Real-Time Quality Control Experiences using QARTOD in Australian Ports

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Abstract
Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) is a set of transparent, state-of-the-art testing procedures that have been optimised for operational under keel clearance management purposes. This paper aims to describe the QARTOD framework and discuss its application for wave and tide data in two Australian ports. The content of the paper includes an examination of the effectiveness of the recommended testing processes, primarily for waves, describing benefits of the approach and lessons learned along the way.

For wave processing, QARTOD has a range of tests covering data processing levels of both raw displacements and parameters. A standard plot output to visualise the processing and output has been developed for these tests. This diagnosis plot quickly enables supporting personnel to critically review and investigate the effectiveness of the applied QC tests, while also reviewing displacements, power spectra and parameters for any given record.

These transparent procedures have been found to be very effective for real-time metocean data quality control at the two ports.

Keywords: monitoring, quality control, instrumentation, ports

1. Introduction

1.1 QARTOD Framework

1.1.1 QARTOD Background

The QARTOD project originated in 2003 as a grass roots effort that involves an ongoing collaboration between numerous United States (US) federal and state based data use agencies, together with sensor manufacturers and operators. In 2012, the US federal agency National Oceanographic and Atmospheric Administration (NOAA) officially adopted the project through the US Integrated Ocean Observing System (IOOS®). The key objectives of QARTOD include sustaining a process for establishing quality assurance (QA) and quality control (QC) procedures for 26 core variables, documenting these through written manuals, as well as coordinating these with other international ocean observation efforts.

The QARTOD manuals are a set of living documents that reflect the best practice QC testing procedures for real-time data. Their purpose is 'to provide guidance for real-time QC using an agreed-upon, documented, and implemented standard process' [4].

In summary, QARTOD represents the best practice QC procedures coming from the US, developed over several decades of operator experience using a large variety of instruments.

1.1.2 QA Verses QC

The process of maintaining data quality from a metocean device network relies on both quality assurance (QA) and quality control (QC). QA processes are characterised by QARTOD as those that lay the foundation of the data quality that is output by metocean devices. QC processes further optimise the supplied data and require both automation and human intervention. While the focus of the manuals is in detailing QC tests, they also provide various general best practise QA descriptions, as well as device type specific considerations.

1.1.3 Conventions

A consistent set of QC flags are adopted by all QARTOD manuals that match the 'primary level' scheme presented in the Intergovernmental Oceanographic Commission (IOC) 54:V3 [2]. These consist of 5 flags for 'pass', 'not evaluated', 'suspect', 'fail' and 'missing'. The framework allows for additional flags to be incorporated.

A further test hierarchy convention has been adopted across the QARTOD manuals that classify individual tests as either 'required', 'strongly recommended', and 'suggested'. While these may form a minimum standard, it enables situation specific flexibility. Individual tests are unique for different variables.

Only two core variables are discussed in this paper, namely those for In-Situ Surface Wave Data, and Water Level observations. These have twenty-one and eleven possible tests, respectively.

1.1.4 Situation Configured QC

Under this framework, the QARTOD tests enable numerous QC configuration parameters to be optimised. There is the flexibility to tailor the QC for specific devices, locations and uses. Once configured, it is important to evaluate the effectiveness and revise a given configuration, which can be done through a manual monitoring plan, as well as periodic statistical evaluation.

1.2 Application

OMC International (OMC) operates Dynamic Under Keel Clearance (DUKC®) software for twenty-five ports internationally, including for Pilbara Ports Authority at Port Hedland, and Fremantle Ports. This software relies on real-time data streams of wave spectra and water levels, amongst others, to provide operational sailing windows for the safe and load optimised navigation of cargo vessels through draft restricted coastal channels. Ensuring reliable, best practice, quality controlled real-time metocean data across the maritime ports industry is therefore an aim that OMC strongly supports and encourages.

The QARTOD implementation described in this paper has been focused on optimising QC and processing for input into the DUKC®. As only wave energy with periods longer than approximately seven seconds are relevant for large vessel wave response calculations, spectra from the swell bands, as well as other swell wave parameters receive a particular QC focus. Availability of real-time data is also of critical importance for transiting vessels under DUKC®, and can make the difference between a vessel sailing, or a cancelled transit. The QC processing and parameters have been configured to provide acceptable under keel clearance conservatism and real-time data availability, rather than having a focus purely on identification and rejection for failing QC.

2. Implementation

In terms of structure, QARTOD provide a suite of tests that are either 'required', 'strongly recommended' or 'suggested'. The prescriptiveness of these tests varies, but typically the manuals provide a degree of flexibility in how the operator implements the tests. Generally, the phrase "Test specification to be established locally by the operator" is used to provide the level of customisation required for the operator's circumstances.

OMC's approach to implementation has been to provide the data value, the overall QC result and also the results and details of each QC check for each piece of processed data. Not all output formats will have the facility to include the full detail of QC data, but the QC results are available when required.

2.1 Software

The OMC QARTOD software has been implemented in Haskell, a modern programming and scripting language. The code is written in a functional style to facilitate testing and reliability. In this scenario, functional has the formal definition of all functions depending purely upon their inputs and in general, not modifying any external state or inputs. The benefit of this approach is that certainty is gained over the behaviour of the code and functions.

An extensive suite of unit, integration and regression tests have been developed, alongside a number of manual checks of plot outputs. These automated tests are run automatically after every change is committed to our software repository. In terms of test coverage, the entire suite is approaching 100% coverage, with the core processing and QC algorithms all having 100% coverage of all cases.

The currently deployed version has no visible user interface. However, the version under development will have a web interface to provide a dashboard of device statuses alongside basic graphs of sensor performance. In itself, this functionality is not intended to be a complete metocean information system; it is targeted more at a support engineer or system manager to quickly debug any data or connectivity issues. The full range of metocean information system requirements is met by other OMC or third party software outside the scope of this paper.

Typically, the data to be processed and quality controlled from the sensors arrives as a stream over either a serial line or network socket. OMC's initial architecture for processing this data is to have a process store that streams into a SQL database (either SQL Server or PostgreSQL) for subsequent processing. A series of scheduled tasks then read this database, parse and process the data as required and subsequently perform QC checks on the various stages in this processing.

Following the processing and QC, the outputs (processed data, QC summary, QC details and potentially other artefacts) are stored for later processing steps, analysis and archiving.

2.2 Devices and Data Streams

Pilbara Ports Authority at Port Hedland operates several Datawell DWRG buoys, which utilise a GPS wave sensor. OMC has been responsible for the processing and QC of these devices since September 2015, and the QARTOD wave implementation example described in this paper is specifically optimised for this device type.

OMC is in the process of implementing QARTOD wave and water level QC on the metocean devices of Fremantle Ports utilised by the DUKC®. These include Digiquartz pressure sensors for tides and waves, Vegapuls water level radar sensors, as well as Datawell accelerometer buoys. The experiences gained from implementing QARTOD water levels in this paper are thus limited to this initial implementation at Fremantle Ports.

3. Wave QC Testing Processes

3.1 Tests Implemented

The latest QARTOD wave manual [3] lists twenty-one possible tests. Eight of these are specific only to acoustic profiler wave sensors and are not discussed in this paper. The tests that have been implemented are listed in Table 1. They apply to short term (ST) or raw data and long term (LT) or processed time steps.

Table 1 Wave tests implemented for optimised DUKC®

Type	Description
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(20)
Strongly Recommended	ST Time Series Gap (Test 9) ST Time Series Spike Test (Test10)

OMC has targeted the implemented tests to provide the greatest value. As such, a number of 'strongly recommended' and 'suggested' tests are not yet implemented. These include ST Time Series Acceleration, ST Time Series Range Test, ST Time Series Segment Shift, LT Time Series Check Ratio, and LT Time Series Mean and Standard Deviation, and Neighbour Check. These are likely to be implemented following either a QC review process recommending their implementation or in the next major upgrade of functionality. Over the year of operation, the present level of QC tests has operated well.

3.2 Review of Implemented Wave Tests

Starting with the raw data, and then moving onto the processed data tests, a brief summary of each of the tests is presented.

3.2.1 ST Time Series Gap Test 9

This is a simple logic test to determine if a gap is longer than a given threshold. The results are either a pass or fail QC flag.

3.2.2 ST Spike Test 10

QARTOD identifies spikes as points more than M configurable times the standard deviation from the mean of a ST time series of water levels. The spike test checks and corrects spikes by taking an average of the immediate adjacent values, for a configurable number of iterations. A total maximum number of spikes is the third configurable parameter. The results are either a pass or fail flag.

Being able to correct spikes and thus retain a continuous complete water level record for Fourier wave analysis is very beneficial. Various thresholds were tested over a sufficient length of raw data covering as many varied observed effects as possible. To do this, it was important to initially review this test's configuration effectiveness regularly during the initial configuration. Figure 1 illustrates the removal and correction of spikes caused by transmission errors from a DWRG buoy.

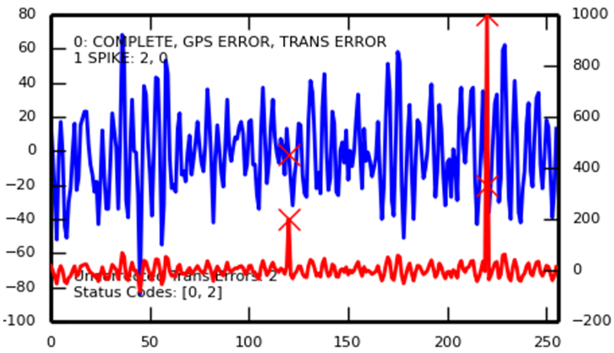

Figure 1 A spike test corrected time series plot of a 200 second segment of water levels. The original red line contains two spikes in the original iteration, and none after having been corrected (blue).

3.2.3 LT Flat Line Test 16

This test checks for continuously repeated observations, within a configurable tolerance, and can be applied to all wave bulk parameters. It compares the present observation to a number of configurable previous observations of different levels, enabling both suspect and fail QC flags.

3.2.4 LT Operational Frequency Range Test 17

This test applies to all systems reporting spectral data. Maximum and minimum instrument frequency limits being exceeded result in a fail, while seasonal or location specific limit exceedance result in a suspect QC. When possible, OMC prefers to calculate its own spectra onto an internal standard frequency base. To achieve this, this test has been extended to check the total number of spectral ordinates match, and thus effectively functions as a recurring test of the spectral calculations.

3.2.5 LT Low-Frequency Energy Test 18

This test checks that the low frequency energy falls within configurable limits. The QARTOD manual specifies that only pass and suspect QC flags are available. For DUKC® optimised purposes, the parameter selected is the swell wave height.

3.2.6 Low-Frequency GPS Energy
DWRG data streams are known to have low frequency energy introduced from GPS dropouts, as shown in Figure 2. When processing data from these devices, OMC has customised test 18 to maximise the availability of real-time data. Rather than introducing a GPS gap repair solution to remove the erroneous low frequency energy, a process was introduced to flag as suspect or fail any 200s segments of water levels that were found to have any Hmo_25s+ wave heights greater than configurable thresholds. A further criterion introduced was a limit on the quantity of GPS dropouts and uncorrected transmission error flags occurring in a segment, or an adjacent one.

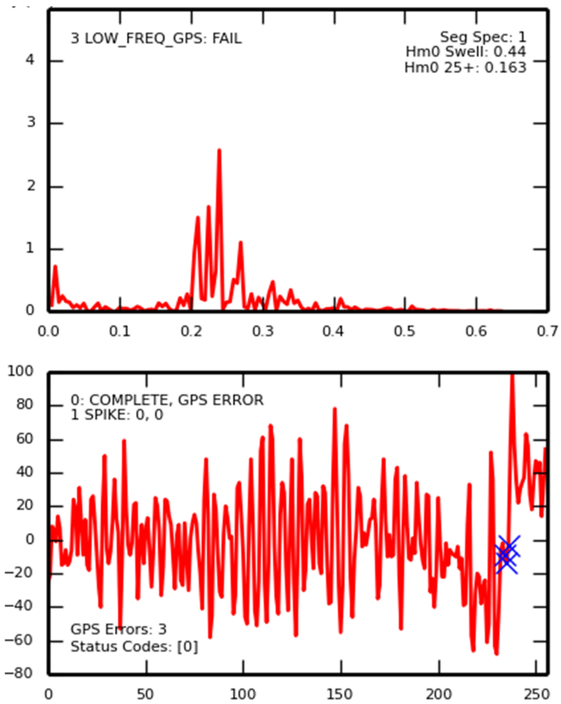

Figure 2 A low frequency GPS energy test flags a 200 second (256 displacement) segment of water levels (bottom plot) and corresponding segment spectra (top plot) as fail. The presence of three GPS errors (blue stars) introduce erroneous low frequency energy, which is visible in both plots, and labelled as having a Hmo_25s+ wave height contribution of 0.163m.

The configurable parameters required careful consideration to strike a balance between passing unacceptable segment spectra and rejecting too many, to keep acceptable data available as an input to the DUKC®. While this occasionally does introduce erroneous spectra, in later processing, up to 9 available segment spectra are further averaged to determine a half hour averaged spectrum. In this way, any passed energy produces a minimal conservative vessel wave response calculation in the DUKC®.

More details on how this test is used are discussed in section 4.1.

3.2.7 LT Bulk Wave Parameters Range Test 19
This test checks wave parameters such as wave height, direction, period and spreading against configurable ranges. If wave height is outside the range then all parameters are flagged as fail, however for the other parameters they are only flagged as suspect.

3.2.8 LT Rate of Change Test 20
This basic test places a maximum limit on the difference between successive wave heights. QC flags are either pass or fail.

3.3 Configuration Process

A general experience applicable to all the tests was that careful investigation of the configurable parameters was required. Configuration of tests requires data analysis of a sufficient length to determine, for example, local and seasonal thresholds. Consequently, it was found that configuration parameters needed to be initially reviewed more frequently, then periodically thereafter.

4. Wave QC Application and Monitoring

This section describes the logic used to link the various individual short and long term time series tests to obtain an overall QC real-time result. It also details the methodology that was developed to review and monitor the effectiveness of the QC configuration.

4.1 Overall Wave QC Process

The overall process has five stages in converting raw 1.28 Hz water level displacements into a thirty-minute 'averaged spectrum'. QC flags are utilised in three of these stages. They include:

- ST data QC and processing;
- 200s 'segment spectra' calculation;
- Spectra QC;
- Averaged spectrum calculation; and
- LT time series data QC.

The case of a DWRG buoy has been used for illustrative purposes and is discussed in more detail below. It incorporates the Datawell wave processing methodology as described in their manual [1]. Details of the individual QARTOD tests can be found in section 3.2.

The first stage begins with parsing and translating Datawell 'vectors' from the receiver, then identifying the buoy's own GPS dropout flags, as well as identifying receiver error transmission status. Next, at a configurable interval, such as 15 minutes, the 1.28Hz displacements are grouped into 200s segments and checked for their completeness while controlling their timestamp. QARTOD ST time series tests 9 and 10 are then conducted for each segment, applying QC flags to a segment level.

The second stage calculates segment spectra as described in Datawell [1].

The third stage applies QARTOD LT time series test 17 and the low-frequency GPS energy test to identify QC flags on the segment level.

The fourth stage calculates an averaged spectrum by averaging as many of the 9 good and suspect segments as possible to give the half hour average spectrum. To maximise data availability while maintaining segments to be representative of the half hour, a configurable matrix of good and suspect segments determines if the overall average spectrum is good, suspect or fail.

Finally, the fifth stage applies QARTOD tests 18,19 and 20 on consecutive average spectra and their derived parameters.

This example illustrates that utilising raw displacements, rather than only having access to on-board processed parameters, has enabled more processing options. In moving from an initial QC process phase, relying just on basic parameter checks and GPS error flags to the process based on QARTOD above, a very substantial reduction of missing data was achieved.

4.2 Wave QC Review Plot

To monitor the effectiveness of the processing and configuration parameters, a single page check plot was developed. Figure 3 illustrates an example where only five of the available nine segments have been averaged to give an averaged spectrum that is still representative of the sea state. This has enabled a real-time spectrum to be obtained for operational use, when previously this entire spectrum may have been rejected. This case is often observed at times of building storms when the limits of the DWRG buoy sensors are reached, due to breaking waves covering the GPS sensor.

In the half hour captured in Figure 3, numerous GPS errors are seen. These introduce artefacts that result in spurious low frequency wave energy within and also in adjacent segments. Figure 3 also illustrates how the careful selection of configuration parameters has enabled the correct selection of the available two suspect spectra. With the configuration requiring at least five good or suspect segment spectra, the processing is set to select the suspect segment with the lower Hmo_25s+, within acceptable configurable limits.
The check plot is a valuable tool for OMC's 24/7 support department. Before a wave source is connected to the DUKC® system, this automated check plot enables a quick, comprehensive review of the spectrum.

5. Water Level QC Testing Processes

The latest QARTOD water level manual [4] lists eleven possible tests, as shown in Table 2. At the time of writing, these were in the process of being implemented.

Table 2 Available QARTOD water level tests

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

The focus of the specified water level QC tests is the water level itself. Often, comparison with other variables such as astronomical forecasts is useful in determining the validity of a data point. Direct scope for including this is provided through Test 9 – Multi-Variate Test or Test 11 – Neighbour or Forecast test. The Multi-Variate test is described as a research project and "an advanced family of tests" and "that it is doubtful anyone is conducting tests such as these in real time".

OMC's approach in this area has been to treat each of the tests as applicable to either residuals from astronomical predictions or the raw water level. This provides greater power for the tests, particularly in regions with large tidal ranges and rates of change where the difference from a residual may provide a greater indication of an error than a direct measurement.

6. Conclusions

Overall, OMC has found the implementation of QARTOD to be very advantageous. Benefits include the level of customisation and configuration, access to best practice, and generally having greater confidence in data being used by the DUKC®. The implementation of QARTOD was found to be no trivial matter and, once operational, was found to require monitoring and review to maintain optimum levels.

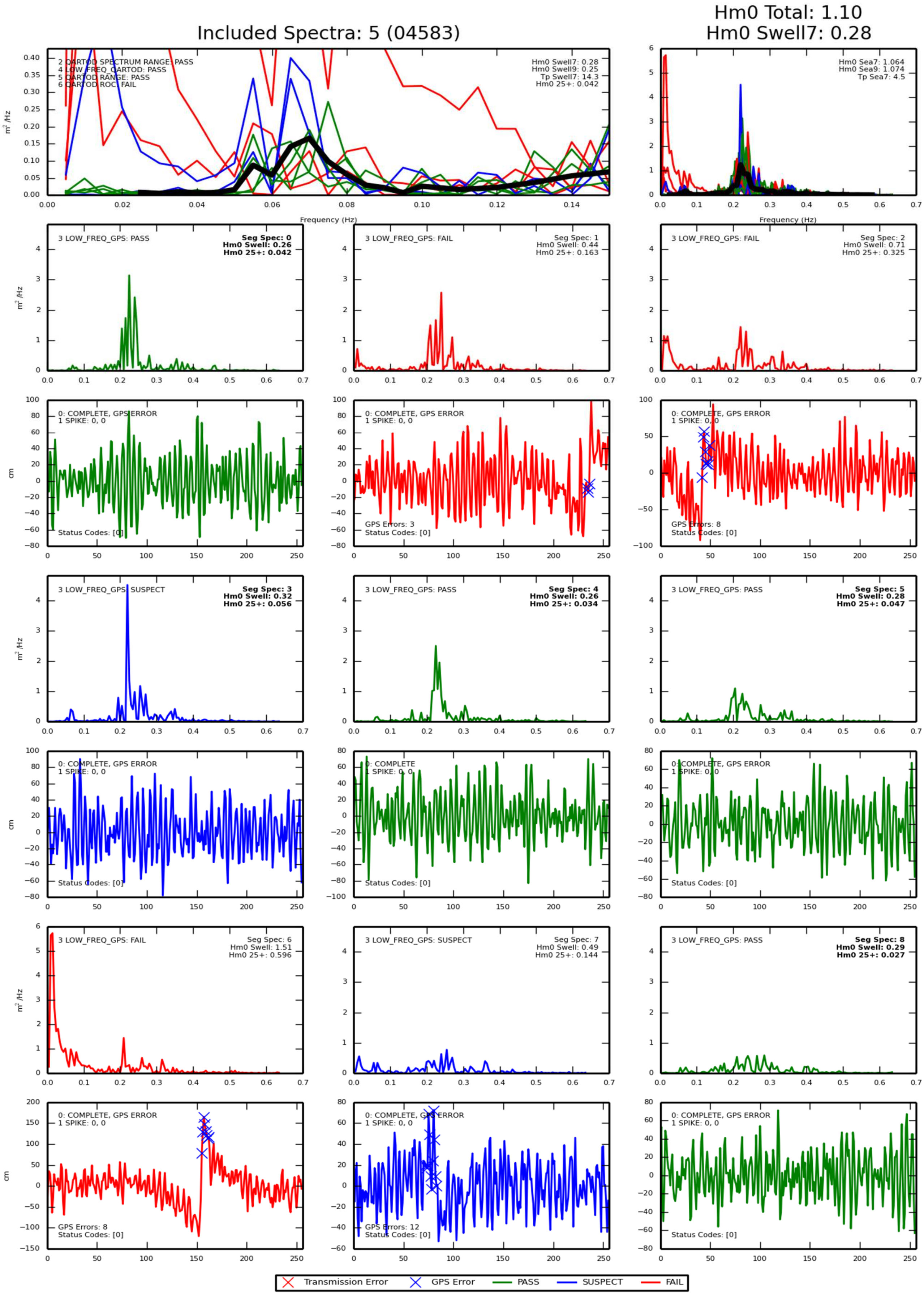

Figure 3 A wave QC check plot. The top row displays the average spectrum over the swell frequency range on the left and over the entire range on the right. The lower rows display nine 200s segment spectra and displacement plot pairs of either green, blue or red indicating pass, suspect or fail respectively. The top left plot provides an overview of how the average spectrum (thick black line) has been averaged from the available passed and suspect segment spectra.

In the example discussed in this paper, the QC processing and parameters have been configured to provide an acceptable balance between under keel clearance conservatism and real-time data availability. For waves, this was achieved by focusing on swell band parameters, and in the case of DWRG buoys, by customising the low frequency test to handle GPS drop out errors. This has helped achieve greater data availability to our real-time DUKC® software. In situations of high metocean data dropout rates, this can mean the difference between a vessel sailing through a channel, or a cancelled transit. To this end, the manuals and the flexibility of the described tests have been very beneficial.

Availability of raw data enables more processing options, rather than only having access to on-board processed parameters, which are known to contain errors. The advantage of working with raw data is that the processing and QC can be further optimised for the intended use. The DWRG example presented in this paper illustrates that utilising raw displacements, rather than only relying on on-board processed parameters, has enabled more processing and QC options. In moving from an initial QC process phase, relying just on basic parameter checks and GPS error flags, to the process based on QARTOD above, a substantial reduction of missing data was achieved.

Implementation of QARTOD is not a trivial matter that can be handed to a software team with an instruction to implement the manuals. The form of individual tests, the purposes the data will be used for and the interpretation of the results of multiple tests by subsequent processing steps all require careful consideration by experienced engineers aware of the uses the data will be put to.

The QARTOD manuals do not provide a description of how the individual tests can be linked together to provide a final operational result, available in real-time. This has been done intentionally to cater for the variety of operator capabilities, instrument sensors types and applications.

In the case of wave processing, a single page check plot was developed to monitor the effectiveness of the processing and configuration parameters. The check plot is a very valuable tool for OMC's 24/7 support department. Before a wave source is connected to the DUKC®, this automated check plot enables a quick, comprehensive review of the spectrum.

A general experience in working with the QARTOD methodology for both waves and tides was that careful investigation of the configurable parameters was required. Greater effort is needed in maintaining this type of customised QC containing many configuration parameters compared to a basic level of generic tests. It was found that configuration parameters needed to be initially reviewed more frequently, then periodically thereafter.

7. Recommendations

OMC recommends that higher levels of QC, such as QARTOD, be implemented for operational metocean data use.

OMC recommends that QARTOD QC, customised for DUKC®, be implemented at all ports operating with this software to obtain benefits such as greater real-time availability.

It is OMC's preference to obtain raw data to provide greater DUKC® optimised QC and processed data.

Monitoring QC effectiveness and review for a further level of QC optimisation is recommended.

On a finishing note, the manuals state 'that operators need the subject matter expertise as well as a sincere interest in selecting the proper thresholds to maximise the value of their QC effort.' This is something that OMC strongly endorses for the benefit of the many stakeholders benefiting from metocean infrastructure, in particular for the safety and optimisation of Australian ports.

8. Acknowledgements

The authors wish to very gratefully acknowledge IOOS QARTOD program for the publication of these manuals, and for their on-going development.

Pilbara Porta Authority and Fremantle Ports are also thanked for the use of their data.

9. References

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