AN EXAMINATION OF COHERENCE OF DIRECTIONAL WAVE TIME SERIES FROM BOTTOM-MOUNTED PRESSURE AND CURRENT SENSORS

James P. McKinney and Gary L. Howell
U.S. Army Corps of Engineers Engineering Research & Development Center
Vicksburg, MS, 39180
James.P.Mckinney@erdc.usace.army.mil
Gary.L.Howell@erdc.usace.army.mil

***Abstract*— This paper examines the coherence between kinematic variables from different types of bottom mounted instruments used for coastal directional wave measurements. Long term field data from *PPP*, *PEMCM* and *PADV* for several locations and wave conditions are analyzed for wave direction and coherence.**

Directional wave measurements analyzed from arrays of sensors assume that the time series of wave kinematics are statistically homogenous. Sensor time series should differ only in amplitude and phase. For real-world field measurements sensor data contains noise components and systematic errors and biases. Coherence between sensor pairs is a common method of quantifying the noise and error.

Our results show very high coherence between individual pressure time series in short base-line pressure arrays. Slope components computed from the pressure array are used for directional analysis. We find slope coherence less than the scalar pressures but generally high. Coherence between U and V components of horizontal velocity measured by current meters should be very high because they are cartesian components of the current vector. Our data show this is generally true for common E-M current meters. For acoustic doppler (*PADV*) velocity meters the coherence was significantly lower.

Coherence is potentially useful as a metric for comparing different sensor systems accuracy for directional estimates. It also is frequently used as a quality control test for automated data analysis. Non-acoustic systems generally exhibit high coherence when operating correctly. For acoustic systems the question arises as to how good must coherence be for acceptable data. We present exploratory analyses that examine the relationship between coherence and the quality of directional estimates.

I. Introduction

The availability of low-cost acoustic doppler current meters has increased their use for coastal data collection. The doppler principle eliminates the requirement for regular tow-tank calibration, further reducing costs. Measurement of wave direction with a vector current meter and a single pressure sensor (PUV) is a proven technique. Early acoustic current meters could not sample fast enough to obtain unaliased orbital velocity time series. The development of high frequency sensors and integrated circuit digital signal processors allowed the development of current meters that sample at 1Hz or higher.

When deployed in typical uncontrolled field environments, the orbital velocity data from acoustic current meters sometimes exhibits anomalous results. This is of course true of all sensors and is the reason for the development of systematic data quality control methods for routine measurements. There have been indications that acoustic current meters exhibit data artifact more frequently than the previous generation electromagnetic current meters.

Figure 1 shows a 20 second time series from the pressure and electromagnetic sensor gage record from Platform Edith on 4/1/1999 0000 GMT. The orbital velocities appear to be in phase with each other. There is the expected 90 deg phase difference between the velocities and the pressure. A qualitative visual inspection of this data concludes that it is reasonable. Figure 2 is a 20 second time series from an acoustic doppler velocimeter at Grays Harbor. Here, the u-velocity appears to be in phase with the water level, and has a different wave shape than the v-velocity. Qualitatively, data such as this raises questions, but it is difficult to rule out that some combination of wave periods and directions could cause the unusual time series. We need a quantitative measure of data quality to make objective decisions on data such as these. The U and V orbital velocity time series are vector components of current vectors and should be linearly related for any sea conditions. Coherence can measure this linearity and provide a metric for data quality.

Coherence is a measure of the linearity of the relationship between two time series in the presence of noise and error. The amount of noise and error affects the accuracy of the directional wave estimates. Noise varies between types of sensors, data acquisition and processing techniques, and the field conditions including waves, currents, and suspended sediment.

We report here preliminary work based on coherence analysis that will provide quantitative comparisons of the performance of acoustic doppler current meters used for directional wave measurement. The objective of the work is to help answer the following questions posed by data users:

1) Do acoustic doppler current meters perform better, as well as, or worse than other types of simple single point wave direction sensors?
2) If coherence is used as a data quality control test, how much coherence is good enough?
3) For time series with low coherence, what is the effect on the directional estimates?

To begin our exploration of these issues we examined the

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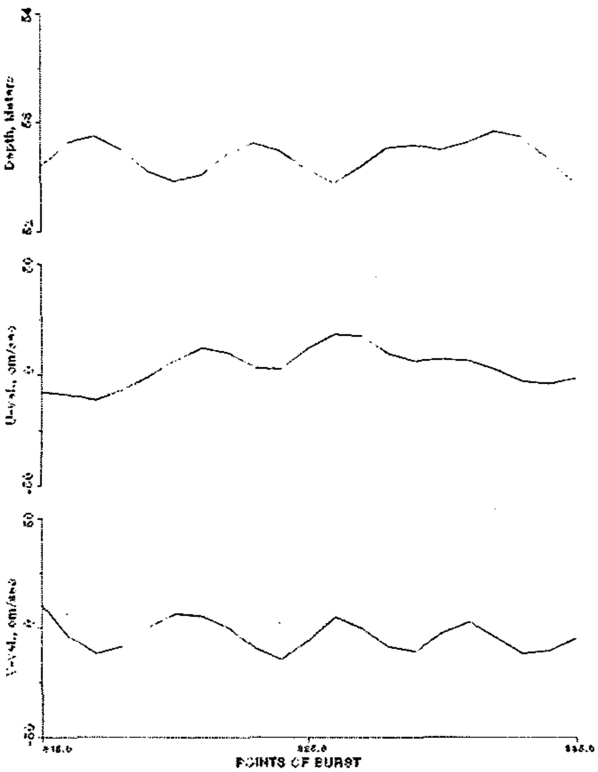

Fig. 1

A 20 SECOND TIME SERIES FROM THE *PEMCM* GAGE AT PLATFORM EDITH. THE TWO VELOCITY COMPONENTS ARE SIMILAR AND HAVE THE EXPECTED 90 deg PHASE DIFFERENCE WITH THE PRESSURE TIME SERIES.

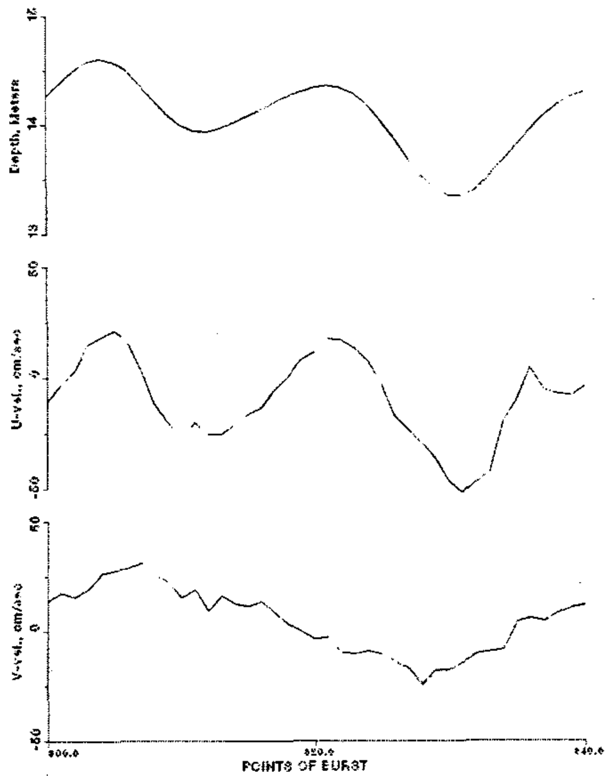

Fig. 2

A 20 SECOND TIME SERIES FROM THE *PADV* GAGE AT GRAYS HARBOR. THE TWO VELOCITY COMPONENTS APPEAR DIFFERENT. THE U VELOCITY APPEARS TO BE IN PHASE WITH THE PRESSURE, WHILE THE V VELOCITY MAY HAVE A PHASE DIFFERENCE.

coherence between kinematic variables from different types of bottom mounted instruments used for coastal directional wave measurements. Field data from short base-line pressure arrays, *PPP*, electromagnetic current meters with single pressure sensors, *PEMCM*, and acoustic doppler velocimeters for horizontal velocity and a single pressure sensor, *PADV*, are presented for different locations and wave conditions. We plan to analyze data from acoustic doppler profiler instruments *ADCP* as well, but these results were not complete in time for this publication.

II. DATA

All data records were selected from archives of data acquired at actual coastal project sites, and represent typical conditions that occur in real-world field deployments.

Ideally, simultaneously measured data sets from all types of sensors at the same site-time would be used. For this initial effort we used data that were available to us, and that were representative of the types of locations where we require directional data.

Table I contains information about the various datasets.

Note that the depth at Platform Edith is listed as 53 meters, however the sensors are attached to the platform about 10 meters from the surface. One 30 day month of data from each location was used in this analysis.

III. ANALYSIS

All data sets for the *PPP*, *PEMCM*, and *PADV* systems were initially analyzed to obtain significant wave height (H_{m0}), peak period (T_p), mean wave direction at T_p (D_p), the directional energy spectrum, co- and quad-spectra, and coherence spectra for $P \times U$, $P \times V$, and $U \times V$ or $P1 \times S_x$, $P1 \times S_y$, and $S_x \times S_y$. These results were stored in our Prototype Measurement and Analysis System, *PMAS* [2] to allow SQL comparisons of analyzed parameters.

The analysis utilized the Welch [4] spectral analysis method with 50% overlapping segments. Since the raw time series were obtained using sub-surface systems, a depth determined

Site	State	Gage type	Mean water depth
Grays Harbor	WA	PADV	14 meters
Morro Bay	CA	PPP	7 meters
Pascaguoula	MS	PADV	3 meters
Platform Edith	CA	PEMCM	53 meters
Westhampton	NY	PPP	9 meters

TABLE I

DATASETS INCLUDED IN THIS ANALYSIS.

high frequency cutoff was applied. The averaged co- and quad-spectra from each analyzed record were used to calculate the coherence spectrum (Coh) for each cross spectrum using equation 1 for ordinary coherence:

$$Coh = \frac{\sqrt{C_{xy}^2 + Q_{xy}^2}}{C_{xx}C_{yy}} \tag{1}$$

where C_{xy} is the cross spectrum of $X(t)$ and $Y(t)$, and Q_{xy} is the quadrature spectrum of $X(t)$ and $Y(t)$ [3].

Figure 3 is an example of the coherence spectrum, Coh, for a *PEMCM* gage record from Platform Edith on 4/1/1999 0000 GMT. The longer period coherence (>10 seconds), and the short period coherence (<4.5 seconds) are low. The low coherence for low energy frequency bands is typical and is related to the lower signal to noise ratio. For periods between 4.5 and 10 seconds, coherence is relatively high. Note that the higher coherence is at the peak of the energy spectrum.

Figure 4 shows the Coh of a 1.4m equilateral triangle *PPP* data record from Westhampton, NY on 2/3/99 0000 GMT that was calculated using the scalar pressure time series. Note that the Coh for all cross spectra is near 1.0, which indicates that low noise is associated with the collection and analysis of the *PPP* data.

Figure 5 is an example of the Coh for the same *PPP* gage time series used in figure 4. This spectrum was calculated using "slope" time series, $S_x(t)$ and $S_y(t)$, which were calculated from $P1(t)$, $P2(t)$, and $P3(t)$ using the following equations [1]:

$$S_x(t) = \frac{P3(t) - P2(t)}{2} \tag{2}$$

$$S_y(t) = \frac{P2(t) + P3(t)}{2} - \frac{P1(t)}{\sqrt{3}} \tag{3}$$

The coherence at the peak of the spectrum in figure 5 is approximately 0.9. For the rest of the spectrum, the coherence is lower. The reduction in coherence for the slope variables is related to the noise amplification caused by computing the slopes over the relatively short base-line of 1.4m. We will distinguish between *PPP* coherence and slope coherence by using the PS_xS_y for the slope spectra.

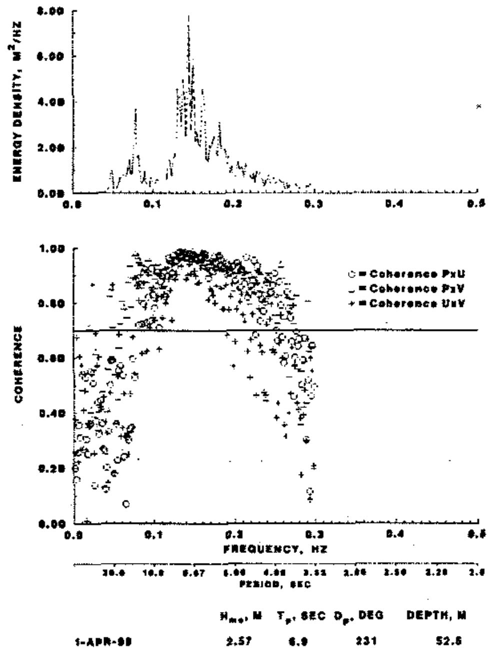

Fig. 3

ENERGY SPECTRUM AND THE ASSOCIATED COHERENCE SPECTRA FOR THE *PEMCM* GAGE AT PLATFORM EDITH ON 4/1/1999 0000 GMT. COHERENCE IS HIGH FOR ALL CROSS SPECTRA FOR WAVE PERIODS BETWEEN 5 AND 10 SEC. COHERENCE IS LESS FOR THE LOWER ENERGY PORTIONS OF THE SPECTRUM.

Figure 6 is an example of the Coh for the *PADV* record from Grays Harbor, WA on 4/6/99 at 1000 GMT. The unexpected result of this *PADV Coh* analysis is that the $P \times U$ spectrum has near perfect coherence for periods between 5 and 15 seconds, however, the coherence of $U \times V$ indicates the V velocity channel is lower than $1/\sqrt{2}$ or the coherence of random noise [3]. It is odd, that the components do not seem to be linearly related. Similar results were noted from other deployments on the west coast. However, figure 7 displays an analyzed record from a similar gage deployed at Pascagoula, MS, which did not exhibit the characteristic of the U component being totally coherent with the water level (pressure) component. Instead, the V component appears more coherent.

Most engineering applications use the basic wave statistics of H_{m0}, T_p, and D_p, so it is important to know how well different systems preform in obtaining these statistics. In particular, directional wave systems need to accurately measure D_p. Fig-

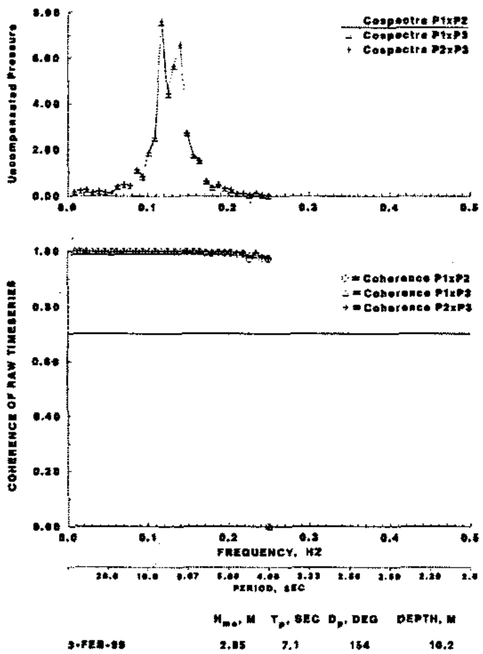

Fig. 4

Coh SPECTRUM FOR THE *PPP* GAGE AT WESTHAMPTON, NY ON 2/3/1999 0000 GMT CALCULATED USING SCALAR PRESSURE TIME SERIES THE TOP GRAPH SHOWS THE PRESSURE CROSS SPECTRA AND THE LOWER PLOT THE ASSOCIATED COHERENCE SPECTRA FOR THE *PPP* GAGE. THE COHERENCE SPECTRUM FOR ALL CROSS SPECTRA IS NEAR UNITY INDICATING VERY LITTLE NOISE IN THE PRESSURE TIME SERIES.

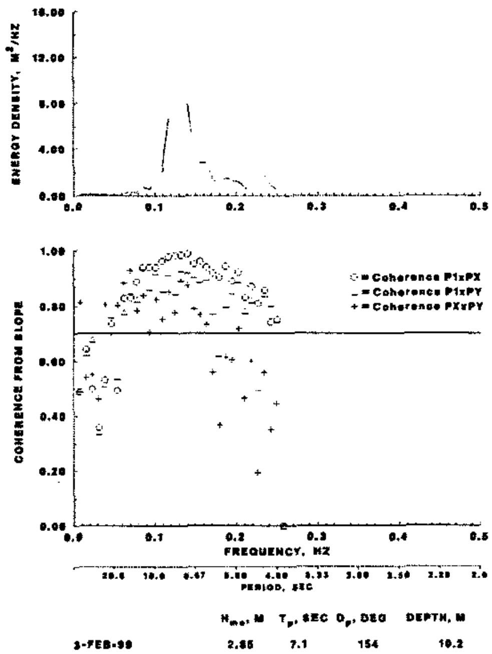

Fig. 5

THE *Coh* OF THE SAME TIME SERIES RECORD USED IN FIGURE 4 CALCULATED WITH SLOPES. COHERENCE IS HIGH,> 0.9 AT THE PEAK OF THE SPECTRUM, AND LOWER ELSEWHERE. THE LOWER COHERENCES IS RELATED TO THE NOISE AMPLIFICATION CAUSED BY COMPUTING THE SLOPES OVER THE RELATIVELY SHORT BASE-LINE OF 1.4M.

ure 8 is a one month graph of results from Platform Edith for April 1999. The upper graph shows energy at the peak of the spectrum, E_p and T_p. The lower plots show the coherence at the peak frequency, Coh_p. One can generally see that when T_p is between 5 and 10 seconds, Coh_p is high.

To place a measure on the relationship between Coh_p and directional stability of D_p, a 6-hr moving standard deviation of D_p (σ_{D_p}) and a 6-hr moving average of Coh_p ($\overline{Coh_p}$) were calculated. For figure 9, the top graph shows H_{m0} and T_p. The second graph displays D_p (*) and the σ_{D_p} (solid line). The lower two graphs show the $\overline{Coh_p}$ for $P \times U$ and $U \times V$. When the $\overline{Coh_p}$ is very high, $\overline{Coh_p} \approx 1.0$, for $U \times V$, σ_{D_p} is generally low. An exception occurs around April 6 when $T_p > 15$ seconds and $\overline{Coh_p}$ falls to around 0.8. Examination of this plot prompted us to plot the relationship between $\overline{Coh_p}$ and σ_{D_p}, figure 10. Figures 11 ,12, 13, and 14 show examples of the same analysis for the *PPP* gage at Westhampton, NY, the *PADV* gage at Grays Harbor, WA, the *PPP* gage at Morro Bay, CA, and the *PADV* gage at Pascagoula, MS. Ideally, we would want to see a small cluster of records in the upper left corner of these plots. This would suggest that high coherence is correlated with low directional variability. A negative slope of the cluster coincides with increased directional variance with decreased coherence. The plots differ from the ideal due to actual directional variability and noise within the systems. The *PEMCM* and PS_xS_y results approximate this ideal. The *PADV* results show substantial scatter. For these plots, σ_{D_p} greater than 10 degrees were omitted since these indicated there may be an actual large change in D_p.

Figure 15 summarizes figures 10 through 14. The distribution of $\overline{Coh_p}$ for $U \times V$ or $Sx \times Sy$ was calculated for 0.5 σ_{D_p} degree bins for each dataset. For these datasets, the *PEMCM* gage at Platform Edith had the highest overall average coher-

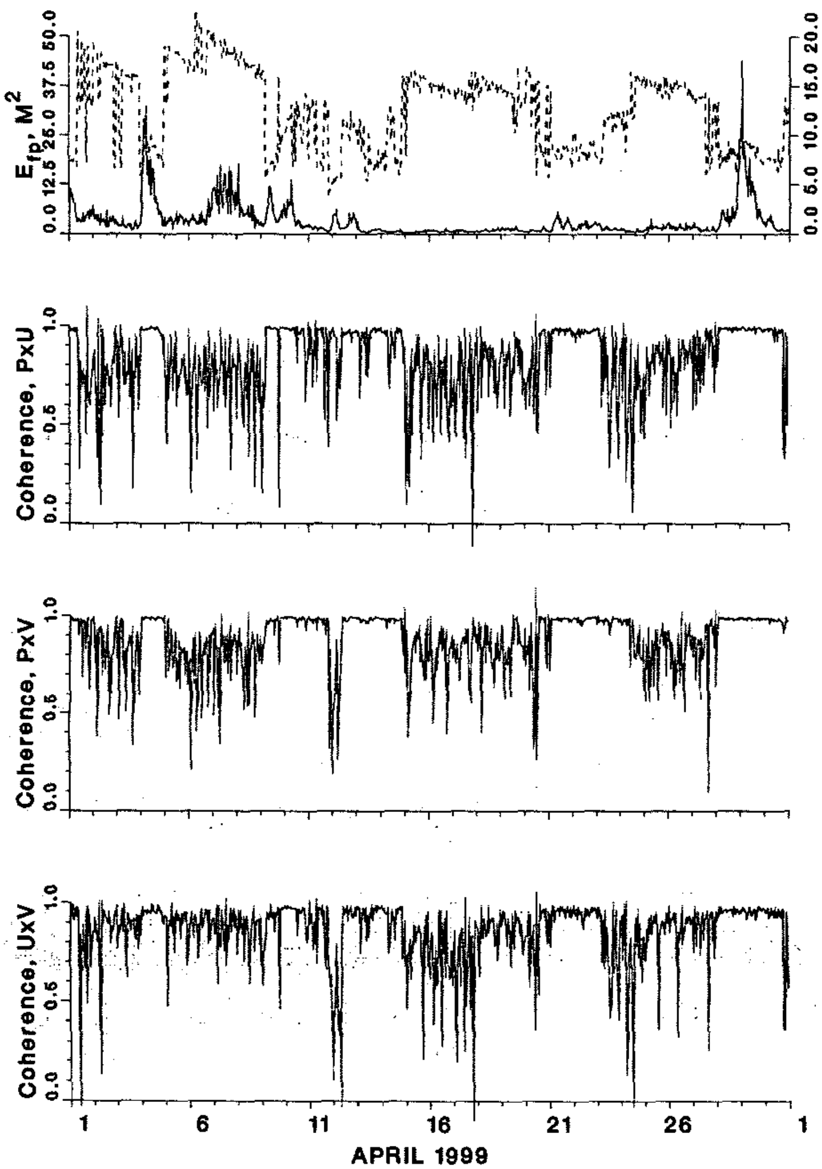

Fig. 8

A MONTH OF E_p, T_p, AND Coh_p FOR THE *PEMCM* GAGE AT PLATFORM EDITH, CA. NOTE THAT THE Coh_p IS GOOD FOR RECORDS WITH SUFFICIENT ENERGY AND PERIODS BETWEEN 5 AND 10 SECONDS.

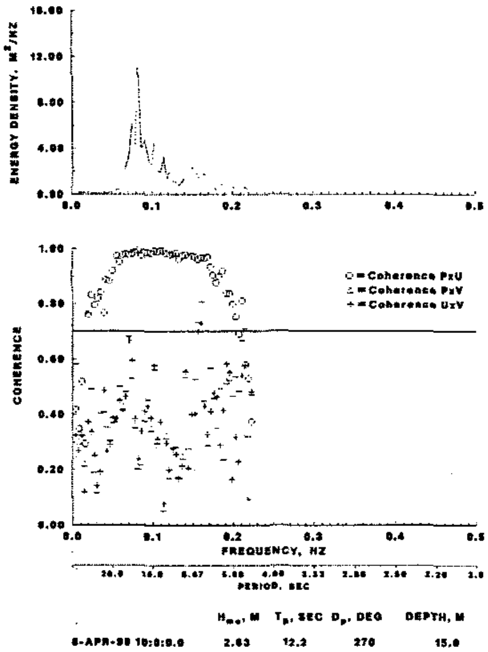

Fig. 6

ENERGY AND COHERENCE SPECTRA FOR A *PADV* GAGE RECORD FROM GRAYS HARBOR, WA. THE COHERENCE SPECTRUM FOR THE $P \times U$ IS NEAR 1.0, HOWEVER, THE $U \times V$ COHERENCE IS LESS THAN THAT OF RANDOM NOISE.

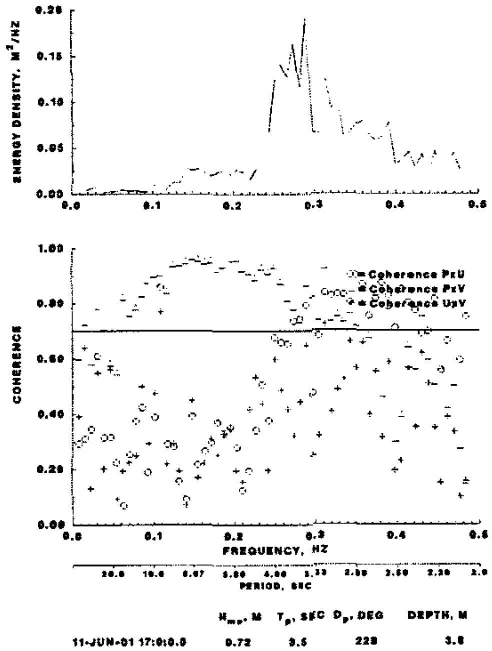

Fig. 7

ENERGY AND COHERENCE SPECTRA FOR A *PADV* GAGE RECORD FROM PASCAGOULA, MS. THE COHERENCE SPECTRUM FOR THE $P \times V$ IS NEAR 1.0, HOWEVER, THE $U \times V$ COHERENCE IS LESS THAN THAT OF RANDOM NOISE.

ence with low variability of D_p. Both *PPP* datasets, Morro Bay and Westhampton preformed slightly less well for $\sigma_{D_p} < 5$ degrees, but better for $\sigma_{D_p} > 5$ degrees. The *PADV* gages, Grays Harbor and Pascagoula underperformed the other two gage types in this analysis.

IV. Conclusion

We have computed coherence and wave direction from three types of directional wave systems, *PEMCM*, PS_xS_y, and *PADV*. We compared coherence and wave direction using simple, exploratory analyses. Our results provide preliminary answers to the questions posed in the introduction:

1) Generally the *PADV* data sets had less coherence than either the *PEMCM* or the PS_xS_y data sets.
2) For *PEMCM* and the PS_xS_y, coherence above 0.8 admits most records and provides low variance in directional estimates. For the *PADV*, coherence above 0.8 will exclude a substantial portion of the records for the data sets we used.
3) As expected, low coherence (< 0.8) is associated with higher variablility in directional wave estimates.

We recommend further examination of additional data from co-located directional sensor systems. Additional analytical and simulation error analysis would be useful in providing general guidance on coherence thresholds for quality control tests.

V. ACKNOWLEDGEMENTS

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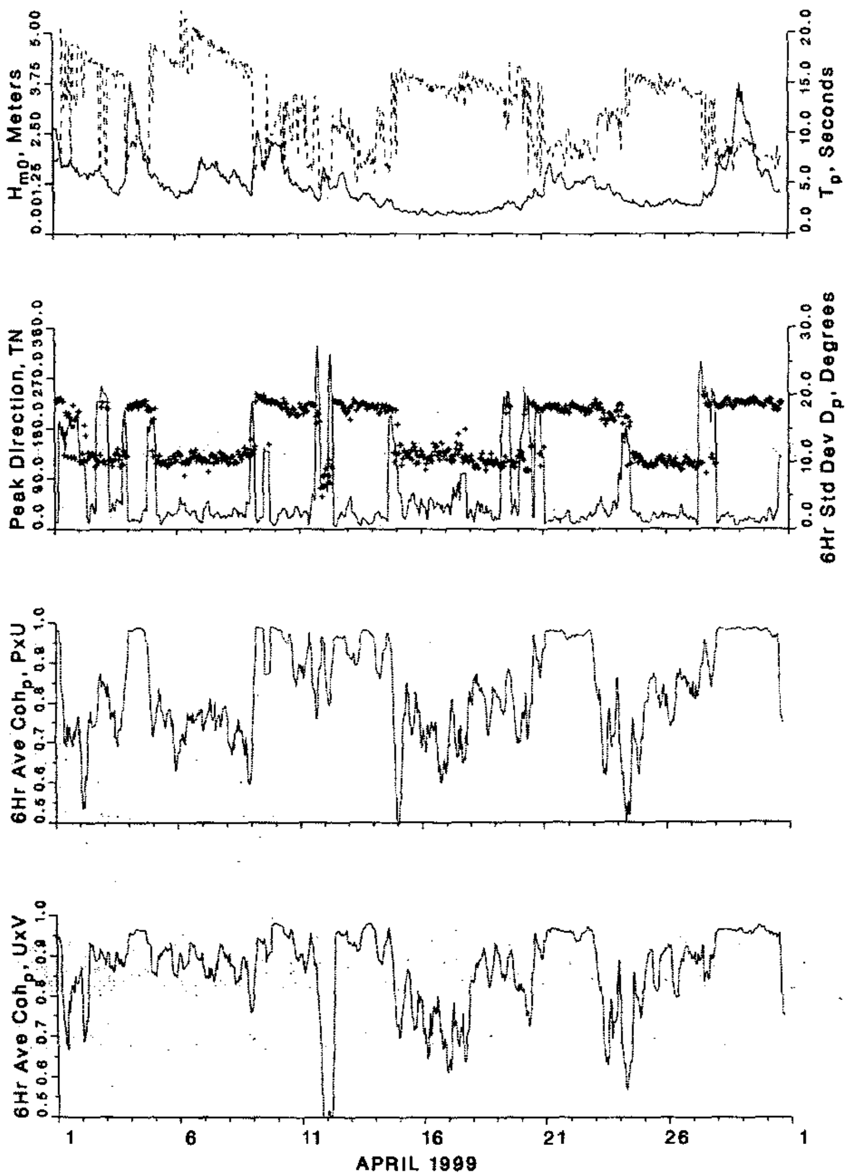

Fig. 9

MONTH PLOTS OF H_{m0}, T_p, AND D_p AS WELL AS MOVING 6 HOUR AVERAGES OF Coh_p ($\overline{Coh_p}$) AND THE STANDARD DEVIATION OF D_p (σ_{D_p}) FOR THE *PEMCM* GAGE AT PLATFORM EDITH. NOTE THAT σ_{D_p} IS LARGE WHENEVER THE DIRECTION CHANGED FROM $\approx$ 145 deg TO $\approx$ 235 deg. THE STANDARD DEVIATION OF D_p IS LOW WHEN THE $\overline{Coh_p}$ IS HIGH FOR $U \times V$ WHEN THE AND T_p IS BETWEEN 5 AND 10 SEC.

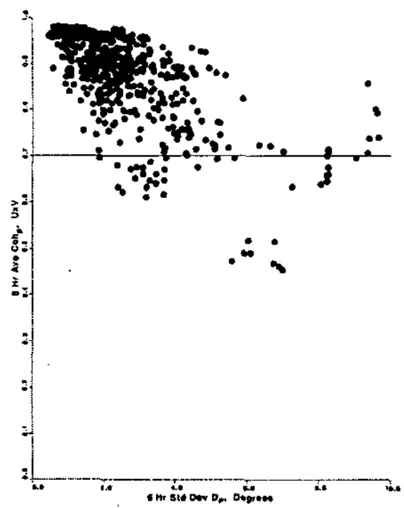

Fig. 10

$\overline{Coh_p}$ AND σ_{D_p} FOR THE *PEMCM* GAGE AT PLATFORM EDITH. WE CAN SEE THAT WHEN COHERENCE IS GENERALLY HIGH, > 0.8, THE DIRECTIONAL VARIABILITY IS SMALL, $\overline{D_p} < 4$ deg.

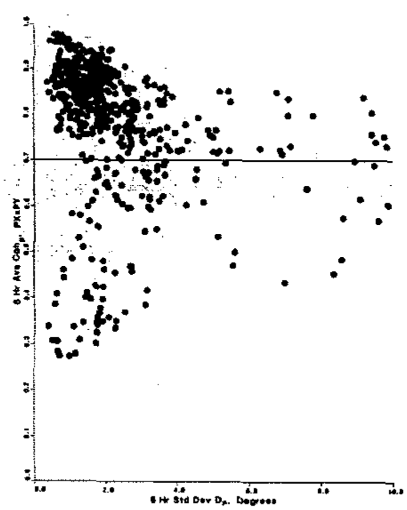

Fig. 11

$\overline{Coh_p}$ AND σ_{D_p} COMPUTED FROM THE S_x, S_y OF THE *PPP* GAGE AT WESTHAMPTON, NY. WHEN THE σ_{D_p} IS LOW, $\overline{Coh_p}$ IS ABOVE 0.7.

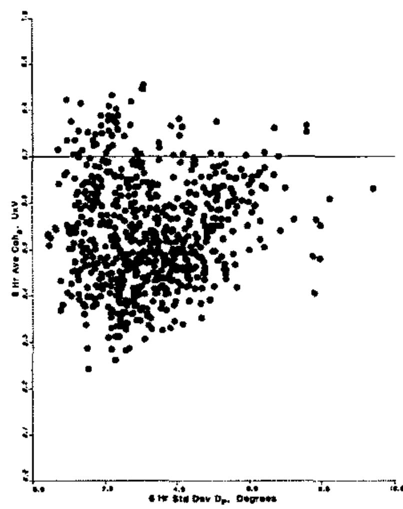

Fig. 12

$\overline{Coh_p}$ AND σ_{D_p} FOR THE *PADV* GAGE AT GRAYS HARBOR, WA. THE $\overline{Coh_p}$ ARE LOW AND DIRECTION VARIABILITY IS HIGH.

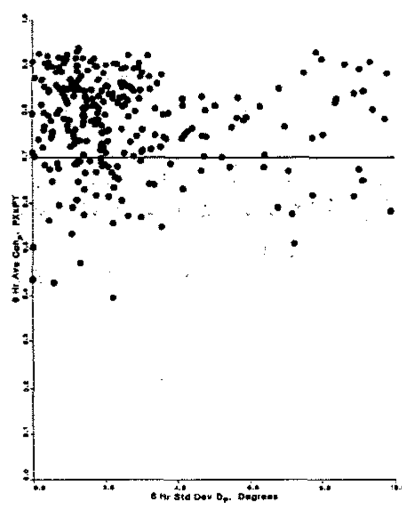

Fig. 13

$\overline{Coh_p}$ AND σ_{D_p} FOR THE *PPP* GAGE AT MORRO BAY, CA. THE σ_{D_p} IS MORE VARIABLE THAN PLATFORM EDITH, BUT HAS VERY LOW MINIMUM σ_{D_p} THAT CORRELATES WITH THE HIGH VALUES OF $\overline{Coh_p}$.

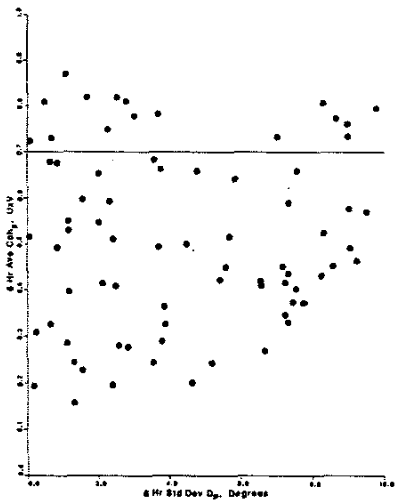

Fig. 14

$\overline{Coh_p}$ AND σ_{D_p} FOR THE *PADV* GAGE AT PASCAGOULA, MS. THE D_p FOR THIS DATASET IS HIGHLY VARIABLE AND CORRELATES WITH THE LOW VALUES OF $\overline{Coh_p}$.

REFERENCES

[1] G. L. Howell, "Shallow water directional wave gages using short baseline pressure arrays," *Coastal Engineering*, Vol. 35(1998) 85-102.

[2] J. P. McKinney, G. L. Howell, "A Data Acquistion and Analysis System for Coastal Ocean Measurements," *Oceans'96* MTS/IEEE Conference Proceedings, 23-26 September 1996, Fort Lauderdale, Fl, p. 560-564.

[3] Julius S. Bendat, Allan G. Piersol, *Random Data Analysis and Measurement Procedures : Second Edition (Revised and Expanded)*. John Wiley and Sons.

[4] P. D. Welch, "The Use of Fast Fourier Transform for the Estimation of Power Spectrum: A Method Based on Time Averaging Over Short, Modified Periodogams," *IEEE Transactions on Audio and Electroacoustics*, June 1967.

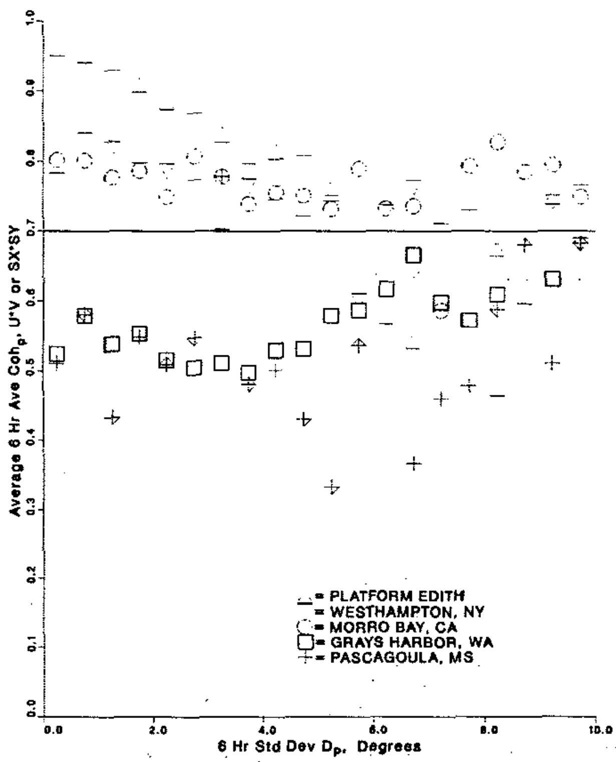

Fig. 15

THE $\overline{Coh_p}$ FOR $U \times V$ OR $Sx \times Sy$ WAS CALCULATED FOR $0.5\ \sigma_{D_p}$ DEGREE BINS. THE *PEMCM* GAGE AT PLATFORM EDITH HAD THE HIGHEST OVERALL $\overline{Coh_p}$ FOR LOW VARIABILITY OF σ_{D_p}. BOTH *PPP* DATASETS, MORRO BAY AND WESTHAMPTON PREFORMED SLIGHTLY LESS WELL FOR σ_{D_p} <5 DEGREES, BUT BETTER FOR $\sigma_{D_p} > 5$ DEGREES. THE *PADV* GAGES, GRAYS HARBOR AND PASCAGOULA UNDERPREFORMED THE OTHER TWO GAGE TYPES IN THIS ANALYSIS.