MEASUREMENT OF THE WAVE WASH GENERATED BY FAST FERRIES WITH UPWARD LOOKING SONAR INSTRUMENTATION

David Fissel, Dave Billenness, and David Lemon
Oceanographers,
ASL Environmental Sciences Inc.

and

John Readshaw, P. Eng.
Project Manager
Sandwell Engineering Inc.

SUMMARY

Extended full scale field trials of a new fast ferry vessel, operating in the Strait of Georgia, British Columbia, were conducted to study the wake and wash characteristics of these vessels. The measurement program was comprised of two components:

(1) detailed measurements of the wake wash in comparatively deep waters (> 65 m) as the ferry was operated at various speeds and loads and

(2) simultaneous measurements of the wake wash in shallow (< 5 m) waters as the wash passed through nearshore waters before encountering the shoreline.

For the shallow, nearshore waters, a conventional bottom-mounted pressure-sensor wave instrument was operated. In the deeper waters, bottom pressure sensors are not usable due to the severe attenuation of the wave signal with increasing depth at the wave frequencies of the vessel wash. Instead, an upward looking sonar unit (ULS) or WaveSonar instrument, was operated from the seabed to measure the vessel wash. The ULS unit provided accurate, linear measurements, at sampling rates of up to 2 Hz, and was operated for many days at a time, storing its measurements internally. Being operated from the seabed, the instrument was safe from vandalism and damage due to collisions with ships, towed barges or types of marine traffic that can cause interruptions in data collection with surface wave buoy instruments in heavily traveled coastal waters. Indeed, the studies included measurements in which the ferry passed directly over the measurement site without risk of damaging the instrument.

Using the detailed measurements obtained with the WaveSonar and bottom pressure instruments, analysis and modeling of the ship wash was carried out by Sandwell Inc. to compute the propagation characteristics, wake height, period and energy density, and effects of the fast ferry vessel wash. Based on these measurements and analysis, a strategy was developed to operate the vessels, with minimal disturbances to other marine and shoreline users and the natural environment.

INTRODUCTION

In the summer of 1999, B.C. Ferry Corporation introduced a new class of ship, the PacifiCat class, to provide a fast ferry service. This new class of vessel is a catamaran of 122.5 m overall length with two hulls, each with a waterline length 96 m. The vessels have a fully loaded service speed of 34 knots, while the maximum speed varies from 34 to 40 knots, as a function of displacement, power and trim settings. The vessels can operate with a payload capacity of 250 vehicles and up to 1,000 passengers.

The PacifiCat fast ferry vessels are operated on a long-established ferry route across the Strait of Georgia, providing vehicle and passenger service between the Departure Bay ferry terminal in the city of Nanaimo (on Vancouver Island) with the Horseshoe Bay terminal, located near the city of Vancouver on the mainland of the west coast of Canada. The route, spanning a total distance of 33.5 nautical miles (nm), crosses the Strait of Georgia, where water depths range from 100 to 400 m over most of the route, as shown in Figure 1.

The field studies of the PacifiCat wake and wash were commissioned in response to concerns expressed by various stakeholders on the possible effect of the ship wash including the effects on beach users, small vessels at dock, and coastal environments. The overall project was managed by Sandwell Engineering Inc. Wave measurements were undertaken under sub-contract to ASL Environmental Sciences Inc.

WAKE MEASUREMENT PROGRAM

The vessel wake and wash measurements were carried out as full-scale field trials in a testing area located about 12 nm to the south of the ferry route itself, in the Strait of Georgia in an area immediately east of Galiano Island. Field tests were conducted in two separate phases. Phase 1 wake measurements were made in October and November 1999 at various speeds (18, 25, 30 and 35 knots) and offsets from straight line courses (0.5 nm to 3 nm, as shown in Figure 2) using a fixed load condition of 75% of capacity. Phase 2 of the study, conducted in March and April 2000, involved multiple runs of the PacifiCat at various speeds and distance offsets to measure wake characteristics at 0% of load capacity, slower speeds and during turn maneuvers. The studies also considered the effect of trim tabs, and the rate and degree of vessel turn. Phase 2 also obtained wake and wash measurements from two of the conventional C class vessels (MV Queen of Alberni and MV Queen of Coquitlam) in the BC Ferries fleet.

The wave measurement program consisted of two components:

(1) detailed measurements of all the wake wash components were obtained in comparatively deep waters as the ferry was operated at various speeds and loads in water depths ranging upward from 68 to 300 m and;

(2) simultaneous measurements of the wake wash in shallow (< 5 m) waters as the wash passed through nearshore waters before encountering the shoreline.

In general, measurement of ocean waves has been conducted with a variety of ocean instrumentation (Reference 1) including sensors mounted on surface buoys, or fixed platforms or from instrumentation located on the seabed. The buoy-based wave instruments use accelerometer sensors, which after analog electronic or digital processing to compute the required double integration, can estimate wave heights and periods. Data is usually relayed by radio or satellite to receivers operated at shore stations. However, wave buoys are prone to damage from the large waves themselves, from vessel traffic, and from vandalism. As well, under extreme wave conditions, in terms of large wave heights or very steep waves, wave buoys are prone to errors arising from limitations in the response of the accelerometer (Reference 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 comparatively safe and calm conditions of the bottom of the ocean. Bottom-mounted, internally recording instruments, that sample the wave-induced fluctuations of pressure, have been widely used for this purpose over the past 20 years (Reference 3). Near-bottom pressures provide an in-phase measure of instantaneous wave heights. However, the amplitude of the wave-induced pressure signal is attenuated, with increasing measurement depth, as a function of wavenumber or frequency. 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.

For the shallow, nearshore measurement site, a conventional bottom mounted pressure-sensor wave instrument was used. The bottom pressure wave instrument was operated from the seabed in 5 m water depth just off the shoreline of Galiano Island (Figure 2). The instrument uses a high precision Paroscientific Digital Quartz pressure sensor having an accuracy of ± 0.015% of full scale range (100 psia) and a resolution of ±0.003% of full scale range. Data is stored internally within the instrument.

Samples of the shallow water measurements, during passages of the PacifiCat vessel as measured using the pressure sensor wave instrument, are shown in Figure 3. Over a period of 3 hours on November 8, 1999, the PacifiCat vessel carried out six runs travelling parallel to the shoreline (Figure 2) at distances ranging from 0.5 nm to 3 nm from the shoreline.

The correction of the measured bottom pressure to surface levels was applied to account for the attenuation of the observed wave height (derived from pressure p). The wave height is reduced as a function of the wavenumber (k) as described in equation 1:

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

where η is the sea surface level, ρ is the density of the 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. The pressure data was converted to water levels by removing a constant atmospheric pressure offset of 10.1325 db and then dividing by ρg. A water density of 1022.7 kg/m^3 was used based on CTD profiles taken near Vancouver Island in January 2000. The wave number k, in turn, was calculated for each analyzed frequency bin based on the dispersion relation:

$$\sigma^2 = g \cdot k \cdot \tanh(kh) \qquad (2)$$

where σ is the angular frequency (2π times the frequency). The correction factor amplified the highest frequency waves the most. For 5 m water depth, the correction factors are generally small, being less than 2 for wave periods of 3 seconds or greater and well within the resolvable signal to noise levels of the instrument for periods exceeding 2 seconds. The frequency dependent correction factors were applied to subsets of the pressure data set, applied over data segments of 3600 point bursts (= 1 hour of data). For each burst data segment, the water depth was taken to be the sum of the mean water height for the burst, and the height of the pressure sensor above the seabed (~ 0.16 m).

For deeper waters, as previously discussed, bottom pressure sensors are not able to measure important parts of the higher frequency (shorter period) portions of the ocean wave spectrum, due to the severe attenuation of the wave signal with increasing depth. At the deepwater wave measurement site of this study, at 68 m water depth, conversion of the bottom pressure data to instantaneous water levels, based on equations 1 and 2, was carried out using an upper frequency cutoff. This frequency cutoff was selected so that the low signal to noise ratio region encountered at high frequencies would not dominate the lower frequency regions of the spectrum. Instead of choosing a single cutoff frequency, after detailed experimentation, the correction factor was limited to 200 and contributions from higher frequencies were set to zero. This approach limits the resolvable wave period from the corrected wave heights to values of 6.8 seconds or larger, which results in the loss of important information on the shorter period wake waves, such as the secondary diverging wave mode from the vessel (see Data Analysis section below) and the decomposition of the initial primary diverging wake into its constituent frequencies.

To allow measurement of the full wave spectrum for ship wakes using a seabed mounted sensor, an upward looking sonar unit (ULS), was used at the deepwater measurement site. The ULS, also known as a WaveSonar instrument, provided accurate, linear measurements, at sampling rates of up to 2 Hz, and was operated for many days at a time.

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, and 2.1 m for 68 m at the deepwater measurement site in the present study. 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.

Like the bottom pressure instrumentation, the ULS or Wave Sonar instrument, stores its measurements internally. 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°.

The WaveSonar instrument, was previously tested through an intercomparison study with a conventional buoy-based accelerometer sensor (a Datawell Waverider buoy) and a bottom pressure sensor in 35 m water depth. The results of the intercomparison study (reference 4) revealed good agreement between the WaveSonar and Waverider instruments.

The instrument was operated from a mounting frame (Figure 4) which allowed upward orientation of the instrument even if the seabed was not level. Installation was accomplished by lowering the instrument and mounting frame from a small vessel. The position of the instrument was determined using a Differential Global Positioning System (DGPS) receiver from the deployment vessel, and measured slant ranges from the vessel to the instrument obtained through an acoustic transponder unit attached to the mounting frame. The accuracy of the WaveSonar position was determined to within ± 5 m.

Being operated from the seabed, the instrument was safe from vandalism and damage due to collisions with ships, towed barges or types of marine traffic that can cause interruptions in data collection with surface wave buoy instruments in heavily traveled coastal waters. Indeed, the studies included measurements in which the ferry passed directly over the measurement site without risk of damaging the instrument or the vessel. This capability provided invaluable information on the characteristics of the transverse wake behind the vessel.

The WaveSonar was operated for three periods: October 21 to Nov. 2, 1999; Nov. 8 to 23, 1999; and March 24 to April 3, 2000. In the first two data sets, continuous measurements of instantaneous water level elevations were obtained at 1 sample each second, while in the third data set, a continuously sampling rate of 2 measurements per second was used. For all data sets, a full record of time series measurements of waves was obtained. A sample of WaveSonar data is presented in Figure 6.

During the full scale field trials, the PacifiCat vessel speeds and positions were logged using the onboard ECDIS (Electronic Chart Display Information System), which was upgraded to provide measurements at 15 second intervals. The times of arrival of wakes at the wave measurement sites were determined from the times of the episodic events measured from the acoustic and pressure instruments, as supplemented using the measured arrival times observed from the PacifiCat's Rescue Boat (deployed at the deepwater measurement site), and plotted times of wake trajectories.

DATA ANALYSIS

From the detailed measurements obtained with the WaveSonar and bottom pressure instruments, analysis and modeling of the ship wash was carried out by Sandwell Inc. to compute the propagation characteristics, wake height, period and energy density of the fast ferry vessel wash (reference 5).

As the route on which the PacifiCat vessels are operated (Figure 1) is almost entirely in water depths exceeding 65 m, the wake waves propagate in a conventional Kelvin wave sub critical pattern. The wake waves consist of diverging wakes and a transverse wake. The diverging wakes have three principle components (Figure 5):

- primary diverging wake, generated by the hull pushing water aside at the bow;
- secondary diverging wake, which is the result of convergence of the primary diverging waves from inner sides of the catamaran hull;
- tertiary diverging wake from the convergence of the water jets astern of the vessel.

As would be expected in areas where the wake waves satisfy the deepwater criteria, the wake pattern generated by the vessel is constant for a given vessel speed.

Wave heights and wave periods were computed using the WaveSonar and bottom pressure data sets for the individual modes of the diverging and transverse waves, for each of the various field trial runs. At a vessel speed of 34 knots, the primary diverging wave has a height of 1.0 m near the vessel and wave period of 9 s.

For the same vessel speed, the secondary diverging wave has a height of 0.3 m with a wave period of about 4 s, and the corresponding values for the transverse wake waves are 0.2 m and 11.2 s.

The period (T in seconds) of the primary and the seconding diverging wave modes were found to be proportional to the vessel speed (S in knots), according to the relationship:

$$T = K \cdot S \qquad (3)$$

where K is a constant value. For the primary diverging wave, K was determined to have a value of 0.27 which is consistent with theory. The secondary diverging wave mode, K had an empirically determined value of 0.135. The primary diverging wave has a period T = 5.4 s, for a vessel speed of 21 knots, while the value of T is 9.2 s at a vessel speed of 34 knots.

The diverging wake wave modes decay according to a power law relationship with the distance (x) away from the vessel, as follows:

$$H(x) = A \cdot x^{-1/3}$$

where H (x) is the wave height in m after the wave has traveled x nautical miles (nm) and A is the wave height decay coefficient, defined as the wave height in m after 1 nm. The wave height decay coefficient, A, was found to increase from values around 0.3 to 0.45 (at vessel speeds of 18 to 25 knots) to values of 0.7 to 0.9 at vessel speeds of 30 to 35 knots. For the secondary diverging wave, the value of A varies less with vessel speed, generally falling in the range of 0.34 to 0.55 over speeds of 20 to 34 knots.

Transverse waves decay in proportion to $x^{-1/2}$, rather than in proportion to $x^{-1/3}$ as is the case for the diverging wave modes. Transverse waves exhibit sensitivity to vessel load, being larger by approximately 0.1 m, for a nominal 75% load by comparison to no (0%) load. Unlike the transverse wave mode, the primary diverging wave height showed no significant sensitivity to vessel load, at the service speed.

The effect of vessel turns on the diverging wake mode wave heights was also examined. At locations on the outside of a turn, the wave heights are significantly smaller compared to the same wave heights at the same distance while the vessel is operated on a straight course. Measurements showed that turns were very effective in reducing wave heights, if carried out at high speeds and at higher rates of turn. Turns made at slow speed were still effective if the turn was made quickly.

The wake wave heights from the PacifiCat vessels operated at 18 to 25 knots were nearly constant and smaller in magnitude than the wake wave heights generated by the conventional C class vessels, which were operating in that area.

OPERATIONAL STRATEGIES AND MITIGATIVE MEASURES

From the results of the full-scale field studies, as briefly described above, a detailed description of the wake characteristics of the PacifiCat was developed. This knowledge base permitted accurate modeling and review of all aspects of the vessel wake and wash effects. Operational strategies were subsequently developed to allow operation of the vessels at normal operating speed, so as to minimize disturbances to other marine vessels, as well as minimizing coastline impacts. The strategies included: speed changes and course changes on the routes. Refinements to vessel handling strategies, when approaching other vessels, were also developed to minimize or eliminate effects, when responding to requests from other vessels for minimum wash ("slow bell"). As well as reducing effects of the wake wash on other vessels and mitigating the environmental impact on the shoreline, the results from the study have led to modified route passage plans which decreased the crossing times by an additional 2 to 3.5 minutes.

REFERENCES

1. "Ocean Wave Measurement Techniques", R. H. Stewart, in "Air-Sea Interaction", ed. F. Dobson et al., Plenum Press, New York, 1980.

2. “Detailed measurements of winds and waves in high seastates from a moored NOMAD weather buoy”, S.G.P. Skey, K. Berger-North, and V.R. Swail, in Proc. “4th International Workshop on Wave Hindcasting and Forecasting”, Oct. 16-20, 1995, Banff AB, Environment Canada, Downsview ON, 1995.
3. “Field Intercomparison of Nearshore Directional Wave Sensors”, W.G. Grosskopf, D.G. Aubrey, M.G. Mattie and M. Mathieson, IEEE Journal of Oceanic Engineering, Vol. 8, 1983.
4. “Wave measurements using upward-looking sonar for continental shelf applications”, D.B., Fissel, J.R. Birch, K. Borg, and H. Melling, in Proc. Offshore Technology Conference, Houston, TX, USA, 3-6 May 1999.
5. “Fast Ferry Program – Wake and Wash Project”, Sandwell Engineering Inc. report to BC Ferry Corporation, August 2000.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the considerable contributions of the masters and crews of the PacifiCat Discovery, whose professional seamanship contributed significantly to the success of this project. The conclusions of this paper reflect the opinions of the authors. The full project report describing all aspects of the project is available from the B.C. Ferry Corporation, Victoria, B.C., Canada.

FIGURES

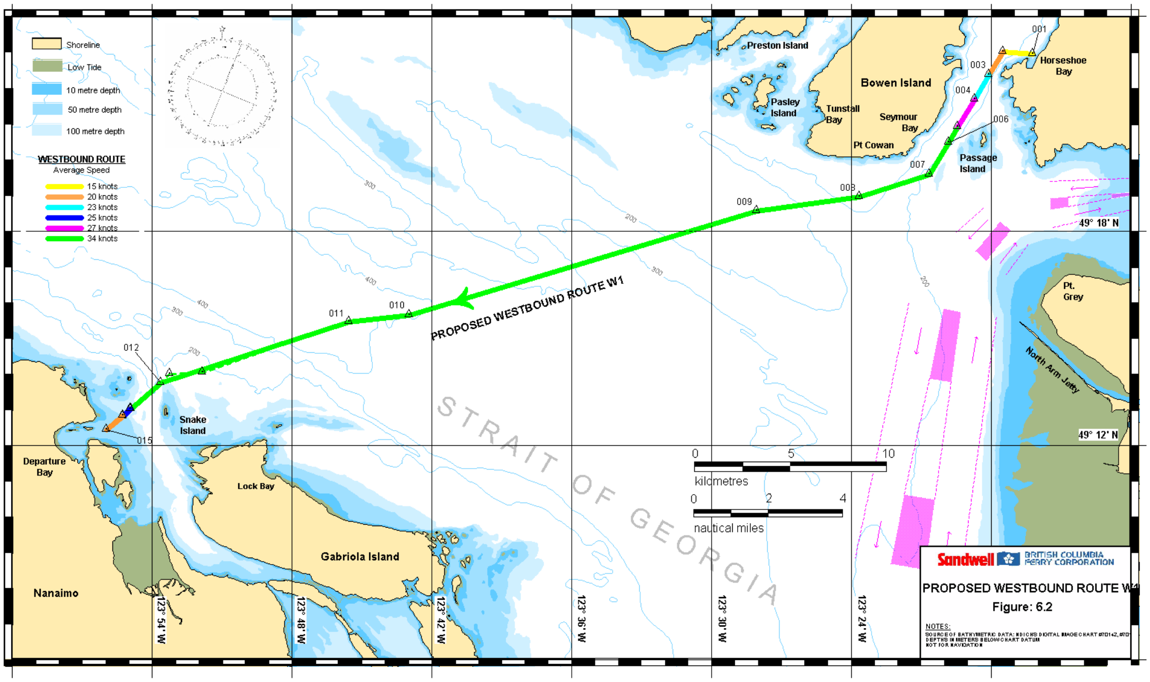

FIGURE 1: Proposed route for westbound service on the PacifiCat run from Vancouver (Horsehoe Bay terminal) to Vancouver Island (Departure Bay terminal).

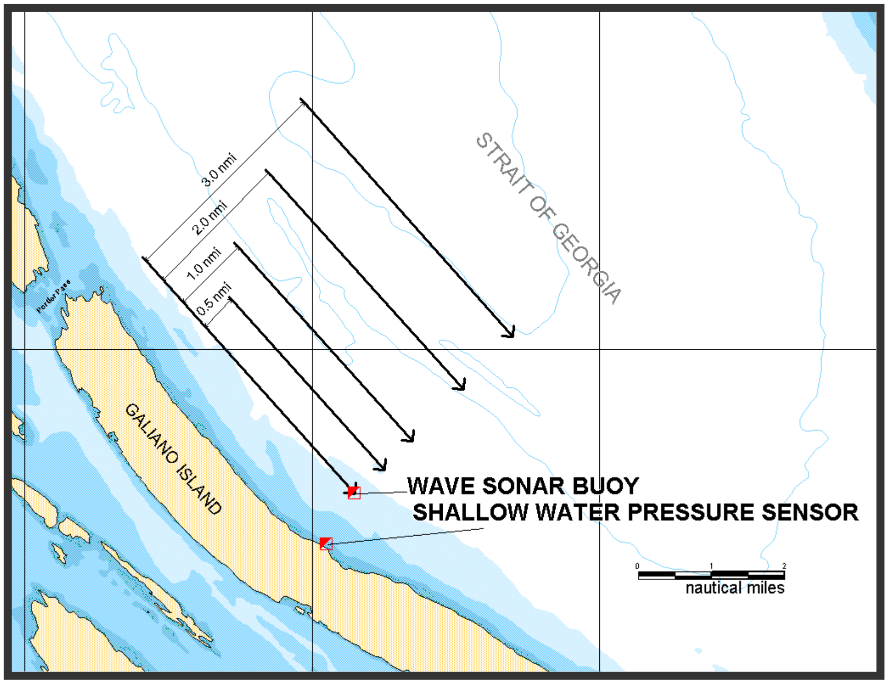

FIGURE 2: The locations of the wave measurement instruments in relation to the measurement offsets used in different runs of the PacifiCat as part of the field trials.

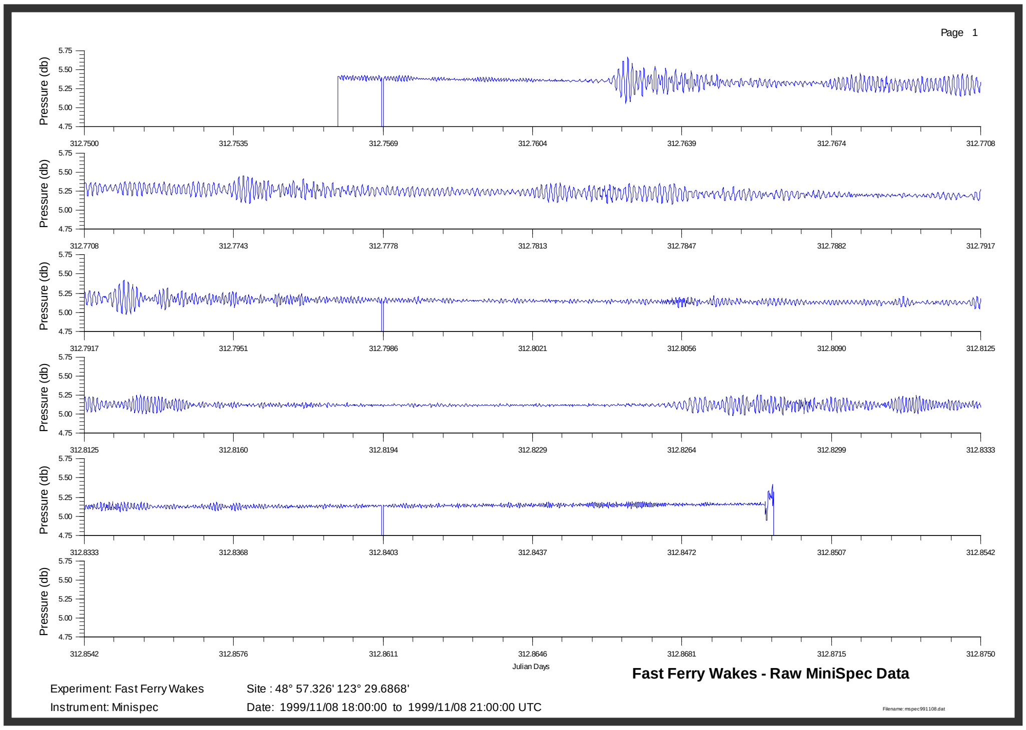

FIGURE 3: A sample data set from the pressure sensor wave instrument, operated in 5 m water depth, over a 3 hour period from 1800 to 2100 UTC, November 8, 1999. The short gaps in the measurements, occurring at 10 minutes after every hour, result from instrument down time required to transfer the data to onboard data storage.

FIGURE 4: Photograph of the upward looking sonar (WaveSonar) instrument as well as the mounting frame, prior to deployment. The WaveSonar was used for ship wake waves measurements at the 68 m deepwater measurement site.

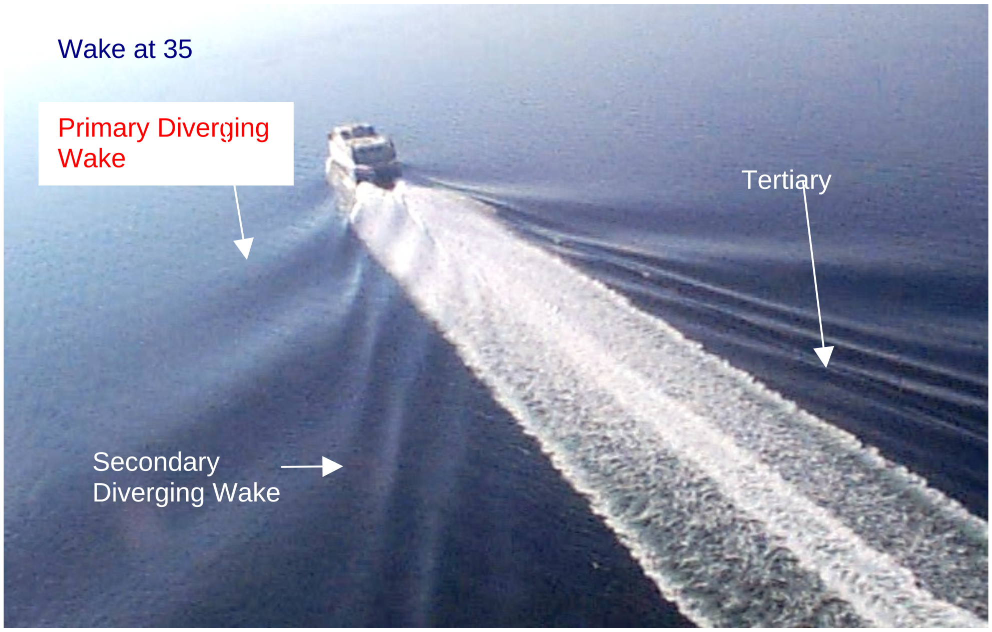

FIGURE 5: A photograph of the PacifiCat wake showing the three diverging wake characteristics. A transverse wake is also present, but barely visible directly behind the vessel.

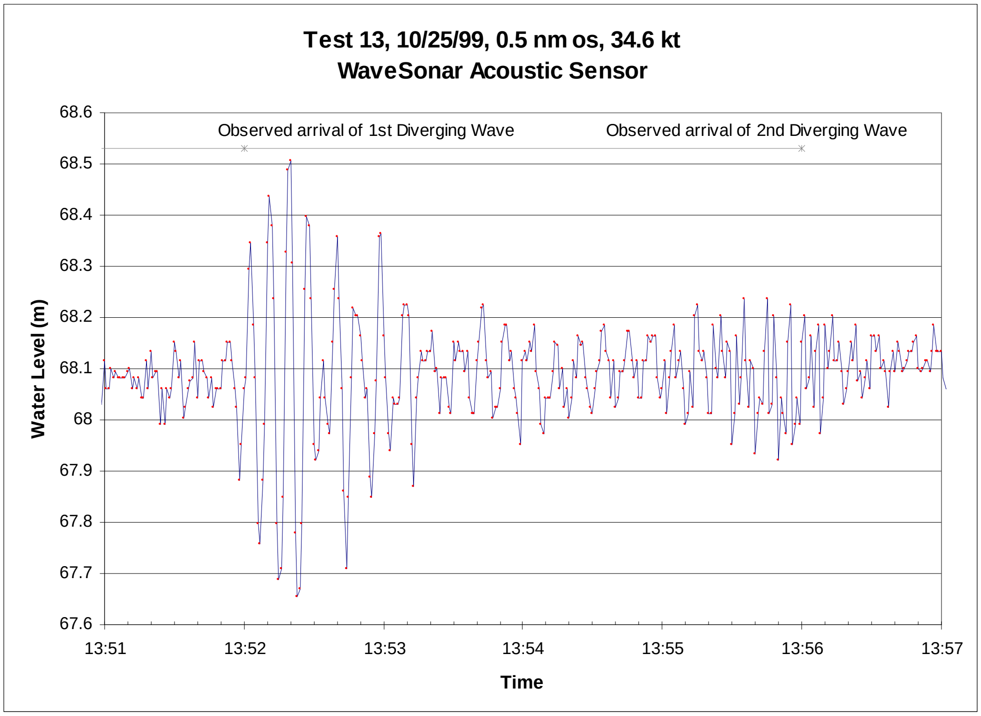

FIGURE 6: An example of typical wake data obtained with the Wave Sonar acoustic instrument.

DAVID B. FISSEL
David Fissel is Vice-President of ASL Environmental Sciences Inc., and recently became the founding president of a new subsidiary company, ASL AQFlow Inc. He graduated from the University of British Columbia with an M.Sc. in Physical Oceanography (1975). He has over 25 years experience as a physical oceanographer, mostly at ASL since joining the company as a founding partner in 1977.

DAVE BILLENNESS
Following graduation from the University of Victoria with a M.A.Sc. in Mechanical Engineering, Dave Billenness joined ASL in 1997. At ASL, his responsibilities include data processing, analysis, programming, report preparation, field measurements and engineering-related studies.

DAVID D. LEMON
David Lemon is President of ASL Environmental Sciences Inc. After completing his M.Sc. in Physical Oceanography at the University of British Columbia, he took a position as Defence Scientist at the Operational Research and Analysis Establishment of the Canadian Dept. of National Defence. Joining ASL in 1978, he has been responsible for many scientific studies, involving oceanography and underwater acoustics.

JOHN READSHAW
John Readshaw is the manager of Coastal and Ocean Engineering, Sandwell Engineering Inc., Vancouver, B.C., Canada. He graduated from Queen’s University at Kingston, Ontario, Canada with an M.Sc. in Applied Science. He has over 25 years experience as a coastal and ocean engineer and he was project manager for the wake and wash study.