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A "BASIS" BUOY FOR AIR/SEA INTERFACE SENSING...DESIGNED TO MEASURE WAVE AND WIND DIRECTIONAL PARAMETERS

by

A.S. Watson

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Engineering Services Section
Hydraulics Division
National Water Research Institute

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ABSTRACT

A body of technology in wave/wind directional sensing using moored buoy systems, has been developed at CCIW during the past decade. It is now available for transfer and wider application. The effectiveness of this technique was recently confirmed by the CCIW wave/wind directional data from the Arsloe experiment, as referenced herein. This report defines a more consolidated and convenient version of the CCIW Arsloe buoy, based on effectively the same, proven technology. This combination of wave-direction sensing, wind-direction sensing, and related atmospheric sensing, all within a relatively small buoy system, is considered advantageous.

RÉSUMÉ

Le CCEI a développé au cours de la dernière décennie toute la technologie de la détection de la direction des vagues et du vent à l'aide de réseaux de bouées amarées. Le transfert et la diffusion de cette technologie sont maintenant possibles. L'efficacité de la méthode de détection a été recemment confirmée par les données de CCEI sur la direction des vagues et du vent dans l'expérience Arsloe à laquelle on se rapporte ici. Le présent rapport porte sur une version plus définitive et plus pratique de la bouée Arsloe du CCIE, qui est effectivement basée sur la même technologie éprouvée. Cette détection combinée de la direction des vagues, de la direction du vent et de paramètres atmosphériques connexes dans un réseau de bouées relativement petit est considérée comme un atout.

TABLE OF CONTENTS

FIGURES

1.0 INTRODUCTION

This report is intended to bring up-to-date, to collate, and to present in an orderly fashion, the current CCIW scientific and design outlook concerning the measurement of wave-and-wind direction by means of relatively-small buoy systems, utilizing some special algorithms. This approach has been developed over a number of years, and is based on a considerable body of CCIW technology and on various small-buoy systems as shown in the references. [Related CCIW work on wave-directionality using relatively large arrays of fixed wave-detectors is also identified.]

As will be seen later, the wave information package (in effect, the wave-direction spectrum-analysis method) is described within the context of a wave/wind directional buoy system. (Called BASIS.....Buoy for Air/Sea Interface Sensing.) That is not the only application or configuration, but is presented here to focus attention on a system implementation of known usefulness. It reflects the now generally accepted fact that wind-wave climatology, hindcasting, and forecasting can best progress if wind-data are obtained concurrently with wave-data.

It is generally appreciated that the main problem in measuring wave-direction using small buoys is the sparcity of spatial sampling points. As an analogy, in the time-domain, if one has a complete, continuous, series of measurements.....a complete time-description of the function....one can estimate with accuracy all the harmonic components (waves) comprising the observed time function. In the water-wave situation, if equally complete spatial coverage existed.....an equivalent full omni-point record of all surface fluctuations.....then all the azimuth wave components could equally well be determined. In practice, of course, the comprehensiveness of this surface spatial record is extremely limited. Even large wave arrays only measure water-surface elevation at 10 or 20 spatial sampling points. Small wavebuoy systems are able to measure water elevation at only one point in space, supplemented by measuring the N-S and E-W slope components of the water surface at this same point, which is a feature of the CCIW approach.

The buoy technique described herein features a moored, slope-following buoy able to measure raw values of acceleration and hull-attitude relative to the earth's magnetic vector....that is, in earth coordinates. Given these raw signals the onboard FFT processor first computes spectra for vertical acceleration and the two slopes, thereafter the six possible co- and quad-spectra, and then the five fourier coefficients of directional spectra. These latter coefficients yield, for each frequency increment in the wave spectrum of interest, a value for mean azimuth direction, r.m.s. amplitude, and angle-of-directional-spread. (See Figure 1.) Given "10-minute" data sections, the data compression achieved is about 20 to 1.....a considerable figure compared to standard wavebuoy technology. With hourly averages, the data compression is about 100 to 1.

(The reason why acceleration, rather than wave displacement, is utilized is twofold. Firstly, being G-normalized and quasi-white, rather than proportional to f^{-4}, the dynamic range for onboard digitization and computation is much less. Secondly, it saves some onboard processing.....double-integration and numeric filtering.....whilst preserving the data-compression feature.)

As wave research at NWRI indicates that wave data is much more useful when accompanied by wind data, so this buoy system also measures the wind vector (amplitude and direction) again averaged for 10 minute series. (The correlation which exists between wind and wave parameters can also provide a valuable crosscheck of correct system operation.) The set of interface parameters shown measured by the system is completed with air temperature, water temperature, humidity and barometric pressure.

Thus, summarizing and in standard scientific notation, the BASIS system is intended to measure:

$S(f)$ = frequency spectra of waves
$\theta(f)$ = mean direction of waves
$\sigma_\theta(f)$ = directional spread of waves
$\bar{U}$ = wind speed, mean
σ_u = standard deviation of windspeed

$\bar{\beta}$ = buoy direction = wind direction, mean
T_a = air temperature
T_w = water temperature
P_a = barometric pressure
Q_a = atmospheric humidity

Two output data paths are available. First, onboard magtape digital recording provides longterm (one-month-plus) data storage without interference, and is a system feature. Second, a standard wavebuoy radio transmission link has also been used, for effectively-realtime telemetry of each hour's processed data. This allows for up-to-date monitoring of wave and wind data, although radio interference has occasionally degraded this second data link. A final choice for radio-telemetry link would almost certainly be via satellite.

On shore there is a small data-recording, printout, and graphics display facility, not necessarily co-located, to complete the processing not actually performed onboard. The data burst each hour is about 1000 digital words which is easily entered in buffer memory. For immediate inspection, the actual fourier coefficients get printed out, which is compatible with the simultaneous printout of the atmospheric parameters. The zero-order fourier coefficient (A_0) effectively yields the non-directional amplitude spectra, as plotted in Figure 1.A. The A_1, B_1, coefficients yield mean direction angle for each frequency, also shown in Figure 1A. Using all the coefficients yields a measure of the angular spread, which is best shown in the perspective of an isometric plot such as that in Reference 17.

Some options and alternatives to the buoy-system approach can readily be conceived. However, the wave-wind package described herein is considered to be the most generally-cost-effective utilization of all the referenced technology developed in the National Water Research Institute.

2.0 SUMMARY OF THEORY

The following material is effectively a summary of the largely-equivalent and common theory presented in Refs. 10, 11, 12.

Given that there is available in the wave-measuring system the three time-series $\frac{d^2z}{dt^2}$, $\frac{dz}{dx}$, $\frac{dz}{dy}$, then by the definitions of co-spectrum and quad-spectrum, (Reference 13), the following six co- and quad-spectra can be obtained (that is, numerically computed).....

$$C_{11}(f),\ C_{22}(f),\ C_{33}(f),\ Q_{12}(f),\ Q_{13}(f),\ C_{23}(f).....$$

where subscript 1 indicates the surface acceleration sample series, subscript 2 one waveslope sample series, and subscript 3 the other waveslope sample series.

Also, if the wave directional spectrum is expressed as $F(\theta,f)$ .....that is, if $\delta z = F(\theta,f)\ \delta\theta\cdot\delta f$, where δz is the wave height increment contributed by frequency increment δf, through bearing increment $\delta\theta$, then it can be shown (Ref. 12) that:

$$\begin{aligned}
C_{11}(f) &= \int_0^{2\pi} d\theta (2\pi f)^4 F(\theta,f) \\
C_{22}(f) &= \int_0^{2\pi} d\theta k^2 \cos^2\theta F(\theta,f) \\
C_{33}(f) &= \int_0^{2\pi} d\theta k^2 \sin^2\theta F(\theta,f) \qquad (1) \\
Q_{12}(f) &= \int_0^{2\pi} d\theta k\, (2\pi f)^2 \cos\theta F(\theta,f) \\
Q_{13}(f) &= \int_0^{2\pi} d\theta k (2\pi f)^2 \sin\theta F(\theta,f) \\
C_{23}(f) &= \int_0^{2\pi} d\theta k^2 \sin\theta \cos\theta F(\theta,f)
\end{aligned}$$

Further, if the directional spectrum $F(\theta,f)$ is considered as the product...

$F(\theta,f)$ = "Omnidirectional" Frequency Spectrum $E(f)$; times the normalized Spreading Function $S(\theta,f)$.....(where $\int_0^{2\pi} S,d\theta = 1$)

then at any given frequency f the angular distribution of energy $F(\theta)$ can also be put in the format of a standard fourier series:

$$F(\theta) = E_f\,[A_0/2 + (A_1 \cos\theta + B_1 \sin\theta) + (A_2 \cos 2\theta + B_2 \sin 2\theta) + \ldots]$$

with the higher harmonics providing improved azimuth resolution.

Unfortunately, as mentioned in section (1), the very limited spatial sampling achievable by a small buoy, limits the derivable fourier coefficients to the five stated above, and thus there is a physical limit on angular resolution, although the mean angle-of-wave-propagation can indeed be closely measured.

These five fourier coefficients, and the six spectra in equation set (1), exhibit the following inter-relationships:

$$A_0 = 1$$

$$A_1 = Q_{12}/[C_{11}(C_{22} + C_{33})]^{1/2}$$

$$B_1 = Q_{13}/[C_{11}(C_{22} + C_{33})]^{1/2}$$

$$A_2 = (C_{11} - C_{33})/(C_{22} + C_{33})$$

$$B_2 = 2C_{23}/(C_{22} + C_{33})$$

Effectively, A_0, being the mean term (though normalized here) yields wave rms amplitude at frequency f (as shown in Figure 1A), A_1 and B_1 yield mean azimuth direction (Figure 1A), and all five coefficients yield angular spread as illustrated in Reference 17.

The question of optimal weighting of the fourier coefficients also arises. This is done to avoid negative lobes in the angular response, which would indicate spurious, reversed wave components. Mathematically, the angular distribution (spreading function) at any frequency f then becomes:

$$S(\theta) = A_0/2 + K_1\ (A_1\cos\theta + B_1\mathrm{Sin}\theta) + K_2(A_2\cos 2\theta + B_2\mathrm{Sin}\ 2\theta)$$

where K_1, K_2 are the weighting factors.

Reference 16 addresses this matter. Different investigators have utilized different K values, though most of the CCIW work has been done with $K_1 = K_2 = 1$. Note that if the fourier coefficients (five digital words) are transmitted (or recorded), this refinement can be performed on land. But if wave amplitude, direction, and angular spread (three digital words) are directly transmitted, this mathematical weighting function must be incorporated in the buoy.

3.0 HARDWARE (BUOY HULL AND MOORING)

Shown in Figure 2 is the basic moored configuration of the NWRI wave/wind directional buoy system, with the wave-information package highlighted.

As mentioned in the theoretical section, the buoy is intended to act as a slope-follower, in addition to following surface elevation changes too. This is achieved by using a toroidal fiberglass float, with a strong righting-moment-to-inertia ratio.

The "vertical" accelerometer is best mounted at the waterline and buoy centre of rotation, otherwise correction terms for radial offset are required (Ref. 3). The buoy is non-magnetic so that the earth's magnetic field vector can be accurately measured along the three buoy-referenced axes.

The buoy is hydrodynamically symmetric and aerodynamically asymmetric, thus it orients itself and the windspeed sensor into the wind. All the "met-type" sensors, the antenna and the superstructure are aimed to be as small and lightweight as possible, for minimum upsetting-moment due to windforces and thus minimum error in wave-slope measurement. More utilisation of solid state types of "met" sensors is the current design outlook.

The mooring cable and ground tackle is similarly intended to be as compliant as possible, to minimum cable tugs and buoy upsetting moments which could distort the wave-slope measurements.

The validity of measuring wind speed and direction in 10-minute averages from this type of deliberately pitching and rolling buoy has been demonstrated by past CCIW work (Ref. 14, 15), which information is included in the data-package.

While not being as small and portable as a standard (non-directional, non-meteorological) wavebuoy, the NWRI wave/wind direction buoy sketched in Figure 2 is transportable by road, and can be towed and deployed by a small launch.

4.0 HARDWARE (BUOY INSTRUMENTATION)

Shown in Figure 4 is a functional block diagram of the BASIS buoy onboard signal-processing and data-compression electronics. (These electronics are 100% solid state, with no moving parts such as gyros, pendulums, compass rotors, etc.).

The sequence effectively starts with the magnetic field signals produced by the three axis magnetometer. These are the three components of the earth's magnetic vector $H/\underline{\alpha,\beta}$ as measured along the buoy's pitch, roll, and yaw (lubber line) axes. Given these three components, and with the direction cosines of the buoy-station magnetic-vector entered into memory, then the buoy attitude (in earth coordinates) is calculated in the first (16- bit microcomputer) stage. With the buoy attitude established, the N-S and E-W slope components are simply derived. (See software package.) Note also, in Figure 3, that the buoy yaw effectively is the measure of wind direction.

The buoy vertical acceleration signals get used directly (after digitization of course), with the traditional need for double integration avoided by this signal processing method.

The next module is the heart of the Package and performs the overall spectral analysis, both co-spectra and quad. It operates on 1024-point data sections (8.5 mins at 2 SPS). It is in effect an FFT spectrum analyzer with fast multiply facility, plus ROM for the trig functions. The spectral band covered is from 1/2 Hz down to 1/32 Hz at a resolution selectable as 1/128 Hz or 1/64 Hz; depending on whether spectral-resolution or data-compression was more important to the user. Pre-processing includes cosine-taper on the ends of the data series, and subtraction of mean slope components. This stage effectively ends when the six spectral estimates for each frequency component are stored in RAM.

Calculation of the five fourier coefficients of directionality is straightforward, and according to the theoretical expression in Section (2) above. With 32 discrete frequency increments, this gives 160 16-bit data words to be entered and stored in buffer memory, every 10 minutes.

Also entered every 10 minutes into this buffer memory (RAM) stage are the six averaged values for atmospheric parameters.....wind speed, wind direction, air temperature, water temperature, air pressure, and relative humidity.....together with time/date words.

Memory readout is done by burst mode every hour, at a burst rate of 400 BPS. Data is stored in the onboard digital recorder at this rate, and/or simultaneously transmitted by satellite or HF digital FM (PM) to the shorebased receiving station, where it is demodulated using phaselock loop circuitry. A radio transmission period of only one minute per hour suffices to telemeter one hour's record of wave-direction, amplitude, and angular spread in the spectrum 1/32 Hz to 1/2 Hz.....together with the related wind and atmospheric parameters.

5.0 SOFTWARE

The major functional subroutines for onboard signal-processing and data-compression are shown in the flowchart of Figure 4, and will not be repeated here. (It may help to also examine the data processing system block diagram, Figure 3.)

Minor subroutines such as associated with scale setting, timebase validation, line-printer plots, data summaries, etc., are not shown. Neither are relatively detailed software options such as sample rate choices (4, 2, 1 SPS have all been used by NWRI); G-contamination correction in-or-out; cosine taper in-or-out; numeric HP filter in-or-out; etc.

The total amount of software to implement both the major routines and subroutines has, in CCIW practise, amounted to approximately 5000 lines of code and this software package is available for transfer. It is written in FORTRAN IV, and exists at present in disc file on a CYBER 171 system. Note that there are areas where a reduction in routines, with consequent improvement in programming efficiency can be made. (For example, double integration and double numeric HP filtering.)

6.0 CALIBRATION (with respect to wave-direction only.)

The technique for accurately calibrating this wave package involves the use of a synthetic motion test jig, to confirm that the direction, amplitude, and frequency (period) as measured by the buoy instrumentation, is the same as that applied by the test jig.

The motion is a rotation around a circular path in the vertical plane, of 2 metre diameter (1 metre radius). This motion is combined with a controllable tilt at the 3 o'clock and 9 o'clock positions, as shown in Figure 5. This motion cannot be realistically applied to an entire buoy system of the type shown, so it is applied to the electronics cannister with accelerometer and magnetometer.

The test jig (which of course is non-magnetic) is set up on land on a site checked to be free of artificial magnetic interference. It is aligned N-S, then E-W. The test jig rotates the motion instrumentation through a 2-metre vertical circle at frequencies 1/32, 1/16, 1/8, 1/4, and 1/2 Hz. (Higher frequencies exceed 1G and are excessive and unrealistic.) At each frequency the corresponding angle of tilt is given by $\tan^{-1} (\omega^2 R/G)\cdot\cos(\omega t) = \tan^{-1} 4f^2$ peak tilt, for the one metre radius used.

At the end of each 10 minute data sequence, the values for direction spectra, amplitude spectra, frequency, and angular spread get printed out on the external monitor unit (or via radio telemetry). These printed values should correspond to the test-jig-applied values of direction, amplitude, and frequency for the simulated wave motion.

Because it is unrealistic to orbit the entire buoy system, particular care has to be taken that after these test jig tests, no magnetic distortion or physical misadjustment occurs when the accelerometer and magnetometer get incorporated within the rest of the buoy system.

7.0 CONCLUSION

This material, coupled with the extensive wave-measurement and atmospheric-measurement information contained in References (1) to (7)*, constitutes the entire wave/wind data package planned for transfer. It should be noted that what specifically exists at this time is the hardware and software described in references (1) to (7)* which should be carefully reviewed by any potential industrial performer. The BASIS buoy system highlighted herein is a derivative representing what is considered to be the most cost-effective and useful embodiment of all this referenced technology.

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* plus References 14, 15, 18

8.0 REFERENCES

* (1) "A Method for the Automatic Measurement of Wave Frequency." Donelan, JFRB, V33-10 (1976).

* (2) "Wave Information from a Floating Buoy." Donelan, NWRI, HRD Report 77-15 (1977).

* (3) "Manual for Maintenance and Use of CCIW Wave-Direction Buoy." Donelan, NWRI, Unpublished Report (1980).

* (4) "Modifications to CCIW Wave-Direction Buoy." Pedrosa, NWRI/ESS, Unpub. Rpt. ES-1096 (1980).

* (5) "Appendices 1, 2 to Manual for CCIW Wave-Direction Buoy." Skafel, NWRI/HRD Unpub. Rpt. (1982).

* (6) "Motion Package Buoy at ARSLOE: Data Summary." Skafel, NWRI/HRD Unpub. Rpt. (1982).

* (7) "Performance of the CCIW Wave-Direction Buoy at ARSLOE", Skafel, Donelan. (Submitted for publication, 1983.)

(8) "Directional Spectra of Wind-Generated Waves", Donelan, Hamilton, Hui. NWRI Unpub. Rpt. (1983).

(9) "High-Resolution Wave-Sensor Array for Measuring Wave Directional Spectra in the Nearshore Zone." Der, Watson. IEEE Oceans 77. 1977.

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(11) "Directional Wave Spectral Data from a Large Discus Buoy." Oceans 78 Proceedings, IEEE. (1978).

(12) "Statistical Evolution of Directional Spectrum Estimates Derived from Pitch-Roll Buoy Data." Long. Journal of Physical Oceanography. VIO-6 (1980).

(13) "Spectral Analysis and Its Applications." Jenkins and Watts. Pub: Holden-Day (1968).

*(14) "Evaluation of Measurements from the CCIW Meteorological Buoy", Donelan et al. NWRI Unpub. Rpt., March 1979.

*(15) "Preliminary Results from Some Recent NWRI Experiences with Wind Direction Sensors on Medium Scale Buoys." Der, Bull, NWRI Unpub. Rpt. (May 1980).

(16) "Storm Directional Wave Spectrum Measured with a Single Buoy." Leblanc. IEEE Oceans 82. (1982).

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*(18) "A Meteorological Buoy Syustem for Great Lakes Studies." Elder, Brady. IWD Tech. Bull #71. (1972).

* Considered part of the transfer-package.

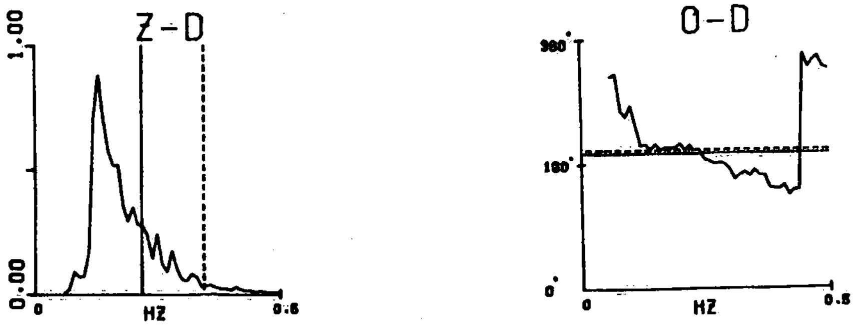
FIGURE 1

PRESENTATIONS OF WAVE DIRECTIONAL OUTPUT SPECTRA

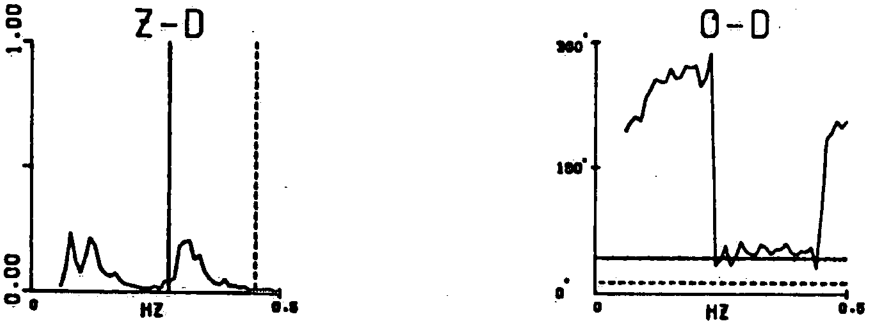
(per 1200-point data sampling)

NWRI HAS (A) GENERATED SEPARATE AMPLITUDE/DIRECTION PLOTS (REF. 6)

(UNI-
MODAL)



(BI-
MODAL)



(B) HAS PROVIDED FOURIER-COEFFICIENT SETS FOR ISOMETRIC PLOTS IN 3-DIMENSIONAL PERSPECTIVE (REF. 16)

(C) POLAR PRESENTATIONS OF WAVE DIRECTIONAL SPECTRA SHOWING EQUI-AMPLITUDE CONTOURS HAVE ALSO BEEN USED ELSEWHERE (REF. 11)

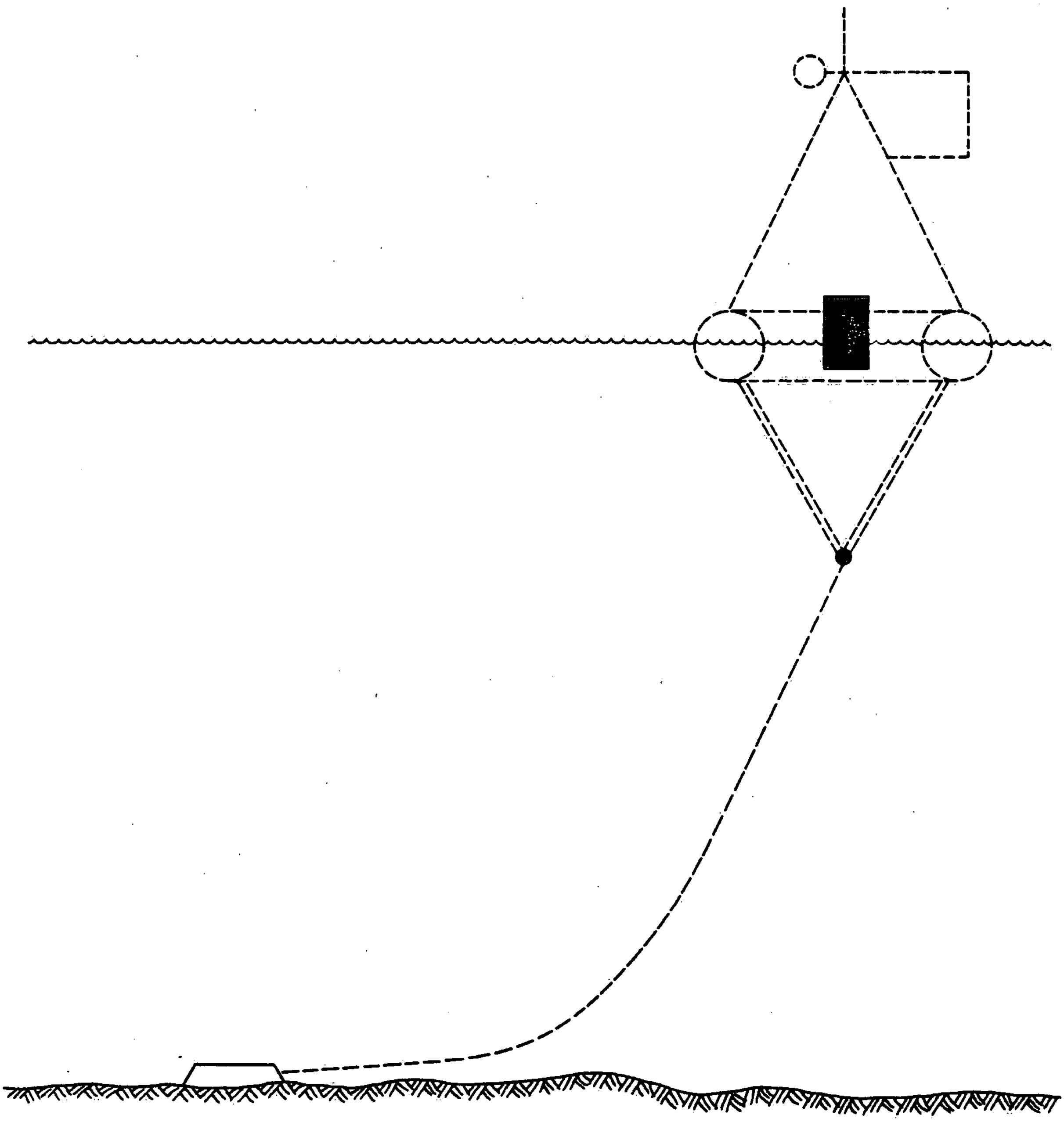
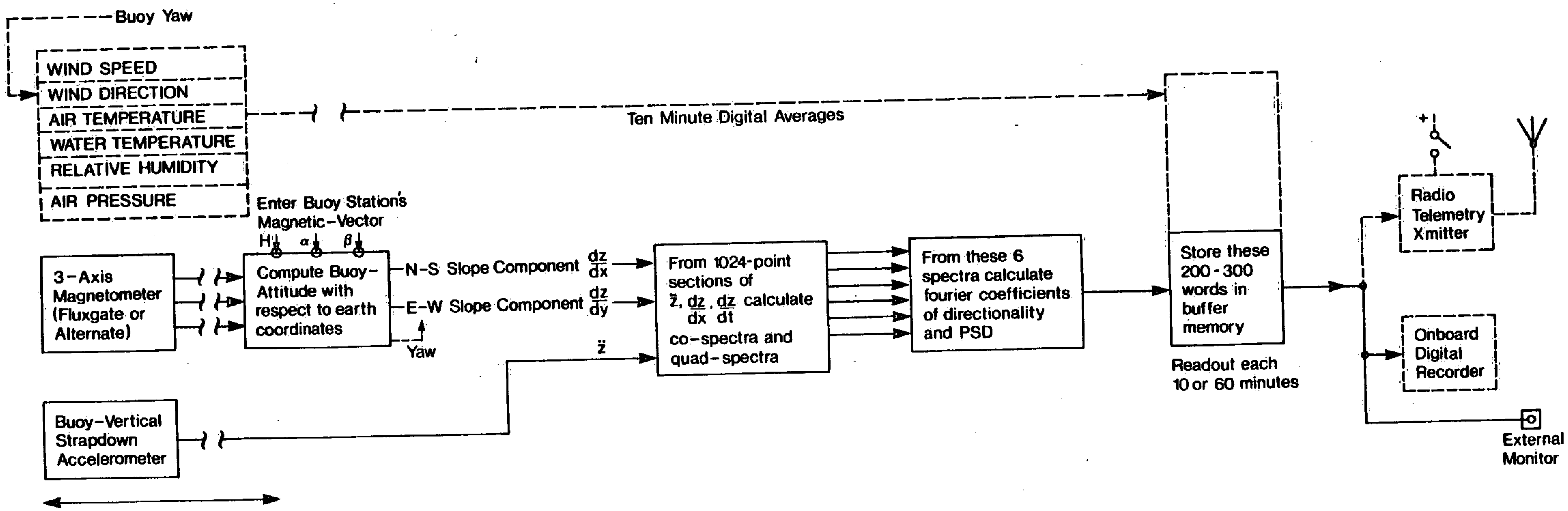


Figure 2 WAVE INFORMATION PACKAGE WITHIN A MOORED WAVE/WIND BUOY SYSTEM

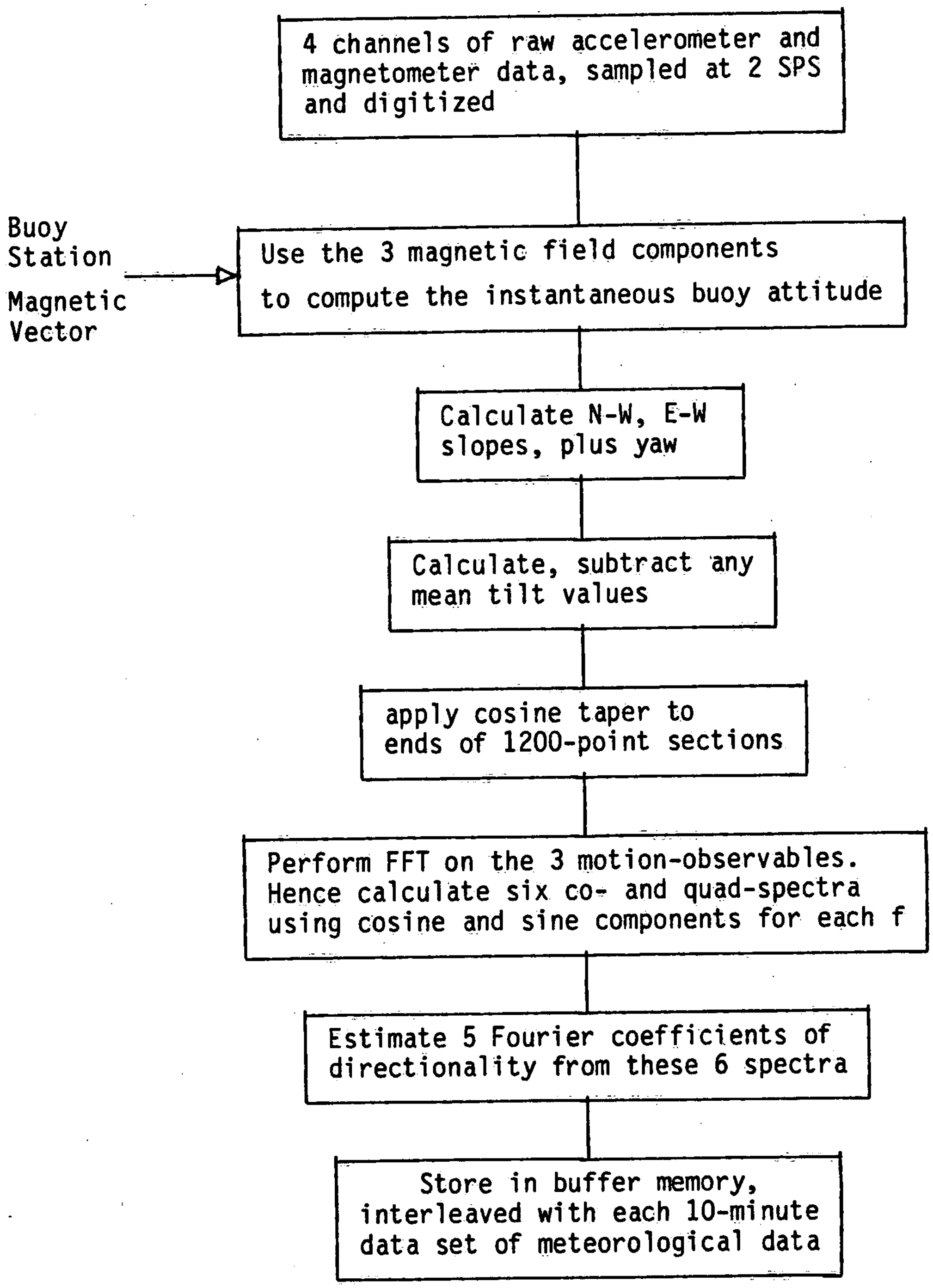


These 4 parameters (plus time, plus a recorder) would comprise a "Raw Data" wave package

Figure 3 SIGNAL-PROCESSING AND DATA-COMPRESSION FOR THE NWRI WAVE-DIRECTION PACKAGE [shown within a wave/wind directional buoy system]

FIGURE 4.

SOFTWARE FLOWCHART FOR DIRECTIONAL WAVE ANALYSIS



$$\text{Tilt } \Theta = \tan^{-1}(\omega^2 R/G) \quad \cos(\omega t)$$

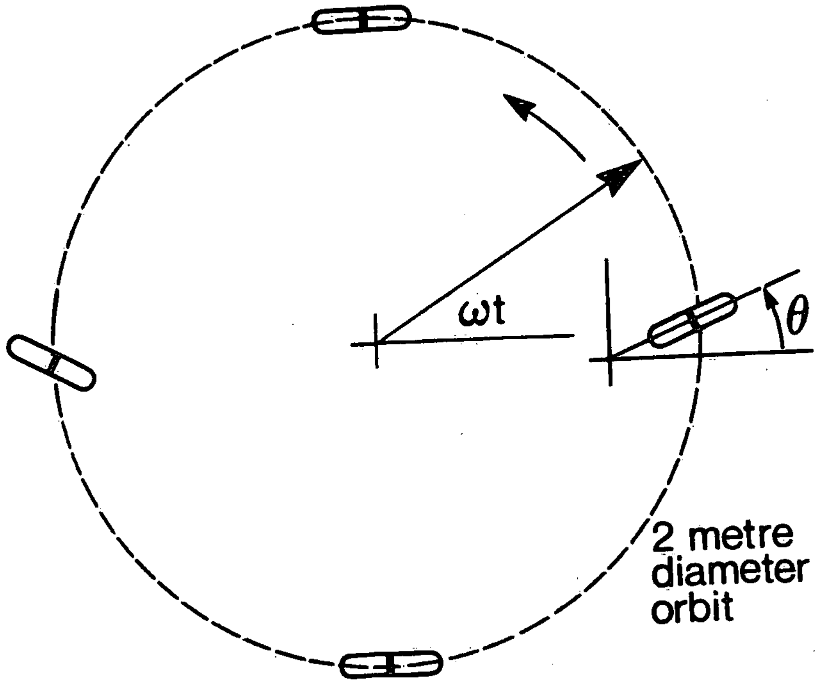


Figure 5 CALIBRATION BY MOTIONAL TEST-JIG (for wave-direction)

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