IOOS
Integrated Ocean
Observing System

QARTOD
QUALITY ASSURANCE/QUALITY CONTROL OF REAL-TIME OCEANOGRAPHIC DATA

Manual for
Real-Time Quality Control of Water Level Data

A Guide to Quality Control and Quality Assurance for Water Level Observations

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Revision History

Date	Revision Description	Notes
May 2014	Original Document Published	
April 2016	Revise cover page to include new IOOS logo. Revise dates on *Document Validation* page and substitute new logo (page ii). Add statement requesting feedback from *Manual Users* (page vi). Update *Acknowledgements* to include Version 2.0 team members (page vii). Update definition of real time in *Definitions of Selected Terms* (page ix). Revise *Background and Introduction* to reflect updated and additional manuals that have been developed (page 1). Revise section 2.0 content in various places to reflect updated content from previous manuals and feedback from reviewers (pages 3-6; 10-11). Update content in section 3.1 (page 12) and add section 3.3.2 (page 22). Update language in section 4.0, *Summary* (page 23). Update *References* and *Supporting Documents* (page 24-26). Revise good process description in table A-1 (page A-4). Update Version 2.0 Water Level Manual Team members (page B-1).	Manual updated with revisions listed sequentially

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Request to Manual Users

To gauge the success of the QARTOD project, it helps to be aware of groups working to utilize these QC tests. Please notify us of your efforts or intentions to implement QARTOD processes by sending a brief email to data.ioos@noaa.gov or posting a notice at http://www.linkedin.com/groups?gid=2521409.

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Acronyms and Abbreviations

ACT	Alliance for Coastal Technologies
AOOS	Alaska Ocean Observing System
CariCOOS	Caribbean Coastal Ocean Observing System
CeNCOOS	Central and Northern California Ocean Observing System
CO-OPS	Center for Operational Oceanographic Products and Services
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GLOS	Great Lakes Observing System
GLOSS	Global Sea Level Observing System
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IOC	Intergovernmental Oceanographic Commission
IOOS	Integrated Ocean Observing System
MARACOOS	Mid-Atlantic Regional Association Coastal Ocean Observing System
NANOOS	Northwest Association of Networked Ocean Observing Systems
NERACOOS	Northeastern Regional Association of Coastal Ocean Observing Systems
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWLON	National Water Level Observation Network
OSTEP	Ocean Systems Test and Evaluation Program
PacIOOS	Pacific Islands Ocean Observing System
PVC	Polyvinyl Chloride
QARTOD	Quality-Assurance/Quality Control of Real-Time Oceanographic Data
QA	Quality Assurance
QC	Quality Control
SCCOOS	Southern California Coastal Ocean Observing System
SD	Standard Deviation
SECOORA	Southeast Coastal Ocean Observing Regional Association
UK	United Kingdom
UNESCO	United Nations Organization for Education, Science, and Culture
UTC	Coordinated Universal Time
USGS	United States Geological Survey
WL	Water Level

Definitions of Selected Terms

This manual contains several terms whose meanings are critical to those using the manual. These terms are included in the following table to ensure that the meanings are clearly defined.

Codable Instructions	Codable instructions are specific guidance that can be used by a software programmer to design, construct, and implement a test. These instructions also include examples with sample thresholds.
Data Record	A data record is one or more messages that form a coherent, logical, and complete observation.
Datum	For marine applications, datum is a base elevation used as a reference from which to reckon heights or depths. It is called a tidal datum when defined in terms of a certain phase of the tide (Gill and Schultz 2001).
Leveling	Leveling is the determination of the elevation differences between bench marks, to extend vertical control and monitor the stability of the water level measurement gauge. The quality of leveling is a function of the procedures used, the sensitivity of the leveling instruments, the precision and accuracy of the rod, the attention given by surveyors, and the refinement of the computations (Gill and Schultz 2001).
Message	A message is a standalone data transmission. A data record can be composed of multiple messages.
Operator	Operators are individuals or entities who are responsible for collecting and providing data.
Quality Assurance (QA)	QA involves processes that are employed with hardware to support the generation of high quality data (section 2.0 and appendix A).
Quality Control (QC)	QC involves follow-on steps that support the delivery of high quality data and requires both automation and human intervention (section 3.0).
Real Time	Real time means that: data are delivered without delay for immediate use; time series extends only backwards in time, where the next data point is not available; and sample intervals may range from a few seconds to a few hours or even days, depending upon the sensor configuration (section 1.0).
Threshold	Thresholds are limits that are defined by the operator.
Variable	An observation (or measurement) of biogeochemical properties within oceanographic and/or meteorological environments.

1.0 Background and Introduction

The U.S. Integrated Ocean Observing System (IOOS®) has a vested interest in collecting high-quality data for the 26 core variables (U.S. IOOS 2010) measured on a national scale. In response to this interest, U.S. IOOS continues to establish written, authoritative procedures for the quality control (QC) of real-time data through the Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) program, addressing each variable as funding permits. This water level (WL) manual was first published in May 2014 as the fifth in a series of guidance documents that address QC of real-time data of each core variable. It is the fifth manual to be updated.

Please refer to http://www.ioos.noaa.gov/qartod/for the following documents.

1) U.S IOOS QARTOD Project Plan dated April 1, 2012.
2) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of Dissolved Oxygen Observations Version 2.0: A Guide to Quality Control and Quality Assurance for Dissolved Oxygen Observations in Coastal Oceans. 48 pp.
3) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of In-Situ Current Observations Version 2.0: A Guide to Quality Control and Quality Assurance of Acoustic Doppler Current Profiler Observations. 51 pp.
4) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of In-Situ Surface Wave Data Version 2.0: A Guide to Quality Control and Quality Assurance of In-Situ Surface Wave Observations. 64 pp.
5) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of In-situ Temperature and Salinity Data Version 2.0: A Guide to Quality Control and Quality Assurance of In-situ Temperature and Salinity Observations. 56 pp.
6) U.S. Integrated Ocean Observing System, 2014. Manual for Real-Time Quality Control of Wind Data: A Guide to Quality Control and Quality Assurance of Coastal and Oceanic Wind Observations. 45 pp.
7) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of Ocean Optics Data: A Guide to Quality Control and Quality Assurance of Coastal and Oceanic Optics Observations. 46 pp.
8) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of Dissolved Nutrients Data: A Guide to Quality Control and Quality Assurance of Coastal and Dissolved Nutrients Observations. 56 pp.

Please reference this document as:

U.S. Integrated Ocean Observing System, 2016. Manual for Real-Time Quality Control of Water Level Data Version 2.0: A Guide to Quality Control and Quality Assurance of Water Level Observations. 46 pp.

This manual is a living document that reflects the state-of-the-art QC testing procedures for water level observations. It is written for the experienced operator but also provides examples for those who are just entering the field.

2.0 Purpose/Constraints/Applications

The following sections describe the purpose of this manual, as well as the constraints that operators may encounter when performing QC of WL data and specific applications of those data.

2.1 Purpose

The purpose of this manual is to provide guidance to the U.S. IOOS and the WL community at large for the real-time QC of WL measurements using an agreed-upon, documented, and implemented standard process. This manual is also a deliverable to the U.S. IOOS Regional Associations and the ocean observing community and represents a contribution to a collection of core variable QC documents.

WL observations covered by these test procedures are collected in oceans and lakes in real time or near-real time. These tests are based on guidance from QARTOD workshops (QARTOD 2003-2009) and draw from existing expertise in programs such as the National Oceanic and Atmospheric Administration National Ocean Service (NOAA/NOS) National Water Level Observation Network (NWLON), the University of Hawaii Sea Level Center, and the Global Sea Level Observing System (GLOSS). The Global Climate Observing System recognizes GLOSS as one of the international operational activities that provides essential sea level climate data. The GLOSS Global Core Network is comprised of 290 globally distributed sea level stations (GLOSS 2012).

This manual differs from existing QC procedures for WL in that its focus is on real-time data. It presents a series of eleven tests that operators can incorporate into practices and procedures for QC of WL measurements. These tests apply only to the in-situ, real-time measurement of WL as observed by sensors deployed on fixed platforms and not to remotely sensed WL measurements (e.g., satellite observations).

Table 2-1 shows technologies that are included and excluded in this manual.

Table 2-1. Technologies included and excluded in this manual

Technologies Included	Technologies Excluded
Microwave radar Acoustic Float/stilling well Pressure Laser Global Positioning System (GPS) buoy	Satellite altimetry Lidar GPS occultation

These test procedures are written as a high-level narrative from which a computer programmer can develop code to execute specific tests and set data flags (data quality indicators) within an automated software program. A code repository exists at https://github.com/ioos/qartod where operators may find or post examples of code in use. Although certain tests are recommended, thresholds can vary among operators. The tests described here are designed to support a range of WL sensors and operator capabilities. Some well-established programs with the highest standards have implemented very rigorous QC processes. Others, with different requirements, may utilize sensors with data streams that cannot support as many QC checks—all have value when used prudently. Users must understand and appropriately utilize data of varying quality, and operators must provide support by documenting and publishing their QC processes. A balance must be struck between the time-sensitive needs of real-time observing systems and the degree of rigor that has been applied to non-real-time systems by operators with decades of QC experience.

High quality marine observations require sustained quality assurance (QA) and QC practices to ensure credibility and value to operators and data users. QA practices involve processes that are employed with hardware to support the generation of high quality data, such as a sufficiently accurate, precise, and reliable sensor with adequate resolution. Other QA practices include: sensor calibration; calibration checks and/or in-situ verification, including post-deployment calibration; proper deployment considerations, such as measures for corrosion control and anti-fouling; solid data communications, including accurate time stamps with time zone identification; adequate maintenance intervals; and creation of a robust quality control process. Post-deployment calibration (instrument verification after recovery) issues are not part of the scope of this manual. Although QC and QA are interrelated and both are important to the process, QA is not the focus of this manual. However, QA considerations are briefly addressed in appendix A.

QC involves follow-on steps that support the delivery of high quality data and requires both automation and human intervention. QC practices include such things as data integrity checks (format, checksum, timely arrival of data), data value checks (threshold checks, minimum/maximum rate of change), neighbor checks, climatology checks, model comparisons, signal/noise ratios, the mark-up of the data, the verification of user satisfaction, and generation of data flags (Bushnell 2005).

The process of ensuring data quality is not always straightforward. QA/QC procedures may be specific to a sensor technology or even to a particular manufacturer's model, so the establishment of a methodology that is applicable to every sensor is challenging.

2.2 Constraints

2.2.1 Datums and Leveling Considerations

Observed water levels are reported relative to another vertical elevation that serves as a reference point or datum (Gill and Schultz 2001). Vertical datums can be a local station datum (relative only to some fixed hardware point or arbitrary value), a tidal datum (such as mean lower low water), a gravimetric datum (such as the North American Vertical Datum of 1988, based on an equipotential gravity surface commonly called the geoid), or a geodetic datum (the fundamental datum for GPS satellites and based on a mathematical model of the earth called an ellipsoid).

To monitor station stability and provide continuity when replacing a WL station, several nearby bench marks are typically installed to support level (or vertical) surveying, and the local station datum and tidal datum elevations are determined relative to them (Hicks et al. 1987). The number of bench marks deployed depends upon the application of the operator, and as many as ten can be called for when the WL station is used for the most demanding applications, such as long-term sea level changes. Three stable bench marks are required to demonstrate stability, and more bench marks are typically required as the duration of station operation increases. Some operators consider the bench marks the most important part of a WL station, as they preserve the tidal datums established by the station long after it is gone. For more detailed information about datums, bench marks, and geodetic leveling, see http://www.ngs.noaa.gov/PUBS_LIB/Geodeticleveling_nos_3.pdf.

While datums and vertical leveling surveys are beyond the scope of this manual, their importance must be noted, as they are critical to the successful use of the WL data. Gradual station subsidence or rise, datum determinations, and leveling precision are not issues that can be addressed through real-time QC, but they are vitally important to the QA of the observing system and its corresponding data. It is especially critical for operators to correctly convey the datum in use to users and to include this important metadata with every water level observation.

2.2.2 Data Processing Methodology

The type of sensor used to collect WL data and the system used to process and transmit the WL measurements determine which QC algorithms are used. In-situ systems with sufficient onboard processing power within the sensor may process the original (raw) data and produce derived products, such as water density or speed of sound. Many sensors may sample at high-rate or burst mode (e.g., 1 Hz or greater). These samples are used to produce the actual real-time value transmitted (e.g., 6-minute value). Statistical information about the high rate sample distributions can also be used and transmitted as real-time QC parameters (e.g., sample standard deviations and outliers). If ample transmission capability is available, the entire original data stream may be transmitted ashore and subsequently quality controlled from there. Therefore, because operators have different data processing methodologies, three levels of QC are proposed: required, strongly recommended, and suggested.

2.2.3 Traceability to Accepted Standards

To ensure that WL sensors produce accurate data, rigorous calibrations and calibration checks must be performed in addition to QC checks. Most operators rely upon manufacturer calibrations and conduct calibration checks only before deployment. These calibration checks are critical to ensuring that the manufacturer calibration is still valid. Manufacturers describe how to conduct these calibration checks in their user manuals, which are currently considered QA and further addressed in appendix A.

Calibrations and calibration checks must be traceable to accepted standards. The National Institute of Standards and Technology (NIST) (http://www.nist.gov/index.html), a provider of internationally accepted standards, is often the source for accepted standards. Calibration activities must be tailored to match data use and resources. Calibration cost and effort increase dramatically as accuracy requirements increase. Fundamental NIST standards such as length, temperature, and pressure will suffice when conducting calibration checks on most WL sensors.

2.2.4 Sensor Deployment Considerations and Hardware Limitations

WL sensors can be deployed in several ways. Most sensors are fixed to platforms that are designed to ensure minimal vertical or horizontal movement, and they observe the water level from at or above the surface. Pressure sensors may be directly submerged or configured within a bubbler system to observe the back pressure. GPS buoys, which measure water elevation derived from a GPS antenna position, have recently been used operationally; this technology should improve as GPS accuracy and real-time processing capability improve.

While outside the scope of the real-time tests described in this manual, QA is critical to data quality. Sensors require attention to proper QA measures both before and after the deployment. Operators must follow the manufacturer's recommendations for factory calibration schedules and proper sensor maintenance.

The following sections describe the sensor technologies that are most often used, with a brief note about their attributes and shortcomings.

Microwave Radar

Microwave radar altimeters have become popular within the past decade as this technology has evolved (Park et al. 2014). While free of many of the drawbacks of other WL sensors, microwave radar technology brings new modes of failure, for example, unknown performance in the presence of large waves, the inability to measure water levels in the presence of ice, and surprise occasional problems such as a bee's nest in the sensor horn. Figure 2-1 shows an example of a Xylem/Design Analysis H3611 microwave water level sensor installation by the NOS Center for Operational Oceanographic Products and Services (CO-OPS).

Figure 2-1. Xylem/Design Analysis H3611 microwave water level sensor as installed by NOS/CO-OPS.

Acoustic

Acoustic altimeters typically use a sounding tube but can also operate in open air. They are sensitive to variations in the speed of sound caused by temperature changes and temperature gradients along the acoustic transmission path. Sounding tubes may become obstructed with biota or ice, causing errors in the measurements. Effects of waves and currents have been partially mitigated using protective wells and orifice configurations (which may be expensive to install and maintain, depending on the project). Figure 2-2 shows a single-pile NOS/CO-OPS installation using an acoustic sensor. The inset depicts an Aquatrak sensor mounted atop a sounding tube in a protective well.

Figure 2-2. An elevated NOS/CO-OPS NWLON station using an Aquatrak acoustic WL sensor (inset) with a sounding tube housed inside a protective 6-inch PVC well.

Float/Stilling Wells

Floats deployed in stilling wells are an old and proven technology. These systems can be fortified to operate in the presence of ice, but they are expensive to install. Intakes can become clogged with sediment, and the mechanisms used to transfer the float elevation to sensors (e.g., shaft-angle encoders) can have unique failure modes. Stilling wells in tidal areas are known to cause significant error in WL observations in the presence of high waves and currents. Figure 2-3 shows a typical NOS/CO-OPS Great Lakes installation of dual shaft-angle encoders and their respective floats deployed in the stilling well, also referred to as the sump. Sumps are large stilling wells that have an intake valve used to dampen wave action that might be transferred through the intake pipe to the sump.

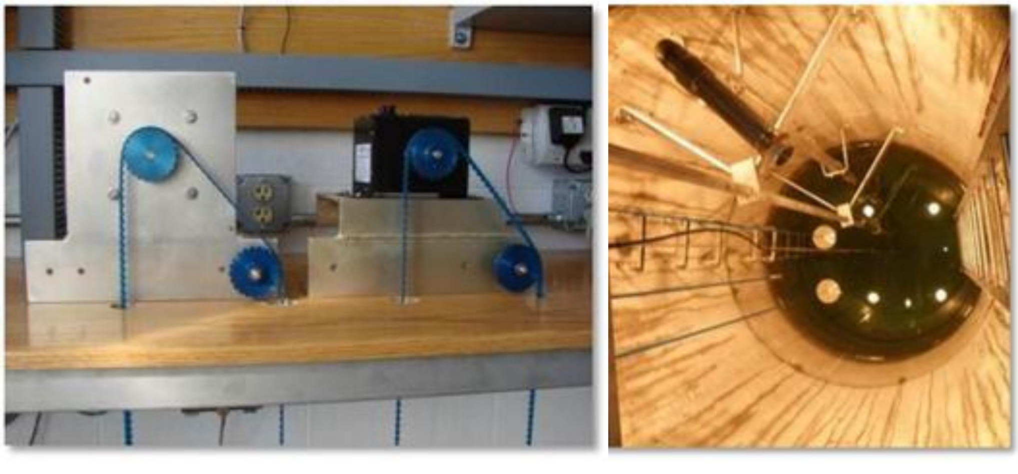


Figure 2-3. Redundant shaft-angle encoders (left) digitize the elevation of floats in a stilling well (right).

Pressure Sensors

Pressure sensors can be immune to ice, but pressure readings must be adjusted for variations in barometric pressure *and* water density in real time as part of the conversion to derived real-time water level measurements. Pressure sensors can be vented to the atmosphere to automatically account for variations in atmospheric pressure; however, water density variations still must be accounted for. Sensor drift can be an issue for low-quality sensors, and moisture damage in the air tube is a common failure mode. Allowance for gravity variations must also be made at each installation site. Figure 2-4 provides a generalized schematic of a typical pressure sensor installation as used by the U.S. Geological Survey (USGS) and many others. The back pressure observed by a sensor that is not submerged yields a much more robust system. Figure 2-5 shows a typical NOS/CO-OPS backup pressure sensor orifice installation, which includes the use of parallel plates to reduce draw-down in the presence of currents.

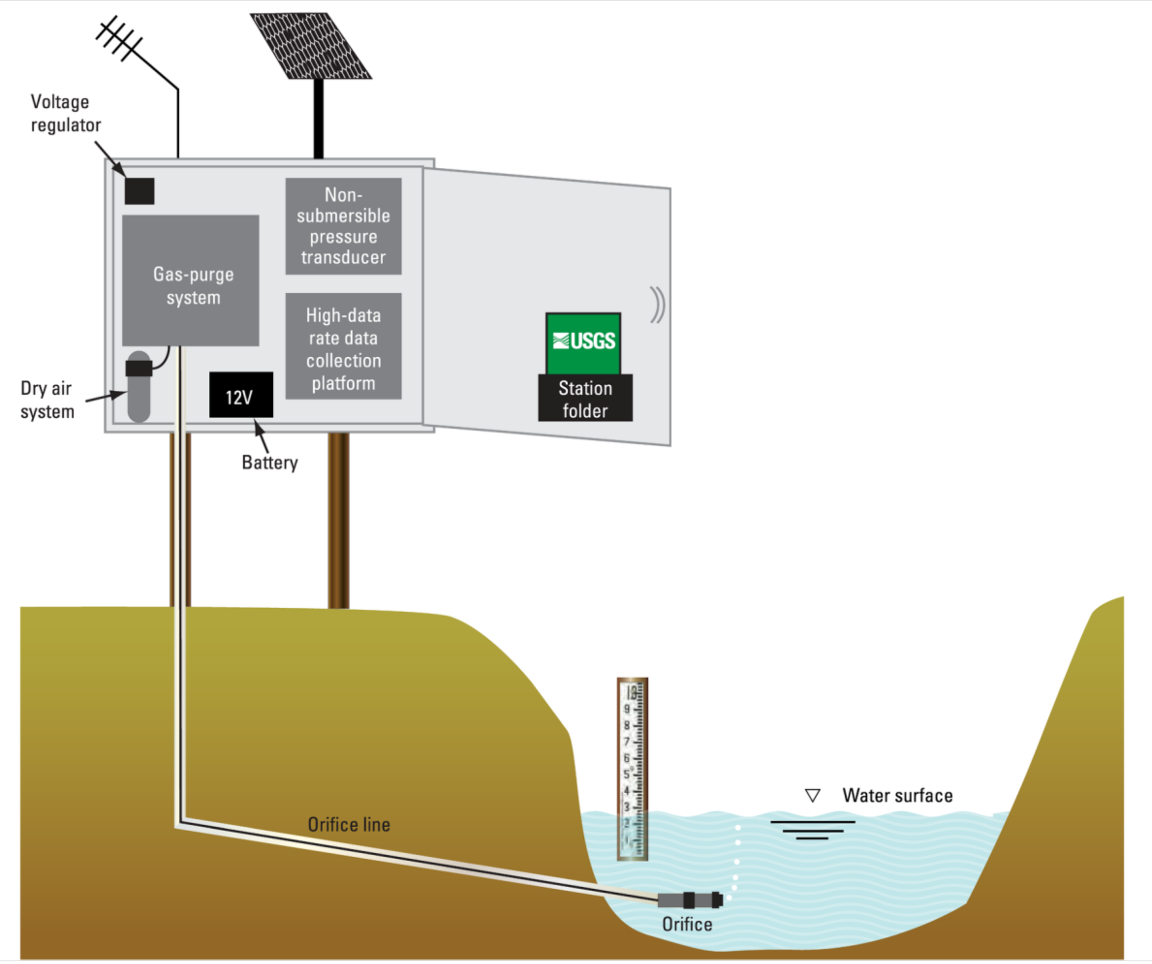


Figure 2-4. Schematic of a typical pressure sensor installation (courtesy of Michael Lee/USGS).

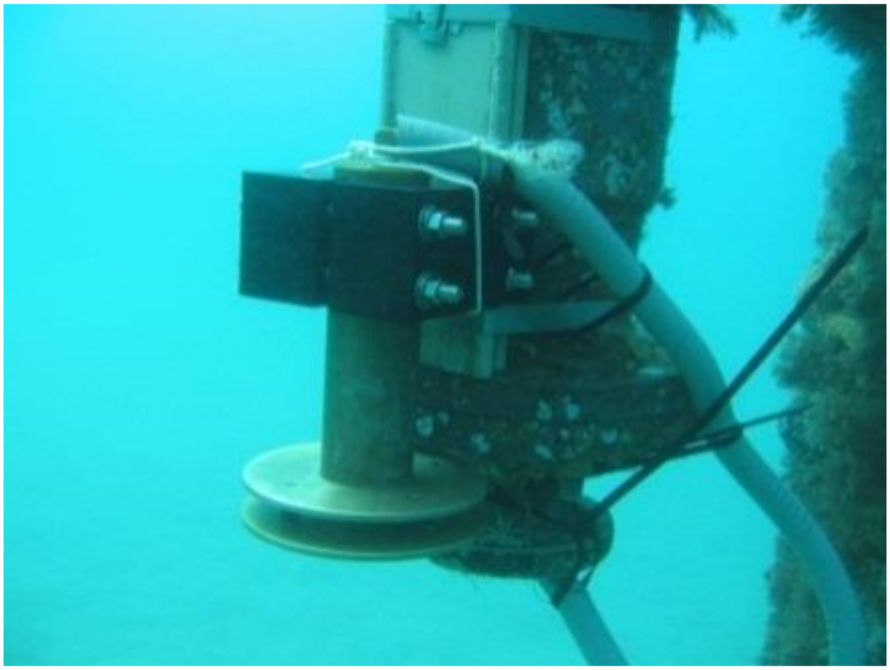


Figure 2-5. A pressure sensor orifice with parallel plates to reduce draw-down in the presence of currents (courtesy of Rich Bourgerie/NOS/CO-OPS).

Lasers

Infrared laser altimeters reflect well from the sea surface, and sensor performance has improved while costs have decreased. However, performance in fog and heavy rain may not be optimum. The sensors are also affected by high waves and ice or other obstructions in the laser path. Figure 2-6 shows an infrared laser used by NOS/CO-OPS as a redundant bridge air gap sensor.

Figure 2-6. Laser Technology infrared Universal Laser Sensors have been used as redundant air gap sensors by NOS/CO-OPS (courtesy of Mark Bushnell, CoastalObsTechServices).

GPS Buoys

The accuracy of elevations derived by GPS continues to improve as enhancements are made to national and international global navigation satellite systems (GNSS). The location of the GPS sensor reference point must be calibrated to reflect the water level on the buoy. The onboard processing system must use a tilt-motion sensor to account for wave action. Mooring configurations must be designed to mitigate effects of high currents. Water density variations and bio-fouling can also create biases. GPS data processing is complicated for real-time application and may require shore-based systems for real-time kinematic deployments. Technology-specific QC checks based upon GNSS parameters, such as Positional Dilution of Precision, number of satellites in view, and ephemeris update rates, will be added as this capability evolves. Figure 2-7 shows a GPS buoy on the deck of a small vessel getting ready for deployment. This particular buoy does not provide real-time water level data and requires post-processing of the GPS data. However, real-time information is obtained on buoy performance and operational status. Although a GPS buoy system has been recently approved by NOAA/NOS for some operational applications, real-time processing of water level data using GNSS parameters is still under development; associated QC guidelines will be addressed in the future.

Figure 2-7. This AXYS GPS water level buoy is ready to be deployed by NOAA/NOS for evaluation in the southern Chesapeake Bay (courtesy of Mark Bushnell, CoastalObsTechServices).

2.3 Applications of WL Data

Real-time water levels are important for a wide variety of applications, including:

- Hydrographic and shoreline mapping surveys
- Safe vessel transit (draft/air gap)
- Safe vessel docking and close-in maneuvering
- Commercial fishing
- Recreational activities
- Storm surge/inundation/evacuation
- Tsunami and meteotsunami detection
- Coastal construction
- Coastal zone management
- Harbor, channel, and inlet maintenance
- Operation of coastal engineering structures
- Input into operational nowcast/forecast system (models) runs
- Validation and verification of numerical ocean models
- Understanding the impacts of long-term sea level variability and inundation on coastal habitats

- Monitoring agreements, memorandums of understanding, and treaties (e.g., the International Great Lakes Datum)

Other applications, such as monthly and annual mean water levels and Federal Emergency Management Agency Flood Insurance Rate Maps, do not require real-time QC but benefit from it through early detection of WL station issues.

2.4 Other Important Considerations

While outside the scope of the real-time tests described in this manual, quality assurance (QA) is critical to data quality. Sensors require attention to proper QA measures both before and after the deployment (appendix A). Operators must follow the manufacturer's recommendations for factory calibration schedules and proper sensor preparation and maintenance.

Also important, but beyond the scope of this document at present, is the determination and reporting of data uncertainty. Knowledge of the accuracy of each observation is required to ensure that data are used appropriately and aids in the computation of error bounds for subsequent products derived by users. All sensors and measurements contain errors that are determined by hardware quality, calibration accuracy, methods of operation, and data processing techniques. Operators should routinely provide a quantitative measure of data uncertainty in the associated metadata. Such calculations can be challenging, so operators should also document the methods used to compute the uncertainty. The limits and thresholds implemented by operators for the data QC tests described here are a key component in establishing the observational error bounds. Operators are strongly encouraged to consider the impact of the QC tests on data uncertainty, as these two efforts greatly enhance the utility of their data.

Sensor redundancy is key to obtaining reliable measurements and ensuring that uncertainties can be assigned to those measurements. Comparing two adjacent instruments can assist in evaluation of data quality, as well as provide two (or more) independent estimates of a parameter of interest. Variation in the estimates of uncertainty provided by those instruments can occur for several reasons, including water mass gradients in the environment.

3.0 Quality Control

The real-time QC of WL observations can be extremely challenging. Events such as storm surge, tsunamis, and strong winds can affect water levels and must be considered when determining acceptable data thresholds. Human involvement is therefore important to ensure that solid scientific principles are applied to data evaluation to ensure that good data are not discarded and bad data are not distributed (e.g., selection of appropriate thresholds and examination of data flagged as questionable).

To conduct real-time QC on WL observations, the first pre-requisite is to understand the science and context within which the measurements are being conducted. For example and as was discussed in section 2.2.4, sensors can be deployed in a number of ways. Each deployment method imposes the need for specific QC methods, with different interpretations of 'real time.' Real-time WL data should have two main attributes: accurate time and accurate elevation relative to a known reference.

This manual focuses specifically on real-time data. For example, for real-time QC, gradual calibration changes or system responses (sensor drift) cannot be detected or corrected. Drift correction for WL measurements during post-processing is difficult even if a valid post-recovery calibration could be obtained. Drift is often caused by bio-fouling, silting/sediment clogging, etc. and affects different systems in different ways (e.g., a sensor's response will be affected by the added mass of bio-fouling). Another example is the ability of some data providers to backfill data gaps. In both of these examples, the observations are not considered to be real time for purposes of QC checks. (However, in some sophisticated 24/7 QC operations, real-time dissemination may be switched from one sensor to another based on real-time QC flags.)

3.1 QC Flags

Data are evaluated using QC tests, and the results of those tests are recorded by inserting flags in the data files. Table 3-1 provides a simple set of flags and associated descriptions. Additional flags may be incorporated to provide more detailed information to assist with troubleshooting. For example, an observation may fail the water level min/max test and be flagged as having failed. If the data failed the water level min/max by exceeding the upper limit, a "failed high" flag may indicate that the values were higher than the expected range. Such detailed flags primarily support maintenance efforts and are presently beyond U.S. IOOS requirements for QC of real-time data. For additional information regarding flags, see the *Manual for the Use of Real-Time Oceanographic Data Quality Control Flags* (U.S. IOOS 2014) posted on the U.S. IOOS QARTOD website. However, all flags must be identified and defined in the metadata.

Further post processing of the data may yield different conclusions from those reached during initial assessments. Flags set in real time should not be changed, ensuring that historical documentation is preserved. Results from post processing should generate another set of flags corresponding to a revised version of the data.

Observations are time ordered, and the most recent observation is n_0, preceded by a value at n_{-1}, and so on moving back in time. The focus of the real-time QC is primarily on observations n_0, n_{-1}, and n_{-2}.

Table 3-1. Flags for real-time data (UNESCO 2013)

Flag	Description
Pass=1	Data have passed critical real-time QC tests and are deemed adequate for use as preliminary data.
Not Evaluated=2	Data have not been QC-tested, or the information on quality is not available.
Suspect or Of High Interest=3	Data are considered to be either suspect or of high interest to data providers and users. They are flagged suspect to draw further attention to them by operators.
Fail=4	Data are considered to have failed one or more critical real-time QC checks. If they are disseminated at all, it should be readily apparent that they are not of acceptable quality.
Missing Data=9	Data are missing; used as a placeholder.

3.2 Test Hierarchy

This section outlines eleven real-time QC tests that are required, recommended, or suggested for WL measurements. Operators should also consider that some of these tests can be carried out within the instrument, where thresholds can be defined in configuration files. Although more tests may imply a more robust QC effort, there are many reasons operators could use to justify not conducting some tests. In those cases, operators need only to document reasons these tests do not apply to their observations. Tests are listed in table 3-2 and are divided into three groups: those that are required, strongly recommended, or suggested. However, for some critical real-time applications with high risk operations, it may be advisable to invoke all groups.

Table 3-2. QC Tests in order of implementation and hierarchy

Group 1 *Required*	Test 1 Test 2 Test 3 Test 4 Test 5	Timing/Gap Test Syntax Test Location Test Gross Range Test Climatology Test
Group 2 *Strongly Recommended*	Test 6 Test 7 Test 8	Spike Test Rate of Change Test Flat Line Test
Group 3 *Suggested*	Test 9 Test 10 Test 11	Multi-Variate Test Attenuated Signal Test Neighbor or Forecast Test

3.3 QC Test Descriptions

A variety of tests can be performed on the sensor measurements to evaluate data quality. Testing the timely arrival and integrity of the data transmission itself is a first step. If the data are corrupted during transmission, further testing may be irrelevant. The checks defined in these eleven tests evaluate data through various comparisons to other data and to the expected conditions in the given environment. The tests listed in this section presume a time-ordered series of observations and denote the most recent observation as previously described.

Some effort will be needed to select the best thresholds, which are determined at the operator level and may require multiple iterations of trial and error before final selections are made. A successful QC effort is highly dependent upon selection of the proper thresholds, which should not be determined arbitrarily but can be based on historical knowledge or statistics derived from recently acquired data. Although this manual provides some guidance for selecting thresholds based on input from various operators, it is assumed that operators have the expertise and motivation to select the proper thresholds to maximize the value of their QC effort. Operators should openly provide thresholds as metadata for user support. Elevation thresholds chosen may be dependent upon the real-time application, (e.g., chart datum or inundation threshold level). This shared information will help U.S. IOOS to document standardized thresholds that will be included in future releases of this manual.

3.3.1 Applications of QC Tests to WL Sensors

These eleven tests require operators to select a variety of thresholds. Examples are provided in the following test tables; however, operators are in the best position to determine the appropriate thresholds for their operations. Some tests rely on multiple data points most recently received to determine the quality of the latest data point. When this series of data points reveals that the entire group fails, the most recent data point is flagged, but the previous flags are not changed. This action supports the view that historical flags are generally not altered. The first example is in Test 8, the Flat Line Test, where this scenario will become clearer. The exception to the rule occurs for Test 6 Spike Check, where the most recent point must be flagged as “2 Not Evaluated” until the next point arrives and the spike check can be performed.

Test 1 - Timing/Gap Test (Required)

Check for arrival of data.

Test determines that the most recent data point has been measured and received within the expected time window (TIM_INC) and has the correct time stamp (TIM_STMP).

Note: For those systems that do not update at regular intervals, a large value for TIM_STMP can be assigned. The gap check is not a solution for all timing errors. Data could be measured or received earlier than expected. This test does not address all clock drift/jump issues.

Flags	Condition	Codable Instructions
Missing Data=9	Data have not arrived as expected.	If NOW – TIM_STMP > TIM_INC, flag = 9
Suspect=3	N/A	N/A
Pass=1	Applies for test pass condition.	N/A

Test Exception: None.

Test specifications to be established locally by the operator.
Example: TIM_INC= 1 hour

Test 2 - Syntax Test (Required)

Check to ensure that the message is structured properly.

Received data message (full message) contains the proper structure without any indicators of flawed transmission such as parity errors. Possible tests are: a) the expected number of characters (NCHAR) for fixed-length messages equals the number of characters received (REC_CHAR), or b) passes a standard parity bit check, cyclic redundancy check, etc. Many such syntax tests exist, and the user should select the best criteria for one or more syntax tests.

Capabilities for dealing with flawed messages vary among operators; some may have the ability to parse messages to extract data within the flawed message sentence before the flaw. A syntax check is performed only at the message level and not within the message content. In cases where a data record requires multiple messages, this check can be performed at the message level but is not used to check message content.

Flags	Condition	Codable Instructions
Fail=4	Data sentence cannot be parsed to provide a valid observation.	If REC_CHAR ≠ NCHAR, flag = 4
Suspect =3	N/A	N/A
Pass=1	Expected data sentence received; absence of parity errors.	N/A

Test Exception: None.

Test specifications to be established locally by the operator.
Example: NCHAR = 128

Test 3 - Location Test (Required)

Check for reasonable geographic location.

Test checks that the reported present physical location (latitude/longitude) is within operator-determined limits. The location test(s) can vary from a simple impossible location to a more complex check for displacement (DISP) exceeding a distance limit RANGEMAX based upon a previous location and platform speed. Operators may also check for erroneous locations based upon other criteria, such as reported positions over land, as appropriate.

Flags	Condition	Codable Instructions
Fail=4	Impossible location.	If LAT > | 90 | or LONG >| 180 |, flag = 4
Suspect=3	Unlikely platform displacement.	If DISP > RANGEMAX, flag = 3
Pass=1	Applies for test pass condition.	N/A

Test Exception: Test does not apply to fixed deployments when no location is transmitted.

Test specifications to be established locally by the operator.
Example: For a GPS buoy WL gauge, the displacement DISP is calculated between sequential position reports, RANGEMAX = 500 m.

Test 4 - Gross Range Test (Required)

Data point exceeds sensor or operator-selected min/max.

All sensors have a limited output range, and this can form the most rudimentary gross range check. No values less than a minimum value or greater than the maximum value the sensor can output (SENSOR_MIN, SENSOR_MAX) are acceptable. Additionally, the operator can select a smaller span (USER_MIN, USER_MAX) based upon local knowledge or a desire to draw attention to extreme values.

NOTE: Operators may choose to flag as suspect values that exceed the calibration span but not the hardware limits (e.g., a value that sensor is not capable of producing).

Flags	Condition	Codable Instructions
Fail=4	Reported value is outside of sensor span.	If WL_n < SENSOR_MIN, or WL_n > SENSOR_MAX, flag = 4
Suspect=3	Reported value is outside of user-selected span.	If WL_n < USER_MIN, or WL_n > USER_MAX, flag = 3
Pass=1	Applies for test pass condition.	

Test Exception: None.

Test specifications to be established locally by the operator.

Examples:
SENSOR_MAX = 10.0 meters (limited by the manufacturer firmware, for example)
SENSOR_MIN = - 0.5 meter
USER_MAX = 5.0 meters
USER_MIN = - 0.5 meter

Test 5 - Climatology Test (Required)

Test that data point falls within seasonal expectations.

This test is a variation on the gross range check, where the gross range Season_MAX and Season_MIN are adjusted monthly, seasonally, or at some other operator-selected time period (TIM_TST). Expertise of the local operator is required to determine reasonable seasonal averages. Longer time series permit more refined identification of appropriate thresholds.

Flags	Condition	Codable Instructions
Fail=4	Because of the potential for extreme water levels without regard to season, no fail flag is identified for this test.	N/A
Suspect=3	Reported value is outside the operator-identified climatology window.	If WL_n < Season_MIN or WL_n > Season_MAX, flag = 3
Pass=1	Applies for test pass condition.	N/A

Test Exception: None.

Test specifications to be established locally by operator: A seasonal matrix of WL_{max} and WL_{min} values at all TIM_TST intervals.

Examples: SPRING_MIN = -2.0 meters, SPRING_MAX = 4.0 meters

Test 6 - Spike Test (Strongly Recommended)

Data point *n*-1 exceeds a selected threshold relative to adjacent data points.

This check is for single-value spikes, specifically the value at point *n*-1. Spikes consisting of more than one data point are difficult to capture, but their onset may be flagged by the rate of change test. The spike test consists of two operator-selected thresholds, THRSHLD_LOW and THRSHLD_HIGH. Adjacent data points (n_{-2} and n_0) are averaged to form a spike reference (SPK_REF). The absolute value of the spike is tested to capture positive and negative spikes. Large spikes are easier to identify as outliers and flag as failures. Smaller spikes may be real and are only flagged suspect. The thresholds may be fixed values or dynamically established (for example, a multiple of the standard deviation over an operator-selected period).

An alternative is a third difference test defined as Diff_n = WL_{n-3} Height - 3* WL_{n-2} + 3* WL_{n-1} - WL_n .

Flags	Condition	Codable Instructions
Fail=4	High spike threshold exceeded.	If | WL_{n-1} - SPK_REF| > THRSHLD_HIGH, flag = 4
Suspect=3	Low spike threshold exceeded.	If | WL_{n-1} - SPK_REF| > THRSHLD_LOW and | WL_{n-1} - SPK_REF| ≤ THRSHLD_HIGH, flag=3
Pass=1	Applies for test pass condition.	N/A

Test Exception: None.

Test specifications to be established locally by the operator.
Examples: THRSHLD_LOW = 0.1 meter, THRSHLD_HIGH = 0.2 meter

Test 7 - Rate of Change Test (Strongly Recommended)

Excessive rise/fall test.

This test inspects the time series for a time rate of change that exceeds a threshold value identified by the operator. WL values can change substantially over short periods in some locations, hindering the value of this test. A balance must be found between a threshold set too low, which triggers too many false alarms, and one set too high, making the test ineffective. Test implementation can be challenging. Upon failure, it is unknown which point is bad. Further, upon failing a data point, it remains to be determined how the next iteration can be handled. The following suggest two ways to select the thresholds:

1) The rate of change between WL_{n-1} and WL_n must be less than three standard deviations (3*SD). The SD of the WL time series is computed over the previous 25-hour period (operator-selected value) to accommodate cyclical diurnal and other tidal fluctuations. The local operator determines both the number of SDs (N_DEV) and the period over which the SDs are calculated (TIM_DEV).
2) The rate of change between WL_{n-1} and WL_n must be less than 0.1 meter +2SD.

Flags	Condition	Codable Instructions
Fail=4	No fail flag is identified for this test.	N/A
Suspect=3	The rate of change exceeds the selected threshold.	If |WL_n – WL_{n-1}|>N_DEV*SD, flag = 3
Pass=1	Applies for test pass condition.	N/A

Test Exception: None.

Test specifications to be established locally by operator.
Examples: N_DEV = 3, TIM_DEV = 25. Some operators use station-specific values, ranging from about 0.02 meter/6-minute sample, to about 0.50 meter/6-minute sample.

Test 8 - Flat Line Test (Strongly Recommended)

Invariant value.

When some sensors and/or data collection platforms fail, the result can be a continuously repeated observation of the same value. This test compares the present observation (*n*) to a number (REP_CNT_FAIL or REP_CNT_SUSPECT) of previous observations. Observation *n* is flagged if it has the same value as previous observations within a tolerance value, EPS, to allow for numerical round-off error. Note that historical flags are not changed.

Flags	**Condition**	**Codable Instructions**
Fail=4	When the five most recent observations are equal, T_n is flagged fail.	For i=1,REP_CNT_FAIL, If WL_n - WL_{n-i}<EPS , flag = 4
Suspect=3	It is possible but unlikely that the present observation and the two previous observations would be equal. When the three most recent observations are equal, T_n is flagged suspect.	For i=1,REP_CNT_SUSPECT, If T_n - T_{n-i}<EPS, flag = 3
Pass=1	Applies for test pass condition.	N/A

Test Exception: Some lakes or estuaries may experience prolonged invariant water level observations.

Test specifications to be established locally by the operator.
Examples: REP_CNT_FAIL = 5, REP_CNT_SUSPECT= 3, EPS = 0.001 meter

Test 9 - Multi-Variate Test (Suggested)

Comparison to other variables.

This is an advanced family of tests, starting with the simpler test described here and anticipating growth towards full co-variance testing in the future. It is doubtful that anyone is conducting tests such as these in real time. As these tests are developed and implemented, they should be documented and standardized in later versions of this manual.

This example pairs rate of change tests as described in Test 7. The WL rate of change test is conducted with a more restrictive threshold (N_WLMV_DEV). If this test fails, a second rate of change test operating on a second variable (wind would be the most probable) is conducted. The absolute value rate of change should be tested, since the relationship between WL and the second variable may be indeterminate. If the rate of change test on the second variable fails to exceed a threshold (e.g., an anomalous step is found in WL and is lacking in wind), then the WL_n value is flagged.

Flags	Condition	Codable Instructions
Fail=4	No fail flag is identified for this test.	N/A
Suspect=3	WL_n fails the rate of change and the second variable (WS wind speed, for example) does not exceed the rate of change.	If $\lvert WL_n – WL_{n-1}\rvert$>N_WLMV_DEV*SD_WL AND $\lvert WS_n – WS_{n-1}\rvert$<N_WS_DEV*SD_WS, flag = 3
Pass=1		N/A

Test Exception: None.

Test specifications to be established locally by the operator.
Examples: N_WLMV_DEV = 2, N_WS_DEV=2, TIM_DEV = 25 hours

NOTE: In a more complex case, more than one secondary rate of change test can be conducted. Wave height or current speed are possible secondary candidates and could be checked for anomalous rate of change values. In this case, a knowledgeable operator may elect to assign a pass flag to a high rate of change observation when any one of the secondary variables also exhibits a high rate of change. Such tests border on modeling, should be carefully considered, and may be beyond the scope of this effort.

The QARTOD WL committee recognized the high value in full co-variance testing but also noted the challenges. Such testing remains a research project not yet ready for operational implementation.

Test 10 - Attenuated Signal Test (Suggested)

A test for inadequate variation of the time series.

A common sensor failure mode can provide a data series that is nearly but not exactly a flat line (e.g., if a well orifice becomes wrapped in debris). This test inspects for an SD value or a range variation (MAX-MIN) value that fails to exceed threshold values (MIN_VAR_WARN, MIN_VAR_FAIL) over a selected time period (TST_TIM).

Flags	Condition	Codable Instructions
Fail=4	Variation fails to meet the minimum threshold MIN_VAR_FAIL.	If During TST_TIM, SD <MIN_VAR_FAIL, or During TST_TIM, MAX-MIN <MIN_VAR_FAIL, flag = 4
Suspect=3	Variation fails to meet the minimum threshold MIN_VAR_WARN.	If During TST_TIM, SD <MIN_VAR_WARN, or During TST_TIM, MAX-MIN <MIN_VAR_WARN, flag = 3
Pass=1	Applies for test pass condition.	N/A

Test Exception: None.

Test specifications to be established locally by the operator.

Examples: TST_TIM = 12 hours
MIN_VAR_WARN=0.5 meter, MIN_VAR_FAIL=0.1 meter

Test 11 – Neighbor or Forecast Test (Suggested)

Comparison to nearby sensors.

This check has the potential to be the most useful test when a nearby second sensor is determined to have a similar response or a water level forecast is available.

Ideally, redundant sensors utilizing different technology would be co-located and alternately serviced at different intervals. This close neighbor would provide the ultimate QC check, but cost may prohibit such a deployment in most cases.

However, there are few instances where a second sensor is sufficiently proximate to provide a useful QC check. WL observations are more readily compared to adjacent sites than many non-conservative observations (such as dissolved oxygen, for example), and this test should not be overlooked where it may have application.

This test is the same as Test 9, *Multi-Variate Check – comparison to other variables* where the second variable is the second sensor. The selected thresholds depend entirely upon the relationship between the two sensors as determined by the local knowledge of the operator.

In the instructions and examples below, data from one site (WL1) are compared to a second site (WL2). The standard deviation for each site (SD1, SD2) is calculated over the period (TIM_DEV) and multiplied as appropriate (N_WL1_DEV for site WL1) to calculate the rate of change threshold. Note that an operator could also choose to use the same threshold for each site, since the sites are presumed to be similar.

A unique and highly valuable version of the neighbor check is the surrogate use of WL forecasts. These 'virtual neighbor' constructs offer a QC check that is also presumed to be similar—again, within operator-selected thresholds.

Flags	Condition	Codable Instructions
Fail=4	No fail flag is identified for this test.	N/A
Suspect=3	$WL1_n$ fails the rate of change and the second sensor $WL2_n$ does not exceed the rate of change.	If $WL1_n – WL1_{n-1}$|>N_WL1_DEV*SD1 AND |$WL2_n – WL2_{n-1}$|<N_WL2_DEV*SD2, flag = 3
Fail=1		N/A

Test Exception: There is no adequate neighbor or forecast.

Test specifications to be established locally by the operator.
Examples: N_WL1_DEV = 2, N_WL2_DEV=2, TIM_DEV = 25 hours

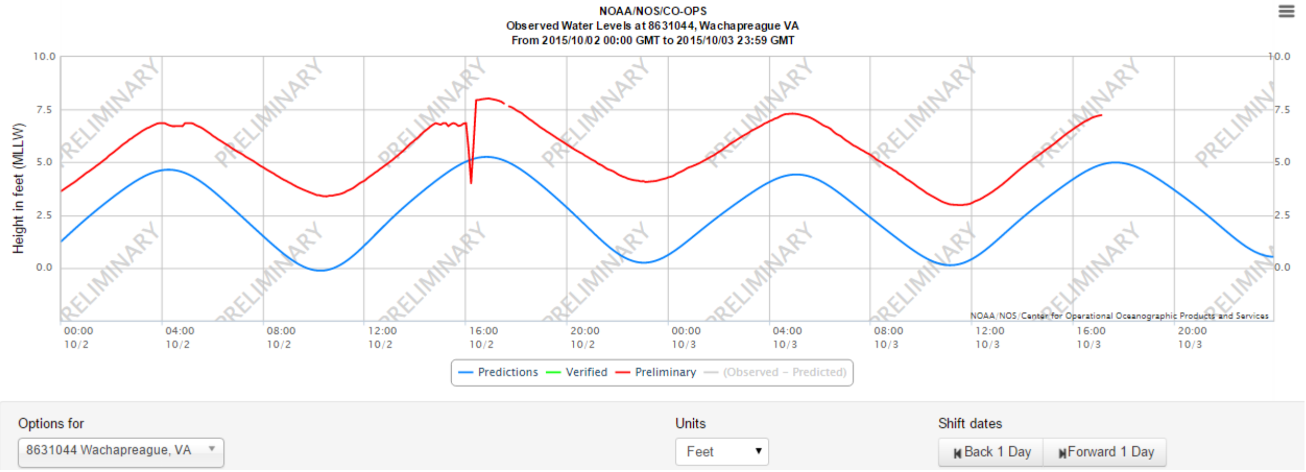
3.3.2 Examples of Test Applications

Figure 3-1 shows several examples of bad data these tests are capable of detecting. The first high tide on 10/02/2015 at about 0400 GMT exceeded the highest water level observation this gauge is capable of observing, and the bad data would be identified by:

Test 4 - Gross Range Test, which uses operator-identified thresholds.
Test 5 – Climatology Test, which uses more restrictive thresholds than the Gross Range Test and would also detect these out-of-range data.
Test 8 – Flat Line Test, where the small, superimposed signal shown on the clipped observations demonstrates the need for a properly operator-identified tolerance value, EPS.
Test 10 - Attenuated Signal Test, if suitable test thresholds for this station are incorporated.
Test 11- Neighbor or Forecast Test, which describes the use of water level forecasts as a 'virtual neighbor' against which these faulty observations would be detected.

The second high tide on 10/02/2015 at about 1600 exhibits the same clipped peak, which would be detected with these five tests. It also shows several further faults where additional tests would identify bad data. They are:

Test 6 – Spike Test would capture the negative-going spike, incurred when switching to the redundent sensor.
Test 7 - Rate of Change Test would detect the large recovering step up from the spike.
Test 1 - Timing/Gap Test, where the small gap shortly after this second high tide (perhaps difficult to see) would be readily flagged as missing from these 6-minute observations.



Options for 8631044 Wachapreague, VA
Units Feet
Shift dates

Figure 3-1. This water level plot from Wachapreague, Va. highlights examples of when real-time data QC tests could identify bad data.

4.0 Summary

The QC tests in this WL manual have been compiled using the guidance provided by all QARTOD workshops (QARTOD 2003-2009). Test suggestions came from both operators and WL data users with extensive experience. The considerations of operators who ensure the quality of real-time data may be different from those whose data are not published in real time, and these and other differences must be balanced according to the specific circumstances of each operator. Although these real-time tests are required, strongly recommended, or suggested, it is the operator who is responsible for deciding which tests are appropriate. Each operator selects thresholds based on the specific program requirements that must be met. The scope of requirements can vary widely, from complex data streams that support myriad QC checks to ensure precise and accurate measurements - to basic data streams that do not need such details. Operators must publish their QC processes via metadata so that data users can readily see and understand the source and quality of those data.

The eleven data QC tests identified in this manual apply to WL observations from a variety of sensor types and platforms that may be used in U.S. IOOS. Since several existing programs such as NWLON and GLOSS have already developed QC tests that are similar to the U.S. IOOS QARTOD tests in this manual, the QARTOD WL committee's objective is for the QC tests of these programs to comply with U.S. IOOS QARTOD requirements and recommendations. The individual tests are described and include codable instructions, output conditions, example thresholds, and exceptions (if any).

Selection of the proper thresholds is critical to a successful QC effort. Thresholds can be based on historical knowledge or statistics derived from more recently acquired data and should not be determined arbitrarily. This manual provides some guidance for selecting thresholds based on input from various operators, but also notes that operators need the subject matter expertise in selecting the proper thresholds to maximize the value of their QC effort.

Future QARTOD manuals will address standard QC test procedures and best practices for all types of common as well as uncommon platforms and sensors for all the U.S. IOOS core variables. Some test procedures may even take place within the sensor package. Significant components of metadata will reside in the sensor and be transmitted either on demand or automatically along with the data stream. Users may also reference metadata through Uniform Resource Locators to simplify the identification of which QC steps have been applied to data. However, QARTOD QC test procedures in this manual address only real-time, in-situ observations made by sensors on fixed platforms or GPS buoys. The tests do not include post processing, which is not conducted real time but may be useful for ecosystem-based management, or delayed mode, which is required for climate studies.

Each QC manual is envisioned as a dynamic document and will be posted on the QARTOD website at www.ioos.noaa.gov/qartod/. This process allows for QC manual updates as technology development occurs for both upgrades of existing sensors and new sensors.

5.0 References

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Supporting Documents Found on the QARTOD Website:

(http://www.ioos.noaa.gov/qartod/water_level/welcome.html)

These documents were particularly useful to the committee and reviewers when developing this manual. They do not contain copyright restrictions and are posted on the U.S. IOOS QARTOD website for easy reference.

Joint IAPSO-IOC Workshop on Sea Level Measurements and Quality Control

Manual on Sea Level Measurement and Interpretation, Vol. II - Emerging Technologies

Developments in Sea Level Data Management and Exchange

Water Level and Wave Height Estimates at NOAA Tide Stations from Acoustic and Microwave Sensors

Supporting Web Links

Tidal Datums Link: http://tidesandcurrents.noaa.gov/datum_options.html

Post-processing Link: http://ilikai.soest.hawaii.edu/uhslc/jasl/slpr2/slman2.html
Sea Level Data Processing on IBM-PC Compatible Computers Version 3.0 (Year 2000 Compliant) Patrick Caldwell Joint Archive for Sea Level of the National Oceanographic Data Center and University of Hawaii Sea Level Center

Stage Measurements at Gaging Stations Link: http://pubs.usgs.gov/tm/tm3-a7/

Introduction to Ocean Tides: https://www.meted.ucar.edu/training_module.php?id=223#.Vul0SbwUWM8 and http://tidesandcurrents.noaa.gov/pub.html#Educational_Materials

National Geodetic Survey Leveling Manual:
http://www.ngs.noaa.gov/PUBS_LIB/Geodeticleveling_nos_3.pdf

National Geodetic Survey Bench Mark Manual: http://www.ngs.noaa.gov/PUBS_LIB/GeodeticBMs.pdf

Appendix A. Quality Assurance

A major pre-requisite for establishing quality control standards for WL measurements is a strong quality assurance program. Remember the mantra that good QC requires good QA, and good QA requires good scientists, engineers, and technicians.

A good QA effort continuously seeks to ensure that end data products are of high value and strives to prove they are free of error. Operators should seek out partnering opportunities to inter-compare systems by co-location of differing sensors, thereby demonstrating high quality by both to the extent that there is agreement and providing a robust measure of observation accuracy by the level of disagreement. Operators should also, if possible, retain an alternate sensor or technology from a second vendor for similar in-house checks.

The lists in the following sections suggest ways to ensure QA by using specific procedures and techniques. Operators should also follow instructions provided by the sensor manufacturer.

A.1 Sensor Calibration Considerations

Observations must be traceable to one or more accepted standards through a calibration performed by the manufacturer and/or the operator. If the calibration is conducted by the manufacturer, the operator must also conduct some form of an acceptable calibration check.

NIST provides a wealth of information on standards and calibrations for many variables, including time, temperature, and pressure. Virtually all manufacturers provide calibrations traceable to NIST standards as part of their standard product services.

An often overlooked calibration or calibration check can be performed by choosing a consensus standard. For example, deriving the same answer (within acceptable levels of data precision or data uncertainty) from four different sensors of four different vendors, preferably utilizing several different technologies, constitutes an acceptable check. Because of the trend towards corporate conglomeration, those wishing to employ a consensus standard should ensure that the different vendors are truly independent.

A.2 Sensor Comparison

An effective QA effort continuously strives to ensure that end data products are of high value and to prove they are free of error. Operators should seek out partnering opportunities to inter-compare systems by co-locating differing sensors. Agreement of multiple systems would provide a robust observation, while disagreement may offer a measure of data uncertainty. If possible, operators should retain an alternate sensor or technology from a second vendor for similar in-house checks. For resource-constrained operators, however, it may not be possible to spend the time and funds needed to procure and maintain two systems. For those who do so and get two different results, the use of alternate sensors or technologies provide several important messages: a) a measure of corporate capabilities; b) a reason to investigate, understand the different results, and take corrective action; and c) increased understanding that when variables are measured with different technologies, different answers can be correct, and they must be understood in order to properly report results. For those who succeed, the additional sensors provide a highly robust demonstration of capability. Such efforts form the basis of a strong QA/QC effort. Further, it provides the operator with an expanded supply source, permitting less reliance upon a single vendor and providing competition that is often required by procurement offices.

A.3 Bio-fouling and Corrosion Prevention Strategies

Bio-fouling is the most frequent cause of sensor failure, so the following strategies may be useful for ameliorating the problem:

- Use anti-fouling paint with the highest copper content available (up to 75%) when possible (not on aluminum).
- Wrap body of sensor with clear packing tape for a small probe or plastic wrap for a large instrument. This keeps the PVC tape from leaving residue on the sensor. Heavy PVC underground cable tape is the best for bad bio-fouling.
- Wrap with copper tape (again, beware of aluminum).
- Coat with zinc oxide (Desitin ointment).
- Remember that growth is sensor, depth, location, and season dependent.
- Plan for routine changing or cleaning of sensor as necessary.
- Check with calibration facility on which anti-foulants will be handled (allowed) by the calibrators.
- Avoid or isolate dissimilar metals.
- Maintain sacrificial anodes and ensure they are properly installed (good electrical contact).
- Maximize use of non-metallic components.
- Use UV-stabilized components that are not subject to sunlight degradation.

A.4 Common QA Considerations

The following lists suggest ways to ensure QA by using specific procedures and techniques:

- Perform pre-deployment calibrations on every sensor.
- Perform post-deployment calibrations on every sensor, plus in-situ comparison before recovery.
- Perform periodic calibration of ready-to-use spares.
- Monitor with redundant sensors whenever possible.
- Take photos of sensor fouling for records.
- Record all actions related to sensors – calibration, cleaning, deployment, etc.
- Monitor battery voltage and watch for unexpected fluctuations.

When evaluating which instrument to use, consider these factors:

- Selection of a reliable and supportive manufacturer and appropriate model
- Operating range (i.e., some instruments won't operate at a certain temperature, depth or pressure range)
- Resolution/precision required
- Sampling frequency – how fast sensor can take measurements
- Reporting frequency – how often the sensor reports the data
- Response time of the sensor – sensor lag – time response
- Instrument check – visual inspection for defects, bio-fouling, etc.
- Power check – master clock, battery, etc. – variability in these among sensors
- Standardize sensor clock to a reference such as GPS timing
- Capability to reveal a problem with data

When evaluating which specifications must be met:

- State the expected accuracy.
- Determine how the sensor compares to the design specifications.
- Determine if the sensor meets those specifications.
- Determine whether result is good enough (fit for purpose: data are adequate for nominal use as preliminary data).

General comments regarding QA procedures:

- A diagram (http://www.ldeo.columbia.edu/~dale/dataflow/), contributed by Dale Chayes (LDEO) provides a visual representation of proper QA procedures.
- Require serial numbers and model ID from the supplier.
- Do not make the checklist so detailed that it will not be used.
- Do not assume the calibration is perfect (could be a calibration problem rather than a sensor problem).
- Keep good records of all related sensor calibrations and checks (e.g., temperature).
- Use NIST-traceable instrumentation when conducting calibrations or calibration checks.
- A sensor that maintains an internal file of past calibration constants is very useful since it can be downloaded instead of transcribed manually introducing human error.

The calibration constants or deviations from a standard should be plotted over time to determine if the sensor has a drift in one direction or another. A sudden change can indicate a problem with the sensor or the last calibration.

A.5 QA Levels for Best Practices

A wide variety of techniques are used by operators to assure that sensors are properly calibrated and operating within specifications. While all operators must conduct some form of validation, there is no need to force operators to adhere to one single method. A balance exists between available resources, level of proficiency of the operator, and target data reproducibility requirements. The various techniques span a range of validation levels and form a natural hierarchy that can be used to establish levels of certification for operators (table A-1). The lists in the following sections suggest ways to ensure QA by using specific procedures and techniques.

Table A-1. Best practices indicator for QA

QA Best Practices Indicator	Description
Good Process	Sensors are swapped and/or serviced at sufficient regular intervals. Sensors' calibration is checked both before and after each deployment.
Better Process	Good process, plus an overlapping operational period during sensor swap-out to demonstrate continuity of observations.
Best Process	Better process, and follow a well-documented protocol or alternative sensors to validate in-situ deployments. Or, the better process employing manufacturer conducted pre- and post-calibrations.

A.6 Additional Sources of QA Information

WL sensor operators also have access to other sources of QA practices and information about a variety of instruments. For example, the Alliance for Coastal Technologies (ACT) serves as an unbiased, third party test bed for evaluating sensors and platforms for use in coastal and ocean environments. ACT conducts instrument performance demonstrations and verifications so that effective existing technologies can be recognized and promising new technologies can become available to support coastal science, resource management, and ocean observing systems (ACT 2012). The NOAA Ocean Systems Test and Evaluation Program (OSTEP) also conducts independent tests and evaluations on emerging technology as well as new sensor models. Both ACT and OSTEP publish findings that can provide information about QA, calibration, and other aspects of sensor functionality. The following list provides links to additional resources on QA practices.

- Manufacturer specifications and supporting Web pages/documents
- QARTOD –http://www.ioos.noaa.gov/qartod/
- ACT - http://www.act-us.info/
- CO-OPS - http://tidesandcurrents.noaa.gov/pub.html under the heading Manuals and Standards
- World Ocean Circulation Experiment http://woce.nodc.noaa.gov/wdiu/
- National Data Buoy Center http://www.ndbc.noaa.gov/

The following samples provide hints for development of deployment checklists taken from QARTOD IV:

Pre-deployment QA Checklist

- ☐ Read the manual.
- ☐ Establish, use, and submit (with a reference and version #) a documented sensor preparation procedure (protocol). Should include cleaning sensor according to the manufacturer's procedures.
- ☐ Calibrate sensor against an accepted standard and document (with a reference and version #).
- ☐ Compare the sensor with an identical, calibrated sensor measuring the same thing in the same area (in a calibration lab).
- ☐ View calibration specifications with a critical eye (don't presume the calibration is infallible). Execute detailed review of calibrated data.
- ☐ Check the sensor history for past calibrations, including a plot over time of deviations from the standard for <u>each</u> (this will help identify trends such a progressively poorer performance). Control chart calibrations.
- ☐ Check the sensor history for past repairs, maintenance, and calibration.
- ☐ Consider storing and shipping information before deploying.
    - o Heat, cold, vibration, etc.
- ☐ Provide detailed documentation.
- ☐ Record operator/user experiences with this sensor after reading the manual.
- ☐ Search the literature for information on your particular sensor(s) to see what experiences other researchers may have had with the sensor(s).
- ☐ Establish and use a formal pre-deployment checklist.
- ☐ Ensure that technicians are well-trained. Use a visual tracking system for training to identify those technicians who are highly trained and then pair them with inexperienced technicians. Have data quality review chain.

Deployment Checklist

- ☐ Scrape bio-fouling off platform.
- ☐ Verify sensor serial numbers.
- ☐ Deploy and co-locate multiple sensors (attention to interference if too close).
- ☐ Perform visual inspection; take photos if possible (verify position of sensors, connectors, fouling, and cable problems).
- ☐ Verify instrument function at deployment site prior to site departure. Allot sufficient time for temperature equilibration.
- ☐ Monitor sensors for issues (freezing, fouling).
- ☐ Automate processing so you can monitor the initial deployment and confirm the sensor is working while still on-site.
- ☐ Specify date/time for all recorded events. Use GMT or UTC.
- ☐ Check software to ensure that the sensor configuration and calibration coefficients are correct. Also check sampling rates and other timed events, like wiping and time averaging.
- ☐ Visually inspect data stream to ensure reasonable values.
- ☐ Compare up and down casts and/or dual sensors (if available).
- ☐ Note weather conditions and members of field crew.

Post-deployment Checklist

- ☐ Take pictures of recovered sensor as is for metadata.
- ☐ Check to make sure all clocks agree or, if they do not agree, record all times and compare with NIST.
- ☐ Post-calibrate sensor and document before and after cleaning readings.
- ☐ Perform in-situ side by side check using another sensor.
- ☐ Provide a mechanism for feedback on possible data problems and/or sensor diagnostics.
- ☐ Clean and store the sensor properly or redeploy.
- ☐ Visually inspect physical state of instrument.
- ☐ Verify sensor performance by:
    - Checking nearby stations;
    - Making historical data comparisons (e.g., long-term time-series plots, which are particularly useful for identifying long-term bio-fouling or calibration drift).

Appendix B. QARTOD Water Level Manual Team

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