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Obtaining wave information from small expendable air-deployable buoys is important for numerous military operations, civilian applications, and research purposes. Such buoys may be deployed when and where wave data are needed. Under U.S. Navy sponsorship, a sonobuoy-sized expendable air-deployable directional wave sensor is being developed. Prototype buoys have been designed and three prototypes have been built for initial wave tank and field testing. Before deployment, the buoy is approximately 90 cm in length by 12 cm in diameter and weighs less than 30 lbs. A nitrogen-inflated flotation collar provides buoyancy after deployment. Small accelerometers, tilt sensors that respond to local acceleration including wave acceleration, and a fluxgate compass are used as sensors for the prototypes. Directional wave information will be calculated within the buoy and transmitted to shore via ARGOS satellite using data compression techniques. Directional wave information will be calculated within the buoy and transmitted to shore via ARGOS satellite using data compression techniques. Directional wave spectra at high frequencies will be used to estimate wind speed and direction to avoid use of an anemometer.

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A Sonobuoy-Sized Expendable Air-Deployable Directional Wave Sensor

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Abstract

Obtaining wave information from small expendable air-deployable buoys is important for numerous military operations, civilian applications, and research purposes. Such buoys may be deployed when and where wave data are needed. Under U.S. Navy sponsorship, a sonobuoy-sized expendable air-deployable directional wave sensor is being developed. Prototype buoys have been designed and three prototypes have been built for initial wave tank and field testing. Before deployment, the buoy is approximately 90 cm in length by 12 cm in diameter and weighs less than 30 lbs. A nitrogen-inflated floatation collar provides buoyancy after deployment. Small accelerometers, tilt sensors that respond to local acceleration including wave acceleration, and a fluxgate compass are used as sensors for the prototypes. Directional wave information will be calculated within the buoy and transmitted to shore via ARGOS satellite using data compression techniques. Directional wave spectra at high frequencies will be used to estimate wind speed and direction to avoid use of an anemometer.

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Introduction and Background

In 1991, U.S. Navy requirements specified the need for a series of A-sized (approximately 90 cm in length by 12 cm in diameter) sonobuoy style Mini-Drifting Data Buoys (MDDB's) to provide real-time environmental data for Naval operations. A meteorological-oceanographic version (air temperature, sea surface temperature, and atmospheric pressure measurements), an omni-directional ambient noise version (equipped with a hydrophone suspended at 100 m depth), and a subsurface temperature versus depth version (equipped with a 300 m thermistor string) have been developed (Selsor, 1993). Further development of these buoys, including possible addition of wind speed and direction measurements, is continuing (Selsor, 1993). The meteorological-oceanographic MDDB has been air-certified for deployment from P-3 and S-3 aircraft. AN/WSQ-6 is the Navy series designation for MDDB's.

Particularly in shallow water, waves pose the greatest environmental threat to Naval operations such as amphibious landings, mine warfare, mine countermeasures, ship operations, and special warfare. Capability to make wave measurements during particular meteorological situations (e.g. severe extratropical storms and hurricanes) is needed for improving and testing numerical wave forecasting computer models. Capability to make wave measurements at locations and in situations of interest has additional scientific applications for coastal processes, air-sea interaction, and remote sensing verification studies. In late 1992, development of a wave measurement MDDB to meet these needs and applications was started.

Design Goals and Constraints

Table 1 lists design goals and constraints of the wave measurement MDDB that is being developed.

Table 1
Design Goals and Constraints

A-sized sonobuoy size (pre-deployment size, 90 cm length by 12 cm diameter)
Air-deployment water impact shock considerations
Relatively low cost (target cost \$5,000 - \$6,000, desirable cost < \$4,000)
Operating lifetime (few days minimum, few weeks desirable)
Maximum utilization of existing MDDB features and hardware
Data transmission via ARGOS satellite with on-buoy data processing
Non-directional and directional wave measurements

Unusual buoy motion associated with an MDDB's small size and configuration will likely cause the most important problems to overcome. An inflatable nitrogen-filled floatation collar provides buoyancy and causes the buoy to behave somewhat as a pitch/roll buoy. Unlike larger wave measurement buoys whose hulls partially attenuate very high frequency waves, the buoy responds well to these waves. Theory is inadequate to model buoy motion considering its geometry with its inflated floatation collar, non-uniform mass distribution, and viscous damping.

The requirement that the buoy be inexpensive enough to be expendable also poses challenges to obtaining accurate wave measurements. Large and expensive pitch/roll sensors (e.g. HIPPY sensors made by Datawell and used in larger buoys) cannot be used. Multiple angular rate sensors and accelerometers could be accommodated within the buoy, but presently available angular rate sensors are too costly. Steele and Earle (1991) describe a magnetometer approach for obtaining buoy angular motions, but this approach could have insufficient accuracy caused by buoy azimuthal motion at frequencies with non-negligible wave variance.

Prototype wave measurement MDDB's that have been built and that are being used for initial wave tank and field testing provide for storage and downloading (without satellite transmission) of digital time series data from all wave-related sensors so that buoy wave responses can be quantified. On-buoy data processing and satellite transmission of results will be added. Appropriate data processing algorithms will correct for buoy motion effects.

While the buoys are called MDDB's, a shallow water moored version is planned after capability to measure waves with such small buoys is demonstrated. There is room within an outer case that is jettisoned after water entry for a mooring line and the case or a weight within the case may serve as an anchor.

Scientific applications of directional wave information usually require high quality directional wave spectra, but most Naval applications for which MDDB's would be employed could be satisfied by the following basic wave parameters: significant wave height, dominant wave period corresponding to the frequency with maximum spectral density, and a primary wave direction (e.g. mean wave direction corresponding to the frequency with maximum spectral density). Although there is little uncertainty that these parameters can be provided with suitable accuracy, design goals have been set higher to provide scientifically better and more complete data without substantial buoy cost increases.

Measurement and Analysis Approaches

Work with theory, computer simulations, and measured data to develop and test wave measurement and analysis procedures used by the National Data Buoy Center (NDBC) indicates that non-directional wave information can be obtained from a wave measurement MDDB instrumented with a buoy-fixed accelerometer. Obtaining accurate directional wave information is thus a main development objective. Several directional wave measurement and analysis approaches could be used.

Directional wave measurement instrumentation used with pitch/roll buoys often consists of a vertically-stabilized accelerometer and pitch/roll sensors. Versions of the Datawell HIPPY sensor that are used in several commercially available wave measurement buoys and in some NDBC buoys are the best examples of this type of instrumentation. A compass or magnetometer provides buoy azimuth for transforming buoy pitch and roll to buoy tilts in two mutually perpendicular earth-fixed horizontal directions. Data processing involves standard calculations of cross-spectra between buoy tilts in the earth-fixed horizontal directions and the vertical component of buoy acceleration (or buoy heave obtained from double integration of the vertical acceleration component) as well as consideration of buoy responses. This approach has been described often (e.g. Longuet-Higgins et al., 1963; Steele et al., 1985; Steele et al., 1992). Large and expensive vertically-stabilized sensors are not suitable for a wave measurement MDDB. However, MDDB microprocessor capability accommodates software that performs these analyses so that developed electronics could be used with larger buoys and more expensive sensors.

Measurement of buoy angular rotation rates about and acceleration components along three mutually perpendicular buoy-fixed axes, as well as measurement of buoy azimuth provides sufficient information to obtain buoy vertical acceleration and tilts in earth-fixed coordinates (e.g. Earle and Longman, 1986). Multiple solid-state angular rate sensors and accelerometers can be accommodated within an MDDB, but presently available solid-state angular rate sensors are too costly. Developed electronics provides for digitization of eight wave measurement channels so that three angular rates, three acceleration components, and two magnetic field components could be utilized when lower cost angular rate sensors are available.

A magnetometer approach for obtaining buoy angular motions (pitch, roll, and azimuth) without use of a sensor specifically to measure buoy pitch and roll has been developed (Steele and Earle, 1991). A buoy-fixed accelerometer would measure the approximate vertical acceleration component. Using NDBC wave data, Wang et al. (1993) show that this approach generally provides good directional wave results. If used with a wave measurement MDDB, this approach could have insufficient accuracy caused by buoy azimuthal motion at frequencies with non-negligible wave variance. MDDB microprocessor capability will permit use of this approach if buoy wave tank and field tests show that it can be used.

Most Naval applications, but not scientific applications, could be satisfied by reasonably accurate values of significant wave height, dominant wave period, and a primary wave direction. These basic wave parameters could likely be determined by a simplified sensor system consisting of a single buoy-fixed accelerometer, two mutually-perpendicular fluid tilt sensors, and a compass or magnetometer. The tilt sensors would not measure true buoy tilt, but would respond to the local acceleration which is nearly perpendicular to the sea surface (e.g. Tucker, 1959; Earle and Longman, 1983). Wave height and period would be obtained by standard non-directional spectral analysis of acceleration data with corrections for fixing of the accelerometer similar to those used by NDBC. If a wave measurement MDDB has a wave response between that of a pitch/roll buoy and a buoy that responds mainly to wave orbital velocity drag forces, a directional probability distribution could provide primary wave direction with use of acceleration data to remove directional ambiguities (e.g. tilts in the direction of wave advance near wave crests and opposite tilts near wave troughs). While this approach could be extended to estimate primary wave directions as a function of frequency using frequency domain calculations, it would not provide standard directional wave spectra.

Prototype wave measurement MDDB's that have been built for testing have been designed to permit evaluation of the best approach to use including a multiple accelerometer approach that has apparently not been used with other buoys. Two mutually-perpendicular fluid tilt sensors provide estimates of buoy tilt deviations from wave slopes assuming linear wave theory. Three mutually-perpendicular acceleration components are measured by accelerometers and buoy azimuth is provided by a gimballed fluxgate compass (possibly later by a magnetometer). Assuming linear wave theory, numerical solutions of equations involving azimuth, acceleration components, and tilt deviations provide estimates of three earth-fixed acceleration components. Non-directional and directional wave information can then be obtained using procedures that are analogous to those used with pitch/roll buoy data.

Wave measurement MDDB's will not transmit complete directional wave spectra due to ARGOS message length limitations. However, directional spectra could be calculated within the buoy using cross-spectral analysis of measured time series. Cross-spectral analysis results can be used with several directional spectra calculation techniques such as the directional Fourier coefficient method (e.g. Longuet-Higgins et al., 1963), maximum likelihood methods (e.g. Oltman-Shay and Guza, 1984), maximum entropy methods (e.g. Lygre and Krogstad, 1986), and other methods (e.g. Benoit, 1993). Non-iterative methods could be applied within an MDDB, but iterative methods have not been examined for MDDB use.

Wind speed and direction will be estimated from non-directional spectral density levels and mean wave directions at high frequencies using extensions of NDBC procedures for wind and wave data quality control (e.g. Palao and Gilhousen, 1993). Field tests will determine whether estimates are accurate enough for Naval use.

Prototype Design

Prototype wave measurement MDDB data acquisition specifications are given in Table 2.

Table 2
Prototype Data Acquisition Specifications

Sampling rate per channel	5.12 Hz
Maximum number of wave channels	8
Analog to digital resolution	12 bits
Data acquisition frequency	Every hour
Date points per acquisition cycle	4096
Record length	800 s (13.33 minutes)
Sensors	3 accelerometers 2 fluid tilt sensors fluxgate compass strain gage atmospheric pressure sensor air temperature thermistor sea temperature thermistor

The fluxgate compass is used for expediency. It may be replaced by a solid-state magnetometer. Two input channels are used by the compass, and would be used by a magnetometer, so that there is a spare wave channel. All wave channels have matched electronic anti-aliasing filters.

Figure 1 illustrates a wave measurement MDDB as packaged before deployment, a pre-deployment cross-section, and a post-deployment cross-section. Prototype buoys for initial testing do not include a parachute nor the clamshells (that are jettisoned) around the floatation collar. Wave tank and field tests are conducted with the mast in its deployed position and an inflated floatation collar. Detachable anti-rotation wings (i.e. fins) and vertical dampers of various sizes are being tested. Tests are being made in which the outer pre-deployment case serves as a subsurface sea anchor for the buoy. There is room between the buoy itself and the outer case for storage of spring-loaded wings and dampers as well as line for deployed suspension of the outer case as a sea anchor.

Three prototype wave measurement MDDB's have been built for initial wave tank and field testing. Figure 2 shows two of the prototypes.

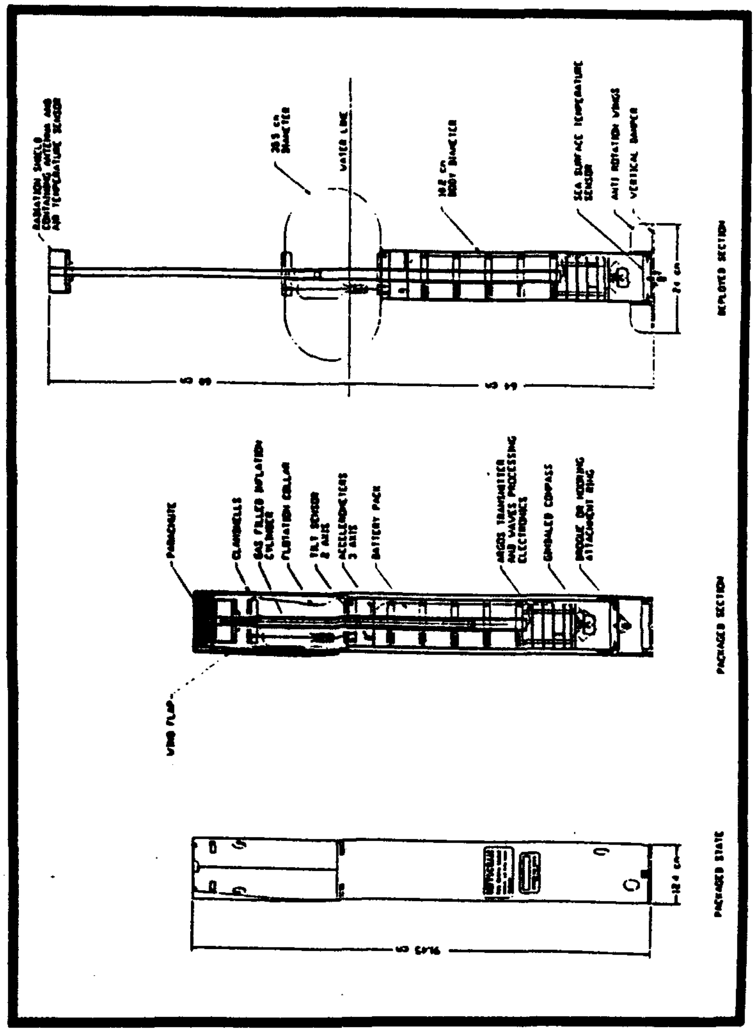

Figure 1. Wave Measurement MDDB. The outer package before deployment, a pre-deployment cross-section, and a post-deployment cross-section are illustrated.

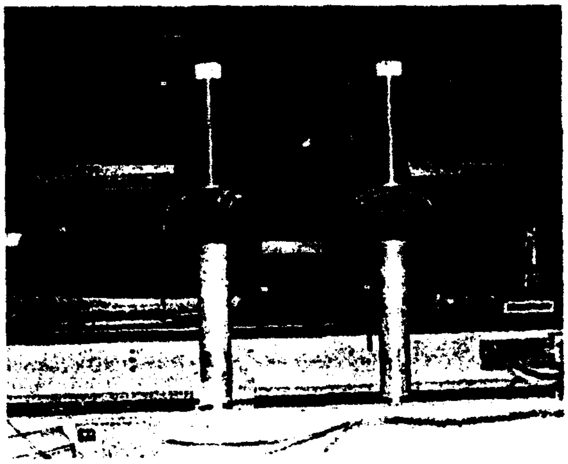

Figure 2. Two Wave Measurement MDDB Prototypes.
The buoy on the left has anti-rotation wings.

Understanding MDDB motion in response to waves is a goal. Several wave measurement buoy descriptions document the need for wave-induced buoy motion information (e.g. Stewart, 1977; Steele et al., 1985; Steele et al., 1992). A high sampling rate is used initially to facilitate analysis of digital time series data from each sensor. Prototype buoys internally store each sensor's digital time series data rather than processing these data. A watertight connector at the top of the buoy mast permits connecting a cable to a notebook computer's serial port. Using the notebook computer, data acquisition procedures are programmed and data are downloaded to the notebook computer's hard disk. Programs used during initial wave tank and field tests plot the data on the computer's screen and perform basic statistical and spectral calculations. Stored data can be analyzed later to study buoy motion and to test described analysis approaches. During initial wave tank and field tests, data will be downloaded after each data acquisition cycle. Initial field tests will not be conducted in high sea states, but later field tests are planned during higher sea states using on-buoy data processing and satellite transmission.

Wave-related electronics boards consist of: a signal conditioning board that filters out high frequency signal components; a data acquisition board that performs analog to digital conversions, stores data in random access memory (RAM), and communicates with a PC via a serial interface; and a digital signal processing (microprocessor) board. The digital signal processing board uses a Motorola CMOS 68000 microprocessor with up to 512 kbytes of programmable read only memory (PROM) and up to 512 kbytes of RAM. The board has been designed to be double-sided, rather than multi-layer, to reduce later production costs. It has not been placed in the three constructed buoys since it is not needed for acquisition and downloading of digital time series data.

Two electronics boards are used from previous MDDB versions. One board contains an Intel 8031 microcontroller which controls overall buoy activities. This board also acquires and processes atmospheric pressure, air temperature, and sea surface temperature data. Another board transmits processed non-wave and wave information to ARGOS satellites.

On-buoy software is being written in C language. Desktop computer simulations of data processing that could occur, including tests with versions of NDBC's on-buoy data processing algorithms, show that processing can be completed within 20 to 120 s depending on microprocessor clock speed.

Wave measurement MDDB's have been designed so that the battery pack, electronics boards, and sensors other than the fluxgate compass can be moved within the case to improve wave response and/or to meet air deployment mass distribution constraints. An expendable weight below the buoy itself can also be used to adjust mass distribution to meet air certification requirements before the parachute opens.

Only 256 bits of information can be transmitted in an ARGOS message. Directional wave spectra or the cross-spectral parameters from which directional wave spectra are calculated cannot be fit into one or a few messages. Three single message formats were developed and a version of a paired (two) message format that was previously developed for NDBC was considered. For Naval applications, transmitted information should fit into one message. Developed single message formats include: an even period message, an even frequency message with particular ordering of the frequencies and transmission of information only for frequencies with non-negligible wave variance, and a simple format consisting of wave parameters. The even period format that is shown in Table 3 will be used initially. The logarithmic encoding schemes are used by NDBC for compression of spectral analysis results for transmission by GOES satellite. Message formats could be changed by changing the on-buoy software.

Mean wave directions rather than directional spectra will be transmitted. It is expected that buoy responses corrections can be made using versions of NDBC's procedures (e.g. Steele et al., 1992). However, for an axially-symmetric buoy, mean wave directions are independent of buoy heave and pitch/roll amplitude and phase responses if the net phase response difference between heave and pitch/roll is between -90° and +90° (e.g. Kuik et al., 1988; Tucker, 1989). Accurate mean wave directions should be obtained even if response corrections have some errors.

Table 3
Even Period ARGOS Message Format

Information	Encoding (if used)	Bits
Date quality assurance:		
Message checksum		12
Error indicators		
Horizontal acceleration		1
Vertical acceleration		1
Tilts		2
Compass		1
Mean azimuth, 6° resolution	linear	6
Bit subtotal		23
Wave/wind information:		
Maximum spectral density band number		4
Maximum spectral density	logarithmic	10
Other 15 spectral densities normalized to maximum, 6 bits each	logarithmic	90
16 mean wave directions, 6° resolution, 6 bits each	linear	96
Crossing wave indicator at maximum spectral density		1
Wind speed, 1 m/s resolution	linear	6
Wind direction, 6° resolution	linear	6
Bit subtotal		213
Other information:		
Atmospheric pressure, 1 mb resolution	linear	8
Air temperature, 1° resolution	linear	6
Sea temperature, 1° resolution	linear	6
Bit subtotal		20
Total bits		256
Spectrum periods (s): 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 16, 18, 20, 22, 24		

Power requirements were determined assuming hourly data acquisition with ARGOS transmissions disabled during data acquisition to avoid radio frequency interference. Prototype buoy power consumption is 46 (mA-hr)/hr. Alkaline C cell batteries provide a capacity of 28 A-hr so that buoy lifetime is approximately 25 days. This lifetime is suitable for Naval applications and most scientific applications for which a small expendable wave measurement buoy would be used.

The total cost of all components (hull, sensors, electronics, etc.) for a prototype buoy is approximately $4,000. Wave measurement MDDB's can likely be built for roughly $4,000 in production quantities.

Further Development

The planned schedule is for air-deployable wave measurement MDDB's to be available for Navy fleet use in exercises and demonstrations by October-December, 1994. These buoys would still be considered prototypes by the Navy pending transition to production and operational status after passing military specification tests and air deployment certification procedures. Table 4 summarizes planned development activities.

Table 4
Development Plan Summary

Activity	Estimated Completion Date(s)
Initial wave tank tests (U.S. Naval Academy)	August, 1993
Initial field tests (CERC Field Research Facility)	September, !993
Test evaluations, design improvements, on-buoy software coding, addition of ARGOS and air-deployment capability	January, 1994
Possible directional wave basin tests and tests near an NDBC buoy, air-deployment field test	June, 1994
Participation in DUCK94 using non-air-deployed buoys outside surf zone to provide data for surf modeling	August and October, 1994
Delivery for fleet use	October - December, 1994

Initial wave tank tests are being made in the U.S. Naval Academy Hydromechanics Laboratory 128 m long high performance towing/wave tank. These tests are being conducted using sinusoidal waves and waves representing realistic spectra with heights up to approximately 1 m.

The U.S. Army Engineer Waterways Experiment Station Coastal Engineering Research Center (CERC) Field Research Facility (FRF) at Duck, NC, is being used for initial field tests. For these tests, prototype wave measurement MDDB's are compliantly moored near wave measurement instrumentation maintained by the FRF.

Wave measurement MDDB technology could be used with larger standard drifting data buoys as well as with non-air-deployable small buoys that have better wave following characteristics than MDDB's. For example, inexpensive discus-shaped hulls could be utilized. If somewhat larger buoys are not considered expendable, more expensive and better sensors (e.g. accelerometers, angular rate sensors, and magnetometers) could be utilized.

Summary and Conclusions

A sonobuoy-sized expendable air-deployable directional wave sensor is being developed as part of a program to make Mini-Drifting Data Buoys (MDDB's) available for operational Naval use. Prototype buoys have been designed and three prototypes have been built for initial wave tank and field testing. Unusual buoy motion related to the buoy's small size and configuration will likely cause the most important problems to overcome. Several measurement and analysis approaches have been examined. Constructed prototypes provide for storage and downloading of digital time series data from all wave-related sensors so that buoy wave responses can be quantified and the most appropriate measurement and analysis approaches can be selected. Initial wave tank and field tests of three constructed prototypes are now being conducted.

The technology that is under development has additional military, civilian, and scientific applications if incorporated into moored buoys, standard drifting data buoys, non-air-deployable buoys, and non-expendable buoys. Wave measurement MDDB development has considered these applications so that developed technology can be put to wider use.

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