Manual for

Real-Time Quality Control of In-Situ Surface Wave Data

A Guide to Quality Control and Quality Assurance of In-Situ Surface Wave Observations

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Table of Contents

List of Figures

List of Tables

Revision History

Date	Revision Description	Notes
6/2013	Original Document Published	
8/2015	Revise cover to reflect correct version and publication date. Revise dates on Document Validation page (page i). Add statement requesting feedback from Manual Users (page vi). Update Acknowledgements to include manual update team members (page vii). Update Acronyms and Abbreviations (pages viii-ix). Add Definitions of Selected Terms (page x). Perform general editing for consistency in style and terminology. Revise Background and Introduction, section 1.0, to reflect update of waves manual and 2009 Waves Plan, as well as additional manuals that have been developed (pages 1-2). Revise/refine various wording in section 2.0, Purpose/Constraints/Applications. Insert updated information about range of waves programs and operator capabilities (page 3). Revise to reflect use of pressure sensors and other types of instruments (page 5 and various). Caption update in fig. 2-3 (page 7). Add fig. 2-5 - photo of pressure sensor (page 8). Add content addressing data uncertainty (pages 9-10). Update content in section 3.1, QC Flags (pages 11-13). Change Stuck Sensor Test (Test 16) to Flat Line Test (pages 13, 14, 35, and Table of Contents). Correct the spelling of "codable" in test tables (various). Revise Tests 1, 5, 10, 14, 16, 17, 18, and 20 (pages 15, 19, 25, 32, 35, 36, 38 and 41). Revise Summary to include additional summary statements found in more current QARTOD manuals (page 46). Update References (page 47). Update Supporting Documents Found on the QARTOD Waves Website (page 48). Update In-Situ Surface Waves Manual Team members (page B-1).	Manual updated with revisions listed sequentially

Date	Revision Description	Notes
2/2019	Revise cover to reflect correct version, publication date, and DOI. Revise dates and signatories on Document Validation (page i). Update Table of Contents (page ii). Update email address in Request to Manual Users (page vii). Update Acknowledgements to include reviewers/contributors to Version 2.1 (page viii). Update Definitions of Selected Terms (page xi). Update Background and Introduction to reflect additional manuals that have been added and updated (pages 1–2). Reorganize section 2 to enhance consistency with previous manual organization (pages 3–11). Update section 2 to address drifting platforms (page 3). Perform general editing for consistency in style and terminology. Update links to websites. Update References (pages 42–44) Update appendix A (pages A-1–A-5)	Manual updated with revisions listed sequentially.

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 all the contributors to version 2.1, with special thanks to Richard Bouchard (now retired from the National Data Buoy Center [NDBC]) and Julie Thomas (Chair, QARTOD Board of Advisors [BOA]). We also appreciate the kind comments from Jeff Hanson at WaveForce Technologies. We are very grateful for the continued support provided by the QARTOD BOA.

Special thanks also go to Zdenka Willis, Director of the U.S. Integrated Ocean Observing System (IOOS), for her continuing support of U.S. IOOS Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD). Thanks also go to Julie Thomas with the Scripps Institution of Oceanography (SIO) Coastal Data Information Program (CDIP) (retired) and former Director of the Southern California Coastal Ocean Observing System (SCCOOS), Richard Bouchard with the National Oceanic and Atmospheric Administration's (NOAA) NDBC, and Kent Hathaway at the U.S. Army Corps of Engineers Field Research Facility (USACE FRF) in Duck, N.C. for their significant contributions to the preparation and review of the document. Also, we are grateful to the manufacturers who participated at their own expense and to numerous document reviewers (see appendix A).

Through the process of five QARTOD workshops, these quality control steps were adapted from existing guidelines of NOAA/NDBC, CDIP, the USACE FRF, and participating manufacturers of wave-measuring systems—Nortek, SonTek, and Teledyne RDI. Additionally, these tests have been guided by the tests described in UNESCO (1993).

QARTOD Meetings (QARTOD 2003-2009)

https://ioos.noaa.gov/ioos-in-action/qartod-meetings/

QARTOD I: National Data Buoy Center, Stennis Space Center, Mississippi. 3-5 December 2003

QARTOD II: Norfolk, Virginia. 28 February-2 March 2005

QARTOD III: Scripps Institution of Oceanography, La Jolla, California, 2-4 November 2005

QARTOD IV: Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. 21-23 June 2006

QARTOD V: Omni Hotel, Atlanta, Georgia, 17-19 November 2009

Acronyms and Abbreviations

ACT	Alliance for Coastal Technologies
ADCP	Acoustic Doppler Current Profiler
ADP	Acoustic Doppler Profiler
ADV	Acoustic Doppler Velocimeter
AOOS	Alaska Ocean Observing System
AST	Acoustic Surface Tracking
AWAC	Acoustic Waves and Currents
CariCOOS	Caribbean Coastal Observing System
CDIP	Coastal Data Information Program
CeNCOOS	Central and Northern California Ocean Observing System
CO-OPS	Center for Operational Oceanographic Products and Services
DMAC	Data Management and Communications
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GLOS	Great Lakes Observing System
GOOS	Global Ocean Observing System
ICES	International Council for the Exploration of the Sea
IOC	Intergovernmental Oceanographic Commission
IODE	International Oceanographic Date Exchange
IOOS	Integrated Ocean Observing System
LT	Long-term
MARACOOS	Mid-Atlantic Regional Association Coastal Ocean Observing System
m	Meter
NANOOS	Northwest Association of Networked Ocean Observing Systems
NDBC	National Data Buoy Center
NERACOOS	Northeastern Regional Association of Coastal Ocean Observing Systems
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
PacIOOS	Pacific Islands Ocean Observing System
QARTOD	Quality Assurance/Quality Control of Real-Time Oceanographic Data
QA	Quality Assurance
QC	Quality Control

RA	Regional Association
RCOOS	Regional Coastal Ocean Observing System
SCCOOS	Southern California Coastal Ocean Observing System
SD	Standard Deviation
SECOORA	Southeast Coastal Ocean Observing Regional Association
SIO	Scripps Institution of Oceanography
ST	Short-term
TRDI	Teledyne RD Instruments
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USACE FRF	U.S. Army Corps of Engineers, Field Research Facility, (Duck, N.C.)
WGOH	Working Group on Oceanic Hydrography
WGOOFE	Working Group on Operational Oceanographic Products for Fisheries and Environment
WMO	World Meteorological Organization

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. Other definitions related specifically to wave observations and coastal engineering terms can be found at http://cdip.ucsd.edu/?sub=faq&nav=documents&xitem=glossary

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	Data record is one or more messages that form a coherent, logical, and complete observation.
Interoperable	Interoperable means the ability of two or more systems to exchange and mutually use data, metadata, information, or system parameters using
Message	Message means a standalone data transmission. A data record can be composed of multiple messages.
Operator	Operators are individuals or entities responsible for collecting and providing data.
Peak Wave Direction (D_P)	The wave direction at the frequency at which a wave energy spectrum (wave spectrum) reaches its maximum.
Quality Assurance (QA)	QA means processes that are employed with hardware to support the generation of high-quality data. (section 2.0 and appendix B)
Quality Control (QC)	QC means 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; data update latency ranging from a few seconds to a few hours or even days, depending upon the variable. (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)
Thresholds	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 34 core variables (https://ioos.noaa.gov/about/ioos-by-the-numbers) 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, addressing each variable when possible and as funding permits. This manual on the real-time QC of in-situ waves was first published in June 2013 as the second core variable to be addressed and was updated in 2015. This is the second update to this manual. Other QARTOD guidance documents have been published to date and are listed in the following paragraphs.

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

1) U.S. Integrated Ocean Observing System, 2017. U.S IOOS QARTOD Project Plan - Accomplishments for 2012–2016 and Update for 2017–2021. 47 pp. https://doi.org/10.7289/V5JQ0Z71

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. https://doi.org/10.7289/V5ZW1J4J

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. https://doi.org/10.7289/V5WM1BMZ

4) 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. https://doi.org/10.7289/V5V40SD4

5) U.S. Integrated Ocean Observing System, 2014. 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. 43 pp. https://doi.org/10.7289/V5QC01Q7

6) 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. https://doi.org/10.7289/V5FX77NH

7) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Ocean Optics Data Version 1.1: A Guide to Quality Control and Quality Assurance of Coastal and Oceanic Optics Observations. 49 pp. https://doi.org/10.7289/V5XW4H05

8) U.S. Integrated Ocean Observing System, 2018. Manual for Real-Time Quality Control of Dissolved Nutrients Data Version 1.1: A Guide to Quality Control and Quality Assurance of Coastal and Dissolved Nutrients Observations. 56 pp. https://doi.org/10.7289/V5TT4P7R

9) U.S. Integrated Ocean Observing System, 2016. Manual for Real-Time Quality Control of High Frequency Radar Surface Currents Data Version 1.0: A Guide to Quality Control and Quality

Assurance of High Frequency Radar Surface Currents Data Observations. 58 pp. https://doi.org/10.7289/V5T43R96

10) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Phytoplankton Data Version 1.0: A Guide to Quality Control and Quality Assurance of Phytoplankton Data Observations. 67 pp. https://doi.org/10.7289/V56D5R6S

11) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Passive Acoustics Data Version 1.0: A Guide to Quality Control and Quality Assurance of Passive Acoustics Observations. 45 pp. https://doi.org/10.7289/V5PC30M9

12) U.S. Integrated Ocean Observing System, 2018. Manual for Real-Time Quality Control of Stream Flow Data Version 1.0: A Guide to Quality Control and Quality Assurance of Stream Flow Observations in Rivers and Streams. 45 pp. https://doi.org/10.25923/gszc-ha43

Please refer to this document as:

U.S. Integrated Ocean Observing System, 2019. Manual for Real-Time Quality Control of In-Situ Surface Wave Data Version 2.1: A Guide to Quality Control and Quality Assurance of In-Situ Surface Wave Observations. 70 pp. https://doi.org/10.25923/7yc5-vs69

This document follows and expands on the National Operational Wave Observation Plan (U.S. IOOS 2009). The U.S. Army Corps of Engineers (USACE), Scripps Institution of Oceanography's (SIO) Coastal Data Information Program (CDIP), and the National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC), well-recognized as established providers of wave data, have long led the nation with wave observation programs. NDBC and CDIP have decades of experience applying QC checks for hundreds of buoys (CDIP 2003; NDBC 2009). However, the observation locations were based on local project or user requirements, resulting in a useful but ad hoc network with limited integration. The National Operational Wave Observation Plan addresses this situation by defining a comprehensive wave-observing network for the United States.

The National Operational Wave Observation Plan documents the extensive effort that QARTOD devoted to the QC of wave data. The process for the development, distribution, review, refinement, and revision of this QC manual was a collaborative effort by the QARTOD Board of Advisors, the U.S. IOOS Regional Associations (RAs), sensor manufacturers, and operators. Operators, who are the individuals or entities responsible for collecting and providing wave data, are a key part of this endeavor.

This manual is a living document that reflects the latest developments in QC testing procedures for wave 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 in-situ surface waves data and specific applications of those data.

2.1 Purpose

The purpose of this manual is to develop and document a series of test procedures for data QC of in-situ surface wave sensors. This manual is also a deliverable to the U.S. IOOS RAs and ocean observing community and represents a contribution to a collection of core variable QC documents. This series of tests for real-time QC procedures provides guidance to the U.S. IOOS and the wave community at large for an agreed-upon, documented, and implemented standard process.

In-situ wave observations covered by these procedures are collected in real-time as a measure of wave characteristics (wave height, wave period, and wave direction) in oceans and lakes. The characteristics of real-time (in no particular order) are:

- data are delivered without delay for immediate use;
- a time series extending only backwards in time, where the next data point is not available; and
- data update latency of a few seconds to a few hours or even days, depending upon the variable.

These tests apply only to the in-situ, real-time measurement of surface waves generated by wind action as observed by sensors deployed on fixed, moored, or drifting platforms. They can be applied to sensors deployed on powered mobile platforms (e.g., autonomous marine vehicles, ships), but such observations require additional data processing to correct for a Doppler shifted spectrum. The tests are not designed for remotely sensed wave measurements (e.g., high frequency radar, X-Band, synthetic aperture radar) or ocean surface waves generated by processes other than wind action (e.g., tides, tsunamis).

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 antifouling; solid data communications; 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 important to the process, QA issues are addressed separately in appendix B.

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 format, checksum, timely arrival of data, threshold checks (minimum/maximum rate of change), neighbor checks, climatology checks, model comparisons, signal/noise ratios, verification of user satisfaction, and generation of data flags (Bushnell 2005).

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. Those implementing QARTOD tests have created a code repository (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 wave 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.

The process of ensuring data quality is not always straightforward. QA and 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.

Table 2-1 includes wave data providers and manufacturers who contributed to the development of this manual. Also included is the specific sensor associated with the operator/manufacturer. This list is not intended to be comprehensive but to acknowledge the efforts of these operators and manufacturers.

Table 2- 1. Significant contributors to development of the QC of waves data manual.

Manual Contributor	Sensor/System/Program
CDIP	Datawell Waverider
USACE Field Research Facility (FRF)	Pressure network, Datawell Waverider, Baylor Staff, Nortek Acoustic Waves and Currents Sensors (AWAC), Acoustic Doppler Velocimeter (ADV)
NDBC	Wave and Marine Data Acquisition System (WAMDAS), Directional Wave Processing Module (DWPM), Digital Directional Wave Module (DDWM)
Nortek	AWACs with Acoustic Surface Tracking (AST)
SonTek	Acoustic Doppler Profiler (ADP)
Teledyne RD Instruments	Acoustic Doppler Current Profiler (ADCP)

2.2 Constraints

Measurements of each U.S. IOOS core variable of interest may utilize different sensing technologies and require substantially different QC methods. QC tests should not be overly generic, so these variables must be divided and grouped so that specific meaningful tests are appropriate to the variable included in the group. In this manual, surface wave measurements that are sufficiently common in nature to have similar QC checks are identified.

2.2.1 Data Descriptions

Surface gravity waves are generated by wind forcing (and momentum transfer to the free surface), with gravity as the restoring force. The waves are roughly constrained between 0.3 seconds and 30 seconds. Practically speaking, few operational wave sensors can detect periods less than 1-2 seconds. To acquire sufficient data to compute wave characteristics, most sensors must collect data over a period of at least 20 minutes. QC on the time series of raw data collected during this sampling period can be conducted. Outlying data points may be removed, and short gaps filled to obtain a satisfactory time series to be used for computation of the wave characteristics.

The term “time series” has two meanings here, and each one is defined more specifically as follows:

1) *Short-term (ST) sample time series* is the time series of sample data points logged during a 1,024-second (or a 2,048-second or similar) sampling period. Editing and gap filling of the data are allowed. An ST sample provides a single determination of wave characteristics, such as significant wave height, peak period, peak direction, and wave spread (collectively referred to as the bulk wave parameters).

2) *Long-term (LT) wave observation time series* is the time series of wave data points produced from successive ST samples, typically a series of bulk wave parameters and other wave characteristics.

Many technologies are available for measuring surface gravity waves. Above the surface, microwave, laser, or acoustic altimeters can observe the surface displacement, and arrays of altimeters can determine wave direction. Satellites use microwaves to observe surface roughness, and shore-based radar systems provide wave measurements using several different techniques. Below the surface, a pressure sensor or a focused acoustic beam can detect waves, with an array of them providing wave direction. ADVs and ADCPs can observe wave orbital velocities using multiple formed beams to determine direction. At the surface, vertical wires can use a variety of electrical properties to sense waves. Buoys use a variety of combinations of accelerometers, tilt and rotation sensors, and compasses to compute wave characteristics. And, GPS measurement of buoys’ velocity or displacement is increasingly used for wave observations.

This manual primarily addresses the QC of wave observations from the most commonly used methods for in-situ wave measurements: pressure sensors, buoys, ADCPs, ADVs, and microwave altimeters. Operators of other wave-sensing systems may find that they can apply a subset of these tests as well. QC can be conducted at the sensor outputs, upon computed values derived from one or more sensors, or upon the resultant wave characteristics. For example, QC can be conducted on raw buoy vertical acceleration, the computed vertical displacement, or the final output of significant wave height. From ADCPs, QC checks can be carried out on the raw acoustic backscatter values from each bin within each formed beam, on the radial component of the orbital velocity derived from the detected Doppler shift, or on the resultant wave direction.

Table 2-2. Sensors commonly used to measure waves

Sensor Technology	Manufacturer
Accelerometers, 3 axis magnetometers, tilt sensors	Aanderaa, Axys, Datawell,
GPS	Axys, Datawell, Spoondrift
Microwave altimeter	Miros
Pressure sensor	Aanderaa, RBR
Acoustic Doppler profiling, acoustic surface tracking	Nortek, Sontek, TRDI, Rowe Technologies

2.2.2 Data Processing Methodology

The system that processes and transmits the information also can affect the QC algorithms that can be applied to the data. In-situ systems with sufficient onboard processing power and limited transmission capability may process the original (raw) measurement and transmit derived values. These values can then be used to reconstruct wave spectra and characteristics. If ample transmission capability is available, the entire raw data stream may be transmitted and quality-controlled on land.

Therefore, because operators have different data processing methodologies, several levels of QC tests are proposed in section 3 of this manual.

2.2.3 Traceability to Accepted Standards

To ensure that wave sensors are producing accurate data, rigorous calibrations and calibration checks must be performed in addition to QC checks. Most operators rely upon manufacturer calibrations and only conduct calibration checks 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 B.

Calibrations and calibration checks must be traceable to accepted standards. The National Institute of Standards and Technology (NIST) is often the source for internationally accepted standards, but there is no standard for ocean surface gravity wave measurement. These activities must rely upon the fundamental standards for length, time, and the earth's magnetic field. Fortunately, traceability to NIST is relatively easy because the standards for length, time, and compass bearing are readily available at the resolutions required.

To validate software used to compute wave characteristics from raw data, standard time series with known output are available for use as input to the code. Additionally, to support a Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) wave sensor evaluation and test effort (http://www.jcomm.info/index.php?option=com_content&view=article&id=62), the SIO CDIP program maintains an inter-comparison Web page. Co-located sensor data can be evaluated using standardized techniques and compared to other evaluations posted on the site.

2.2.4 Sensor Deployment Considerations

Wave sensors can be deployed in several ways (figs. 2-1 through 2-5). With the proper mooring configuration, buoys might be deployed in all depths, but are typically deployed at depths of 10 meters (m) or more. Current velocities and the subsequent load imparted on the mooring may be limiting factors in some locations.

ADCP wave sensors are usually bottom-mounted on fixed platforms (fig. 2-4). Manufacturers may use a pressure sensor, an AST beam, or both. When mounted on subsurface moorings, ADCPs require motion detection and compensation. As noted earlier, a variety of depth limitations must be considered, and these limitations are generally well understood and documented by the manufacturer.

Figure 2-1. NDBC 3-m discus buoy (left); NDBC 6-m NOMAD buoy (right). (Photo courtesy of Richard Bouchard/NDBC)

Figure 2-2. NDBC 3-m discus buoy being serviced at sea from U.S. Coast Guard vessel. (Photo courtesy of Richard Bouchard/NDBC)

Figure 2-3. CDIP personnel deploy a Datawell directional Waverider. As of 2019, the CDIP network is composed of approximately 65 wave observation sites. (Photo courtesy of SIO/CDIP)

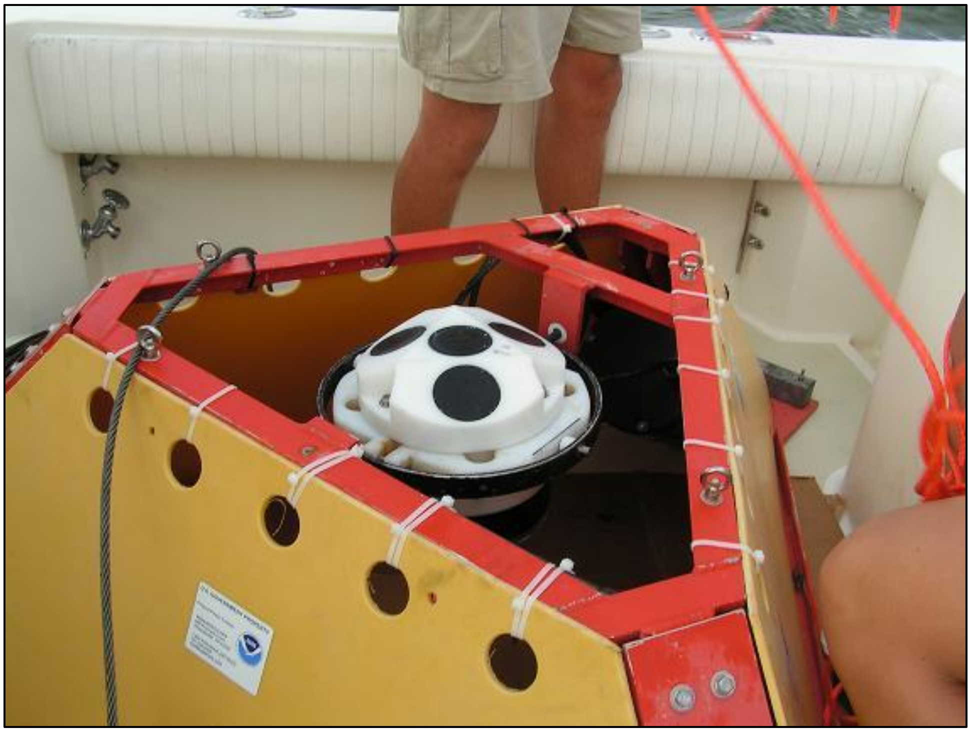

Figure 2-4. Nortek AWAC in a stable, bottom-mounted platform prepared for deployment. (Photo courtesy of Jennifer Patterson, formerly with CeNCOOS/Monterey Bay Aquarium Research Institute)

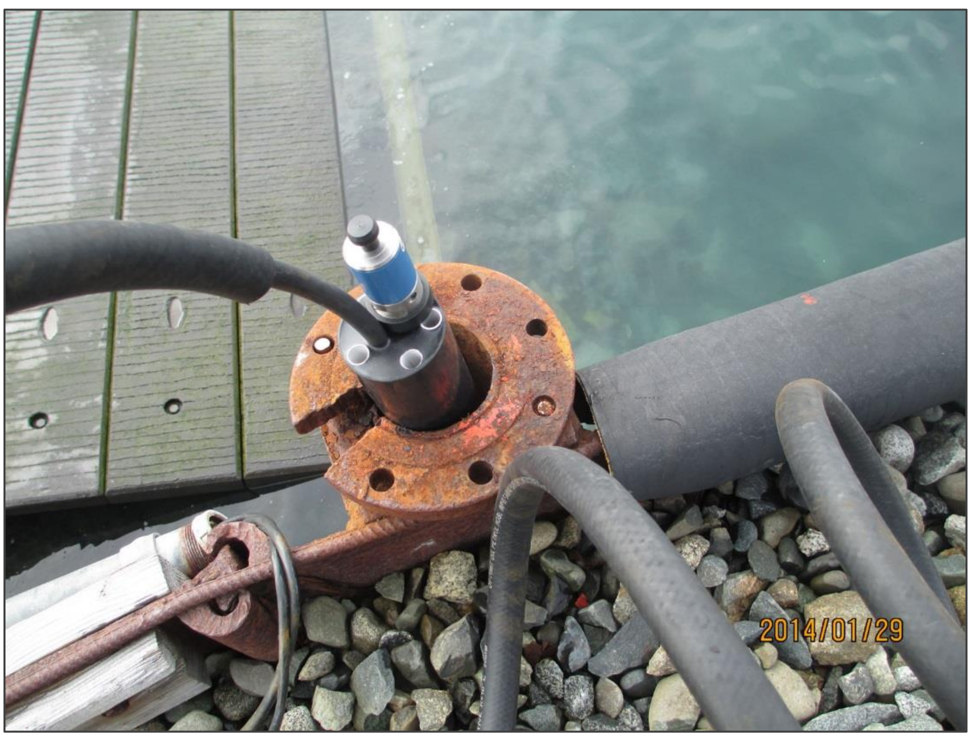

Figure 2-5. An Aanderaa 5218 pressure sensor is lowered into a protective well, providing single point, non-directional wave observations. (Photo courtesy of Richard Butler/Aanderaa)

2.2.5 Hardware Limitations

Advances in wave sensor technology have eliminated many problems encountered in older devices. Sensors are smarter, smaller, more reliable, and draw less power. More sensors can be employed to make corrections that provide additional accuracy, such as temperature compensation of pressure sensors or tilt sensors on stabilized platforms. Most notably, signal processing hardware and software capabilities have grown substantially.

Most wave sensors can withstand moderate bio-fouling, but observational accuracy gradually degrades as marine growth becomes excessive. As the fouling mass increases on a buoy, it will become less able to follow the ocean surface, and the high-frequency response diminishes. Buoys can also be compromised by ice growth on the superstructure or by mammals climbing on the buoy. Unfortunately, these disturbances may only be verified by site visits or the detection of a degraded wave-period observation. In the case of the ADCP, effective acoustic power output and transducer reception sensitivity degrades, leading to reduced signal-to-noise ratios and less accurate observations across the frequency spectrum. Pressure sensors may have dampened output as the orifice becomes obstructed. However, effective antifouling materials and coatings may permit system deployments in excess of two years.

Buoy hull shape and mooring configuration can also affect accuracy. In general, response is improved by reducing buoy mass, reducing superstructure, and employing a highly compliant mooring—which is particularly important for the higher-frequency observations. A compliant mooring allows the buoy to follow the wave motions in an unconstrained way. Buoys utilizing a rigidly fixed “strapped-down” vertical accelerometer must correct for persistent tilts, typically encountered during high wind/wave events, to avoid transference of horizontal accelerations into the vertical and overestimating wave heights (Bender et al. 2010).

ADCPs are depth-limited by both individual beam spreading and multiple beam spatial resolution reduction. Pressure sensors are also depth-limited, since the signal of a passing wave decays with increasing depth. The reduced performance for both is more pronounced in the high frequencies. For buoys and bottom-mounted gauges, operators should be aware of the challenges associated with deployments within the surf-zone; most operational deployments will avoid this temporal- and spatial-moving region.

ADCP transducer side lobe reflections must also be considered. These reflections can come from the bottom, the surface, or adjacent structures and will degrade ADCP performance. These errors are mitigated by proper deployment procedures. Manufacturer user manuals should be consulted to ensure that proper procedures are followed.

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.

Corrections for magnetic declination and deviation are important and must be given careful consideration. Although these corrections are beyond the scope of this manual, manufacturer user manuals provide processes for making corrections that are specific to the sensor make/model. Care should be taken to avoid ferrous and magnetic materials when designing instrument mounts and deployment locations.

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 data point is required to ensure that data are used appropriately, and it 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, 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 enhances system robustness and supports the determination of the uncertainties associated with the observations. Comparing two adjacent instruments (or multiple wave observations using differing technologies from one instrument) can assist in evaluation of data quality, as well as provide two (or more) independent estimates of a variable of interest. Variation in the estimated values can be useful in uncertainty calculations.

2.3 Applications of Wave Data

Real-time wave data are used for a wide variety of applications, including safe maritime commerce, coastal engineering, recreational safety, wave model validation, and storm surge / inundation modeling. Observations are relied upon by ship pilots, coastal resource managers, commercial and recreational fishing vessels. The National Weather Service relies upon the observations when issuing small craft advisories, commonly used for easing decision-making by many field operations managers.

3.0 Quality Control

To conduct real-time QC on wave observations, the first pre-requisite is to understand the science and context within which the measurements are being conducted. Waves are dependent upon many things, such as local and remote wind fields (e.g., strength, fetch, and duration), bathymetry and coast shape (e.g., shoaling, refraction, and reflection), and coincident ocean currents. The real-time QC of these observations can be extremely challenging. Human involvement is therefore important to ensure that solid scientific principles are applied to the process so that good data are not discarded, and bad data are not distributed. Examples include selection of appropriate thresholds and examination of data flagged as questionable.

This manual focuses specifically on real-time data. For example, for real-time QC, gradual calibration changes or system responses (sensor drift) can be hard to detect or correct. Drift correction for wave sensors during post-processing is difficult, even when a valid post-recovery calibration can be obtained. Drift is often caused by bio-fouling, affecting different systems in different ways—a wave buoy's response will be affected by the added mass of bio-fouling (Thomson et al. 2015). Another example is the ability of some data providers to backfill data gaps. In both of these examples, the corrected or backfilled observations are not considered to be real-time for purposes of QC checks. (However, over time, drift can be observed in real-time data trends, and in some sophisticated 24/7 QC operations, real-time dissemination may be switched from one co-located 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. Operators may incorporate additional flags for inclusion in metadata records. For example, a data point may fail the acoustic velocity min/max and be flagged as having failed the test. Additional flags may be incorporated to provide more detailed information to assist with troubleshooting. If the data point failed the acoustic velocity min/max by exceeding the upper limit, a "failed high" flag may indicate that the values were higher than the expected range, but 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 2017) posted on the U.S. IOOS QARTOD website.

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 to ensure that historical documentation is preserved. Results from post processing should generate another set of flags.

Data points are time ordered, and the most recent observation (Present Observation) is PO_0, preceded by a value at PO_{-1}, and so on backwards in time. The focus of this manual is primarily on the real-time QC of data points PO_0, PO_{-1}, and PO_{-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 operators 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 QC Test Types and Hierarchy

This section outlines the 21 real-time QC tests that are required, recommended, or suggested for wave sensors. Through the process of the first four QARTOD workshops, guidelines were collected and submitted to the Ocean.US Data Management and Communications (DMAC) Steering Committee (Bouchard et al. 2007). Those guidelines were adapted from existing guidelines developed and implemented by established providers of wave data and participating manufacturers of wave measuring systems—Nortek, SonTek, and Teledyne RDI—and are the basis for these 21 tests. Additionally, these tests have been guided by the tests described in UNESCO (1993).

Frequency-based tests apply only to operators who provide wave spectra. Those operators not providing frequency-based spectra are not required to incorporate test 17 and test 18. 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 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. Such flexibility is needed to support the U.S. IOOS Regional Information Coordination Entities certification, since the number of tests conducted and the justification for not applying some tests are useful for evaluating an operator's skill level. Tests are listed in table 3-2 and are divided into three groups: one that applies only to acoustic profiler wave sensors and a second that applies to sensors providing ST time series. The third group applies tests to LT wave observation time series. Table 3-3 shows the test hierarchy.

Some effort will be needed to select the best thresholds, which are determined at the operator level and may require trial and error/iteration 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, statistics derived from more recently acquired data, or existing guidance. For example, the World Meteorological Organization (WMO) and others (CDIP 2003) often define a spike as exceeding 4*SD. And, while preparing the Comprehensive Ocean-Atmosphere Data Set (COADS), Woodruff (2001) noted that thresholds were too conservative, "…resulting in the distortion or elimination of some large climate signals …" during strong El Niños. Although this manual provides some guidance for selecting thresholds based on input from various operators, it is assumed that operators have the subject matter expertise as well as a sincere interest in selecting the proper thresholds to maximize the value of their QC effort. Operators are required to 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.

Table 3-2. QC tests for real-time ADCP and buoy-mounted sensors

	Test Name	Status
Applies Only to Acoustic Profiler Wave Sensors	Signal Strength (Test 1)	Strongly Recommended
	Correlation Magnitude (Test 2)	Strongly Recommended
	Acoustic Noise (Test 3)	Strongly Recommended
	Signal-to-Noise (Test 4)	Strongly Recommended
	Pressure or Acoustic Surface Tracking (Test 5)	Strongly Recommended
	Acoustic Velocity Min/Max (Test 6)	Strongly Recommended
	Acoustic Velocity Mean Value (Test 7)	Strongly Recommended
	Sample Count (Test 8)	Strongly Recommended
Applies to Many Sensors that Output an ST Time Series	ST Time Series Gap (Test 9)	Strongly Recommended
	ST Time Series Spike (Test 10)	Strongly Recommended
	ST Time Series Range (Test 11)	Strongly Recommended
	ST Time Series Segment Shift (Test 12)	Suggested
	ST Time Series Acceleration (Test 13)	Strongly Recommended
	LT Time Series Check Ratio or Check Factor (Test 14)	Strongly Recommended
Applies to all Wave Sensors	LT Time Series Mean and Standard Deviation (Test 15)	Strongly Recommended
	LT Time Series Flat Line (Test 16)	Required
	LT Time Series Operational Frequency Range (Test 17)	Required
	LT Time Series Low-Frequency Energy (Test 18)	Required
	LT Time Series Bulk Wave Parameters Max/Min/Acceptable Range (Test 19)	Required
	LT Time Series Rate of Change (Test 20)	Required
	Neighbor Check (Test 21)	Suggested

Table 3-3. QC test requirement hierarchy.

Group 1 Required	LT Times Series Flat Line (Test 16) LT Time Series Operational Frequency Range (Test 17) LT Time Series Low-Frequency Energy (Test 18) LT Time Series Bulk Wave Parameters Max/Min/Acceptable Range (Test 19) LT Time Series Rate of Change (Test 20)
Group 2 Strongly Recommended	Signal Strength (Test 1) Correlation Magnitude (Test 2) Acoustic Noise (Test 3) Signal-to-Noise (Test 4) Pressure or Acoustic Surface Tracking (Test 5) Acoustic Velocity Min/Max (Test 6) Acoustic Velocity Mean Value (Test 7) Sample Count (Test 8) ST Time Series Gap (Test 9) ST Time Series Spike Test (Test 10) ST Time Series Range (Test 11) ST Time Series Acceleration (Test 13) LT Time Series Check Ratio or Check Factor (Test 14) LT Time Series Mean and Standard Deviation (Test 15)
Group 3 Suggested	ST Time Series Segment Shift (Test 12) Neighbor Check (Test 21)

3.3 QC Test Descriptions

A variety of tests can be performed on the sensor measurements to evaluate data quality. Testing the integrity of the data transmission is a first step. If the data are corrupted during transmission, further testing may be irrelevant. The checks defined in these 21 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 data points and denote the most recent one as previously described.

3.3.1 ST Time Series QC Tests for ADCPs

Signal quality tests are applied to data from acoustic sensors to ensure that the measurements of wave variables are good quality. The strength of the signal from each of the acoustic transmitters must be sufficient to measure the intended variables. Checks of data against selected threshold values include noise, signal strength, signal-to-noise ratio, correlation magnitude, and percent good. Thresholds must be exceeded for each variable collected to proceed with processing of the acoustic signal into usable data. The signal quality tests are applied for each signal for each acoustic beam and at each depth level collected. The first seven tests are used to identify suspect or bad data in the ST time series. The eighth test determines if sufficient data remain to proceed with the calculation of the wave characteristics.

Signal Strength (Test 1) – Strongly Recommended

Check that acoustic signal strength exceeds noise floor threshold values.

The operator defines the signal strength threshold values, SSTHRESH_FAIL and SSTHRESH_SUSPECT. SIGSTRNB(*i*) is the value of the received signal strength for beam *i*. The test is performed for each beam, *i*.

Flags	Condition	Codable Instructions
Fail = 4	The threshold value for signal strength is not exceeded; data are failed.	If SIGSTRNB(*i*) < SSTHRESH_FAIL, flag = 4
Suspect = 3	The fail threshold value for signal strength is exceeded, but the suspect threshold is not exceeded; data are suspect.	If SIGSTRNB(i) ≥ SSTHRESH_FAIL and SIGSTRNB(i) < SSTHRESH_SUSPECT, flag = 3
Pass = 1	Values of signal strength exceed the thresholds; data are good.	If SIGSTRNB(*i*) ≥ SSTHRESH, flag = 1

Test exceptions: None.

Test specifications to be established locally by the operator.
Example: Threshold is operator-defined. Operators to provide examples as procedures are implemented.

Correlation Magnitude (Test 2) – Strongly Recommended

Test that correlation magnitude is above an acceptable threshold.

A key quality-control parameter for broadband ADCPs, such as the TRDI ADCPs, is the correlation magnitude (CMAG). This is essentially a measurement of how much the particle distribution has changed between phase measurements. The less the distribution has changed, the higher the correlation, and the more precise the velocity data points.

Correlation magnitude is provided for each bin (*i*) and each beam (*j*). This test needs only to be performed on bins used in wave computations.

Flags	Condition	Codable Instructions
Fail = 4	If the correlation magnitude (CMAG[*i*,*j*]) falls below a certain count level (CMAGMIN), the data point for that bin and beam fails.	If CMAG(*i*,*j*) < CMAGMIN, flag = 4
Suspect = 3	If the correlation magnitude (CMAG[*i*,*j*]) is between the minimum (CMAGMIN) and maximum (CMAGMAX) count levels, the data point for that bin and beam passes, but is considered suspect.	IF CMAG(*i*,*j*) ≥ CMAGMIN AND CMAG(*i*,*j*) ≤ CMAGMAX, flag = 3
Pass = 1	If the correlation magnitude (CMAG[*i*,*j*]) is above a maximum count level (CMAGMAX), the data point for that bin and beam passes.	IF CMAG(*i*,*j*) > CMAGMAX, flag = 1

Test Exception: This test is primarily for the TRDI ADCP sensors.

Test specifications to be established by the manufacturer.
Example: Operators to provide examples as procedures are implemented.

Acoustic Noise (Test 3) - Strongly Recommended

Check that acoustic noise is less than noise floor threshold values.

The operator/manufacturer defines the noise threshold value, NOITHRESH.

NOISE(*i*) is the value of the noise for beam *i*. The test is performed for each beam, *i*.

Flags	Condition	Codable Instructions
Fail = 4	The threshold value for noise is exceeded; data are failed.	If NOISE(*i*) ≥ NOITHRESH, flag = 4
Suspect = 3	No result; no flag.	N/A
Pass = 1	All values of noise are less than the threshold; data are good.	If NOISE(*i*) < NOITHRESH, flag = 1

Test exceptions: None.

Test specifications to be established locally by the operator.
Example: Threshold is operator-defined. Operators to provide examples as procedures are implemented.

Signal-to-Noise (Test 4) - Strongly Recommended

Check that signal-to-noise ratio exceeds noise floor threshold.

The operator defines the signal-to-noise ratio threshold value, SNRTHRESH.

SIGSTRNB(*i*) is the value of the received signal strength for beam *i* and NOISE(*i*) is the value of noise for beam *i*. The test is performed for each beam, *i*.

Flags	Condition	Codable Instructions
Fail = 4	The threshold value for SNR is not exceeded; data are failed.	If (SIGSTRNB(*i*)/NOISE(*i*)) < SNRTHRESH, flag = 4
Suspect = 3	No result; no flag.	N/A
Pass = 1	All values of signal strength exceed the threshold; data are good.	If (SIGSTRNB(*i*)/NOISE(*i*)) ≥ SNRTHRESH, flag = 1

Test exceptions: None.

Test specifications to be established locally by the operator.
Example: SNR threshold = 3.

Pressure or Acoustic Surface Tracking (Test 5) - Strongly Recommended

Check that pressure or AST recorded at the instrument is within an acceptable range.

For non-directional pressure or AST measurements, or directional measurements using the PUV or AST-UV method, the pressure or AST measurement can be tested to ensure it falls within an acceptable range, defined by the operator. If both pressure and AST are available, both should be tested.

The test described here is for a pressure measurement – an AST test would similar. PUVPRES is the value of the pressure and/or AST provided by the instrument. PRESCMIN and PRESCMAX are the pressure variability values allowed to consider the instrument at a constant depth.

Flags	Condition	Codable Instructions
Fail = 4	The PUV pressure exceeds the maximum pressure allowed or the PUV pressure is less than the minimum pressure allowed; data are failed.	If PUVPRES > PRESCMAX or PUVPRES < PRESCMIN, flag = 4
Suspect = 3	No result; no flag.	N/A
Pass = 1	The PUV pressure values are within the range limits provided for pressure variance; data are good.	If PUVPRES ≥ PRESCMIN and PUVPRES ≤ PRESCMAX, flag = 1

Test exceptions: None.

Test specifications to be established locally by the operator. Minimum and maximum pressure or AST measurement.
Example: For an AWAC deployed in water depth of 10 m and a tidal range of ±1 m, after considering storm surge and wave heights, PRESCMIN = 7 decibars and PRESCMAX = 16 decibars.

Acoustic Current Velocity Min/Max (Test 6) - Strongly Recommended

Check that current velocity recorded falls within expected ranges.		
VELVAL is the current velocity value provided by the instrument. VELMIN is the minimum current velocity value and VELMAX is the maximum current velocity value allowed.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	The velocity value exceeds the maximum velocity allowed or the velocity value is less than the minimum velocity allowed; data are failed.	If VELVAL > (VELMAX) or VELVAL < (VELMIN), flag = 4
Suspect = 3	No result; no flag.	N/A
Pass = 1	The velocity value is within the range limits provided for velocity; data are good.	If VELVAL ≥ (VELMIN) and VELVAL ≤ (VELMAX), flag = 1
Test exceptions: None.		
Test specifications to be established locally by the operator. **Example:** VELMIN = 0, VELMAX = 2.0 m/s		

Acoustic Current Velocity Mean Value (Test 7) - Strongly Recommended

Check that current velocity recorded falls within expected standard deviation ranges.		
VELVAL is the horizontal value of the current velocity provided by the instrument. VELMEAN is the mean current velocity value and VELSTDEV is the standard deviation allowed. VELMEAN and VELSTDEV are calculated from the ST time series. TRDI ADCP operators will use radial velocities (beam coordinates) instead of u,v,w.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	The velocity value exceeds the mean velocity plus one standard deviation or the velocity value is less than the mean velocity minus one standard deviation; data are failed.	If VELVAL > (VELMEAN + VELSTDEV) or VELVAL < (VELMEAN - VELSTDEV), flag = 4
Suspect = 3	No result; no flag.	N/A
Pass = 1	The velocity value is within the range limits provided for velocity standard deviation; data are good.	If VELVAL ≥ (VELMEAN - VELSTDEV) and VELVAL ≤ (VELMEAN + VELSTDEV), flag = 1
Test exceptions: None.		
Test specifications will be calculated by the local operator. **Example:** Operators to provide examples as procedures are implemented.		

Sample Count (Test 8) - Strongly Recommended

Check that the number of samples is sufficient to calculate the value.

The ST time series is comprised of a nominal series of values. The operator determines the minimum number of good samples threshold value, NGSTHRESH. If an insufficient number of good samples remains after conducting tests 1-7, no bulk wave parameters can be calculated.

NGS(*i*) is the value for the number of good samples for beam *i*. The test is performed for each beam, *i*.

Flags	**Condition**	**Codable Instructions**
Fail = 4	The threshold value for number of good samples is not exceeded; data are failed.	If NGS(*i*) < NGSTHRESH, flag = 4
Suspect = 3	No result; no flag.	N/A
Pass = 1	The number of good samples exceeds the threshold value; data are good.	If NGS(*i*) ≥ NGSTHRESH, flag = 1

Test exceptions: None.

Test specifications to be established locally by the operator.
Example: Number of good samples suggested by SonTek for ADV/ADP is 128.

3.3.2 ST Time Series QC Tests

ST time series tests are applied to the raw data points from a wide variety of wave sensors. When data are received from the field, they are first checked for gaps and missing values. A minimum amount of data with a pass flag is needed to perform the statistical and time series tests required for producing quality data. The checks are based on time tags and/or counters included in the data stream. After the ST data set has been deemed good and given a passing flag, the operator should perform a best fit to fill in data gaps.

The failure of any one of these tests means that the bulk wave parameters cannot be computed. Nevertheless, it is appropriate to complete all tests to provide information that might assist in troubleshooting the problem.

ST Time Series Gap (Test 9) - Strongly Recommended

The gap check test determines whether a gap is too large. A time series is accepted if there is no single gap that lasts longer than N points.

Check for missing data in ST sample time series.

Check for N consecutive missing data points. This defines the size of an unacceptable gap in the time series. It is the maximum number of consecutive missing data points allowed.

A counter (C2) increments from 0 (zero) as consecutive data points are missed. At the end of a gap of missing data, this counter is compared to N. If C2 > N, the test is failed, and a suspect flag is set. The counter (C2) is reset to 0 after a data point is encountered.

Flags	Condition	Codable Instructions
Fail = 4	Gap maximum exceeded. ST time series data are failed.	If C2 > N, flag = 4
Suspect = 3	N/A	
Pass = 1	Pass/data are good.	If C2 < N, flag = 1

Test Exception: None.

Test specifications to be established locally by the operator.
N is the number of consecutive points allowed to be missed. The value, N, is operator-defined.
Example: Operators to provide examples as procedures are implemented.

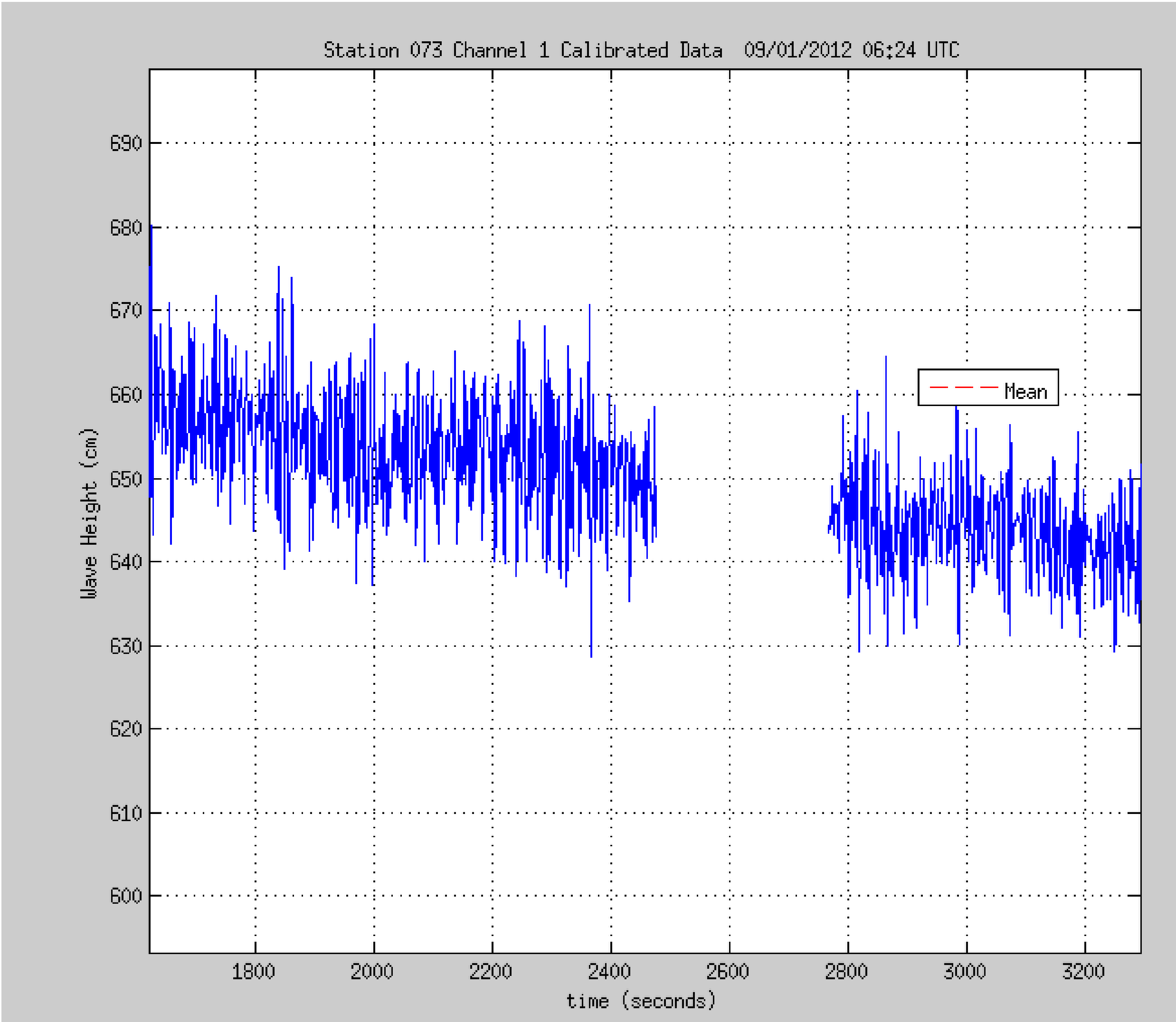

Figure 3-1. The plot shows an example of a data gap that would be identified by the ST time series gap test. (Graphic courtesy of SIO/CDIP)

ST Time Series Spike (Test 10) - Strongly Recommended

The spike test checks for spikes in a time series. Spikes are defined as points more than M times the standard deviation (SD) from the mean—a WMO standard of 4 * SD is often used. After the ST time series is received, the mean (MEAN) and standard deviation must be determined. Counters M1 and M2 are set to 0. Once a spike has been identified, the spike is replaced with the average (AVG) of the previous point (*n* - 1) and the following point (*n* + 1). Alternative interpolation methods such as a spline fit may also be used. The counter, M1, is incremented as spikes are identified. The algorithm should iterate over the time series multiple (P) times, re-computing the mean and standard deviation for each iteration. After the P^{th} iteration, a final spike count, M2, is run. The counters M1 and M2 are compared to the number of spikes allowed. The time series is rejected if it contains too many spikes (generally set to N% of all points) or if spikes remain after P iterations (M2 > 0).

For ADCP wave observations, a beam-by-beam spike test can be used to identify potentially bad values caused by a single beam.

Check for spikes in the time series.		
Operator defines M, N%, and P (iterations). TSVAL(*n*) is the time series value being evaluated.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	Spikes remain in the time series after P iterations **OR** the allowed number of spikes is exceeded. The entire ST time series is failed.	Compute the series mean and SD. Scan series, excluding endpoints, for spikes where: |TSVAL(*n*) - MEAN| > M * SD Replace spike with AVG and increment M1. Repeat P times, summing M1, and then scan series for final spike count, M2. If M1 ≥ N% OR M2 > 0, THEN flag = 4
Suspect = 3	N/A	N/A
Pass = 1	No spikes remain in the time series after P iterations, **AND** deleted spike count is less than the specified percentage N% of the ST time series.	M1 < N% AND M2 = 0, THEN flag = 1
Test Exceptions: None.		
Test specifications to be established locally by the operator. **Example:** N% = 10, M = 4, P = 2		

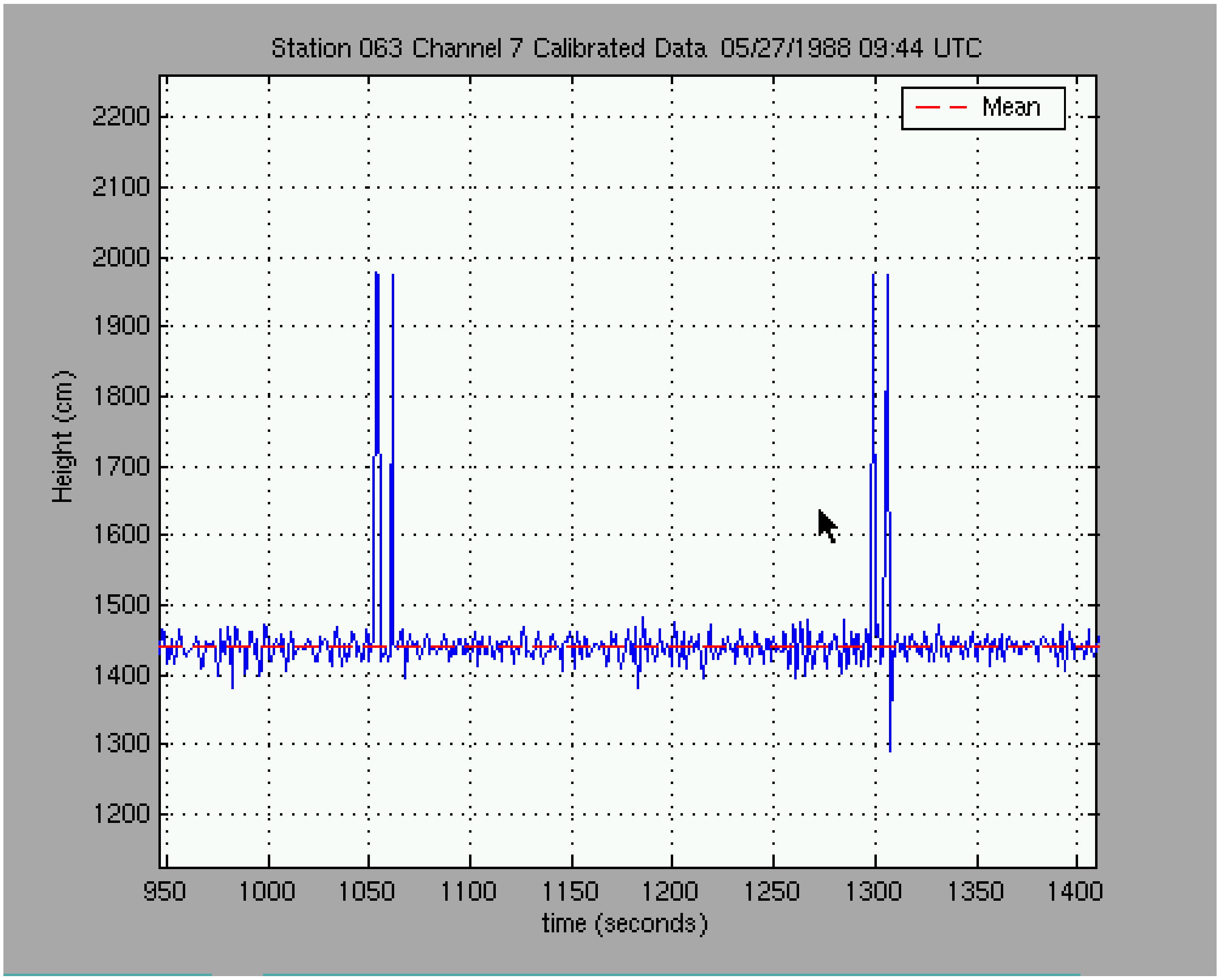

Figure 3-2. The spikes shown in this plot would be detected by the ST time series spike test. (Graphic courtesy of SIO/CDIP)

ST Time Series Range (Test 11) - Strongly Recommended

The range test checks that the values (e.g., pressure, AST, u, v) of the time series fall within limits defined by the operator. The operator should at least define the instrument range for these tests. Regional or seasonal/climate ranges may also be provided. If the instrument range is exceeded, data should be flagged as failed.

Ensure that time series values fall within an expected range.		
The operator defines the instrument minimum (IMIN) and instrument maximum (IMAX) and may also define the local minimum (LMIN) and local maximum (LMAX). The local maximum and minimum may be location-, season-, and/or sensor-dependent. TSVAL is the value of the time series at point, *i*.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	The instrument range is exceeded, results in a flag (4); data are failed.	If TSVAL > IMAX or TSVAL < IMIN, flag = 4
Suspect = 3	The location/season range is exceeded, results in a flag (3); data are released with suspect flag.	If TSVAL > LMAX or TSVAL < LMIN, flag = 3
Pass = 1	All time-series values in range; data are good (flag = 1).	If TSVAL ≥ LMIN and TSVAL ≤ LMAX, flag = 1
Test exceptions: None.		
Test specifications to be established locally by the operator. **Example:** Operators to provide examples as procedures are implemented.		

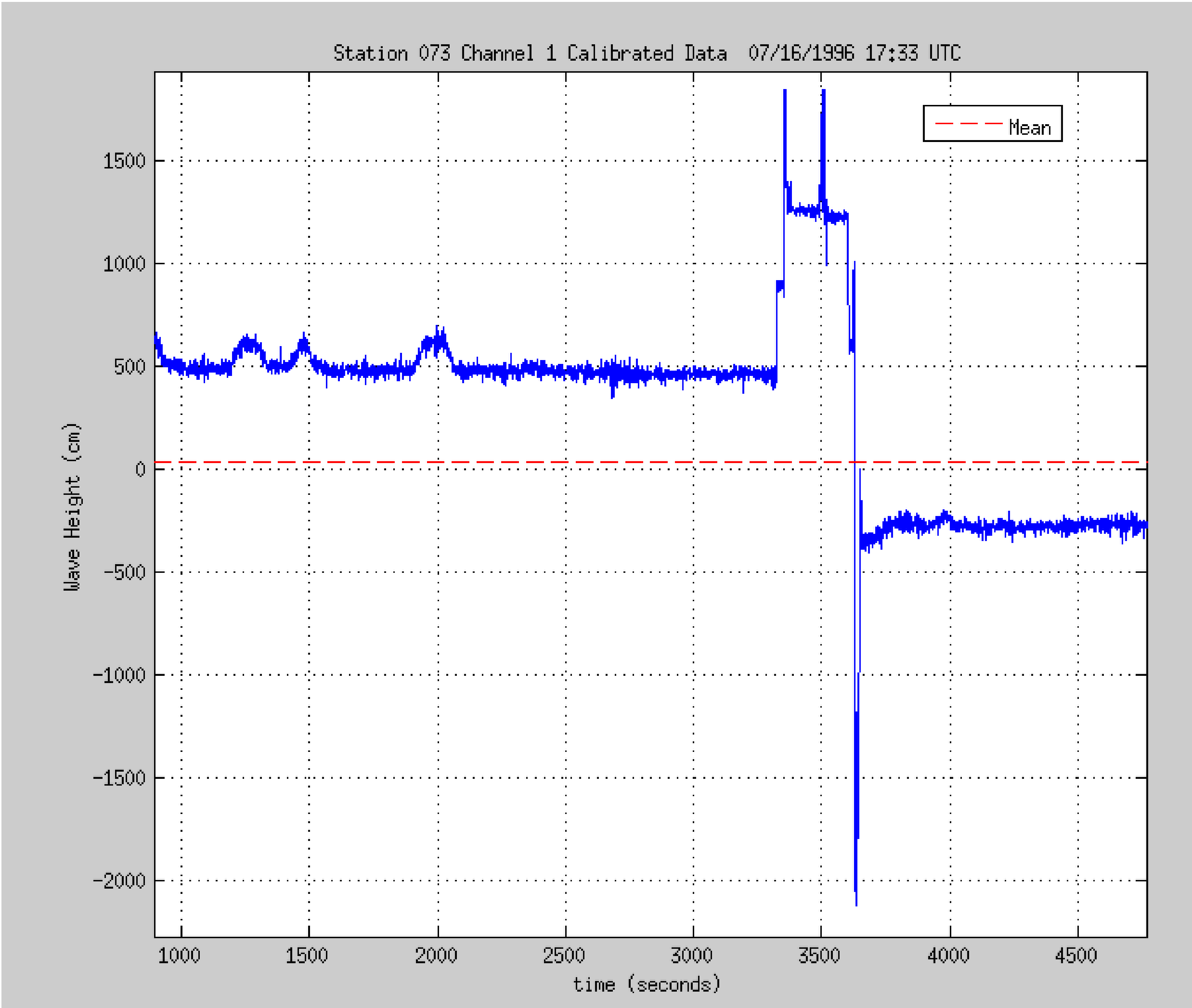

Figure 3-3. The plot shows an example of bad data that would be identified by the ST time series range test. (Graphic courtesy of SIO/CDIP)

ST Time Series Segment Shift (Test 12) - Suggested

The time series is broken into *n* segments *m* points long. Segment means are computed for each of the *n* segments. Each segment mean is compared to neighboring segments. If the difference in the means of two consecutive segments exceeds P, the ST time series data are rejected. The operator defines *n* segments, *m* points, and P.

A test for a large mean shift in the time series.		
The operator determines the number of segments (*n*) to be compared in the time series and the length of each segment (*m*) to be compared in the time series. Then, *m* or *n* can be computed by the other in conjunction with the length of the entire time series. The length of *m* should be consistent with statistical best practices. The operator also defines the mean shift (P) that is allowed in the time series. A mean value (MEAN [*n*]) is computed for each of the *n* segments. The means of consecutive segment are then compared. If the differences of the means exceed the allowed mean shift (P) provided by the user, the entire time series is failed.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	The allowable mean difference, P, between two adjacent segments in the time series is exceeded. Data are failed.	If [MEAN(*n*) – MEAN(*n* + 1)] ≥ P, flag = 4
Suspect = 3	N/A	N/A
Pass = 1	Data are good.	If [MEAN(*n*) – MEAN(*n* + 1)] < P, flag = 1, for all values of *n* - 1
Test Exception: None.		
Test specifications to be established locally by the operator: *m*, *n*, and P are operator-provided. **Example:** UNESCO (1993) recommends: *n* = 8 and P = 0.20 m (for displacement).		

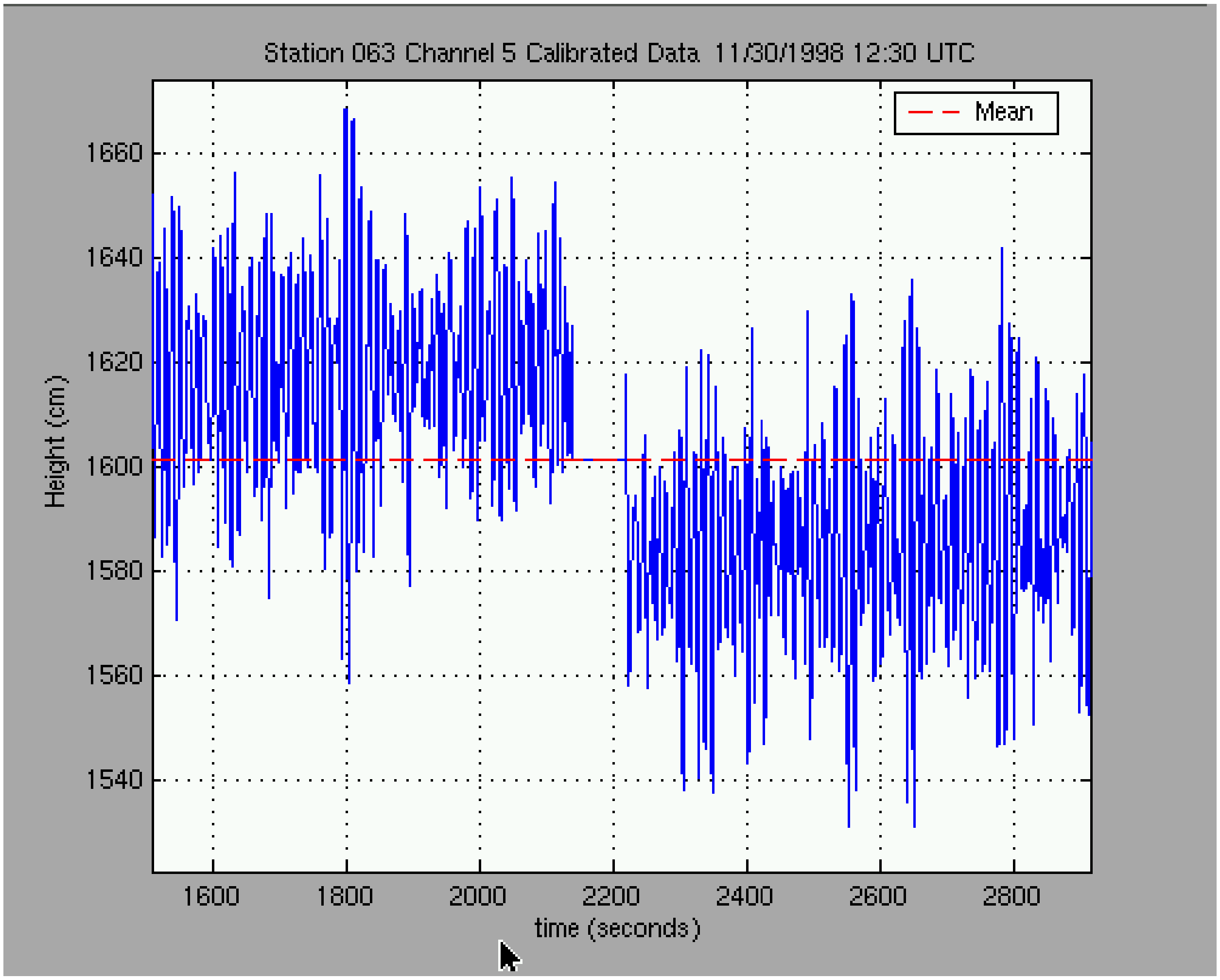

Figure 3-4. The plot shows an example of an abrupt shift in the ST time series mean, which would be detected by the ST time series mean test. (Graphic courtesy of SIO/CDIP)

ST Time Series Acceleration (Test 13) - Strongly Recommended

The in-situ systems that collect these time series data can accumulate accelerations in all directions from multiple sensors. Any acceleration that exceeds a practical value should be replaced by an interpolated/extrapolated value.

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

Acceleration (a) is defined as the product of M and G, M is an operator-defined value, and G is the gravitational acceleration (9.80 m/s^2).

Any acceleration values exceeding M*G are replaced with operator-defined interpolated/extrapolated values. A counter, M5, is initially set to 0 and is incremented by one as each point is replaced. The operator defines up to N points that may be replaced.

Flags	Condition	Codable Instructions
Fail = 4	N/A	N/A
Suspect = 3	Reported value is outside of operator-selected span.	If a > (M * G), increment N= N + 1, then interpolate, flag = 3.
Pass = 1	Data are good.	If a ≤ (M * G), flag = 1.

Test exception: Applies only to buoys using accelerometers.

Example: UNESCO (1993) recommends M ≥ 0.5. Include in % count. The operator defines M and N, and the method of replacement.

3.3.3 LT Time Series QC Tests for Bulk Wave Parameters

The next tests operate on the long-term wave observation time series of fundamental, derived wave characteristics known as bulk wave parameters, which consist of significant wave height (H_s), peak wave period (T_p), peak wave direction (D_p), and wave spread. Many of the QC checks on the bulk wave parameters are applicable to any measurement system. Several tests include the correlation with data collected by other operators. QARTOD participants have recognized the importance of full co-variance testing but also noted the challenges. Such testing may not yet be ready for operational implementation but is mentioned here because, in rare instances, it can be done.

LT Time Series Check Ratio or Check Factor (Test 14) - Strongly Recommended

The check ratio or check factor, R(*f*), is loosely defined as the ratio of vertical-to-horizontal wave orbital motions. R is more formally defined by:

$$R(f) = \left\{\frac{1}{\tanh(k(f)h)}\right\} \bullet \sqrt{\frac{C11(f)}{C22(f)+C33(f)}}$$

where:

f is the frequency
C11(*f*), C22(*f*), and C33(*f*), are the cross-spectra of heave, pitch, and roll, respectively.
k(*f*), is the wave number,
h is the water depth, and
tanh is the hyperbolic tangent function.

This check ratio is a function of frequency and depth and should theoretically be 1.0 for relatively deep water waves. But, it tends to deviate substantially from that value at periods longer than the peak frequency and at short periods outside the response range of the buoy.

The operator should choose one of the following methods of the check ratio test:

1) Compute at the peak wave energy period and at a short period (but within response range of the buoy) flag values outside the range of 0.9 to 1.1; or
2) Test at least three frequencies distributed one each in the low, mid, and high frequency ranges; or
3) Compute the percentage of all frequencies whose check ratio is within acceptable limit of 1.0, and flag if the percentage is outside of an established criterion.

Ratio of vertical-to-horizontal wave orbital motions.		
The check ratio or check factor, R, is a function of frequency, with a nominal value near 1.0. When a fail or suspect check factor occurs, bulk wave parameters should be flagged.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	N/A	N/A
Suspect = 3	If R, the ratio of vertical to horizontal wave orbital motions, is not in the range of 0.9 to 1.1, data are suspect.	If R < 0.9 or R > 1.1, flag = 3
Pass = 1	Data are good.	If R ≥ 0.9 or R ≤ 1.1, flag = 1.
Test exceptions: Applies only to directional wave sensors that measure the cross-spectra—not to single-point altimeters, pressure sensors, or pressure-sensor arrays.		
Test specifications: Should be approximately 1.0. **Example:** Range defined as 0.9 to 1.1.		

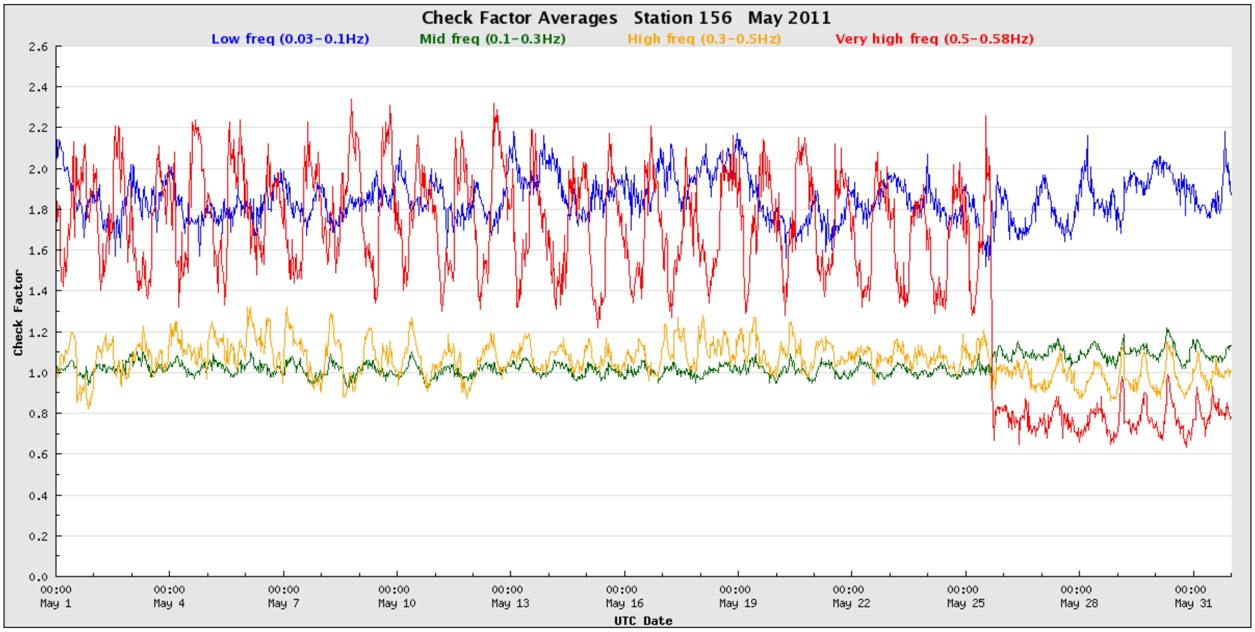

Figure 3-5. The plot shows an example of check or R factor data calculated at four different frequencies. The very high frequency data (red line) shows an abrupt shift after cleaning the heavily bio-fouled buoy hull, indicating the buoy had not been following short period waves due to the increased buoy mass. Selection of the appropriate threshold for the check ratio or check factor test permits detection of the problem before cleaning. (Graphic courtesy of SIO/CDIP)

LT Time Series Mean and Standard Deviation (Test 15) - Strongly Recommended

This test applies to all in-situ wave measuring systems and most bulk wave parameters (few operators will test wave spread). Series mean values are compared to thresholds defined by the operator. Thresholds are determined by an operator-defined mean plus an operator-defined allowable variance from the mean.

Time series value is within operator-provided mean and standard deviation.		
Check that TSVAL value is within limits defined by the operator. Operator defines the period over which the mean and standard deviation are calculated and the number of allowable standard deviations (N).		
Flags	**Condition**	**Codable Instructions**
Fail = 4	N/A	N/A
Suspect = 3	TSVAL is outside operator-supplied MEAN plus/minus N * SD.	If TSVAL < (MEAN - N * SD) or TSVAL > (MEAN + N * SD), flag = 3.
Pass = 1	TSVAL passes test.	If TSVAL ≥ (MEAN – N * SD) and TSVAL ≤ (MEAN + N * SD), flag = 1.
Test exception: None.		
Test specifications to be established locally by the operator. Suspect Flag, Fail Flag if value exceeds threshold. Operator-defined, location dependent. **Example:** Mean calculated over 24 hours, N = 2.		

LT Time Series Flat Line (Test 16) - Required

This test checks for invariate observations and can be applied to all bulk wave parameters that are reported.

When some sensors and/or data collection platforms fail, the result can be a continuously repeated observation of the same value. This test example compares the present observation (PO_n) to a number (REP_CNT_FAIL or REP_CNT_SUSPECT) of previous observations. PO_n is flagged if it has the same value as previous observations within a tolerance value, EPS, to allow for numerical round-off error. The value chosen for EPS should be selected carefully after considering the resolution of the sensor, the effects of any data processing, and the performance of the test. Similar tests evaluating first differences or variance among the recent observations may be implemented.

Note that historical flags are not changed.

Flags	Condition	Codable Instructions
Fail = 4	When the five most recent observations are equal, PO_n is flagged fail.	$PO_n \neq 0$ AND For I = 1,REP_CNT_FAIL PO_n - PO_{n-i} < EPS
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, PO_n is flagged suspect.	For I = 1,REP_CNT_SUSPECT PO_n - PO_{n-I} < EPS
Pass = 1	Applies for test pass condition.	

Test Exception: None.

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

LT Time Series Operational Frequency Range (Test 17) - Required

The operational frequency test applies to all in-situ wave measuring systems that report spectral data, either directional or non-directional. Spectral data should be reported only for the valid range of frequencies (selected by the operator as appropriate to the region and sensor). The operator may choose to use instrument frequency ranges provided in the manufacturer's specifications.

Check for validity of the operational frequency range.

Defined by the instrument and the environment.

The operator defines the instrument minimum frequency (IMINF) and instrument maximum frequency (IMAXF), which are usually provided by the manufacturer. The operator may also define the local minimum frequency (LMINF) and local maximum frequency (LMAXF). The local maximum and minimum may be location-, season-, and/or sensor-dependent.

FVAL is the value of the frequency.

Flags	Condition	Codable Instructions
Fail = 4	Frequency reported is outside the manufacturer's reported frequency range; data are failed.	If FVAL > IMAXF or FVAL < IMINF, flag = 4
Suspect = 3	Frequency reported is outside the local reported frequency range.	If FVAL > LMAXF or FVAL < LMINF, flag = 3
Pass = 1	Frequency reported is within the local reported frequency range; data are good.	If FVAL ≥ LMINF and FVAL ≤ LMAXF, flag = 1

Test exception: This test is used by those who report wave spectra (non-directional and directional).

Test specifications to be established locally by the operator.
Example: IMINF = 0.334 Hz, IMAXF = 0.625 Hz, LMINF = 0.05 Hz, LMAXF = 0.5 Hz.

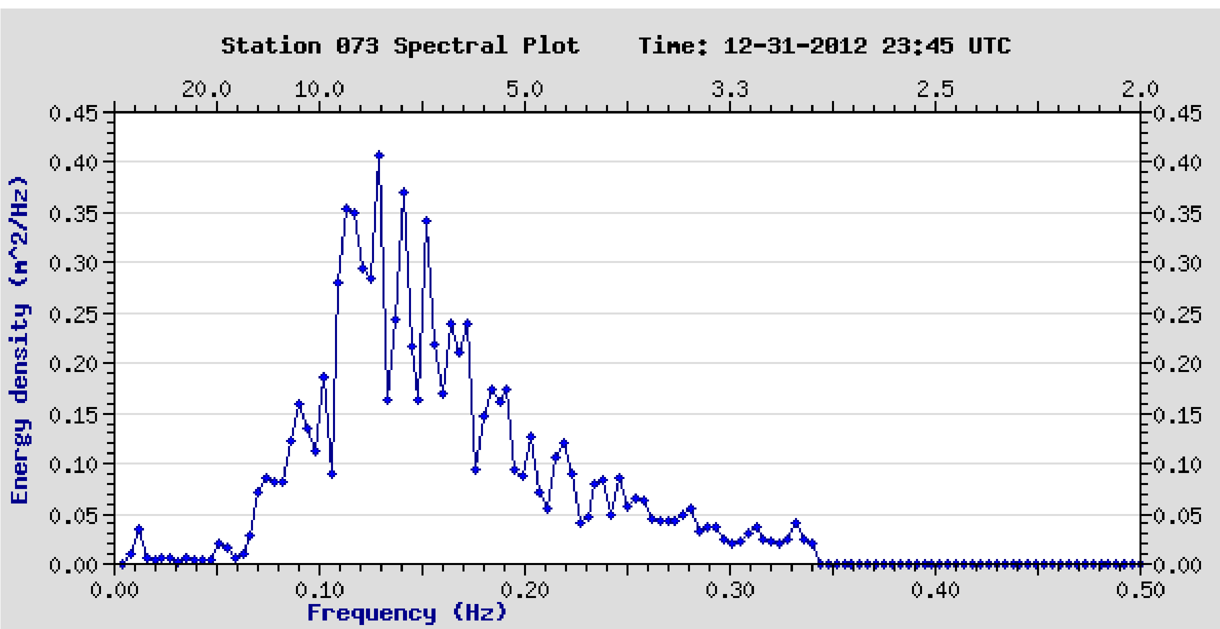

Figure 3-6. The plot shows an example of data that would not pass an LT time series operational frequency range test. The energy at 0.01 Hz is beyond the manufacturer-specified low frequency detection capability of the buoy. (Graphic courtesy of SIO/CDIP)

LT Time Series Low-Frequency Energy (Test 18) - Required

The incident low-frequency energy test determines if incident energy levels at low frequencies are within allowed values as defined by the operator. Low-frequency gravity waves are constrained by basin dimensions and depth. Thresholds are based upon the available fetch and the direction of swell waves, so the test could be carried out as a function of swell direction.

Note that this test may need to have broad limits or may not be appropriate for data collected in harbors, bays, or coastal sites with highly dissipative beaches. Infragravity waves with periods in the range of 30 seconds to several minutes can often dominate the energy spectra in these regions, but such waves are beyond the scope of this document at present.

Check low-frequency energy and direction.		
Location-defined. Operator defines minimum energy (MINE) and maximum energy (MAXE) as determined by available fetch and swell wave direction at low frequencies. These values are compared to the energy (NRG) levels in the low frequencies.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	N/A	N/A
Suspect = 3	If energy is less or greater than the expected values, data are suspect.	If NRG < MINE or NRG > MAXE, flag = 3
Pass = 1	Energy levels are within the expected values.	If NRG ≥ MINE or NRG ≤ MAXE, flag = 1
Test Exception: None.		
Test specifications to be established locally by the operator. **Example:** Operators to provide examples as procedures are implemented.		

LT Time Series Bulk Wave Parameters Max/Min/Acceptable Range (Test 19) - Required

The bulk wave parameters are to be tested against operator-provided ranges, including heights (usually significant wave heights), periods, directions, and spreading parameters.

A test for maximum, minimum, and acceptable range for bulk wave parameters.

The operator should establish maximum and minimum values for the bulk wave parameters: wave height (WVHGT), period (WVPD), direction (WVDIR), and spreading (WVSP) (if provided). If the wave height fails this test, then no bulk wave parameters should be released. Otherwise, suspect flags are set.

Operator supplies minimum wave height (MINWH), maximum wave height (MAXWH), minimum wave period (MINWP), maximum wave period (MAXWP), minimum spreading value (MINSV), and maximum spreading value (MAXSV).

Flags	Condition	Codable Instructions
Fail = 4	Wave height fails range test.	If WVHGT < MINWH or WVHGT > MAXWH, flag = 4 for all parameters.
Suspect = 3	Wave period, wave direction, or spreading value fails range test.	If WVPD < MINWP or WVPD > MAXWP, flag = 3. If WVDIR < 0.0 or WVDIR > 360, flag = 3. If WVSP < MINSV or WVSP > MAXSV, flag = 3.
Pass = 1	Bulk parameters pass tests.	If WVHGT ≥ MINWH and WVHGT ≤ MAXWH, and If WVPD ≥ MINWP and WVPD ≤ MAXWP, and If WVDIR ≥ 0.0 and WVDIR ≤ 360, and IF WVSP ≥ MINSV and WVSP ≤ MAXWV, flag = 1

Test exceptions: None.

Test Specifications are operator-defined and parameter and location dependent.
Reject entire record if WVHGT exceeds limit, otherwise reject individual bulk wave parameter.
Example: MINWH = 0.05 m, MAXWH = 8 m, MINWP = 2 seconds, MAXWP = 16 seconds, MINSV = 0.07, MAXSV = 1.0

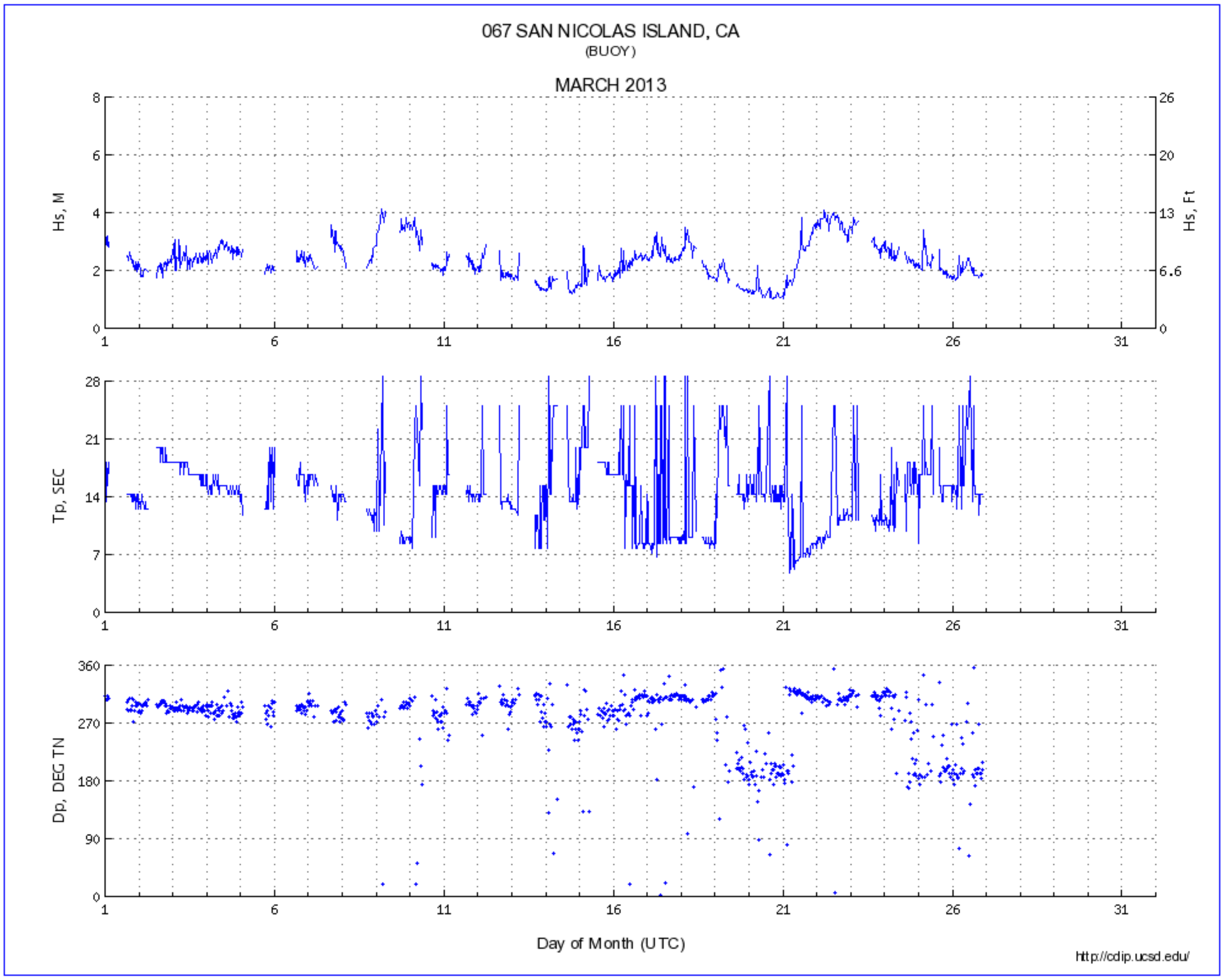

Figure 3-7. The plot shows an example of data that may not pass the LT time series bulk wave parameters max/min/acceptable range test. The central plot shows multiple instances where the peak wave period (T_p) exceeds an operator-provided maximum wave period. (Graphic courtesy of SIO/CDIP)

LT Time Series Rate of Change (Test 20) - Required

This test evaluates the rate of change with time, i.e., a maximum limit is placed on the rate of change between successive data points, or specific data points at defined times. It can also be considered a spike test.

A test for acceptable rate of change.		
This test is applied only to wave heights, average wave periods, and parameters that are a result of expected changes due to winds and constitute an integration of the whole or relevant portions of the spectrum (e.g., wind waves). The test described here uses significant wave height as an example. The operator selects a threshold value, MAXHSDIFF, and the two most recent data points $H_s(n)$ and $H_s(n-1)$ are checked to see if the rate of change is exceeded.		
Flags	**Condition**	**Codable Instructions**
Fail = 4	Rate of change exceeds threshold.	$\|H_s(n) - H_s(n-1)\|$ > MAXHSDIFF, flag = 4
Suspect = 3	N/A	N/A
Pass = 1	Test passed.	$\|H_s(n) - H_s(n-1)\| \leq$ MAXHSDIFF, flag = 1
Test exception: Does not apply to discrete parameters such as peak period or peak direction that may change abruptly. Some operators disable this test during known extreme storms, when many wave characteristics might change quickly.		
Test specifications to be established locally by the operator. **Example:** MAXHSDIFF=2 m. Alternative rate of change tests are documented in NDBC 4.1.2 Time continuity. (NDBC 2009)		

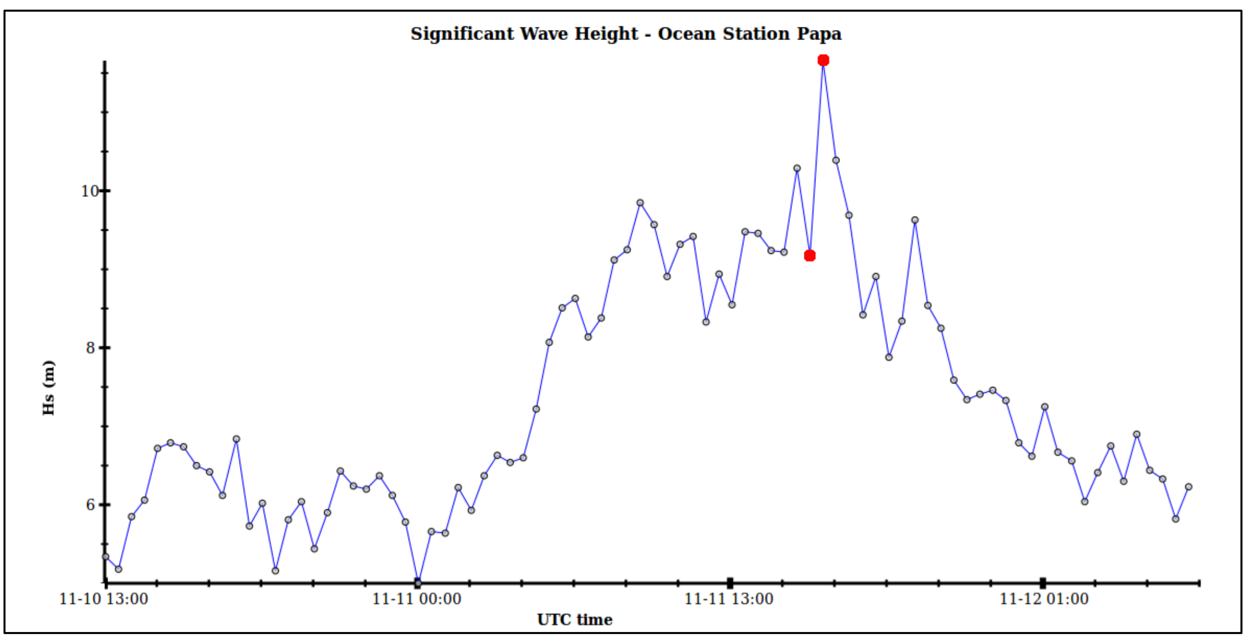

Figure 3-8. The plot shows an example of data that may not pass the LT time series rate of change test. The time series of significant wave height (H_s) shows a rate of change (highlighted by the red dots) that may be excessive. (Graphic courtesy of SIO/CDIP)

Neighbor Check (Test 21) - Suggested

Comparison of bulk parameters 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.

Ideally, redundant wave 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 prohibits such a deployment in most cases.

However, there are very few instances where a second sensor is sufficiently proximate to provide a useful QC check. Just a few hundred meters of horizontal separation can yield greatly different results. Only an experienced operator can determine the extent to which adjacent waves sensors would agree. Nevertheless, the test should not be overlooked where it may have application.

This test is similar to the LT time series wave parameters max/min/acceptable range (test 19), where the agreement is constrained to matching the second wave sensor within allowable difference (Delta). 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, bulk parameter data from one site (W1) are compared to a second site (W2).

Flags	Condition	Codable Instructions
Fail = 4	Because of the dynamic nature of wave fields, no fail flag is identified for this test.	N/A
Suspect = 3	The difference threshold between a bulk wave parameter at W1 and W2 is exceeded.	$\|W1 - W2\| > Delta$, flag = 3
Pass = 1	The difference threshold between a bulk wave parameter at W1 and W2 is not exceeded.	$\|W1 - W2\| < Delta$, flag = 1

Test exception: Surface wave measuring systems may not be subject to the same wave field.

Test specifications to be established locally by operator.
Example: $|W1H_s - W2H_s| > \text{Delta } H_s$

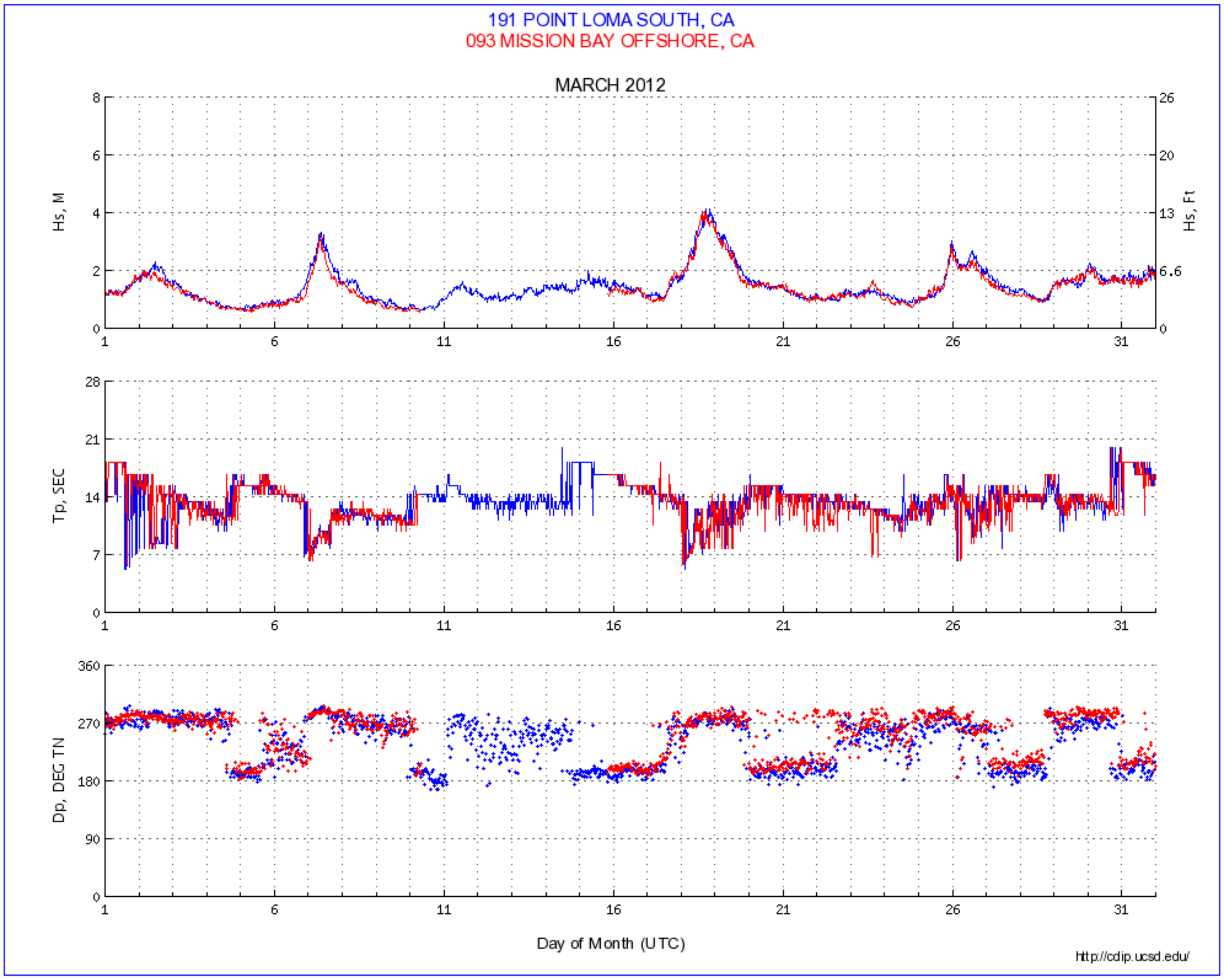

Figure 3-9. The plot shows an example of data that may not pass the neighbor check test. While several differences can be seen between these two buoys, the most noticeable difference is in the peak period (T_p) on day 1. Point Loma often reported a much lower T_p than did Mission Bay. (Graphic courtesy of SIO/CDIP)

4.0 Summary

The QC tests in this in-situ waves document have been compiled from QARTOD workshops (QARTOD 2003-2009). Test suggestions came primarily from ADCP and buoy operators, which were refreshed in the 2015 updated manual where additional wave observing technologies were included. Wherever possible, redundant tests have been merged. The tests described here are designed to support a range of wave 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. It is the responsibility of the users to 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.

The 21 QC tests identified in this manual apply to wave observations from accelerometer-based buoys, ADCPs, ADVs, pressure sensors, GPS-based buoys, and other technologies. The tests fall into three groups: required, strongly recommended, and suggested. Some tests apply only to ADCPs, others only to sensors providing an ST time series in real-time, and some to all wave observations. The individual tests are described and include codable instructions, output conditions, example thresholds, and exceptions (if any). Several also include a graphic depiction of real data that would fail the test, providing clarity and justification for the test.

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, but they 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 as well as a sincere interest in selecting the proper thresholds to maximize the value of their QC effort. Use of existing standards such as those provided by the WMO or NOAA National Weather Service should be strongly considered.

Future QARTOD reports 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 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 or moored platforms. The tests do not include post-processing, which is not conducted in 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.

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Supporting Documents Found on the QARTOD Waves Website

(https://ioos.noaa.gov/ioos-in-action/wave-data/)

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.

NDBC Handbook of Automated Data Quality Control

Data Quality Control in the U.S. IOOS

Manual of Quality Control Procedures for Validation of Oceanographic Data

Real-Time Quality Control Tests for In-Situ Ocean Surface Waves

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Appendix B. Quality Assurance

A major pre-requisite for establishing QC standards for wave measurements is a strong QA 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. Steele et al. (1985) provide details on the theory and calibration of wave measurements made by buoys. 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 following sections suggest ways to ensure QA by using specific procedures and techniques.

B.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.

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 towards corporate conglomeration, those wishing to employ a consensus standard should ensure that the different manufacturers are truly independent.

Post-deployment calibrations, even a limited number, can provide a gage of the confidence in the quality of the data, estimate possible drift characteristics, and establish the accuracy of real-time quality control measures during an entire deployment (Riley and Bouchard 2015).

B.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 provides several important messages: a) a measure of the accuracy and precision achieved by an operator; 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 operator 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 manufacturer and providing competition that is often required by procurement offices.

B.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 antifouling 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 – manufactured by Johnson and Johnson Inc.; 1 Johnson and Johnson Plaza, New Brunswick, NJ 08933 (732) 524-0400).
- Remember that growth is sensor, depth, location, and season dependent; plan instrument recovery frequency accordingly.
- Plan for routine changing or cleaning of sensor as necessary.
- Check with calibration facility on which antifoulants 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.

B.4 Common QA Considerations

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

- Pre-deployment calibrations on every sensor
- Post-deployment calibrations on every sensor, plus in-situ comparison before recovery
- 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.

B.5 QA Levels for Best Practices

Several 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. Nevertheless, operators should always strive to achieve the best possible level of QA. If they are unable to do so, then they should provide valid justification. Operators must show due-diligence in maintenance of their systems. 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 are pre- and post-deployment calibration checked.
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.

B.6 Additional Sources of QA Information

Wave 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 testbed 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
- CDIP - http://cdip.ucsd.edu/?nav=documents&sub=index&units=metric&tz=UTC&pub=public&map_sta ti=1,2,3&xitem=gauge
- 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
- WOCE - https://www.nodc.noaa.gov/woce/
- NDBC - 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 (do not 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.
    - 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:
    - o Checking nearby stations;
    - o Making historical data comparisons (e.g., long-term time-series plots, which are particularly useful for identifying long-term bio-fouling or calibration drift.)