# *“WAVESONAR”* - AN UPWARD-LOOKING SONAR FOR WAVE MEASUREMENTS ON THE CONTINENTAL SHELF

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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. The IPS instrument capabilities have since been expanded to provide accurate measurement of ocean waves. This new instrument, the *WaveSonar*, uses a high frequency acoustic transducer (420 kHz), with a very narrow conical beam (2° width at -3 dB) to minimize the spatial smoothing of surface waves across the sonar footprint. With low power consumption, and large storage capacity (64 Mbytes flash EPROM), the instrument is capable of continuous measurements of wave amplitude at a sampling rate of 1 Hz over deployments of up to nine months. From March 4 to April 28 1998 an evaluation of the performance of this instrument, through intercomparison with a Waverider 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 show good agreement between the *WaveSonar* and Waverider measurements. The *WaveSonar* has the advantage of operating from the relative safety of the ocean floor, thereby avoiding surface hazards such as ships, vandalism and adverse weather.

## INTRODUCTION

Measurement of waves at continental shelf depths has been addressed with a variety of ocean instrumentation (Stewart, 1980). For some applications, such as where information on the waves encountering an offshore platform are required, rig-mounted sensors offer the best solution. Another approach is to use buoy-based accelerometers, with data relayed by radio or satellite to receivers at shore stations. However, wave buoys are prone to damage from the large waves themselves, from ice if it is present in the area, from vessel traffic, and 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., 1995), 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-induced pressure signal is reduced with increasing measurement depth as a function of wavenumber. 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 this *WaveSonar* instrument off the west coast of Vancouver Island, in a water depth of 35 m. The data are analysed and compared to measurements obtained from a nearby Waverider buoy.

## INSTRUMENT DESCRIPTION

The upward looking sonar used for this study is based on the Ice Profiling Sonar, model IPS4, 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., 1995. The *WaveSonar* evolved from the IPS4, and uses the same upward-looking sonar, but is specifically designed for wave measurements.

### Acoustic Range and Tilt Measurements.

The *WaveSonar* instrument operates with a high frequency acoustic transducer (420 kHz). It emits a very narrow conical beam (1.8º 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 *WaveSonar* 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 amplitudes of the echo returns are scanned to select a single target for each ping. The selection procedure chooses the target with the longest persistence from all targets having amplitudes 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 degraded due to variations in the actual speed of sound from the assumed value (1450 m/s, for this project). However, variations in the integrated speed of sound tend to occur over much longer time scales than the 26-minute blocks from which the wave information is derived.

The *WaveSonar* design features reduced power consumption, and an expanded internal storage capacity of 64 Mbytes (flash EPROM). As a result, the 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 *WaveSonar* also measures instrument tilt in the x- and y- axes, with an accuracy of ±0.5° and a resolution of ±0.01°.

### Instrument Gain Settings

During over-winter deployments (‘96-‘99) of the IPS4 off Sakhalin Island, Russia, for ice keel depth measurements, ocean waves were clearly resolved in the 1 Hz range measurements. However, the wave signal was occasionally obscured by subsurface targets, several metres below the actual sea surface. These “false” targets were tentatively identified to be of biological origin (zooplankton), or subsurface bubbles generated at the surface under strong winds and large waves, and then swept downward in clouds (Zedel and Farmer, 1991). On the basis of theoretical calculations derived from published volume scattering returns for the ocean surface, bubble clouds and biological volume scatterers, it was determined that the receiver gain should be reduced by 25 dB (from that normally used for detection of the weaker sea ice targets) for wave measurements. This formed the basis for the gain settings of the new *WaveSonar* instrument, used for the wave intercomparison study off Tofino.

An examination of the *WaveSonar* data of March and April 1998 revealed that subsurface targets were much less common than in the IPS data, likely due to the lower gain settings used in the instrument. Even under the strongest 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.

## BOTTOM PRESSURE DATA

For this wave intercomparison study, the *WaveSonar* instrument was fitted with a Paroscientific 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). The overall accuracy of the sensor, which is largely due to responses varying with temperature, is estimated as 0.06 dbars. The wave data derived from these pressure measurements will not be discussed here, but can be found in Fissel et al. (1999).

## 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, Datawell of the Netherlands, the 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 x $10^{-3}$ $m/s^2$ for 6 $m/s^2$ amplitude.

## DATA COLLECTION

The *WaveSonar* instrument was deployed in the N.E. Pacific Ocean off the west coast of Vancouver Island (**Fig. 1**) in 35 m water depth. Deployment and recovery of the instrument was carried out using a local crab-fishing boat. The instrument was deployed at 09:08 on 4 March 1998 PST (Z+8) and recovered at 09:11 on 28 April 1998.

A near-bottom taut line mooring system (Fig. 2) supported the WaveSonar instrument. The acoustic and pressure sensors were located at a depth of 29 m below lowest normal tide level, in a total water depth of 35 m. Because the instrument was attached to 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 sensors showed 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.

About 300 m to the east of the *WaveSonar* was a Datawell Waverider buoy, operated by the Canadian Department of Fisheries and Oceans, at approximately 26 m water depth. The Waverider data are transmitted to a shore station at the Tofino BC airport, where they are stored on computer, and forwarded to MEDS for data processing and archival. The Waverider measurements are collected in discrete bursts, 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

Based on 26 years of historical data from the Tofino wave station (1972-1997), measured significant wave heights ($H_{s)}$ have a median 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 set, have a median value of 12 s, with 5% and 95% exceedance levels of 8 s and 17 s, respectively.

During the March 4 - April 28 1998 study period a series of comparatively large wave events occurred. Significant wave heights ($H_s$) varied from 1 to 7 m; while peak periods ($T_p$) ranged from 5 to 20 s (**Fig. 3**). The *WaveSonar* - and Waverider-derived wave heights and periods agree very closely. A scatter plot of $H_s$-*WaveSonar* versus $H_s$-Waverider (**Fig. 4A**) shows very close agreement up to 3 m $H_s$ (±0.15 m rms; or within 5.6%); beyond 3 m $H_s$ there is slightly more scatter (±0.18 m rms; or 6.9%). A similar scatter plot for $T_p$ (**Fig. 4B**) shows more scatter, as expected. A combined $H_s$ vs $T_p$ presentation (**Fig. 4C**) shows good agreement. The *WaveSonar* data extend from 20 to 25 s period, whereas the Waverider data stop at 20 seconds. This may be inherent in the Waverider hardware.

Wave spectra results, based on data from the two instruments, are compared in **Fig. 5** for a typical "event" (April 18-20). For this comparison the *WaveSonar* data have been subsampled to every third value. The two plots are very similar, with the Waverider indicating slightly higher peak values.

A large, short-duration wave event occurred on March 24 during which significant wave heights increased rapidly from 2-3 m, to over 6 m (**Fig. 6** - middle). No Waverider data were available at the peak of the storm due to a suspected power failure at the shore station (S. Fairburn, pers. Comm.). At 00:00 UTC March 24, the observer at the Tofino airport noted wind gusts of up to 26 m/s (52 knots), and also noted at 01:00 that the significant wave height was 6.91 m. The largest individual wave measured by the *WaveSonar* was 11.5 m (02:16 UTC). Another DFO 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.

The winds prior to this large wave event were directed offshore, with limited fetch (**Fig. 6 –** upper; hourly vector-averaged; dir'n towards which wind was blowing). Just prior to the event the winds rotated so that they blew towards the northwest, alongshore, at speeds up to 18.6 m/s (gusts to 26 m/s; gale force). The winds continued to rotate clockwise and within 12 hours had decreased to less than 5 m/s. The time series plot of the wave spectral density as a function of frequency (**Fig. 6 –** lower) shows the sharp build up in wave energy, with peak energy centred at 11 s period. The large waves ($H_s$>4 m) lasted just over 2 hours, decreasing within 12 hours to $H_s$~2 m.

## CONCLUSIONS

The *WaveSonar* acoustic range measurements of ocean waves, obtained in March and April 1998, were of high quality. The number of "false" targets (i.e. targets that were not the sea surface) was very small, representing less than 0.1% of all measured values. The completeness of the *WaveSonar* 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 *WaveSonar* acoustic range data with the Datawell Waverider buoy data revealed good agreement. The significant wave heights agreed to within 7%, and the peak periods to within 3.5 s. The difference in $H_s$ increased with wave height which may be due to the difference in total water depth of the two instrument locations (35 m for the *WaveSonar* 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 all/some of the differences in the wave heights.

Another possible contributor to differences in wave heights is tilt of the *WaveSonar* instrument, due to being mounted on a near-bottom taut line mooring. Further investigation is needed to examine the effect of instrument tilt and mooring motion on acoustic range wave measurements. Note that tilts can be reduced/eliminated through use of a gimbaled bottom mount.

Waverider buoys 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 vandalism.

Acoustic-based range measurements offer an alternate 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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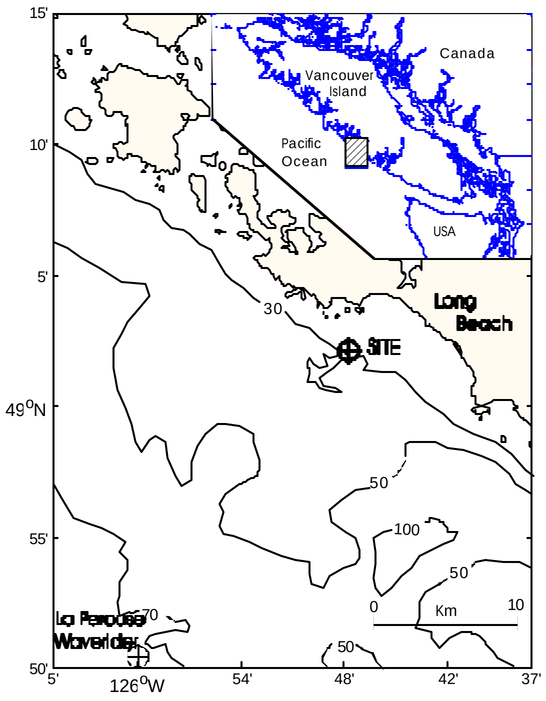


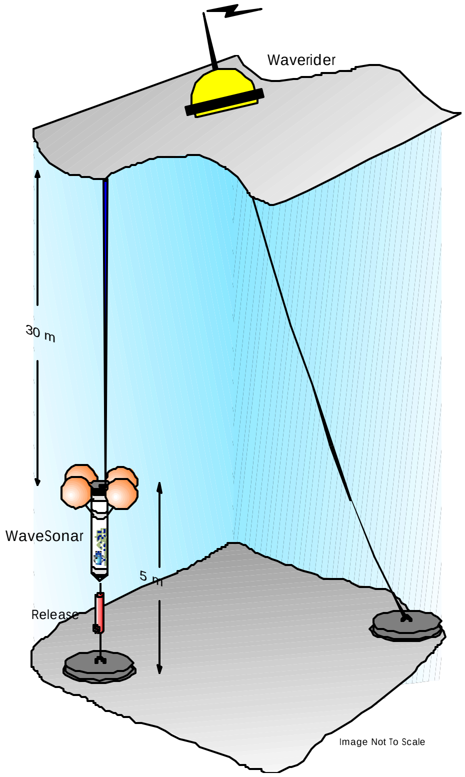
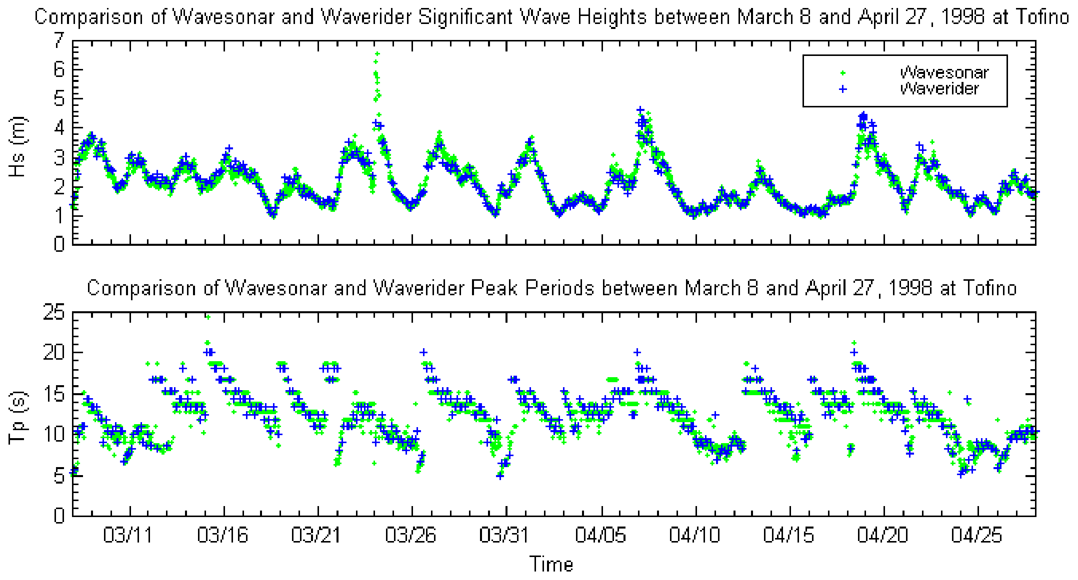


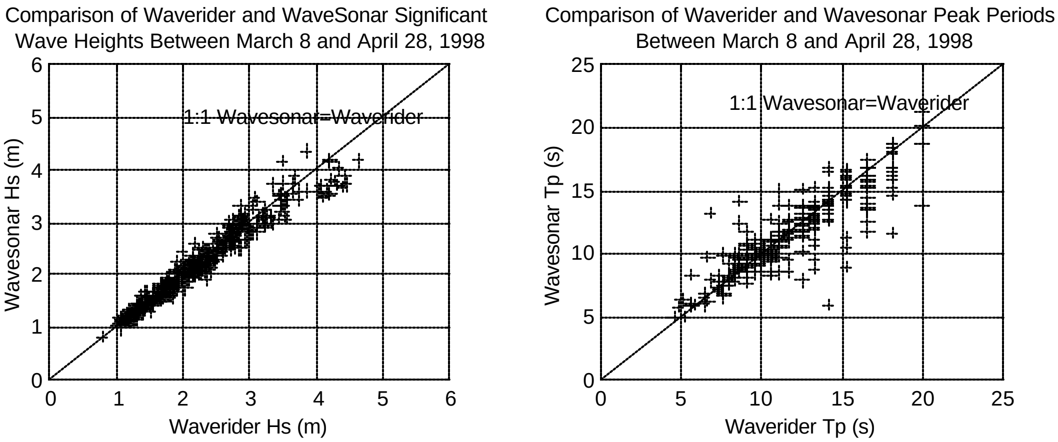
Figure 1: The location of the *WaveSonar* and Tofino Waverider intercomparison site, in relation to the Vancouver Island coastline and local bathymetry (depths in m). Also shown is the location of the La Perouse wave buoy further offshore.

Figure 2: A schematic diagram of the taut line mooring system used to support the *WaveSonar* instrument, along with a Waverider buoy.


Comparison of Wavesonar and Waverider Significant Wave Heights between March 8 and April 27, 1998 at Tofino

Comparison of Wavesonar and Waverider Peak Periods between March 8 and April 27, 1998 at Tofino

Figure 3: Comparison of the Wavesonar and Waverider significant wave heights and peak periods respectively between March 8 and April 27, 1998.


Comparison of Waverider and WaveSonar Significant Wave Heights Between March 8 and April 28, 1998

Comparison of Waverider and Wavesonar Peak Periods Between March 8 and April 28, 1998

Figure 4A/B:  Comparison of the Waverider and WaveSonar significant wave heights and peak periods between March 8 and April 28, 1998.  The solid line denotes the curve to expect if the WaveSonar and Waverider measurements are identical on every measurement.

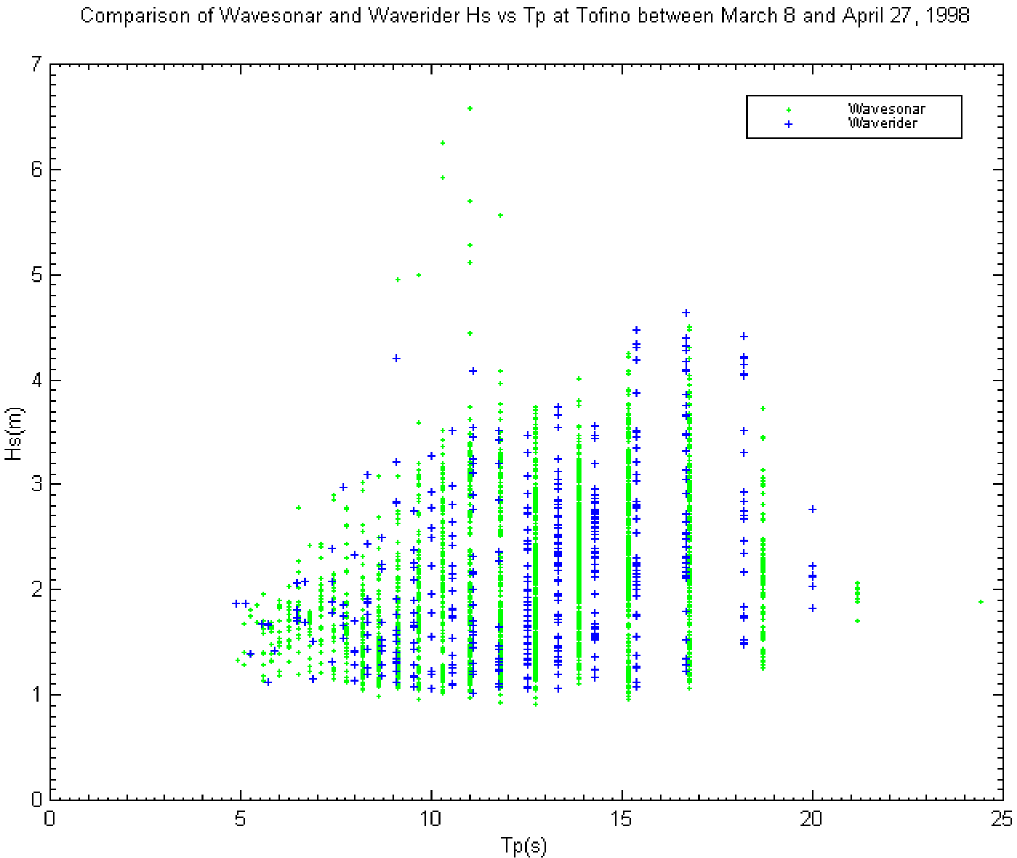

Comparison of Wavesonar and Waverider Hs vs Tp at Tofino between March 8 and April 27, 1998

Figure 4C: Comparison of the *WaveSonar* and Waverider significant wave heights ($H_s$) and peak periods ($T_p$) between March 8 and April 28, 1998.  Note the large $H_s$ values due to the March 24 storm, which only the *WaveSonar* measured, and the upper limit of 20 s may be a property of the Waverider.

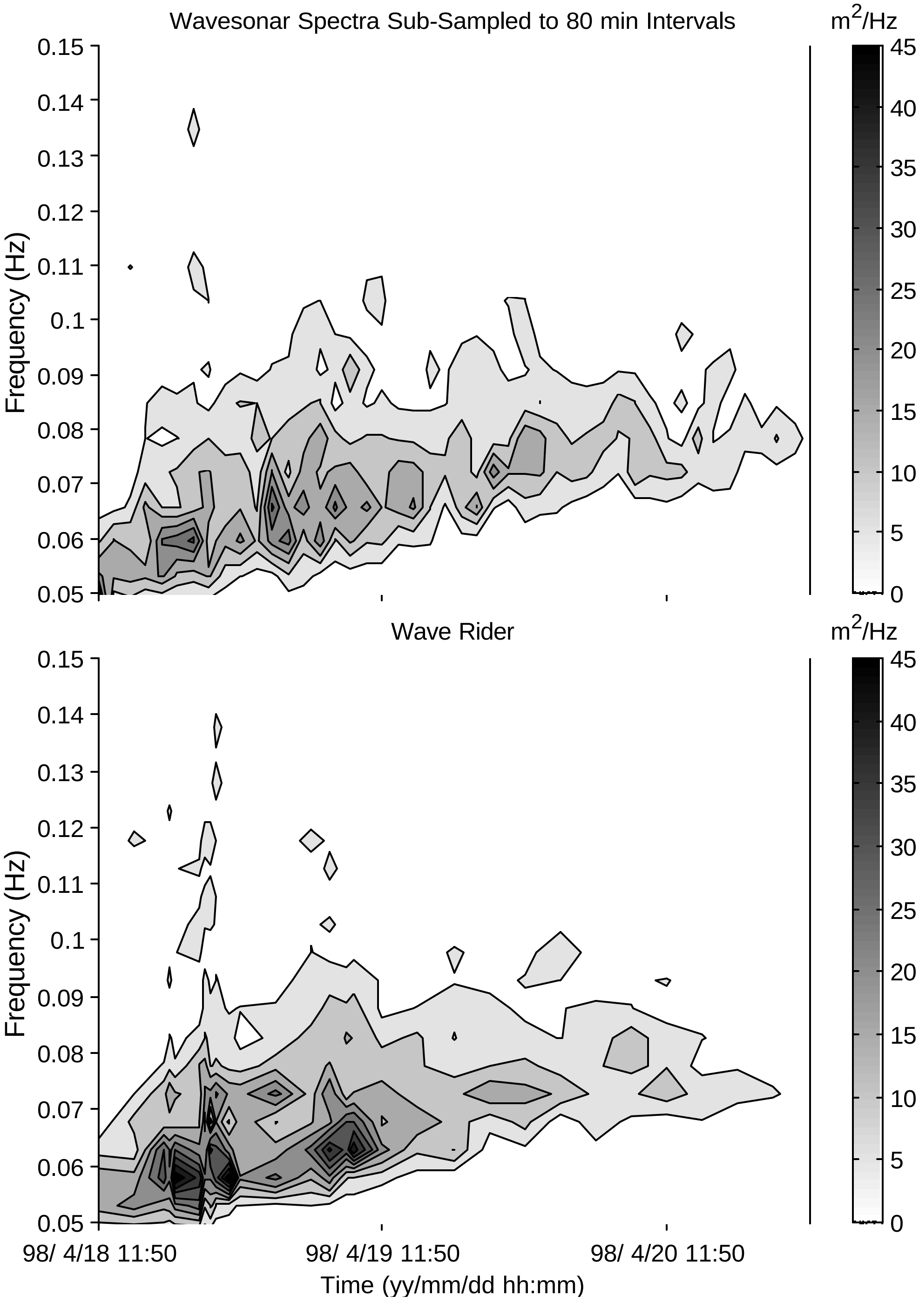


Figure 5: Comparison of the *WaveSonar* and Waverider wave spectral density as a function of frequency for April 18 to April 20, 1998.

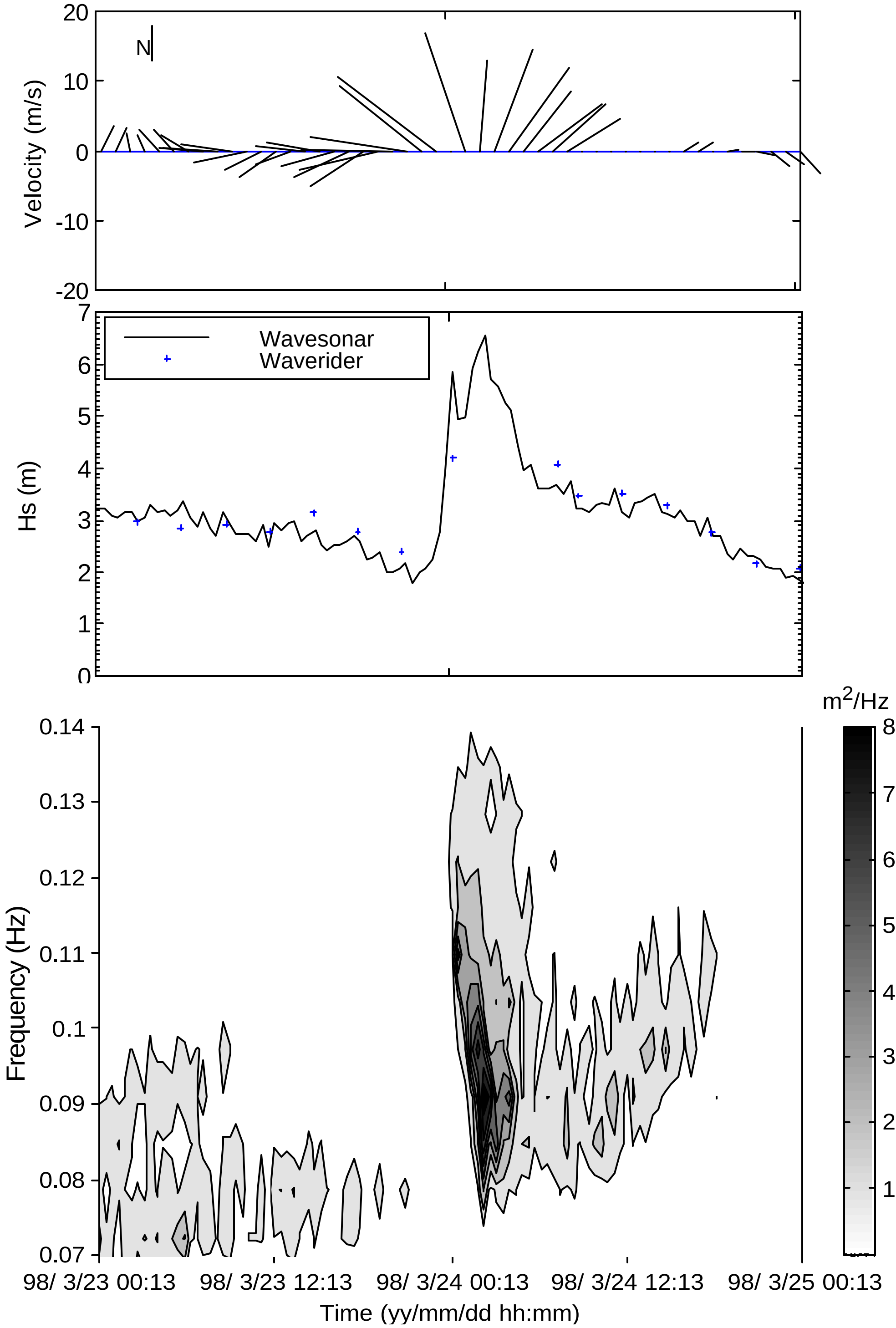


Figure 6: Waves generated by the March 24th storm. The top panel depicts the winds at La Perouse (hourly-averaged; dir'n towards). The middle panel shows the significant wave heights, measured by both the *WaveSonar* and Waverider. The bottom panel shows the wave spectral density as a function of frequency, as measured by the *WaveSonar* instrument.