ESTIMATING TOTAL VERTICAL UNCERTAINTY OF SHORT TERM AND PARTNER WATER LEVEL OBSERVATIONS

Silver Spring, Maryland
April 2025

noaa National Oceanic and Atmospheric Administration

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

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) provides the national infrastructure, science, and technical expertise to collect and distribute observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and tidal current products required to support NOS's Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), a national network of Physical Oceanographic Real-Time Systems (PORTS®) in major U. S. harbors, and the National Current Observation Program consisting of current surveys in near shore and coastal areas utilizing bottom mounted platforms, subsurface buoys, horizontal sensors and quick response real time buoys. The Center: establishes standards for the collection and processing of water level and current data; collects and documents user requirements, which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

NOAA Technical Report NOS CO-OPS 112

ESTIMATING TOTAL VERTICAL UNCERTAINTY OF SHORT TERM AND PARTNER WATER LEVEL OBSERVATIONS

Laura Fiorentino
National Ocean Service
Center for Operational Oceanographic Products and Services
Chesapeake, VA, USA

Gregory Dusek
National Ocean Service
Center for Operational Oceanographic Products and Services
Silver Spring, Maryland, USA

Shachak Pe'eri
National Geodetic Survey
Center for Operational Oceanographic Products and Services
Silver Spring, Maryland, USA

April 2025

U.S. DEPARTMENT OF COMMERCE
Howard Lutnick, Secretary

National Oceanic and Atmospheric Administration
Laura Grimm, Acting NOAA Administrator and Under Secretary of Commerce for Oceans and Atmosphere

National Ocean Service
Nicole R. LeBoeuf, Assistant Administrator

Center for Operational Oceanographic Products and Services
Marian Westley, Director

NOTICE

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Various organizations across the United States, including local and state governments, and academic institutions, collect water level data. These datasets range from short-term deployments for specific, one-time purposes, to long-term local water level monitoring networks. Many of these organizations are NOAA partners, providing measurement data that can be considered reliable. These observations have potential applications within NOS, including VDatum, model validation, and hydrographic surveying. However, the lack of uncertainty estimates for these datasets makes it difficult to determine their appropriate use cases.

This report aims to review the currently available technologies for measuring water levels, to assess their associated errors, and provide a methodology for a first-order approximation of uncertainty. This methodology accounts for instrument measurement errors as well as those related to survey technology and geodetic control. By quantifying uncertainty, partner water level observations can be evaluated for suitability based on specific application requirements.

There are significant challenges to quantifying uncertainty due to limited information on instrument performance across different conditions and the many factors influencing uncertainty estimation. To address these challenges, we focus on two primary contributors to uncertainty: measurement and vertical control. Measurement uncertainties are derived from CO-OPS documented accuracies where available or estimated when necessary. Vertical control uncertainties are based on local leveling to a benchmark and/or referencing to the national spatial reference system. To ensure the validity of these accuracy estimates, we must make several assumptions, including that instrumentation is installed, operated, and vertically controlled correctly in accordance with NOAA standards.

The water level measurement technologies evaluated in this report include ultrasonic acoustic sensors, radar sensors, pressure gauges, Global Navigation Satellite System (GNSS) tide buoys, and land-based GNSS interferometric reflectometry (GNSS-IR) stations. For each technology, we provide example uncertainty computations.

The outcomes from this report allow NOAA:

1. To improve accuracy of NOAA products that depend on water level observation by providing a method for estimating the total vertical uncertainty of the final product,
2. To enhance the coverage and density of observations by utilizing partner water level observations in NOAA's products and services, and
3. To reduce observation costs by incorporating partner data. This cost-effective solution offers a budget-friendly alternative without compromising significantly on data quality.

1. INTRODUCTION

1.1. Purpose

The purpose of this document is to provide guidance on calculating uncertainty estimates for short-term and NOAA partner water level stations and to clarify how these measurements can be utilized for operational National Oceanic and Atmospheric Administration (NOAA) products. This task presents significant challenges due to the variety of available sensors and the range of installation and maintenance practices. Accurately estimating water level measurement uncertainty is further complicated by factors such as the specific geographic location of the water level stations and the influence of varying environmental conditions. The sources and magnitudes of error can vary substantially depending on all of these factors, thus making a total propagated uncertainty difficult to compute. To reduce complexity in this process, we will standardize the various observations by using only two components of uncertainty: water level sensor uncertainty and the geodetic control uncertainty.

Defining this process will enable NOAA to potentially utilize hundreds of partner-collected or short-term water level observations to improve our products and services where otherwise no data exists. By sharing these best practices with government, industry, and academic partners we will be able to provide general water level uncertainty estimates for a wide range of applications. Though the use cases of short-term water level data are potentially very broad, we initially intend for these uncertainty estimates to be suitable for several critical applications including VDatum, hydrographic planning, and operational forecast and reanalysis model validation.

1.2. Background

The NOAA National Ocean Service (NOS) FY24-FY28 Strategic Plan (NOS, 2022) focuses on coastal resilience, economic growth, and marine ecosystem conservation and restoration. These priorities are supported by NOS through the provision of innovative products and services, made possible by extensive data and innovative technology. Expanding the availability of data for integration into NOAA products enhances their accuracy, functionality, and overall effectiveness.

A prime example is VDatum[1], a software tool that transforms elevation data among different vertical datums, ensuring consistency and enhancing the accuracy of datasets. NOAA uses hydrographic surveys to deliver precise and up-to-date bathymetric data that support safe navigation and inform coastal management. To generate accurate marine grids from circulation models, water level data must be incorporated to link tidal datums to the national spatial reference system and to support product evaluation (Seroka et al., 2024). The accuracy of these grids improves with high-quality input data and validation from additional observations, but insufficient water level coverage in many areas limits this process. With the possibility to include a broad network of locations from partner stations, both the VDatum software and hydrographic surveys can become even more accurate and effective, improving decision-making and resource management.

Another set of applications that will benefit from additional water level observations are flooding and inundation monitoring and prediction. Flooding poses a significant threat to coastal communities across the nation. NOAA has developed numerous tools and technologies to provide accurate, up-to-date oceanographic information, empowering local governments and communities with the resources they need for effective planning and flood mitigation. Key efforts include the

[1] https://vdatum.noaa.gov/

CO-OPS Coastal Inundation Dashboard, the Coastal Ocean Reanalysis (CORA) (Rose et al., 2024), the Sea Level Rise Viewer, among others. These tools support coastal flood response strategies, with their effectiveness increasing as more data becomes available (Maoyi et al., 2022; van der Westhuysen et al., 2022).

NOAA NOS Center for Operational Oceanographic Products and Services (CO-OPS) maintains over 200 National Water Level Observation Network (NWLON) water level stations around the coastal United States. Despite this extensive network, there are still significant gaps and areas without coverage (McLaughlin, 2024). As demands for better marine monitoring and forecasting services increase, NOAA is looking at the potential use of publicly-available in-situ observation networks managed by trusted partners within the government, academia, or industry to supplement the limited resources of NOAA to conduct marine observations (e.g., water levels, currents, salinity and temperature). These efforts address data gaps and support local community concerns, such as storm surge and rising sea levels, and improved marine navigation infrastructure for commercial industries and recreational boaters.

One potential source of partner water level observations comes from regional and state associations. To enhance flood mitigation efforts, these organizations are developing networks of local water level stations that complement NOAA's National Water Level Observation Network (NWLON) and help fill critical data gaps (Hernandez et al., 2024). These cost-effective, community-based sensors provide hyper-local, real-time water level and coastal flood observations. While they may not meet the same rigorous standards of accuracy and durability as NOAA-maintained stations, they offer valuable supplemental data for coastal resilience efforts.

Universities are also advancing low-cost water level monitoring initiatives. For example, the Georgia Institute of Technology Smart Sea Level Sensors Project (https://www.sealevelsensors.org/) and Florida Atlantic University's sense Stream Project (https://www.sensestream.org/) develop and deploy their own water level instrumentation support local monitoring efforts.

Additionally, NOAA itself conducts short-term water level measurements through various offices. The Office of Coast Survey (OCS), for example, collects water level data for hydrographic surveys. All of these potential sources for water level information may be suitable for use in some NOS products.

The existence of new and existing water level observation technologies presents NOAA with the opportunity to improve its approach for evaluating observation data based on its total vertical uncertainty (TVU). In this effort, we adopt the International Hydrographic Organization (IHO) definition of TVU, which is the combined measurement uncertainty associated with finding the vertical position of a feature; in this case, water level (IHO, 2020). However, some of the technologies used by partners have not yet been fully tested and approved for NOAA operations. As a result, we do not yet know the level of uncertainty or its impact on NOAA's products and services.

This report provides a short review on the current available technologies for measuring water levels and their associated errors. In addition, the report provides explanation and examples for calculating first-order approximation of the TVU, i.e., using the errors associated with the water level measurement (including quality control or processing), and the geodetic control. As a result, short-term water level observations can be further evaluated or rejected based on the application requirements. This initial effort focuses on methods to establish uncertainties for partner water level observations used in federal products that support VDatum, hydrographic surveying efforts, modeling, and model evaluation.

2. APPLICATIONS

2.1. VDatum

Since 1999, NOS has supported the development of VDatum (https://vdatum.noaa.gov/), a software tool designed to provide height relationships and convert geospatial data among tidal, geopotential and geometric vertical datums, allowing users to establish a common reference system for mapping and other applications. The need for a single tool to combine multiple geospatial data sets into one common base has long been valued by the surveying and mapping community. The availability of VDatum models covering coastal areas of the United States has aided the accurate and efficient acquisition of hydrographic and shoreline data. VDatum's effectiveness continues to advance as a result of ongoing modeling advances and technical development, but building it to a consistent and mature level depends upon the improved observational data.

The requirements for VDatum are based on internal technical documentation and communications between CO-OPS, NOAA's National Geodetic Survey (NGS) and OCS (Milbert, 2002, Parker et al., 2003; Hess and White, 2004; Myers and Hess, 2006; Spargo, Hess., and White 2006; White, Jeong, and Hess, 2016; Tolkova et al., 2023). The key requirements for water level observations include:

Requirement (#1): Coverage - Denser observations, including inland and offshore

The density of water level observations and the extent varies based on the geographic settings. With more inland hydrographic mapping efforts, there is a need to collect water level observations in more locations along the US coasts. For example, in geographic areas that contain complex shorelines (e.g., Maine and Alaska) water level observations are needed both at the coast and inland locations that include back bays and along rivers.

Requirement (#2): Minimum observation time of at least 30 days

The VDatum marine grids are products from NOAA-internal circulation models. For developing a reasonable skill assessment of products of these circulation models, the water level observation period should be at least 30-day long.

Requirement (#3) - Positioning (benchmark and tide station)

It is important to know the position of the tide gauge within 5 m accuracy horizontally. Vertically, the accuracy of the marine grids produced by VDatum models typically require that the water level uncertainty is within 10 cm for the continental US. For remote locations that do not currently have a permanent water level station, such as Alaska, Caribbean Island, and Pacific Islands, there is a practical consideration for accepting 30 cm uncertainties rather than not having any observation available.

Requirement (#4) - Proper documentation - Metadata

It is important to have a complete record of the identification number (ID) of the water level measurement, ties to the benchmarks, survey date, configuration and calculation (e.g., level survey and adjustment), and the reference system that the water observations were defined. CO-OPS maintains a seven-digit ID for its water level stations. NGS maintains a 6-character ID for key benchmarks. Using these IDs, it is possible to query NOAA databases for historical observations and compare results to recent observations for benchmark stability and analyzing trends. Today, NGS also provides geospatial models for correcting the motion of key benchmarks over time.

2.2. Hydrographic Surveys

NOAA's OCS is responsible for creating and maintaining accurate nautical charts for U.S. coastal waters. To keep charts current, OCS conducts mapping to acquire precise, up-to-date hydrographic data. NOAA nautical charts portray water depths relative to Chart Datum: typically, the Mean Lower Low Water (MLLW) datum, in tidally-influenced waters. The determination of Chart Datum and accurate water level heights in situ relies upon data from CO-OPS' network of water level stations. In remote areas, OCS establishes temporary tide gauges to complement CO-OPS data and may also leverage partner water level stations for additional support. OCS has evaluated different water level observations for their Ellipsoidally Referenced Surveying operations and summarized the work of different hydrographic offices around the world in a FIG publication (Mills and Dodd, 2014). In addition to the VDatum requirements mentioned above, OCS-acquired water level data and accompanying metadata (sensor and station) are sent to CO-OPS in accordance with Hydrographic Survey Specifications and Deliverables (HSSD) standards (OCS, 2022).

2.3. Other potential applications

Other applications that would benefit from additional water level data include NOAA coastal model validation and skill assessment, and potentially data assimilation. The NOAA Coastal Ocean ReAnalysis (CORA) is one modeling capability that could leverage short term observations. CORA is a wave and water level model reanalysis that provides over 40 years of hourly coastal wave and water level data at sub-500-meter resolution along the entire U.S. coastline (Keeney et al., 2025; Rose et al., 2024). CORA relies on a subset of NOAA NWLON stations for data assimilation, and holds out many stations to provide validation. The availability of additional short-term water level observations would enable a wider-range of model validation, and potentially allow the inclusion of additional NWLON stations into the assimilation. A second NOAA modeling capability that could leverage these water level observations is the Operational Forecast Systems (OFS). These operational, high-resolution, coastal hydrodynamic models predict coastal conditions, including water levels, days into the future (e.g., Peng et al, 2023; Weston et al., 2023). Short-term water level observations would provide additional validation away from NWLON stations, and enable broader model skill assessment and comparisons than what is presently possible.

There are many other NOAA applications of partner or short-term water level observations beyond coastal models. Though we do not seek to provide a comprehensive review here, applications include: real-time water level and coastal flood monitoring via tools like the NOAA Inundation Dashboard; post-event verification of NOAA storm surge forecasts; and support for a wide-range of NOAA coastal and estuarine research.

3. UNCERTAINTY COMPUTATION

3.1. Method

IHO defines uncertainty as: "Estimate characterizing the range of values within which the true value of a measurement is expected to lie as defined within a particular confidence level. It is expressed as a positive value" (IHO, 2020). IHO also defines TVU as "a one-dimensional quantity with all contributing vertical measurement uncertainties included." In other words, uncertainty allows scientists and users to assess the performance and accuracy of measurement instrumentation and techniques, as well as form accurate conclusions from the data (Parker, 2016). Understanding the uncertainty of a measurement helps to better understand the measurement itself and use the observation data appropriately. It is important to note that the uncertainty value is different from the measurement error, which is the difference between the measurement and the true value (Elipot et al., 2022).

To illustrate the difference between "uncertainty" and an "error" value, consider taking a water level measurement using a tide staff (imagine we know the exact true water level). The measurement error is the difference between a single reading and the "true" level. The uncertainty reflects the variability in multiple measurements, and the two types of errors that contribute to uncertainty are classified as either *random* or *systematic* (JCGM, 2008) (Figure 1). In Figure 2, a high systematic error component will cause the observations to have a bias in a particular direction with respect to the true water values, whereas a high random error component will cause the observations to fluctuate above and below the true water level values.

For instance, in the water level example, the standard deviation of repeated measurements captures random uncertainty, indicating how repeatable the process is; however, the presence of (unidentified) systematic bias effectively transforms minimum and maximum range into a "standard uncertainty". Potential causes for random errors may be due to the resolution of the tide staff or small movements in the water. Systematic contributions to a tide staff measurement may include incorrect positioning of the staff (the measurements will all be off by that amount) or user error reading the tide staff from a bad angle. Another example cause for systematic errors is cumulative bias in the geodetic control: Incorrect positioning of the measurement apparatus by a fixed amount means all measurements will all be off by that amount. A visualization of the random and systematic uncertainties in water level data is shown in Figure 1.

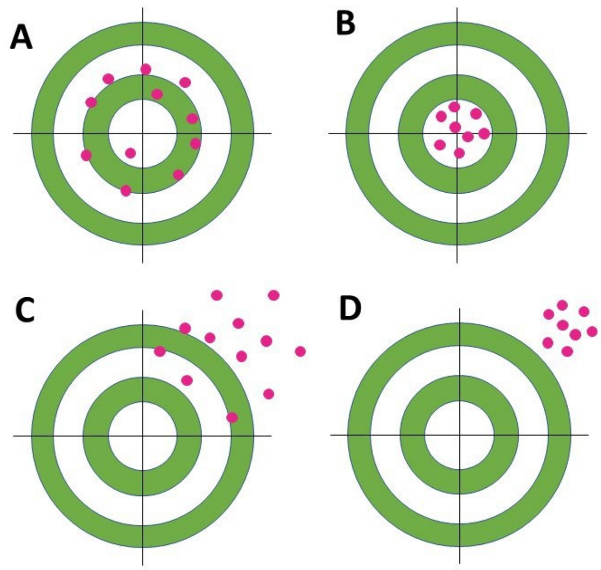


Figure 1. Visualization of random and systematic contributions to uncertainty. The center of each circle is the true measurement, and the A) High random, low systematic; B) Low random, low systematic; C) High random, high systematic; D) Low random, high systematic

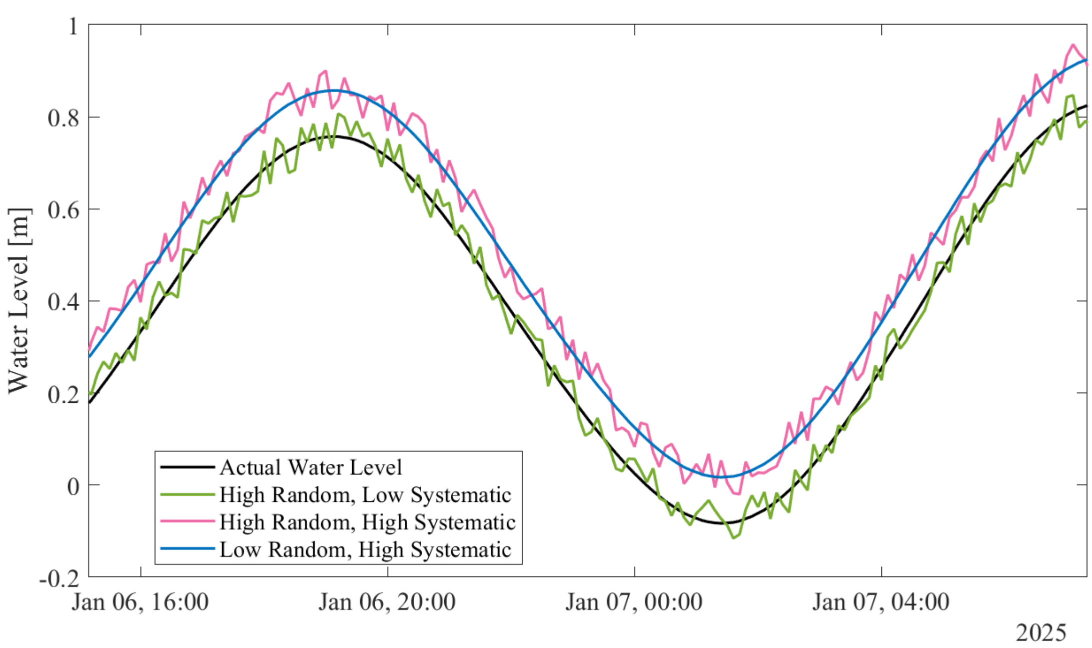


Figure 2. Water level time series, with examples of high and low random and systematic uncertainties

In particular to the measurement of water levels, contributions to uncertainty may arise from the measurement itself (e.g., sensor accuracy, setup, installation), vertical control (e.g., local and national references), and processing (e.g., data pre-processing, quality control, and manual review). Ideally, statistical evaluations would be performed on the water level time series to determine the TVU, along with some formulation of the full range of potential systematic errors. However, when a reliable uncertainty value for the water level technology is unavailable, uncertainty components are typically assessed by assembling available information from measurement test data, experience, and manufacturer specifications. The manufacturer specifications typically represent best case scenarios in lab conditions. However, field work experience has shown that these uncertainty values are typically larger. One can use the NWLON requirements to help determine the information needed to compute an uncertainty estimate and determine whether the data should be used (Dusek et al., 2024). The NWLON Requirements Technical Report defines NWLON's observing system requirements, focusing on accuracy, data continuity, transmission, documentation, and system survivability. It serves as a public guide for NOAA and its partners to establish best practices, standard operating procedures, and operational specifications. The report incorporates lessons learned, internal SOPs, and technical references.

After identifying individual components of uncertainty, it is then possible to combine all uncertainties into a total uncertainty. To do this, ensure all components are expressed in the same units and are independent from each other. Total uncertainty is calculated by summing the squares of the individual uncertainties and taking the square root of the sum (Bell, 1999). For partner water level stations, uncertainty will include components connected to the water level instrumentation technology, stability of the station, and the geodetic control. Geodedic control includes creating a height relationship between the water level station to a nearby bench mark and referencing the benchmark to a national reference system. In the case discussed here, the uncertainty associated with the water level measurement is assumed to be independent from the uncertainty associated with the geodetic control. As such, it is possible to calculate the epoch-by-epoch (i.e., over a single deployment) TVU as the root mean square of these two uncertainties.

$$\text{TVU} = \sqrt{(water\ level\ observation)^2 + \ (geodetic\ control)^2}$$

It is important to note that accuracy of the instrumentation, setup and installation, and processing are included as part of the water level observation and geodetic control. This includes the possibility of taking into account the confidence interval for the *variations* in the systematic error, if such a range of values has been assessed for a particular water level measurement technology (e.g., see GNSS-IR in the Examples section).

3.2. Water Level Sensors

3.2.1. Types of Sensors

The suite of instrumentation options currently used by CO-OPS and its partners for water level measurements includes (Table 1):

- Acoustic and ultrasonic acoustic
- Microwave radar
- Pressure sensors
- Global Navigation Satellite Systems Interferometric Reflectometry (GNSS-IR)
- Global Positioning System (GPS) tide buoys

Although all these instruments are potentially capable of water level data acquisition of sufficient quality for NOAA applications, there is limited published information regarding the performance of the different instrumentation-specific uncertainties associated with each sensor type. For this analysis, we will assume a range of uncertainty for each general sensor category.

The primary sensor at many CO-OPS NWLON stations is the Aquatrak, acoustic tide gauge (Miller et al., 2019). This instrument emits a sound pulse down a sounding tube housed in a protective well, measuring the distance to the sea surface by calculating the time it takes for the pulse to travel to the water and reflect back. In recent years, lower cost alternatives include ultrasonic acoustic sensors available from companies or custom-built versions. These sensors emit high-frequency sound waves to measure distance to the sea surface. These are easier to install and maintain because they don’t need a sounding tube or well. They can cost between several hundred and several thousand dollars.

In 2008, CO-OPS began testing microwave radar sensors for use in NWLON stations. Microwave radars, which measure the time it takes for microwave pulses to travel to the water surface and back, offer a reliable option for water level measurements (Park et al., 2014). These sensors present several advantages over Aquatrak acoustic tide gauge systems: they are non-contact, simpler to install without requiring diving, easier to maintain due to the lack of underwater components, and provide improved accuracy. Given these benefits, CO-OPS is actively transitioning most NWLON stations with acoustic tide gauge systems to microwave radars.

Pressure sensors are also widely used in NOAA operations for water level measurement. CO-OPS employs single orifice and dual orifice bubbler systems. These types of systems infer changes in the water level height by measuring pressure at fixed depths in the water column. Similarly, bottom mounted pressure sensors, i.e., pressure sensors located on the seafloor, can serve as tide gauges by measuring variability in the pressure that is directly related to the volume of water above the sensor.

GNSS/GPS tide buoys are another option to measure sea level that is currently used by NOAA and its partners for tidal reconnaissance, water level observations, and mean sea surface computation offshore. Tide buoys, which typically make use of an anchored wave-following hull form (e.g., spherical or discus buoys) or a relatively stable, small water plane area shape (e.g., spar buoys), are equipped with a GNSS receiver antenna at some height above the water surface. The instantaneous antenna position must be compensated for the dynamic vertical offset to the water surface, mainly a function of forces influencing the buoyancy and tilt of the buoy. Common approaches for determining the GNSS position on a buoy include: Real-Time Kinematic (RTK), Post-Processed Kinematic (PPK), Real-Time GIPSY (RTG), and Post-processed Precise Point Positioning (PPP). When calculating water level using GNSS tide buoy (averaging observations), all four methods provide somewhat comparable results (Dodd et al., 2009). The key contributions for uncertainties are the GNSS receiver accuracy (as a function of the distance to a base station and satellite coverage), and accuracy measuring the offset from the GPS receiver to the water surface (as a function of buoyancy and tilt of the buoy). The environmental conditions also play a factor in the accuracy. In general, buoy water level measurement performance is degraded in the presence of strong currents, high waves, and drawdown resulting from biological fouling. Accuracies also vary based on the shape of the buoy.

GNSS-IR uses reflected GNSS signals to determine water level (Larson et al., 2013). The principle of operation is to use the multipath signal to determine the water level. Multipath signals are satellite signals that reach a receiver by distinct paths as they happen to be reflected off surfaces. GNSS signals reflections of interest here are off the water: Such signals will be delayed in reaching a shoreline receiver, compared to a direct GNSS signal. Depending on the angles the GNSS signals are collected by the receiver (i.e., overhead from the satellites or from the water bouncing back to the receiver) the intensity of the signal will vary. At some times the reflected signal will be in phase with the main signal, enhancing it, at other times it will be out of phase, dampening its strength. These variations in the signal strength are measured by the receiver's signal-to-noise ratio (SNR). With a fixed antenna height, it is possible to analyze the GNSS signals and determine the water level relative to a vertical datum. Purnell et al. (2020) investigates and quantifies sources of uncertainty using GNSS for water levels.

CO-OPS and NGS evaluated the performance of GNSS-IR through two evaluation efforts that include the IOOS Ocean Technology Transition program and the NOS Foundation Four research to operations efforts. In both cases, the GNSS stations were located close to standard water level stations. Eight stations in the Permanent Service for Mean Sea Level (PSMSL) GNSS-IR (https://psmsl.org/data/gnssir/) suite were compared to CO-OPS water level stations (IOOS, 2025). The results of the study support using data from a PSMSL station (i.e., long-term stable station) in ideal observation conditions (continuous record with good GNSS observations).

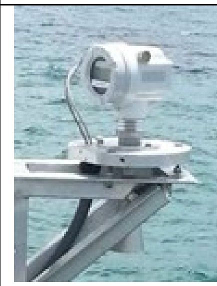
Uncertainty levels vary across different sensor technologies and their respective subcategories. Accuracy can also differ depending on the brand and model of the sensor. Various factors, such as installation, environmental conditions, and sampling methods, can all contribute to total water level uncertainty. Some technologies require additional data to provide accurate water level measurements. For example, the Aquatrak acoustic sensor often necessitates temperature corrections to account for the change in the sound speed profile down the length of the sounding tube. Thermal expansion of its calibration tube and change in the sound speed profile down the length of the sounding tube and bubbler systems rely on precise density measurements to ensure accurate readings (Portep and Shih, 1996; Hunter, 2003).

The suitability of sensor placement also varies: certain technologies have more specific location requirements. For instance, ultrasonic acoustic sensors are more affected by wind than other types (Masoudimoghaddam and Shahsavandi, 2024). And high frequency microwave radars have shorter wavelengths and may be more responsive to surface conditions than their lower frequency counterparts. These are just some examples of how and why uncertainty can vary from sensor to sensor.

A list of sensors and their estimated accuracy ranges, based on available information, is presented in Table 1. The table also includes a photo of the sensor as a visual aid. These accuracy estimates are primarily based on CO-OPS test and evaluation efforts (CO-OPS, 2023). Others are based on available information from vendor specifications and should be updated as more testing and information becomes available.

Table 1. List of water level sensors and associated accuracies. Photo credits to CO-OPS, Axys, Hohonu, and Sutron.

Sensor	Common commercial systems	Estimated accuracy	Image
Air Acoustic	Aquatrak 3003-XCR-4, Model 3000, Transducer with Model 4110 Controller	± 0.02 m to ± 0.05 m	 Aquatrak acoustic
Ultrasonic Acoustic	MaxBotix MB7388 (used by Hohonu)	± 0.01 m to ± 0.10 m	 Hohonu ultrasonic acoustic (Maxbotix)

Pressure - Single and Dual Orifice Bubbler	Paroscientific Digiquartz® Intelligent Transmitters - Model #: 6000-30G SUTRON Compact Constant Flow Bubbler with built-in Accubar® Pressure Sensor GE Druck UNIK PDCR 5031 Pressure Transducer KPSI 500T	± 0.02 m to ± 0.05 m	 Sutron Accubar
Microwave Radar	YSI WaterLog® H-3611 YSI Nile 502 VegaPuls C22	± 0.02 m	 YSI WaterLog microwave radar
Tide Buoy	AXYS HydroLevel™ Tide Level Buoy Freooceans PPK & PPP GNSS Tide Buoy Custom built	± 0.10 m to ± 0.15 m	 Axys Hydrolevel tide buoy
GNSS IR	Geodetic grade GNSS antenna/receiver (e.g., Trimble, Ashtec, Septentrio, and Leica) SparkFun RTK Express	± 0.10 m to ± 0.20 m	 GNSS-IR station

3.2.2. Processing and QA/QC

To obtain a water level value, an average is conducted on the raw values. For instance, NWLON water level observations are six-minute averages of 1 Hz measurements. Outliers are removed from the measurements. After this processing, the water level data should be further assessed for quality using the Quality Assurance/Quality Control of Real Time Data (QARTOD) Manual for Real-Time Quality Control of Water Level Data (Bushnell, 2021). Following these automated post-processing methods, a manual review will be conducted as a final precaution. Any one of these methods of quality control can affect uncertainty.

For the purposes of this document, we will consider the data cleaning, processing and QA/QC steps as part of the water level measurement uncertainty. If there is concern that the uncertainties associated with the data cleaning, processing and QA/QC steps should be captured separately. As a first-order approximation, we can estimate that the uncertainty contribution from processing, including QA/QC is, at most, 1 cm (Dusek, 2024).

3.2.3. Assumptions and Metadata

We must assume that partners are following CO-OPS guidance for establishing a water level station and conducting appropriate processing and quality control techniques. When computing uncertainty estimates for partner water level stations, several key assumptions are necessary:

1. Sensors are installed and operated correctly, with malfunctions or issues identified through quality control procedures. Common installation problems include discrepancies in leveling point offsets, poor site selection, unstable mounting, improper instrumentation setup, and other potential factors.
2. Uncertainty computations and methods provided here are intended for individual time series occurring within a single epoch; therefore, multiple time series should not be combined.
3. When a water level measurement system is serviced or adjusted in any way, a new uncertainty value should be computed.
4. Water level measurement uncertainty values should be computed and recorded for each installation and leveling survey, in addition to any analysis and record of uncertainty assessed from repeat surveys.
5. Choose a stable benchmark when possible, and assess benchmark stability, considering the platform's condition or unstable ground (e.g., areas without rocky outcrops), as these factors may impact measurement accuracy.
6. We acknowledge the potential for environmental biases, which may differ from one site to another.

In order to be able to make the assumptions listed above, we need to ensure that partners make the appropriate metadata available. Metadata should include: sensor type and brand/model, instrument frequency (if applicable), antenna type (if applicable), sampling frequency, sampling period, station location, and deployment period. Partners should also provide relevant processing and QA/QC metadata, such as a description of tests and flagging codes.

3.3. Geodetic vertical control

In this document, we define the geodetic control of a water level station as the measurement that provides a height relationship between the water level and a local and national reference system. Two key steps for geodetic control include: 1) establishing the height relationship between the water level gauge to a local permanent mark, "benchmark", typically using leveling surveys or GNSS Real-Time Kinematics (RTK); and 2) defining the mark within the national reference system, typically using GNSS observations. The reference system itself can be either mathematically defined as an ellipsoid (with no uncertainties associated with reference) or using a physical geospatial model based on gravity observations defined as a geopotential surface (with uncertainties ranging between 2 to 5 cm, depending on the geoid model).

3.3.1. Geodetic Leveling

Current CO-OPS procedures require establishing height relationships between the water level station to several permanent benchmarks, typically, up to 5 benchmarks for a short-term water-level observation (Hailegeberel et al., 2018). Traditionally, CO-OPS conducts spirit leveling for vertical control between a water level station to local benchmarks (up to 4 km distance from the station). This survey approach utilizes an optic instrument (called a level), which is a small telescope and a vial filled with a colored spirit or alcohol, leaving a bubble in the tube. The level is used to read values from a set of specially constructed and marked rods while maintaining observations at a fixed horizontal surface. Accuracy of surveyor-grade level instruments is such that the bubble will move when the vial is tilted about 0.005 degree. The instrument and rod combined resolution's least count should be 1.0 millimeters, or 0.005 feet, or better (FGCS, 2004). The accuracy associated with a geodetic survey is referred to as the "order" of a point. Orders are often subdivided farther by a "class" designation. Based on the survey type (accuracy), it is possible to define the survey performance key standards (order classes) (Bossler, 1984):

Table 2. Elevation tolerances for 2 runnings, where D is the shortest one-way length of section in kilometers (Smith, 2010).

Standard (Order Class)	Accuracy in mm (95% confidence)
1st Order, Class II	*4mm* $*\sqrt{D}$
2nd Order, Class I	*6mm* $*\sqrt{D}$
2nd Order, Class II	*8mm* $*\sqrt{D}$
3rd Order	*12mm* $*\sqrt{D}$

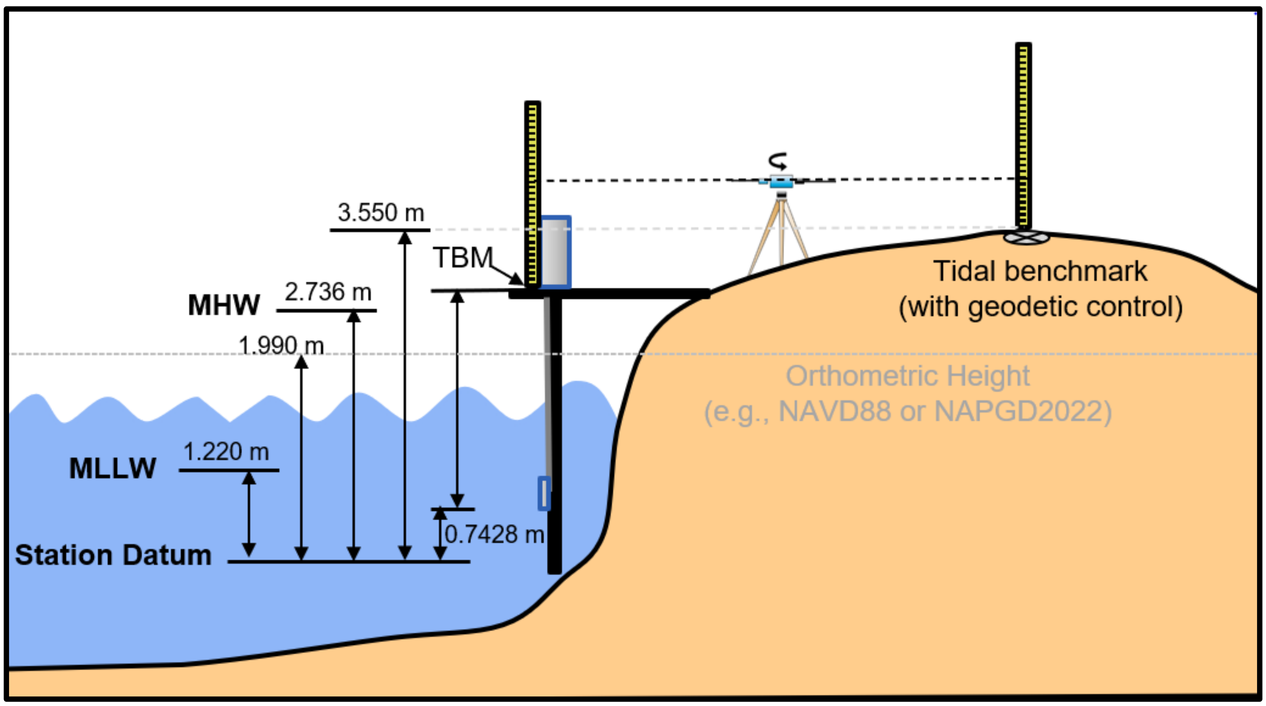


Figure 3. Schematic illustration of leveling between two rods referencing the water level observation to a local tidal benchmark.

3.3.2. GNSS

When leveling the water level station to a benchmark (Figure 3), it is assumed that the benchmark position is provided either with respect to an ellipsoid or with respect to a geopotential surface (orthometric height). An ellipsoid is a mathematical reference system (geospatial model), such as ITRF2020 (using a GRS80 ellipsoid) or WGS-84, with zero uncertainty to the model because no error has been introduced in that process. Orthometric heights, those referenced to the geoid, are based on gravity and leveling observations and do include measurement uncertainty. In the case of GEOID2022, the uncertainty value is assumed to be 2 cm (NGS, 2024).

In order to reference a benchmark to either an ellipsoidal height or an orthometric height, NGS has adopted the use of satellite navigation systems in land surveying. These satellite navigation systems, known as Global Navigation Satellite Systems (GNSS), continuously broadcast signals containing information about their position and precise time. NOAA manages a Continuously Operating Reference Stations (CORS) and provides the public free access to the high-accuracy National Spatial Reference System (NSRS) coordinates using an Online Positioning User Service (OPUS) (Gillins, 2017). GNSS observations can be used to directly relate the height of water level to an ellipsoidal height (GNSS co-location). More commonly, GNSS observations are collected using a post-processing survey configuration (i.e., occupying a benchmark for at least 4 hours) in order to link survey leveling from the tide station to the national network over the benchmark. In the context of this report, a discussion will only focus on post-processing survey configurations. Any discussion on GNSS co-location configurations that typically require permanent occupation are beyond the scope of this report.

Based on multiple studies on the accuracies from GNSS observations in different configurations (Gillins, 2017; Jamieson, 2018; Gillins, 2019), NGS recommends the following requirements for Network and Local Accuracy classifications. With the recognition that different geographic location and available resources (time and money), the vertical uncertainty results (with respect to the ellipsoid height and the orthometric height) from the GNSS observation can be classified into three groups:

- Primary network (ellipsoid: **2 cm**; orthometric: **3 cm)**
- Secondary network (ellipsoid: **3 cm**; orthometric: **4 cm**)
- Local network (ellipsoid: **5 cm**; orthometric: **6 cm**)

A new guidance for Classification, Standards, and Specifications for GNSS geodetic control surveys is provided through NOAA NGS Technical Memorandum 92 (NGS, 2024). This Technical Memorandum supplements other guidance documentations, and allows end users from the public to utilize the OPUS service and achieve geodetic quality results from their GNSS survey data. GNSS requirements and associated uncertainties are provided in Table 3.

Table 3. GNSS observation requirements and their associated uncertainties ** Network and Local Accuracies are stated at the 95% confidence level*

Requirement	**Primary**	**Secondary**	**Local**
Ellipsoid Height (m)	**0.02 m**	**0.03 m**	**0.05 m**
Orthometric Height (m)	**0.03 m**	**0.04 m**	**0.06 m**
Requirements for OPUS PP **- Required TOTAL Static GNSS Observation Time (T)** **and Recommended GNSS sessions**	T = 20 hours (for 0 to 200 km) (2) 10-hour sessions or (3) 7-hour sessions or (4) 5-hour sessions Requires at least 2 sessions, with at least 1 session on a different day	T = 8 hours (for 0 to 200 km) (2) 4-hour sessions T = 6 hours (for 0 to 150 km) (2) 3-hour sessions T = 4 hours (for 0 to 100 km) (2) 2-hour sessions Requires at least 2 sessions.	T = 4 hours (for 0 to 200 km) (2) 2-hour sessions Requires at least 2 sessions.

In some scenarios, partner water level observations measure the height relationship between the water level observation to a given benchmark using GNSS Real-Time Kinematics

(RTK) or Real Time Network (RTN) instead of leveling or static GNSS surveys. This is a relative observation that does not "tie" the water level observation to the national reference system. The relative uncertainty using GNSS RTK can range between 0.02 m to 0.05 m, depending on the configuration (e.g., stability of the rover and the distance from the base station located over the benchmark).

3.3.3. Assumptions and Metadata

To compute uncertainty components associated with local leveling and referencing to a national system, we must assume that leveling is conducted according to standards and benchmarks are stable for leveling (i.e., bluebooking). Partners should provide the method of leveling. For geodetic leveling, we will need to know the class and order, number of benchmarks including stamping name and ID, and the distance of benchmarks from the tide stations. For GNSS occupations, we will need to receive a report that includes: the other GNSS stations used in determining the benchmark position, the benchmark information, antenna type and height from the phase center to the benchmark, time of observation, satellites observed and the number of sessions.

4. EXAMPLES

The following scenarios are hypothetical case studies based on past efforts in order to provide examples for different water level observation technologies (Section 3.2) and their associated uncertainties. Based on the available metadata from the water level station, one should select an uncertainty value from the range of each technology provided in Table 1 and combine with the uncertainty value based on the geodetic control (Tables 2 and 3). The cases below include observations in VDatum, hydrographic surveys, and research projects. Please note that the examples below represent general cases, and the values provided may vary depending on environmental conditions and hardware design. We have not included error associated with data processing in these examples. If data quality is a concern or if there are significant data gaps, users should consider adding 2 cm, which aligns with standard CO-OPS uncertainty estimation practices.

4.1. Microwave Radar

Case Study A: A contractor installed a water level station according to CO-OPS standards.
Instrumentation: Xylem/YSI Nile 502, CO-OPS standard processing
Geodetic Control: The station leveling is second order, class I
Total Vertical Uncertainty: The YSI Nile 502 microwave radar measurement accuracy is 2 cm. Local leveling contributes 1.2 cm to uncertainty. And referencing the water level to the ellipsoid contributes no uncertainty.

Component	Specifications	Uncertainty Contribution (cm)
Instrumentation	YSI Nile 502	2
Geodetic Control	Local spirit leveling	1.2

$$TVU = \sqrt{measurement^2 + leveling^2}$$

$$TVU = \sqrt{2.0^2 + 1.2^2} = 2.3\ cm$$

Case Study B: A partner water level station with a Vega high frequency microwave water level sensor
Instrumentation: VegaPuls C22
Geodetic Control: The station leveling is second order, class I
Total Vertical Uncertainty: The VegaPuls C22 microwave radar measurement and processing accuracy is 2 cm (estimation for purposes of this document). Local leveling contributes 1.2 cm to uncertainty.

Component	Specifications	Uncertainty Contribution (cm)
Instrumentation	VegaPuls	2
Geodetic Control	Local spirit leveling	1.2

$$TVU = \sqrt{measurement^2 + leveling^2}$$

$$TVU = \sqrt{2.0^2 + 1.2^2} = 2.3\ cm$$

4.2.GNSS-IR

Case Study A: PSMSL GNSS-IR long term installation
Instrumentation: PSMSL GNSS-IR long term installation
Geodetic Control: Reference to ellipsoid
Total Vertical Uncertainty: The PSMSL long term installation accuracy is 15 cm, and the reference to the ellipsoid is 2 cm.

Component	Specifications	Uncertainty Contribution (cm)
Instrumentation	PSMSL long term installation	15
Geodetic Control	Reference to ellipsoid	2

$TVU = \sqrt{15^2 + 2^2} = 15.1\ cm$

Case Study B: Short-term GNSS-IR station
Instrumentation: The F4 evaluated short-term GNSS-IR stations (at least 30 days) along four locations in Alaska. This approach does require good power supply and communication support. Four (4) stations were evaluated against traditional VDatum water level stations (technology) and compared at the Station Datum level.
Geodetic Control: Reference to geoid beyond height relationship from the GPS antenna to the national network (active benchmark).
Total Vertical Uncertainty: Comparing the GNSS-IR to traditional VDatum observation a random error of 6 cm (1 standard deviation) and a systematic error of 5 cm (1 standard deviation) were observed. Since this observation is using a GNSS antenna, the geodetic uncertainty is 3 cm (Table 4).

Component	Specifications	Uncertainty Contribution (cm)
Instrumentation	Short term GNSS installation	11
Geodetic Control	Reference to geoid	3

$TVU = \sqrt{11^2 + 3^2} = 11.4\ cm$

4.3. Tide Buoys

Case Study A: OCS uses a tide buoy to support hydrographic surveys in a back bay environment.
Instrumentation: AXYS Hydrolevel System
Geodetic Control: The tide buoy uses GNSS to measure the sea surface height relative to the ellipsoid.
Total Vertical Uncertainty: In a back bay environment, the buoy contributes 10 cm to uncertainty, and the reference to the ellipsoid contributes 2 cm.

Component	**Specifications**	**Uncertainty Contribution (cm)**
Instrumentation	AXYS Hydrolevel, back bay	10
Geodetic Control	Reference to ellipsoid	2

$TVU = \sqrt{10^2 + 2^2} = 10.2\ cm$

Case Study B: OCS uses a tide buoy to support hydrographic surveys in a rough, open ocean environment.
Instrumentation: AXYS Hydrolevel System
Geodetic Control: The tide buoy uses GNSS to measure the sea surface height relative to the ellipsoid.
Total Vertical Uncertainty: In the open ocean, the buoy contributes 15 cm to uncertainty, and the reference to the ellipsoid contributes 2 cm.

Component	**Specifications**	**Uncertainty Contribution (cm)**
Instrumentation	AXYS Hydrolevel, open ocean	15
Geodetic Control	Reference to ellipsoid	2

$TVU = \sqrt{15^2 + 2^2} = 15.1\ cm$

4.4.DART Buoy

Case Study A: DART Buoys (Deep-ocean Assessment and Reporting of Tsunamis) are real-time tsunami monitoring systems operated by the National Weather Service (NWS).

Instrumentation: DART uses a bottom pressure recorder (BPR) to measure the pressure on the sea floor, usually at several thousand meters water depth.

Geodetic Control: Geodetic control for a DART buoy is a logistical challenge for this type of observation (i.e., a buoy drifts horizontally within a radius). A GPS receiver on top of the DART buoy provides the location of the buoy. There is also an acoustic modem that can also be used as an acoustic pinger for a more accurate location of the BPR (similar to Seafloor Geodesy operations).

Total Vertical Uncertainty: DART buoys have a measurement accuracy of 5 cm (PMEL, 2007). As a first order approximation, the vertical reference is accurate within 20 cm.

Component	**Specifications**	**Uncertainty Contribution (cm)**
Instrumentation	DART ETD Tsunami Buoy	5
Geodetic Control	GPS on top of the Buoy	20

$$TVU = \sqrt{5^2 + 20^2} = 20.6\ cm$$

4.5. Ultrasonic Acoustic Radar

Case Study A: IOOS Regional Association funded the deployment of a system of ultrasonic acoustic radars to fill spatial gaps in water level measurements.
Instrumentation: Hohonu water level monitoring system (utilizes the Maxbotix MB7388 radar); 6 minute average of 1 Hz samples, QA/QC following QARTOD.
Geodetic Control: 3rd order differential leveling to local benchmarks was conducted.
Total Vertical Uncertainty: The accuracy of the Maxbotix radar is 10 cm in this example. Third order leveling uncertainty is $12mm * \sqrt{D\ Km}$ = 48 mm = 4.8 cm for a 4 km benchmark.

Component	**Specifications**	**Uncertainty Contribution (cm)**
Instrumentation	Hohonu	$\sqrt{10^2 + 2^2}$=10.2
Geodetic Control	Local spirit leveling	4.8

$$TVU = \sqrt{10.2^2 + 4.8^2} = 11.3\ cm$$

Case Study B: IOOS Regional Association funded the deployment of a system of ultrasonic acoustic radars to fill spatial gaps in water level measurements, and provide highly localized real-time monitoring.
Instrumentation: Hohonu water level monitoring system (utilizes the Maxbotix MB7388 radar); 6-minute average of 1 Hz samples, QA/QC following QARTOD.
Geodetic Control: RTK/RTN and static GNSS observation at the benchmark for height relationship to an orthometric height.
Total Vertical Uncertainty: The accuracy of the Maxbotix radar is 10 cm in this example. RTK/RTN measurements can range between 2 to 5 cm vertical uncertainty with an additional 3 cm for linking the station to an orthometric height, in this case we used a 6 cm value for the geodetic control.

Component	**Specifications**	**Uncertainty Contribution (cm)**
Instrumentation	Hohonu	$\sqrt{(10^2 + 2^2}$=10.2
Geodetic Control	RTK/RTN and Static GNSS	6

$$TVU = \sqrt{10.2^2 + 6^2} = 11.8\ cm$$

5. CONCLUSIONS

NOAA supports a range of short-term and partner water level data collection efforts to help meet partner, community and internal needs. These data have significant potential to enhance various NOAA products, including VDatum, hydrographic surveys, and coastal models such as CORA and OFS. A better understanding and methods for uncertainty will enable NOAA to address existing gaps in data coverage, enhancing the quality of its products and services by integrating these new water level initiatives. Using trusted partner datasets offers a cost-effective solution, providing a budget-friendly alternative without substantially compromising data quality.

This document provides an overview of current technologies for partner and short-term water level measurements, along with their associated errors. It also outlines a methodology to compute a first-order approximation of the uncertainty of these water level measurements and vertical control, with case study examples illustrating different scenarios.

It is important to note that limited research exists comparing these technologies to standard CO-OPS water level observations that are operationally used for marine navigation, measuring long-term sea level change and determining the National Tidal Datum Epoch (NTDE). Many of the technologies referenced here are relatively new, commercial products, with limited data on their relative uncertainties. Therefore, partner data should be considered secondary gauges in comparison to the primary gauges that make up CO-OPS NWLON and PORTS systems, which meet CO-OPS standards. The methodology presented here offers a first-order approximation, but more rigorous research is necessary to accurately determine the uncertainty associated with each technology.

Additionally, the value of long-term NWLON stations, which establish a height relationship between chart datums, local mean sea level, and the ellipsoid or geopotential surface, should not be underestimated. In particular, calculating a tidal datum for the short-term water level observations requires relating the datum to a known NWLON control station. The uncertainty of the resulting datum depends on the similarity of tidal characteristics between sites, the observation time period, and the accuracy of the water level height determination (Mills and Dodd, 2014). Thus, long-term stations not only provide highly accurate water level and tidal datum measurements, but also enable the calculation of more accurate datums at short-term stations.

ACKNOWLEDGEMENTS

The authors would like to thank Robert Heitsenrether, Ryan Hippenstiel, Liujuan Tang, Katie Kirk, Nathan Murray, Jack Riley, and Stephen White for reviewing the document and providing valuable comments.

REFERENCES

Bell, Stephanie, 1999. A Beginner's Guide to Uncertainty of Measurement, N0. 11, Issue 2, ISSN 1368-6550, Centre for Basic, Thermal and Length Metrology, National Physical Laboratory, Teddington, Middlesex, United Kingdom, p. TW11 0LW.

Bossler, John D., 1984, Standards and Specifications for Geodetic Control Networks, Federal Geodetic Control Committee, Dept of Commerce, Rockville, MD. https://www.ngs.noaa.gov/FGCS/tech_pub/1984-stds-specs-geodetic-control-networks.pdf

Bushnell, M., Waldmann, C., Seitz, S., Buckley, E., Tamburri, M., Hermes, J., & Lara-Lopez, A. (2019). Quality assurance of oceanographic observations: Standards and guidance adopted by an international partnership. Frontiers in Marine Science, 6, 706.

Bushnell, M., & Worthington, H. (2021). Manual for real-time quality control of water level data: a guide to quality control and quality assurance for water level observations. IOOS QARTOD.

CO-OPS. Environmental Measurement Systems Sensor Specifications and Measurement Algorithms. 2023 https://tidesandcurrents.noaa.gov/publications/CO-OPS_Measurement_Spec.pdf

Dieck, 2017. Measurement Uncertainty—Methods and Applications, 5th Edition. The Instrumentation, Systems, and Automation Society. ISBN-10: 1941546943, ISBN-13: -13: 978-1941546949.

Dodd, D., B. Mehaffey, G. Smith, K. Barbor, S. O'Brien, M. van Norden (2009). "Chart Datum Transfer Using a GPS Tide Gauge Buoy in Chesapeake Bay." International Hydrographic Review, November 2009 on-line edition. http://www.iho-ohi.net/mtg_docs/IHReview/2009/IHR_Intro.htm

Dusek, G., Loesch, R., Stone, P., Heilman, L., & Fiorentino, L. (2024). National Water Level Observation Network (NWLON) requirements. https://doi.org/10.25923/h9h9-6p20

Elipot, S., Drushka, K., Subramanian, A., & Patterson, M. (2022). Overcoming the challenges of ocean data uncertainty. Eos (Washington, DC), 103.

Federal Geodetic Control Subcommittee (FGCS), 2004. Specifications and Procedures to Incorporate Electronic Digital/Bar-Code Leveling Systems. https://www.ngs.noaa.gov/FGCS/tech_pub/Fgcsvert.v41.specs.pdf

Gillins, D., and Eddy, M. (2017). "Comparison of GPS Height Modernization Surveys using OPUS-Projects and Following NGS-58 Guidelines," J. Surv. Eng. (ASCE)., 143(1):05016007.

Gillins, D.T., Kerr, D., and Weaver, B. (2019). "Evaluation of the Online Positioning User Service for Processing Static GPS Surveys: OPUS-Projects, OPUS-S, OPUS-Net, and OPUS-RS," J. Surv. Eng. (ASCE), 145(3):05019002.

Hailegeberel, M., Glassmire, K., Johnson, A., Samant, M., & Dusek, G. (2018). User's Guide to Vertical Control and Geodetic Leveling for CO-OPS Observing Systems. https://tidesandcurrents.noaa.gov/publications/Users_Guide_to_Vertical_Control_and_Geodetic_Leveling_for_CO-OPS_Observing_Systems-May_2018.pdf

Heitsenrether, Robert and Davis, Edgar (2011). Test and evaluation report: limited acceptance of the design analysis WaterLog® H-3611i microwave radar water level sensor. https://repository.library.noaa.gov/view/noaa/14753

Hernandez; D.; Dorton, J., Alsbrooks, C., Clark, R., Morano, K., Troxler, T., Glazer, B., Fiorentino, L., Rome, N., Wilson, C., Dusek, G. (2024). Building Resilience in Vulnerable Coastal Communities with the Southeast Water Level Network Initiative. Marine Technology Society Journal, 59(1), 80-85. DOI: https://doi.org/10.4031/MTSJ.59.1.1

Hess, K. W., and White, S. A. (2004). VDatum for Puget Sound: Generation of the grid and population with tidal datums and sea surface topography. NOAA Technical Memorandum NOS CS 4. pp. 27. https://vdatum.noaa.gov/download/publications/TM_NOS-CS04_FY04_Hess_PugetSoundVDatum.pdf

Huang, M., Arcas, D., Van der Westhuysen, A., Seaton, C., Warner, J., Moghimi, S., Peeri, S., Wei, Y., Yang, Z., Haas, K., Taylor, A., Pringle, W., Zyserman, J., 2022. Risk Reduction Sub-Group Models Model Evaluation Report. NOAA technical memorandum NOS 33; NOAA technical memorandum NWS 01; NOAA Technical Memorandum OAR 01, DOI: https://doi.org/10.25923/x2jk-xh48

Hunter, J. R. (2003). On the temperature correction of the Aquatrak acoustic tide gauge. Journal of Atmospheric and Oceanic Technology, 20(8), 1230-1235.

International Hydrographic Organization (IHO) 2020. IHO Standards Publications 44 (S-44) Edition 6.1.0 - Standards for Hydrographic Surveys. Monaco: International Hydrographic Bureau. https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.1.0.pdf

Jamieson, M., and Gillins, D.T. (2018). "Comparative Analysis of Online Static GNSS Post-Processing Services." J. Surv. Eng. (ASCE), 144(4):05018002.

Keeney, A., Dusek, G., Callahan, J., Ratcliff, J., Jima, T., Brooks, W., ... & Waring, B. (2025). NOAA's Coastal Ocean Reanalysis: Gulf of Mexico, Atlantic, and Caribbean. https://repository.library.noaa.gov/view/noaa/66833

Larson, K. M., Ray, R. D., Nievinski, F. G., & Freymueller, J. T. (2013). The accidental tide gauge: A GPS reflection case study from Kachemak Bay, Alaska. IEEE Geoscience and Remote Sensing Letters, 10(5), 1200-1204.

McLaughlin, L. R., Dusek, G., Jima, T., Haynes, A., & Guerin, C. (2024). National water level observation network (NWLON) prioritization.

Masoudimoghaddam, M., Yazdi, J., & Shahsavandi, M. (2024). A Low-Cost Ultrasonic Sensor for Online Monitoring of Water Levels in Rivers and Channels. Flow Measurement and Instrumentation, 102777.

Milbert, D. G. (2002) Documentation for VDatum and a datum tutorial: Vertical datum transformation software, version 1. 06. https://vdatum.noaa.gov/download/publications/2002_milbert_VDatum106.pdf

Miller, A., & Luscher, A. (2019). NOAA's national water level observation network (NWLON). Journal of Operational Oceanography, 12(sup2), S57-S66.

Mills, J., and Dodd, D., (2014). Ellipsoidally Referenced Surveying for Hydrography, International Federation of Surveyors (FIG) Guide, Publication 62, Copenhagen, Denmark, pp. 80. ISBN 978-87-92853-16-5 (pdf)

Myers, E. P., and Hess, K. W. (2006). Modeling of tidal datum fields in support of VDatum development along the north and central coasts of California. NOAA Technical Memorandum NOS CS 6. 15 p. https://vdatum.noaa.gov/download/publications/TM_NOS-CS06_FY06_Myers_CaliforniaVDatum.pdf

National Geodetic Survey (NGS), 2024. Classification, Standards, and Specifications for GNSS geodetic control surveys is provided through NOAA NGS Technical Memorandum 92. https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0092.pdf

National Ocean Service (NOS), 2022. Strategic Plan: Fiscal Year 2024-2028.

Office of Coast Survey (OCS), 2022. Hydrographic Survey Specifications and Deliverables. https://nauticalcharts.noaa.gov/publications/docs/standards-and-requirements/specs/HSSD_2022.pdf

Park, J., Heitsenrether, R., & Sweet, W. (2014). Water level and wave height estimates at NOAA tide stations from acoustic and microwave sensors. Journal of Atmospheric and Oceanic Technology, 31(10), 2294-2308. https://repository.library.noaa.gov/view/noaa/14423

Parker, W. S. (2016). Reanalyses and observations: What's the difference?. Bulletin of the American Meteorological Society, 97(9), 1565-1572.

Parker, B., Hess, K. W., Milbert, D. G., and Gill, S. (2003). National VDatum - the implementation of a national vertical datum transformation database U. S. Hydrographic Conference. Biloxi, Mississippi. https://vdatum.noaa.gov/download/publications/2003_parker_USHydro_nationalvdatum.pdf

Peng, Machuan et al. (2023). Implementation of the upgraded Lake Ontario Operational Forecast System and Lake Superior Operational Forecast System and the semi-operational nowcast/forecast skill assessment. https://doi.org/10.25923/xcc1-px89

PMEL (2007). Capability Assessment of the DART-ETD Tsunami Buoy Deep Ocean Assessment and Reporting of Tsunami – Easy To Deploy. https://nctr.pmel.noaa.gov/Dart/docs/TechNote_DART_ETD_Report.pdf

Portep, D. L., & Shih, H. H. (1996). Investigations of temperature effects on NOAA's next generation water level measurement system. Journal of Atmospheric and Oceanic Technology, 13(3), 714-725. https://doi.org/10.1175/1520-0426(1996)013%3C0714:IOTEON%3E2.0.CO;2

Purnell, D., Gomez, N., Chan, N. H., Strandberg, J., Holland, D. M., & Hobiger, T. (2020). Quantifying the uncertainty in ground-based GNSS-reflectometry sea level measurements. IEEE journal of selected topics in applied earth observations and remote sensing, 13, 4419-4428.

Rose, L., Widlansky, M. J., Feng, X., Thompson, P., Asher, T. G., Dusek, G., ... & Tilson, J. (2024). Assessment of water levels from 43 years of NOAA's Coastal Ocean Reanalysis (CORA) for the Gulf of Mexico and East Coasts. Frontiers in Marine Science, 11, 1381228.

Seroka, G., Fujisaki-Manome, A., Kelley, J., Pe'eri, S., Sienkiewicz, J., Feyen, J., Doty, O., Ide, K., Gramp, B., Ogden, F., Fanara, T., Myers, E., Moghimi, S., Cockerill, T., Wu, W., Anderson, E., Huelse, K., Forbes, C., Liu, Y., John, S., Di Lorenzo, E., Park, K., Wipperfurth, S., Sannikova, N., Titov, V., Wei, Y., Akan, C., Mani, S., Lindley, C., (2024). UFS Coastal Applications Team Report: Round 1 Summary of a Unified Forecast System Model Evaluation for Marine Navigation. NOAA Technical Memorandum NOS 36; NOAA Technical Memorandum NWS 04; NOAA Technical Memorandum OAR 04. DOI: https://doi.org/10.25923/nws6-kx30

Smith, C (2010). Bench Mark Reset Procedures. National Geodetic Survey. https://geodesy.noaa.gov/PUBS_LIB/Benchmark_4_1_2011.pdf

Spargo, E. A., Hess, K. W., White S. A. (2006). VDatum for the San Juan Islands and Strait of Juan de Fuca with updates for Puget Sound: Tidal datum modeling and population of the grids. NOAA Technical Report NOS CS 23. 50 p. https://vdatum.noaa.gov/download/publications/TR_NOS-CS25_FY06_Hess_VDatumSanJuanIslands.pdf

Tolkova, E., L. Tang, J. Riley, I. Jeong, S. White (2023). VDatum Update for Chesapeake Bay, Delaware Bay, and Adjacent Waters: Tidal Datums, Sea Surface Topography, and Their Spatially Varying Uncertainties. NOAA Technical Memorandum NOS CS 55. https://vdatum.n.oaa.gov/download/publications/noaa_48085_DS1.pdf

van der Westhuysen, A., Ogden, F., Flowers, T. Fanara, T. Myers, E., Dean, C., Allen, A., Lindley, C., Zachry, B. Fujisaki-Manome, A., Warner, J., Doran, K., Palmsten, M., Massey, C., Sanders, B., and He, R. (2022). Whitepaper on the Development of a Unified Forecast System for Coastal Total Water Level. NOAA Technical Memorandum NOS 35, DOI: https://doi.org/10.25923/170a-cv35

Weston, N. et al. (2023). Global ESTOFS, STOFS-3D-Atlantic and OFS Water Level Skill Assessment Comparisons. https://doi.org/10.25923/zkax-t757

White, S., Jeong, I., Hess, K. (2016). An Assessment of the Revised VDatum for Eastern Florida, Georgia, South Carolina, and North Carolina. NOAA Technical Memorandum NOS CS 38. https://vdatum.noaa.gov/download/publications/TM_NOS_CS38_FY17_White_VDatum_SAB_Update_Analysis.pdf