Australian Wave Buoy Operations and Data Management Guidelines

Australian Research Data Commons - Australian Data Partnerships:
Development of a National Infrastructure for in-situ wave observations

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Cover photograph: A Datawell Waverider DWR4 Buoy deployed off the coast of Albany, Western Australia. (source: J. Hansen)

Contents

1 Introduction

1.1 Overview

This is a reference and guidance document for existing and prospective wave buoy operators and wave buoy data users in Australia. The document outlines wave buoy instruments most commonly in use and the wave data types and formats typically generated. Guidance is provided for Wave Buoy Deployment (Quality Assurance) and Wave Buoy Data Management (Quality Control) procedures and processes. The overarching objective is to encourage consistency in wave buoy data collection and delivery across Australia and provide a common basis from which emerging wave buoy operators can develop their practices, considering the recent proliferation of affordable and accessible wave buoy instruments due to technology miniaturisation and cost reduction. The guidance has been developed from a review of the current practices of wave buoy operators in Australia, as well as international literature and practices, and thus may be of broad interest.

1.2 Purpose

The primary purpose of this document is to provide guidance for wave buoy operators and wave buoy data users on quality assurance and quality control techniques for surface wave buoy data to increase the integrity, transparency and accessibility of in-situ wave data from across the Australian wave buoy network. The network includes a mix of established wave buoy operators and data providers (e.g., state government agencies, port authorities) as well as emerging contributors from the research and commercial sectors. The guidance has been developed to accommodate diverse existing practices while moving towards data standards and quality control consistent with international best practice.

1.3 Scope and contributors

This document focuses on wave buoy operations and practices in Australia and is not a comprehensive account of international practices. Where relevant to working towards consistency with international best practice, information and documents from global wave buoy operators and wave data working groups have been considered and referenced.

The Australian Research Data Commons (ARDC) Australian Data Partnerships project, *Development of a National Infrastructure for in-situ wave observations* (*Catching Oz Waves*), was established to enhance the accessibility, transparency and use of Australian in-situ wave data within and beyond Australia, and, to develop best practices for the Australian wave data community across the data lifecycle. This document is an output of *Work Package 3: Development of Standard Operating Procedures*, which was co-led by A/Prof Jeff Hansen (University of Western Australia) and Dr Mike Kinsela (University of Newcastle, previously NSW Department of Planning & Environment).

The *Catching Oz Waves* project was funded by the Australian Research Data Commons (ARDC) and led by the University of Tasmania and Integrated Marine Observing System (IMOS). Project contributors included Commonwealth agencies (Bureau of Meteorology, CSIRO) university partners (University of Western Australia, University of Melbourne, Deakin University, University of Newcastle), state governments (NSW Department of Planning & Environment, NSW Manly Hydraulics Laboratory, QLD Department of Environment & Science, WA Department of Transport), industry partners (RPS Metocean, Pilbara Ports Authority, OMC International, Tidetech) and international collaborators (Department of Environment & Climate Change, Canada).

1.4 Background

In-situ wave measurement instruments are routinely deployed in coastal waters and continental shelf seas around Australia by State and Commonwealth government agencies, industry (e.g., metocean and engineering consultancies), and increasingly by university-based research groups. Due to their proven technology and the ability to transmit data in near real-time, wave buoys are the dominant technology deployed for operational purposes, over other in-situ wave sensing instruments such as pressure transducers and Acoustic Doppler Current Profilers (ADCPs). Wave buoys are deployed to collect data for a range of purposes, including maritime operations and shipping, hazard advisories for commercial and recreational coastal users, engineering design (e.g., ports and coastal defences), to inform the development of coastal management strategies and monitor their effectiveness, and for research into oceanographic and coastal processes.

A range of wave buoy instruments are used in practice that are based on differing principals of wave measurement. Some Australian wave buoy operators have collected wave buoy data continuously since the 1970s, with equipment and methods evolving over time. The deployment of wave buoys has been increasing across other sectors (e.g., research), due to the miniaturisation of wave buoy sensors and decreasing costs to purchase and operate wave buoys.

In Australia, there is currently no national standard approach for processing and delivering wave data, whether in *real-time* (i.e., data telemetered from wave buoys and published in near real-time) or *delayed mode* (i.e., data post-processed after instrument recovery and/or data processing and quality control). The lack of standards and consistency extends to data Quality Assurance and Quality Control (QA/QC) measures. Most wave buoy operators and data providers have developed independent, in-house, approaches over time based on their own objectives and available resources. Considering the recent proliferation of low-cost and accessible satellite positioning wave buoys (e.g., Sofar Technologies Spotter), and the recognised priority to increase wave observations around Australia [e.g., Greenslade et al., 2020; Power et al., 2021], developing standardised wave data formats, QA/QC approaches, and publication standards, has become increasingly important.

Consistency in wave buoy data QA/QC approaches and published wave data formats will increase the value gained from wave buoy observations by increasing data accessibility, applications, and end users, including those lacking expertise or resources to process and evaluate the quality of wave data themselves. Data consistency will also enable comparative analyses and data applications across the Australian wave buoy network.

1.5 Methods

These guidelines have been developed through consultation with the Australian wave buoy operator and data-user community to gather information and insights from across the spectrum of wave buoy deployment objectives and data use cases. A review of international literature on wave buoy data collection, processing, QA/QC and management practices also informed the guidelines.

Representatives from six established Australian wave buoy operators (Table 1) were interviewed in the preparation of these guidelines to document current practices, identify areas for improvement in data workflows, and identify opportunities for improving consistency, transparency and accessibility of wave buoy data. The organisations operate a range of wave buoy equipment for different clients and purposes, and accordingly, have differing data workflows and data QA/QC strategies. The Work

Package 3 co-leads also considered their own knowledge and experience in establishing and managing wave buoy deployments and wave data in New South Wales, Western Australia and Victoria (Table 1).

Data gathered during the interviews were compiled and analysed by the Work Package 3 co-leads and presented at a national workshop of project contributors (see below) on 13 May 2022. Feedback gathered from the workshop on the review of current practices and international literature was also considered in developing the guidelines. The information considered at the national review workshop is summarised in Appendix A.

***Table 1**. List of established and emerging Australian wave buoy operators and data providers from which information was sourced to develop the guidance presented here.*

	Organisation	Sector	Instruments
	Established operators		
BOM	Bureau of Meteorology	Government (Commonwealth)	Datawell, TriAXYS
DES	Department of Environment and Science	Government (QLD)	Datawell, TriAXYS, Spotter
MHL	Manly Hydraulics Laboratory	Government (NSW)	Datawell
DOT	Department of Transport	Government (WA)	Datawell
OMC	OMC International	Commercial	Datawell
RPS	RPS Metocean	Commercial	Datawell
	Emerging operators		
DPE	Department of Planning and Environment	Government (NSW)	Datawell, Sofar
UWA	University of Western Australia	Research	Datawell, Sofar
VCMP	Victorian Coastal Monitoring Program - Deakin University and University of Melbourne	Research	TriAXYS, Sofar

2 Wave buoy instruments

Wave buoy instruments currently in use in Australia can be grouped into two categories based on their hull size (large or small), which often (but not always) align with different use cases, due to the varying deployment platform requirements for handling large or small instruments at sea. The list below is limited to instruments known to have been deployed in Australian waters. Other proprietary and custom wave buoy instruments used by wave buoy operators globally are not described in detail here.

Figure 1 shows a comparison of a large format wave buoy (Datawell DWR4) and two small format wave buoys (Sofar Spotter) moored nearby each other for a data comparison experiment. Note the scale difference between the large and small format buoys.

Figure 1. Large and small format wave buoys deployed at Torbay near Albany, Western Australia - a Datawell DWR4 (0.9 m diameter) in the foreground with two Sofar Spotter buoys (0.4 m diameter) in the background. (source: J. Hansen)

2.1 Large format wave buoys

Large format wave buoys have hull diameters of 0.7 m or greater with weights typically exceeding 100 kg and therefore require capable vessels with appropriate winching and lifting equipment for deployment and retrieval. They are typically used in long-term measurement/monitoring programs and in offshore (deep-water) settings where durability, longevity and visibility are prioritised.

The large hull sizes accommodate long-term battery banks, motion sensor instruments, and in some models, additional sensors for measuring other ocean properties, such as temperature sensors and acoustic-doppler current profilers (ADCP) for measuring currents in the water column. They may also feature satellite positioning receivers additional to or in place of mechanical motion sensors.

2.1.1 Datawell accelerometer buoys

Datawell accelerometer buoys in use in Australia include the DWR-MkIII and DWR-Mk4 Waverider buoys, and in limited cases, the non-directional DWR-SG Waverider buoy. The Datawell Waverider buoys come in either a 0.7 or 0.9 m diameter hull.

Until recently, most wave buoys deployed in the Australian network were Datawell accelerometer wave buoys, which are established industry-standard instruments used by wave buoy operators globally who manage long-term wave data programs. Datawell accelerometer wave buoys measure the buoy's displacement using a fluid-filled electro-mechanical accelerometer. Most Waverider buoy models can also include temperature sensors and Global Positioning System (GPS) receivers (for monitoring position), while the Mk4 buoys can also incorporate an in-hull ADCP to record near surface observations of currents.

More information on Datawell accelerometer wave buoys is available from Datawell BV:
https://datawell.nl

2.1.2 Datawell GPS buoy

The Datawell DWR-G Waverider buoys have similar sized hulls to the accelerometer buoys (e.g. 0.7 or 0.9 m in diameter), however, they use a GPS receiver and the doppler shift principle to record their displacements, rather than accelerometers.

GPS or multi-constellation Global Navigation Satellite System (GNSS) buoys have the advantage of being able to accurately record waves at lower frequencies (down to 0.001 Hz) and do not require calibration. However, they do require a clear view of the sky and a sufficient number of satellites. Wave splash and overtopping, or temporary submergence, as well as adverse atmospheric conditions can degrade satellite geometry, which in some cases may lead to poor data quality.

More information on Datawell DWR-G wave buoys is available from Datawell BV:
https://datawell.nl

2.1.3 TriAXYS buoy

AXYS Technologies produces TriAXYS wave buoys in both a 'mini' 0.7 m diameter buoy and a 'full size' version which is 1.1 m in diameter. Both hull sizes include their proprietary motion units with three accelerometers, three gyros and compass, providing buoy motion in six-degrees-of-freedom. The full size TriAXYS buoy can also incorporate an in-hull ADCP to record current profiles beneath the buoy.

More information on TriAXYS wave buoys is available from AXYS:
https://axys.com

2.2 Small format wave buoys

Small format wave buoys have hull diameters of <0.7 m and due to their compact size and light weight are readily deployable from small vessels with limited equipment and personnel. Small format wave buoys that are available on the market today may measure displacements using GPS/GNSS satellite receivers, miniature accelerometers, or both methods.

Although Datawell have offered a small format Waverider buoy for around two decades, small format wave buoys have grown in availability and popularity in recent years with miniaturisation and reduced power consumption, as well as the decreasing costs of key aspects including batteries, solar panels and data telemetry. This growth has increased wave buoy applications and small format buoys have replaced large format buoys in some use cases. Several comparisons of data capture and quality between large and small format buoys to date have been promising and further comparative testing remains in progress [Raghukumar et al. 2019, Lancaster et al. 2021].

2.2.1 Datawell GPS buoy

The Datawell DWR-G4 buoy is a small format version of the DWR-G buoy. It has a 0.4 m diameter hull and shares the same operating principal and GPS equipment to the DWR-G buoy described above. It is typically utilised for short-term monitoring and targeted experiments as it has a battery life of only 30 days and thus is not suited for long term deployments.

More information on the Datawell DWR-G4 wave buoy is available from Datawell:
https://datawell.nl

2.2.2 Spotter buoy (Sofar Ocean)

The Sofar Spotter buoy is a 0.4 m diameter GNSS buoy with a hull made of plastic resulting in a weight <10 kg. Similar to Datawell GPS buoys, displacements are measured using a GNSS receiver rather than accelerometers. Power is provided by an internal battery that is charged by solar panels allowing long deployments (power may decrease as biofouling covers the solar panels or if sunlight is limited, such as in polar areas). Like all GPS/GNSS buoys they require a clear view of the sky and any wave splash or overtopping/submergence may degrade data quality. Spotter buoys were originally developed for drifting (unmoored) deployments and Sofar operates a global network of drifting buoys.

More information on Spotter wave buoys is available from Sofar Ocean:
https://www.sofarocean.com

2.2.3 Other small format buoys

With the reduction in cost of both solid-state accelerometers and GNSS receivers, several other manufactures are producing small format wave buoys. This includes the Obscape OBS-Buoy 400 (https://obscape.com/site/wavebuoy/), which is a 0.37 m diameter accelerometer-based buoy. The Scripps Institution of Oceanography also makes a Directional Wave Spectra Drifter (DWSD, https://gdp.ucsd.edu/ldl/dwsd/), which is a 0.35 m diameter GPS based buoy. Similar to Sofar Spotter buoys, the DWSD buoys were originally developed for drifting applications but they can also be used for moored deployments.

2.3 Power systems

Most large and small format wave buoy manufacturers now offer solar-battery power systems either as an option or increasingly as standard equipment. Solar-battery power systems have the advantage that deployment duration should not be limited by the power supply, and only by biofouling and the condition of the instrument and mooring. They also contribute to reducing waste and ongoing costs in the form of purchasing and disposing of batteries.

In selecting a suitable instrument, wave buoy operators should consider the duration of intended deployments, and if over the lifetime of their program any additional upfront cost associated with a solar-battery power system will be offset by cost savings in avoiding use of disposable batteries. Some battery-only power systems may also be compatible with rechargeable batteries.

2.4 Data storage and telemetry

Data telemetry may be a key decision when choosing a wave buoy manufacturer and model. While all wave buoys store wave data on onboard memory or data cards, options for real-time data telemetry vary between wave buoy models. Table 2 provides an overview of data telemetry options with some potential advantages and disadvantages provided for each. Wave buoy operators should review data telemetry options and subscription costs when evaluation which wave buoy to purchase.

Table 2. Data telemetry options for commercially available wave buoy instruments and relative cost.

Telemetry mode	Cost	Advantages	Disadvantages
Onboard storage	-	No telemetry cost Less equipment to fail	No real-time data/tracking No redundancy if buoy lost
HF radio	$	Can stream displacement data in real time and also telemeter periodic wave spectra and parameters No telemetry subscription	Requires a shore receiving station, which may amount to a significant expense Suffers outages caused by weather conditions
Mobile (cellular) network	$$	Telemeter periodic wave spectra/parameter data Lower cost than satellite May be a good option for nearshore deployments	Offshore coverage of mobile networks is limited and can suffer from shadow effects, even close to the shore Need to check compatibility with local providers
Satellite network	$$$	Robust and reliable data telemetry in most settings Telemeter periodic wave spectra/parameter data	Expensive data subscription with limited bandwidth Subscription model may be time-based and thus use the allocation even when buoy is inactive or in storage

3 Wave buoy data

Surface wave buoys work on the principle of calculating their displacement (translation in x/y/z planes) through time. This can be done by measuring the buoy's motion (e.g., pitch, roll, heave, yaw, surge, sway) and orientation using mechanical and/or electronic accelerometers, or in the case of GNSS buoys the buoys position change or velocity via the Doppler-shift in the satellite signals. Buoy displacement data are the base level of derived data (e.g., computed by time integrating the measured acceleration or velocities). Lower order data are typically specific to the sensing instrument and are not usually used in wave data processing and analysis. More common wave data types and formats used by end users are derived from the buoy displacement data and include spectral wave data (e.g., energy density spectra) and wave parameter time-series data (spectral and time-domain derived).

Data collected by wave buoys that describes the surface wave field can be broadly grouped into four categories, from most basic (and comprehensive) to most processed (and summarised):

- Buoy displacement
- Wave spectra
- Wave parameters (time domain)
- Wave parameters (spectral)

3.1 Displacement data

The time series of displacement of the wave buoy on the water surface captures its horizontal translation in two planes (x,y) and its vertical movement or heave (z) between each observation. The frequency of observations depends on the sampling and recording frequencies of the wave buoy instrument, which typical vary between 1-3 Hz. Depending on the instrument type, buoy displacement may be measured using onboard mechanical sensors (e.g., accelerometers, gyros, compass), satellite positioning observations through GNSS networks (including GPS), or both.

Accelerometer-based buoys record the horizontal and vertical accelerations which are then integrated twice to yield the displacements, while GPS/GNSS buoys can measure displacements by change in satellite-derived positions or by calculating the buoys velocity from the Doppler shift in the satellite signals and time integrating to yield the displacements. Depending on the displacement observation method, primary sensor measurement data (e.g., motion readings) may also be stored and may be used for data quality control, however, regardless of the method most instruments provide derived observations of buoy displacement (x/y/z translations through time).

Displacements data are the most basic data type recorded by wave buoys and are usually stored on an onboard memory card. They may be transmitted to shore in real-time depending on the instrument and data telemetry options. Both spectral and time-domain wave data processing approaches use the buoy displacement data to derive more useful data formats for describing the surface wave field. As such, displacement data are often not accessed by end users and may be only kept as archive data by buoy operators once the derivative spectral and parametric datasets have been created. Operators may also inspect and evaluate displacement data records within their quality control procedures, most often in preparing delayed mode data.

Buoy displacement data may be subject to the instrument manufacturer's data filtering, optimisation, and quality control methods onboard during data collection and onboard processing. Such processes may be poorly documented or commercial in confidence, such that buoy displacement data are not necessarily raw instrument observations (and typically only the filtered/optimised displacement data is saved). In essence, the buoy operator and data end users accept that any manufacturer's processing works to achieve the cleanest displacement data based on the specification of the instrument.

Importantly, the integrity of derived wave spectra and wave parameters depend on the quality of buoy displacement data.

Figure 2 provides an example of wave buoy displacement data for a 30-minute measurement period, showing the translation of the wave buoy in the vertical (heave) and horizontal (east, north) planes.

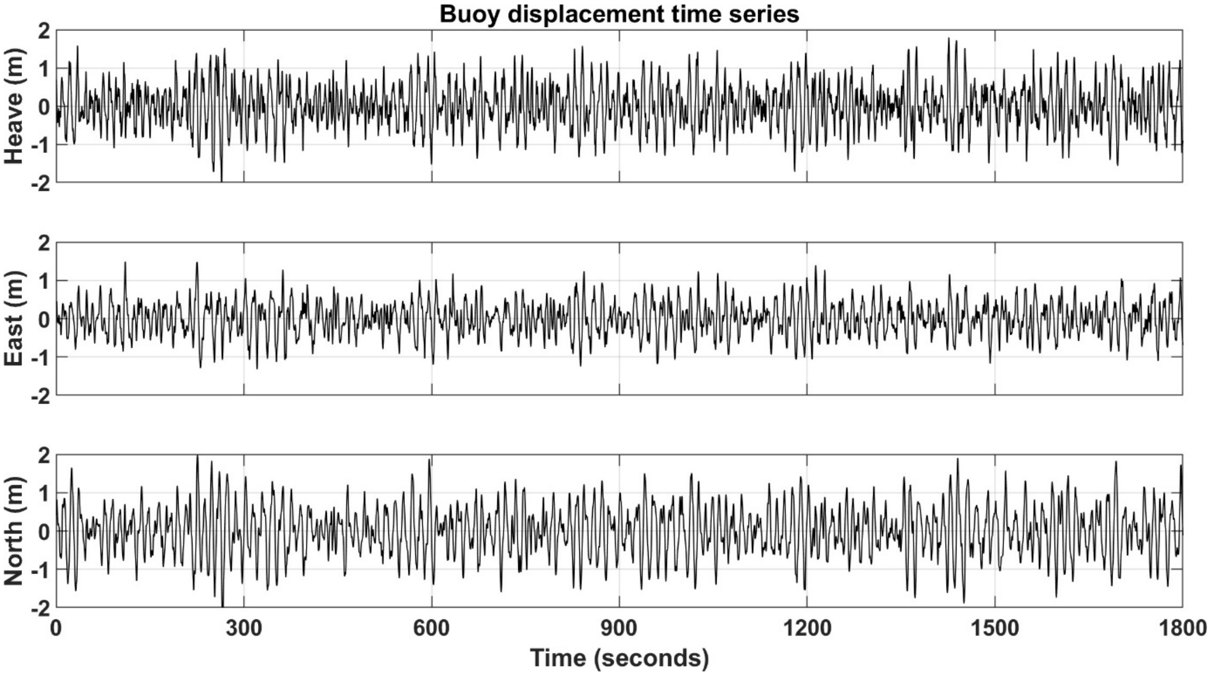

Figure 2*.* Example time series of heave (top), east (mid), and north (lower) wave buoy displacement data from a Datawell DWR4 deployed at Torbay near Albany, Western Ausralia. (source: J. Hansen)

3.2 Wave spectra

Spectral wave data describes the distribution of wave properties (usually energy) across frequencies (1D) and also directions (2D) throughout a fixed sampling interval (number of displacement records). Wave spectra are calculated onboard wave buoys at regular intervals (usually half an hour) from the displacement data (typically logged at 1-3 Hz).

While variations exist in the exact methodology, most spectral processing follows the well-established Fourier transform approach [e.g., Longuet-Higgins et al. 1963, Kuik et al. 1988], and generates a range of Fourier coefficients (e.g., centred, first four) that summarise the wave energy distribution (and direction) across the frequency range sampled by the wave sensor. From these, standard integral (or bulk) spectral wave parameters can be calculated (see Spectral wave parameters, Section 3.3.2). Further processing can be carried out to construct a 2D frequency-direction energy spectrum using statistical modelling techniques, such as the Maximum Entropy Method [Lygre and Krogstad, 1986].

The spectrum and resulting spectral parameters describing key attributes of the wave height and direction spectra that summarise the wave conditions are usually calculated onboard and may also be telemetered in real time. The higher data volumes of full spectral wave data mean that operators may choose to telemeter only a limited suite of Fourier coefficients and/or the bulk wave parameters summarising wave height, period and direction calculated onboard. The full wave spectra data may be retrieved from onboard data cards (with displacement data) during buoy servicing or removal.

Figure 3 provides an example of the wave energy spectrum derived from the heave displacement time series shown in Figure 2.

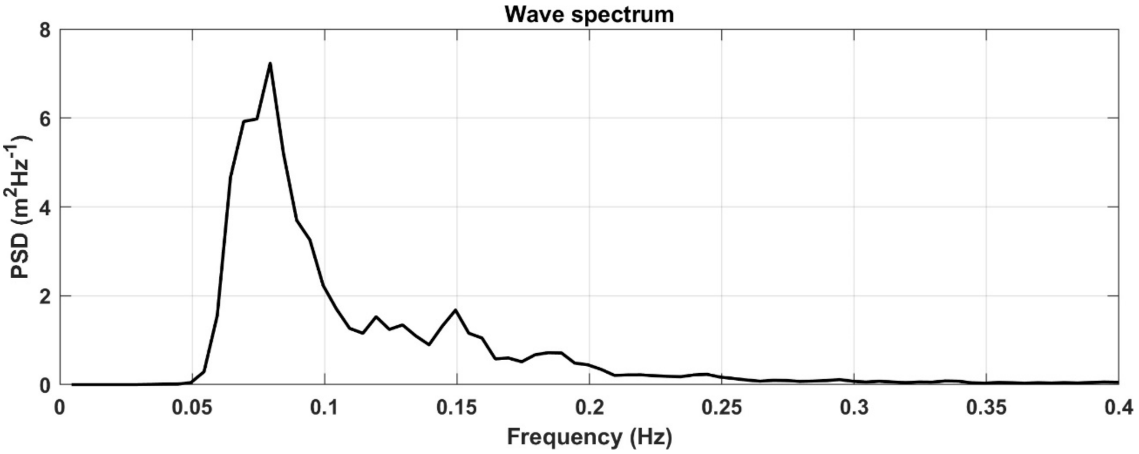

Figure 3. Example of a wave energy spectrum (the distribution of wave energy across the surface wind-wave frequency range) derived from the heave displacements shown in *Figure 2*. (source: J. Hansen)

3.3 Wave parameters

Time series of wave parameter data are usually of the greatest interest and application by end users. Parameters summarising key wave properties (height, period, direction) over uniform time intervals (half-hourly or hourly) can be measured and calculated through time-domain analysis or derived from wave spectra using standard formulae applied to the spectral moments. Either approach can be taken if the wave buoy displacement data are available.

The processing methodologies used will determine which wave parameters are available. Wave buoy manufacturers have their own standard methods, data types and formats for onboard processing, and operators may be limited by those methods if they are relying on onboard processing and proprietary software only. Operators may include a mix of time-domain and spectral parameters in published data tables, which may also include the spectral moments data (M0, M1, M2…) from which other spectral parameters that are not present in the table may be derived.

Figure 4 provides an example of wave parameter time series data, including wave height, period and direction parameters. On the wave height panel, significant wave height (H_{m0}) was derived through spectral analysis, while maximum wave height (H_{max}) was derived through time-domain analysis.

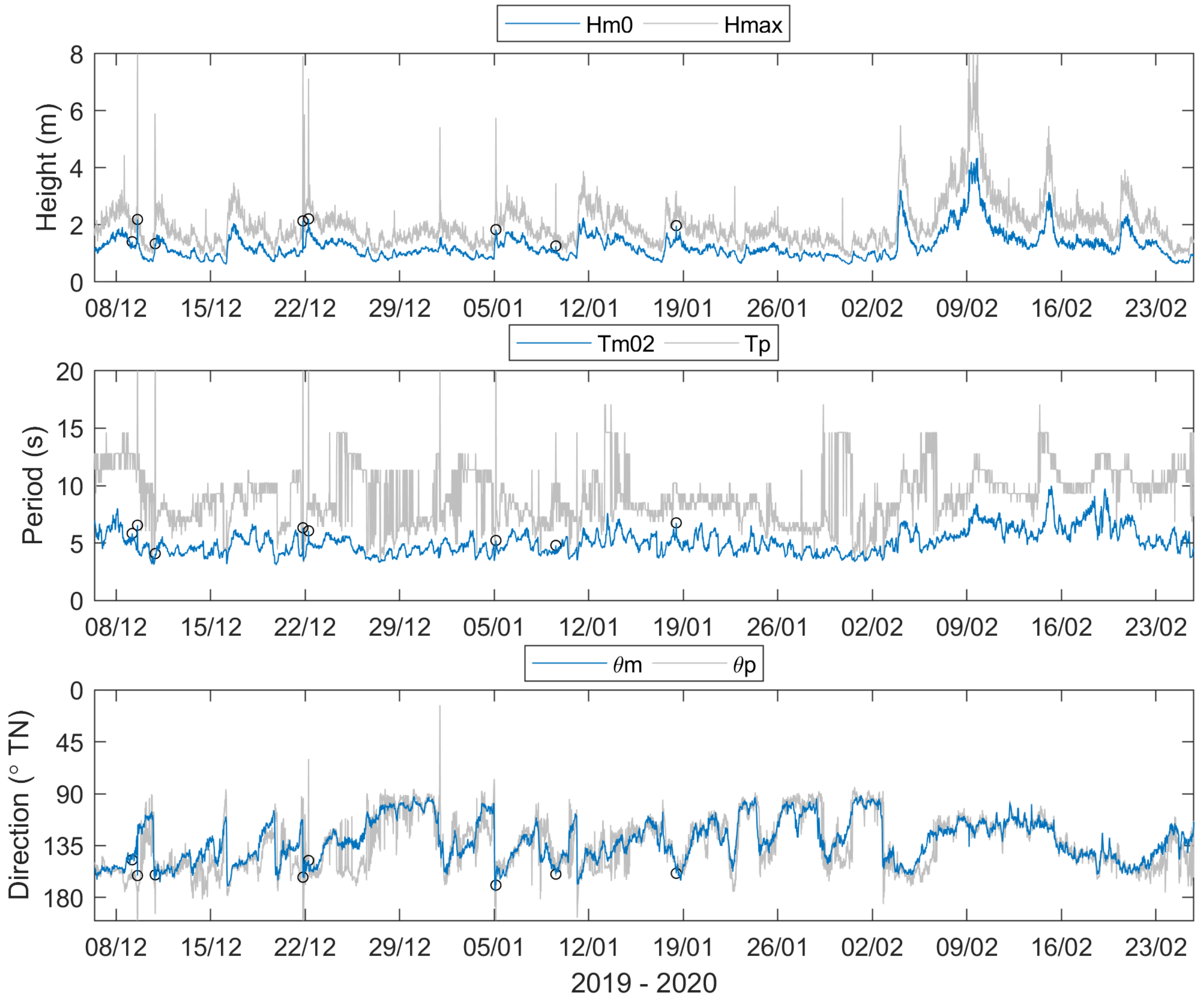

Figure 4. Example of wave parameter time series data showing wave height, period and direction measured by a Sofar Spotter wave buoy during 2019-2020. Circled data indicate data points that failed quality control tests. (source: NSW Department of Planning & Environment)

3.3.1 Time domain wave parameters

Some buoy manufacturers and operators use the time series of displacement data over a given time period (e.g., half an hour) to calculate time domain wave statistics. These analyses are usually based on a zero up- or down-crossing method to identify individual waves (trough to crest) and calculate summary statistics of wave height and period. Time-domain analysis has the advantage of allowing the identification and measurement of individual waves, and their steepness, which can be important in certain applications such as the design of offshore structures or ports. It also provides an absolute measure of maximum wave height, which can only be estimated through time-domain analysis.

Wave height statistics typically include the maximum wave height (H_{max}), significant wave height (H_{sig}, average of largest 1/3 of waves) and often the root-mean-square wave height (H_{rms}). Wave period statistics typically include significant wave period (T_{sig}) and the average (zero-crossing) wave period (T_z). Wave directions cannot be derived from time-domain analysis.

3.3.2 Spectral wave parameters

Spectral wave parameters are derived from the moments of the wave energy spectra calculated for each observation period (half-hourly or hourly). Spectral parameters for wave height and period describe similar properties to corresponding time-domain parameters but are calculated through a different analysis method. For example, spectral significant wave height (H_{m0}) is comparable to time-domain significant wave height (H_{sig}), and the 'm0' notation indicates that it is derived from the zeroth-order moment of the wave energy spectrum. Spectral wave periods typically include derivations from the zeroth and first-order moments (T_{m01}), which is comparable to T_{sig}, and from the zeroth and second-order moments (T_{m02}), which is comparable to T_z. Directional properties are estimated from the lowest-order directional moments using the co/quad-spectra and displacement spectra and standard parameters include the mean wave direction (Dir_m) and peak wave direction (Dir_p).

3.4 Real-time and delayed mode data

Real-time wave data may be telemetered from wave buoys continuously (displacements) or at regular intervals (e.g., half hourly) and is published in its telemetered format or a derivative of that format in near real-time. The real-time data may be onboard or onshore processed. There may be a fixed delay of 1-2 hours in publishing real time data due to operator's data processing and publication workflows.

Quality control (QC) procedures may be absent or limited. If QC is conducted on real-time data, it is typically limited to basic automated range tests and data thus data is often published with appropriate disclaimers. While no national or international standard exists, existing QC protocols established in Australia by wave buoy operators are generally loosely based or similar to the Quality Assurance of Real-Time Ocean Data: Manual for Real-Time Quality Control of In-Situ Surface Wave Data (QARTOD) manual produced by the United States Integrated Ocean Observing System [IOOS, 2019]. Published real-time data is usually limited to a subset of parameters that may include a mix of spectral and time-domain parameters and may be provided in the form of rolling data plots and/or as tabulated data.

Delayed mode data is usually published by operators at regular intervals (e.g., monthly) for ongoing deployments or upon the completion of temporary deployments. As previously mentioned, some operators carry out near real-time onshore wave data processing from continuously telemetered displacement data rather than waiting to retrieve onboard data during buoy service or retrieval. In such cases, the delayed mode data typically features more data (e.g., additional parameters) and more extensive quality control that may include repairing missing data. Delayed mode data may include a mix of onboard and onshore processed data types and formats.

3.5 Onboard and onshore data processing

While all wave buoys calculate wave spectra and parameters from the displacement data onboard at regular intervals, some operators choose to calculate their own wave spectra and parameters from buoy displacements separately. This may be carried out in real time at shore receiving stations, using displacement data that is continuously telemetered from active wave buoys (e.g., via HF radio) or using displacement data that has been retrieved from onboard data cards during buoy servicing or retrieval.

Onshore processing of wave spectra and parameters allows for variations from the onboard processing methods, such as: number of displacement observations or segments used in spectral processing, methods of spectra and parameter calculation, time interval of processed spectra and parameter data (e.g., hourly rather than half-hourly), and quality control of displacement data prior to calculation of wave spectra and parameters. Operators who calculate their own spectra and parameters from buoy displacement data usually also retain and archive the displacement, spectral and parametric data files that are created and stored onboard the buoy data card and may also receive the onboard-processed spectral and parametric data in real time.

Established operators who manage wave buoy networks with operational dependencies tend to carry out near real-time onshore wave data processing from continuously telemetered displacement data. This allows for earlier publication of quality-controlled data without needing to wait for the wave buoy to be retrieved to inspect displacement data and carry out onshore processing. This approach is usually only viable where HF radio transmission to shore is possible, due to the costs of mobile/cellular and satellite data transmission and the inability of most buoys to transmit displacements in real-time using non-HF radio telemetry.

Data telemetry via HF radio may however be vulnerable to weather-influenced interruptions to real-time buoy data transmission and receiving, in which case data may need to be repaired using displacement data from onboard data cards once the buoy is retrieved. Once a buoy is recovered some operators may reprocess all onboard displacement data as part of their QA/QC procedure, while others only reprocess card data in cases where significant real-time data loss occurred. In some workflows, operators may combine some onboard processed data (e.g., directional spectra and derived direction parameters) with their onshore processed data in developing their standard outputs.

4 Wave Buoy Deployment and Recovery (Quality Assurance)

With the recent development of small format (and low cost) commercial wave buoys, the use of wave buoys in Australia has increased beyond a limited number of previously established operators: government agencies and consultancies that have historically operated large format wave buoys.

Many of the deployment and operational considerations are similar for large and small format wave buoys. The general guidance provided below should be reviewed and considered when planning and carrying out wave buoy deployments.

Readers are also referred to the Coastal Data Information Program (CDIP), which is part of Scripps Institution of Oceanography in the United States, who run a very large wave buoy network and provide documentation of their wave buoy deployment and recovery, data analysis, and QA/QC procedures online: http://cdip.ucsd.edu/m/documents/index.html.

4.1 Deployment location

There are many considerations in planning a wave buoy deployment. Whether it be for operational monitoring, engineering design and applications, or research experiments, the location of a wave buoy deployment or network of deployments, is critical to the quality and usability of the wave data. The choice of location often needs to balance both data quality and representativeness, and practical considerations, as described below.

4.1.1 Water depth, exposure and wave climate

As water depth decreases across continental shelves and adjacent to the coast, deep-water waves will become increasingly transformed (e.g., shoaling, refraction, diffraction) and wave energy dissipated and dispersed through interactions with the seabed. In deeper offshore waters, wave heights will generally be larger and reflect the ocean wave climate that influences a larger area of the coast. However, measuring waves in exposed deep waters provides less information about wave conditions at a particular beach or port facility.

The choice between a deep-water or shallow-water wave buoy deployment will often be governed by the specific project objectives and the intended uses of the resulting data. The key consideration is that the water depth of the chosen location is commensurate with the objectives. In Australian settings, deep-water deployments are typically at mid-continental shelf depths of around 100 m (noting that for swell conditions the waves may already be interacting with the sea bottom in 100 m), while shallow-water deployments may be targeted around the interface of the shoreface and inner-continental shelf (e.g., 30 m) or pre-breaker waves beyond the surf zone (e.g., 10 m). Deployments are also made in shallower waters within sheltered or inshore settings such as harbours and estuaries.

Exposure refers to how much of the regional offshore (ocean) wave climate the deployment location is exposed to, considering both wave energy and directions. Exposure may be reduced by coastline shape, islands, reefs, submerged banks/shoals and seabed habitats (e.g., kelp forests). Operators should consider how all of these factors in the deployment setting might influence wave conditions at a location in determining suitability for the intended data uses.

For nearshore deployments, the effects of shallow-water wave transformation and sheltering on the measured waves are of key interest to capture rather than influences to be minimised. In such applications, an important consideration is that the wave buoy is not deployed in water so shallow that depth limited wave breaking might occur around the mooring, which would greatly increase the chance of the buoy breaking free from the mooring or drowning, while simultaneously complicating analysis of the resulting wave data.

Thought should also be given to what is already known about the wave climate in the deployment setting. For example, is the region subject to extreme storm events that might pose hazards to wave buoy deployments during particular seasons. A rigorous deployment program plan should identify such risks and describe any control measures to mitigate data and/or equipment loss.

4.1.2 Seabed substrate and habitats

Beneath the water surface, the nature of the seabed at the deployment location is also important. Sedimentary seabeds are usually preferred to provide good purchase for the mooring anchor and/or weights and to reduce the risk of the mooring fouling on hard substrate, precluding its retrieval. The mooring anchor and/or weight may drag more easily on a smooth hard substrate (e.g., planed rocky reefs), while a sandy seabed usually provides greater hold as the anchor/weights and chain can work its way under the seabed surface. Sedimentary substrates also usually have lower populations of sessile marine fauna at the seabed (including potentially protected habitats and species) reducing any potential environmental impacts.

All available data and information about the seabed in the deployment setting should be reviewed in selecting the mooring location to plan for a successful deployment that minimises any potential impacts on other uses and values. Sacrificial mooring footings should be avoided where possible and necessary permissions sought if they are used.

Early consultation with waterways/maritime management, ports (if relevant), environmental and heritage authorities is essential and operators should be aware that deployments in marine/aquatic protected areas or proximal to port facilities may require additional permits (see Section 4.1.6).

4.1.3 Accessibility and logistics

A determining factor when selecting a deployment location is usually accessibility and efficiency in visiting the site for deployment operations. Proximity to suitable ports, boat launching facilities or third-party providers (if contracting deployment services) are important to identify early in planning. Any physical constraints that might limit the availability of such facilities (e.g., wind, tide, waves) should also be considered. In reviewing the accessibility of a site, it should be kept in mind that the need might arise to visit the mooring at short notice if, for example, the wave buoy breaks free from the mooring or the mooring drags under heavy strain. With the above in mind, it is generally preferable if there are multiple access points for a deployment location (e.g., proximal boat ramps with varying aspect/sheltering for different weather and wave conditions).

4.1.4 Data telemetry

Deployment location should also take into consideration any real-time data requirements. For example, if real-time displacement data are required the buoy will need to be suitably located to transmit high-frequency radio signals to a shore station that will also need to be established, due to the constant stream and volume of data transmission. For an offshore or remote locations, satellite telemetry may be the only option and thus the relatively high cost of satellite data should be considered. For nearshore deployments, most buoy manufacturers offer models with telemetry via mobile phone networks, although the reliability of the network in the chosen setting should be established prior to deployment.

If real-time data telemetry is not used, consideration should be given as to how to monitor the position and function of the wave buoy to avoid potential data and mooring loss.

4.1.5 Safety of navigation and exclusion zones (permits required)

A range of permits for the deployment of wave buoys may be required based on the location and, in all cases, a ***Notice to Mariners*** must be issued. For deployments within three nautical miles of the coast, state/territory governments have jurisdiction and typically will issue notices to mariners and permits if required. Adjacent to port facilities port authorities often have jurisdiction and may require a separate permitting process to state government agencies. Offshore of three nautical miles, permitting and navigational requirements are specified by the Australian Maritime Safety Authority (AMSA) and the Australian Hydrographic Office (AHO). For small format buoys, additional lighting may be required to improve visibility (see Mooring design, Section 4.2.2).

A review of navigation charts should be carried out during initial planning of a deployment. Areas around maritime ports, shipping lanes (both proximal and distal to ports) and military bases are some locations where exclusions zones may apply. Early consultation with local waterways/maritime management authorities can avoid wasted time in planning a deployment in an unsuitable location.

Locations with considerable recreational or commercial vessel traffic should generally be avoided as this greatly increases the chances of the buoy being struck by a vessel – even with a Notice to Mariners issued. AMSA provides online maps of commercial shipping traffic that are derived from vessel AIS location transponders. These data can reveal areas of high vessel traffic which should be avoided. Maps can be accessed from the link below:

https://www.operations.amsa.gov.au/Spatial/DataServices/DigitalData

In some locations, temporary deployments might be allowed during low vessel traffic seasons if full-time deployment is not considered appropriate.

4.1.6 Marine parks and cultural heritage (permits required)

A permit is usually required to deploy wave buoy moorings in marine protected areas, even if the deployment is located in a general use zone or other zone where uses such as boat anchoring and fishing are permitted. The relevant marine park authority (State or Commonwealth) should be approached early in planning any deployment in a marine park as acquiring a permit could be a time-consuming process. Zones offering high ecological protection (e.g., sanctuary zones) should generally be avoided if a similar location with lower protection status could achieve the objectives.

Another consideration is the presence of known cultural heritage sites (Indigenous and European) in the vicinity of the deployment area, noting that the precise locations of some cultural heritage sites might not be generally known. For example, national and state registers of shipwreck sites should be reviewed to ensure that deployments are not made in sensitive areas, and that moorings do not become fouled on wrecks.

4.1.7 Infrastructure and other uses

While sedimentary seabeds are preferred for wave buoy deployments, they are also the preferred settings for underwater infrastructure such as telecommunications cables. Care and consultation must be taken to identify any infrastructure in the vicinity of planned deployment locations.

Operators should also keep in mind any fishing activities in the deployment setting, and particularly commercial fisheries. For example, a deployment in the vicinity of a trawl fishery might be damaged or removed by fishing activities. Early consultation with fisheries authorities might help to identify the most suitable locations.

Lastly, for nearshore deployments, consideration should be given to the visibility of navigation lights on wave buoy instruments. While essential for safety of navigation, they may also be mistaken by foreshore residents and visitors as distress signals if there is no awareness about the deployment. Operators who are deploying wave buoys proximal to busy coastal settings should also consider informing water police, volunteer marine rescue, local governments and surf lifesaving clubs.

4.1.8 Existing wave buoy network

Another consideration in planning a deployment is how the proposed wave measurement location fits with other active or past wave buoy deployments in the area. For example, does it complement the network of data in that region and potentially service value-adding use cases? Has there been past deployments in that area, in which case co-locating with a past deployment might facilitate a longer data record? And for the case of a nearshore deployment, is there an offshore wave buoy in that region that could provide concurrent deep-water wave data? These questions among others should be considered when considering a new wave buoy deployment [Greenslade et al. 2020].

4.2 Deployment hardware

4.2.1 Wave buoy instrument

The specific type of wave buoy(s) selected for a particular project will depend on the available budget, deployment duration and servicing interval, wave climate, and resources available for deployment and recovery. For example, a small-format wave buoy might be the preferred choice for relatively short-term deployment (several months to a years) in shallow coastal waters. Conversely, for an offshore location only safely accessible by larger vessels, operators may favour a large format wave buoy with higher durability and reduced servicing intervals – e.g., due to more limited impacts from biofouling compared to small format wave buoys [Campos et al. 2021, Thomson et al., 2015]. Deploying small format wave buoys on heavy deep-water moorings is still considered a nascent application. Consideration of the telemetry options for the buoy (and cost) as well as available on-board and telemetered data options/formats should also be evaluated against project objectives.

4.2.2 Mooring design

After a properly functioning and calibrated (if required) wave buoy instrument, a correctly designed mooring is the most critical factor in ensuring that quality wave data is collected by a moored wave buoy. The mooring needs to both safely tether the wave buoy in place while also allowing it to move freely and unencumbered to make accurate measurements of its displacement through time.

Standard mooring designs for different instruments and depths are often provided by the buoy manufacture and may specify specific materials and floats. These designs are usually rigorously tested, however, experienced operators have often adapted these designs or developed different designs to suit particular environments and/or based on the availability and costs of components.

A typically wave buoy mooring might comprise the following components (e.g., Figure 5):

- an anchoring weight to keep the mooring in place (scrap steel, chain and/or a boat anchor)

- a mooring line (often synthetic polypropylene) of length some multiple of the water depth
- one or more in-line floats to keep the mooring off the sea floor
- in-line weights to keep the mooring line submerged near the surface
- a surface (or near surface) float to keep the mooring near vertical in the water column
- a catenary or bridle line that tethers the buoy to the mooring and allows it to move vertically and horizontally on the water surface.

Figure 6 and Figure 7 show recommended mooring designs from Datawell for both deep- and shallow-water wave buoy deployments [Datawell BV, 2020].

In all cases, care should be taken to minimise self-entanglement between mooring components. High quality components should be used, such as marine grade stainless steel fittings, marine-grade rope/line, and high-visibility surface floats with the appropriate buoyancy rating. Contact between differing types of metals should be avoided or components properly isolated to prevent electrolysis.

Figure 5. Components of a shallow-water wave buoy mooring for a small format Datawell DWR-G4 buoy laid out on deck for deployment, including: wave buoy, surface floats, mooring line with in-line weights, chain weight and anchor. The mooring design is similar to the example diagram shown in *Figure 7*. (source. M. Kinsela)

Deep deployments (>40 m)

In deeper water, the surface float may be absent, particularly for large format buoys that have high buoyancy (Figure 6). Due to their lower buoyancy, small-format buoys should typically have a surface float on their mooring even in deeper water. For large format Datawell and AXYS buoys, the catenary (~30 m) is also often composed of a bungee/rubber cord to further minimise mooring influence on buoy motion and stress on the mooring. Large format buoys may also include an acoustic release located immediately above the anchor weight (with an inline float ensuring the release stays off the bottom) to recover the mooring while leaving the anchor weight in place.

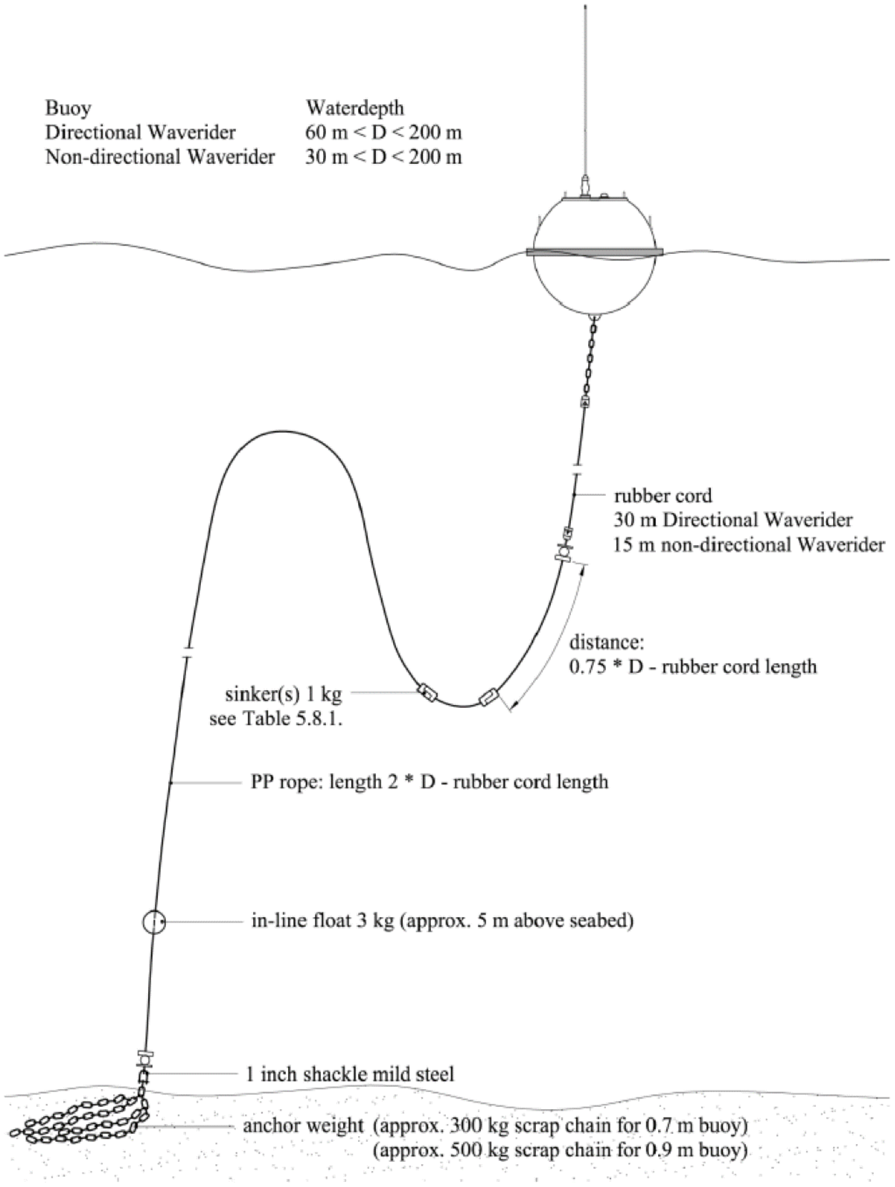

***Figure 6**.* Example of a deep-water mooring design for Datawell Waverider buoys. (source: Datawell BV)

Shallow deployments (< 40 m)

Given their relatively small buoyancy, compared to large format buoys, it is particularly important to minimise mooring influences on small-format buoys as this can result in poor data quality if the buoy becomes partially or temporarily submerged (e.g. GNSS drop outs for GNSS buoys), or in the worst case, drowning of the buoy. This is typically achieved by including a surface float that keeps slack line (lightly weighted to keep below the water surface) between the surface float (that absorbs mooring movement) and wave buoy. The generally smaller size of components used for small format wave buoys also increases the chances of wear of both the mooring line and any metal components.

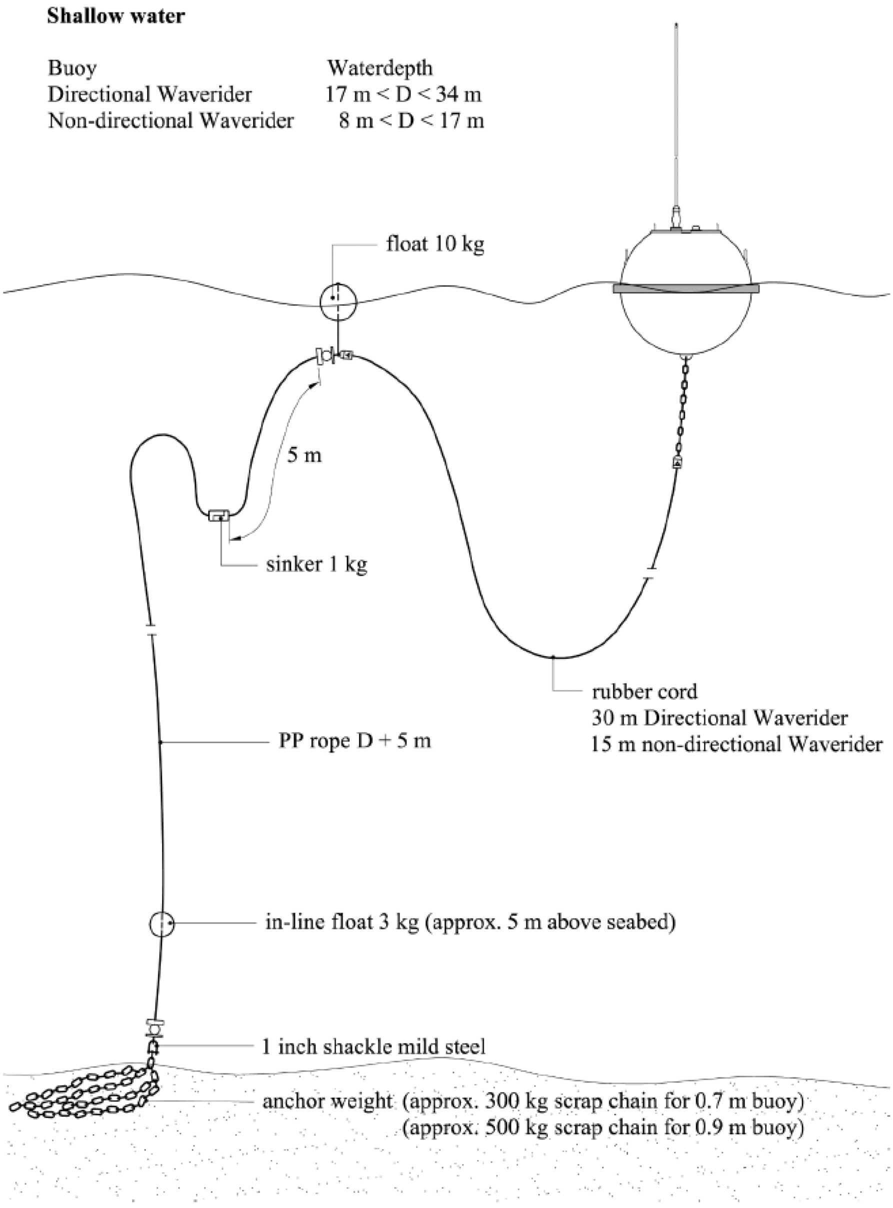

***Figure 7**.* Example of a shallow-water mooring design for Datawell Waverider buoys. (source: Datawell BV)

Mooring visibility

Aside from tethering the wave buoy while allowing sufficient free movement, the visibility of the wave buoy and mooring is another important consideration. Although wave buoy instruments are typically brightly coloured and fitted with a navigation light, they sit low in the water and may not be easy to see in poor visibility conditions (e.g., chop, sun glare, night time). If the deployment location is a high-traffic area or a setting where vessels may not be expecting to encounter a mooring (e.g., a coastal transit route), the mooring design should also maximise visibility.

Figure 8 shows examples of moorings with differing visibility that are suited to different settings. While surface floats provide for extra visibility on shallow-water moorings, the absence of surface floats on deep-water moorings means that it is important to maximise the visibility of the wave buoy itself.

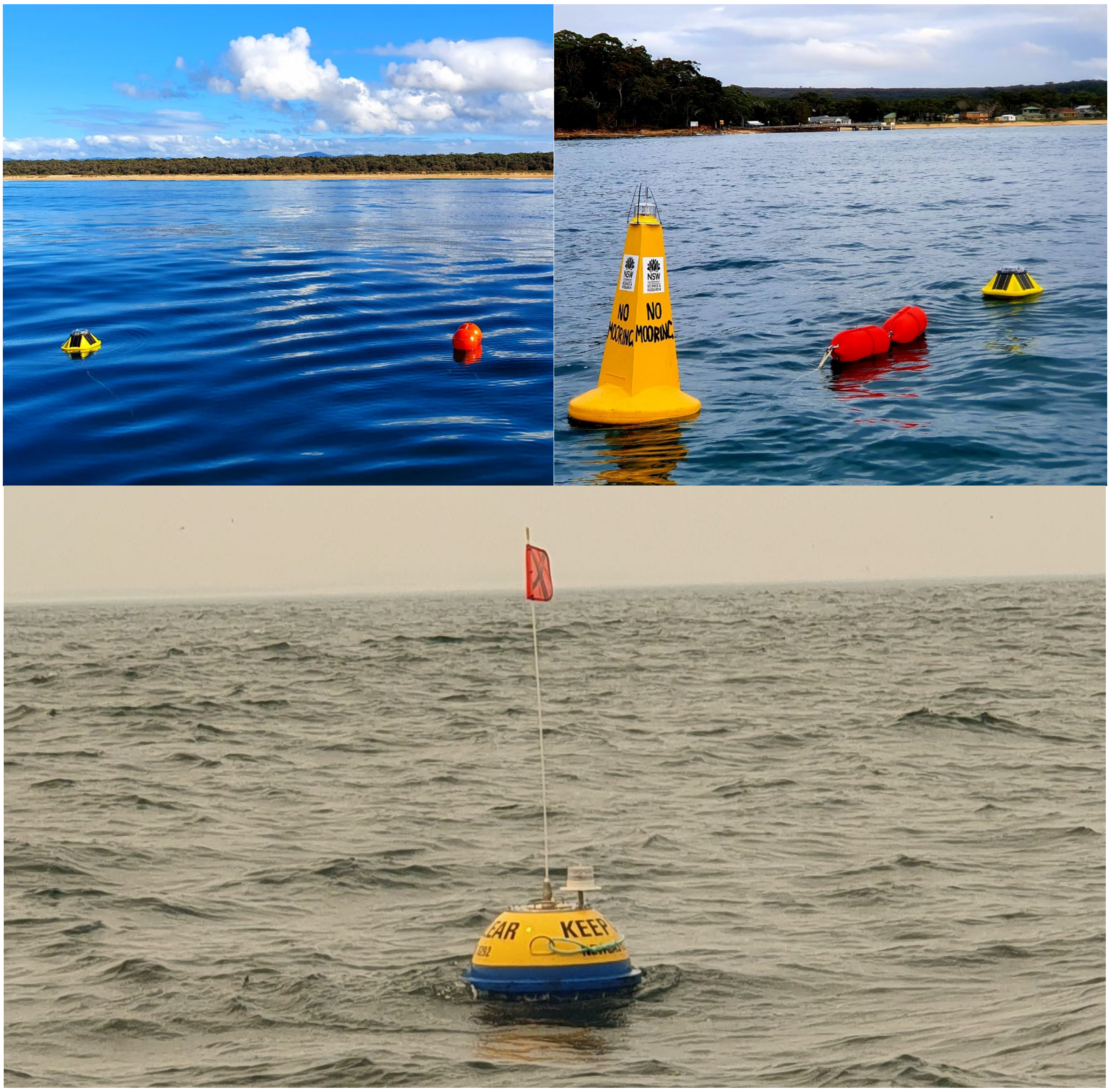

Figure 8*.* *Sofar* Spotter wave buoys deployed on shallow-water nearshore moorings with different levels of visibility: the basic swing mooring (top left) is located in a low-traffic setting and is less visible, while the high-visibility swing mooring (top right) is located in a high-traffic setting – note the spar buoy (special marker) with light and surface line floats to increase visibility. For deep-water buoy deployments without surface floats a flag can increase visibility of the wave buoy (bottom). (source: M. Kinsela)

4.2.3 Additional sensors

A number of commercially available wave buoys now measure additional water properties or can accommodate sensors that measure a range of variables beyond the buoy displacements. A water temperature sensor is now common for most wave buoys. Large format wave buoys now are also able to incorporate acoustic current measurements (Datawell Waverider Mk4) or house 3rd party current profilers (AXYS TriAXYS buoy). Some small format buoys (Sofar Spotter) now come with the option to incorporate a data cable as the mooring line. This allows the connection of 3rd party sensors to measure (and report in near real-time) a range of ocean variables, for example water column pressure and temperature. In instances where a wave buoy is used to also make other measurements it is important to ensure that any impacts to the quality of wave observations is minimised (or at least be aware of these impacts). There may also be further considerations to the mooring design.

4.3 Deployment and recovery operations

4.3.1 Procedures and risk assessment

On-water operations for managing wave buoy deployments should be carefully planned and tested prior to application. The procedures for deployment and retrieval should be written down and the roles of all participants clearly identified and communicated. Procedures should be live documents that are updated and improved as new and unforeseen circumstances arise.

Potential hazards and their consequences should be identified and avoided or reduced through the implementation of appropriate controls. A risk assessment process should be followed to ensure that potential hazards and mitigation controls are considered, documented and communicated to all relevant parties to reduce the risk of accidents and injuries.

4.3.2 Permits and advisories

Prior to and immediately after deployment of a wave buoy mooring, operators should liaise with relevant authorities and agencies to ensure that the precise location and activity of the wave buoy mooring is known and is communicated to waterway users. Similarly, notice should be given to the same parties on the removal of a wave buoy mooring.

To ensure safety of navigation, a ***Notice to Mariners*** should be published upon installation of a new mooring, which is issued by the relevant waterway authority. Wave buoy moorings can be identified as *Special Markers* on electronic navigation charts.

A checklist of relevant authorities to liaise with and advise on deployment operations follows:

- State maritime or waterways management authority (if < 3 nautical miles from the coast)
- State protected areas authorities (marine/aquatic parks)
- Water Police (Marine Area Command)
- Ports authorities (if deploying near a port area)
- Volunteer marine rescue groups
- Local commercial fisheries
- Local government and surf lifesaving clubs (nearshore deployments)

If deploying in Commonwealth Waters (beyond State administered waters, typically 3 nautical miles), operators should liaise with relevant national authorities, including:

- Australian Maritime Safety Authority (AMSA)
- Australian Hydrographic Office (AHO)
- Parks Australia (Marine Parks)

4.3.3 Mooring deployment

There is no general method for mooring deployment that is applicable to all vessels, equipment, locations and conditions. Some general points are provided here, however, operators must ensure appropriate planning of the deployment procedure by experienced hands and should complete a thorough risk assessment prior to commencing deployments. Deploying and retrieving moorings in ocean settings in particular can be a hazardous exercise.

The wave buoy model and size, anchor weight, location (water depth) and consequently mooring design will mostly dictate the required deployment and recovery platform and equipment. Large-format wave buoys will require the use of a vessel with a lifting capability (crane or A-frame) of several hundred kilograms, or more if the anchor weight is to be recovered. Offshore deployment locations usually also require a large vessel that can safely (and legally) operate in ocean conditions.

Small-format wave buoys can be deployed from various smaller vessels, and in shallow settings where lighter anchor weights are used, mechanical lifting equipment may not be required. It is crucial, however, to consider that while deploying a mooring is relatively easy and may not require lifting equipment, retrieving a wet and usually biofouled mooring is a very different exercise and usually requires mechanical lifting assistance to do safely.

Some general considerations for deploying a wave buoy mooring include:

- Prepare all mooring equipment in a clear space on the vessel deck, check all fastenings and connection points, check the instrument is operational, and lay out the mooring neatly in the order that the components will be deployed
- Approaching the deployment location into the wind to maintain vessel control and reduce the risk of fouling the vessel propulsion with the mooring
- Prior to reaching the deployment location (approximately the length of the mooring line away or closer if a circular pattern is traversed) the wave buoy attached to the mooring line, is placed in the water first (Figure 9)
- The mooring line is then trailed out carefully from the stern of the vessel as the vessel slowly moves toward the deployment coordinates (care should be taken here to minimise towing the buoy behind the vessel, which can strain the mooring and submerge the buoy)
- Once at the deployment site, with all mooring line in the water and trailing the vessel but not under strain, the anchor weight is lowered into the water and then released, after ensuring the mooring line is clear of any entanglement with people, itself or the vessel
- The location of the deployed mooring is captured using the vessel navigation system, handheld GPS, and/or hydrosurvey equipment and software.

Figure 9. When deploying a wave buoy mooring, the wave buoy should be placed in the water first, then the mooring line (including surface floats if present) laid out steadily as the vessel approaches the deployment location (taking care not to tow the wave buoy), and the anchor weight deployed last. Compare the equipment in the water here with that shown on deck in *Figure 5* (source: M Kinsela)

4.3.4 Mooring recovery

Recovering a buoy permanently or for servicing is generally more complicated than deployment. Unless a buoy has been in place for a very short period of time it is generally not recommended to reuse the mooring as biofouling might compromise mooring performance and durability.

Recovery typically involves bringing the buoy on-board the vessel (which will require sufficient lifting capability for large format buoys) and partial (sacrificial anchor) or complete recovery of the mooring. If the anchor weight is to be recovered sufficient lifting capacity is required and a stronger mooring line should be used and its condition assessed to avoid breakage. Many operators of large format wave buoys opt to leave a sacrificial mooring weight (scrap steel) in place and recover the mooring above by triggering an acoustic release that is attached inline close to the anchor weight. If this approach is adopted a permit will likely be required to discard material on the seafloor.

4.4 Deployment maintenance and management

4.4.1 Service visits

Wave buoy deployments need to be visited routinely to assess the condition of the instrument and mooring and to de-foul or replace equipment as it becomes colonised by marine fauna. The timing between service visits will vary depending on a range of factors, including:

- Wave buoy size (large or small format)
- Instrument power supply (batteries or solar)
- Instrument data storage capacity
- Mooring design including resilience to biofouling and wear on mooring components
- Deployment location (biofouling fauna and wave climate)
- Deployment timing (biofouling and wave conditions may vary seasonally)
- Operational considerations

Operators should review manufacturers recommendations and speak with experienced operators in their region if deploying in unfamiliar settings.

Service visits should be planned as time windows with redundancy to accommodate routine delays in being able to visit deployments due to weather and wave conditions, and/or issues with vessel and personnel availability etc.

4.4.2 Managing biofouling

Biofouling is a pervasive influence on mooring durability and longevity and is known to influence mooring behaviour and buoy motion, if the fouling gets to a level that compromises the buoyancy properties of the mooring or greatly increases its drag in the water column [Thomson et al. 2015, Campos et al. 2021]. That can lead to damping of high frequencies or introduce artefacts at low frequencies due to increased drag on mooring lines and pull on the wave buoy.

Biofouling should be monitored/recorded and kept in check through regular visits to swap the mooring and wave buoy equipment. When commencing a deployment in a new location more frequent visits initially may help to gauge the rate of growth, which may also vary through time (seasons). On recovering a mooring, the motion of the wave buoy should be inspected first to check for any abnormalities due to biofouling. Painting the lower half of a wave buoy with anti-fouling paint can delay or limit biofouling on the hull. Datawell buoys can also be optionally purchased with a hull made of a copper-nickel-iron alloy that minimises biofouling on the hull.

Figure 10 shows some examples of heavy fouling of shallow-water wave buoy moorings when service visits were delayed due to operational constraints.

Figure 10*.* Examples of a heavy fouling of wave buoys and moorings with goose barnacles (*Lepas pectinata*) and green algae (*Ulva sp.*) (left), and blue mussels (*Mytilus galloprovincialis*) (right). (source: M. Kinsela)

4.4.3 Record keeping

Good record keeping is essential to produce high quality data. Record keeping might include a mix of hard copy (check sheets) and digital (planning documents, emails) written formats as well as photos of equipment throughout the deployment procedures. Photos are particularly useful for recording the condition of equipment in and out of the water and are typically time-stamped when captured using mobile devices, providing a secondary record of the timing of deployment activities.

Prior to deployment detailed records should be prepared documenting instrument preparation and programming, the equipment used (e.g., serial numbers), firmware versions and notes of updates, mooring design, battery voltages, deployment location and times and vessels used. Screenshots and log files of any software programming should be kept as well as detailed photos of the buoy and all mooring components should be taken. This is critical to diagnose any mooring failures that arise. All telemetry systems should be tested prior to loading on the vessel.

The exact coordinates of the deployed buoy must also be recorded, and these reported to the agency responsible for issuing a Notice to Mariners so the notice can be issued as soon as possible. It is also extremely important that once a buoy is deployed that some type of monitoring software is running that can provide alerts if the buoy is offsite (e.g., due to mooring failure) or has stopped reporting data back. Some buoy manufactures provide this as part of their data service or in-house software can be developed and utilised.

After recovery of the buoy any damage or failures should be noted, and the condition of the mooring assessed as this can reveal information about required service intervals or potential failure points. When a buoy is retrieved and not redeployed at the same location, all relevant authorities must be notified, and the Notice to Mariners cancelled.

Appropriate record keeping is also essential for publishing wave buoy data through online ocean data portals, such as the Australian Ocean Data Network (AODN) portal, which require rigorous metadata to communicate the provenance, nature and quality of wave data (see Section 6).

4.5 Drifting deployments

Drifting wave buoy deployments involve deploying a wave buoy on the water surface without a mooring and allowing it to drift with currents and wind while collecting wave (and potentially other) data along its path. Often the expectation is that the wave buoy will not be recovered, particularly if deployed in the open ocean, and thus data recovery is solely by real-time (satellite) telemetry. For drifting deployments targeting particular wave or storm events, however, the wave buoy might be recovered after the desired observations have been made.

Drifting deployments are typically used as a means of collecting ocean wave observations far from shores, particularly for data assimilation in metocean forecasting (e.g., Sofar Ocean drifting Spotter buoy network), without the high cost of maintaining deep-water moorings (e.g., US National Data Buoy network). They can also be used to collect targeted observations for investigating wave conditions during particular events, such as tropical cyclones (e.g., Boswood et al. 2017).

Drifting buoys can be deployed from ships, including 'vessels of opportunity', or from aircraft. As drifting deployments are a more specialised application, the specifics of deployment, recovery (if attempted), and data telemetry/management will be somewhat unique and thus are not detailed here. They will generally need to be tailored to the specific application with appropriate planning. However, some typical considerations include:

- General knowledge of currents, including their temporal variability, in the proposed deployment area. In Australia, IMOS provides satellite altimetry inferred currents (see http://oceancurrent.imos.org.au) which can resolve eddies and other sub-mesoscale features which can inform potential deployment locations and where a buoy is likely to go after deployment initially. Many public and commercial modelling products are also available. Small versus large format wave buoys will also likely drift differently in response to winds and currents (e.g., small format wave buoys have less windage), such that wind conditions should also be considered along with currents.
- Similar to moored deployments, drifting deployments should, as much as is possible, avoid areas of heavy shipping as to minimise causing a navigational hazard.
- Satellite telemetry is critical for drifting deployments as this will in most cases be the only reliable way of ensuring wave data is received and/or the buoy can be tracked for recovery.
- Given the much higher probability (or near certainty in some cases) of not recovering the buoy, careful consideration should be given if the wave observations can be collected in any other way. Buoys contain batteries, electronics and plastics which can be harmful to the environment and have a finite lifespan in the ocean and/or can wash up in remote areas. Thus, drifting deployments will likely have a higher environmental impact than moored deployments.

Operators considering drifting deployments should consult with state and Commonwealth maritime authorities for awareness and any necessary permits or approvals to carry out drifting wave buoy deployments in state and/or Commonwealth waters.

4.6 Deployment checklist

Table 3 provides an example pre-deployment checklist. A similar recovery checklist should also be used that also documents the state of the wave buoy and mooring prior to recovery and any issues.

Table 3. An example of a deployment check list for a wave buoy mooring.

Site details	
Site name	
Target coordinates	
Target water depth	
Deployment date & time	
Deployment vessel and crew	
Permits/advisories	
Maritime authority approval	
Marine protected area permit	
Notice to mariners issued	
Wave buoy	
Buoy type and serial number	
Firmware version and update if required	
Last calibration date (if applicable)	
Sufficient space on memory card	
Telemetry type (e.g. Iridium/cellular)	
Telemetry tested	
Clock synced	
Battery voltage/level	
All O-rings cleaned and greased	
Navigation lights working	
Desiccant in hull	
Ancillary sensors checked (if applicable)	
Mooring	
Mooring design (e.g. single catenary with surface float)	
Photos taken of mooring	
Check all rope and components are in good condition	
All splices whipped	
All shackles appropriately moused	
Contact between differing metals avoided or isolated	
Acoustic release armed, communication and battery checked (if applicable)	
Anchor weight in good condition/connections checked?	

5 Wave Buoy Data Management (Quality Control)

Wave buoy operators in Australia have mostly developed in-house workflows to receive, process, and archive wave data collected by buoys (Appendix A). A few key considerations differentiate how buoy operators treat data, often shaped by objectives and operational considerations. However, broadly speaking data workflows can be separated into real-time or delayed mode, with some operators doing one or the other, and some both.

- **Real-time data**: includes the transmission of any on-board processed data (wave spectra and parameters) usually at a fixed interval, e.g., 30 or 60 minutes. If the telemetry method support it (e.g., HF radio), displacements may also be transmitted in real time.
- **Delayed mode data**: includes the processing or re-processing of data stored on the buoy data card once the buoy has been recovered (and also the delayed analysis and quality control of banked real-time data, e.g., real-time displacements post-processed at monthly intervals).

The Quality Assurance of Real-Time Ocean Data (QARTOD) manuals published by the Integrated Ocean Observing System (IOOS) are the most recent and relevant published guidance on the quality control of wave buoy data. The QARTOD guidance was adopted at the Australian Wave Buoy Data Quality Assurance/Quality Control workshop in May 2022 (Appendix A) and is referred to herein.

5.1 Real-time wave data

5.1.1 Onboard data processing and storage

Commercially available buoys conduct onboard spectral processing with some also completing time-domain processing (see Section 3, Wave buoy data). In most, if not all, instances the settings in the onboard methods for processing displacements through to spectra and parameters are hard coded and cannot be changed by the user, thereby limiting the options of custom processing. Users typically only have the choice of the transmission interval and variables to transmit. Some users choose to use the onboard processed (and transmitted) data as the primary data product with onboard data only utilised as archive or to fill in any potential gaps (e.g., due to missed satellite transmissions).

All commercially available buoys store data onboard. The buoy type and manufacturer will determine the exact type of data stored on the onboard memory card. This may include a proprietary binary format containing both the displacements and processed spectra, where other manufactures save ASCII or similar files containing the displacement data.

5.1.2 Data telemetry

Commercially available buoys typically have the ability to transmit onboard processed data to shore via high-frequency radio link to a nearby shore station, via satellite (e.g., Iridium network), or through a cellular mobile network (Table 2). Some manufactures include several options within each buoy, for example cellular with satellite fallback. Satellite telemetry has the advantage of coverage globally however with the considerable disadvantage of cost. If satellite telemetry is the only option given the deployment location, the cost to send full spectral data hourly can be as high as AUD$1000/month. Of the current commercially available buoys, real-time displacement data can only be transmitted using high-frequency radio link to a nearby shore station. Some buoys may also allow retrieval of stored displacement data (non-real time) via satellite or cellular telemetry from the onboard storage.

5.1.3 *Near real-time data processing*

Near real-time data that is received via telemetry, depending on its form, can be utilised as is, further processed, or simply archived. Displacement data received in real-time can be processed into spectral and time domain parameters using proprietary or custom software. Similarly, onboard computed spectral data can also further be processed to, for example, compute the two-dimensional spectrum [Lygre & Krogstad, 1986]. If real-time data is to be received an appropriate workflow needs to be developed which may include setting up a server or other appropriate computing resource to receive the incoming buoy data or in the case of high-frequency radio telemetry a shore station with an antenna, power, and computer to store and/or further pass on the data.

5.1.4 *Near real-time QA/QC and display*

A particular consideration for the use of near real-time data is if any QA/QC is to be applied to flag and/or remove data before it is utilised further, archived, or displayed. QA/QC options are more limited for real-time data as only historical context is available when evaluating the data quality. The IOOS QARTOD manual provides a framework and series of test that can be applied to wave bulk parameters. These include, for example, range (maximum and minimum) test, flat-line (repeated value), and rate of change test. Based on the results of the QC tests, data can be flagged, for example as ‘good’, ‘suspect’ or ‘bad’ (see Section 5.3.2). An advantage of using previously developed QA/QC methodologies is the availability of resources and documentation. For example, the QARTOD tools are available in an open-access Python based GitHub repository (https://github.com/ioos/ioos_qc).

If displacement data is transmitted in real-time and subsequently processed, QA/QC can be conducted on the displacement data in near real-time (although this is less common) and/or otherwise on the resultant bulk parameters, as can be done with the transmitted bulk parameters alone.

5.2 Delayed mode wave data

5.2.1 *Data pre-processing*

Once a buoy has been recovered, any internally stored data should be retrieved/downloaded from the buoy and archived. Depending on the type and format of the data stored onboard, some pre-processing may be required to get the data into a usable format. For example, binary data stored on board Datawell Waverider buoys can be converted to CSV files using a library of executables freely provided by Datawell. This produces data files containing the spectral and bulk parameters, displacements, and in some cases time domain bulk parameters as well. Similarly, Sofar Ocean provide an open-source Python script that can be used to pre-process the CSV files saved on the memory card in the buoy. In any pre-processing steps that are completed it is important to be familiar with how the data are being treated, for example if displacements are being passed through a frequency filter this may impact further processing. It should be noted that pre-processing steps using proprietary software may be poorly documented (or commercial in-confidence) and thus require contact with the manufacturer.

5.2.2 *Data processing*

A key distinction of delayed mode data processing is if the starting point is the buoy displacement timeseries directly, or derived quantities produced on-board or using the manufacturer’s proprietary software. Wave buoy operators may use the onboard processed data, derived quantities generated using propriety software, or derive their own data from displacements using custom software. The derived quantities may be further processed, such as estimation of the full two-dimensional spectrum from the energy-frequency spectrum and Fourier coefficients, or spectral partitioning to estimate wave bulk parameters in differing parts of the spectrum (e.g., sea and swell). However, if computing additional wave parameters from already derived quantities it is best to have an understanding of how the data has already been processed as this may limit the ability or robustness of any further processing. For example, if the onboard spectral processing generates a relatively coarse frequency resolution, sea/swell partitions can be impacted by the size and specific frequencies of adjacent bins.

Rather than rely on onboard or commercial software, with limited user options, some operators opt to process data directly from the displacement measurements. This has the advantage of providing the most flexibility in processing methods and processing settings. However, processing directly from displacements will require the development of a more complex workflow. As described in Section 3, displacement data are typically processed to produce spectral or time domain parameters describing the gross sea state, however other methodologies are becoming more common (e.g., wavelet analysis, Massel [2001]).

For classical spectral analysis the approach generally follows that of Kuik et al. [1988], with a direct Fourier transform computed to estimate the sea surface heave spectrum which is then integrated to derive the spectral significant wave height, H_{m0}. The co- and quadrature spectra between the heave and north and east displacements can be utilised to derive directional properties of the waves [Longuet-Higgins et al. 1963]. While this approach is similar to that conducted in most onboard processing, if beginning from the displacements directly, the user has the option to define all (and determine optimal) settings in the spectral analysis.

Those settings include the length of data (segment block) to analyse in each Fourier analysis (a stationary sea state is assumed in each block), the number of samples to analyse in each block (e.g., 512, 1024, 2048), any windowing or overlapping between adjacent blocks, as well as ensemble averaging and frequency merging. Readers are referred to Thomson and Emery [2014] for more details on spectral processing. Understanding and optimising the setting in spectral analysis of wave buoy displacements can be important particularly in areas with very short or long period waves or in nearshore areas where tides and currents may impact wave conditions.

Similarly, if conducting time domain analysis, carrying that out from displacement data using custom software, rather than using values calculated onboard or using proprietary software, allows the choice of methodology to be selected (e.g., up/down zero crossing) and settings therein such as the minimum peak heights or separation.

5.3 Delayed mode QA/QC

5.3.1 Quality testing

Real-time data streams provide limited opportunity and context for QA/QC, such that to achieve the highest quality wave record, delayed mode processing is typically required. Delayed mode QA/QC can involve re-processing the real-time telemetered data stream after a certain time period (e.g., monthly) after a buoy is recovered for servicing (including using the data stored on the memory card), or, a more detailed QA/QC process applied to displacement data and derived spectra/parameters.

Delayed mode QA/QC often begins with simple visual examination of time series of computed bulk parameters for visibly bad data values. Similar to real-time QA/QC the IOOS QARTOD series of test (or similar) [IOOS 2019] can be applied to wave bulk parameters, usually in a semi-automated fashion. However, by being completed in delayed mode the additional context and time period allows for some of the QARTOD test to be applied more rigorously. For example, the mean and standard deviation tests (QARTOD test 15) can be computed over a range including both before and after a given time point thereby allowing complete events (e.g., storms) to be incorporated in the range analysed.

Quality testing on displacement data can incorporate many of the same tests (e.g., QARTOD) as are completed on bulk parameters. While more complex, if processing from displacements there is a greater opportunity to salvage resulting bulk parameter estimates for a given time period. For example, the spectral or time domain analysis for a particular 30- or 60-minute analysis window can be corrupted by a small number of erroneous displacement values (e.g., due to momentary GNSS satellite lock). If these erroneous displacement values are identified, they can be excluded from the analysis and thus often allow the data record to be assessed as high quality.

5.3.2 Quality flagging

Buoy operators globally have developed various strategies to flag or otherwise identify bad or suspect data. Broadly speaking, upon completing a QC test on a given data set, individual data points can be assessed as being ‘good/pass’, ‘bad/fail’ or in some cases ‘suspect’ (Appendix A). Flags can also be assigned to indicate if data have been evaluated (or not) or to indicate that data are missing (e.g., temporary equipment malfunction). Table 4 shows a flagging system that was developed for wave buoy data as part of the QARTOD tests. A consideration for applied data flagging strategy is if data is going to be flagged on a variable-by-variable basis, given a ‘global’ flag for all variables for a given time point, or both. If a global flag is assigned to data for a given time point a consideration is which flag is assigned in instances where only one or a small number of variables for a given time are flagged as bad or suspect. For example, if the significant wave height is assigned a ‘good’ flag but the peak direction is assigned a ‘bad’ flag.

Ultimately, the adopted flagging system will be influenced by data use cases and the expectations of end users. Some organisations do not publish data points flagged as being bad or suspect, while others provide all data with appropriate flags and allow the data user to decide if bad or suspect data is omitted from any analysis.

As part of this project, a national standard flagging scheme for in-situ wave data was agreed to be used for wave buoy data being published on the Australian Ocean Data Network (AODN) portal, the national repository for ocean data. The primary level quality flagging system that was chosen is the QARTOD system (Table 4) [IOOS 2020], which is an implementation of the Intergovernmental Oceanographic Commissions quality flagging system (Appendix A).

Table 4. QARTOD quality flag definitions [IOOS 2020].

Flag	Label	Description
1	Pass	Data have passed critical real-time quality control tests and are deemed adequate for use as preliminary data
2	Not evaluated	Data have not been QC-tested, or the information on quality is not available
3	Suspect or of high interest	Data are considered to be either suspect or of high interest to data providers and users. They are flagged suspect to draw further attention to them by operators
4	Fail	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
9	Missing data	Data are missing; used as a placeholder

5.3.3 Data repair

Data repair options are strongly influenced by the processing strategy and workflow. In instances where commercial or proprietary software is used, data repair options may be limited. Poor data can result from a range of equipment or environmental issues, common issues include momentary GNSS satellite lock in the case of satellite receiver buoys, a buoy becoming taught or tangled in a mooring, accelerometer malfunction/failure, or biofouling impacts on the mooring (and potentially the power system in the case of solar charged buoys). If the buoy has been recovered and displacement data is available there are potentially more data repair options.

Ultimately in many instances bad or poor data results from erroneous acceleration, position, or velocity and subsequent displacement measurements. In the worst case this may be the result of failure of the motion unit but in some cases erroneous displacements can result from transient issues like momentary loss of GNSS satellite lock or the buoy becoming tight on the mooring. If QC is completed on the displacement time series erroneous displacements can be identified, and if not widespread throughout a given analysis period (e.g., 30 or 60 minutes), be excluded from the spectral or time domain analysis thus preserving a spectral/time-domain data point that would otherwise be flagged as bad and potentially discarded.

Although a variety of approaches can be taken, erroneous displacement measurements are either deleted or filtered and replaced with interpolated values (thus preserving a time series with a fixed sample frequency as required for spectral analysis) or displacement blocks including erroneous displacement measurements can be excluded from an ensemble average as is typically done in most spectral processing routines. Figure 11 shows an example of a displacement record with spurious displacement values and the resulting spectra when these are included and excluded. By excluding the spurious displacement values the low frequency peak in the spectrum is removed and the significant wave height (H_{m0}) decreases from 2.60 m to 2.44 m (Figure 11b).

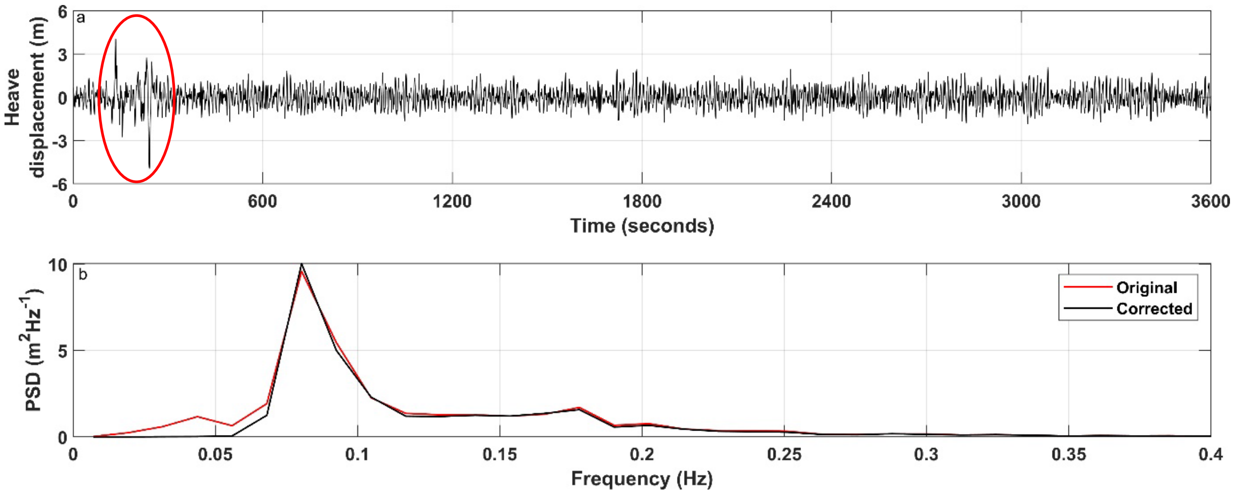

Figure 11. (a) Example hour-long GNSS buoy heave displacement time series with spurious displacement values early in the record (area indicated by red oval). (b) Energy-frequency spectrum of the heave time series shown in (a), the red line represents the spectral analysis considering the full displacement record while the black shows the results if the segments containing the spurious displacements are excluded from the ensemble average. By excluding the spurious displacement values the significant wave height (H_{m0}) calculated from the spectra shown in (b) decreases from 2.60 m to 2.44 m. (source: J. Hansen)

5.4 Data archiving

Once all processing and QA/QC has been completed data sets should be archived in a secure and accessible manner. A key consideration when archiving data is a descriptive and consistent naming convention and if wave data is to be archived on a location basis or on a per instrument basis. Many organisations maintain wave buoys at a given location for many years and these data form the basis of long-term studies of wave climatology for example. In these instances, where different individual buoys will be deployed at a site over time it will generally make the most sense to base the archiving structure around a site name/location. However, it should be noted that successive deployments at the 'same' site may be geographically separated by tens to hundreds of meters (or more in deep water) based on practicalities of deployment. Conversely for some applications archiving based on an instrument (i.e., specific serial number) basis may be preferred. A good practice is to organise data in a hierarchical system that preserves all location and instrument metadata.

In addition to any processed data products (either real-time or delayed mode) it is important to also archive any raw data, such as that stored on wave buoy onboard memory cards, any raw telemetered data, any intermediate processing data sets, as well as any metadata including deployment and recovery checklists (Table 3), field notes, and photos.

Final data formats that are archived and published will vary based on the application, but increasingly, NetCDF format is becoming the standard for archiving atmospheric and ocean data. NetCDF files have the advantage of including metadata records within the data file, and also allowing partial opening and access (i.e., a subset variables), which can optimise processing for large data sets. Similar to the decision about archiving on a site or instrument basis, operators may decide to archive one NetCDF file for one site or produce files for individual deployments. A disadvantage of NetCDF files is they are less approachable for casual or less experienced data users, so consideration should be given to the range of data end users.

Wave data file sizes can become quite large (100 Mb- 1Gb), particularly if displacement data are saved, such that any archiving system should be established to appropriate scale and be expandable as the data set grows. Increasingly with the low cost of cloud storage, many wave buoy providers are archiving data in cloud storage, which in most cases has the advantage of robust data backup and even distributed redundancy.

6 Accessing and Publishing Wave Buoy Data

The Australian Research Data Commons (ARDC) project, *Development of a national infrastructure for in-situ wave observations (Catching Oz Waves)*, which this document is a contribution of, has delivered a nationally consistent Australian wave buoy dataset through the Australian Ocean Data Network (AODN) online portal – https://portal.aodn.org.au

Wave data users should inspect the open-access Australian wave buoy dataset on the AODN portal.

New wave buoy operators should approach the AODN portal administration team early to establish appropriate metadata processes and publish their wave buoy data on the AODN portal.

Many existing wave buoy operators also provide the wave data that they collect through their own online portals, which may include additional data visualisations and data formats. Table 5 provides a list of other online wave data portals that are managed by wave buoy operators.

Table 5. Online wave data portals managed by wave buoy operators.

Organisation	Wave data portal
Australian Bureau of Meteorology	http://www.bom.gov.au/metadata/catalogue/19115/ANZCW0503900478
Department of Environment and Science (QLD)	https://www.qld.gov.au/environment/coasts-waterways/beach/monitoring/waves-sites
Manly Hydraulics Laboratory (NSW)	https://mhl.nsw.gov.au/Data-Wave
Department of Planning and Environment (NSW)	https://datasets.seed.nsw.gov.au/dataset/nsw-nearshore-wave-buoy-parameter-time-series-data-active-deployments
Port Authority of NSW	http://wavewindtide.portauthoritynsw.com.au/
Department of Transport (WA)	https://www.transport.wa.gov.au/imarine/wave-data-real-time.asp
University of Western Australia	https://wawaves.org
Victorian Coastal Monitoring Program	https://vicwaves.com.au/
Flinders University/ SARDI	https://sawaves.org

7 Summary

The community of Australian wave buoy operators has grown in recent years due to the increased accessibility of low-cost and comparatively easy to manage small format wave buoy technologies. This has had a positive impact through an ongoing increase in the distribution of in-situ wave observation devices in Australian waters, which provides opportunities to support research and knowledge growth beyond the objectives of individual wave buoy operators.

The Australian Research Data Commons (ARDC) Australian Data Partnerships project, *Development of a National Infrastructure for in-situ wave observations* (*Catching Oz Waves*), was established to enhance the accessibility, transparency and use of Australian in-situ wave data within and beyond Australia, and, to develop best practices for the Australian wave data community across the data lifecycle. This document provides general guidance for both established and emerging wave buoy operators by summarising techniques and best practices for both planning and managing wave buoy deployments, and processing and managing wave buoy data.

Given the variety of objectives and use cases for operating wave buoys across the nation, the approaches, equipment and procedures will vary across the Australian wave buoy network. Therefore, the guidance described here focuses on aspects and principles that will be common to most wave buoy applications. In-situ wave buoy data may be collected using different sensors and platforms, however, from buoy displacement data the spectral and parametric wave data commonly used are processed using variations of well-established techniques. Documentation of processing methods and consistent approaches to communicating data quality (e.g., a common quality flagging system) are paramount in delivering accessible and transparent wave buoy data.

Although operational aspects of wave buoy programs (e.g., mooring designs and deployment/retrieval procedures) will vary naturally between wave buoy operators based on their facilities, resources and objectives, the intention of the *Catching Oz Waves* project and this guidance document is to foster knowledge and experience sharing, and to work towards consistency in describing the provenance and quality of wave buoy data collected in Australia.

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Appendix A: Summary of existing QA/QC approaches & data formats

Information for consideration at the Australian Wave Buoy Data Quality Assurance/Quality Control workshop held online on Friday 13th May 2022, convened by Dr Jeff Hansen and Dr Mike Kinsela.

Introduction

In situ wave buoy observations are collected around Australia by State and Commonwealth Governments, industry, and increasingly research organisations. These data are collected for a range of different reasons (e.g. maritime operations, coastal management, research, marine safety) and using various wave buoy platforms, and some organisations have collected wave buoy data since the 1970s. Currently there is no national standard approach for the delivery of real-time or delayed mode (i.e. post-processing after recovery) wave data or for data Quality Assurance and Quality Control (QA/QC). Each data provider has developed independent approaches based on their particular needs/objectives and available resources. With the development of low-cost and accessible GPS/GNSS based buoys (e.g. Sofar Spotter) as well as the recognised need for more national wave observations [e.g. *Greenslade et al.*, 2020; *Power et al.*, 2021] developing standardised data formats and QA/QC approaches is increasingly important. Standardised data formats and QA/QC will unlock the most value out of wave buoy observations, including enabling comparative studies and increasing the application of wave data sets across a broader range of stakeholders, including those without the expertise to process and assess the quality of wave data themselves.

As part of the Australian Research Data Commons project '*Development of a National Infrastructure for in-situ wave observations*' a national standard operating procedure for the analysis and QA/QC of wave buoy observations will be developed. As a first step, interviews were conducted with wave buoy operators nationally, spanning government and industry, to understand how wave buoy data is currently being collected and delivered with a particular focus on data formats and QA/QC procedures. The interviews were standardised and asked for information on both real-time and delayed mode wave buoy data streams. This document summarises the outcomes of the interviews with an aim to understand current procedures as a way to inform the development of a national standard. This document will also form the basis of a national workshop involving the interviewees as well as other wave data collectors and users to agree on what the national standards should include and look like.

Six organisations were interviewed spanning Commonwealth and State government and industry (Table A1). Between them these six organisations operate a range of different wave buoys, for different purposes, and have a range of different workflows and QA/QC strategies.

Table A1. Organisations interviewed for this summary report

Organisation	**Acronym**
Bureau of Meteorology (Commonwealth)	BOM
Western Australia Department of Transport (State Government)	DOT
Department of Environment and Science, Queensland (State Government)	DES
Manly Hydraulics Laboratory, New South Wales (State Government)	MHL
OMC International (Industry)	OMC
RPS MetOcean (Industry)	RPS

Data types and workflows

Displacements, wave spectra and parameters

Wave buoys currently in use in Australia measure the wave field by recording the buoy motion (displacement) through time using mechanical motion-sensing instruments (e.g. accelerometers, gyros, compass) or a satellite receiver that uses GPS/GNSS to calculate position and/or signal doppler shift. The time series of buoy displacement (x,y,z) is the most basic data type recorded by wave buoys and is usually stored on the buoy's data card and may be transmitted to a shore based station in real time. Both spectral and time-domain wave data processing approaches are carried out using the buoy displacement data, which itself is not always accessed by data users once the derivative spectral and parametric datasets have been created. Buoy displacement data may be subject to manufacturer's quality control flagging/filtering or optimisation methods onboard and may be inspected and evaluated by buoy operators in their quality control procedures (typically in delayed mode). The integrity of wave spectra and parameters depends on the quality of buoy displacement data.

Spectral wave data describing the distribution of wave energy across frequencies (1D) and directions (2D) over a fixed sampling interval (number of displacement records) are calculated onboard buoys at regular intervals (usually half an hour) using the displacement data which is logged typically at 1-2.5 Hz. While variations exist in the exact methodology, most spectral processing follows the methodology outlined by *Kuik et al.,* [1988], and results in Fourier coefficients (e.g. centred, first four) describing wave energy distribution and direction across the frequency range sampled by the wave motion sensor. From these, standard bulk wave parameters can be calculated (e.g. significant wave height, peak period) and can be further processed producing the 2D spectrum following statistical modelling techniques [e.g. Maximum Entropy Method, *Lygre and Krogstad*, 1986]. The spectrum and resulting spectral parameters describing key attributes of the wave height and direction spectra that summarise the wave conditions are usually calculated onboard and may also be telemetered in real time. The higher data volumes of full spectral wave data mean operators may choose to telemeter only the bulk wave parameters (e.g. significant wave height, peak period, peak direction) calculated onboard and retrieve the wave spectra data from onboard data cards during buoy servicing or retrieval.

In addition to the parameters derived from calculated wave spectra, similar wave parameters can also be computed through wave-by-wave time-domain analysis (e.g. zero-crossing) of the displacements. Significant and mean parameters may be derived from spectral or time analysis, whereas peak parameters relate to the peak of the energy spectra and thus are only available through spectral analysis. Operators may include a mix of both spectral and time-domain parameters in their data tables, which might also include spectral moments (M0, M1, M2…) from which other spectral parameters that are not present in the table may be derived. Bulk wave parameters are the most commonly used type of wave data sought by end users.

Onboard and onshore processed data

While all wave buoys calculate wave spectra and parameters from the displacement data onboard at regular intervals (e.g. half hourly), some operators choose to calculate their own spectra and parameters from buoy displacements separately. This may be carried out in real time at shore receiving stations using displacement data that is continuously telemetered from active buoys (e.g. via HF radio) or using displacement data retrieved from onboard data cards following buoy servicing or retrieval. Onshore processing of wave spectra and parameters allows for variations from the onboard processing methods, such as: number of displacement observations or segments used in spectral processing, methods of spectra and parameter calculation, time interval of processed spectra and parameter data (e.g. hourly), and quality control of displacement data prior to calculation of wave spectra and parameters. Operators who calculate their own spectra and parameters from buoy displacement data usually also retain and archive the displacement, spectral and parametric data files that are created and stored onboard the buoy data card and may also receive the onboard-processed spectral and parametric data in real time.

Established operators who manage wave buoy networks with operational dependencies tend to carry out near real-time onshore wave data processing from continuously telemetered displacement data. This allows for earlier publication of quality-controlled data without needing to wait for the wave buoy to be retrieved to inspect displacement data and carry out onshore processing. This approach is usually only viable where HF radio transmission to shore is possible, due to the costs of mobile/cellular and satellite data transmission and the inability of most buoys to transmit displacements in real-time using non-HF radio telemetry. HF radio telemetry may however be vulnerable to interruptions to real-time buoy data transmission and receiving, in which case data may need to be repaired using displacement data from onboard data cards once the buoy is retrieved. Once a buoy is recovered some operators may reprocess all onboard displacement data as part of their QA/QC procedure, while others only reprocess card data in cases where significant real-time data loss occurred. In some workflows, operators may combine some onboard processed data (e.g. directional spectra and derived direction parameters) with their onshore processed data in developing their standard outputs.

Real-time and delayed mode data

Real-time wave data may be telemetered from wave buoys continuously (displacements) or at regular intervals (e.g. half hourly) and is published in its telemetered format or a derivative of that format in near real time. The real-time data may be onboard or onshore processed. There may be a fixed delay of 1-2 hours in publishing real time data due to operator's data processing and publication workflows. Quality control procedures are absent or limited to basic automated range tests and data is published with appropriate disclaimers. Published real-time data is usually limited to a subset of parameters that may include a mix of spectral and time-domain parameters and may be provided in the form of rolling data plots and/or as tabulated data.

Delayed mode data is usually published by operators at regular intervals (e.g. monthly) for ongoing deployments or upon the completion of temporary deployments. As previously mentioned, some operators carry out near real-time onshore wave data processing from continuously telemetered displacement data rather than waiting to retrieve onboard data during buoy service or retrieval. In such cases, the delayed mode data typically features more data (e.g. additional parameters) and more extensive quality control that may include repairing missing data. Delayed mode data may include a mix of onboard and onshore processed data types and formats.

Data publishing and archiving

Data retention is high in the data workflows of established buoy operators, who typically archive all data types (displacements, spectra, parameters) and formats (binary, ascii), including both onboard and onshore processed data, regardless of whether they use or publish each type/format in their workflow.

The data archives of established buoy operators present opportunities to make available historical wave data in useful formats that may not have been made available previously (e.g. wave spectra) and displacement data archives also allow for re-processing of wave buoy data for specific applications. The formats both real-time and delayed mode data is archived in (and delivered to external users in the case of delayed mode) varies greatly from CSV and ascii files to NetCDF files.

Wave buoy data quality assurance (QA) & quality control (QC) in practice

Quality control of real-time or delayed mode wave buoy data can be classified into two general categories; 1) the QA/QC process is conducted on the buoy displacement time series prior to calculation of derived quantities or, 2) QA/QC process is conducted on the derived quantities (wave spectra and parameters). While the latter approach is most commonly used in practice, ultimately, erroneous spectra and parameter data result from poor and/or absent measurements in the buoy displacement time series.

This section summarises insights on current wave data QA/QC practices in Australia. It is intended to be read with reference to Table A1, which summarises the results of interviews with six established wave buoy data operators from the government and commercial sectors.

Real-time data

The established buoy operators interviewed focus their real-time QA/QC on the derived quantities with the exception being if QA/QC is conducted on the displacement time series onboard by the proprietary data processing software. For example, the newest generation of Datawell Waverider buoys (DWR4) automatically flag displacement values when the buoy angle exceeds 89 degrees and/or when the acceleration exceeds the rate of acceleration due to gravity (9.8 m/s^2) [*Datawell BV*, 2021]. Segments containing flagged displacements are excluded from onboard spectral processing (and thereby do not influence the calculation of derived spectral parameters) prior to data transmission to shore [*Datawell BV*, 2021]. Based on our interviews, operators who receive the displacement data in real time (e.g. via HF radio) perform real-time QA/QC on derived quantities rather than on the transmitted displacements.

Given the nature of the data stream, real-time QA/QC must be automated and thus may lack important context that would otherwise be considered in flagging and removing bad data. Of the organisations interviewed the real-time QA/QC procedures mostly included hard-coded checks on parameter values including range tests (e.g. maximum significant wave height or peak period values), repeated values tests (flat line), and spike tests (standard deviation exceedance of parameter values). As some real-time QA/QC tests require multiple data points (e.g. flat line or standard deviation) some organisations assign a ‘unknown’ quality to the most recent data point, which is then updated based as subsequent data points become available. For buoy operators who complete time-domain analysis on the transmitted displacements, data may also be flagged if, for example, there is a marked difference between values for comparative spectral and time-domain parameters (e.g. Hm0 and Hsig). While government wave buoy operators limit real-time QA/QC to parametric data, commercial operators noted that they also carried out real-time QA/QC on displacement data (steepness, spikes, flat line) where requested by the client. For industry applications real-time QA/QC may also include additional tests based on client requirements.

If real-time wave data is identified as being suspect, it is ‘flagged’ primarily as a means to exclude suspect data points from real-time data plots on public websites, or in commercial applications, to exclude from real-time plots and tabulated data streams available to clients. Real-time data flagging is typically separate from delayed mode flagging, in that real-time flags are not considered when more thorough delayed mode QA/QC processes are carried out. The primary objective of real-time QA/QC is to omit suspect/bad data points from real-time data products to improve the end user experience and applications. Standard disclaimers typically accompany public real-time data products, due to the necessary simplicity of real-time QA/QC, noting that data provided have not been examined by humans and the end user carries any risk in their applications. None of the operators interviewed delete real-time data that is flagged as suspect or bad, rather, all data are saved for subsequent delayed mode QA/QC and potential data re-processing.

Delayed mode data

Real-time data streams provide limited opportunity and context for QA/QC such that to achieve the highest quality wave record delayed mode processing is typically required. Delayed mode QA/QC can involve re-processing the real-time data stream after a certain time period (e.g. monthly) or after a buoy is recovered for servicing (including using the data stored on the memory card), or, a more detailed QA/QC process applied to displacement data and derived spectra/parameters received in real time. Due to high data volumes (and telemetry costs) real-time transmission of displacement data is usually only feasible via HF radio telemetry, which requires a shore receiving station. Thus, not all operators receive buoy displacement data in real time, and some buoy manufactures (e.g. Triaxys, Sofar) do not currently support real-time displacement telemetry. If displacements are not transmitted in real time, recovering the buoy and accessing the onboard data card is the only way to retrieve the record of displacements.

All but one organisation interviewed conducted delayed mode QA/QC. All organisations who conduct delayed mode QA/QC used in-house developed software which typically followed a regular (e.g. weekly, monthly) cycle carried out by dedicated staff, and in some cases also included an annual review and repeat QA/QC of all data. Delayed mode QA/QC may be carried out on spectra and parameters derived from displacement data that were received in real time, and/or by re-processing from the displacement data stored on the buoy data cards. Some buoy operators conduct interim and less exhaustive delayed-mode QA/QC, at weekly or monthly intervals, with full QA/QC occurring at longer regular intervals that may align with buoy servicing intervals (e.g., biannually or annually). In other cases, most QA/QC is carried out weekly/monthly and data retrieved during buoy servicing is only processed and used if significant real-time data loss occurred during the deployment period.

In most instances the overall approach to delayed mode QA/QC began with similar automated tests to those applied in real-time to flag suspect data, but then involved human examination of the data and benefitted from being able to review data across complete discrete events like storms. The most significant difference to the real-time processing was that many buoy operator's delayed mode QA/QC process included examining derived wave spectra and buoy displacement data to reveal the source of spurious spectral or time-domain parameters. This then provided the opportunity to exclude bad displacement data in reprocessing the derived data. Because HF radio data transmission can be subject to interference resulting in intermittent loss of real-time displacement data, some operators maintained the option to later reprocess data from onboard displacements where significant data loss occurred, while still being able to issue fully quality-controlled data containing outages in the interim.

Generally, the delayed-mode QA/QC is more rigorous and can be classified into several broad categories:

- **Range, spike and flatline checks**: All organisations interviewed had hard-coded ranges checks in place to identify suspect data. This includes identifying unrealistically high or low significant wave heights or periods for a given site. Most organisations also had flatline (repeated values) automatically flagged for inspection. These checks are similar to those conducted in real-time but by virtue of examining a longer time-series these checks become more rigorous. The threshold values used in these tests to identify bad or suspect data varied between operators.
- **Cross-comparison of data:** Many of the organisations interviewed conducted cross-checks on suspect data. This includes cross comparing estimates of, for example wave height, calculated spectrally versus in the time-domain or calculating ratios of various parameters with limits based on known wave theory. For example, the ratio of the maximum time domain wave height is rarely likely to exceed 2.5 times the significant wave height for a given time period. While these

tests are similar to those conducted in real-time, analysing long-blocks of data provides additional context. One organisation also compared data from adjacent sites to determine if visible spikes were consistent along the coast and thus more likely to be real or spurious.

- **Visual review of data:** As well as the tests to automatically identify suspect parameter values above, it was common for delayed mode QA/QC to involve the visual inspection of data including parameter time series, calculated wave spectra and in some case displacement time series. The objective of visual review was to provide context around bad or suspect data flagged by automated tests, such that expert reviewers can maximise good data retention and ensure that sound reasoning has been applied in flagging any data points as suspect or bad. Conversely, visual review might also identify suspect/bad data points that were not captured by automated tests.
- **Displacement data:** As all derived wave parameters result from processing of buoy displacement data, erroneous wave spectra, and spectral or time-domain wave parameters, all result from suspect of spurious displacement data. For organisations that reviewed displacement data, the individual blocks (usually 30-minute) were typically only reviewed in instances where derived data had been identified as suspect by one of the above checks. The displacement review process might involve visual review of the displacement time series simply to confirm bad records as the reason for flagged derived parameters, or automated tests (e.g. spike/flatline) applied to the displacement time series to identify compromised areas of the record. Some operator's data processing software included error parameters that count bad displacement readings identified using such tests in every displacement record. Comparison of displacement time series with buoy movement within its watch circle was another approach. While one industry organisation reviews the onboard displacement record following each deployment with each block re-processed excluding any spurious displacement values, for most operators displacement data is only re-processed when deemed necessary. Lastly, due to known issues of displacement artefacts in GPS buoys (e.g. DWR-G, Spotter), operators using GPS buoys typically included displacement filtering in their data processing workflow for GPS instruments, but not for wave buoys with mechanical wave motion sensors.

Flagging of data

The buoy operators interviewed had different methods of flagging data that had been subject to real-time or delayed mode QA/QC checks. Real-time flagging was usually binary ("good"/"bad") as the primary objective was to omit bad data from data plots and/or tables, in which case an intermediate flag is of little use. Some operators also used binary flagging for their delayed mode data, while others introduced a third "suspect" category to identify data points that might be compromised although were not definitively bad. A "missing" flag was used by some to identify bad data associated with a buoy being off station. A flag for "unchecked" data was also used in some operator's QA/QC software, although data is not published with such a flag as all data is quality controlled before release. Similarly, others had the opposite "verified" flag to keep track of data that been quality controlled.

Data flagging may be a functionality that is only used in the operator's QA/QC process in preparing quality-controlled data, or it may be communicated to the end user in published datasets. If data is flagged as 'bad' some organisations delete the data points (often with a detailed log of the times and reasons), others omit the data points from their published quality-controlled records, while others include bad data points in their time series identified with an appropriate flag. Where bad data points are omitted, the published data is usually delivered with only a flag confirming that the provided data has be checked or verified, and the user does not know if omitted data was not recorded by the buoy (i.e. missing data) or was removed in the QA/QC process. It was not typical for government data providers to publish/deliver data flagged as bad or suspect, although all flagged data was retained in their databases and thus could be provided on specific request.

For data points/time stamps when no data is available (e.g. buoy adrift, during a service visit, or instrument malfunction), it was more common to omit the data points/time stamps in published data records rather than preserve the data points/time stamps and flag them with a “missing” data flag. Again, the omission of data points/time stamps means that the end user remains unaware if data was not recorded by the instrument, or if compromised data has been removed in the QA/QC process.

Published wave buoy data QA/QC standards

Procedures and standards for wave buoy data QA/QC have been published by various data collectors and data collaboratives internationally over the past few decades. Similar to the diversity of practices in Australia as documented here, QC procedures and data flagging vary between groups, although there are many commonalities in the tests that are applied to identify suspect or bad data. This section provides some context on existing QC approaches (particularly notable points of difference) that have informed our recommendations. Readers are directed to the individual resources for detailed accounts.

Coastal Data Information Program (CDIP), Scripps Institute of Oceanography.

The long-running US CDIP coastal wave data program provides a wealth of knowledge on in-situ surface wave buoy data collection and management, including data processing and quality control. CDIP operates a large network of Datawell Waverider buoys, which remains the dominant platform for government operated wave buoy programs in Australia, and thus CDIP data workflows and QA/QC approaches will be relevant to application in Australia. CDIP maintains documentation of all aspects of their data workflows in an online document portal: https://cdip.ucsd.edu/m/documents/index.html.

CDIP has also published a comparative summary of quality control tests applied to wave data by various buoy operators and collaboratives, including: QARTOD, CDIP, FRF, IOC, NDBC, and for popular acoustic wave sensors manufactured by Nobska, Nortek, RDI and Sontek: http://cdip.ucsd.edu/documents/index/product_docs/qc_summaries/waves/waves_table.php

Manual for Real-Time Quality Control of In-Situ Surface Wave Data, IOOS/QARTOD (2019) and Manual for Real-Time Oceanographic Data Quality Control Flags, IOOS/QARTOD (2020).

The Quality Assurance of Real-Time Ocean Data (QARTOD) manuals are the most recent published guidance relevant to wave buoy data QC and present a data testing and flagging framework that has been developed and agreed on by multiple experienced wave buoy operators. The manuals focus on real-time data, however, many aspects are equally relevant to delayed mode data. The broad group of QARTOD members ensures that recommendations are sufficiently flexibility to accommodate the activities of different wave data collectors.

QARTOD recommends a simple primary data quality flag scheme as a minimum standard that is sufficient to distinguish between good, suspect, bad or missing data, as well as data that has not been subject to QC evaluation. More advanced secondary flag schemes that provide further information on parameters and/or tests leading to the choice of primary result are accommodated at the discretion of the data collector. The primary flag scheme provides a convenient means for data users to easily omit a questionable or bad data point from their applications, which is likely to suit many cases where the user is not interested in salvaging or repairing partial data from compromised data records.

Table A2. QARTOD quality flag definitions (QARTOD, 2020)

Flag	Label	Description
1	Pass	Data have passed critical real-time quality control tests and are deemed adequate for use as preliminary data
2	Not evaluated	Data have not been QC-tested, or the information on quality is not available
3	Suspect or of high interest	Data are considered to be either suspect or of high interest to data providers and users. They are flagged suspect to draw further attention to them by operators
4	Fail	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
9	Missing data	Data are missing; used as a placeholder

The quality flagging system adopted by QARTOD follows the Primary Level flagging standard that has been recommend by the Intergovernmental Oceanographic Commission's (IOC) Ocean Data Standards Volume 3 [*UNESCO*, 2013] and thus is a consistent international standard.

Table A3. IOC 54:V3 Primary Level quality flags (UNESCO, 2013)

Flag	Label	Description
1	Good	Passed documented required QC tests
2	Not evaluated, not available or unknown	Used for data when no QC test performed or the information on quality is not available
3	Questionable/suspect	Failed non-critical documented metric or subjective test(s)
4	Bad	Failed critical documented QC test(s) or as assigned by the data provider
9	Missing data	Used as place holder when data are missing

Quality Assurance and Quality Control of Wave Data, Channel Coastal Observatory (2017).

The National Network of Regional Coastal Monitoring Programmes of England includes a coastal wave data network that collects wave buoy data in shallow coastal waters. Documentation on their quality assurance and quality control of wave data has been published by the Channel Coastal Observatory (CCO). QC processes are carried in real time (automated), with both monthly and annual manual review of processed data. QC tests are performed on select spectral and time-domain parameters (and SST), using spike/range tests and inspection of plotted data.

The CCO quality flagging system provides a more detailed description of the parameter/s that failed a diagnostic test, resulting in a quality flag for that data point (time stamp) other than good/pass. As flag codes 1, 2, 3 and 4 overlap the IOC 54:V3 primary level flags of those values with different meanings, this system is not compatible with the IOC standard. Rather, this example represents a hybrid quality flagging system that combines aspects of primary and secondary flag systems described elsewhere in a single series of flags that are intended to provide users more information on the nature of suspect or bad data records. In identifying the parameter/s that failed quality control tests it potentially provides the option for users to accept "good" parameters from potentially compromised data points, if they are not interested in the parameter/s that failed tests and are confident that their parameter/s of interest are not compromised.

Table A4. Channel Coastal Observatory wave data quality flags (CCO, 2017)

Flag	Description
0	All data pass
1	Either HS or TZ fail, so all data fail (except SST)
2	TP fail + derivatives
3	Dir fail + derivatives
4	Spread fail + derivatives
5	TP fail jump test
7	Buoy off location
8	SST fail
9	Missing data

Handbook of Automated Data Quality Control Checks and Procedures, NOAA/NDBC (2009).

The US National Data Buoy Centre operated by NOAA manages a global network of ocean data buoys that measure meteorological and oceanographic properties and is a partner of the Integrated Ocean Observing System (IOOS) who publish the QARTOD manuals. The NDBC (2009) Handbook includes a detailed account of QC testing and documentation procedures specific to NDBC buoy platforms, which includes wave data validation tests such as spike, range and comparative parameter tests, as well as algorithms for the evaluation of wave spectra.

The NDBC quality flag scheme pre-dates the UNESCO (2013) and QARTOD (2020) standards and comprises an extensive set of 9 hard flags and 20 soft flags that are applied to individual data parameters rather than all parameters from a given data point (time stamp). Hard flags indicate that the parameter is almost certainly compromised while soft flags indicate that the parameter value is questionable. The various hard and soft flags correspond to the reason why the parameter is deemed to be compromised or questionable. The system was developed to cater for an extensive suite of complex metocean data buoys featuring many additional sensors and measurements relative to standard wave buoys.

Table A5. NDBC quality control hard flags (NDBC, 2009)

Flag	Description
T	Transmission parity error (Applies to continuous winds and non-WPM wave data, and DART® data)
M	Missing sensor data (A result of a garbled or missing message)
W	A WPM wave message is short, missing a checksum, or parity errors are detected
D	Delete measurement from release and archive (A Data Analyst or automated QC has failed the sensor)
S	Invalid statistical parameter (in waves, QMEAN is not between QMIN and QMAX, flags WVHGT)
V	Failed time continuity
L	Failed range limits
H	Hierarchy reversal has occurred (BARO, WSPD, WDIR only)
R	A related measurement has failed a hard QC check

Way forward

Appetite for a national standard

Across the wave buoy operators interviewed there was general agreement that a national standard for data formats and QA/QC would be beneficial, and most organisations are willing to adopt at least some aspects of a national standard and associated methodology. Most organisations indicated that they would only consider adopting a new approach for quality-controlled published data if it was as least as stringent as what they are currently applying. Some providers also indicated they would be more likely to adopt a new system if similar organisations nationally also agreed to adopt changes. The positive response to the proposal for a national standard across government and industry organisations with varying processes and resources for wave data management is encouraging to the goals of the ARDC project.

Proposed QA/QC framework

Noting that several international standards already exist (Section 4) it would be redundant and inefficient to develop a new independent QA/QC protocol and flagging system. As such, an initial proposal to the Australian community would be to adopt one of the existing standards. Given a number of the interviewed organisations indicated their QA/QC protocols are partly consistent with or based on the QARTOD manuals (and QARTOD has been adopted by research organisations, e.g. UWA), we propose QARTOD as the basis of Australian wave data QA/QC standards. However, it is worth noting that QARTOD (and similar standards) only outline tests to be conducted, they do not mandate which parameters the tests are to be applied to, nor the thresholds/settings for each test. For example, QARTOD test 15 determines if a given data point is within *n* standard deviations from the mean of that variable. However, the practitioner must determine which variables to apply the test to, as well as the number of standard deviations that are acceptable and the number of data points across which the standard deviation is calculated. The standard deviations and number of data points are ideally informed by expert knowledge of the wave climate and temporal variability. An example of the QARTOD protocol as implemented by UWA is provided in Table A6.

However, it is noted that the above summarised QA/QC protocols in Section 4 and example in Table A5 have been developed and primarily applied to spectral wave parameters rather than at the level of displacements. As noted above in almost all circumstances spurious spectral or time domain data points result from spurious displacements in the time series used to calculate the wave parameters. Thus, ideally some level of QA/QC is conducted on the displacements prior calculation of the spectral parameters. This will of course be difficult to do in many cases in real-time but could be carried out in delayed mode in many cases. This approach is already taken by one of the industry parties interviewed. For most standard spectral analysis methods, a record of displacements (e.g. 30-mintues) is broken into discrete segments (often overlapping) which are passed through a Fast Fourier Transform [e.g. see *Emery and Thomon*, 2001]. The resulting spectra from the discrete blocks are then typically recombined as an ensemble average. segments that contain spurious displacements (as identified by some of the same tests outlined above) can be excluded from the ensemble average or the spurious displacements can be removed and the timeseries made continuous using a filter (e.g. Butterworth). If QA/QC is conducted on the displacements it is likely less spectral parameters would be flagged as a result of a limited number of bad displacement data points in a half or one- hour time series.

Table A6. QARTOD standards as implemented by UWA

QA-QC Test	Variables tested	Example Settings
Mean and standard deviation	Significant wave height (Hs), Peak wave period (Tp), Peak wave direction (Dp)	standard deviation range = 3 time window = 72 hours
Flat line	Significant wave height (Hs), Peak wave period (Tp), Peak wave direction (Dp), Temperature	Hs tolerance = 0.025 m Tp tolerance = 0.01 sec Dp tolerance = 0.5 deg Temperature tolerance = 0.01 degC number of hours for suspect = 144 number of hours for fail = 240
Range	Significant wave height (Hs), Peak wave period (Tp), Peak wave directional spread (PkSpr), Temperature	min/max Hs = 0.10/10 m min/max Tp = 3/25 s min/max DirSpread = 0.07/80 deg min/max Temp = 5/55 degC
Rate of Change	Significant wave height (Hs), Peak wave period (Tp), Peak wave direction (Dp), Peak wave directional spread (PkSpr), Temperature	Hs rate of change = 2 m Tp rate of change = 10 s Dp rate of change = 50 deg PkSpr rate of change = 25 deg Temperature rate of change = 2 degC

Adopting a QARTOD testing scheme applied to spectral (and time-domain) parameters does not preclude some operators from reviewing (and repairing) displacement records as part of their QA/QC procedures. In that case, spectral data points that may have failed tests initially may subsequently pass once compromised displacements have been removed and spectral analysis is carried out using the repaired displacement record. This approach is common, for example, in processing data from GPS wave buoys in which artefacts and absent measurements occur relatively frequently in displacement records. In that case, it might be considered to include an additional flag (e.g. 5) in the primary QARTOD scheme to indicate to end users that while a data point has passed the tests, the spectra and parameters have been calculated from an incomplete displacement record and bad segments were omitted during spectral analysis. Thus, the proposed framework is designed to accommodate more detailed QA/QC processes where available (leading to higher data retention), but does not exclude more limited processes, with end users receiving consistent and transparent communication on the quality of data points based on application of the QARTOD tests to parametric data.

Regarding data flagging, the QARTOD primary flagging scheme (Table A2) provides flexible quality control documentation that is compatible with the varying QA/QC processes of all organisations interviewed. While not all operators use a “suspect” flag, the QARTOD scheme accommodates that if it is available, but need not be used where an operator uses only a binary flagging scheme. As suspect data points are, by definition, not definitively compromised, the presence of suspect data points simply provides a warning for end users, who may then wish to inspect the displacement or spectral data. The missing (9) flag accommodates the inclusion of continuous time stamps in datasets published under the national standard. The most significant change for most current data providers would be the delivery of “bad” data (transparently flagged with 4) in published datasets, which in current practice are often omitted from published data records. A further consideration is if a ‘master’ flag is applied to a given time point as in some instances certain variables will be flagged as bad/suspect for a given time point when others are not.

Potential barriers to implementation

The largest barriers to adoption indicated with the interviewees was potential inconsistency with the methods that have been applied often for many years thus impacting the robustness of continuous time series. In the near term, primarily based on the broad hesitation about making significant changes to existing systems, the most likely scenario is parallel data processing pathways. This would allow buoy operators to maintain their existing systems and workflows, while also allowing data to be processed following a new workflow and QA/QC protocols. Given the complexity of real-time data systems it is envisioned any new workflow would be applied, at least initially, to delayed mode data.

A topic that was raised by nearly all interviewees was the cost of implementing any new system. Majority of the wave buoy providers nationally are publicly funded and thus often face challenges maintaining their existing systems. As a result, most of the organisations interviewed indicated that additional funding and/or toolboxes would need to be provided to facilitate any transition. It was generally agreed that centrally and shared codes, as part of a large toolbox, was a preferred way forward. This would remove some of the burden on the wave buoy operators, reduce redundant code and tool development nationally, and allow version control and continual improvement of tools (e.g. initially starting with delayed mode and gradually developing tools for real-time). It was also suggested that ‘raw’ data could be provided and centrally processed (e.g. by AODN) however some organisations did not prefer this option as they would have less opportunity to approve final data products before public release. A key conclusion drawn from the interviews is that dedicated funding needs to be secured to develop a national open-source wave buoy QA/QC toolbox and code repository. Who would lead the development is open for discussion but it is clear that without such a toolbox uptake of any nationally agreed standard will remain low.

Next steps

To develop a nationally consistent path forward it is proposed a workshop is convened with the wave buoy data providers interviewed for this report as well as others who collect wave data across industry and research as well as parties likely to receive and use wave data (e.g. AODN). During the workshop the findings of this review will be presented as well as the broad structure for a national approach proposed here. This will then form the basis for a broad discussion among all participants leading ideally to an agreed structure for a nationally consistent QA/QC protocols for both real-time and delayed mode delivery as well as data formats. The workshop will also discuss and develop a strategy to implement the agreed outcomes including strategies to attract funding to develop an open-source toolbox.

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