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TIDES AND WATER LEVEL REQUIREMENTS FOR *N.O.S* HYDROGRAPHIC SURVEYS

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Abstract

The Center for Operational Oceanographic Products and Services (CO-OPS) of the National Ocean Service (NOS) contributes to the NOAA Nautical Charting Program by establishing requirements for, and providing the critical water level data necessary to produce accurate depth measurements. CO-OPS efforts involve six main functional areas: 1) tide and water level requirement planning; 2) preliminary tidal zoning development; 3) water level station installation, operation and removal; 4) data quality control, processing, and tabulation; 5) tidal datum computation and tidal datum recovery; and 6) generation of water level reducers and final tidal zoning. For each functional area, CO-OPS maintains appropriate specifications and standard operating procedures under the umbrella of an overall Data Quality Assurance Plan (DQAP). The objective of this effort is to provide the tide and water level correction information necessary to reduce soundings to Chart Datum. The goal is to provide water level correction information that meets current error budgets for correctors to soundings. The total uncertainty in the water level corrections are derived from three main sources: 1) errors in the actual measurement of water level; 2) uncertainties in the computation of tidal datums based on short period observations and in the datum recovery process at historical locations; and 3) uncertainties in the application of tidal zoning within the survey area. CO-OPS plans tide and water level requirements by balancing these uncertainties to provide the most effective combination of water level observations and zoning that meets allowable error budgets.

INTRODUCTION

This paper is intended to present an overview of the operational requirements for tide and water level support required for National Ocean Service (NOS) hydrographic surveys. NOS is carrying out hydrographic surveys using both in-house resources and via contract. The requirements for in-house surveys are documented in project instructions, manuals, and reference material to NOAA field parties and survey vessels.

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The requirements for contract surveys are found in project instructions, and in specifications and deliverables documents as part of the request for proposal process. The NOS Center for Operational Oceanographic Products and Services (CO-OPS) is responsible for maintaining the standards and specifications for tides and water levels and provides input into project instructions, manuals, and specifications and deliverables documents prepared by the NOS Office of Coast Survey (OCS).

BACKGROUND

CO-OPS manages the National Water Level Observation Network (NWLON) of approximately 175 continuously operating water level observation stations in the U.S. coastal zone, including the Great Lakes. As most of these stations are equipped with satellite radios, near real-time (within approximately 3-hours of collection) raw data are made available to all users through the interface to the CO-OPS Home Page on the Web (see www.opsd.nos.noaa.gov). Verified products, such as edited 6-minute data, hourly heights, high and low waters, and monthly means are made available over the Web. NWLON data and accepted tidal datums are used in hydrographic surveys either to provide tide reducers directly or for control for datum determination at subordinate (short-term) stations.

CO-OPS has an in-place Continuous Operational Real-Time Monitoring System (CORMS) that provides quality control and system monitoring functions on a 24 hour/day, 7-day/week basis. CORMS provides monitoring of the status and performance of all stations equipped with satellite radios using the NOS satellite message format installed by the hydrographer, as it does for all other NOS water level systems, including all NWLON stations. CORMS is a NOS provided support function to the operational field parties and does not relieve the hydrographer of responsibility for performing QC and ensuring proper gauge operation.

SCOPE

The requirements and specifications reviewed in this paper cover the water level and vertical datum requirements for operational support of hydrographic surveys conducted as part of the NOAA Nautical Charting Program. This scope of the effort is comprised of the following functional areas:

1. Tide and water level requirement planning
2. Preliminary tidal zoning development
3. Control water level station operation; supplemental water level station installation, operation and removal
4. Data quality control, processing, and tabulation
5. Tidal datum computation and tidal datum recovery
6. Generation of water level reducers and final tidal zoning

For in-house surveys, the National Ocean Service (NOS) CO-OPS headquarters personnel are responsible for functional areas 1,2,4,5, and 6. NOS hydrographers and CO-OPS Field Operations Branch shall be responsible for functional area 3 above. For contract surveys, CO-OPS personnel are responsible for functional areas 1 and 2. NOS contract hydrographers shall be responsible for functional areas 3 through 6 above, except NOS continues to be responsible for operating and maintaining the control stations (e.g., the NWLON).

The data and derived output products acquired during hydrographic survey operations, including the water levels, tidal datums, and bench mark elevations have the potential of being required for legal proceedings. As such, CO-OPS is frequently required to testify to and certify water level and related data. A Level III Data Quality Assurance (DQA) is implemented through systematic use of independent data quality control steps and reviews, use of sensors and systems with established performance characteristics and documented pre-deployment and post deployment calibrations, use of audit trails for all data processing and product generation, and an integrated error analysis and assessment.

OBJECTIVES

The main objective for the tides and water level support is to provide a continuos time series of water level reducers that can be applied to hydrographic soundings so that they can be corrected to chart datum. A second objective is to establish and/or recover tidal datums relative to local bench marks at each station that can be used for continuing and future hydrographic surveys in the area. The third objective is to provide new information or updated information that can be used to update NOAA tide prediction products and tidal zoning for promote safe navigation applications.

Functional Area Descriptions

1. Requirement Planning

The NOS CO-OPS is responsible for all planning of tide requirements for NOS hydrographic surveys. Using preliminary survey area locations and H- sheet layouts, CO-OPS analyzes historical data and tidal characteristics for each project area, specifies operational NOS control stations, specifies subordinate tide station locations to be installed, and provides the preliminary tidal zoning to be used by the during survey operations. CO-OPS provides 6-minute interval tide predictions relative to chart datum for appropriate NOS control stations prior to each survey and also provides available historical published bench mark information for all historical tide stations specified for reoccupation.

2. Preliminary Tidal Zoning

As tidal characteristics vary spatially, data from deployed water level gauges may not be representative of water levels across a survey area. Tidal zoning is

implemented to facilitate the provision of time series water level data relative to chart datum for any point within the survey area such that prescribed accuracy requirements are maintained for the water level measurement component of the hydrographic survey. Tidal characteristics are determined using available historical tide station data summaries and output from estuarine and global tide models. Spatial variations in tidal characteristics are assessed using geographic placement of summary data in a MapInfo GIS format. Corange and cophase maps are generated to provide the base for development of zoning schemes. NOS currently utilizes the "discrete tidal zoning" method for operations, where survey areas are broken up into a scheme of cells bounding areas of common tidal characteristics.. The minimum requirement is for a new cell for every 0.06 m change in mean range of tide and every 0.3 hour progression in time of tide (determined from Greenwich high and low water intervals). Phase and amplitude corrections for appropriate tide station data are assigned to each cell. Preliminary zoning is the time and range correctors referenced to the applicable NOS tidal prediction reference station(s) for utilization during field work.

3. Tide Station Installation and Operation

There is a general requirement for continuous data series from each station. Accurate datums cannot be computed for a month of data with a break in the water level measurement series in excess of three days. Even breaks of significantly less than three days duration will not allow for interpolation during times when strong meteorological conditions are present and in areas with little periodic tidal influence. Any break in the water level measurement series affects the accuracy of datum computations. Breaks in data also result in increased error in the tide reducers when interpolation is required. At a critical measurement site where the water level measurement data cannot be transmitted or monitored during hydrographic operations, an independent backup sensor or a complete redundant water level collection system should be installed and operated during the project.

The duration of continuous data acquisition is categorized as a 30-day minimum. Data acquisition is required from 4 hours before to 4 hours after the period of hydrography and/or shoreline verification in the applicable areas. Stations identified as "30-day" stations are the "main" subordinate stations for datum establishment, providing tide reducers for a given project, and for harmonic analysis from which harmonic constants for tide prediction can be derived. At these stations, data must be collected throughout the entire survey period in specified areas for which they are required, and not less than 30 continuous days are required for accurate datum determination. Additionally, supplemental and/or back-up gauges may also be necessary based upon the complexity of the hydrodynamics and/or the severity of environmental conditions of the project area.

The water level sensors are self-calibrating air acoustic, pressure (vented), or other sensor type. The sensor measurement range must be greater than the range of water level. Gauge and sensor systems must be calibrated prior to deployment and the calibration should be checked after removal from operations. The data collection platforms (DCP's) must acquire and store water level measurements at least every six-minutes. The six-minute interval water level measurements should consist of at least three minutes of discrete water level samples with the time period of the average centered about the six-minute mark (i.e. :00, :06, :12, etc.) In addition to the average measurement, the standard deviation of the discrete water level samples which comprise the six-minute average must be computed and stored. The clock accuracy of

satellite radio systems must be within 5 seconds per month so that channel "stepping" does not occur. Non-satellite radio systems must have a clock accuracy of within one-minute per month. Known error sources for each sensor must be handled appropriately through correction algorithms, ancillary measurements, and sensor configuration. Examples are water density variations for pressure gauges, sound path air temperatures for acoustic sensors, and high frequency wave action and high velocity currents for all sensor types

The ability to remotely monitor water level measurement system performance for near-rela-time quality control is essential to properly support hydrographic survey operations. Where access to the GOES satellite is available, the measurement systems must be equipped with a GOES transmitter to telemeter the data to the NOS Data Processing and Analysis System (DPAS) and CORMS using an NOS specified message format.

A complete water level measurement station installation consists of 1) the installation of the water level measurement system, ancillary measurement sensors, and supporting structures, 2) installation and/or recovery of a minimum of five bench marks and a level connection (third-order minimum) between the bench marks and the water level sensor zero or tide staff zero as appropriate, 3) the completion of all station, bench mark, and leveling forms, and 4) the routine collection of primary and backup sensor data and tide staff observations and collection of required ancillary data.

4. Data Quality Control and Data Processing

CO-OPS CORMS monitors the installed system operation information for all gauges equipped with GOES satellite radios and provides feedback to appropriate field parties. The six-minute interval water level data from the water level gauges must be quality controlled to NOS standards for invalid and suspect data as a final review prior to product generation and application. This includes checking for data gaps, data discontinuities, datum shifts, anomalous data points, data points outside of expected tolerances such as expected maximum and minimum values and for anomalous trends in the elevations due to sensor drift or vertical movement of the tide station components and bench marks. Quality control should include comparisons with simultaneous data from backup gauges, predicted tides or from nearby stations.

For new stations without MLLW established, water level measurements from each station shall be related to a single, common datum, referred to as Station Datum (usually tide staff '0') and are recorded on UTC.. For stations with a MLLW datum recovered, the measurements should be referenced to MLLW and UTC. All discontinuities, jumps, or other changes in the gauge record (refer to the specific gauge user's guide) that may be due to vertical movement of any the gauge, staff, or bench marks must be fully documented.

The continuous six-minute interval water level data are used to generate the standard tabulation output products. These products include the times and heights of the high and low waters, hourly heights, maximum and minimum monthly water levels, and monthly mean values for the desired parameters. The times and heights of the high and low waters are derived from appropriate curve-fitting of the 6-minute interval data. Monthly means are derived on a calendar month basis in accordance with the definitions for the monthly mean parameters are found in the NOS Tide and Current Glossary. For purposes of monthly mean computation, monthly means are not be

computed if gaps in data are greater than three consecutive days. Monthly mean sea level and monthly mean water level are computed from the average of the hourly heights over each calendar month of data.

Data gaps in six-minute data are not filled if the gaps are greater than three consecutive days in length unless data are available form a backup sensor. Data gap filling must use documented mathematically and scientifically sound algorithms and procedures and an audit trail shall be used to track all gap-fills in observed data. Data gaps of less than 3-hours can be inferred using interpolation and curve-fitting techniques. Data gaps of longer than three hours use external data sources such as data from a nearby station, if backup data do not exist. All data derived through gap-filling procedures are marked as inferred. Individual hourly heights, high and low waters, and daily means derived from inferred are also be designated as inferred.

5. Tidal Datum Computation and Datum Recovery

The present NOAA Nautical Chart Reference Datum for tidal waters is Mean Lower Low Water (MLLW). All tidal datum computations and water level reductions are referenced to this datum. In non-tidal areas (other than the Great Lakes, special low water datums have been defined for specific areas and are used as chart datum in these locations. Tidal datums must be computed relative to a specific 19 year tidal cycle adopted by the National Ocean Service (NOS) called the National Tidal Datum Epoch (NTDE). The present NTDE is the period 1960 through 1978. A primary datum determination is based directly on the average of tide observations over the 19-year Epoch period at NOS permanent long term primary control stations in the National Water Level Observation Network (NWLON). The data from NOS primary stations are used to compute datums at short term subordinate stations by reducing the data to equivalent 19 year mean values through the method of simultaneous comparison.

Tidal datums for subordinate stations are computed for certain phases of the tide using tide-by-tide comparisons or monthly mean comparisons with an appropriate NOS long term control station. Accepted 19 year mean values of mean tide level (MTL), mean range (Mn), diurnal high water inequality (DHQ), diurnal low water inequality (DLQ), diurnal tide level (DTL), and great diurnal range (Gt) are required in the reduction process in which a "short series" of tide observations at any location is compared with simultaneous observations from an NOS control station. Datums are computed by the "standard" method of range ratio comparison generally on the West coast and Pacific Islands where their exists a large diurnal inequality in the low and high waters. The "modified" method of range ratio comparison is generally used on the East coast and Caribbean where small differences exist in the low and high water diurnal inequality. For stations requiring a datum determination, at least 30 continuous days of tide observations is required for stations in the conterminous U.S. where adequate primary datum control exists.

In cases where historical sites are re-occupied, site datum must be zeroed to a pre-established MLLW datum held on a bench mark. In that case, data can then be acquired relative to MLLW. At present, in Great Lakes areas the IGLD 85 is the reference datum. Whenever tide stations are installed at historical sites, measures are taken to "recover" the established tidal datums through leveling which shall be accomplished by referencing the gauge or tide staff zero "0" to more than one existing bench mark with a published tidal elevation. Through this process, the published MTL elevation is transferred by level differences to the "new" gauge or tide staff and

compared to the MTL elevation computed from the new data on the same zero "0". Factors affecting the datum recovery (i.e. differences between old and newly computed datums) include the length of each data series used to compute the datums, the geographical location, the tidal characteristics in the region, the length of time between reoccupations, the sea level trends in the region, and the control station used. Hence, this process also serves as a very useful quality control procedure. After a successful datum recovery is performed and benchmark stability is established, the historical value of Mean Lower Low Water (MLLW) is used as the operational datum reference for data from the gauge during hydrographic survey operations.

It is essential for tidal datum quality control to have data processing and leveling procedures carried out to the fullest extent. Caution must also be used in computing tidal datums in riverine systems or in regions of unknown tidal regimes. Tide-by-tide comparisons between subordinate and control station data will often detect anomalous differences which should be investigated for possible gauge malfunction or sensor movement. Datums must be established from more than one bench mark. Differences in elevations between bench marks based on new leveling must agree with previously established differences from the published bench mark sheets. Any changes in the elevation differences must be reconciled before using in any datum recovery procedure. Datum accuracy at a subordinate station depends on various factors, but availability and choice of an adequate control station of similar tidal characteristics, similar daily mean sea level and seasonal mean sea level variations, and similar sea level trends are the most important. The length of series will also determine accuracy. The longer the series, the more accurate the datum and the greater quality control and confidence gained from analyzing numerous monthly mean differences between the subordinate and control station. At reoccupied historical stations for which datum recoveries are made, updated datums are computed from the new time series and compared with the historical datums as the survey progresses.

Tidal datums are local vertical datums which may change considerably within a geographical area. A geodetic datum, is a fixed plane of reference for vertical control of land elevations. The North American Vertical Datum of 1988 (NAVD 88) is the accepted geodetic reference datum of the National Geodetic Spatial Reference System and is officially supported by the National Geodetic Survey (NGS) through a network of GPS continuously operating reference stations. The relationship of tidal datums to NAVD has many hydrographic, coastal mapping and engineering applications including monitoring sea level change and the deployment of GPS electronic chart display and information systems. An orthrometric level connection or ellipsoidal GPS tie is required at subordinate tide stations which have geodetic bench marks located within a radius of 0.25 miles. At least two geodetic bench marks should be used to complete the connection for quality control purposes. In addition, at stations with no geodetic bench marks located nearby, GPS ellipsoidal heights must be established for at least three of the bench marks in the local tide station network

In non-tidal areas the correctors for hydrographic soundings are simply water level measurements relative to a specified local low water level datum established for navigational purposes. Laguna Madre and Pamilco Sound are examples of such areas classified as non-tidal which have special low water datums. Some river areas also have special datums due to the effects of seasonal changes on the river, e.g., Columbia River Low Water Datum is an example of this case. Great Lakes NWLON permanent stations will provide water level data referenced to an established Low Water Datum relative to International Great Lakes Datum of 1985 (IGLD '85).

6. Water Level Reducers and Final Tidal Zoning

Data relative to MLLW from subordinate stations or from NOS NWLON stations, as appropriate, shall be applied to reduce sounding data to chart datum, either directly or indirectly through a correction technique referred to as tidal zoning. Whether corrected or direct, time series data relative to MLLW or other applicable LWD applied to reference hydrographic soundings to chart datum are referred to as "tide reducers" or "water level reducers". For final processing, preliminary zoning is superseded by "final zoning" which is a refinement based on new data collected at subordinate stations during the survey. With the final zoning scheme, correctors for each zone are derived from a subordinate station specifically installed for the survey rather than the reference station used with preliminary zoning. Zoning errors minimized such that when combined with errors from actual water level measurement at the gauge and errors in reduction to chart datum, the total error of the tide reducers is within specified error budgets.

ERROR BUDGET DISCUSSION

The water level reducers can be a significant corrector to soundings to reduce them relative to chart datum especially in shallow water areas with relatively high ranges of tide. The errors associated with water level reducers are generally not depth dependent, however. The portion of the error of the water level reducers must be balanced against all other sounding errors to ensure that the total sounding error budget is not exceeded. The allowable contribution of the error for tides and water levels to the total survey error budget falls between 0.21 and 0.42m depending on depth and the amount of tidal zoning. The total error of the tides and water levels can be considered to have component errors of:

1) the measurement error of the gauge/sensor and processing error to refer the measurements to station datum. Gauges/sensors need to be calibrated, and sensor design and data sampling needs to include strategies to reduce measurement errors due to waves, currents, temperature and density effects. The measurements need to be properly referenced to the bench marks and tide staffs, as appropriate and monitored for vertical stability. The processing also include interpolation errors in the water level data to the time of the soundings. The measurement error, including the dynamic effects, should not exceed 0.10m at the 95% confidence level. A estimate for a typical processing error is 0.10m at the 95% confidence level.

2) the error in computation of tidal datums for the adjustment to 19-year National Tidal Datum Epoch (NTDE) periods for short term stations. The shorter the time series, the less accurate the datum. The NTDE does not apply in the Great Lakes, however the accuracy of datum based on shorter time series is analogous. The estimated error of an adjusted tidal datum based on one month of data is 0.08m for the east and west coasts and 0.11m for the gulf coast (95% confidence level).

3) the error in application of tidal zoning. Tidal zoning is the extrapolation and/or interpolation of tidal characteristics from a known shore point(s) to a desired survey area using time differences and range ratios. The greater the extrapolation/interpolation, the greater the uncertainty and error. Estimates for typical

errors associated with tidal zoning are 0.20m at the 95% confidence level. However, errors for this component can easily exceed 0.20 meter if tidal characteristics are very complex or not well-defined.

Project planning by NOS attempts to minimize and balance these potential sources of error through the specification of accurate reliable water level gauges, minimization of zoning required, maximizing the number of station locations required, and maximizing the length of observations within practical limits of the survey area and survey duration. The practical limits depend upon the tidal characteristics of the area and suitability of the coastline for the installation and operation of water level gauges. The zoning error can easily dominate the error budget and is the hardest to estimate. This makes the operational minimization of the measurement error and the datum error even more important.

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