Wave Measurement from Data Buoys

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Abstract

The principles and practices of using buoys to measure both non-directional and directional wave data are presented. The system of wave-measuring buoys and its subsystems (including the buoy hull, mooring, measurement instrument, electrical and electronic components, wave data quality control, and field support) are discussed. Data and examples obtained from wave-measuring buoys are used to illustrate these components and wave data processing. The U.S. National Data Buoy Center's (NDBC) operations and operational wave-measuring buoy systems are introduced.

1. Introduction

Buoys have been used to measure marine environmental data for many years. Most of the marine environmental data measured from a buoy (e.g., wind speed, wind direction, air temperature, water temperature, etc) can be considered as direct measurements because they usually do not need complicated data processing or supplemental data from other sensors. Since the wave data are actually "derived" from buoy motion and require extensive data processing and analysis, measuring wave data from a buoy is categorized as an indirect measurement. For directional wave measurement, outputs from more than one sensor are needed to derive the desired wave information. Thus, measuring wave data from data buoys is more complex and expensive than measuring other oceanographic and meteorological data.

As discussed in Teng (1992b, 1994, 1995a), to use a buoy to measure environmental data, one has to regard it as an integrated "system" which includes several subsystems. All these subsystems are inter-related and individually critical. Therefore, a failure or error of any single subsystem may result in missing or inaccurate data. Thus, one needs to design, fabricate, operate, and maintain all the subsystems correctly, and all the subsystems have to work together as an integrated system to measure reliable and accurate data. Of course, this system concept is also applicable and important to a wave-measuring buoy system.

Data buoys for long-term operational purposes are significantly different from buoys used for short-term research or data collection purposes. Usually, an operational data buoy needs to report measured data regularly (e.g., every hour or every 3 hours) in real time or nearly real time for a relatively long time period (e.g., one year or more). Thus, design/operation of the buoy system and the requirements/format of measured data are different.

In this paper, the process and system concept of buoy wave measurements are discussed first. The principles and practices of using data buoys to measure both non-directional and directional wave data are presented. Subsystems of a wave-measuring buoy system, which include the buoy hull/mooring, measurement instruments, electronic/electrical equipments, wave data quality control, and field and maintenance support, are then discussed in detail. Data and examples from wave-measuring buoys are used to illustrate the principles, practices, and subsystems. Differences between operational buoys and buoys used for short-term purposes are identified. Finally, the U.S. National Data Buoy Center's (NDBC) operations and operational wave-measuring buoy systems are introduced.

2. Precess and System of Buoy Wave Measurement

Buoys can be used to measure either non-directional (or uni-directional) wave or directional wave data. Actually, what a buoy measures from its instruments is not the wave itself, but the motion of the buoy. The buoy motion is then "transformed" into wave motion. Figure 1 presents a flow diagram for the buoy wave measurement process. As shown in the figure, to derive the wave information from the measured buoy motion, it requires extensive data processing and analysis, either onboard a buoy or when the data is sent back to the shore. Either way, it requires that the final wave data (i.e., the last block) represent the real ocean waves (i.e., the first block). Thus, the wave processing and analysis need to consider all the effects which might affect buoy wave measurements.

From the "hardware" viewpoint, effects from the dynamics and design of buoy hull/mooring, measurement instruments, electrical and electronic equipments, and buoy field and maintenance support are crucial for buoy wave measurement. From the "software" viewpoint, the processing algorithms and techniques, wave data formats, and data quality control are all the key issues to obtain reliable and accurate wave data. All of these will be discussed in the following sections. From the system viewpoint, the above items are closely related and linked together to form the whole wave buoy system. For example, the processing algorithm needs to work hand-in-hand with the electronic system to process the data.

3. Principle and Practice of Wave Measurement Using Buoys

3.1 Non-directional Wave Measurement

The buoy's heave motion is needed for non-directional (or one-dimensional) wave measurement. Once the heave motion is measured, the wave frequency spectrum $S_w(f)$ can be derived from the spectrum of the buoy heave motion $S_h(f)$.

$$S_w(f) = \frac{S_h(f)}{PTF} \tag{1}$$

in which *PTF* is the power transfer function between the wave vertical motion and the buoy heave motion. Since the power transfer function is a function of wave frequency, wave data measured from a buoy are usually processed in the frequency domain in the form of wave spectra. Since both spectral values and the power transfer functions are functions of wave frequency, both the waves and the motion responses are assumed linear. Thus, nonlinear waves can not be measured from data buoys.

Figure 2 shows the heave response amplitude operator (RAO), which is the square root of the power transfer functions, for three different buoy shapes: 3-meter discus, spar, and spherical buoys. It is clear that the heave motion of a spar buoy does not follow the wave motion as well as those for the discus and sphere buoys. In order to measure waves more accurately, it is desired that the buoy motion follows the waves as closely as possible, which will ultimately reduce potential errors from either the transfer functions or low signal/noise ratio. Thus, in general, spar-shaped buoys are not suitable floating platforms for wave measurement.

Since the wave's vertical motion is described in an earth-fixed coordinate system, it is desired that the buoy's heave motion can also be measured in the same coordinate system. In other words, it is preferred that a motion sensor can measure the buoy's vertical motion from an earth-fixed coordinate without being affected by the buoy's pitch and roll motion (e.g., a gimbaled-accelerometer or an accelerometer on a vertically-stabilized platform). Thus, the wave spectrum can be directly obtained from the measured heave motion.

However, if a motion sensor is fixed on the buoy hull, the heave motion is measured from a buoy-fixed coordinate. Due to buoy's pitch and roll motion, the measured heave motion is not truly parallel to the wave vertical motion (which is described from the earth-fixed coordinate), but is contaminated by the corresponding tilting motion. Earle and Bush (1982) showed that acceleration spectra measured with an accelerometer that is fixed on a buoy hull have excess low-frequency energy, which is considered as noise. Since the displacement spectrum is derived by dividing the acceleration spectrum by a factor of ω^4 (ω is equal to 2π times the wave frequency), the low-frequency noise will be significantly amplified during the conversion. Accordingly, the wave spectrum at the low frequency range (i.e., the swell range) and the wave parameters derived from the wave spectrum will be significantly affected. Earle, et al. (1984) proposed the following noise correction function (*NC*) to empirically remove the low-frequency noise of an acceleration spectrum.

$$NC(f) = \begin{cases} K(f_c - f) & ;\ for\ \ f \le f_c \\ 0 & ;\ otherwise \end{cases} \tag{2}$$

in which K is a correction parameter and f_c is a fixed frequency which is the upper limit for noise correction (i.e., no correction above this frequency). Based on real measurements, the correction parameter was empirically derived by Lang (1987a) for NDBC data buoys.

$$K = G \cdot \frac{S_{0.01} + S_{0.02}}{2} \tag{3}$$

in which G is a constant, and $S_{0.01}$ and $S_{0.02}$ are values of the acceleration spectral energy at f = 0.01 and 0.02 Hz, respectively. Lang (1987a) also showed that G varied from 13 to 18 and f_c varied from 0.150 to 0.178 Hz for different buoy hulls, water depths, and mooring configurations.

An example of the noise correction on a wave spectrum measured by a buoy with a fixed accelerometer is shown in Figure 3. Figure 3-a shows the original acceleration spectrum. It is clearly seen in Figure 3-b that there is significant low-frequency noise in the displacement spectrum when no noise correction is applied. In Figure 3-c, the low-frequency noise is effectively removed by using the above noise correction technique.

3.2 Directional Wave Measurement

For directional waves, in addition to the heave motion, other buoy motions are required to derive the information on wave direction. Currently, there are three techniques of using buoys to measure directional waves: (1) based on the slope-following characteristics; (2) based on the orbital-following characteristics; and (3) based on the particle-following characteristics. All of these methods, which will be further discussed in the following subsections, are based on three orthogonal buoy motions.

Measuring directional waves from data buoys is usually based on the assumption that a directional spectrum, $S(f, \theta)$, can be expressed as a Fourier series expansion,

$$S(f,\theta) = \frac{a_o}{2} + a_1\cos\theta + b_1\sin\theta + a_2\cos2\theta + b_2\sin2\theta + \cdots \qquad (4)$$

in which f is the wave frequency, θ is the direction, and a_i and b_i are Fourier coefficients. For the three techniques mentioned above, the Fourier coefficients can be determined from the auto and cross spectra between three orthogonal motion measurements.

Due to its motions in a dynamic marine environment, a buoy's position varies from one time instance to the next. Since the sensors that measures the buoy motion are usually fixed on the buoy, it is necessary to transform the motions measured from a buoy-fixed coordinate system into an earth-fixed coordinate system. Then, directional wave information can be derived from the buoy motions described in an earth-fixed coordinate system. For the three techniques, the heave motion (or wave vertical motion) not only provides the non-directional wave information, but also plays an important role in determining directional information (through cross spectra). Allender, et al. (1989) compared the directional wave data measured from several commercially-available buoys. Gnanadesikan and Terray (1993) also compared the performance of three wave-measuring buoys and directional wave data measured from them.

3.2.1 Slope-following buoys

Using a slope-following buoy to measure directional wave data was first proposed by Longuet-Higgins, et al. (1963) and is widely used for directional wave measurement. Figure 4 shows a sketch demonstrating the basic principle of measuring wave direction from buoy's pitch and roll motions. As shown in Figure 4-a, there is only pitch motion and no roll motion if an uni-directional wave propagating in the buoy's bow direction. On the other hand, the wave direction is perpendicular to the bow direction if there is roll motion and no pitch motion (Figure 4-b). If a wave comes from an oblique direction, both pitch and roll exist (Figure 4-c) and the wave direction can be determined from the correlation of pitch and roll measurements. For random directional waves, cross-spectral analysis is needed to determine the wave direction information. Similar to the wave profile and buoy heave, there is a transfer function between wave slope and buoy's pitch/roll. It is expected that a slope-following buoy can follow the wave vertical motion and slopes as closely as possible.

For a slope-following buoy, the first five Fourier coefficients in Eq. (4) can be determined from the co- and quad-spectra of the vertical water surface displacement (subscript 1) and two orthogonal components of surface slope (subscripts 2 and 3).

$$\begin{aligned} a_o &= (1/\pi)C_{11} \\ a_1 &= (1/\pi k)Q_{12} \\ b_1 &= (1/\pi k)Q_{13} \\ a_2 &= (1/\pi k^2)(C_{22}-C_{33}) \\ b_2 &= (2/\pi k^2)C_{23} \end{aligned} \qquad (5)$$

in which k (=2π/wave length) is the wave number, C and Q represent the co- and quad-spectra, respectively. Eq. (4) can be re-expressed as

$$S(f,\theta) = C_{11} \cdot \frac{1}{\pi}\left[\frac{1}{2} + r_1\cos(\theta-\alpha_1) + r_2\cos(\theta-\alpha_2)\right] \qquad (6)$$

in which C_{11} is the nondirectional wave spectrum, $r_1=(a_1^2+b_1^2)^{1/2}$, $r_2=(a_2^2+b_2^2)^{1/2}$, $\alpha_1=tan^{-1}(b_1/a_1)$, and $\alpha_2= \frac{1}{2}tan^{-1}(b_2/a_2)$. α_1 and α_2 are referred to as the mean and principal wave directions, respectively. Note that all the above wave parameters are functions of wave frequency.

The transfer functions between the buoy motions (heave, pitch, and roll) and water surface motions (surface elevation and two orthogonal wave slopes) play a key role in determining directional waves. Generally, the transfer functions discussed here only take the buoy hull mooring effect into consideration. However, in order to make the algorithm and computation simpler, the effects from both sensors/electronics and data acquisition/processing, which can be easily determined from manufactures' specifications and signal processing theories, are sometime included in the transfer functions (see Steele, et al., 1985 and 1992). The transfer functions for buoy hull and mooring effects are more complicated. As discussed in Steele, et al. (1992), there are three methods to handle the transfer functions: (1) assuming the slope-following buoy is a perfect surface-follower (i.e., the magnitudes of the transfer functions are 1 and phase shifts are 0); (2) determining transfer functions from numerical models, physical models, or a combination of a mechanical model (e.g., a forced linear oscillator) and some measurements; and (3) calculating Fourier coefficients and wave parameters without directly using all the transfer functions (Steele, et al., 1985 and 1992), based on the following equation (which is derived from the linear wave assumption).

$$k^2C_{11} = C_{22} + C_{33} \qquad (7)$$

Figure 5 shows an example of directional wave data obtained from an NDBC discus buoy which is a slope-following buoy. The bottom panel shows the non-directional wave spectrum (i.e., C_{11}) versus wave frequency and the upper one panel show the wave directions α_1 and α_2. The straight line indicates the mean wind direction. It is clear that a local wind from 140° (clockwise from north) generates wind-driven waves with a peak at $f = 0.14$ Hz while 16-second swells were coming from about 310°.

3.2.2 Orbital-following buoys

For an orbital-following buoy, the measured motions used to derive the wave direction information are from both the buoy hull itself (heave motion) and a lower strut (pitch and roll motions) which is rigidly attached to the buoy hull by a long rigid rod, as shown in Figure 6-a. The lower strut, which contains the motion sensors and the compass, responds to the orbital particle velocity in the water column such that the buoy attains a maximum tilt angle at the wave crest. The buoy motions measured are the two orthogonal tilt motions and the vertically-stabilized heave motion. These measurements are very similar to those from slope-following buoys with one major difference: the tilt motions are 90 degrees out of phase compared to the tilt motions measured by a slope-following buoy, as shown in Figures 6-a and 6-b. The algorithm of data processing and analysis to obtained the directional wave information is very similar to that for the slope-following buoys (i.e., Eqs. (5) and (6)). More details about the data processing algorithm can be found in LeBlanc and Middleton (1982).

Since the tilt motions from the strut are used to derive the wave direction information, it is desired that the surface buoy will not significantly affect the strut's tilt motions. In addition, the long rigid rod may introduce some nonlinear hydrodynamic effects. Thus, the surface buoy, the rod, and the strut need to be carefully designed to minimize the unwanted effects that may contaminate the tilt motion measurement.

3.2.3 Particle-following buoys

Based on the wave theory, the horizontal particle motion is directly related to the surface slope. Thus, the wave direction information can be derived from the two orthogonal horizontal motions, instead of the buoy's tilt motions. The algorithm of deriving directional wave information, which is similar to the slope-following buoys, is based on the cross and auto spectra between the heave motion and the two orthogonal horizontal motions. The subscripts 2 and 3 in Eq. (5) now represent the two orthogonal horizontal motions, instead of the two orthogonal tilt motions.

Note that the two orthogonal measured accelerations need to be perpendicular to the true vertical (i.e., they are on a vertically-stabilized plane). Therefore, if the accelerations are measured from accelerometers fixed on a buoy hull, they have to be converted using tilt measurements. Either the acceleration (which is measured directly from the motion sensor) or the displacement (which is converted from measured acceleration) of the horizontal motions can be used. However, based on the algorithm, it does not seem to have any advantage to use displacement.

Barstow and Kollstad (1991) used wave data measured in deep water to show the performance of the Datawell Directional Waverider which is a particle-following buoy. O'Reilly, et al. (1996) showed directional wave data measured from a Waverider are comparable to or slightly better than NDBC's slope-following wave buoy over the swell range. Although it is not necessary, it is preferred that the buoy has less tilt motions to minimize the coupling effect between the surge and tilt motions.

3.3 Wave Data Format and Processing

To design/develop a wave measurement system, the wave data format and basic processing algorithm are among the first things to be determined. These include:

- scheme of data acquisition: sampling rate and total data record length
- wave format: reporting wave frequencies, number of reporting frequency bands, and frequency bandwidth.
- spectral analysis is based on conventional FFT method or other methods (e.g., maximum entropy method, maximum likelihood method, etc.)
- use of data window and digital filter

The decision on the above items is generally based on specification of sensors, power requirements, processing speed and memory of the onboard microprocessor, limitations on payload and transmission systems, pre-existing formats to conform, required reliability of spectrum estimates, etc. The sampling rate should be higher or equal to 1 Hz to avoid possible low-frequency aliasing and is usually not higher than 4 Hz as a practical consideration. For operational wave buoys, wave data should be reported every one, two, or three hours. The data record length usually should not be shorter than 10 minutes, and is usually not longer than 40 minutes from a practical viewpoint. Allender, et al. (1989) presented the wave data format and processing algorithm for many commercially available wave buoys. Steele, et al (1992) and Chaffin, et al. (1993) presented this information for NDBC directional wave buoys.

In addition to the basic processing and format, further processing and analysis, which may include applying the power transfer function, conducting noise correction, determining the Fourier coefficients or the directional wave spectra, and computing wave parameters (including wave height, wave period, wave direction, etc.), are required.

Wave data processing can be conducted either onboard a buoy or at the shoreside. Most of the time (especially for operational buoys), a part of the processing can be done onboard the buoy and the rest can be done at the shoreside. The decision on where to conduct data processing depends on many factors, including the onboard processing capability, power consumption, transmission capability, and data distribution and download (e.g., the transmitted data are immediately distributed to many locations, users can dial-in to get the data). It is preferred to minimize onboard processing so the data can be re-processed if there is anything wrong. However, sometimes, due to the transmission limitation or other requirements, some or all of the processing has to be conducted onboard the buoy.

Due to the limitations of transmission space and format (especially for satellite transmissions), sometimes, data needs to be encoded and packed in a specified format before being transmitted. Then, the data received at a shoreside station is decoded and converted back to the original data. Determination of the encoding/decoding techniques and transmitted data format to use depends on the transmission capability/speed and the transmitted data's precision and significant ranges. Teng (1995b) reviewed several encoding/decoding techniques and data formats.

4. Dynamics and Design of Buoy/Mooring Systems

The basic functions of a data buoy are (1) to provide a platform for all the instruments and equipments; (2) to support the weight of the buoy, mooring, and everything onboard; (3) to provide enough reserve buoyancy and survive in dynamic and severe marine environments. However, buoy motion and responses certainly will affect the measurement instruments onboard the buoy. Thus, it is important to know the hydrostatic and hydrodynamic characteristics of the buoy. This is especially true for wave measurement, since wave data are derived from the buoy's motion. Every buoy might respond differently based on its shape, weight distribution, and other attachments (e.g., mooring, rigid rod, etc.). In order to ensure that a data buoy can perform its functions, analysis and testing of the buoy/mooring system must be conducted. The tools for analysis and testing include mathematical and numerical analysis, physical model testing, and prototype testing. Teng and Timpe (1994) discussed and reviewed the use, principles, techniques, limitations, advantages, and disadvantages of these tools.

In order to simplify the dynamic characteristics and to minimize unexpected motions/responses, buoy hulls with a simple shape (e.g., discus, spherical, spar, etc) are usually used for wave measurement. To measure directional waves, it is necessary to have an axi-symmetric (with respect to the buoy's vertical axis) buoy so that the two orthogonal tilt motions or horizontal motions (which are denoted by subscripts 2 and 3 in Eq. (5)) have the same transfer functions to avoid complex coupling effects. Usually, discus buoys follow both the wave vertical motion and wave slopes better and, hence, are suitable for slope-following directional wave measurement. Spherical shape buoys follow the wave vertical motion better, but not the wave slope. Wang and Teng (1994) also showed that the spherical buoy pitch motion shows strongly nonlinear behavior in the presence of high sea states and are not good wave-slope followers. Timpe and Teng (1993) discussed in details the buoy hull characteristics and important considerations of buoy hull design/selection.

A mooring system is used to hold a buoy on station (i.e., to prevent the buoy from moving or drifting away from the deployed location). For data buoys, a single-point mooring is usually used. As discussed in Teng (1995a), there are three types of single-point mooring: taut, semi-taut, and slack moorings. The mooring system which is attached to the buoy will, more of less, affect the buoy motion. For a wave-measuring data buoy system, the mooring system should be carefully designed to avoid or minimize its effect on buoy motion. This can be achieved in several methods, including (1) placement of a bungee section along the mooring, (2) use of surface or subsurface floats to hold the mooring line, (3) cable payout spools, (4) mooring with excess cable on the ocean floor, and (5) use of an inverse-catenary mooring. Choice of these methods depends on cost/budget, water depth, duration of deployment, survivability, field support and maintenance, effects on buoy dynamics and design, and other environmental considerations. Teng and Wang (1995) showed that buoy motions are affected by various mooring configurations, and concluded that a buoy moored with excess cable on the sea floor follows the wave surface and slope better than that with a taut mooring. Gnanadesikan and Terray (1993) used a simple model to show that the transfer function of a discus buoy is strongly affected by mooring tension. Teng, et al. (1996) also studied the transfer functions for a slack-moored wave-following buoy using both the field measurement and the numerical modeling.

5. Measurement Instrument and Payload

Since the wave information from a data buoy is based on the buoy motions, the motion sensors play a key role in wave measurement. Motion sensors that may be used in wave measurement include accelerometers, inclinometers, pitch/roll sensors, and tilt rate sensors. Like any other sensor and electronic/electrical equipment used on a data buoy, the motion sensors need to be compact, low-power, and accurate to desired precision within specified measurement ranges. For a wave-measuring buoy, it is preferred that the motion sensor is placed at the center of gravity of the buoy system, which can avoid/reduce the coupling effects between two different motions (e.g., heave and pitch). Thus, a donut-shaped buoy, which does not have any enclosed space to house any sensors at the center of gravity, probably is not suitable for wave measurement.

For directional waves, it also needs a sensor to provide directional information. To determine wave directions, the buoy's direction with respect to an earth-fixed coordinate system must be determined first. Based on the considerations of cost, power consumption, accuracy, and weight, a magnetometer is usually used to provide direction information. Due to the presence of magnetic metal from the buoy hulls and electrical/electronic equipments onboard the buoys, the earth's magnetic field measured by a magnetometer may be distorted. Remond and Teng (1990) developed an automatic procedure to determine the magnetic constants which are used for correcting the distortion.

For automated data buoy systems, electrical systems and electronic components represent the heart and brain.

Functions of these systems may include (1) connecting to sensors and conducting data acquisition, (2) processing the acquired data, (3) preparing the data for transmission or storage, (4) communicating with transmission devices, mass storage devices, test set, and modem, (5) controlling the clock and the timing table, (6) controlling and executing the parameters for the system and sensors, (7) connecting the power system and distributing power, etc. The processing equipment is commonly known as the "payload" of the buoy system. Figure 7 shows a typical block diagram of an overall electrical and electronic system.

Since using buoys to measure wave data is regarded as an indirect measurement and needs extensive processing and analysis, the hardware and associated software for wave processing onboard a buoy play a crucial role for wave-measuring buoys. This is especially true for operational buoys. Usually, the hardware for wave processing includes a microprocessor, signal conditioning components, A/D converter, storage memory, interface to sensors, and interface to a payload system or a mass storage device. The software includes both the processing software, which processes the acquired data into the desired wave data and format (as discussed in Section 3.3), and the system software, which provides communication and control of the hardware and corresponding external devices (e.g., sensors, payload, storage device, setup terminal). Chaffin, et al. (1993) presented the development, design, and testing of a new wave data acquisition and processing system called the Wave Processing Module (WPM).

Power, which is the blood for data buoys, provides electricity to all the sensors and electrical/electronic components on the buoy. The total power budget for a data buoy needs to be carefully examined and computed, which may significantly affect the buoy system design. Generally, non-rechargeable batteries are used for short-time data measurement. For long-term operational buoys, the power requirement is much higher than a short-term buoy. Thus, the rechargeable batteries with a proper charging device (e.g., solar panels) need to be used to keep all the electrical and electronic devices running for a relatively long period of time.

The measured and/or processed data can be either stored on an mass storage device or transmitted to a shoreside station. Data stored in the buoy can contain all or more detailed data, but only become available when the storage device is retrieved. For operational buoys, the data have to be transmitted to shoreside stations due to the requirements of real (or nearly-real) time at a regular time interval. Data can be transmitted through either satellite transmission or line-of-sight (or radio) transmission. Satellite transmission has wider coverage, but has limited transmission space/speed and is expensive. The line-of-sight transmission, which is inexpensive and flexible in transmission space and format, has limited transmission distance and is suitable for buoys at coastal regions.

Due to rapid progress in electronics and measurement technology, new and more advanced sensors, microprocessor, and electronic and electrical equipments are available from time to time. By carefully adopting new technology and equipments, one can make a wave-measuring buoy system more capable and efficient.

6. Wave Data Quality Control

As shown in Fig. 1, measuring wave data using a buoy can be considered successful when the final wave information (the last block) can fully represent the ocean waves (the first block). Data quality control (QC) is conducted to make sure that the whole wave-measuring process and buoy system work correctly and the final wave data can truly represent the real sea state. Generally speaking, data QC is based on three common principles:

(1) Reasonability: the data should be in reasonable ranges and intervals.
(2) Continuity: the data should maintain the continuity in time and space.
(3) Consistency (or correlation): the data should have proper time correlation, spatial correlation, and correlations with other measurements

The most common examination on reasonability is the "range check", which checks if values of the measured data fall into a reasonable range. This range is set up by specifying the maximum and minimum. For marine environmental data, the maximum and minimum values generally depend on the locations, seasons, and sensors used. Table 1 presents an example of upper and lower limits of the significant wave height (H_s), average wave period (T_z), peak wave period (T_p), and wind speed. Battjes (1970) developed the following expression for the lower limit of T_z.

$$T_z = 3.2 \cdot H_s^{0.5} \tag{8}$$

in which H_s is in meters and T_z is in seconds. Using 13 years of hourly wave data from two NDBC wave buoy stations (one is in the Pacific Ocean and the other is in the Atlantic Ocean), Teng, et al. (1993) proposed the following two expressions.

$$\begin{aligned} T_z &= 3.23 \cdot H_s^{0.47} \quad \textit{(Atlantic buoy station)} \\ T_z &= 3.28 \cdot H_s^{0.43} \quad \textit{(Pacific buoy station)} \end{aligned} \tag{9}$$

Teng, et al. (1994) used 13 years of data from 10 buoy stations and proved the above expressions are also appropriate for waves higher than 9 meters. Using the same data, Teng (1997) also suggested the following upper limit of the wave spectral values for frequencies higher than the peak frequency.

$$S(f)_{upper\ limit} = \frac{1}{92} \cdot f^{-4} \tag{10}$$

in which $S(f)$ is in m^2/Hz. This can be used as a range check for measured spectral values at various wave frequencies.

For wave directions, a typical range check is the direction of long-period swells which should come from an open area, i.e., in the directions where the swells come from should not have any huge obstacles (e.g., island, land). In addition, directions of the high-frequency waves should be very close to that of the local wind, based on the characteristics of wind-generated waves. The example presented in Figure 5 shows this consistency. However, if the wave field is turning, directions of the high-frequency waves do not follow the turning immediately, but with a time lag, as shown in Teng (1992a).

Since ocean waves measured at a specific location do not change drastically in time, a time-continuity check, which usually checks the time rate of change of a quantity with a given threshold, can be used for wave data QC. A standard time-continuity check, based on the following expression, was developed by NDBC (1996).

$$\sigma_T = \sigma\sqrt{2(1-R(\tau))} \tag{11}$$

where σ_T is the standard deviation about the mean difference between measurements at a specific time and the corresponding measurements τ hours later, σ is an estimate of the standard deviation of an ensemble of measurements, and R(τ) is the autocorrelation function of an ensemble of measurements for a time lag, τ. The time-continuity check compares the difference between the last acceptable measurement and the current measurement, Δx, with σ_T. If Δx is smaller than σ_T, the current measurement passes the time-continuity check.

Since there is an approximate linear relationship between R(τ) and τ for values of τ less than 12 hours, Eq. (11) can be rewritten as

$$\sigma_T = c\sigma\sqrt{\tau} \tag{12}$$

in which c is a constant. In practice, NDBC (1996) uses c = 0.58 for its buoy stations. Values of the standard deviation σ are 6.0 and 31.0 for H_s and T_z (or T_p), respectively. The time-continuity check for H_s may not work if the wind speed is greater than 30 m/s.

Based on the characteristics of wave generation process, the relationship between wind and high-frequency waves can be used as a consistency check of wave data QC. For non-directional waves, Lang (1987b) developed an algorithm, which uses the relationship between wind speed and energy of high-frequency waves, for wave data QC. Lang found that the highest statistical wind-wave correlation was between the sum of the spectral energy densities in the frequency range from 0.20 to 0.27 Hz during the current hour to the square of the mean of the wind speed during the current hour and the wind speed of the previous 3 hours. Based on 22 months of wave and wind data from various NDBC buoy stations, Lang (1987b) proposed the upper and lower limits of the wave energy (as shown in Figure 8). Any wave energy observation falling outside the upper or lower limit is flagged for further check. Note that this algorithm does not perform well during the cases of light winds, changing of wind speed/direction, or fetch restrictions.

Based on the same basis as that from the Lang algorithm, Palao and Gilhousen (1993) proposed another wind-wave algorithm, using wave energy at a higher frequency range (0.30 - 0.35 Hz). The characteristic relationship of wind energy and wave energy can be visualized by plotting the sum of the high-frequency wave energy against the square of the 4-hour average wind speed. The plots are divided into sectors and the conditional probability density distribution calculated. The upper and lower limits of wave energy corresponding to a given wind speed are then delineated by the 1-percent contour line. Points outside of the contour are easily identified. The major disadvantage of this algorithm is that the limits of wave energy calculated by this procedure vary with buoy hull type or geographic characteristics of the buoy location. Thus, this algorithm is not suitable for newly-deployed or newly-developed data buoys, but is a great supplement to the Lang algorithm.

Numerical wave models can also be used as a QC tool for buoy-measured wave data. Although wave models are driven by surface wind (or wind stress) fields and has some limitations, the forecasted wave data can be used as an initial check of the measured wave data to alert potential inaccurate data. Based on the observations and the wave models, Etala and Burgers (1994) proposed a comprehensive wave-data QC system, which conducts both local checks and interpolation checks on three kinds of values: the observation itself, the difference between the observation and the model first guess, and the difference between the observation and a previous observation.

The above checks are based on the processed wave data. In addition to these data, it will be useful to get some housekeeping information (which is not directly related to the wave information); such as the minimum, maximum, and mean values of the measurements before they are converted into wave information (e.g., heave, pitch, roll, buoy azimuth, and magnetic vector measurements). These information can be used as data QC tools. For examples, based on the conservation principle, the mean value of the heave motion should approach to zero or be very small.

In general, data QC tries to find, correct, or delete "wrong" or "inaccurate" data. However, sometimes, it is very difficult to define "wrong" (vs. right) or "inaccurate" (vs. accurate). In some cases, some "suspicious" or out-of-bound data actually represent rare, extreme, or special conditions. It is preferred that data QC will not delete or correct such precious data. Therefore, it is important that the wave data QC is conducted with considerations on local and global meteorology, oceanographic features (e.g., strong ocean current, eddies), topography, and buoy system design and data processing. In addition to knowledge and information, experience also plays an important role in data QC.

7. Field and Maintenance Support

A buoy can be deployed by being launched from a vessel at the deployment site or towed to the site. Due to the speed limit of a towed buoy, towing a buoy to a deployment site is only feasible for a short distance from shore or a port, most likely in coastal water area. When the buoy is towed or deployed on the site, the mooring/anchor system can then be deployed. If a buoy is deployed from a vessel, the anchor first deployment technique (Berteaux, 1991), which lowers the anchor first with the help of mooring and then deploys the buoy, can be used. One needs to be very cautious to use this technique because the mooring line is always under high tension during anchor deployment. Deployment from air by aircraft is not feasible for large-size buoys, especially with a heavy mooring/anchor system. Although there are some recent studies on small and light-weighted air-deployable wave buoys (e.g., see Earle, et al., 1993), these buoys are not suitable for long-term operational purposes.

If a buoy will be retrieved back on a vessel, the buoy is first brought back onboard the vessel. Then, the mooring and anchor system is recovered. If a buoy will be towed back to shore or port, only the mooring system needs to be recovered. In many cases, a portion or the entire mooring system is abandon when the buoy is retrieved. The decision for this depends on many factors including available equipment onboard the vessel, cost of the mooring system, condition of the mooring system, and valuable instrument or information on the mooring (e.g., current meter), and local marine environmental regulation. If any instrument or valuable information on the mooring system needs to be recovered, a release mechanism may be used to ensure the recovery. To facilitate the deployment and retrieval, some auxiliary (e.g., tow ring, lift ring, line-retrieval mechanism) needs to be designed and installed.

Sometimes, it is very expensive and not necessary to retrieve the buoy to just repair/replace one or a few components of the buoy system. Instead, repair and replacement can be done on site. The weather and sea conditions during the service need to be calm. Servicing a buoy in a harsh marine environment is not a very easy and pleasant task. Safety of the vessel and personnel is the most important factor to consider during field servicing. Therefore, if it is expected to service the buoy at sea, the buoy and system design need to consider how to make the field service as easy and safe as possible (e.g., locations of sensors, auxiliary for service).

8. An Example: NDBC Operation and Wave Buoy Systems

NDBC, a part of the National Weather Service (NWS) in the U.S. National Oceanic and Atmospheric Administration (NOAA), operates networks of buoys and fixed platforms to measure oceanographic and meteorological data. Currently, NDBC has more than 70 moored buoys at the U.S. east and west coasts, Gulf of Mexico, Great Lakes, Gulf of Alaska, Hawaiian Islands, and Guam. Depending on the missions, locations, and environmental conditions expected at the buoy stations, a variety of different buoy types are used. The types of moored buoys currently being used by NDBC include 2.4-m discus, 3-m discus, 10-m discus, 12-m discus, and 6-m boat-shaped NOMAD buoys (NDBC, 1994b).

NDBC's wave measurement systems can provide both nondirectional and directional wave measurements. Strong emphasis is placed on providing accurate wave data both in real time and to the archives to a variety of users, including marine weather forecasters, navigators, pilots, ocean and coastal engineers, ocean researchers and scientists, fishermen, and surfers. The sophistication of NDBC wave measurement systems has grown from a simple fixed accelerometer system first used in 1973 to wave-direction system used today (NDBC, 1994a). Presently, there are more than 60 buoy stations producing wave data, of which over 15 provide wave direction information from the standard Hippy heave/pitch/roll sensor and the less expensive, NDBC-developed magnetometer-only system (Teng, et al., 1991). Detailed descriptions of NDBC directional wave systems were presented in Steele, et al (1985 and 1992) and summarized by Wang (1993). Over the years, many wave processing systems were developed and used at NDBC. Currently, the following wave processing systems are in operational use to process wave records: Wave Data Analyzer (WDA), Wave Analyzer (WA), Directional Wave Analyzer (DWA), and Wave Processing Module (WPM). More details on NDBC wave processing systems can be found in NDBC (1996), Chaffin, et al. (1993), and Tullock and Lau (1986).

Data collected by NDBC buoys are made available to users in two forms: real-time processed data, and detailed time series data. The real-time data are transmitted to shore hourly via Geostationary Operational Environmental Satellite (GOES). Due to the message length limit of satellite transmission, data are processed and reduced onboard the buoy before transmission. After being received on shore, the data undergo further processing, including real-time automated data quality control, and are disseminated over the NWS networks. On a next-day basis, NDBC also performs more extensive data quality control, using a mixture of manual and computerized methods. This ensures that the measured data are of the highest quality. Some buoys are equipped to acquire time series data. These more detailed data are recorded on a mass storage device onboard the buoy. The time series data recorder can be retrieved during service visits.

One important and special arrangement on NDBC's operation is that NDBC receives the technical and logistics support provided by the U.S. Coast Guard (USCG) and the NDBC Technical Services Contractor (NTSC). Through an interagency agreement, USCG provides for the assignment of USCG personnel to certain key technical and operating positions at NDBC and also provides for USCG vessel, aircraft, industrial base, and communications support for the NDBC data network (NDBC, 1994a). It is very important and convenient for NDBC that the USCG provides support for buoy deployment, retrieval, and necessary field service. NDBC contracts out network operation and technical support to an in-house support contractor NTSC. The NTSC, with a staff of approximately 120 engineers, scientists, data analysts, programmers, technicians, and other specialists, provides support in response to technical directives and work requests initiated by NDBC. The NTSC support is provided in the areas of engineering, operations, data processing and dissemination, quality assurance, and technical services (NDBC, 1994a). The dedicated support contractor adds flexibility to the NDBC program and allows timely adjustments to changing program needs. The contractor has the ability to access resources within its corporate structure for special short-term skill requirements. The contractor also needs to remain cost-efficient in its support to remain competitive.

NDBC has earned and retains a reputation for producing quality wave data from its data buoys. The key to achieving this is to regard wave data measurement using a data buoy as an integrated system. Every subsystem or component in the integrated system is carefully developed/designed/operated and works smoothly with others. Of course, the excellent team work among personnel from NDBC, USCG, and NTSC is extremely important for this achievement.

9. Concluding Remarks

Using a buoy to measure wave data needs to be regarded as an integrated system, not just a wave-measuring sensor. This system includes many sub-systems: buoy hull/mooring, measurement instrument, electronic and electrical equipments, wave data quality control, and field and maintenance support. All these sub-systems are inter-related. Failure or error of any of the sub-systems may make the whole wave-measuring buoy system fail, and cause the wave data to be unavailable or inaccurate.

From what is presented and discussed in this paper, it is clear that using buoys to measure ocean wave data requires broad knowledge and experience in various fields, including characteristics of ocean waves, techniques of data and signal processing, dynamics and design of buoy/mooring systems, measurement instruments, digital electronics, communication, power, marine operations, etc. Thus, it requires a team of experts working together to make the whole wave-measuring buoy system and the wave measurement process successful.

From the wave buoy system or the wave data viewpoint, finishing designing and deploying a wave buoy system is just the beginning of the whole wave data measurement process. After a wave-measuring buoy is deployed, it still needs continuous attention. To say the least, the buoy needs to be regularly maintained, and measured data needs to be continuously monitored. Any malfunctions of any component of the buoy system or any significant data quality problems need to be diagnosed, repaired, and solved as soon as possible. This is especially true for operational buoys which need to provide the regular and long-term data to fulfil the operational requirements. Therefore, no matter whether a buoy is newly designed or purchased, the buoy owner/operators need to have adequate knowledge and experience on the buoy system to keep the buoy working and measuring accurate wave data continuously.

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Table 1 Lower and upper limits for the wave height, wave periods, and wind speed.

	unit	lower limit	upper limit
Significant wave height	m	0	15
Average wave period	sec	0	15
Peak wave period	sec	1.95	26
Wind speed	m/sec	0	60

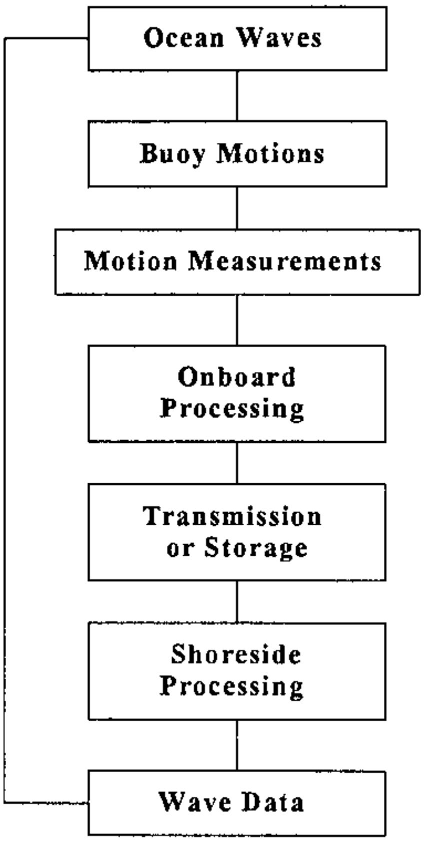


Figure 1 Buoy wave measurement

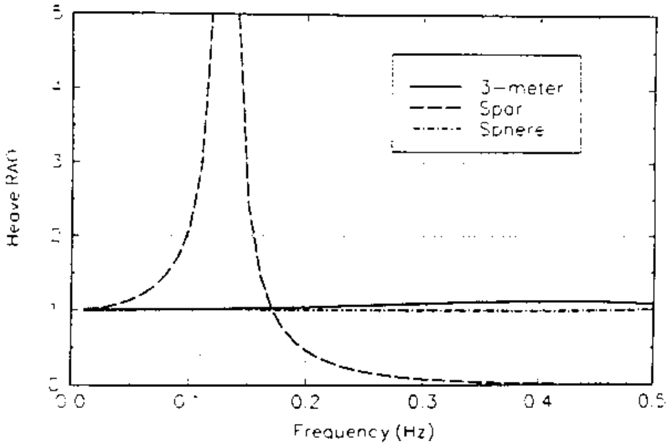
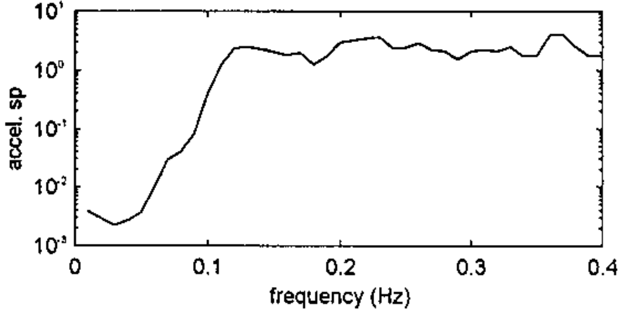
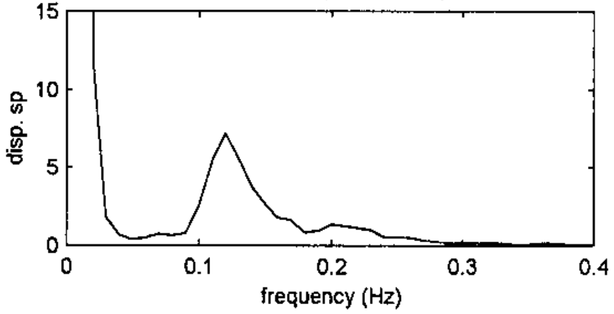


Figure 2 RAO of the heave motion versus frequency for three buoy shapes

(a) acceleration spectrum



(b) uncorrected displacement spectrum



(c) corrected displacement spectrum

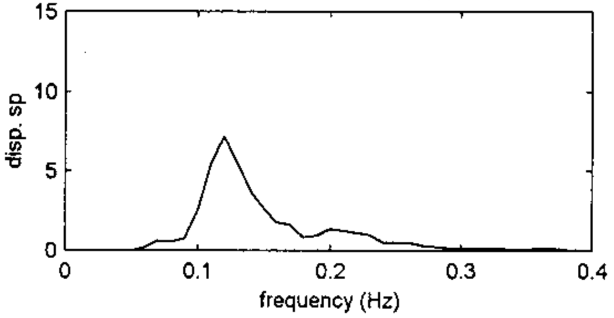
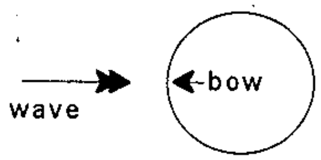
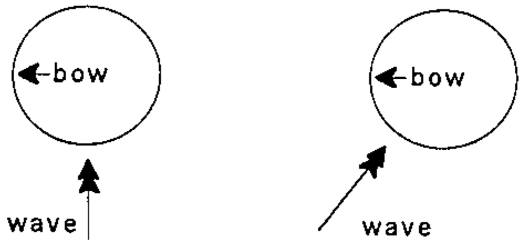


Figure 3 Effects of noise correction on wave spectra

(a) pitch only





(b) roll only

(c) pitch & roll

Figure 4 Measuring directional waves using a slope-following buoy

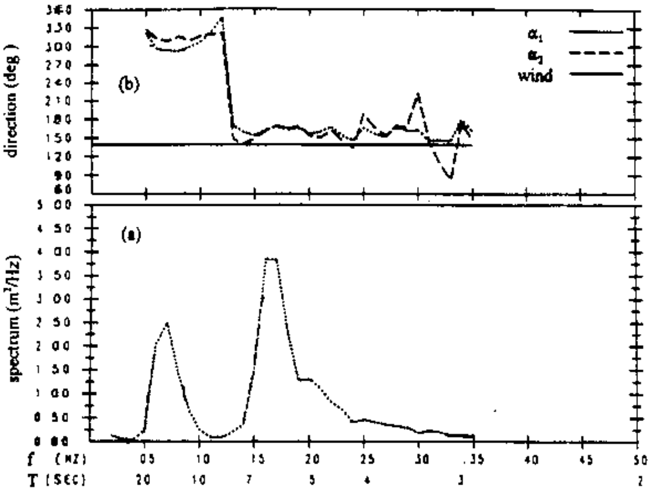


Figure 5 An example of directional wave information (a) non-directional wave spectrum, and (b) wave and wind directions.

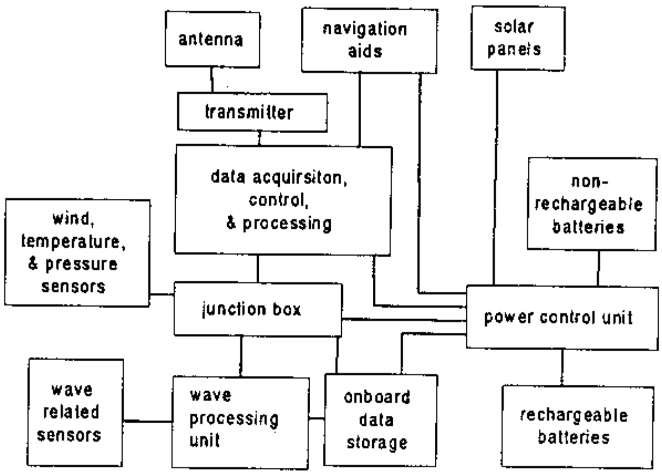


Figure 7 Block diagram of a electronic and electrical systems onboard a wave-measuring buoy

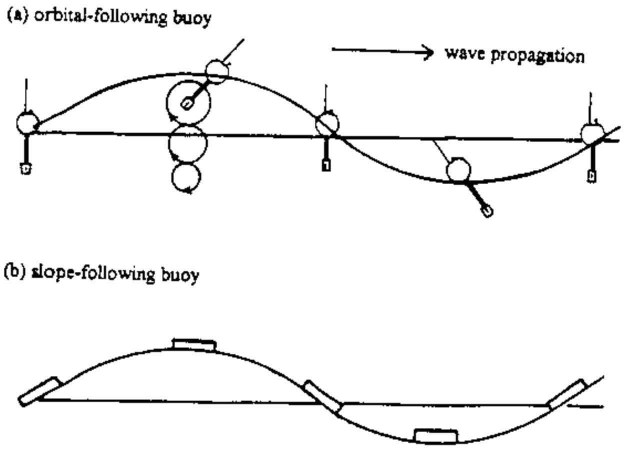


Figure 6 Measuring directional waves using an orbital-following buoy (from LeBlanc and Middleton, 1982).

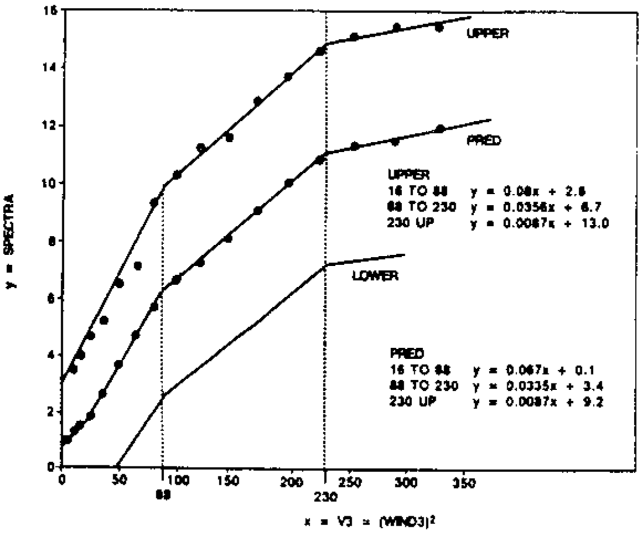


Figure 8 Upper and lower limits of total wave energy from 0.20 to 0.27 Hz (from Lang, 1987b)

由資料浮標量測波浪之探討

鄧中柱

美國國家資料浮標中心

本文探討了用資料浮標量測非方向波浪及方向波浪之原理及方法。浮標測波之流程、系統、及系統內之子系統〔包括浮標殼體及錨錠、量測儀器、電子及電機設備、波浪資料品管、作業支援〕均加以討論、說明。最後，美國國家資料浮標中心之運作及作業化之浮標測波系統，也予以介紹。