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Wave Measurements Using Upward-Looking Sonar for Continental Shelf Applications

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Abstract

An upward looking sonar instrument, the Ice Profiling Sonar (IPS), has been developed, and successfully used for obtaining time series measurements of ice keel depths over the continental shelves of the Arctic in support of scientific research. Since the winter of 1996/97, it has been extensively used off the coast of Sakhalin Island, Russian Federation, in support of offshore oil and gas research aimed at characterizing the seasonal sea-ice regime. The IPS instrument has now been modified to extend its capabilities to provide accurate measurement of ocean waves. The instrument uses a high frequency acoustic transducer (420 kHz). It has a very narrow conical beam (2 degrees width at -3 dB) to minimize the spatial smoothing of surface waves across the sonar footprint. With reduced power consumption, and an expanded internal storage capacity of 64 Mbytes (flash EPROM), the new instrument is capable of continuous measurements of wave amplitude at a sampling rate of 1 Hz over deployments of up to nine months duration. During March to April 1998, an evaluation of the performance of the modified IPS instrument, through intercomparison with a wave-rider buoy, was conducted in open ocean conditions off the Pacific west coast. Instantaneous wave heights of up to 11.5 m were measured. The results indicate good agreement between the measurements obtained from the IPS instrument and those measured using the wave-rider buoy. The subsea IPS instrument is very well suited to wave measurement in areas where sea ice or shipping are hazards to surface installations.

Introduction

Measurement of waves at continental shelf depths has been addressed with a variety of ocean instrumentation (Stewart[1]). For some applications, such as where information on the waves encountering an offshore platform are required, rig-mounted sensors offer the best solution. However, often wave data are required before the oil and gas platforms are in an area, or for the purpose of providing inputs to, or validation of, wave models. For these applications, accelerometers operated within surface buoys are used, with data relayed to receivers at shore stations, or via satellite. However, wave buoys are prone to damage from the large waves themselves, from ice if it is present in the area, from vessel traffic or from vandalism. As well, under extreme wave conditions, wave buoys are prone to errors arising from limitations in the response of the accelerometer due to pitch and roll of the buoys (Skey et al.[2]) and possibly due to the buoys not following the waves themselves under such extreme conditions.

An alternate approach is to obtain wave measurements from the comparative safe and calm conditions of the bottom of the ocean. Bottom-mounted, internally recording instruments, that sample the wave-induced fluctuations of pressure and velocity, are widely used for this purpose. However, the amplitude of the wave signal in pressure (p) is reduced with increasing measurement depth as a function of wavenumber (k) as:

$$p(z) = ?\cdot g\cdot \eta\cdot \cosh[k(h+z)]/\cosh(kh) \qquad (1)$$

where η is the sea surface level, ρ is the density of sea water, g is the local acceleration due to gravity, p is the measured pressure at height z (measured positive upward from mean water level), and h is the water depth (Stewart[1]). The wavenumber, k, can be determined from the wave frequency, f, using linearized hydrodynamic equations at wave frequencies (Bretschneider and St. Denis[3]). In practice, the frequency-dependant attenuation of the waves with depth limits these instruments to use in water depths of 20 m or less. Beyond this depth, the higher frequency portion of the surface wave spectra cannot be adequately measured, even with correction for the attenuation, because the signal-to-noise ratio of the wave fluctuations is too low.

Upward looking sonar offers another approach for wave measurements from the ocean seafloor. In contrast to pressure-velocity sensors, the acoustic range signal can be used in considerably greater water depths. In this paper, we describe an upward looking sonar instrument, originally designed for measurement of sea-ice drafts, which has been adapted for ocean wave measurements. We present the results of an extended test of the instrument in a water depth of 35 m. The data were analysed and compared to measurements obtained from an on-board pressure sensor, and with a nearby waverider buoy. The results are presented, and the implications for wave measurements obtained with an upward looking sonar instrument over the full range of continental shelf depths are discussed.

Instrument Description

The upward looking sonar used for this study is an Ice Profiling Sonar, model IPS4. The instrument was originally developed and designed by the Institute of Ocean Sciences (IOS), Canadian Department of Fisheries and Oceans (DFO). The principles of operation for application to Ice Profiling are presented by Melling et al.[4]. The latest version of the instrument, the IPS model 4 (IPS4), was designed and built in prototype form by IOS. ASL Environmental Sciences Inc. further implemented the design and now manufactures the IPS4 instrument under license to DFO.

Acoustic Range and Tilt Measurements. The IPS4 instrument operates with a high frequency acoustic transducer (420 kHz). It uses a very narrow conical beam (1.8 degrees width at -3 dB) which results in a small area being insonifed at the surface. The diameter of the insonifed area is 0.9 m for an acoustic range of 30 m, 3.1 m for 100 m range and 6.3 m for a 200 m range. The IPS4 transmits a short pulse of acoustic energy corresponding to an acoustic pulse length of 0.1 m. The acoustic returns from the outgoing pulse are amplified and subjected to compensation through a Time Varying Gain circuit which corrects for acoustic losses associated with beam spreading and attenuation in sea water. After digitization, the amplitude of the echo returns are scanned to select a single target for each ping. The selection procedures chooses the target with the longest persistence from all targets having an amplitude above a user specified threshold level.

The nominal precision of the acoustic range is ± 2.5 cm. The absolute accuracy of the target range can be considerably degraded from this value primarily due to variations in the actual speed of sound from the assumed constant speed of sound (1450 m s^{-1}, for this project). However, variations in the integrated speed of sound tend to occur over much longer time scales of many hours to many days rather than the 26 minute duration of the individual blocks from which the wave information is derived.

The IPS4 design features reduced power consumption, and an expanded internal storage capacity of 64 Mbytes (flash EPROM). As a result, the new instrument is capable of continuous acoustic range measurements at a sampling rate of 1 Hz over deployments extending up to nine months in duration.

The IPS4 also measures instrument tilt in the x- and y-axes of the instrument with an accuracy of ± 0.5° and to a resolution of ± 0.01°.

Bottom Pressure Data. For this wave intercomparison study, the IPS4 instrument was fitted with a Paroscientific Model 2200A-101 digital quartz pressure sensor having a full scale range of 400 psia or 275 dbars (one decibar [dbar] represents the pressure of 1 m of seawater). According to the manufacturers' specifications, the pressure sensor is repeatable to 0.005% of full scale range, or 0.014 dbar. As interfaced in the IPS4 instrument, the least bit resolution of the sensor is 0.001 dbars. The overall accuracy of the sensor, which is largely due to responses varying with temperature, is estimated as 0.06 dbars.

The Paroscientific pressure sensor also includes a temperature sensor, providing measurements of near-bottom sea water temperatures to a resolution of 0.045 °C.

Datawell Waverider Buoy Measurements. The waverider buoy measures waves by means of an accurate accelerometer mounted within the buoy. Through analog circuitry, the accelerometer signal is integrated twice, resulting in a measure of vertical displacement. To reduce the effects of unwanted measurements of acceleration due to roll and pitch of the buoy, the accelerometer is mounted on a stabilized platform within the buoy, suspended by means of thin wires.

According to the manufacturer, the Datawell waverider buoy has the following instrument specifications:
Wave height: minimum – noise peak-peak (bandwidth 1 Hz) 0.02 m; maximum – twice maximum amplitude 2 x 20 m; wave frequency range: 0.035 Hz – 0.65 Hz (3 dB); accelerometer linearity: non-linear rectification < 2×10^{-3} m/s^2 for 6 m/s^2 amplitude.

Data Collection

The IPS4 instrument was deployed in the N.E. Pacific Ocean off the westcoast of Vancouver Island (**Fig. 1**) in approximately 35 m water depth. Deployment and recovery of the instrument was carried out from a local fishing vessel. The instrument was deployed at 0908 on 4 March 1998 PST (Z+8) and recovered at 0911 on 28 April 1998.

The IPS4 instrument was supported by a near-bottom taut line mooring system (**Fig. 2**). The acoustic and pressure sensors were operated at a depth of approximately 29 m below lowest normal tide level, in a total water depth of 35 m. Because the instrument was operated on a taut line mooring, it was subject to tilts arising from the drag forces, due to near-bottom currents, acting on the instrument and mooring elements. The tilt sensor shows that the tilt angles were generally small (< 5° for 95% of all observations) during most of the measurement record. Larger tilts of up to 11° (95% exceedance level) were encountered during a few occasions, under the largest near-bottom current conditions. Tilts of 5 and 11° represent horizontal displacements at the surface of 2.5 and 5.6 m, respectively. The acoustic range values are corrected for the effect of non-zero tilt angles, by applying a corrective factor computed as the cosine of the total tilt angle.

The IPS4 instrument was located about 300 m to the west of a Datawell waverider buoy, which is operated by the Marine Environmental Data Service (MEDS) of the Canadian Department of Fisheries and Oceans, in approximately 26 m water depth. The waverider data is transmitted to a shore station at the Tofino BC airport, where it is stored on computer, and forwarded to MEDS for data processing and archival. The waverider measurements are collected in discrete burst data sets, each consisting of 2048 samples obtained over a burst duration of 1600 s (26 minutes and 40 s). The individual bursts are typically obtained once every three hours, and more often when the waves are large. However, there are occasional gaps in the record, attributed to problems encountered at the shore-based recording station.

Results

Instrument Gain Settings. Ocean waves were clearly resolved in the 1 Hz range measurements acquired off the northeast coast of Sakhalin Island in November of 1996, prior to the onset of sea ice for the area. However, these features were occasionally obscured by subsurface targets, at a few to several metres below the actual sea surface. These “false” targets were tentatively identified to be of biological origin (zooplankton) or to be subsurface bubbles generated at the surface under strong winds and large waves, and then swept downward in clouds (Zedel and Farmer[5]). On the basis of theoretical calculations derived from published volume scattering returns for the ocean surface, bubble clouds and biological volume scatterers, the receiver gain was reduced by 25 dB (from that normally used for detection of the weaker sea ice targets).

An examination of the IPS4 data of March and April 1998 reveal that subsurface targets were much less common than previously, likely due to the lower gain settings used in the instrument. Even under the strong wind speeds experienced during the deployment (winds measured at Tofino airport gusting to 52 knots on 23-24 March), the frequency of “false” targets was very low and did not have any appreciable impact on using acoustic ranges to measure surface waves.

Waverider Buoy Data. The significant wave heights (H_s) and peak periods (T_p) were determined from the waverider measurements over the duration of the IPS4 instrument operation. The waverider results (Fig. 3) reveal that a series of comparatively large wave events occurred during March and April. The largest of these wave events occurred on April 6-7, 1998 attaining H_s values of up to 4.7 m and T_p values of 12 to 20 s.

Based on 26 years of historical data from the Tofino wave station (1972-1997), measured H_s have a median value of 2.1 m, with the largest measured value (in March) being 8.3 m. The 5% and 95% exceedance levels for H_s are 0.9 and 4.5 m, respectively. Peak periods, as derived from the same record sets, have a median value of 12 s, with 5% and 95% exceedance levels of 8 s and 17 s, respectively.

Selection of Wave Events. To assess the capabilities of the IPS4 acoustic range measurements for wave applications, a set of four data segments (**Table 1**) were selected. Three of the data segments, representing smaller, moderate and large waves were chosen on the basis of the waverider measurements (**Fig. 3**). From the measurements obtained during the largest wave event of 6-7 April, the segment having the largest maximum wave height, H_{max}, of 7.7 m was selected. A second segment, late on March 10, having more moderate levels of wave height and shorter periods, was also selected. The third data segment for April 11, was selected as being representative of comparatively small waves.

The fourth event for intercomparison was selected on the basis of scanning the IPS4 wave data sets for the largest individual wave height, H_{max} of nearly 11.5 m on 24 March 1998. Unfortunately, the waverider buoy was not recording data at this time, so there are there no direct comparisons from the waverider buoy. (The waverider data has a gap of several hours during the early part of March 24, apparently due to a problem at the shore station.)

Wave Heights Derived From Bottom Pressure Sensor. As well as comparing the IPS4 acoustic range measurements of waves with waverider buoy data, comparisons were also made with the pressure sensor measurements made from the IPS4 instrument. The pressure sensor response for high frequency waves is poor due to the attenuation of wave energy with increasing frequency. A frequency dependent correction factor, derived using eq.1, is applied to the bottom pressure data. However at frequencies between 0.1 and 0.18 Hz, the instrument noise levels start to exceed those of the wave signal. Thus for waves having periods shorter than 5.5 to 10 s, the instrument noise levels exceed the attenuated wave signal resulting in no useful information for these short period waves. For computational purposes, we chose the noise level of the pressure sensor to be half the instrument repeatability value, or $0.5 \cdot 0.014$ dbars. Based on this value and typical wave pressure spectral levels, the highest frequency for meaningful pressure spectra densities was 0.116 Hz (or a period of 8.6 s).

Within these limitations, the pressure measurements can be used to examine the longer period (or low frequency portion) of the wave spectra. Moreover, for the very large waves of 7 April and 24 March, the period of the largest waves is sufficiently large at about 10 – 18 s, that the corrected pressures provide a meaningful representation of large individual waves.

Large Wave Event of 7 April. The comparison between the waverider and acoustic range data (**Table 1, Fig. 4 and Fig. 8**) shows good overall agreement. (Note that the differences in character and timing of individual waves are expected due to the 300 m separation between the IPS and waverider locations.) The amplitudes of the IPS-derived waves are somewhat smaller by about 15%. A similar reduction is evident in the comparison of the autospectra derived from IPS range and buoy measurements (**Fig. 8**). The spectral shape is very similar, though resulting in good agreement for the peak period values.

Moderate and Smaller Waves. The comparisons of the IPS-derived and buoy waves for these two selected episodes show very good agreement (**Figs. 5 and 6**). Overall, the wave magnitudes agree to within a few percent, and the peak periods exhibit reasonable agreement. A comparison of the wave spectra also indicate very good agreement in spectral levels and shape.

Note that the waves computed from bottom pressure measurements are much reduced in magnitude. This is expected given the cutoff frequency of 8.5 s period, dictated by the water column attenuation of the wave signal for the measurement depth of 29 m. By comparison, the case of the larger waves (Fig. 4) reveals a better correspondence, although still having significant degree of signal loss. This better agreement results from the longer periods dominating the wave spectra (Fig. 8) for this particular measurement period.

Largest Measured Waves of 24 March. The largest individual wave, from all IPS4 data in March and April, was measured at about 0200 UTC on 24 March. The IPS range data recorded during this period (**Fig. 7**) reveal very large waves with H_s of 6.2 m. No waverider data were available at this time due to a suspected power failure of the shore station which is unmanned overnight (S. Fairburn, pers. comm.). At 0000 UTC, the observer at Tofino airport noted wind gusts of up to 52 knots, and that the significant wave height was 6.91 m (at 0100). Unfortunately, the waverider data during this period (from 0100 through to 0700) were not recorded due to the suspected power outage.

Note the very large individual maximum wave height measured at 11.5 m (**Fig. 7**; 0216 UTC). The pressure sensor data is consistent with the timing of these very large waves, although the signal is reduced in magnitude as expected from the signal attenuation. Another wave buoy, located 27 km further offshore at La Perouse Bank, recorded a maximum wave height of 10.8 m, with an H_s value of 6.0 m, at this same time.

Conclusions

The IPS acoustic range measurements of ocean waves, obtained in March and April 1998, were of high quality. The number of "false" targets (i.e. targets not t the sea surface) was very small, representing less than 0.1% of all measured values. The completeness of the IPS range measurements was good for periods having large H_s values of up to 6.2 m, including the largest measured individual wave height of 11.5 m.

Comparison of the IPS acoustic range data with waverider buoy data revealed good agreement under small, moderate and large wave conditions during the March – April period. The spectral peak agreed to within 1 – 2 s, and the wave heights agreed to within 15% or better. There were some differences in wave height values for the data sets containing larger waves. In these cases, the IPS-derived wave heights were lower by 10 and 15% than those derived from the waverider data. The differences in wave height may be due to the difference in total water depth of the two instrument locations (35 m for the IPS instrument vs. 26 m for the waverider buoy). For larger waves, associated with longer wave periods and larger wavelengths, the effect of shallower water could account for the computed differences in the wave heights.

Another possible explanation for differences in wave height is the effect that the tilt of the IPS instrument, experienced due to being mounted on a near-bottom taut line mooring, may have on the measurements. Further investigation is needed to examine the effect of instrument tilt and mooring motion on acoustic range wave measurements. Note this problem can be eliminated through use of a better mooring system to minimize instrument tilt and vertical mooring movements.

Waverider buoy measurements also have problems, particularly in breaking seas, where surface-floating instruments are subjected to large accelerations. Under such conditions, waverider measurements may overestimate the actual wave heights. The waverider buoy measurements are also prone to missing data due to shore-station problems, or damage to the buoy arising from collisions with vessels or sea-ice, or due to vandalism.

Overall, acoustic-based range measurements offer a promising means of measuring ocean waves from the comparative safety and stability of the ocean floor. This technique can be used in considerably greater water depths than is possible for bottom pressure instruments. The method has definite advantages for use in hazardous marine environments.

Acknowledgements

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References

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Tables

Table 1 – Summary information on the four data segments selected for detailed examination of the IPS4 wave data sets.

			Hmax(m)	
Date	Start Time (GMT)	Stop Time (GMT)	IPS	WR
1998/03/10	23:50	00:16:39	5.2	4.9
1998/04/07	03:50	04:16:39	5.2	7.7
1998/04/11	02:50	03:16:39	2.3	2.6
1998/03/24	01:50	02:16:39	11.5	n/a

	Hs (m)		Tp (s)	
Date	IPS	WR	IPS	WR
1998/03/10	2.9	3.0	7.8	7.7
1998/04/07	3.6	4.2	16.8	18.2
1998/04/11	1.5	1.5	7.8	6.9
1998/03/24	6.2	n/a	10.3	n/a

Figures

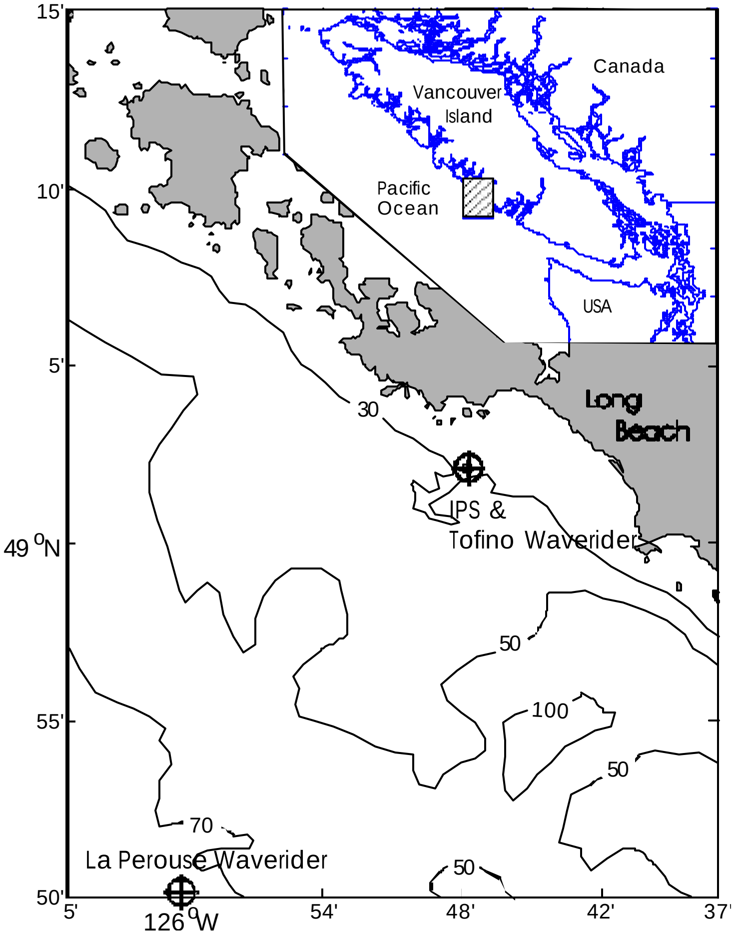

Fig.1 – The location of the IPS and Tofino Waverider intercomparison site, in relation to the Vancouver Island coastline and local bathymetry (depths in m). Also shown is the location of the La Perouse wave buoy further offshore.

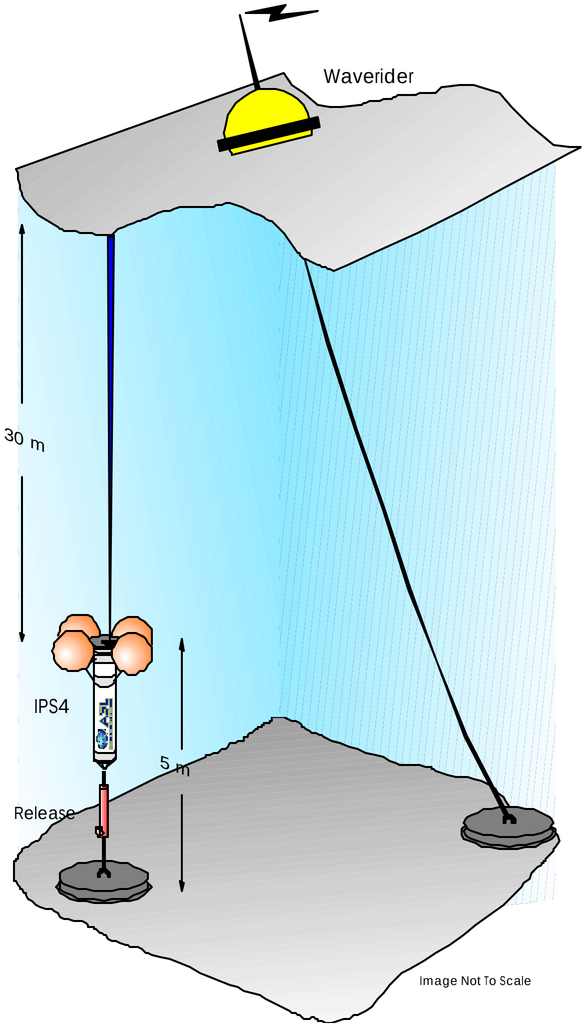

Fig. 2 – A schematic diagram of the taut line mooring system used to support the IPS4 instrument, along with a Waverider buoy.

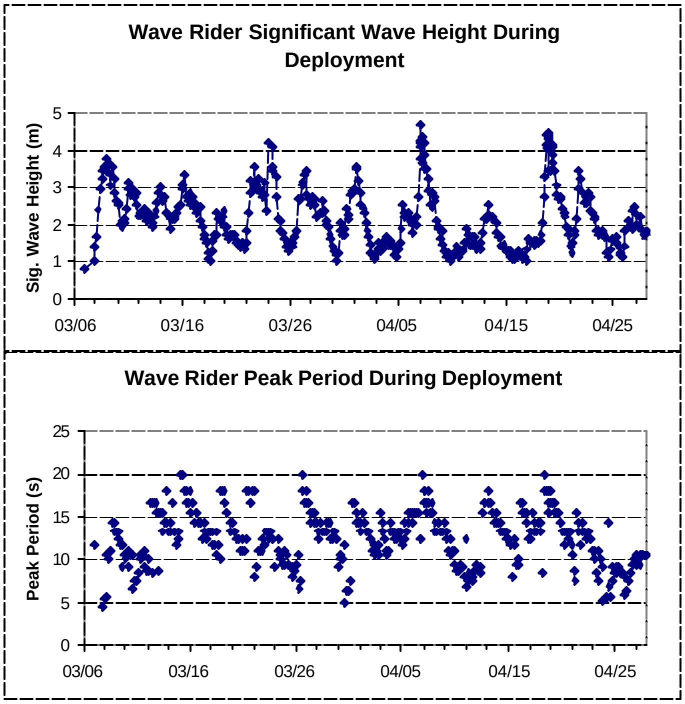

Fig. 3 – The wave heights and peak periods as computed from the waverider measurements while the IPS4 instrument was in operation. The values of Hs and Tp are computed from bursts of 2048 samples over 1600 s. Typically each burst measurement is available at 3 hourly intervals.

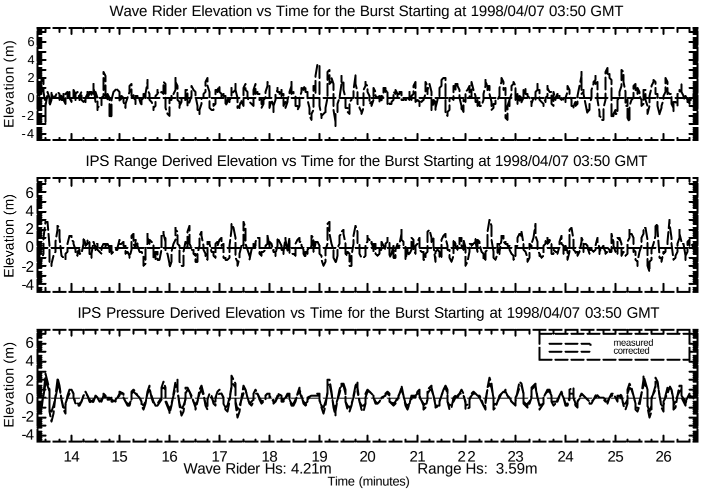

Fig. 4 – Wave data of 0350Z 7 April 1998 (large waves), as determined from: the waverider measurements (upper panel); the IPS4 acoustic ranges; and the IPS4 pressure sensor, with and without correction for frequency dependent attenuation (lower panel).

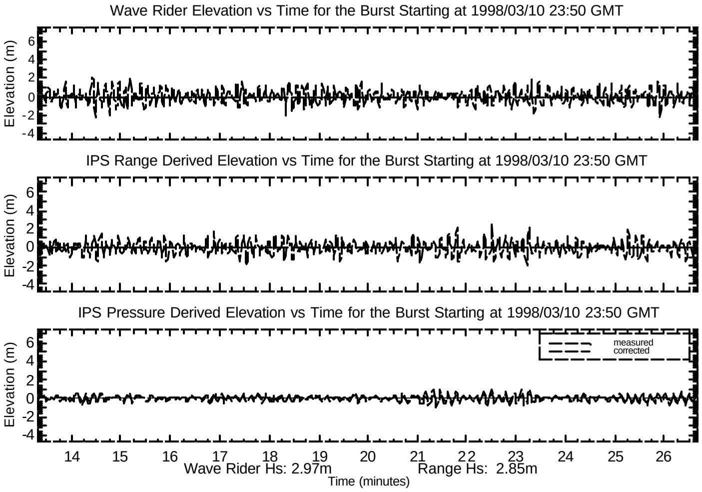

Fig. 5 – Wave data of 2350Z 10 March 1998 (moderate waves), as determined from: the waverider measurements (upper panel); the IPS4 acoustic ranges; and the IPS4 pressure sensor, with and without correction for frequency dependent attenuation (lower panel).

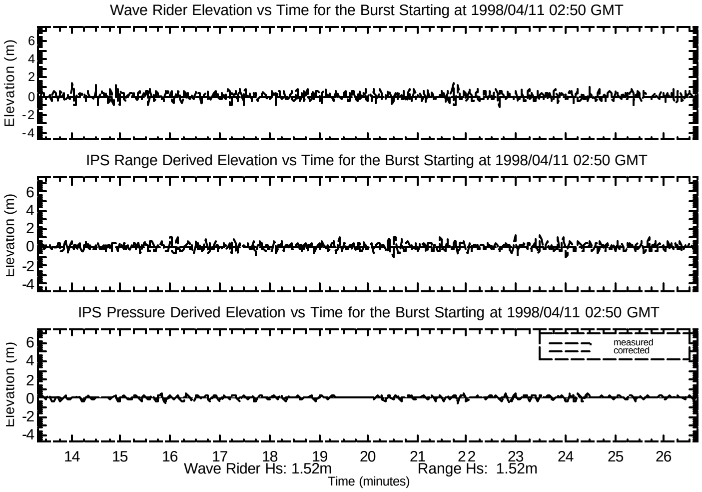

Fig. 6 – Wave data of 0250Z 11 April 1998 (small waves), as determined from: the waverider measurements (upper panel); the IPS4 acoustic ranges; and the IPS4 pressure sensor, with and without correction for frequency dependent attenuation (lower panel).

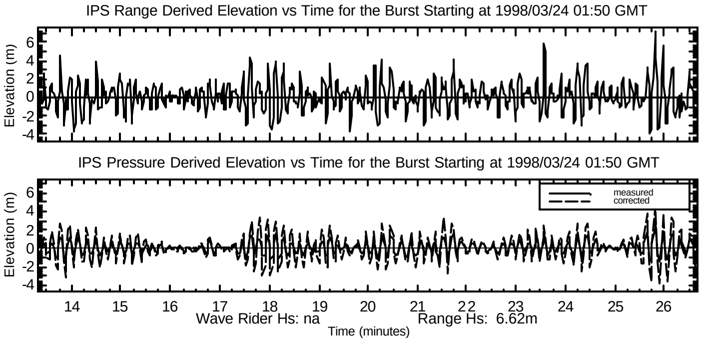

Fig. 7 – Wave data of 24 March 1998 (largest individual waves), as determined from: the IPS4 acoustic ranges; and the IPS4 pressure sensor, with and without correction for frequency dependent attenuation (lower panel).

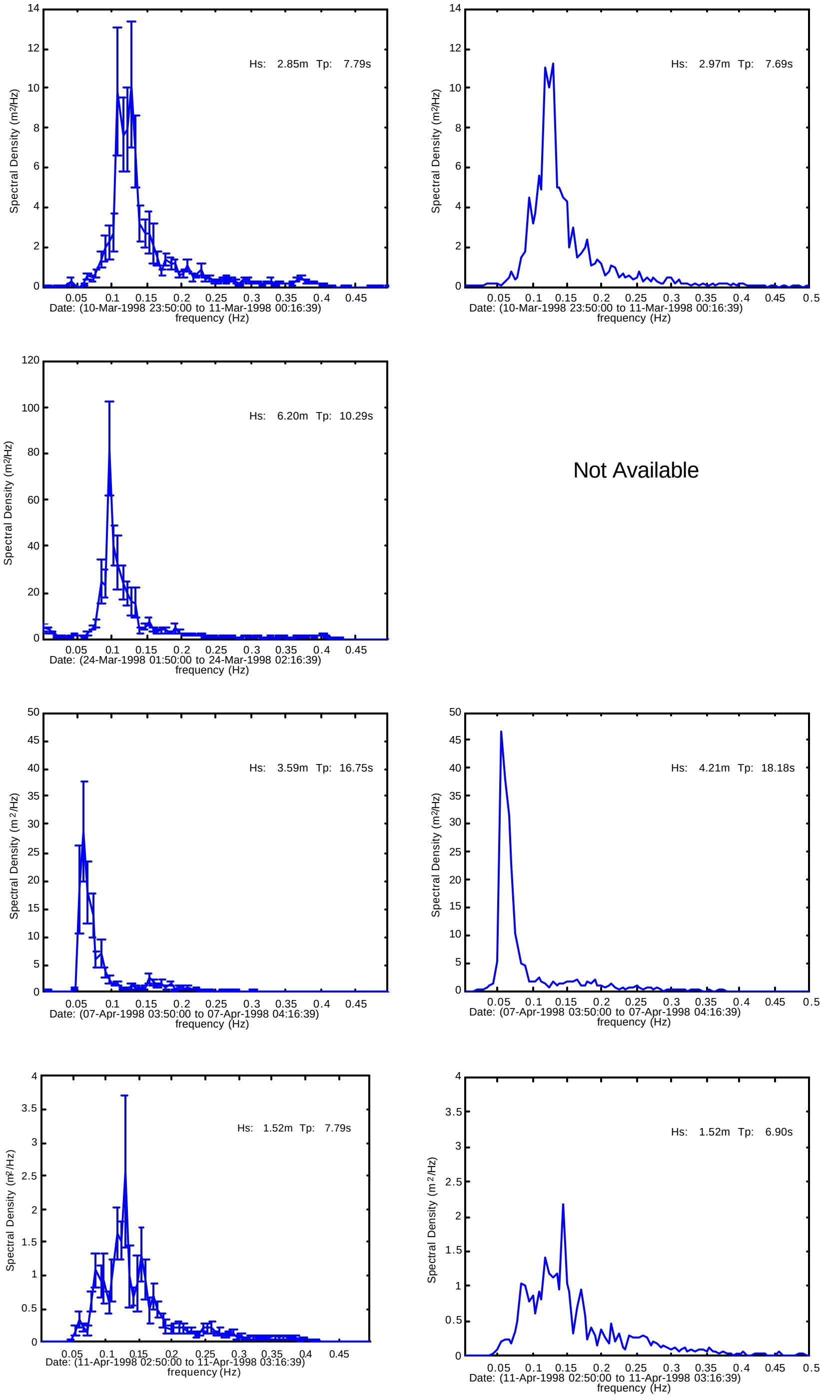

Fig. 8 – Wave spectra of the four data segments (Table 1, Figs. 4-7) as derived from the IPS (left column) and the waverider, except for 150Z 24 March for which there was no waverider data.