studied over the years and existing numerical models may be readily utilized to assess the tidal datum relationships—e.g., activities studied under the ERDC/CHL "Diagnostic Modeling System."

c. Projects requiring hydrodynamic tidal modeling to define the MLLW datum can be accomplished by any number of organizations. Some of these include:

(1) District Hydrology & Hydraulics (H&H) sections.

(2) Coastal Engineering A-E firms.

(3) NOAA CSDL VDatum Team.

(4) ERDC/Coastal and Hydraulics Laboratory (CHL).

d. Each of the above options will have different approaches, costs, and turn-around response. Cost estimates for this modeling effort can be obtained from any of these organizations. These costs may include gaging programs which will have to be obtained from NOAA. Actual gage installation can be accomplished via an A-E contract with a coastal engineering firm or through NOAA.

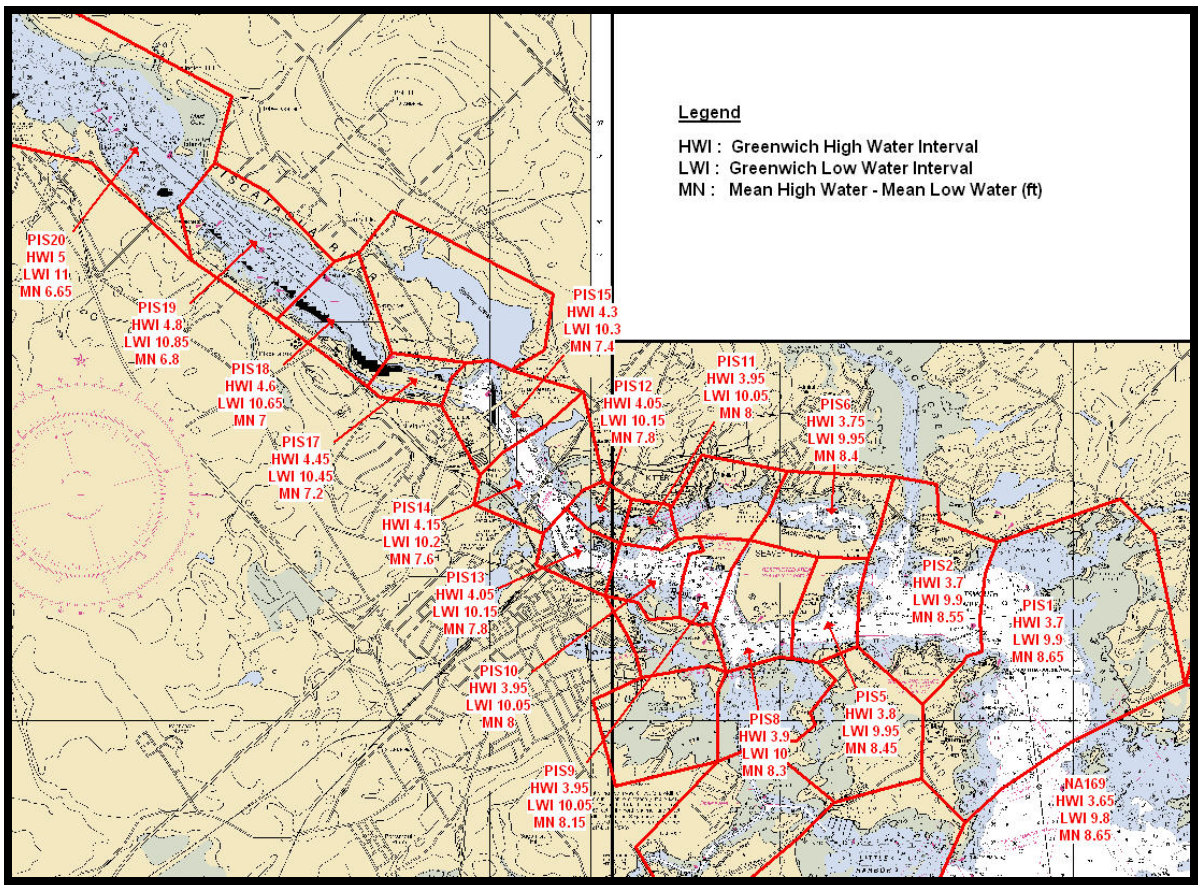

Figure E-8. NOAA discrete tidal zoning scheme for Portsmouth, New Hampshire.