INTERCOMPARISON OF THE OFFSHORE WAVE MEASUREMENTS DURING ARSLOE

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ABSTRACT

Preliminary results of an intercomparison between several wave measurement systems used during the ARSLOE experiment are presented. The comparison consists of some of the measurements in the offshore region, 12 km to 40 km offshore, taken during a storm that occurred October 23 to 26, 1980. The results indicate that differences in significant wave heights can be larger than the random variability.

DISCLAIMER

1. Introduction

During the fall of 1980, the Coastal Engineering Research Center of the U.S. Army Corps of Engineers and the Coastal Waves Program (CWP) of the National Ocean Survey, National Oceanic and Atmospheric Administration jointly hosted the Atlantic Remote Sensing Land-Ocean Experiment (ARSLOE). Participation in the experiment was broad with investigators from Government agencies, foreign countries, industry, and academic institutions using various surface, subsurface, and remote sensing wave measurement systems. One of the purposes of the experiment was to test and compare available wave measurement systems.

ARSLOE included a configuration of wave measurement systems that covered a 40 km x 40 km region off the coast of Duck, North Carolina. This intercomparison concentrates on some of the measurements in the offshore region taken during a 4-day period from October 23 to 26, 1980, when a major storm passed through the site area. The storm was of interest since it consisted of a complex frontal system which resulted in opposing seas.

Table 1 summarizes those systems to be discussed. The location of these systems are displayed in Figure 1. The Cloverleaf Directional Buoy measured waves in various locations ranging from 12 to 40 km offshore while tethered to the Research Vessel CAPE HENLOPEN. The locations for the Airborne Radar systems shown in Figure 1 represent the approximate location of the center for the flight paths. 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 have the measurement systems identically located so any difference found could be related only to the measurement systems. Since this is not possible, allowance must be made for differences due to natural variability between deployment locations. Similarly, differences should be expected when comparing a buoy that measures at a point location with a radar system which measures over some finite area. There are other differences due to the dynamics of different moorings, varying sample lengths, and varying analysis methods, such as the window used when computing spectra. Therefore, when interpreting the results, it is important to consider these limitations.

ARSLOE ALPHA, a study prior to ARSLOE, was conducted to provide a measurement of the natural site variability. Three Waveriders were deployed in a line parallel to shore at the 12 km site with the 2 outermost ones positioned 1 km apart. All three instruments were calibrated, used identical mooring configurations, and the data were processed and analyzed with the same software routines. This was done in hope that any differences would be limited to natural variability. It was found, based on 57 pairs of observations, that the significant heights measured by the two outermost Waveriders agreed within their 90 percent confidence limits 80 percent of the time. Although this may vary somewhat under different wave conditions, the comparison of two different types of measurement systems would not be expected to agree any better.

2. Method of Analysis

Since each participant was responsible for his/her processing and analysis, the methods described in this section pertain mainly to Waveriders which were analyzed by the CWP. For details on the analysis of other measurement systems, the respective participant should be contacted. Most of the participants are presenting their findings during these ARSLOE
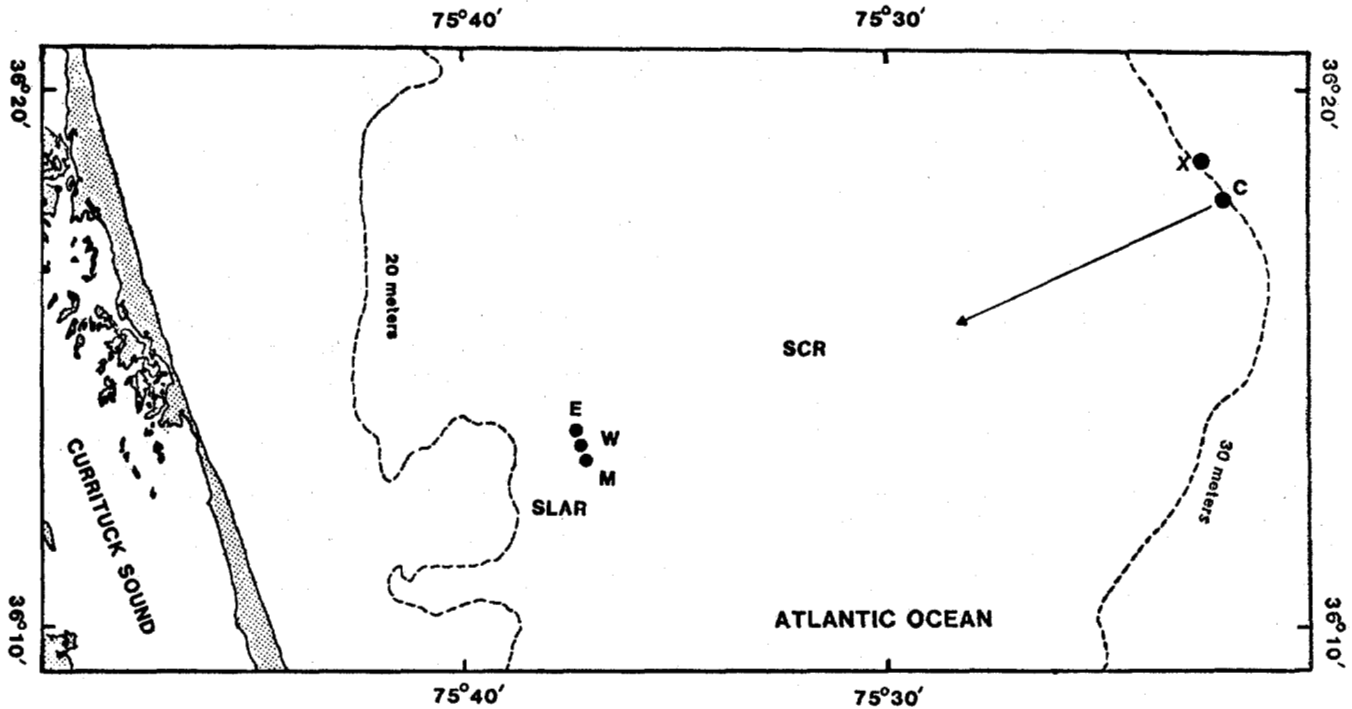
Figure 1. Station locations: E - ENDECO Wavetrack Buoy, W - Waverider Buoy, M - Canadian "MET" Buoy, X - XERB Buoy, C - Cloverleaf Buoy, SCR - Surface Contouring Radar, SLAR - Side looking Airborne Radar; ●indicates a buoy system.

Table 1. 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	heave	12	25	NOAA/NOS	x	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

sessions at Oceans 82. The names of those contributing their data for this intercomparison can be found in the acknowledgements.

The Waverider signal was sampled at a 4 Hz rate. The time series were separated into lengths of 4096 data points representing 1024 seconds so that a FAST Fourier Transform (FFT) algorithm could be used. 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

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

was used. The spectral estimates were then corrected for variance loss due to the window by applying a ratio of the variance of the spectra and the variance of the original time series before the window. Calibration corrections, which are frequency-dependent, were applied after the variance correction. The applied corrections did not include temperature effects on Waverider sensitivity. This introduced an amplitude error of about 1 percent for the temperatures observed during the storm [1].

The spectral estimates were band-averaged over 11 frequencies resulting in spectral estimates with frequency resolution of 0.011 Hz and 22 degrees of freedom. Variability of the spectral peak is dependent upon frequency resolution and degrees of freedom.

Assuming a narrow band spectrum, the significant wave height was calculated by,

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

where, m_0 = area under the wave spectrum [2].

The α percent confidence limits for the true significant wave height, H_s', were found by:

$$\left(\frac{\nu}{X_{\nu; \frac{100-\alpha}{2}}} \right)^{1/2} H_s \leqq H_s' < H_s \left(\frac{\nu}{X_{\nu; \frac{100+\alpha}{2}}} \right)^{1/2}$$

where H_s is estimated significant wave height, x^2 values are obtained from a chi-square distribution, and ν the total degrees of freedom is given by:

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

where E_n is wave variance at the nth Fourier frequency and the summations are over all Fourier frequencies.

The comparison of wave direction pertain only to mean wave direction. The mean wave direction $\overline{\emptyset}$ (f) for each frequency band can be computed for the directional wave buoy systems from

$$\overline{\emptyset} (f) = \tan^{-1} \left[b_1(f)/a_1(f) \right]$$

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

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

of Longuet-Higgins et al. [3].

3. Results

Figure 2 displays the time history of the suite of wave parameters: significant wave height, frequency of the spectral peak, and mean wave direction of the spectral peak. When interpreting these plots, one must be careful to compare only those stations at the same site. In Figure 2, 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 were taken between these locations.

3.1 Significant Wave Height

Significant wave heights from the measurement systems are plotted in Figure 2a. As shown in this figure and summarized in Table 2, the significant wave heights measured by the Waverider and ENDECO buoys had better agreement before passage of the front, mid-day (GMT) on October 25. Then ENDECO and Waverider agreed within the Waverider 90 percent confidence limits, 65 percent of the time. After the passage of the front, this decreased to 33 percent.

The nondirectional spectra were compared in hope of resolving this difference in significant wave height. It was not possible to differentiate the source of these differences between the ENDECO and Waverider. However, the analysis did distinguish some basic characteristics between the spectra. The examples in Figure 3 represent the spectra normalized by the total spectral density. For this comparison, the spectral estimates for the Waverider were averaged by a moving window over 50 frequency bands to have the same resolution as the ENDECO. It was found that spectral peaks for the ENDECO data were generally broader at the lower frequencies than those for the Waverider. A possible cause for this could have been the different type of window applied. It was also found that the high frequency end of the Waverider spectra did not trail off as quickly as for the ENDECO spectra. A possible reason for this may be the differences in buoy response which were not adequately removed by calibration corrections.

The comparison between the Canadian "MET" buoy and the Waverider is limited to two measurement periods early on October 23. Although these data are insufficient to draw conclusions, Table
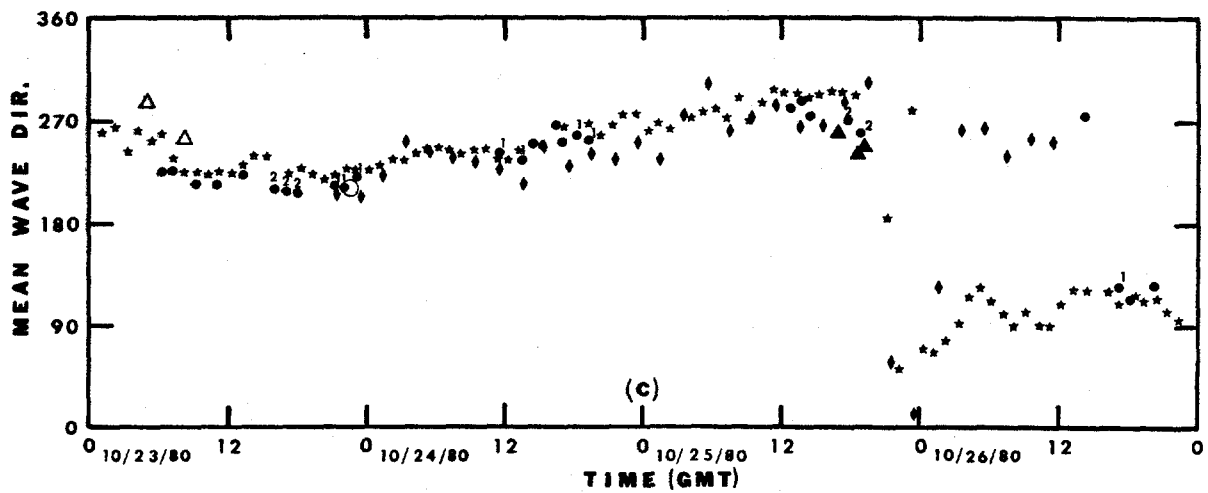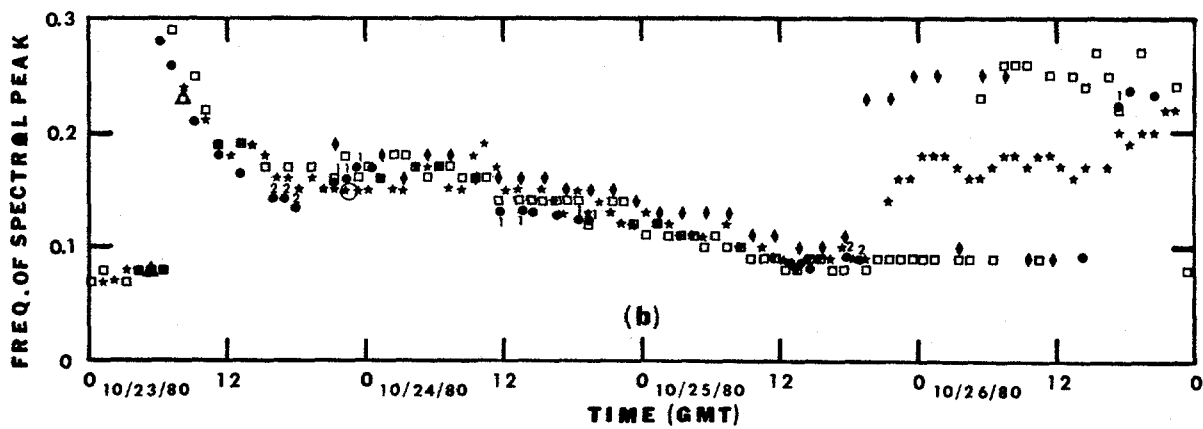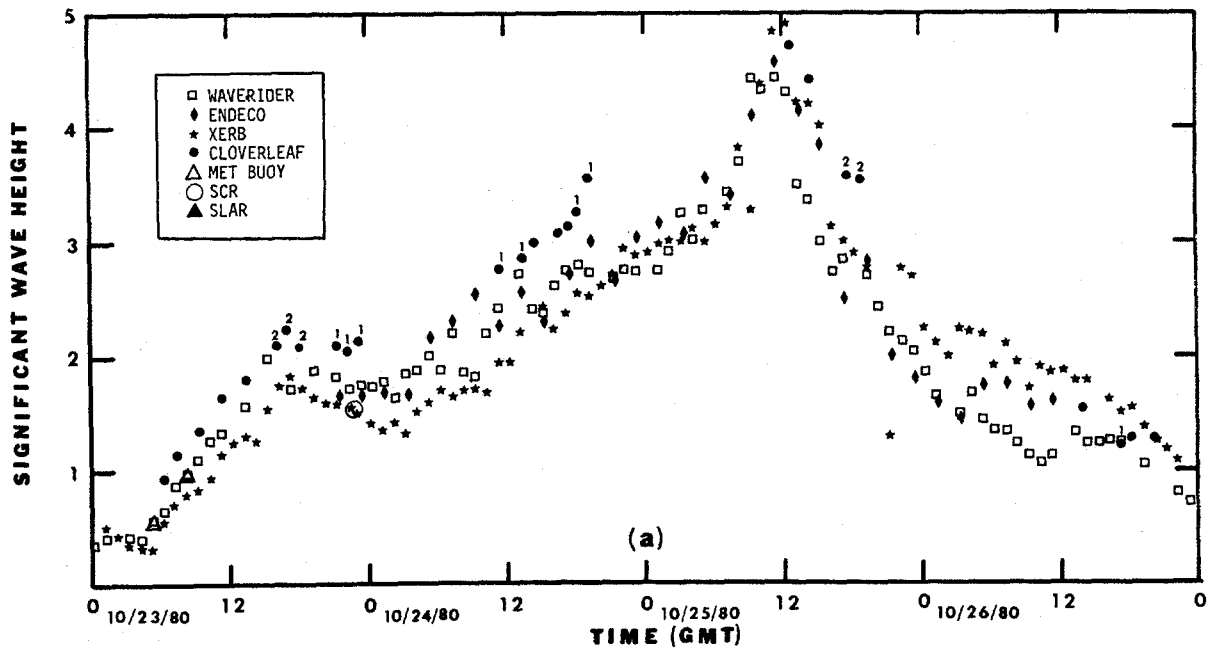
Figure 2.   Wave Parameters: (a) Significant Wave Height, (b) Frequency of the Spectral Peak, (c) Mean Wave Direction for the Frequency of the Spectral Peak.
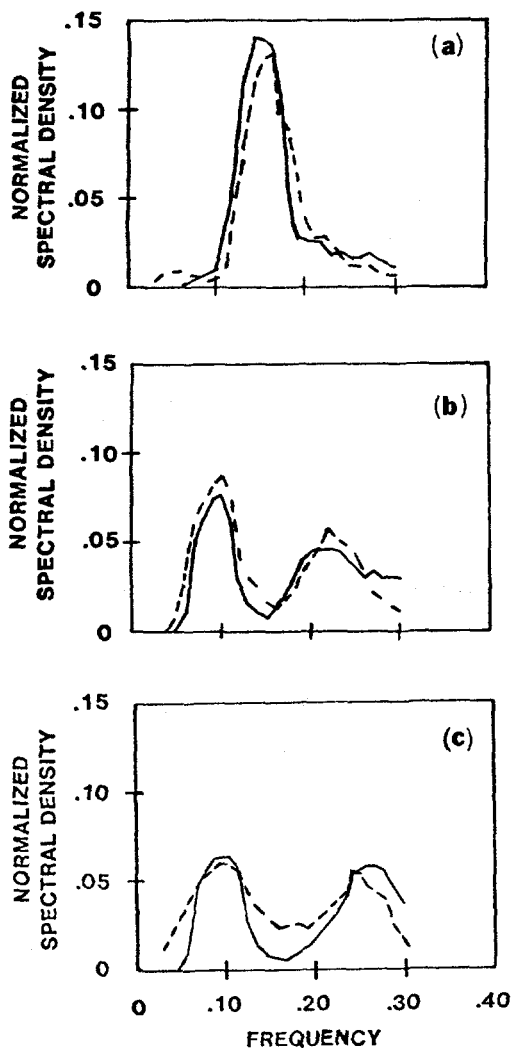
Figure 3. Spectral Density for Waverider (———)
and ENDECO (----): (a) 24 hours before the frontal
passage mid-day October 25,1980, (b) 15 hours after
frontal passage, (c) 21 hours after frontal passage.

Table 2. Comparison of Significant Wave Heights
Measured by the Waverider 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.

2 shows the significant wave heights measured by
the "MET" buoy were within the 90 percent
confidence limits of the Waverider.

The significant wave heights measured by the
Cloverleaf buoy were found to be consistently
higher than those measured by nearby systems.
When compared with the values measured at the 12
km site by the Waverider, the Cloverleaf data
averaged 15 percent higher. There was one
measurement at 1715 (GMT) on October 26, when
the Cloverleaf measurement was within the
Waverider 90 percent 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 2220 (GMT) on
October 23. The Waverider which had been
deployed at the center of the SCR pattern
located 20 km offshore malfunctioned and thereby
limited the ground truth data to those data
measured at the 12 km and 36 km sites. The
significant wave height of 1.55 m measured by
SCR had better agreement with that measured by
XERB (1.58 m) at 36 km offshore than the Wave-
rider (1.73 m) at 12 km offshore. This might be
expected since the bottom slope was greater
between the 12 km and 20 km site than between
the 20 km and 36 km site.

3.2 Frequency of Spectral Peak

The frequencies of the center of the frequency
bands in which spectral peaks occurred for the
wave measurements systems are plotted in Figure
2b. After the front passed through the site on
October 25, opposing waves developed. The dual
spectral peaks of sea and swell, as shown in
Figure 3c, were at times about equal which
resulted in a random choice of which peak was
recognized as the principal peak causing the
bifurcation shown in Figure 2b. Table 3 sum-
marizes the results of the spectral peak com-
parison for single peak spectra. As shown in
Figure 2b, the Waverider measured the spectral
peak at a lower frequency when compared with the
ENDECO. Although this difference is a consis-
tent shift in the spectra, 83 percent of the
time it was within the ENDECO frequency resolu-
tion of ±.025 Hz for the single peak spectra.

Although there were only two spectra available
for comparison, the "MET" and Waverider measured
the same frequency for the spectral peaks.
These cases included single peak sea and swell
spectra.

The frequency of the spectral peak for the
Cloverleaf spectra was found generally in
agreement with those spectra from buoys nearby.
When compared with the Waverider during both
swell or sea, spectra agreed within their
frequency resolution 71 percent of the time.
When compared with XERB spectra, the measure-
ments agreed 80 percent of the time within the
frequency resolution. When comparing the fre-
quency of waves measured by a buoy with

TABLE 3. Comparison of Spectral Peaks for Single Peak Spectra

Measurement System SYS A / SYS B	Number of Comparison	Number Within Frequency Resolution*	Percent Within Frequency Resolution*	Frequency Resolution (Hertz) SYS A / SYS B
Waverider / ENDECO	23	19	83	.011 / .025
Waverider / Met	2	2	--	.011 / .010
Waverider / SCR	1	1	--	.011 / **
Waverider / 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 K space.

frequency measured by a remote sensor like SCR, it is important to consider that SCR measures in "K" (wave number) space and therefore, computes frequency from the measured wavelengths based on wave theory. The October 23 flight of SCR provided peak frequencies similar to the buoys in the area. From the SCR measurements, the peak spectral frequency at 2220 (GMT) was calculated to be 0.147 Hz. During this period, the Waverider spectra indicated the spectral peak at 0.145 Hz. The XERB spectra indicated 0.149 Hz.

3.3 Mean Wave Direction of the Spectral Peak

The mean wave direction for the frequency of the spectral peak are summarized in Figure 2c for those systems measuring wave direction. Wave directions are referenced to True North and indicate the direction toward which waves propagate.

As shown in Table 4, when the Cloverleaf buoy was near the ENDECO buoy, mean wave directions agreed within 4° to 20°. The wave direction measured by the Cloverleaf buoy indicated a slightly more northerly wave direction than the ENDECO buoy. The Cloverleaf buoy, when in the vicinity of the XERB buoy, showed similar agreement with the difference in mean wave direction ranging between 1° to 24°. The Cloverleaf buoy indicated a more southerly direction of the waves than 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. These measurements, as shown in Figure 2c, indicate the direction for the ENDECO buoy may be more northerly than that measured by 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 to be 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 for the 12 km site. The only other system measuring wave direction at this time was XERB, some 24 km further offshore. The "MET" data during this time show the wave direction to be some 30° more northerly.

Table 4. 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	14 N
XERB	5	1 - 24	16 S

N - Cloverleaf data was more northerly.
S - Cloverleaf data was more southerly.

Acknowledgements

References

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