CHAPTER 21

A New Nearshore Directional Wave Gage

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1 Introduction

A field directional wave gage has been developed for requirements in coastal, port, and harbor engineering. Uses include planning and design studies, long term wave climatology, and post construction monitoring. The gage provides high quality directional wave spectra measurements from a compact, easily installed instrument. Stand alone installation with long term internal data recording is provided. Real time data access may be simultaneously provided by connecting a cable.

The gage is completely bottom mounted with no surface components. Optimized for shallow and intermediate water depths required by coastal engineers, the gage may be reliably deployed in water depths too shallow for buoys or acoustic instruments. The sensors are three high resolution pressure transducers that permit the mounting frame to be resistant to fishing activities.

Reliable data storage and long term deployment are achieved by performing preliminary data analysis within the instrument. Intermediate analysis results are recorded on reliable non-volatile solid state memory. The recorded data may be post processed to obtain simple estimates of mean water level, wave height, period, and direction. If desired, the Fourier series coefficients of the directional spectrum may be computed from the intermediate data. Optionally, modern high resolution methods may be used.

2 Background

2.1 Motivation

Deep ocean directional wave measurement has progressed rapidly during the last

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twenty years. In-situ buoy measurements are routinely collected by the industrialized nations. Commercial directional buoys are available for site specific studies. The development of satellite technology has provided deep water measurements assumed to be homogeneous over the large range cells of satellite sensors.

Unfortunately for coastal engineers, progress in nearshore measurements has lagged. The typical coastal regime, characterized by shoaling, refraction, diffraction, and reflection, makes the use of large spatial averaging remote sensors, inappropriate. Data are often required in areas subject to large breaking waves and strong currents. These conditions capsize directional buoys, and aerate the water column, blinding acoustic sensors.

2.2 Requirements

Modern coastal engineering practice requires use of increasingly sophisticated models. Properly calibrated and verified, models can yield accurate information on waves at a project site. Frequently data are not available, and models must be employed with only deep water data, or shallow water data from a distant or unrepresentative site. In undeveloped areas, models may be applied without any calibration or verification. The goal of this development is to make high quality, site specific wave data commonplace.

A requirements based design approach was employed to guide development efforts. First, engineering data requirements were identified:

- Wave height
- Wave period
- Wave direction
- Wave spectrum
- Radiation stress
- Water level

While many other statistics could be added, routine availability of these parameters constitutes a useful parameter set. This paper will focus on the key parameter of wave direction, in particular mean wave direction.

2.3 Measuring wave direction with arrays

In-situ directional wave gages can be generalized as arrays of sensors that spatially and temporally sample the *true* directional wave spectrum over a section of the sea surface. The estimated directional spectrum is the convolution of the *true* directional spectrum with the transfer function of the sensor array. Isobe et al. (1984) expressed this using the cross power spectra, Φ_{mn}, between arbitrary measured wave parameters and the directional wave spectrum $S(\vec{k},\sigma)$, where $\vec{k}$ is the wave number vector, and σ is angular frequency.

$$\Phi_{mn} = \int_{\vec{k}} H_m(\vec{k},\sigma) H_n^*(\vec{k},\sigma) e^{-i\vec{k}(\vec{x_n}-\vec{x_m})} S(\vec{k},\sigma)\, d\vec{k} \tag{1}$$

The H_m is the hydrodynamic transfer function between the water surface and the mth sensor and $\vec{x_m}$ is the sensor's location vector.

Common practice for engineering applications assumes linear wave theory for the transfer functions H_m, and a linear dispersion relationship between wave length and frequency expressed as

$$\sigma^2 = (2\pi f)^2 = gk \; tanh \; kd \tag{2}$$

where d is the water depth.

Equation 1 can then be expressed in the frequency domain as

$$\begin{aligned} \Phi_{mn}(f) &= \int_0^{2\pi} H_m(f,\theta) H_n^*(f,\theta) \{cos(k[x_{mn}cos\theta + y_{mn}sin\theta]) \\ &- \quad i\, sin(k[x_{mn}cos\theta + y_{mn}sin\theta])\} S(f,\theta)\, d\theta \end{aligned} \tag{3}$$

where θ is the wave direction, f is wave frequency, $S(f,\theta)$ is the wave frequency directional spectrum, and

$$x_{mn} = x_n - x_m \tag{4}$$

$$y_{mn} = y_n - y_m \tag{5}$$

Directional wave analysis is the method of estimating solutions to the integral equation 3. Horikawa (1988) provides a summary of current methods. For many engineering applications, mean wave direction is sufficient. Note that $\Phi_{mn}(f)$, the cross-spectral matrix, is sufficient information to employ any directional analysis technique.

2.4 Existing instrumentation

Existing instrumentation and field procedures were reviewed to identify required improvements. The following types of in-situ, nearshore directional measurement instrumentation systems are being used, or have been evaluated in the past.

PUV Co-located EM current meter and absolute pressure gage. Both real-time, cable connected, and self recording versions are used routinely.

Borgman array Shore parallel array of absolute pressure transducers with spacing comparable to wave lengths (Panicker and Borgman, 1970). This array is capable of high resolution and is routinely used at research facilities.

S_{xy} **array** A 6m right triangle, absolute pressure transducer array, analyzed as a slope array (Higgins, et al., 1981).

DPG Differential Pressure Gage. Two orthogonal short base line differential pressure gages, and one absolute gage. Developed and successfully tested by Bodge and Dean (1984).

ADCP Acoustic Doppler Current Meter. Measures three components of current velocity at several range cells in the middle part of the water column. The data analysis is similar to a *PUV*.

Short base-line slope array A real time, cable connected, 1.6 m equilateral triangle, absolute pressure transducer array, analyzed as a slope array. This gage was developed as a precursor to the gage reported here and has been in routine use by CERC since 1989.

Economy and reliability are the most needed improvements. Measurement and analysis techniques were less so. When the total costs of obtaining an analyzed data report are considered, instrument cost was less important than costs associated with field operations, maintenance, and data analysis.

An integrated approach addressed the entire function from sensor to analyzed data report. Instrument requirements were part of the overall systems analysis. Existing instruments require improvement in one or more of the following areas:

Directional resolution Most important for sediment transport formulae, but benefits all applications.

Gage orientation accuracy Errors or suspected errors in the orientation of directional gages can render data useless.

Site selection flexibility Often sites must be selected based on survivability or operational requirements, rather than engineering data needs.

Deployment period Frequent service requirements are a principal cause of high costs. At many sites, weather permits servicing only during the summer.

Measurement interval Shallow water wave conditions can change rapidly. Instrument limitations force sub-sampling.

Reduce total cost of analyzed data Site specific data costs must be within the budget of a typical engineering project.

3 New Developments

3.1 Principles of operation

The enabling development is the very short baseline absolute pressure transducer array (Figure 1). Traditional directional wave gages using pressure transducers have relied on arrays with dimensions on the order of water wave lengths (Panicker and Borgman, 1970).

Figure 1: DWG-1 ready for deployment. Base version uses 3 transducers in a 1.6 m equilateral triangle array.

Scripps Institute of Oceanography developed slope gages using absolute pressure transducers in a 6 m right triangle array. Higgins, et al. (1981) analyzed the errors due to length of the baseline. Error was reduced by making the baseline as short as possible, limited only by the noise of the absolute pressure transducers.

Bodge and Dean (1984) demonstrated that differential pressure transducer arrays could employ very short base lines. The differential transducer array requires a fluid filled tubing system to transmit the pressure to the transducer. Construction and maintenance of the tubing system requires care.

The new gage has the advantages of the short baseline array, yet still uses absolute pressure sensors. An absolute pressure sensor using a quartz crystal transducer and a specially designed digitization circuit was developed. The combination provides pressure samples with an order of magnitude less noise than previous strain gage based transducers. The sampling period for this resolution is less than 180msec.

Numerical simulation of various directional wave spectra measurements using the noise characteristics of the new transducer examined the effect of baseline dimension on error in mean wave direction. Results were very encouraging. To verify these results a field experiment was conducted. Figure 2 shows the layout of a seven transducer array of transducers arranged to provide multiple baseline lengths. The array was placed in 8m of water at the CERC Field Research

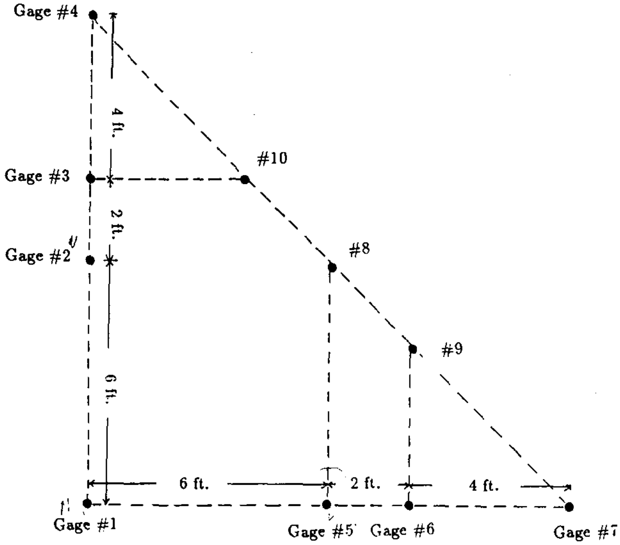

Figure 2: Array layout used at the DUCK 85 field test to evaluate the effect of the baseline length of slope arrays on mean wave direction measurement error.

Facility, Duck, N.C.

A total of 1567 wave records from October to December 1986 were analyzed. Significant wave height ranged to 4 m, and spectral peak periods ranged from 4 to 20 sec. Data from sensor number 1 was discarded due to excessive noise. Virtual sensors 8, 9, and 10 were created by linear interpolation of data from sensors 1 and 4. Figure 3 is an example of a scatter plot of mean direction from a slope analysis of effective 1.2 m and 1.8 m arrays. As predicted by the simulation, the reduction in base line length has little effect on the mean direction estimate.

The new gage has a base configuration of a 1.6 m equilateral triangle, absolute transducer array. This array will give accurate mean direction estimates at low cost. Figure 1 shows the geometry of the standard installation pod. The hexagonal shape allows the minimum configuration triangular array to be augmented with additional transducers. Numerical simulations using the Bayesian analysis method (Hashimoto and Kobune, 1988) have been performed using 4 and 6 transducers. Directional resolution is improved over the minimum three transducers. Directional resolution performance of the new gage will be reported when planned field tests of the four and six transducer versions have been completed.

The short base line reduces construction costs and simplifies installation and recovery. Problems of spatial homogeneity in the complex bathymetry of coastal projects are eliminated. The hexagonal array facilitates design of a high strength, trawler resistant pod.

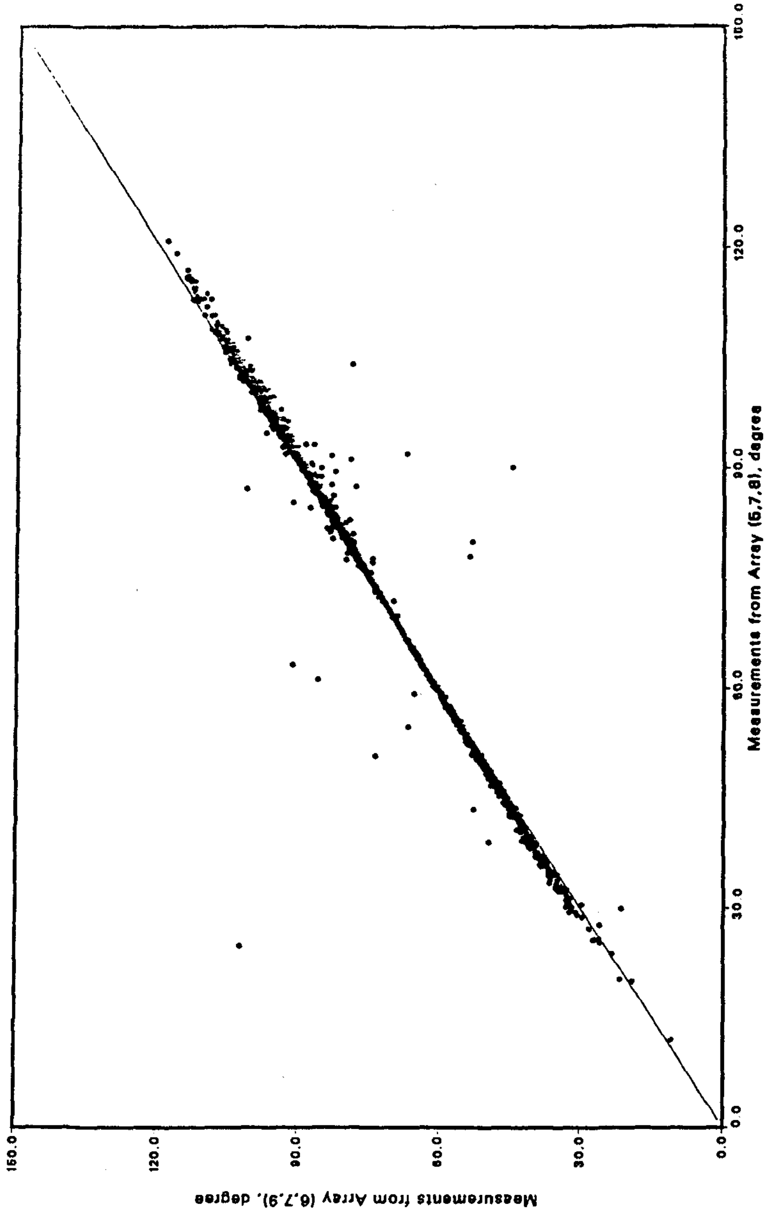

Figure 3: Correlation of mean wave direction estimates from Array (5,7,8) and Array (6,7,9).

3.2 Gage design

The performance requirements were translated into the following design specifications.

Specifications.

Internally recorded data: Mean water level, cross-spectral matrix, and calendar date and time.

Post-processed data: Water level, significant wave height, spectral peak period, mean wave direction, and directional spectrum.

Internal data storage: Removable EPROM modules.

Real time option: Simultaneous with internal recording and analysis, calibrated pressure time series data are available in real time. Adds a standard 7-conductor well logging cable up to 1.7 km length and a shore located PC or modem.

Principle: 3-transducer pressure array. 1.6 m equilateral triangle.

Sampling interval: Acquires and analyzes 30 min data record every hour.

Deployment period: Records hourly data for 13 months.

Operational depth: Bottom mounted in water depths from 2 to 20 m.

Accuracy: Water level, wave height, and spectral energy error - 1 cm rms. Mean wave direction error - 2 degrees rms.

Implementation of the gage is achieved through very low power microcomputer design and custom firmware. Firmware controls data acquisition, quality control, calibration, analysis, and storage functions. The most difficult specification is simultaneous 13 month deployment, 1 hour continuous record interval, and 30 min record length. Existing instrumentation requires compromise of one or more of these requirements.

Achieving 13 month deployment requires internal data analysis. The cross spectral matrix is computed internally and stored. These data provide the maximum data compacting while still permitting various analysis techniques for post processing. For the base level gage is treated as a space array. To reduce the amount of information saved, redundant information in the cross spectral array is eliminated.

Expressing the cross spectral matrix as real and imaginary parts, the usual definitions of Co (real) and Quad (imaginary) spectra are defined as

$$\Phi_{mn}(f) = C_{mn}(f) - iQ_{mn}(f) \tag{6}$$

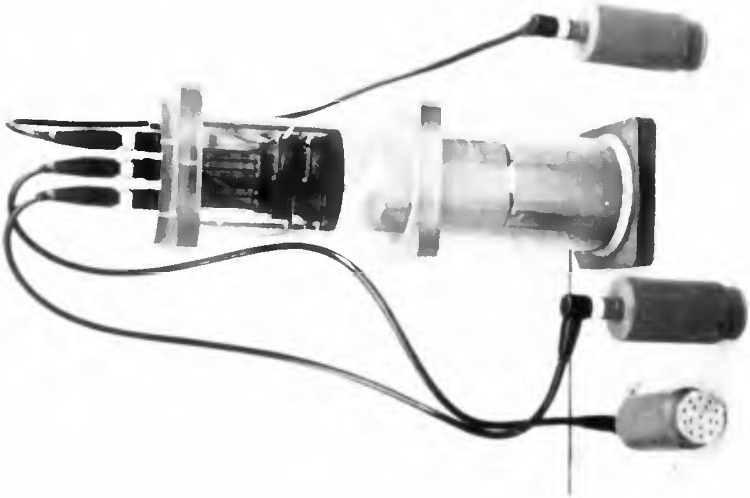

Figure 4: DWG-1 cylinder containing the electronics and batteries. The three pressure transducers connect to the main cylinder.

and for 3 sensors

$$\Phi_{mn} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} - i \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{bmatrix} \tag{7}$$

Observing that each nm term is the complex conjugate of the corresponding mn term, three each Co and Quad spectra are eliminated from storage. By definition $Q_{11} = Q_{22} = Q_{33} = 0$, and for the case of a space array, $C_{11} = C_{22} = C_{33}$ except for statistical variability. Substituting

$$\hat{C} = \frac{C_{11} + C_{22} + C_{33}}{3} \tag{8}$$

and

$$\hat{C}_{nm} \approx \sqrt{\hat{C}^2 - Q_{nm}^2} \tag{9}$$

allows the saved parameters to be reduced to $\hat{C}, Q_{12}, Q_{13}$, and Q_{23}. These assumptions are sufficient for accurate mean direction estimates. High resolution directional estimates require that Co-spectra terms also be saved, resulting in a small cost increase.

The mean water level computed during the first and last six minutes of each measurement interval are also saved. All data are calibrated in engineering units and tagged with UCT time. Each gage permanently stores its sensor calibrations, identification, location, quality control, and status information in the removable EPROM modules.

A prototype diverless deployment and recovery system has been developed to reduce operation cost and improve the gage directional orientation measurement. The unit is operated from a boat using a PC interface. The fixture contains a remotely operated air jetting controls and release, depth and attitude read outs, and a gyrocompass for orientation measurement.

4 Field test results

The completed gage has been field tested at two sites. Both gages functioned successfully, obtaining better that 99% data return. A comparison of the gage results with a 15-element linear array at the Coastal Engineering Research Center (CERC), Field Research Facility (FRF) in Duck, North Carolina was independently conducted by William Birkemeier of the FRF. The linear array is composed of 9 shore parallel and 6 shore normal sensors. Figures 5 and 6, prepared by Mr. Birkemeier, summarize the results. The comparison data represent 1090 records during the period February 1 - March 31, 1992. Records with $H_s < 0.4\ m$ or $T_p < 4\ sec$ were not included. An unexplained time difference of 1 hour between the two data sets was compensated. No manual editing or quality control was applied to data from the new gage.

Both gages rely on the autospectrum of a pressure transducer to estimate significant wave height and peak period. The agreement shown in Figure 5 is expected for properly calibrated and analyzed gages. Fig. 6 compares mean direction estimates. For these data the new gage's mean direction was obtained from a space array analysis. Agreement is quite good. Outliers result from bimodal spectra where approximately equal peaks can cause a different T_p to be picked by the analysis codes. Agreement is best near shore normal angle of 70 degrees. Waves at oblique angles to the beach are underestimated by the linear array compared to the new gage. Similar differences were observed with comparisons of the linear array to a *PUV* gage.

5 Conclusions

The new gage is a high quality, directional wave gage, capable of simple installation, and year long deployment. The low cost availability of nearshore directional wave data will impact the planning, engineering, and maintenance of coastal projects. Wave measurements will be possible in most locations. Stand-alone internally recording gages will be more economical than real-time, cable connected gages. Low cost and site selection flexibility will permit multiple gages

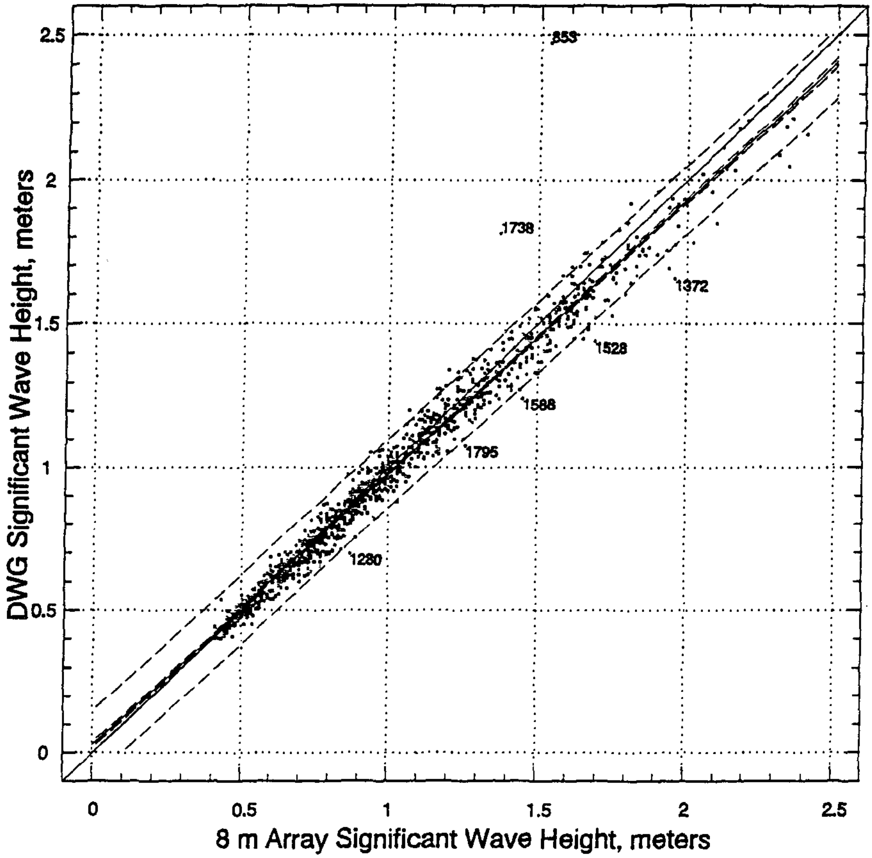

Figure 5: Linear regression of H_s of DWG-1 and the FRF Linear Array. Outer dashed lines are 95% prediction limits. The correlation coefficient is 0.987.

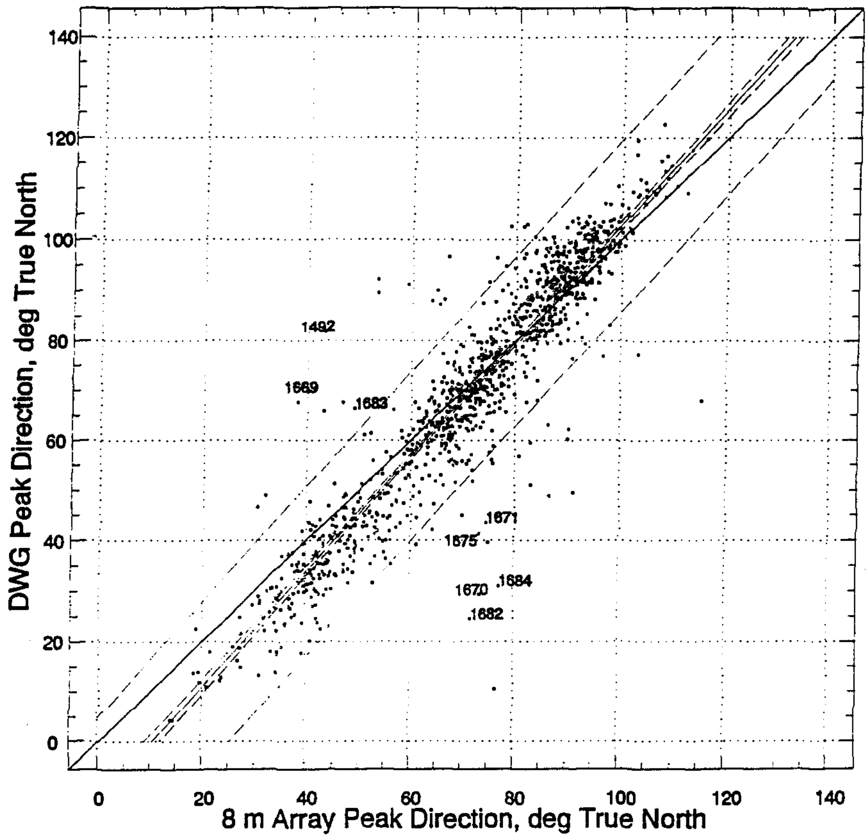

Figure 6: Linear regression of mean wave direction at the spectral peak period of DWG-1 and the FRF Linear Array. Outer dashed lines are 95% prediction limits. The correlation coefficient is 0.931

at a project site. Routine monitoring for engineering requirements will increase. New monitoring objectives of environmental assurance and litigation prevention will emerge.

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