TRIAXYS DIRECTIONAL WAVE BUOY

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ABSTRACT

The TRIAXYS\textsuperscript{TM} Directional Wave Buoy is a precision instrument incorporating new technologies that make it an easy to use, rugged and economical buoy for accurate measurement of directional sea states. It is the result of a collaborative development and testing program between Axsys and the Canadian Hydraulics Centre (CHC) of the National Research Council of Canada (NRC). The software components used in this buoy are derived from the well-proven CHC GEDAP\textsuperscript{TM} software package that has been developed over many years at the CHC to satisfy a broad range of real-world project requirements with particular emphasis on random wave generation and data analysis in hydrodynamic laboratories. GEDAP\textsuperscript{TM} has also been used extensively to analyze full-scale data.

RÉSUMÉ

La bouée à houles multidirectionnelles TRIAXYS\textsuperscript{TM} est un instrument de précision incorporant de nouvelles technologies qui la rendent facile à utiliser, robuste et économique pour des mesures précises de mers multidirectionnelles. C’est le résultat d’un programme commun de développement et d’essais entre AXYS et le Centre d’hydraulique canadien (CHC) du Conseil national de recherches Canada (CNRC). Les différentes composantes de logiciel contenues dans cette bouée proviennent du logiciel GEDAP\textsuperscript{TM}. GEDAP\textsuperscript{TM} a été développé et validé sur une période de plusieurs années au CHC, pour satisfaire principalement une vaste gamme de projets en nature, avec une emphase particulière sur la génération et l’analyse des houles aléatoires en laboratoires hydrodynamiques. GEDAP\textsuperscript{TM} est également utilisé pour l’analyse des données en nature.

INTRODUCTION

Sophisticated wave generation capabilities have led to laboratory testing of coastal processes and structures under multidirectional waves. Many researchers have also demonstrated the usefulness of testing under multidirectional waves in order to get more accurate information on the performance of coastal and offshore structures (see Funke and

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Mansard, 1992). However, very little data exist on the directional characteristics of prototype waves. Hence, the Canadian Hydraulics Centre of the National Research Council of Canada and Axys Environmental Systems of Sidney, B.C. have jointly developed a new directional wave buoy, called the TRIAXYS Directional Wave Buoy. The technology used for this purpose is based on laboratory instrumentation and software used for measuring motions of floating bodies and analysis of directional waves.

This paper provides a description of the analysis algorithms and their validation, including a comparison of the performance of this buoy with the well-known Datawell directional buoy to show that the results obtained by these buoys are comparable.

CANADA’S MARINE NETWORK

AXYS Environmental Systems (AXYS) is a leader in meteorological, oceanographic, and environmental data acquisition systems. AXYS delivers complete monitoring solutions for measuring parameters in air and water by providing turnkey integrated hardware, software and field service. Most systems provide real-time or near real-time data with a wide range of data telemetry options including radio, cellular phone, and various satellite systems.

AXYS has designed, built, and operated a combined buoy, AVOS Automatic Voluntary Observing Ship System (AVOS) and coastal monitoring station network in collaboration with Environment Canada for Canada’s Marine Network during the past two decades. These systems are located on the West and East Coasts of Canada, in the Great Lakes, Lake Winnipeg, Great Slave Lake and on the St. Lawrence River. AXYS has maintained design, supply and service contracts to manage these meteorological and oceanographic systems. AXYS successful partnership with Environment Canada has benefited from the accumulation of two decades of ocean observing systems experience that has resulted in a very successful program with data recovery rates averaging better than 95%.

Figure 1: Location of AXYS Buoys in the Canadian Buoy Network
AXYS has continuously improved Canada’s Marine monitoring systems. Performance enhancements have included testing of new sensors, power supply systems, cabling systems, and data acquisition systems. AXYS developed many new components including the Watchman™, which is the core controller processor technology in all of Canada’s marine environmental monitoring systems. As the technical marine network authority, AXYS has been conducting routine training programs for regional Environment Canada technicians to keep them up-to-date with the new systems. The TRIAXYX buoy described here is one of its latest developments.

TRIAXYS™ DIRECTIONAL WAVE BUOY

The TRIAXYS™ buoy is a precision instrument equipped with technologies that make it an easy to use, rugged and economical buoy for accurate measurement of wave height, period and direction. The sensor unit contained in this device is comprised of three accelerometers, three rate gyros, a flux-gate compass, and the proprietary TRIAXYS™ Processor. (The TRIAXYS™ Processor was developed from the successful low-power Watchman 100™ payload processor especially designed by Axys Environmental Systems for the marine environment).

Figure 2: Photograph of a TRIAXYS Buoy

The innovative features of this TRIAXYS™ buoy are:
- full frequency domain and time domain wave analyses are done on the buoy;
- both processed data and raw data, can be stored on the buoy;
- spectral data and wave statistics can be transmitted from the buoy using a variety of transmission options (VHF, ARGOS, cell phone etc.);
- the buoy is solar powered thus avoiding the need for frequent battery replacement. The solar panels are housed inside a polycarbonate dome;
- the light, and transmission antenna are also housed inside the dome, leaving a completely clean exterior for ease and safety of deployment and recovery; and communication with the buoy is through an infrared port also housed inside the dome; and
- through a process of simple menus the user can adjust many of the buoys’ functions including the sampling duration and interval, storage options, transmission intervals and options, and test transmissions.

A description of its capabilities, and its characteristics including its mooring assembly are given below:

**Capabilities**

<table>
<thead>
<tr>
<th>Capability</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height range:</td>
<td>± 20 m</td>
</tr>
<tr>
<td>Accuracy:</td>
<td>Better than 2%</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1 cm</td>
</tr>
<tr>
<td>Wave period:</td>
<td>1.6 to 30 seconds</td>
</tr>
<tr>
<td>Wave directional range:</td>
<td>0 to 360°</td>
</tr>
<tr>
<td>Sea surface temperature:</td>
<td>Range: -5 to +50°C, Accuracy: 0.1°C</td>
</tr>
</tbody>
</table>

**Buoy (Transmitter Unit)**

1. **Shape:** Spherical  
2. **Diameter:** 0.9m; Can withstand current conditions in excess of 6.5 knots without being submerged (mooring dependent).  
3. **Material:** Stainless steel 316 hull with a polycarbonate Lexan® dome suitable to withstand marine conditions without any fouling and accidental ship impacts.  
4. **Transmitter:** Choice of: VHF: 29 to 50 MHz standard or Cellular (GSM or CDMA). Argos satellite telemetry (often used as backup to VHF) or Cellular as it can be used for data only, data plus position or position only. Immarsat D+ satellite telemetry (currently available for position only).  
5. **Flash Light:** Programmable, amber, 3 nautical miles visibility, ODAS sequency to caution navigating ships.  
6. **Power Supply:** Four (4) 100Ahr, 12v rechargeable batteries with ten (10) 6-watt solar panels that provide suitable power resources for 3 to 5 years of continuous system use before battery replacement is required.  
7. **Temperatures:**  
   - Operation: -30 to +60°C  
   - Storage: -40 to +70°C
Mooring Assembly

The TRIAXYS™ Directional Wave Buoy has special mooring requirements, which need to be observed to achieve maximum performance. The key feature required is the need to de-couple the mooring from the buoy to allow unrestricted buoy motions in wave fields. The de-coupling is accomplished either by operating the TRIAXYS™ buoy in an untethered free-floating configuration, or by use of a compliant mooring section. The compliant mooring section is composed of a special extruded 32 mm (1.25”) rubber cord, 15 m in length, terminated with stainless steel compression fittings. The elastic nature of the compliant component allows the TRIAXYS™ buoy to follow waves in an unrestricted fashion. The compliant section is usually attached directly to the buoy.

SOFTWARE ASSOCIATED WITH THE TRIAXYS BUOY

The TRIAXYS™ Directional Wave Buoy provides measurements of the wave conditions in the form of zero-crossing and spectral statistics as well as directional and non-directional spectra. Measurements include wave height and period statistics including:

- $H_{\text{max}}$, $H_{1/10}$, $H_{1/3}$, $H_{\text{avg}}$
- $T_{\text{max}}$, $T_{1/10}$, $T_{1/3}$, and $T_{\text{avg}}$
- $T_z$ (mean spectral period)
- $T_p$ (peak period)
- $T_{p5}$ (Read method of peak period)
- $T_s$ (significant period)
- Mean Direction
- Mean Spread and others.

The two main components of the TRIAXYS software are:

- A motion analysis algorithm to analyze data from the six inertial motion sensors and the flux-gate compass contained in the buoy; and
- An algorithm to resolve the directional and the non-directional characteristics of sea states from the above data.

A PC-104 microprocessor in the buoy performs the analysis described above.

MOTION ANALYSIS

The motions of the buoy are measured in six degrees of freedom by a strap down inertial system consisting of three accelerometers and three angular rate sensors. The accelerometers measure the total acceleration, including earth gravity components, along the $x$, $y$ and $z$ body axes of the buoy. The angular rate sensors measure the three-
dimensional angular rotation rate vector of the buoy resolved along the instantaneous positions of the $x$, $y$ and $z$ body axes. A unique iterative algorithm based on FFT integration techniques is used to solve the full nonlinear equations that relate the motions of the buoy to the body-axes accelerations and angular rates measured by the six strap down sensors. The dynamic roll and pitch induced acceleration components due to earth gravity are removed by the motion analysis procedure so that accurate time series measurements of the roll, pitch, yaw, surge, sway and heave motions of the buoy are obtained. Since the full nonlinear equations of motion are used, accurate motion data can be obtained for extreme conditions with large roll and pitch angles. Although all six degrees of freedom are computed internally, only the heave displacement and the surge and sway velocity components are used for the subsequent directional wave analysis. The buoy also contains a gimbal-mounted flux gate compass that provides a magnetic heading reference so that the surge and sway velocities can be resolved in the north and west directions.

The motion analysis software in the TRIAXYS buoy, called MOTION4, is based on the MOTAN inertial motion measurement system that was previously developed by CHC to measure the motions of ship models and other floating structures in laboratory wave basins and towing tanks. This system is currently used by several other laboratories as well as CHC. The MOTAN software has been verified both by computer simulations and by ship model tests carried out in a multidirectional wave basin with a high precision QUALISYS optical tracking system for comparison. These tests have demonstrated that the MOTAN system provides a typical accuracy of 1 mm for surge, sway and heave motions and 0.1 degrees for roll, pitch and yaw motions in model testing applications.

**WAVE ANALYSIS**

The wave analysis software in the TRIAXYS buoy is based on the GEDAP software package, which was originally developed for internal use by CHC [Miles, 1997]. Many other laboratories around the world are now also using GEDAP for random wave generation and analysis in basins and flumes including multidirectional waves generated by segmented wave machines. Consequently, the GEDAP wave analysis routines are well proven and reliable.

A wave analysis program named WAVAN4 is run on the PC-104 computer in the buoy. WAVAN4 first performs zero-crossing analysis of the wave elevation record in the time domain. The zero down-crossing method is used in which each wave cycle is defined by a trough followed by the next peak. Various standard IAHR wave parameters are then computed including the average, significant and maximum wave heights, average wave period, average period of the significant waves, etc.

WAVAN4 next computes the non-directional wave spectrum $S(f)$ using the same FFT procedure as the GEDAP spectral analysis program VSD. Various spectral parameters
including $H_{\text{mo}}$, $T_p$ and $T_{p5}$ are then computed where $T_{p5}$ is the peak wave period computed by the Read method [Mansard and Funke, 1990].

Finally, WAVAN4 performs preliminary directional wave analysis using a modified version of the KVH method described in Kuik et al, 1988. It first computes the various cross spectra of the wave elevation $z(t)$ and the north and west velocities $u(t)$ and $v(t)$ and then computes the first four Fourier coefficients $A_1(f)$, $B_1(f)$, $A_2(f)$ and $B_2(f)$ of the directional spreading function $D(f, \theta)$. These coefficients are then used to compute the mean wave direction $\theta_m(f)$ and the directional spreading width $\sigma_\theta(f)$ as functions of frequency.

Final directional wave analysis is performed on the shore-based computer due to the memory limitations of the microprocessor in the buoy. The four Fourier coefficients $A_1(f)$, $B_1(f)$, $A_2(f)$ and $B_2(f)$ are transmitted to the shore computer which then performs the final directional wave analysis using the Maximum Entropy (MEM) method [Nwogu et al, 1987] to obtain the directional wave spectrum $S(f, \theta)$. Recent comparison studies of various directional wave analysis methods have shown that this MEM technique is one of the most accurate and reliable methods for calculating directional wave spectra [Benoit et al, 1994 and 1997]. Most of the data analysis is performed in the buoy with final processing and data logging performed on a remote PC base station. The TRIAXYS buoy can also be configured to transmit time series data of the vertical and horizontal buoy motions to the shore station for users who may wish to apply their own directional wave analysis methods.

**COMPUTER SIMULATIONS**

Numerical simulations have extensively tested the various software components developed for the TRIAXYS wave buoy. This was done by using a combination of existing CHC/NRC GEDAP programs and the following custom GEDAP programs that were written specifically for simulating the operation of the TRIAXYS buoy.

- **AXYS_SIM1** – synthesizes a pseudo-random multidirectional wave field for a given wave spectrum and spreading function by the single summation method with random wave angles.

- **AXYS_SIM2** – computes the motions of a virtual buoy with zero yaw motion in a given wave field.

- **AXYS_SIM4** - synthesis of the total yaw motion of a wave buoy including low frequency drift and high frequency oscillations.
AXYS_SIM5 – computes the roll, pitch, yaw, surge, sway and heave motions of the actual buoy in a given multidirectional wave field.

MOTAN4 – GEDAP version of the TRIAXYS buoy program MOTION4.

MOTSYN4 – computes the signals for the three accelerometers and the three angular rate sensors for a given set of buoy motions.

Program AXYS-SIM5 computes time series of displacement, velocity and acceleration for each of the roll, pitch, yaw, surge, sway and heave motions of the buoy. This is done by applying a linear transfer function for each of the six motions to the wave field previously synthesized by program AXYS_SIM1. Program MOTAN4 uses the same motion analysis procedure as the TRIAXYS buoy program MOTION4. The only difference is that it uses GEDAP input and output files and produces output files for all six motions instead of the three motions output by MOTION4. Program MOTSYN4 computes the sensor signals that would result from a given set of buoy motions. It also adds a specified level of Gaussian random noise to each sensor signal to simulate the effects of measurement noise.

The simulations were carried out using a JONSWAP spectrum, for a narrow spreading function with $\sigma_\theta = 12.7$ degrees and for a broader spreading function with $\sigma_\theta = 31.7$ degrees. The procedure files that were used for carrying out the simulation allow the significant wave height, the peak period and the mean wave direction to be specified as well as the measurement noise levels for the accelerometers and the angular rate sensors.

The procedure file generates first a JONSWAP target wave spectrum and a $\cos^2(\theta - \theta_m)$ spreading function where $\theta_m$ is the mean wave direction; AXYS_SIM1 then synthesizes the multidirectional wave field. Programs AXYS_SIM4 and AXYS_SIM5 are run next to compute the actual motions of the buoy in the synthesized multidirectional waves. Program MOTSYN4 is then run to compute the sensor signals that would result from the actual buoy motions computed by AXYS_SIM5. These signals also include a specified level of random noise for each sensor. Program MOTAN4 is run next to compute the roll, pitch, yaw, surge, sway and heave motions from the synthesized sensor signals to simulate the operation of program MOTION4 in the buoy. The resulting motions can then be compared with the actual motions from AXYS_SIM5 in order to check the accuracy of the motion data that would be obtained from MOTION4.

Subsequently, another procedure file is used to perform wave analysis using the following programs: MOTION4, WAVAN4, KVH4 and MEM4. Some typical results of the simulations are shown in Figures 3 to 5 for the sea state listed below:

\[
H_{m0} = 4.0\text{m} \quad T_p = 10\text{s} \quad \theta_m = 55\text{ degrees} \quad \sigma_\theta = 12.7\text{ degrees}
\]
All of these simulations were run with an RMS accelerometer noise level of 0.0005 g and an RMS angular rate sensor noise level of 0.05 degrees/second. The low frequency limit for program MOTION4 was set to 0.030 Hz. The surge and sway velocities and the heave displacement motion computed from the sensor signals are plotted together with the corresponding actual buoy values in Figure 3. A typical segment from 500 to 560 seconds is shown in these plots for clarity although the computed motions have a duration of 1350 seconds.

![Figure 3: Surge, sway and heave simulation results for test case D5R2](image)

Figure 3: Surge, sway and heave simulation results for test case D5R2

Figure 4 presents a comparison between the target spectra and the TRIAXYS buoy wave spectra calculated by program MOTION4 and WAVAN4. The significant wave height and peak period from WAVAN4 are also shown on these plots together with the corresponding values for the actual waves. It can be seen that there is very good agreement between the TRIAXYS wave spectra and the actual wave spectra.
The mean wave direction $\theta_m(f)$ and the spreading width of $\sigma_\theta(f)$ computed by the TRIAXYS buoy programs KVH4 and MEM4 are plotted in Figure 5, with the corresponding values for the actual synthesized waves. The target values are shown in dashed lines on these plots. The actual values are plotted over the full frequency range since the full directional characteristics of the synthesized waves are known. However, the KVH4 and MEM4 values are only computed over the frequency range where there was sufficient wave energy to define them from the buoy motions.
SEA TRIALS

Initial sea trials of the TRIAXYS buoy were carried out in September, 1998. The buoy was moored in the Pacific Ocean off the west coast of Vancouver Island at Long Beach, near Tofino. A Datawell Directional Waverider buoy was used to collect wave data for comparison purposes. The two buoys were moored about 100 m apart in the same depth of water. Data were collected from both buoys once every two hours over a period of two weeks.

The record lengths used for wave analysis were 22 minutes and 26 minutes for the TRIAXYS and Directional Waverider buoys, respectively. The significant wave heights measured by the two buoys are plotted together for comparison in Figure 6 for the period from September 18 to September 30. No data were available for September 24 and September 28 due to data transmission problems. It can be seen that there is very good agreement between the significant wave heights measured by the TRIAXYS and Directional Waverider buoys over the full duration of the sea trials.
The peak wave periods $T_p$ measured by the two buoys are plotted in Figure 7. The TRIAXYS peak periods generally agree very well with the Datawell peak periods.

The mean wave directions measured by the two buoys are shown in Figure 8. The mean directions in Figure 9 were computed by averaging $\theta_m(f)$ over all frequencies with the weighting function $S(f)$. It can be seen that there is very good agreement between the mean wave directions measured by the TRIAXYS buoy and the Directional Waverider buoy. The small positive bias of the TRIAXYS mean directions relative to the Datawell mean directions is probably due to alignment differences in the compasses and could easily be removed by applying a deviation correction.
Figure 8: Comparison of the mean wave directions averaged over frequency with weighting function $S(f)$ measured by the TRIAXYS and Directional Waverider buoys.

Detailed wave analysis results for one of the records are shown in Figures 9 and 10 where the wave spectrum $S(f)$, the mean wave direction $\theta_m(f)$ and the spreading width of $\sigma_\theta(f)$ are all plotted as functions of frequency. The Datawell wave spectra in these figures were computed from the Directional Waverider heave displacement time series using NRC GEDAP program VSD. It can be seen that the TRIAXYS wave spectra match the Datawell wave spectra very well and the differences are within the expected range of statistical variability for the spectral estimates.

Figure 9: Comparison of $S(f)$ from the TRIAXYS and Datawell boys
The $\theta_m(f)$ and $\sigma_0(f)$ measurements from the TRIAXYS buoy also agree very well with the measurements from the Datawell buoy and show the same variation with frequency. Thus, the directional wave characteristics measured by the two buoys are very similar over the frequency range of interest.

CONCLUSIONS

A new type of directional wave buoy has been developed that uses three accelerometers and three angular rate sensors in a strapdown configuration together with a gimbal-mounted flux-gate compass. The CHC MOTAN inertial motion measurement technology has been successfully adapted to operate on the PC-104 microcomputer in the TRIAXYS buoy in order to compute the motions in six degrees of freedom so that accurate measurements of the vertical displacement and the north and west velocities are obtained. Zero-crossing analysis, spectral analysis and preliminary directional wave analysis are performed on board the buoy. The results are then sent to a shore station by a VHF or ARGOS data transmission link. Final directional wave analysis is performed on a shore station computer using the CHC Maximum Entropy Method (Nwogu et al, 1987).

The performance of the motion and wave analysis software developed by CHC for use in the TRIAXYS buoy has been verified by extensive computer simulations for a wide range of known multidirectional wave conditions. The simulation results have shown that there is excellent agreement between the motions computed from the sensor signals and the actual buoy motions. Consequently, there was also very good agreement between the
wave analysis results from the TRIAXYS software and the actual wave conditions that were being simulated.

Initial sea trials of the TRIAXYS directional wave buoy have also been carried out with a Datawell Directional Waverider buoy for comparison. The significant wave heights, peak periods and average wave directions measured by the TRIAXYS buoy were all in very good agreement with the corresponding wave parameters measured by the Datawell buoy.

REFERENCES


