Comparison of Offshore Wave Measurements

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(Invited Paper)

Abstract—Preliminary results of a comparison between several wave measurement systems used during the Atlantic Remote Sensing Land Ocean Experiment (ARSLOE) are presented. Measurements in the offshore region 12–40 km offshore, taken during a storm that occurred October 23–26, 1980, are compared. Disagreement between significant waveheights resulting from the different measurement systems in some cases are larger than can be explained by random variability.

I. INTRODUCTION

ONE OF THE PURPOSES of the Atlantic Remote Sensing Land Ocean Experiment (ARSLOE) was to test and compare available wave measurement systems. The configuration of wave measurement systems covered a 30- X 40-km region off the coast of Duck, NC. The comparison presented here concentrates on measurements in the region 12-40 km offshore taken during a 4-day period from October 23-26, 1980, when a storm passed through the site area. The storm consisted of a complex frontal system which generated waves with a significant height of approximately 5 m [1].

Table I summarizes those measurement systems to be discussed. The locations of these systems are displayed in Fig. 1. The Cloverleaf Directional Buoy measured waves in various locations ranging from 12-40 km offshore while tethered to the research vessel *Cape Henlopen*. The locations for the Airborne Radar systems shown in Fig. 1 represent the approximate location of the center of the flight pattern. Most buoy measurements are either at 12 or 36 km offshore.

There are some difficulties and limitations when comparing different instrumentation *in situ*. It would be ideal to compare measurement systems so that any discrepancy found could be attributed only to the differences in the systems themselves and not to sampling variability. Since this is not possible even for two closely spaced *in situ* systems, consideration must be given to the effect of sampling variability. Additional variability should be expected between results from *in situ* instruments and from remote sensing instruments which measure over a finite area.

ARSLOE ALPHA, a study prior to ARSLOE, was conducted to provide a measurement of the sampling variability. Three Waveriders were deployed in a line parallel to shore at the 12-km site with the two outermost buoys positioned 1 km apart. All three instruments were standard Datawell Waverider buoys, calibrated as described by Ribe [2]. The moorings used were basically of Datawell design, modified by the Engineering Development Office of NOAA and de-
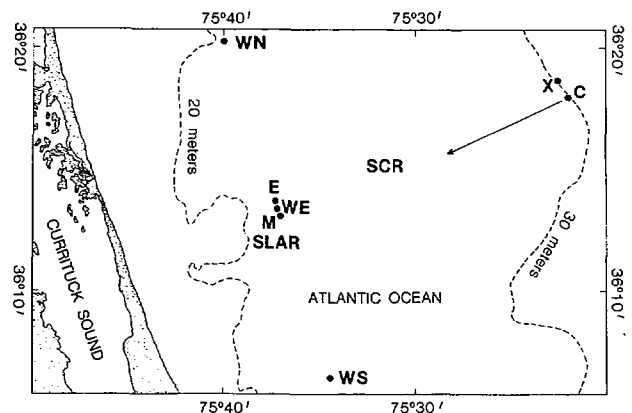
Fig. 1. Station locations: E–ENDECO Wavetrack Buoy, WE–Waverider East Buoy, WN–Waverider North Buoy, WS–Waverider South Buoy, M–Canadian "MET" Buoy, X–XERB Buoy, C–Cloverleaf Buoy, SCR–Surface Contouring Radar, SLAR–Side Looking Airborne Radar; ●–indicates a buoy system.

scribed in Kahn [3]. The buoy at the central location malfunctioned shortly after deployment, thus none of its measurements are considered in this work. This buoy was later replaced with another Datawell system which operated during ARSLOE. Fifty seven pairs of concurrent measurements were collected from the outermost buoys. Data were processed and analyzed with the same software package.

Estimates of the same variable obtained from adequately spaced, different, though equivalent systems are expected to belong to the same population. Thus the combined set of estimates from the two systems should be randomly distributed, with approximately half the estimates from one system being higher than the estimates from the other. To test whether this randomness was exhibited by estimates of significant waveheight (H_s) values from the two outermost buoys, the ratios of pairs of their simultaneous H_s estimates were examined. As shown in Fig. 2(a) and Table II, the ratio values were equally distributed about one. Thus, it is accepted that although 1 km apart, both buoy systems are sampling the same population.

It was determined that the two systems yield the same results for H_s by two methods: the comparison of confidence intervals and the F Test. First, the significant waveheights were compared at the 90-percent confidence interval for each buoy. In this case, 81 percent of concurrent pairs of samples from the same population should be expected to fall within each other's confidence interval. For the data set, 80.7 percent (46 pairs) passed this test. Secondly, the assumption was tested under the hypothesis that corresponding pairs of H_s measurements are equal using the F distribution. The hypothe-

TABLE I
WAVE MEASUREMENTS SYSTEMS COMPARED

Measurement System	Wave Sensor Type	Location From Shore (km)	Water Depth (m)MLW	Analysis Organization	Parameters Compared			Number of Observations
					Significant Wave Height	Frequency of the Spectral Peak	Mean Wave Direction	
Waverider East	heave	12	25	NOAA/NOS	x	x		83
Waverider North	heave	12*	22	NOAA/NOS	x			83
Waverider South	heave	12**	25	NOAA/NOS	x			83
ENDECO Wavetrack	pitch, roll, heave	12	25	Univ. of Rhode Is.	x	x	x	32
XERB	pitch, roll, heave	36	30	NOAA/Data Buoy Office	x	x	x	85
Cloverleaf	pitch, roll, heave	10-40	20-30	Kyushu Univ.	x	x	x	26
Met Buoy	pitch, roll, heave	12	25	Canadian Centre for Inland Waters	x	x	x	2
Side Looking Airborne Radar System (SLAR)	Airborne Radar	12	25	NOAA/Atlantic Oceanographic and Meteorological Lab.			x	3
Surface Contouring Radar (SCR)	Airborne Radar	20	27	NASA, Wallops Flight Center	x	x	x	1

* Located 15 km North of Waverider East
** Located 15 km South of Waverider East

sis could be accepted at the 90-percent confidence level (Table II); that is, about 10 percent of the H_s ratio values failed the F test at the 90-percent level. It is concluded from these tests, which confirm each other, that the two buoys were measuring the same results for H_s and disagreements in resulting measurements from the two Waveriders may be attributed only to sampling variability.

II. METHOD OF ANALYSIS

Since participants were responsible for the processing and analyses of their data, the methods described in this section pertain only to Waveriders which were analyzed by the authors. For details on the analysis of other measurement systems, the respective participants should be contacted. Some of the participants are presenting their findings in this issue. The names of those contributing their data for this comparison can be found in the acknowledgment.

The Waverider signal was sampled at a 4-Hz rate. The time series was separated into sections of 4096 data points representing a 1024-s duration, and a fast Fourier transform (FFT) algorithm was used to compute spectra from each section. To reduce side lobe leakage in the spectral estimates the Tukey or cosine bell window

$$w(N\Delta t) = 1/2 \left[1 - \cos(2\pi n/N) \right]$$

was applied before the Cooley-Tukey FFT method for computing the complex Fourier series

$$A_j = t \sum_{n=0}^{N-1} A_k \exp(2\pi ijk/N)$$

was used. The spectral estimates were then corrected for variance loss due to the window by forcing the variance under the estimated spectrum to equal the variance computed from

the time series before application of the window. Calibration corrections which are frequency dependent, were applied after correcting for the window effect. The applied corrections did not include temperature effects on Waverider sensitivity. This omission introduced an amplitude error not greater than 1 percent for the temperatures observed during the storm [2].

The spectral estimates were band-averaged over 11 adjacent frequencies resulting in spectral estimates with frequency resolution of 0.011 Hz and 22 degrees of freedom.

Assuming a narrow-band spectrum, the significant waveheight was calculated from

$$H_s = 4\sqrt{m_0}$$

where m_0 = area under the wave spectrum [4].

The 90-percent confidence limits for the true significant waveheight H_s' were found by

$$\left(\frac{\nu_T}{\chi_{\nu_T;\frac{100-\alpha}{2}}^2} \right)^{1/2} H_s \leq H_s' \leq H_s \left(\frac{\nu_T}{\chi_{\nu_T;\frac{100+\alpha}{2}}^2} \right)^{1/2}$$

where H_s is the estimated significant waveheight, χ^2 values are obtained from a chi-square distribution, and ν_T are the total degrees of freedom from

$$\nu_T = \frac{2\left(\sum_n E_n \right)^2}{\sum_n E_n^2}$$

where E_n is wave variance at the nth Fourier frequency and the summations are overall Fourier frequencies.
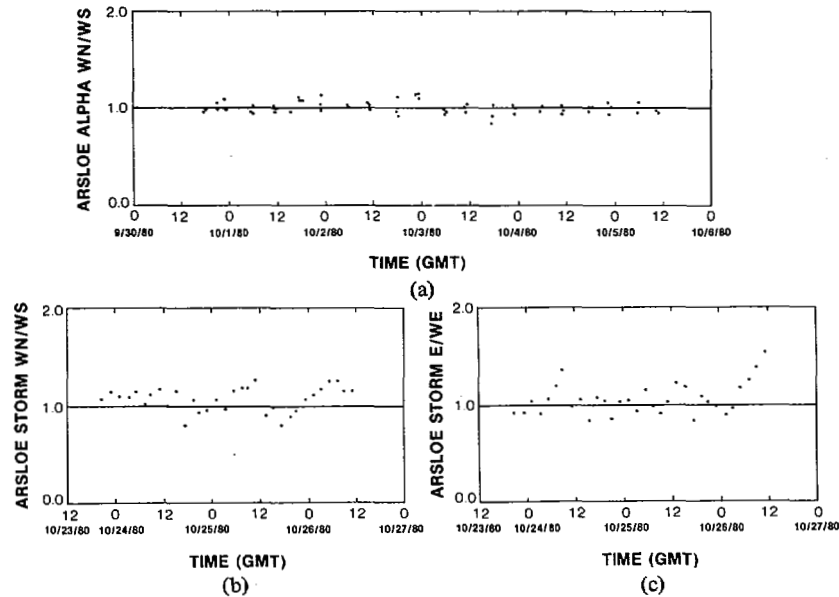
Fig. 2.   Ratios of simultaneous H_s values from buoy pairs: (a) ARSLOE ALPHA for the two outermost Waveriders (WN/WS) during ARSLOE ALPHA; (b) for Waveriders North and South (WN/WS), and (c) for the ENDECO and Waverider East (E/WE), during the ARSLOE storm.

TABLE II
RESULTS OF TESTS BETWEEN SIGNIFICANT WAVEHEIGHTS
(H_s)

Buoy Pair	Number of Comparisons	Percent Failure of F-Test at 90% Level	Bias (Mean Ratio of Occurrence of the Higher H_s)
ARSLOE ALPHA WN/WS	57	9	1:0.97
ARSLOE STORM WN/WS	32	47	1:0.39
ARSLOE STORM E/WE	32	44	1:0.62

TABLE III
COMPARISON OF SIGNIFICANT WAVEHEIGHTS MEASURED
BY THE WAVERIDER LAST BUOY WITH OTHER SYSTEMS
AT THE 12-km SITE

Measurement System	Number of Comparisons	Number Within Waverider 90% Confidence Limits	Percentage Within Waverider 90% Confidence Limits
ENDECO*	20	13	65
ENDECO**	12	4	33
ENDECO***	32	17	53
Cloverleaf	8	1	12
Met	2	2	--

*   Only those measurements taken before frontal passage on October 25, 1980
**   Only those measurements taken after frontal passage on October 25, 1980
*** For all measurements

III. RESULTS

Fig. 3 displays the time history of the suite of wave parameters: significant waveheight, frequency of the spectral peak, and mean wave direction of the spectral peak. When interpreting these plots, the locations of the different measurement systems must be taken into account. In Fig. 3, the notation "1" located above the symbol for the Cloverleaf data represents those data recorded within 1 km of the 12-km site. The "2" above the symbol represents those data recorded within 3 km of the 36-km site. All other Cloverleaf data shown were taken between these locations.

A. Significant Waveheight

Significant waveheights from several measurement systems are plotted in Fig. 3. Of the *in situ* systems clustered at the center of the 12-km site, only the Waverider East (WE) and the ENDECO (E) (Fig. 1) collected a suitably long set (32) of simultaneous observations during the storm for a meaningful comparison. Separation between these two buoys was approximately 150 m.

Table II summarizes results of different tests performed on pairs of simultaneous H_s values. The table includes results of the tests using the ARSLOE ALPHA data already discussed in the Introduction. Also included in Table II are results of comparisons involving the Waveriders 15 km North (WN) and South (WS) of the Waverider East buoy. These Waveriders were the same ones previously located 1 km apart during the ARSLOE ALPHA. Observations were available from these Waveriders for the same times as for the E/WE pair. Fig. 2(b) and Table II show that H_s values from the Waverider North buoy during the storm period have a tendency to be higher than those from the Waverider South buoy. This bias is interpreted as being due to differences in the actual H_s at the two locations since the same two instruments showed no bias during the ARSLOE ALPHA experiment.

Fig. 2(c) shows the ENDECO buoy tends to give H_s values higher than the Waverider East buoy. It would be expected that these two buoys, being only 150 m apart would be sampling the same population; thus this bias is attributed to differences in the total buoy sytems. As seen in Table
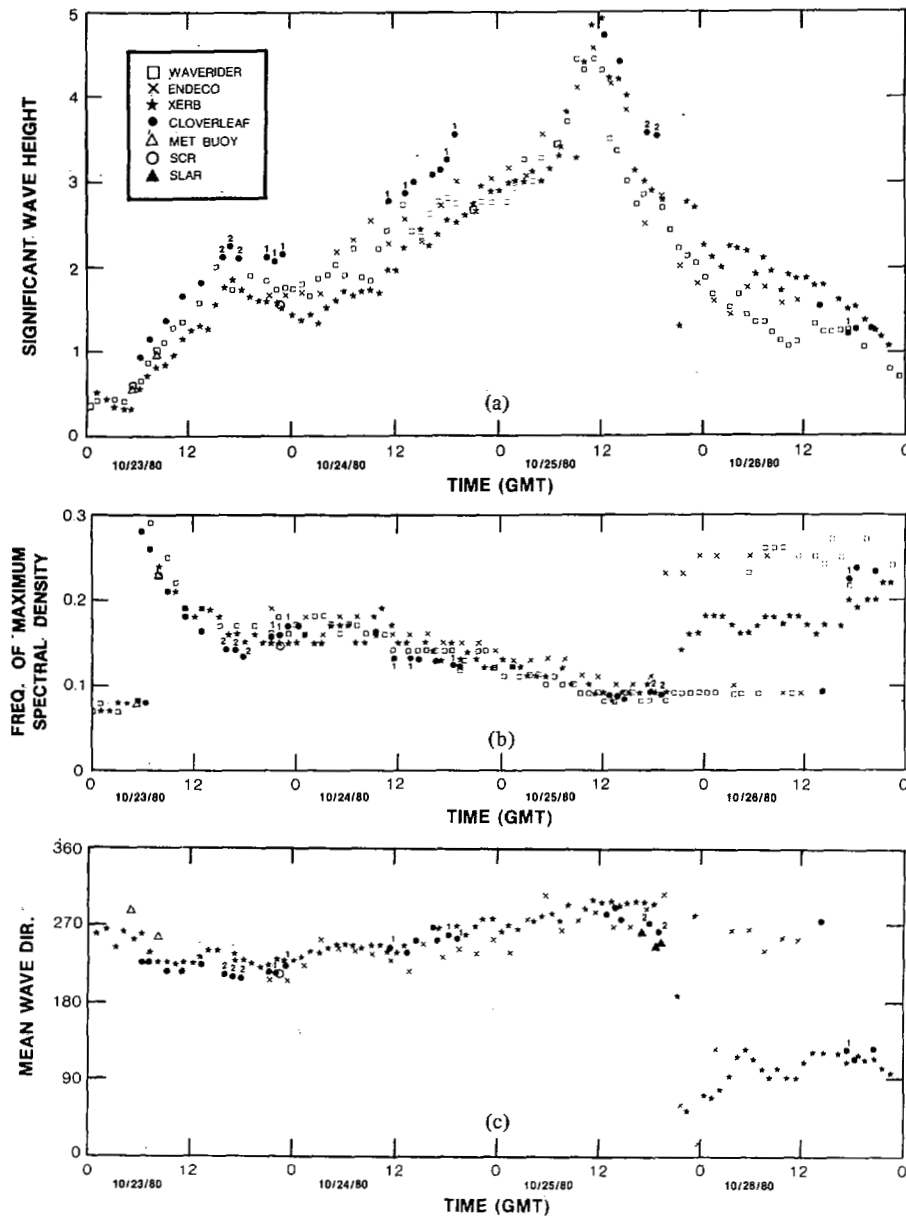
Fig. 3. Wave parameters: (a) Significant waveheight, (b) Frequency
of maximum spectral density, (c) Mean wave direction for the fre-
quency of maximum density.

II, the E/WE pair showed failure of the F test at a level com-
parable to that of the WN/WS pair. According to the Binomial
Distribution, the probability of that level of failure for the
E/WE pair being a chance occurence is 0.0000008. Thus it is
concluded that the Waverider and ENDECO buoys yield dif-
ferent results for significant waveheight.

As shown in Fig. 3(a) and summarized in Table III, the sig-
nificant waveheights measured by the Waverider East and
ENDECO buoys had better agreement before passage of the
front, midday (GMT) on October 25. Then ENDECO and
Waverider East agreed within the Waverider 90-percent con-
fidence limits, 65 percent of the time. After the passage of
the front, the agreement decreased to 33 percent.

It was not possible to identify the causes(s) of the dis-
crepancies in significant waveheights between the ENDECO
and Waverider East from comparison of the nondirectional

spectra. However, the comparison did reveal some basic
discrepancies between the spectra. The examples in Fig. 4
represent spectra normalized by their respective total spectral
density. For this comparison, the spectral estimates for the
Waverider were averaged by a moving window over 50 fre-
quency bands to approximate the resolution of the available
spectra from the ENDECO. It was found that spectral peaks
from the ENDECO data were generally broader at the lower
frequencies than those from the Waverider data. A possible
cause for this could be the different type of window applied.
It was also found that the high-frequency end of the Wave-
rider spectra did not trail off as quickly as for the ENDECO
spectra. The dotted curves in Fig. 5 are the Kitaigorodskii
et al. theoretical curve for the equilibrium range computed
using a representative water depth at the 12-km site and
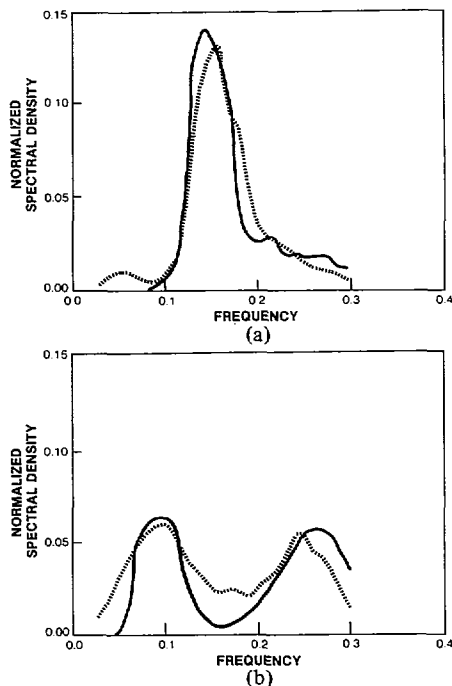normalized relative to the total spectral density in the corre-

Fig. 4.   Spectral density for Waverider East (——) and ENDECO (---);
(a) 24 h before the frontal passage midday October 25, 1980, (b)
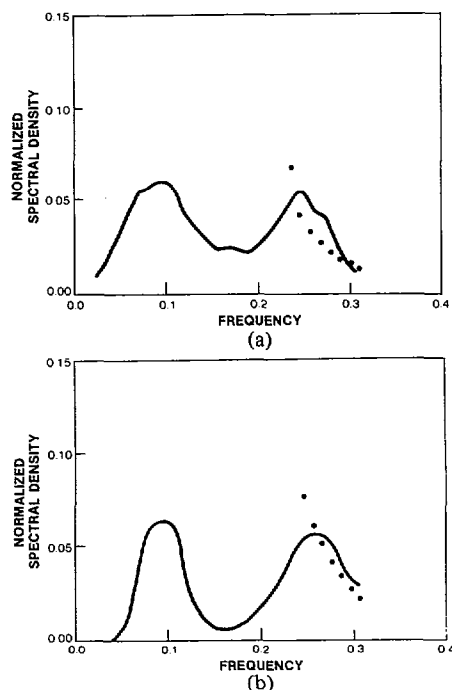21 h after frontal passage.

Fig. 5.   Comparison of normalized spectra in Fig. 4 with identically
normalized limiting depth related equilibrium spectrum according
to Kitaigorodskii *et al.*; (a) for ENDECO; (b) for Waverider East.

sponding spectrum. It can be seen that the Waverider East data
fit the theoretical curve better than the ENDECO [5]. A pos-
sible reason for this may be the differences in buoy response.

The comparison between the Canadian "MET" buoy
and the Waverider East is limited to two measurement periods
early on October 23. Although these data are insufficient
to draw conclusions, Table III shows that the significant
waveheights measured by the "MET" buoy were within the
90-percent confidence limits of the Waverider.

The significant waveheights measured by the Cloverleaf
buoy were found to be consistently higher than those meas-
ured by nearby systems. When compared with the values
measured at the 12-km site by the Waverider East buoy,
the Cloverleaf data averaged 15 percent higher. There was
one measurement at 17:15 GMT on October 26, when the
Cloverleaf measurement was within the Waverider 90-per-
cent confidence limits. The Cloverleaf buoy measurements
taken near the 36-km site averaged 20 percent higher than
those taken by the XERB buoy.

The Surface Contouring Radar (SCR) was flown over the
experiment area at 22:20 GMT on October 23. The Wave-
rider which was deployed 20-km offshore at the center of the
SCR pattern malfunctioned and thereby limited the ground
truth data to those data measured at the 12- and 36-km
sites. The significant waveheight of 1.55 m measured by SCR
had better agreement with that measured by XERB (1.58 m)
at 36 km offshore than with the Waverider East (1.73 m)
at 12 km offshore. This might be expected since the bottom
slope was greater between the 12- and 20-km site than be-
tween the 20- and 36-km site.

B. Frequency of Spectral Peak

The central frequencies of the bands with maximum spec-
tral density for the different measurements systems are plotted
in Fig. 3(b). After the fronts passed through the site on
October 25, nearly opposing waves developed. The spectral
densities associated with the existing old sea (swell) and with
the newly developed sea were at times approximately equal.
This led to the bifurcation shown in Fig. 3(b). Table III sum-
marizes comparison of the frequencies of maximum density
for single-peak spectra. As shown in Fig. 3(b), the Waverider
East measured the spectral maximum at a lower frequency
than the ENDECO. Although this difference is a consistent
shift in the spectra, 83 percent of the time it was within the
ENDECO frequency resolution of ±0.025 Hz.

Of the two pairs of spectra from the "Met" and Wave-
rider East buoys available for comparison, one was unimodal
and the other bimodal. The central frequencies of the spectral
maxima agreed for both cases.

The frequencies of the spectral maxima for the Cloverleaf
spectra were generally in agreement with those of spectra
from nearby buoys. When compared with the Waverider
East during both swell and sea, the distribution indicated
no bias, and agreement between these frequencies within their
frequency resolution occured 71 percent of the time. When
compared with XERB, agreement was found 80 percent of the
time. The frequency of the spectral maxima for the XERB
spectra were biased higher than the Cloverleaf spectra by an
average of 0.014 Hz.

When comparing the frequencies of waves resulting from
buoy measurements to those obtained from a remote sensor
such as the SCR, it is important to keep in mind that remote
sensors measure in wavenumber space and then the frequency
is computed using linear wave theory. Despite this, the fre-
quencies of maximum spectral density obtained from the
October 23 SCR flight were similar to those from the buoys
in the area. From the SCR measurements, the frequency of
the spectral peak at 22:20 GMT was calculated to be 0.147

TABLE IV
COMPARISON OF FREQUENCY OF MAXIMUM DENSITY FOR SINGLE-PEAK SPECTRA

Measurement System System A/System B	Number of Comparison	Number Within Frequency Resolution*	Percent Within Frequency Resolution*	Frequency Resolution (hertz) Sys A/Sys B
E/WE	23	19	83	.011/.025
WE/Met	2	2	--	.011/.010
WE/SCR	1	1	--	.011/**
WE/Cloverleaf	7	5	71	.011/.007
XERB/Cloverleaf	5	4	80	.010/.007
XERB/SCR	1	1	--	.010/**

* Resolution used was the larger value of System A or B
** SCR resolution of data in wave number space

Hz. During this period, the Waverider spectra indicated the spectral peak at 0.145 Hz, the XERB at 0.149 Hz.

C. Mean Wave Direction of the Spectral Peak

The mean wave directions for the frequency of the spectral peaks are summarized in Fig. 3(c) for those systems providing wave direction. Wave directions are referenced to True North and indicate the direction towards which waves propagate. The comparison of wave direction pertains only to mean wave direction. The mean wave direction $\bar{\phi}(f)$ for each frequency band was computed for the directional wave buoy systems from

$$\bar{\phi}(f) = \tan^{-1} [b_1(f)/a_1(f)]$$

where a_1 and b_1 are the Fourier coefficients from the weighted Fourier expansion

$$F(f, \phi) = 1/2a_0 + c_1[a_1 \cos (\phi) + b_1 \sin (\phi)]$$
$$+ c_2[a_2 \cos (2\phi) + b_2 \sin (2\phi)]$$

of Longuet-Higgins et al [6].

Comparisons of mean wave directional results from in situ systems are made only when the systems were close. As shown in Table V, mean wave directions from the Cloverleaf and ENDECO buoys agreed within 5 to 20°. The wave direction measured by the Cloverleaf buoy was slightly more northerly than indicated by the ENDECO buoy. Similar agreement was shown between the Cloverleaf and the XERB buoys. Difference in their mean wave direction ranged between 1 and 24°. The Cloverleaf buoy indicated a more southerly direction than the XERB.

Data from the SLAR overflight near the 12-km site on October 25 did not coincide with the available ENDECO data. The nearest measurements were about an hour apart. The ENDECO buoy, as shown in Fig. 3(c), indicates a more northerly direction than the SLAR.

Surface Contouring Radar measurements taken in the region 20 km offshore on October 23 agreed with those measured at the 12-km site by the Cloverleaf buoy. The SCR measured the wave direction to be 210°, while the Cloverleaf measured the direction at 212°. At the same time, the XERB at 36 km offshore measured the wave direction at 226°.

When the Canadian "MET" buoy recorded measurements on October 23, there was no other wave-direction data available at the 12-km site. The only other system measuring wave direction at this time was XERB, some 24 km further off-

TABLE V
COMPARISON OF MEAN WAVE DIRECTIONS MEASURED BY THE CLOVERLEAF BUOY WITH OTHER DIRECTIONAL BUOYS

Measurement System	Number of Comparisons	Differences in Degrees Range	Differences in Degrees Average
ENDECO	4	4-20	14N
XERB	5	1-24	16S

N - Cloverleaf data were more northerly
S - Cloverleaf data were more southerly

shore. The "MET" data during this time show the wave direction to be 30° more northerly than that measured by XERB.

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