https://doi.org/10.7289/V5PC30M9

IOOS
Integrated Ocean
Observing System

QARTOD
Quality Assurance/Quality Control of Real-Time Oceanographic Data

Manual for Real-Time Quality Control of Passive Acoustics Data

A Guide to Quality Control and Quality Assurance for Passive Acoustics Observations

Version 1.0
June 2017

Document Validation

IOOS
Integrated Ocean
Observing System

U.S. IOOS Program Office Validation

June 30, 2017

Carl C. Gouldman, U.S. IOOS Program Director Date

QARTOD Project Manager Validation

June 30, 2017

Kathleen Bailey, U.S. IOOS Project Manager Date

QARTOD Board of Advisors Validation

Julianna O. Thomas

June 30, 2017

Julianna O. Thomas, Southern California Coastal Ocean Observing System Date

Table of Contents

List of Figures

List of Tables

Revision History

Date	Revision Description	Notes
June 2017	Original Document Published	

Endorsement Disclaimer

Mention of a commercial company or product does not constitute an endorsement by NOAA. Use of information from this publication for publicity or advertising purposes concerning proprietary products or the tests of such products is not authorized.

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 qartod.board@noaa.gov **or posting a notice at** http://www.linkedin.com/groups?gid=2521409.

Acknowledgements

We thank the staff and scientists at Ocean Networks Canada (ONC), specifically Maia Hoeberechts and Marlene Jeffries, for their invitation to attend a two-day workshop focused on the quality assurance and quality control of their cabled observatory and data products, where the idea for this QARTOD QC manual was initiated. We also thank Tom Dakin (ONC) for his reviews and input to the manual.

We greatly appreciate the comments and suggestions provided by Kaus Raghukumar (Integral Consulting), and Christoph Waldmann (MARUM), and the thought-provoking questions and points offered by Amy Scholik (NOAA/National Marine Fisheries Service).

Acronyms and Abbreviations

ACT	Alliance for Coastal Technologies
ADCP	Acoustic Doppler Current Profiler
AOOS	Alaska Ocean Observing System
CariCOOS	Caribbean Coastal Ocean Observing System
CeNCOOS	Central and Northern California Ocean Observing System
CTD	Conductivity/Temperature/Depth
DMAC	Data Management and Communications
DSP	Digital Signal Processing
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GLOS	Great Lakes Observing System
GMT	Greenwich Mean Time
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
ONC	Ocean Networks Canada
PA	Passive Acoustics
PacIOOS	Pacific Islands Ocean Observing System
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
SEL	Sound Exposure Level
SPL	Sound Pressure Level
UNESCO	United Nations Organization for Education, Science, and Culture
UTC	Coordinated Universal Time
WHOI	Woods Hole Oceanographic Institution

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.
Message	A message is a standalone data transmission. A data record can be composed of multiple messages.
Interoperable	Interoperable means the ability of two or more systems to exchange and mutually use data, metadata, information, or system parameters using established protocols or standards.
Operational	Operational means routine, guaranteed, and sustained provision of data streams and data products of known quality, in perpetuity or until no longer needed, at rates and in forms specified by user groups regardless of the intended use (operational support or research and development).
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).
Sensor	A sensor is a device that detects or measures a physical property and provides the result without delay. A sensor is an element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured. (JCGM 2012)
Threshold	Thresholds are limits that are defined by the operator.
Variable	A variable is 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) Project. Specific variables are addressed as funding permits and when sufficient interest is deemed to exist within the specific community. This passive acoustics (PA) manual is the eleventh in a series of guidance documents that address QC of real-time data of each core variable.

Please refer to https://ioos.noaa.gov/project/qartod/ for the following documents.

1) U.S. Integrated Ocean Observing System, 2015. U.S IOOS QARTOD Project Plan - Accomplishments for 2012–2016 and Update for 2017–2021. 47 pp.

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, 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.

7) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Wind Data Version 1.1: A Guide to Quality Control and Quality Assurance of Coastal and Oceanic Wind Observations. 47 pp.

8) 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.
9) 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.
10) U.S. Integrated Ocean Observing System, 2016. Manual for Real-Time Quality Control of High Frequency Radar Surface Currents Data: A Guide to Quality Control and Quality Assurance of High Frequency Radar Surface Currents Data Observations. 58 pp.
11) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Phytoplankton Data: A Guide to Quality Control and Quality Assurance of Phytoplankton Data Observations. 67 pp.

Please reference this document as:

U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Passive Acoustics Data: A Guide to Quality Control and Quality Assurance of Passive Acoustics Observations. 45 pp.
https://doi.org/10.7289/V5PC30M9

This manual is a living document that reflects the state-of-the-art QC testing procedures for passive acoustics 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, and Technologies

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

2.1. Purpose and Scope

The purpose of this manual is to provide guidance to the U.S. IOOS and the passive acoustics community at large for the real-time QC of PA 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.

PA observations covered by these test procedures are collected in oceans and lakes in real time. These tests are based on guidance from QARTOD workshops (QARTOD 2003-2009) and draw from existing expertise in programs such as the Ocean Networks Canada (ONC) cabled observatory, programs conducted by the National Oceanic and Atmospheric Administration (NOAA)[1] and the Woods Hole Oceanographic Institution (WHOI)[2], and Germany's Federal Maritime and Hydrographic Agency[3], which limits sound exposure level (SEL) when driving monopiles for offshore wind farm construction.

This manual differs from existing QC procedures for the observation of PA 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 PA observations. These tests apply only to the in-situ, real-time measurement of PA as observed by sensors deployed on fixed or mobile platforms.

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
• Streaming hydrophones • Acoustic collection/compression systems • Acoustic threshold detection systems • Acoustic signal identification systems	• Acoustic vector sensors • Geophones

These test procedures are written as a high-level narrative from which computer code can be developed 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 PA 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

---

[1] https://www.pifsc.noaa.gov/cetacean/passive_acoustic_monitoring.php

[2] http://www.whoi.edu/page.do?pid=79177 and http://www.whoi.edu/fileserver.do?id=163064&pt=2&p=9906

[3] http://www.bsh.de/en/Products/Books/Standard/Prediction_of_Underwater.pdf

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 ensuring that the PA sensor shows sufficient accuracy, precision, and reliability regarding the sensor specifications. Other QA practices include: sensor calibration; visual sensor checks for mechanical damage, calibration checks and/or in-situ verification, including post-deployment; 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 QC process. Post-deployment calibration (instrument verification after recovery) issues are not part of the scope of this manual. QC and QA are interrelated and both are important to the process; therefore, 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), uncertainty reporting (for classification and localization results), neighbor checks, climatology checks, model comparisons, signal/noise ratios, the mark-up of the data, 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 specific manufacturer's model, so the establishment of a methodology that is applicable to every sensor is challenging.

2.2. Constraints

2.2.1. Hardware, Firmware, and Software Limitations

Almost all hydrophones used to monitor acoustic signals are composed of ceramic transducers that make use of the piezoelectric effect. They are specifically constructed to accommodate targeted frequency response characteristics and are available in a wide variety of frequency ranges and bandwidths. Preamplifiers are typically employed, especially when the hydrophone is not closely cabled to receiver circuitry. Typical failure modes include water absorption, cracked or aged ceramics, preamplifier failure, and loss of signal or power due to cable/connector issues. These can result in changes to frequency response characteristics, signal attenuation, decreased signal-to-noise ratios, and complete loss of signal.

When acoustic systems are not directly cabled, they are subject to challenges related to power and data communications. Batteries, battery charging systems, acoustic modems, satellite or surface radio frequency data communications, all bring complexity and perhaps less reliability.

In addition to system component failures, local noise sources can also reduce signal-to-noise ratios and degrade or mask signals of interest. Examples include undesired environmental noise, CTD pump noise, nearby acoustic Doppler current profiler (ADCP) operations, flow noise, electronics shot noise, and strumming of the mooring or vortex shedding. Furthermore, structure-borne noise must be isolated from the PA system by selecting an insulating mounting.

2.2.2. Data Processing Methodology

The type of system used to process and transmit the PA measurements determines 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 SEL-threshold exceedance. If ample transmission capability is available, the entire original acoustic stream may be transmitted ashore and 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 PA measurement systems produce accurate data, rigorous calibrations and calibration checks must be performed in addition to QC tests. 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 carried out by the manufacturer or the operators must be traceable to accepted standards. The National Institute of Standards and Technology[4] (NIST), 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. Therefore, operators need to select a standard calibration protocol, e.g., the reciprocity method, and provide documentation of the calibration results. Robinson et al. (2014) and Ainslie (2011) provide excellent information about calibration standards. Additional information can be found in the Supporting Web Links section on page 24 of this manual.

2.2.4. Sensor Deployment Considerations and Hardware Limitations

PA measurement systems can be deployed in several ways, on fixed or mobile platforms. While outside the scope of the real-time tests described in this manual, QA is critical to data quality. Systems 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 applications of PA data and the sensor technologies that are most often used, with a brief note about their attributes and shortcomings.

2.3. Applications of PA Data

Real-time PA data are important for a wide variety of applications, including:

- Marine mammal, fish, invertebrate abundance, tracking, and strike avoidance
- Anthropogenic sound (pile-driving for wind farms and other construction, shipping, use of sonar, geophysical exploration and its effects on marine life, underwater communications, sovereignty)
- Observation of weather at sea (e.g., Wind Observation Through Ambient Noise [WOTAN] and rain)
- Acoustic propagation
- Ambient noise measurements in support of baseline noise characterization

---

[4] http://www.nist.gov/index.html

Some applications may not require real-time QC but benefit from it through early detection of PA system issues.

2.4. Passive Acoustics Technologies

Real-time passive acoustics systems can be directly cabled ashore, placed on a mooring with telemetry supported through a surface buoy, or installed on mobile platforms such as autonomous surface or subsurface vessels.

Figure 2-1 shows a bottom-mounted instrument platform that forms a component of a cabled observatory operated by ONC. Such configurations offer the benefit of abundant power and data bandwidth, are generally very reliable, but have extraordinary initial costs. Maintenance costs can be unpredictable and high. They offer stability and decoupling from the surface, but accessibility is more challenging than other deployment methods, and other sensors such as CTD pumps and ADCPs can create noise. Single hydrophone tripods as shown in fig. 2-2, or hydrophone arrays as shown in fig. 2-3 can be connected some distance from the instrument platform for noise reduction.

Passive acoustics systems can be deployed on moored buoys (fig. 2-3). Hydrophones can be deployed at various depths along the mooring, with the surface buoy providing power and data communications. While somewhat more accessible than a bottom-mounted platform, they are subject to the harsh ocean interface, as well as considerably greater background noise levels than bottom-mounted cabled systems.

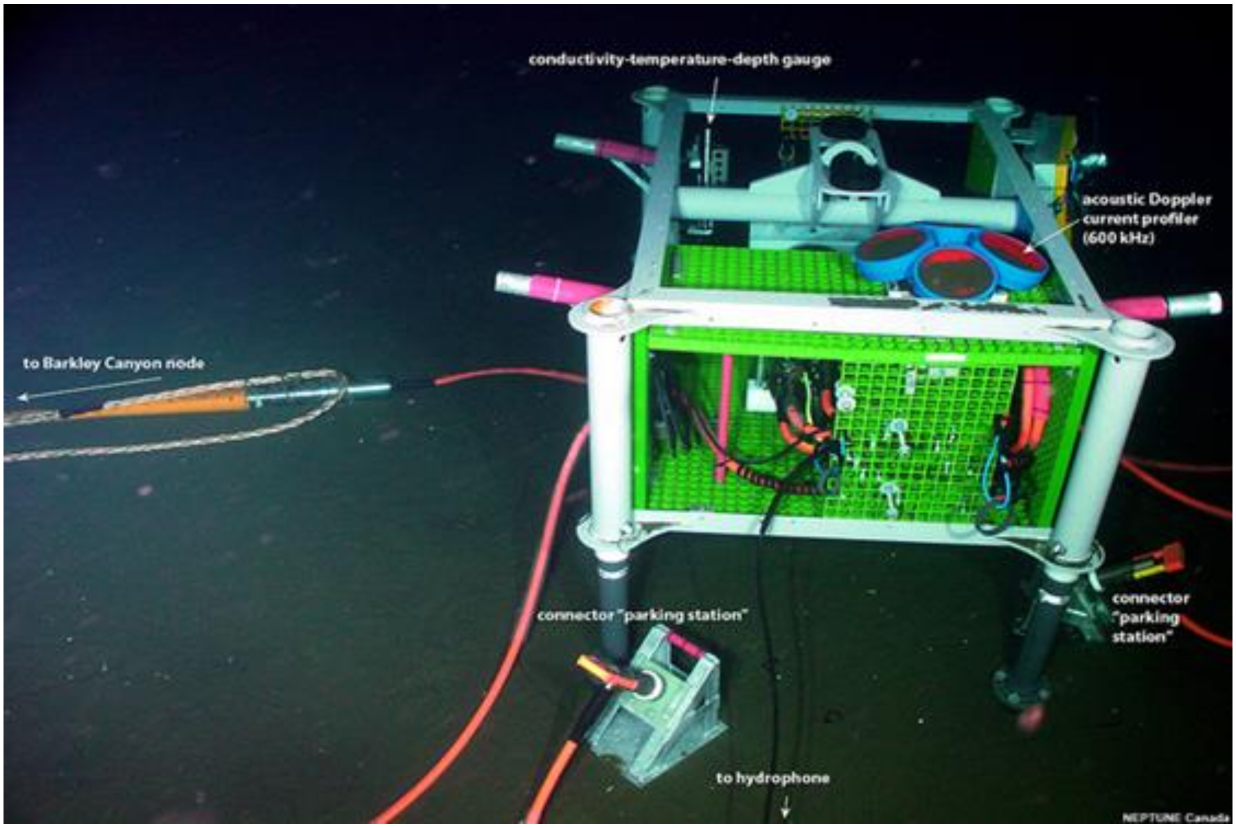

Figure 2-1. This bottom-mounted component of an ONC cabled observatory can support passive acoustics observations. (Photo courtesy of Tom Dakin/ONC)

Figure 2-2. Single hydrophone tripod (L) and tetrahedral hydrophone array (R). (Photo courtesy of Tom Dakin/ONC)

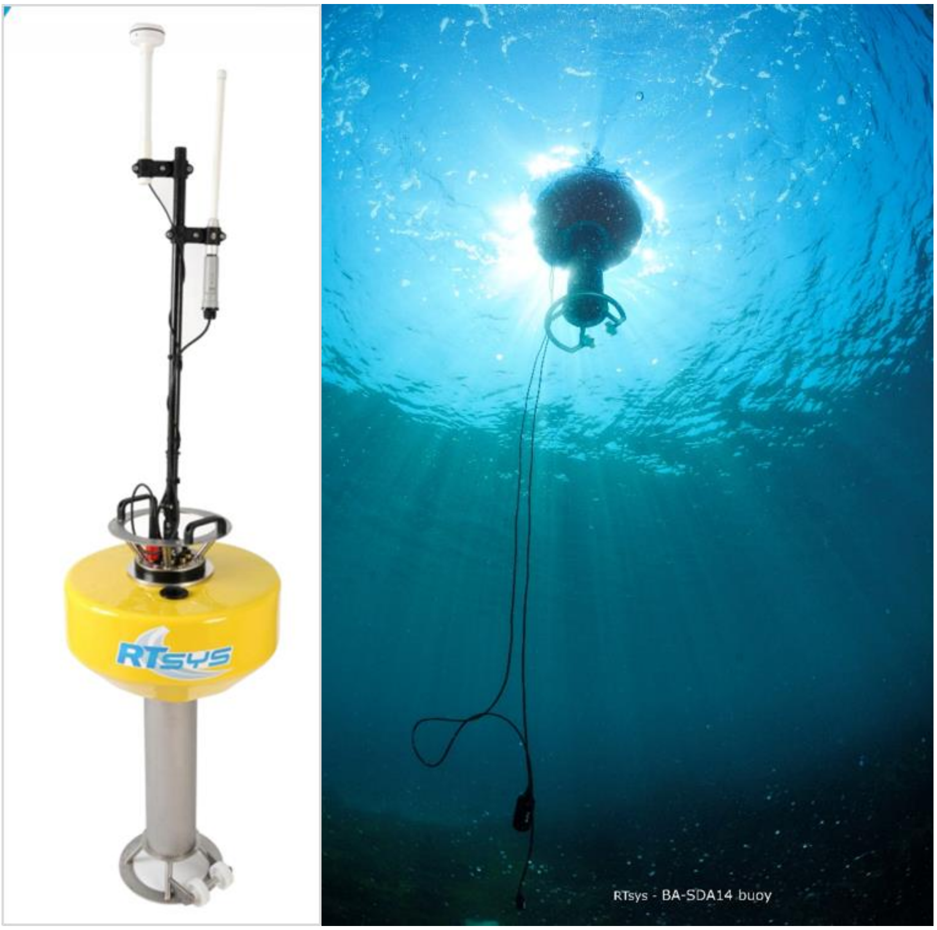

Figure 2-3. This RTSYS buoy has a passive acoustics recorder with multiple hydrophone inputs, onboard digital signal processing with built-in threshold detection, and real-time Wi-Fi data telemetry. It can be configured to monitor and trigger alarms. (Photo courtesy of Steven Pasco, RTSYS)

Passive acoustics recorders can also be deployed on mobile platforms such as gliders, profiling floats, or autonomous surface vehicles. Indeed, the Liquid Robotics Wave Glider® was funded and developed to host passive acoustics systems for whale detection. Improvements to power and data telemetry bandwidth limitations are continually emerging for such deployments.

Figure 2-4. Liquid Robotics wave gliders were originally developed for passive acoustic monitoring of marine mammals. (Photo courtesy of Christoph Waldmann/MARUM)

2.5. Other Important Considerations

Important, but beyond the scope of this document at present, is the determination and reporting of data uncertainty. Knowledge of the accuracy of the observations 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 variable of interest. Variation in the estimates of uncertainty provided by those instruments can occur for several reasons, including real spatial variability and instrumentation differences.

3.0 Quality Control

The real-time QC of PA observations can be extremely challenging. Desired signals and interfering noise levels can span several orders of magnitude. 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 PA observations, the first pre-requisite is to understand the science and context within which the measurements are being conducted. For example, and as discussed in section 2.2.4, sensors can be deployed in several ways. Each deployment method imposes the need for specific QC methods.

This manual focuses specifically on real-time data. For real-time QC, gradual calibration changes or system responses (hydrophone sensitivity drift) are detected only by very sophisticated and expensive systems with co-located projectors, such as the Strait of Georgia Underwater Listening Station. For most systems, drift correction for PA measurements during post-processing is difficult even if a valid post-recovery calibration could be obtained. Drift is often caused by water absorption, biofouling, silting/sediment clogging, etc.; it affects different systems in different ways (e.g., a sensor's response will be affected by the added mass of biofouling) and cannot be addressed in real time. Another example of an issue that is not considered to be real time is the ability of some data providers to backfill data gaps. In both cases, 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.)

Passive acoustics observations can be produced in real time in several ways:

- Continuously streamed acoustic signals, perhaps spectrally banded
- Discrete, discontinuous samples, or duty-cycle based recordings, e.g., 30-second recordings every 4 minutes
- Digital signal processing (DSP) output results such as SEL (sound exposure level) or SPL (sound pressure level)
- DSP output such as species-specific signal detection (Baumgartner and Mussoline 2011)

Each of these observation types may require a different series of QC tests. As tests are implemented, examples will be added when this living manual is updated.

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 U.S. IOOS (2017) 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 PA 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	Timing/Gap Test
	Test 2	Syntax Test
	Test 3	Location Test
	Test 4	Gross Range Test
	Test 5	Climatology Test
Group 2 *Strongly Recommended*	Test 6	Flat Line Test
Group 3 *Suggested*	Test 7	Spike Test
	Test 8	Rate of Change Test
	Test 9	Multi-Variate Test
	Test 10	Attenuated Signal Test
	Test 11	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. 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 PA Systems

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 6, the Flat Line Test, where this scenario will become clearer. The exception to the rule occurs for Test 7 Spike Test, where the most recent point must be flagged as "2 Not Evaluated" until the next point arrives and the spike check can be performed. In the tests below, PAo is used generically to denote a PA observation or measurement such as SEL.

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 = 30 minutes

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. Bottom-mounted cabled installations may use tilt and compass heading changes to detect platform motion in real time.

Test specifications to be established locally by the operator.

Example: For a mobile PA system, 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. To avoid spectral distortion, a hydrophone saturation limit may be used to establish the gross range limit. 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 (i.e., a value that sensor is not capable of producing).

Flags	Condition	Codable Instructions
Fail=4	Reported value is outside of sensor span.	If PAo_n < SENSOR_MIN, or PAo_n > SENSOR_MAX, flag = 4
Suspect=3	Reported value is outside of user-selected span.	If PAo_n < USER_MIN, or PAo_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 = (limited by the manufacturer firmware, for example)
SENSOR_MIN =
USER_MAX =
USER_MIN =

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 ranges (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 PAo_n < Season_MIN or PAo_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 PAo_{max} and PAo_{min} values at all TIM_TST intervals**.**

Examples: SPRING_MIN = SPRING_MAX =

Test 6 - 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, PAo_n is flagged fail.	For i=1,REP_CNT_FAIL, If PAo_n - PAo_{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, PAo_n is flagged suspect.	For i=1,REP_CNT_SUSPECT, If PAo_n - PAo_{n-i} <EPS, flag = 3
Pass=1	Applies for test pass condition.	N/A

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

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

Test 7 - Spike Test (Suggested)

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 (e.g., a multiple of the standard deviation over an operator-selected period).

An alternative is a third difference test defined as $Diff_n = PAo_{n-3} - 3* PAo_{n-2} + 3* PAo_{n-1} - PAo_n$.

Flags	Condition	Codable Instructions
Fail=4	High spike threshold exceeded.	If $\mid PAo_{n-1}$ - SPK_REF$\mid$ > THRSHLD_HIGH, flag = 4
Suspect=3	Low spike threshold exceeded.	If $\mid PAo_{n-1}$ - SPK_REF$\mid$ > THRSHLD_LOW and $\mid PAo_{n-1}$ - SPK_REF$\mid \leq$ 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 = , THRSHLD_HIGH =

Test 8 - Rate of Change Test (Suggested)

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. PAo 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 PAo_{n-1} and PAo_n must be less than three standard deviations (3*SD). The standard deviation of the PAo time series is computed over an operator-selected period to accommodate any fluctuations. The local operator determines both the number of allowed standard deviations (N_DEV, equal to three in this example) and the period over which the standard deviation is calculated (TIM_DEV).
2) The rate of change between PAo_{n-1} and PAo_n must be less than an operator selected fixed value +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 $\|PAo_n – PAo_{n-1}\|$>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: None.

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 toward 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 8. The PAo rate of change test is conducted with a more restrictive threshold (N_PAoMV_DEV). If this test fails, a second rate of change test operating on a second variable (for example, wind as a surrogate for background noise level) is conducted. The absolute value rate of change should be tested, since the relationship between PA 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 PAo and is lacking in wind), then the PAo_n value is flagged.

Flags	Condition	Codable Instructions
Fail=4	No fail flag is identified for this test.	N/A
Suspect=3	PAo_n fails the rate of change and the second variable (WS wind speed, for example) does not exceed the rate of change.	If $\lvert \text{PAo}_n - \text{PAo}_{n-1} \rvert > \text{N\_PAoMV\_DEV*SD\_PAo}$ AND $\lvert \text{WS}_n - \text{WS}_{n-1} \rvert < \text{N\_WS\_DEV*SD\_WS}$, flag = 3
Pass=1	N/A	N/A

Test Exception: None.

Test specifications to be established locally by the operator.
Examples: N_PAoMV_DEV = 2, N_WS_DEV=2, TIM_DEV = 3 hours

NOTE: In a more complex case, more than one secondary rate of change test can be conducted. 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 PA 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 hydrophone becomes wrapped in debris). This test inspects for a standard deviation 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 = 4 hours MIN_VAR_WARN= , MIN_VAR_FAIL=		

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 PA system is determined to have a similar response.

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. PA 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 (PAo1) are compared to a second site (PAo2). The standard deviation for each site (SD1, SD2) is calculated over the period (TIM_DEV) and multiplied as appropriate (N_PAo1_DEV for site PAo1) 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.

Flags	Condition	Codable Instructions
Fail=4	No fail flag is identified for this test.	N/A
Suspect=3	$PAo1_n$ fails the rate of change and the second sensor $PAo2_n$ does not exceed the rate of change.	If $PAo1_n – PAo1_{n-1}$|>N_PAo1_DEV*SD1 AND |$PAo2_n – PAo2_{n-1}$|<N_PAo2_DEV*SD2, flag = 3
Fail=1	N/A	N/A

Test Exception: There is no adequate neighbor.

Test specifications to be established locally by the operator.
Examples: N_PAo1_DEV = 2, N_PAo2_DEV=2, TIM_DEV = 4 hours

3.3.2. Examples of Test Applications

Although no subject-matter experts provided examples of test applications for the initial version of this manual, examples may be inserted when the manual is updated.

4.0 Summary

The QC tests in this passive acoustics manual have been compiled using the guidance provided by all QARTOD workshops (QARTOD 2003-2009). Test suggestions came from both operators and PA 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 with the specific circumstances of each operator. Although these real-time tests are required, strongly recommended, or suggested, the operator 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 PA observations from a variety of sensor types and platforms that may be used in U.S. IOOS. Since existing programs (such as the WHOI Robots4Whales) may have already developed QC tests that are similar to the tests in this manual, the objective is for the QC tests of these programs to guide and comply with these 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 https://ioos.noaa.gov/project/qartod/. This process allows for QC manual updates as technology development occurs for both upgrades of existing sensors and new sensors.

5.0 References

Ainslie, 2011. Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units. TNO-DV 2011 C235. The Netherlands.

Baumgartner, M. F. and Sarah E. Mussoline, 2011. A generalized baleen whale call detection and classification *System*, J. Acoust. Soc. Am. 129(5):2889-2902

Bushnell, M., Presentation at QARTOD III: November 2005. Scripps Institution of Oceanography, La Jolla, California.

Joint Committee for Guides in Metrology (JCGM), 2012. International Vocabulary of Metrology: Basic and General Concepts and Associated Terms. 3rd Edition.

Paris. Intergovernmental Oceanographic Commission of UNESCO. 2013. *Ocean Data Standards, Vol.3: Recommendation for a Quality Flag Scheme for the Exchange of Oceanographic and Marine Meteorological Data*. (IOC Manuals and Guides, 54, Vol. 3.) 12 pp. (English) (IOC/2013/MG/54-3) http://www.nodc.noaa.gov/oceanacidification/support/MG54_3.pdf

QARTOD I-V Reports 2003-2009: https://ioos.noaa.gov/ioos-in-action/qartod-meetings/

Robinson, Stephen, P. Lepper, and R. Hazelwood, 2014. Good Practice Guide for Underwater Noise Measurement. National Measurement Office, Marine Scotland, the Crown Estate. NPL Good Practice Guide No. 133, ISSN: 1368-6550.

U.S. IOOS Office, November 2010. A Blueprint for Full Capability, Version 1.0, 254 pp. https://www.ioos.noaa.gov/wp-content/uploads/2015/09/us_ioos_blueprint_ver1.pdf

U.S. Integrated Ocean Observing System, 2017. Manual for the Use of Real-Time Oceanographic Data Quality Control Flags Version 1.1. 43 pp. https://ioos.noaa.gov/wp-content/uploads/2017/06/QARTOD-Data-Flags-Manual_Final_version1.1.pdf

Additional References to Related Documents:

National Oceanographic Partnership Program (NOPP) January 2006. The First U.S. Integrated Ocean Observing System (IOOS) Development Plan – A report of the national Ocean Research Leadership Council and the Interagency Committee on Ocean Science and Resource Management Integration. The National Office for Integrated and Sustained Ocean Observations. Ocean US Publication No. 9.

Ocean.US, 2006. National Office for Integrated and Sustained Ocean Observations. The First U.S. Integrated Ocean Observing System (IOOS) Development Plan, Publication 9, January 2006.

U.S. IOOS QARTOD Project Plan, February 18, 2012. Revised 2016. https://ioos.noaa.gov/wp-content/uploads/2017/02/QARTOD-ProjectPlanUpdate_v2.0_2017_Final.pdf

Dudzinki, K.M., S. Brown, N. Erikson, M. Lammers, K. Lucke, D. Mann, …C. Wall. 2011. Trouble-shooting deployment and recovery options for various stationary passive acoustic monitoring devices in both shallow- and deep-water applications. J.Acoust.Soc.Am.129(1).

Simon, L. 2016. Underwater Noise-Monitoring Buoy: Real-Time Monitoring for Wind Farm Construction. Sea Technology Magazine, March 2016, pp 25-27.

Charif, Russell; Clapham, Phillip; and Clark, Christopher, "Acoustic Detections of Singing Humpback Whales in Deep Waters Off The British Isles" (2001). Publications, Agencies and Staff of the U.S. Department of Commerce. Paper 163. http://digitalcommons.unl.edu/usdeptcommercepub/163

Norris, T.F., J.O. Oswald, T.M. Yack, and E.L. Ferguson. 2012. An Analysis of Marine Acoustic Recording Unit (MARU) Data Collected off Jacksonville, Florida in Fall 2009 and Winter 2009-2010. Final Report. Submitted to Naval Facilities Engineering Command (NAVFAC) Atlantic, Norfolk, Virginia, under Contract No. N62470-10-D-3011, Task Order 021, issued to HDR Inc., Norfolk, Virginia. Prepared by Bio-Waves Inc., Encinitas, California. 21 November 2012. Revised January 2014.

Christopher W. Clark, Peter J. Dugan, Dimitri W. Ponirakis, Marian Popescu, Mohammad Pourhomayoun, Yu Shiu, John Zelweg. 2013. Bioacoustics Research Program, Cornell Lab of Ornithology, Cornell University, Ithaca, New York 148504, USA. https://www.mathworks.com/videos/listening-to-the-worlds-oceans-searching-for-marine-mammals-by-detecting-and-classifying-terabytes-of-bioacoustic-data-in-clouds-of-noise-90425.html and http://www.birds.cornell.edu/brp/

Charif, Russell, and Christopher Clark, Acoustic monitoring of large whales in deep waters north and west of the British Isles: 1996 – 2005, 2009. Bioacoustics Research Program Cornell Laboratory of Ornithology Cornell University 159 Sapsucker Woods Rd. Ithaca, NY 14850 USA.

Aaron N. Rice, K. J. Palmer, Jamey T. Tielens, Charles A. Muirhead, and Christopher W. Clark. Potential Bryde's whale (Balaenoptera edeni) calls recorded in the northern Gulf of Mexico. *J. Acoust. Soc. Am.* 135, 3066 (2014); http://dx.doi.org/10.1121/1.4870057.

Brandon L. Southall, Peter L. Tyack, David Moretti, Christopher Clark5, Diane Claridge6, and Ian Boyd, 2009. Behavioral responses of beaked whales and other cetaceans to controlled exposures of simulated sonar and other sounds. 18th Biennial Conference on the Biology of Marine Mammals, Quebec City, Quebec, Canada. 12-16 October 2009.

Dakin, Tom, 2016. Ocean Networks Canada Hydrophones. QARTOD Workshop, University of Victoria.

Supporting Documents Found on the QARTOD Website:

https://ioos.noaa.gov/ioos-in-action/passive-acoustics/

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.

An Analysis of Marine Acoustic Recording Unit (MARU) Data Collected off Jacksonville, Florida in Fall 2009 and Winter 2009-2010

Listening to the World's Oceans: Searching for Marine Mammals by Detecting and Classifying Terabytes of Bioacoustic Data in Clouds of Noise

Supporting Web Links

IEC 60565:2006, Underwater acoustics - Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz
http://www.oceanicengineering.org/page.cfm/page/360/Standards-for-Underwater-Noise-Measurement

ANSI/ASA S1.20-2012, Procedures for calibration of underwater electroacoustic transducers, 53 pp, 2012
http://acousticalsociety.org/standards

Acoustics Metadata
http://tethys.sdsu.edu/
http://www.rtsys.eu/en/

Robots4Whales – Autonomous Real-time Marine Mammal Detections
http://dcs.whoi.edu

Appendix A. Quality Assurance

A major pre-requisite for establishing quality control standards for passive acoustics 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. Generally, QA practices relate to observing systems' sensors (the hardware) and include things like appropriate sensor selection, calibration, sensor handling and service, and evaluation of sensor performance. 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 manufacturers, preferably utilizing several different technologies, constitutes an acceptable check. Because of the trend toward corporate conglomeration, those wishing to employ a consensus standard should ensure that the different manufacturers 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 manufacturer 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 so that results can be properly reported. 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, these efforts provide the operator with an expanded supply source, permitting less reliance upon a single manufacturer and allowing competition that is often required by procurement offices.

A.3 Biofouling and Corrosion Prevention Strategies

Biofouling is the most frequent cause of sensor failure, so the following strategies may be useful for ameliorating the problem.

For non-acoustic parts of the system:

- 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 biofouling. Scotch super 88 adheres very well underwater compared to many other PVC tapes.
- Wrap with copper tape (again, beware of aluminum).
- Coat with zinc oxide (Desitin ointment).
- Remember that growth depends on the sensor, depth, location, and season.
- Plan for routine changing or cleaning of sensor as necessary.
- Check with calibration facility to see 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 nonmetallic components.
- Use UV-stabilized components that are not subject to sunlight degradation.

For the active acoustic element:

- Do not apply paints or tape to the active element, as these will affect the calibration.
- Shrouds made of spandex are very effective anti-fouling systems and also reduce flow noise. As a guide, the supporting cage rods should be less than one-tenth of the shortest wavelength, and the calibration should be performed with the shroud in place. A shroud is shown in figure A3-1.
- UV anti-fouling systems can be used; however, this will hasten the aging of the typically polyurethane jacket over the acoustic element.

Figure A.3-1. Shrouded hydrophone

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.
- Monitor tilt and heading, if available, to check for tripod knock-overs.
- Use shrouds over the hydrophone in high biofouling or high current applications.
- Lock down all cables to avoid strumming.
- Tape metal tubes to dampen ringing from particles in the flow and to prevent biofouling.
- On long struts, wrap the strut with course windings of rope to break up the constant diameter exposed to flow. This will reduce flow noise from Karman vortices.
- Where possible, acoustically decouple the hydrophone from the mooring.

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)
- Dynamic range (i.e., the self-noise should be lower than the quietest measurement to be made and the saturation level should be higher than the loudest measurement to be made)
- 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 – lag-time response
- Instrument check – visual inspection for defects, biofouling, 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, which introduces 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 ensure 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

Passive acoustics 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 – https://ioos.noaa.gov/project/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 - https://www.nodc.noaa.gov/woce/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 each (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.
    - 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 biofouling off platform.
- ☐ Verify sensor serial numbers.
- ☐ Check for and secure loose cables, ties, and rope ends.
- ☐ Check for ground faults prior to deployment.
- ☐ 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:
    - o Checking nearby stations;
- ☐ Making historical data comparisons (e.g., long-term time-series plots, which are particularly useful for identifying long-term biofouling or calibration drift).

Appendix B. Passive Acoustics Manual Team

Passive Acoustics Manual Committee and Reviewers

Name	Organization
Mark Bushnell	U.S. IOOS
Carrie Wall Bell	Cooperative Institute for Research in Environmental Sciences
Tom Dakin	Ocean Networks Canada
Walter Johnson	Bureau of Ocean Energy Management
Stanley Labak	Bureau of Ocean Energy Management
Kaus Raghukumar	Integral Consulting, Inc.
Christoph Waldmann	University of Bremen/MARUM
Neil Weston	NOAA/National Ocean Service

QARTOD Board of Advisors

Name	Organization
Kathleen Bailey – Project Manager	U.S. IOOS
Julie Bosch	NOAA/National Centers for Environmental Information
Eugene Burger	NOAA/Pacific Marine Environmental Laboratory
Janet Fredericks	Woods Hole Oceanographic Institution
Matt Howard	GCOOS/Texas A&M University
Bob Jensen	U.S. Army Corps of Engineers
Chris Paternostro	NOS/Center for Operational Oceanographic Products and Services
Mario Tamburri	University of Maryland Center for Environmental Science / Chesapeake Biological Laboratory
Julie Thomas – BOA Chair	SCCOOS/Scripps Institution of Oceanography/Coastal Data Information Program

U.S. IOOS Regional Associations

Name	Organization
Josie Quintrell	IOOS Association
Clarissa Anderson	SCCOOS
Francisco Chavez	CeNCOOS
Debra Hernandez	SECOORA
Barbara Kirkpatrick	GCOOS
Gerhard Kuska	MARACOOS
Molly McCammon	AOOS
Julio Morell	CariCOOS
Ru Morrison	NERACOOS
Jan Newton	NANOOS
Melissa Iwamoto	PacIOOS
Kelli Paige	GLOS

DMAC Community

Regional Associations

AOOS
Carol Janzen

GCOOS
Bob Currier

CARICOOS
Miguel Canals
Roy Watlington

SECOORA
Abbey Wakely
Debra Hernandez
Filipe Pires Alvarenga Fernandes

Research Organizations

Gulf of Maine Research Institute
Eric Bridger

Scripps Institution of Oceanography
Darren Wright

Monterey Bay Aquarium Research Institute
Aric Bickel
Anderson David
Fred Bahr

Smithsonian Environmental Research Center
Matthew Ogburn

Federal and State Agencies

Bureau of Ocean Energy Management
Brian Zelenke
Jonathan Blythe

Environmental Protection Agency
Dwane Young

Great Lakes Commission
Guan Wang

National Oceanic and Atmospheric Administration
Becky Baltes
Bill Woodward
Kenneth Casey
Mark VanWaes
Alexander Birger
Bob Simons
Byron Kilbourne
Dave Easter
Derrick Snowden
Eric Johnson
Frank Lodato
Gabrielle Canonico
Jack Harlan
Jason Gedamke
Jeff de La Beaujardiere
Jenifer Rhoades
Jennifer Bosch
Jennifer Patterson
Jessica Morgan
Kevin O'Brien
Lynn Dewitt
Mark Bushnell
Mathew Biddle
Micah Wengren
Rita Adak
Robert Bassett
Samantha Simmons
Thomas Ryan
Tiffany Vance
Tim Boyer
Tony Lavoi
Xiaoyan Li

U.S. Army Corps of Engineers
Jeff Lillycrop

U.S. Geological Survey
Abigail Benson
James Kreft
Rich Signell
Sky Bristol

Academic Institutions	
University of Maine	Bob Fleming
University of Maryland	Mario Tamburri
Dalhousie University	Brad Covey
	Lenore Bajona
	Richard Davis
University of Puerto Rico	Jorge Capella
	Juan Orlando Gonzalez Lopez
	Julio Morell
University of Hawaii	Chris Ostrander
	James T. Potemra
	Melissa Iwamoto
University of Washington	Emilio Mayorga
Texas A & M University	Felimon Gayanilo
Rutgers University	John Kerfoot
	Michael Vardaro
University of Tasmania	Peter Walsh
Private Industry	
LimnoTech	Kathy Koch
	Tad Slawecki
RPS Group	Kelly Knee
	Luke Campbell
	Melanie Gearon
Axiom	Kyle Wilcox
	Rob Bochenek
	Shane StClair
Animal Tracking Network	Jonathan Pye