A STUDY OF ECHO SOUNDING FROM HIGH SPEED HYDROGRAPHIC LAUNCHES

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A STUDY OF ECHO SOUNDING FROM HIGH SPEED HYDROGRAPHIC LAUNCHES

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1. INTRODUCTION

Beginning in 1968, the Pacific region of the Canadian Hydrographic Service has conducted hydrographic surveys in sheltered, coastal waters using high speed Bertram launches. While highly successful for operations in shallower water, the launches cannot make soundings at high speeds (> 6 m/s or 12 knots) in deep water (350-400 m or more). The problem has arisen in surveys of the deep, steep-sided B.C. coastal inlets, forcing sounding operations at half the vessel speed (avoiding the high speed vessel planing mode); this limitation results in a significant loss of time over what could be achieved by sounding at full vessel speed.

The objective of this study was to carry out a system analysis of the acoustic signal and noise characteristics of the echo-sounder system in a typical hydrographic launch, based on previously collected data and earlier studies. Based on the results of this analysis, the principal sources of performance degradation would be tentatively identified. Measures to confirm the diagnosed noise sources and, where practical, to improve the system performance would be implemented and tested in conjunction with the Canadian Hydrographic Service, Institute of Ocean Sciences, using one of the launches. Successful completion of the project would aid in the long range objective of improving signal levels in order to extend the application of electronic depth digitization for 'automated' survey operations (Watt, 1978).

2. THE PRESENT SYSTEM

2.1 HYDROGRAPHIC LAUNCHES

The Bertram launches are of fibreglass construction 7.6 m (25 feet) in length, with a draft of approximately 0.7 m (2.3 feet) and a beam of 2.4 m (8 feet) as shown in Figure 1. At full speed, the launches attain speeds ranging from 8.2 to 9.3 m/s (16 to 18 knots), varying among the individual units. The launches are powered by a Detroit Diesel GV-53N engine through a V drive transmission and a 19" x 19" propeller turning at approximately 1800 RPM at full speed. On attaining a speed of approximately 5 m/s (10 knots), the vessels begin to plane; the level of the bow relative to sea level rises approximately 0.4 m (1.3 feet).

The launches are equipped with Skipper (Simrad) echo sounders operating at 50 KHz with a power output of 750 watts. Having a downward beamwidth of 20 degrees, the sounder transducer is situated in a well within the hull. The bottom of the well consists of 1/8" thick fibreglass mounted in the 1" hull.

2.2 PREVIOUS STUDIES

As part of an ongoing effort to improve the sounding capabilities of the launches, the acoustic noise characteristics of these vessels were measured at the Esquimalt Sound Range from 0925 to 1148 PST April 17, 1978 (Naval Engineering Unit Pacific, 1978). Weather and sea conditions consisted of: wind speeds of 5 to 10 knots at the start and 15 to 20 knots by the completion with sea states increasing from sea state 1 to sea state 2. In total, 14 individual runs were carried out. In half of these, the launch passed the hydrophone on the starboard side, while in the other half, the launch passed over the range with the hydrophone on the port side. The number of tests as a function of engine RPM were: 2 (2850), 4 (2700), 2 (2500), 2 (2250), 2 (2000) and 2 (1000). One of the tests (2700 RPM, starboard side) was performed with the ship engine clutch disengaged. The results, shown in Figure 2, reveal that acoustic noise levels at 50 KHz generated by the launches range from 111 to 121 dB (expressed as an equivalent source pressure re 1 micro Pascal at 1 m) at full speed (2700-2800 engine RPM). The levels are reduced by approximately 7 dB for an engine speed of 2000 RPM and reduced by 22 dB (to approximately 93 dB) for an engine speed of 1000 RPM. In the latter case of low engine speeds, the generated sound levels were 2-3 dB greater than the noise generated by the launches running at full engine speeds with the clutch disengaged.

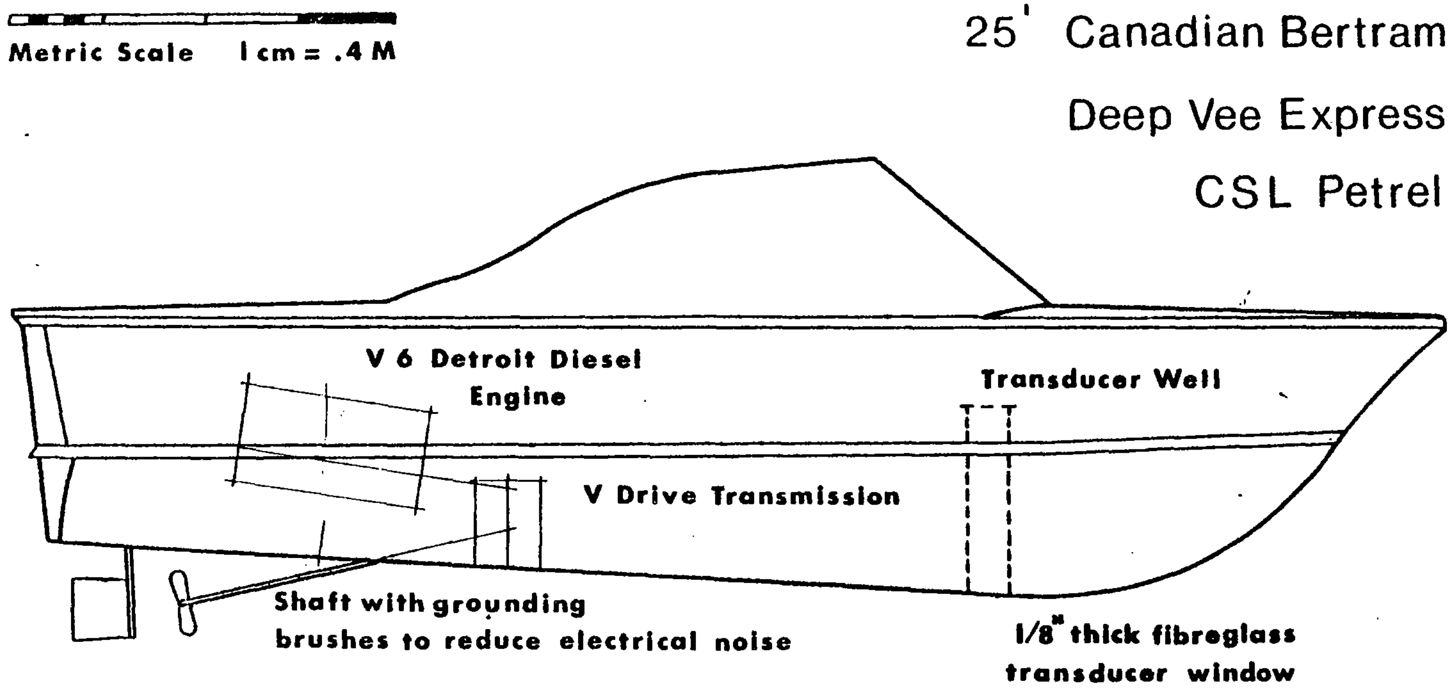

Figure 1: The hull design and location of equipment on the C.S.L. Petrel.

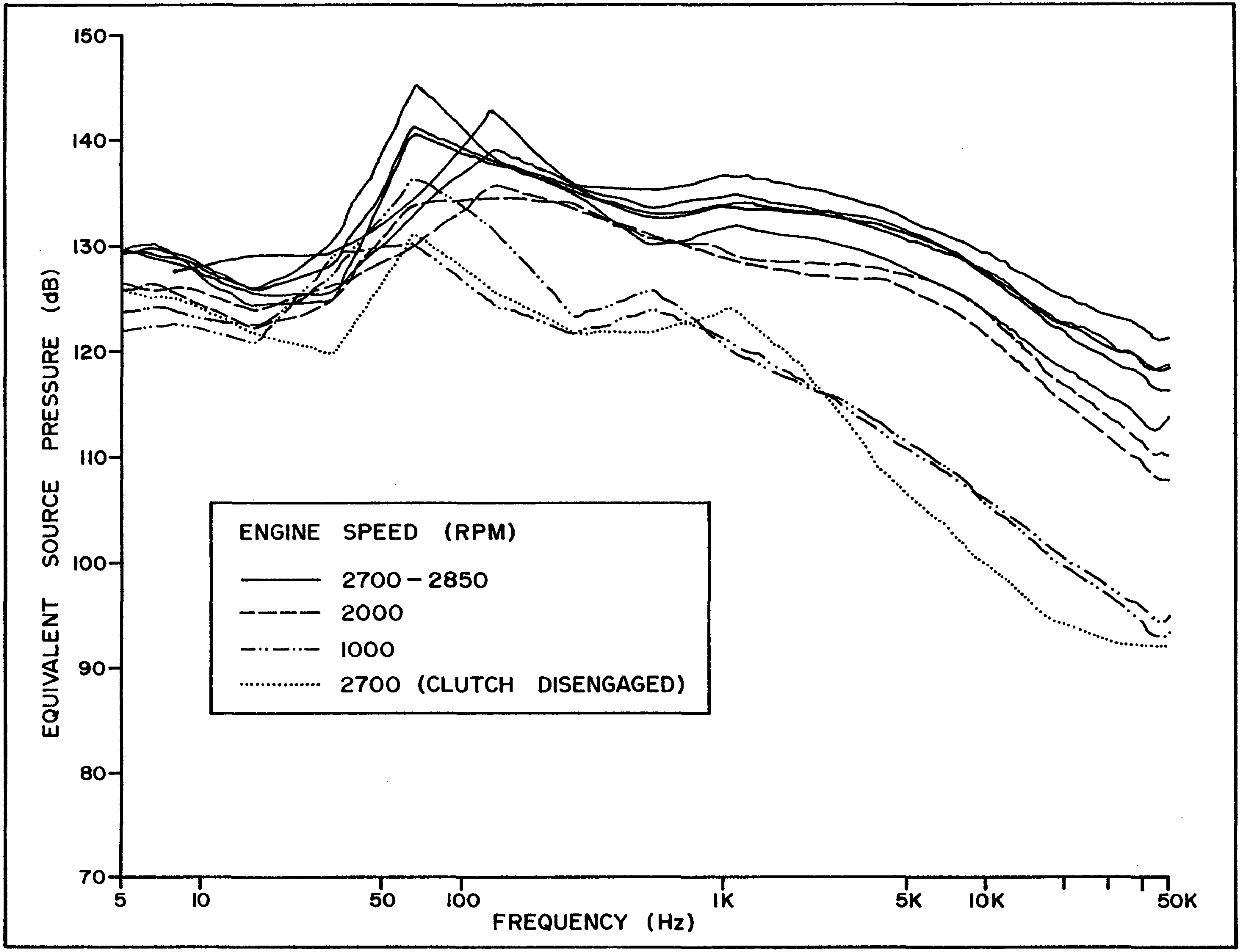

Figure 2: A summary of noise source levels for the C.S.L. Petrel, as measured at the Esquimalt test range, April 17, 1978. Results are shown for all tests obtained at engine speeds of 2750, 2700, 2000 and

In 1979, a detailed study was undertaken by O'Connor (1980) to optimize the sounding records from the high speed launches. The key findings of this study were:

1) The optimum placement of the sounder transducer was approximately 2/3 of the vessel length from the stern. Increasing the distance from the stern reduced received acoustic noise levels due to the machinery and propellers, but placement too close to the bow resulted in acquiring noise from the bow wave.

2) A major source of acoustic noise was identified as cavitation around the blades of the propeller. Comparisons in sounder output and generated noise levels (Figure 2) were made between Bertram launches and a 9.5 m (31 foot) water jet driven launch, of aluminum hull construction, capable of reaching speeds of 12.4 m/s (24 knots). A notable improvement in signal to noise levels was evident on the sounder charts obtained from the jet boat over a test range in Haro Strait (maximum depth - 380 m). At 50 KHz, generated noise levels from the jet boat were approximately 4-5 dB lower than those of the launch.

3) Sources of electrical noise were identified and remedied by means of grounding of the machinery, installation of electrical noise suppression kits and use of an isolated power supply for the echo sounder. These measures have been applied to all of the Bertram launches presently in use, although the degree to which these electrical noise prevention techniques are maintained is not clear.

An earlier study by Watt (1978) was carried out to extend the bathymetric capabilities of the M.V. Pandora II. While the vessel is much larger than the Bertram launches, the problem and solution to it may be of some relevance to the present study. The greatly reduced bottom returns detected by the 12 KHz hull-mounted transducers were identified as being due to an aeration effect. This problem was greatly exacerbated in moderate to heavy seas, when the ship's motion (rolling and pitching) caused severe bubble sweep down from the bow wave and heavy aeration. Tests carried out in Saanich Inlet, using an upward-looking 200 KHz transducer mounted on a tripod beneath the hull revealed that the thickness of the aerated water layer was 15 to 30 cm, when small surface waves were presented (0.6 to 0.7 m, peak to trough). The solution involved construction of a retractable transducer arm mounted through the hull; for surveying operations, the transducer was extended 1.2 m beneath the hull. This arrangement provided excellent results, providing bottom returns to depths of 3000 m, even in moderate seas.

The possibility of signal attenuation due to a bubble layer beneath the transducer was investigated in the 1979 tests. The sounder transducer was mounted on an arm extending beneath the hull; no significant difference was noted in comparisons with the soundings obtained in the conventional well mounting arrangement (O'Connor, personal communication).

3. THEORETICAL ANALYSIS OF ACOUSTIC LEVELS

3.1 SONAR EQUATION

Theoretical analysis of the echo sounding system aboard the launch begins with the sonar equation for an active system in which the background is most likely to be noise (Urick, 1975):

$$SL - TL - TS - DT = NL \tag{1}$$

where SL is the source level of the transmitter, TS is the target strength of the bottom, NL is the noise level, DT is the detection threshold of the receiver and TL is two-way transmission loss through the water to the target (the bottom, in this case). (Note: Sonar quantities are expressed on a logarithmic scale in decibel units, where the decibel value is $10 \log_{10}$ times the physical value relative to a reference level.) The dependent parameter in this case is TL, the transmission loss, which is mainly a function of depth. Changes in any of the other parameters will thus be reflected in a corresponding change in the allowable value of TL which still results in signal detection, and determines the depth in which the sounder can operate. This requirement can be expressed as

$$EL - NL > 0 \tag{2}$$

where the echo level (EL) represents the left-hand terms of Eq. (1).

In order to identify the sources of echo sounding performance degradation, and any compensating measures, a literature search was carried out to identify pertinent information related to the various terms in Eq. (1). This involved manual searches of the libraries of the Institute of Ocean Sciences and the University of Victoria. In addition, computer-assisted searches were conducted by the Canada Institute for Scientific and Technical Information of the National Research Council (NRC), Ottawa. In the NRC literature search, emphasis was placed on identifying reports addressing the question of underwater air bubble acoustics (Section 3.3.2). The following data bases were consulted:

MRIS/NTIS	(U.S. Marine Research Information Service/ National Technical Information Service)	1970-present
ASFA	(Aquatic Sciences and Fisheries Abstracts)	1978-present
OCEANIC	(Oceanic Abstracts)	1964-present

During the literature review, other groups engaged in sonar research (Defence Research Establishment Pacific (DREP); Royal Roads Military College) were consulted as well.

Along with the literature review, the results of previous studies of echo sounding from the launches (Section 2.2) and records from routine surveying operations were studied. The information gathered from the literature review and previous IOS field studies are applied below to provide quantitative estimates of the expected values of each term in Eq. (1).

3.2 SOURCE LEVEL (SL)

The sounder source level is given in terms of its radiated acoustic power P (in watts)

$$SL = 170.7 + 10 \log_{10} P + DI \quad \text{(Urick, 1975)}$$

DI is the projector directivity index and is given by the reciprocal of the fraction of the whole solid angle of 4π steradians that its beam occupies. The 50 KHz sounders in question have a beamwidth of 19° are driven at 750 watts (electrical power) with a 21% efficiency. Assuming that the outgoing power is uniformly distributed over the beamwidth, we therefore have

$$DI = 10 \log_{10} \left[1/4\pi \int_{0}^{2\pi} \int_{0}^{9.5} \sin\theta d\theta d\phi\right]$$

$$= -10 \log_{10} \left[1/2\ (1 - \cos 9.5)\right]$$

$$= 21.6$$

The beam is in effect not that precise. According to the manufacturer (Giske, 1984), the transmission response of the transducer is 185 dB re 1 micro Pascal per watt. Therefore DI = 185 - 170.7 = 14.3 dB. At 21% transducer efficiency, $10 \log_{10} P = 10 \log_{10} (0.21 \cdot 750) = 22.0$.

Then, SL = 170.7 + 22.0 + 14.3 = 207 dB

Uncertainties in estimating SL arise from the use of nominal values for transducer efficiency and by neglecting side lobes in the angular distribution of the outgoing acoustic signal. Combined errors due to both of these uncertainties likely amount to less than 5 dB.

3.3 TRANSMISSION LOSSES

Transmission losses result from three distinct sources: attenuation as the acoustic pulse travels through the water column; attenuation due to the possible existence of a boundary layer immediately beneath the hull containing air bubbles; and losses of the signal in the transducer well and the hull of the launch. The first two types of attenuation are described in some detail below in (Subsections 3.3.1 and 3.3.2, respectively) on the basis of the existing literature. The third type of loss is highly dependent on the acoustic properties of the hull and transducer well. Some inferences can be made concerning this type of attenuation from the results of the field trials (Section 4).

3.3.1 SEAWATER ATTENUATION

The transmission loss through the water column (TL) consists of spherical spreading (inverse-square law) and absorption, as given by:

$$20 \log_{10} (r) + \alpha r$$

where r is the distance travelled and α is the absorption coefficient.

Absorption losses in the water column result from a conversion of acoustic energy into heat. In seawater, this conversion is very complex, involving three distinct processes. Empirical formulae have been derived, from which the absorption coefficient, α_o (at a pressure of one atmosphere) can be calculated given the temperature and salinity characteristics of the water column (Urick, 1975; pp. 99-100). According to the formula:

$$\alpha_o = a \cdot S \cdot f^2$$

where S is the salinity, f is the sound frequency and a is a temperature dependent empirical factor. The temperature and salinity dependence was interpolated from tabulated values provided in Urick, 1975, Table 5.2, p. 100. Values of the surface absorption coefficient at the surface for a range of B.C. coastal TS conditions are given in Table 1.

Table 1: Sound absorption coefficient (α_0) in seawater computed at 50 KHz for various temperature (°C) and salinity values (parts per thousand) at the surface.

T/S	28	30	32	34
6°	.0189	.0202	.0215	.0229
8°	.0173	.0185	.0197	.0210
10°	.0158	.0169	.0180	.0192
12°	.0144	.0154	.0164	.0175

In the inlets of the B.C. coastline, the water column consists of a shallow upper zone, having higher temperatures and lower salinities overlying a deep zone of relatively uniform temperature-salinity properties. The boundary between the two zones is marked by very large vertical gradients. Typical depths of this boundary range from a few metres up to 10-15 m. Because of the comparatively small vertical dimension of the shallow zone, the absorption coefficient can be computed to a good approximation, on the basis of the temperature-salinity values of the deep zone. For this purposes, the inlets of the B.C. coast can be divided into three groups (Pickard, 1961): a northern group (Smith Inlet and those to the north of it), a southern group (Indian to Loughborough Inlets) and an intermediate group located between the other two. The deep zone temperature-salinity values are summarized in Table 2. (Note that temperature and salinities during the field tests (Section 4) in Haro Strait are expected to be approximately 8°C and 31 in late winter, based on the historical data presented in Pickard, 1975, p. 1573).

Table 2: Mean values of subsurface temperature and salinity of the water in the inlets of the British Columbia mainland coast (from Pickard, 1961, p. 938).

Inlets	Depth 20 m		50 m		100 m		200 m		400 m	
	T	S	T	S	T	S	T	S	T	S
Northern Group	7.0	31.0	6.5	32.0	6.5	32.7	6.3	33.0	6.3	33.2
Intermediate Group	8.0	29.4	7.0	30.5	6.6	30.8	7.3	31.2	7.3	31.2
Southern Group	8.0	29.0	8.0	29.5	7.5	30.0	8.1	30.5	8.3	30.7

For a northern inlet (T = 6.4, S = 33.0, representative of conditions over the subsurface layer to 400 m) the surface value of the absorption coefficient, as interpolated from Table 1, would be approximately 0.022. In one of the more southern inlets (T = 8.0, S = 30.5, representative of conditions over the subsurface layer to 400 m), the surface absorption coefficient, as interpolated from Table 1, would be lower at 0.019. This latter value would be close to that encountered in the field tests of this study.

The absorption coefficient also varies with depth according to

$$\alpha = \alpha_o (1 - 3.27 \times 10^{-5} P)$$

where P is the pressure at total depth in decibars. For a depth of 400 m, the surface coefficient would be reduced by a factor of 0.987, a small amount by comparison with other factors.

In the deeper waters of the B.C. inlets, the range in the absorption coefficient is small, 0.019 to 0.022. For example, over this range of absorption coefficients, in 400 m water depth, the limit of depth detection would change by approximately 36 m (i.e. $TL = 20 \log_{10} \cdot r + \alpha r = 73.26$ dB for $\alpha = 0.019$, r = 800 m, and $\alpha = 0.022$, r = 728 m).

3.3.2 BUBBLE LAYER ATTENUATION

It is well-known that the presence of bubbles in seawater can lead to a significant increase in the attenuation of sound passing through the bubbly region (Clay and Medwin, 1977). At the high frequencies used for echo-sounding equipment, the attenuation is primarily due to absorption and scattering by microscopic bubbles which undergo resonant oscillations at the frequency of the acoustic radiation. The primary loss is caused by absorption due to viscous and thermal damping, with a smaller fraction (about 10-20%) arising from scattering through re-radiation.

The relative intensity I/I_o of sound which has passed through a layer of water of thickness x containing a spatially uniform distribution of bubbles is given by

$$I/I_o = \exp(-S_e x)$$

where S_e is the extinction cross-section per unit volume for a mixture of non-interacting bubbles. The excess attenuation per unit distance due to bubbles is then

$$\alpha_b = 4.34 S_e \text{ dB/m}.$$

The extinction cross-section S_e is given by

$$S_e = \int_0^\infty \sigma_e \, n(a) \, da$$

where σ_e is the extinction cross-section for a single bubble of radius a, and n(a) is the number of bubbles between radius a and a+da per unit volume. The expression for σ_e is a complicated function which cannot be evaluated analytically; while estimates of S_e to any desired degree of accuracy can be found numerically, a useful approximation can be made by assuming that only bubbles close to the resonance radius contribute to S_e, and that the number of bubbles per unit volume and their characteristic damping constants remain constant (Clay and Medwin, 1977). The approximate attenuation is then

$$b = \frac{85.7 a_r^2 n(a_r)}{k_r}$$

where a_r is the resonant radius, k_r is the wavenumber $(2\pi/\lambda r)$ of the sound and $n(a_r)$ is n(a) at $a=a_r$. For 50 KHz sound, k_r = $209 m^{-1}$ and $a_r = 6.5 \times 10^{-5}$ m. Table 3 shows α_b for various concentrations of resonant bubbles.

Table 3: Bubble attenuation coefficient, α_b, for 50 KHz sound as a function of resonant bubble density.

$n(a_r)$ (m^{-3} in a 1 micrometre band)	α_b(dB/m)
100	0.2
500	0.9
1000	1.7
2000	3.5
3000	5.2
4000	6.9
5000	8.7
6000	10.4
8000	13.8
10000	17.3

The actual attenuation experienced by a signal travelling through a layer of bubbly water depends therefore on the thickness of the layer and the mean concentration of bubbles within it. Johnson and Cooke (1979) photographically measured bubble concentrations in coastal waters produced by wind and wave action at the sea surface at depths of 0.7, 1.8 and 4 m. At wind speeds between 11 and 12 ms^{-1}, they found 65 micrometre radius bubbles in concentrations of 4.9×10^3, 1.9×10^3 and 0.26×10^3 m^{-3} per 1 micrometre interval, respectively. Reference to Table 3 shows that a 50 KHz signal traversing uniform 1 m layers containing bubbles in the concentrations above would suffer attenuations of 8.3 dB, 3.2 dB and 0.5 dB, respectively.

It is certainly possible that bubbles from the bow-wave of a vessel can be entrained and swept under the hull where they can interfere with the performance of hull-mounted sonars. Studies of this phenomenon appear, however to have been confined to vessels much larger than the hydrographic survey launches (Wang et al., 1977; Watt, 1978; Day, 1979). Since the characteristics of the layer are strongly dependent on the vessel itself, it is not possible to calculate its effects without specific measurements. The examples of attenuation due to bubbles produced by breaking wind-waves show that significant signal loss can arise by this process. The processes by which bubbles are injected into the water are not likely to differ much between bow-waves and wind-generated waves; however the number of bubbles carried beneath the hull to the site of the sonar well depends entirely on the characteristics of the flow past the hull, which are not known. Operation of the launches in high sea states would of course also lead to signal loss through the ambient bubble layer. This loss would not, however depend on the launch speed, and it seems unlikely that such sea states would be encountered very often in the sheltered waters of B.C. coastal inlets.

3.4 BOTTOM REFLECTIVITY

The sea bottom acts as both a reflecting and scattering surface to acoustic energy. For the reflected portion of the signal, the component of transmission loss due to spreading follows the form of spherical spreading for twice the ocean depth (H) (i.e. 20 log (2H)). However, for the scattered returns, each portion of the insonified bottom radiates spherical waves, and the spreading loss becomes $20 \log (H^2) = 40 \log (H)$. For the purpose of the present study, scattering losses are assumed to be small for the relatively smooth flat bottoms of most B.C. coastal waterways.

The reflected acoustic pulse is always weaker than the incident pulse, by an amount TS. For near normal incidence angles, the bottom loss varies according to the porosity of the bottom materials. Highly porous materials (water soluble clays and silts) result in the largest reflection losses while the least porous materials (sand) result in comparatively small reflection losses. While no data on TS values could be found for frequencies of 50 KHz, both theoretical (Shumway, 1960) and empirical (Mackenzie, 1960) studies show that at lower frequencies (4 to 16 KHz), reflection losses range from 5 dB (low porosity, sandy bottoms) to 16 dB (high porosity silt or clay bottoms). The bottom reflection losses for either high or low porosity materials exhibited no significant frequency dependence from 4 to 16 KHz; however, a rocky bottom did indicate a possible increase in TS at higher frequencies (from 5 dB to 10 dB) apparently due to a difference in the losses due to scattering (Mackenzie, 1960).

In the steep-sided B.C. inlets, sediments covering the broad, relatively flat central portion of the channels consist of highly porous materials (clays and silts) resulting from deposition of glacial silts (Pickard, 1961). Clayey materials predominate in the mainland inlets, with silty sediments more dominant in the inlets of Vancouver Inland. Rare occurrences of sandier sediments can be found, most often in the deeper portion of the inlets, on the sills or at the head of the inlet (Cockbain, 1963). On the steeply sloping sides of the inlets, a rocky bottom is often found due to the large grade (20 to 45 degrees) providing a potential for turbidity flows. In the vicinity of the test range used in this study, the bottom materials are much coarser, consisting of sand or silty-sand (Cockbain, 1963).

Thus, a considerable difference in bottom reflectivity is anticipated for sounding in the inlets and in the test range. Note however that the appropriate values of TS for B.C. coastal waters is unknown; no direct measurements of TS are available. Data obtained in other coastal areas at lower frequencies suggests a possible range from 5 (e.g. test range) to 15 (inlets).

3.5 NOISE LEVELS

Noise which can mask the echo returning to the sounder is of two types: the ambient noise background existing in the ocean, and noise generated by the launch itself as it moves through the water. The chief sources of ambient noise near the sounder frequency of 50 KHz are wind and rain at the ocean surface. Wind-generated noise spectrum levels vary at that frequency from approximately 20 dB re 1 micro Pascal^2/Hz at 1 m/s windspeed to about 45 dB at 19 m/s (Urick, 1975, p. 189). (The level at 19 m/s may in fact be lower due to the absorptive effects of bubbles generated near the surface during high winds.) During periods of heavy rainfall, ambient noise levels approaching 75 to 80 dB may occur (Urick, 1975, p. 196).

Underwater radiated noise spectra are shown in Figure 2 for a series of measurements made on the launch Petrel at the Esquimalt test range in 1978 (Naval Engineering Unit, 1978). At 50 KHz, the noise levels range from 93 dB re 1 micro Pascal^2/Hz with the motor running and clutch disengaged, to between 116 and 122 dB at full speed through the water. The noise generated by the launch when in full speed operation is at least 36 dB above ambient noise levels, even during periods of heavy rainfall. It is therefore clear that ambient noise levels are not significant in comparison to noise generated by the launch itself.

With the launch engine operated at full speed, a large increase in launch-generated noise levels was evident once the clutch was engaged (Figure 2). This result suggests that the major portion of the noise when under way is generated by the propeller and the engine itself.

In this study, the important characteristics of the launch-generated noise are the sound levels as received by the transducer. The test range results of Figure 2 are measured under far-field conditions (i.e. over several tens or hundreds of metres from the noise source). As a result, the results can be considered equivalent to a point source, expressed in dB re 1 micro Pascal^2/Hz re 1 m. The transducer, as mounted in the well of the launch, is only 4 to 5 m from the propeller. Over such short distances, the generated noise levels are expected to propagate as a complex (and difficult to predict) pattern. In the simplest approximation of a spherical spreading (noise DI=0) the attenuation with distance would decrease over 4.5 m as $10 \log_{10} (4.5) = 6.5$ dB. Given the unknown value of the noise DI and other possible deviations from spherical spreading, the actual loss in noise from the propeller to the well-mounted transducer can only be very roughly estimated to be in the range of 0-10 dB. Direct measurements using transducers mounted from the hull are required to determine the correct value. An additional loss in the detected noise levels results from the reduced sensitivity of the received signal of the transducer for the near-grazing incidence angles (approximately 85 degrees from vertical axis of the transducer) of the propeller noise source. While the receiver sensitivity as a function of incidence angle is not known for the uncalibrated transducers used in hydrographic surveying, nominal calibration curves available from the manufacturer suggest that the received noise signal could be reduced by as much as 25 to 40 dB from the sensitivity for near normal incidence angles. It is not known whether such large losses are reasonable for the noise generated from the propeller, since:

1) the transducers are not individually calibrated and large deviations from the nominal curves are possible and;

2) the exact pathway of the propeller noise is not known; effects such as scattering or refraction in the boundary layer of the hull could significantly alter the incidence angle.

Although it is not possible to quantify the contributions to the noise from these sources without more detailed measurements, it is possible to identify some of their characteristics, which may aid in assessing their relative importance.

3.5.1 CHARACTERISTICS OF THE ONSET OF PROPELLER CAVITATION NOISE

The sudden increase in high-frequency noise between engine speeds of 1000 RPM and 2000 RPM shown in Figure 2 is suggestive of some noise generation mechanism which abruptly comes into play. The most likely candidate is propeller cavitation (U.S. Navy, 1969; Urick 1975). The sound is primarily generated by what is called tip-vortex cavitation, in which the pressure decrease following the tip of the propeller blade exceeds the tensile strength of the water, causing bubbles to form. The subsequent collapse of the bubbles is responsible for generating the accompanying noise, which undergoes a rapid increase as cavitation begins (Aleksandrov, 1962). The occurrence of tip-vortex cavitation is governed by the cavitation index K_T (Urick, 1975).

$$K_T = \frac{Po - Pv}{1/2\ \rho v_T 2}$$

where
Po = static pressure at the propeller
Pv = vapour pressure of water
ρ = density of seawater
v_T = tip velocity of the propeller blade.

Urick (1975) states that cavitation is unlikely if $K_T > 6$, that it begins when $0.6 < K_T < 2$ and is certain if $K_T < 0.2$. The hydrographic launches have propellers with blade lengths of 24.2 cm (O'Connor, 1980) and transmission gear ratios of 1.5:1 (G. Richardson, personal communication). The tip velocity is therefore

$$v_T = \frac{2\pi \times 24.2}{60 \times 1.5} R \text{ cm/s}$$

where R is the engine speed in RPM. The mean depth of the propeller is 1.25 m (O'Connor, 1980) , giving a value for P_o of 1.1396×10^6 dynes/cm^2. The vapour pressure of water is approximately 0.0124×10^6 dynes/cm^2 and the density of seawater is about 1.026 gm/cm^3, with the result that

$$K_T = \frac{3.25 \times 10^{-6}}{R^2}$$

Figure 3 shows K_T as a function of R. The onset of cavitation is predicted between 2000 and 3300 RPM, in agreement with the test range results.

It is also possible that the motion of the hull through the water, with its associated bow wave and wake are significant sources of noise, but difficult to quantify. It is more likely however that noise from these sources would exhibit a steady increase with speed, and that propeller cavitation is the primary cause of the sudden large increase in high-frequency noise with increasing speed. It is not possible to state how much of the noise increase beyond the onset of cavitation arises from hull effects.

3.6 SUMMARY

In this section, the value of each term in the sonar equation

$$SL - TL - TS = NL$$

has been identified for the high speed launch operation on the basis of existing information. The estimated value and uncertainty in each term is:

1) Source Level (SL): 207 dB, but could be reduced up to 5 dB due to less than optimal transducer efficiency and the neglect of side lobes (Section 3.2);

2) Transmission Losses (TL): consisting of path losses ($20 \log_{10}(r) + \alpha r$, where r is the distance travelled); losses due to the possible existence of a bubble layer beneath the hull; and losses through the boat's hull. Evaluation of the former contribution is straightforward, with an absorption coefficient of 0.019 to 0.022 being appropriate for B.C. coastal waters. Losses due to the latter two terms cannot be evaluated

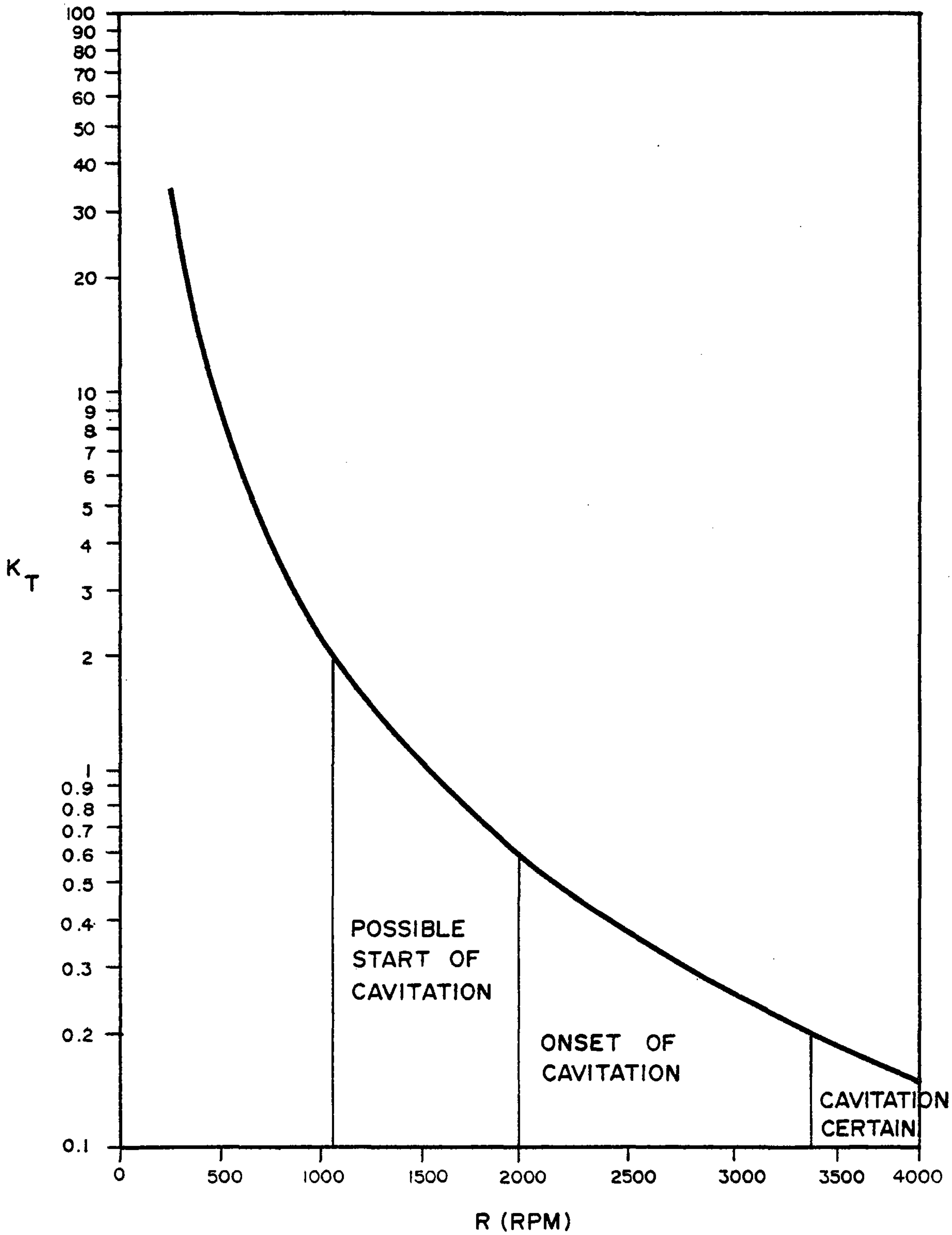

Figure 3: Cavitation index K_T vs. engine speed R for hydrographic survey launches (semi-logarithmic scale).

theoretically, although the results of the empirical tests of this study (Section 4) suggest that they are small in value (est: <2 dB).

3) Bottom Reflectivity Loss (TS): 5 to 15 dB, based on studies of coastal sea bottoms. Note that the applicability of this range to B.C. coastal waterways is uncertain; since no direct acoustic measurements of sea-bottom reflectivity are available for this region;

4) Noise Level (NL): consisting of ambient noise levels (<75 to 80 dB); boat generated noise. The latter has two sources, noise due to the propellers, of 116 to 122 dB, likely associated with propeller cavitation and an unknown contribution due to the generation of a bow-wave. The propeller generated noise source is thought to be the largest, but the actual noise levels as detected by the transducer in the well are likely reduced from the far-field sound levels given above due to spreading losses and reduced receiver sensitivity at the near-grazing angle of the propeller noise relative to the well.

In B.C. inlets, the bottom return is often lost during high speed launch operations at depths of 350 to 400 m (G. Richardson, pers. comm.). At a depth of 375 m, Eq. (1) becomes

$$EL = 207 - 20 \log (750) - 0.019 (750) - TS$$

$$= 135 - TS = NL$$

neglecting transmission losses due to bubble layers and the well. For a bottom of poor acoustic reflectivity, which would be anticipated for the mud of the inlets (TS = 15), then the EL = NL would amount to approximately 120 dB. This result appears to be consistent with the measured noise levels of the launch, although the anticipated reductions in the propeller generated source levels as detected by the transducer in the well would appear to be notably smaller than expected.

In the test range results (Section 4) obtained in Haro Strait, good bottom returns were received at the same depth of 375 m (i.e. EL > NL). Since all other terms (source levels, transmission losses and noise levels) are very similar for the inlets and Haro Strait, the better returns in the latter area are likely due to the better reflectivity of the sea bottom. It is known that Haro Strait has a sandy bottom, which would produce better acoustic reflections than the muddy bottoms of the inlets.

Assuming that the bottom returns approach the limit of the highest coastal bottom reflectivity (TS = 5), then EL = 135 - 5 = 130, approximately 10 dB above the system noise level as estimated from the performance in the inlets. Under the highly reflective bottom (TS = 5) conditions, the depth at which the echo levels are reduced to the estimated noise levels (120 dB) is 525 m, some 150 m in excess of that for a poorly reflective bottom (TS = 15).

4. FIELD TESTS

On two occasions, field tests of the echo sounding system were carried out on the C.S.L. Petrel. The tests were conducted off Turn Point, on Stuart Island in Haro Strait (see Figure 4) over maximum depths of 370-380 m. In the previous study by O'Connor (1980), the same vessel and test range were used.

4.1 TEST OF MARCH 7, 1984

In the first test (the afternoon of March 7, 1984), preliminary measurements were obtained under calm winds and glassy-smooth seas. On the way to the test range, the horizontal dimensions of vessel wake were estimated while the vessel was travelling at full speed (2650 engine RPM), as summarized in Figure 5. The bow wave separates from the hull approximately 3 m back from the bow. From this point to the stern, relatively clear water flows past the hull. Travelling at full speed in the planing mode, the attitude of the vessel changes, tilting upwards at the bow by approximately 5 degrees.

An arm was made on which the transducer could be mounted outside of the vessel away from the hull. This arm was mounted on the starboard side from a bracket located almost even with the forward end of the cabin (see Figure 5). When travelling at full speed, the transducer was approximately 0.6 m beneath the water line. The transducer was enclosed in a faired casing to eliminate cavitation and reduce the boundary layer effects on the mounting arm.

At the test range, three different equipment configurations were used:

Run 1: A 50 KHz transducer, used previously in surveys, was operated from the vessel's well.

Run 2: The same transducer (as used in Run 1) was mounted on the arm outside the hull.

Run 3: A new 50 KHz transducer was operated from the vessel's well.

The results are shown in Figure 6. Note that the chart recorder was operated at minimum gain and chart intensity, with TVG (time variable gain) set at 5 and the power output at 500 watts. In each run, the launch was operated at full speed (with the mounting arm attached to the side of the vessel, the maximum

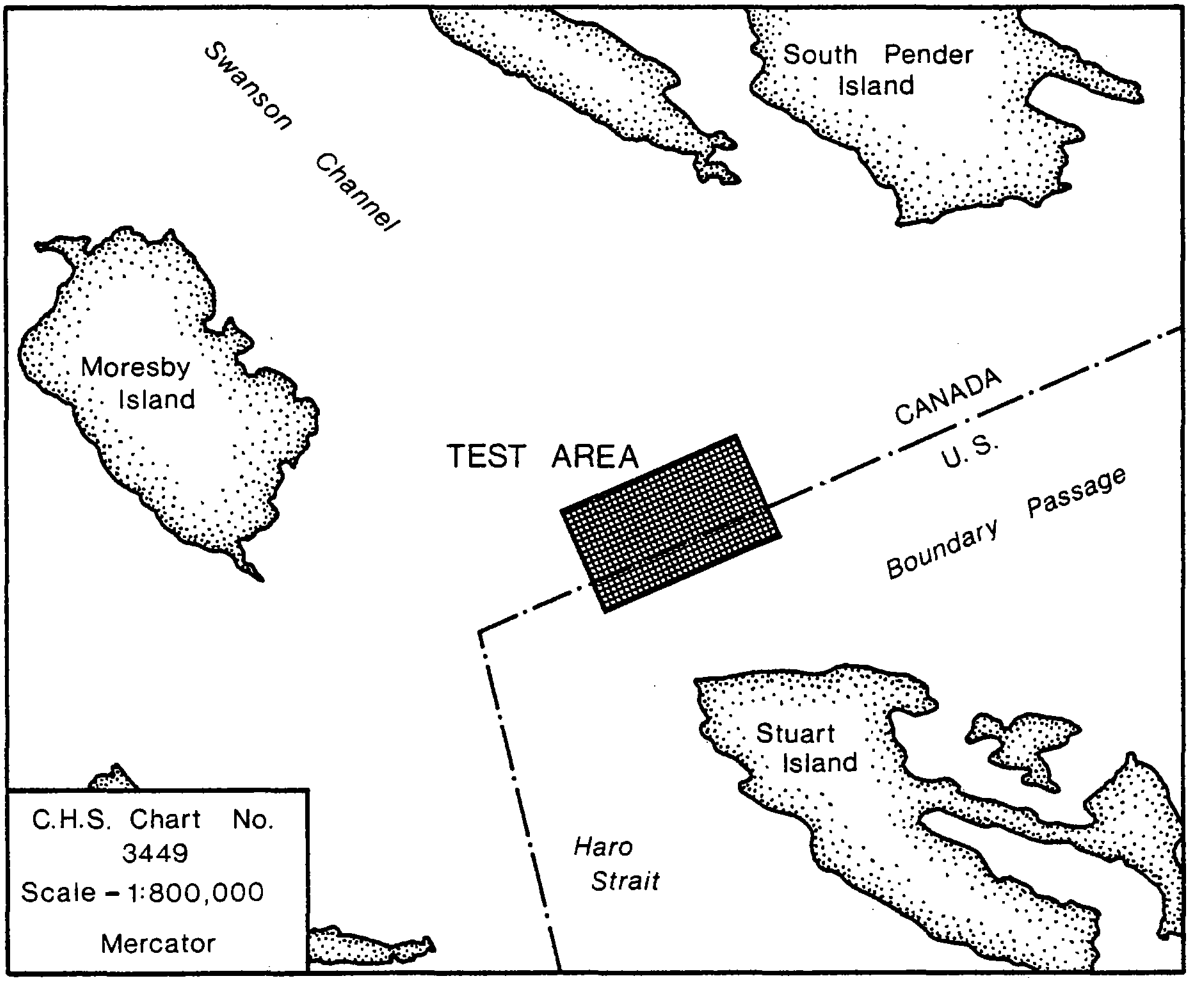

Figure 4: Location of the Haro Strait test range used in this study.

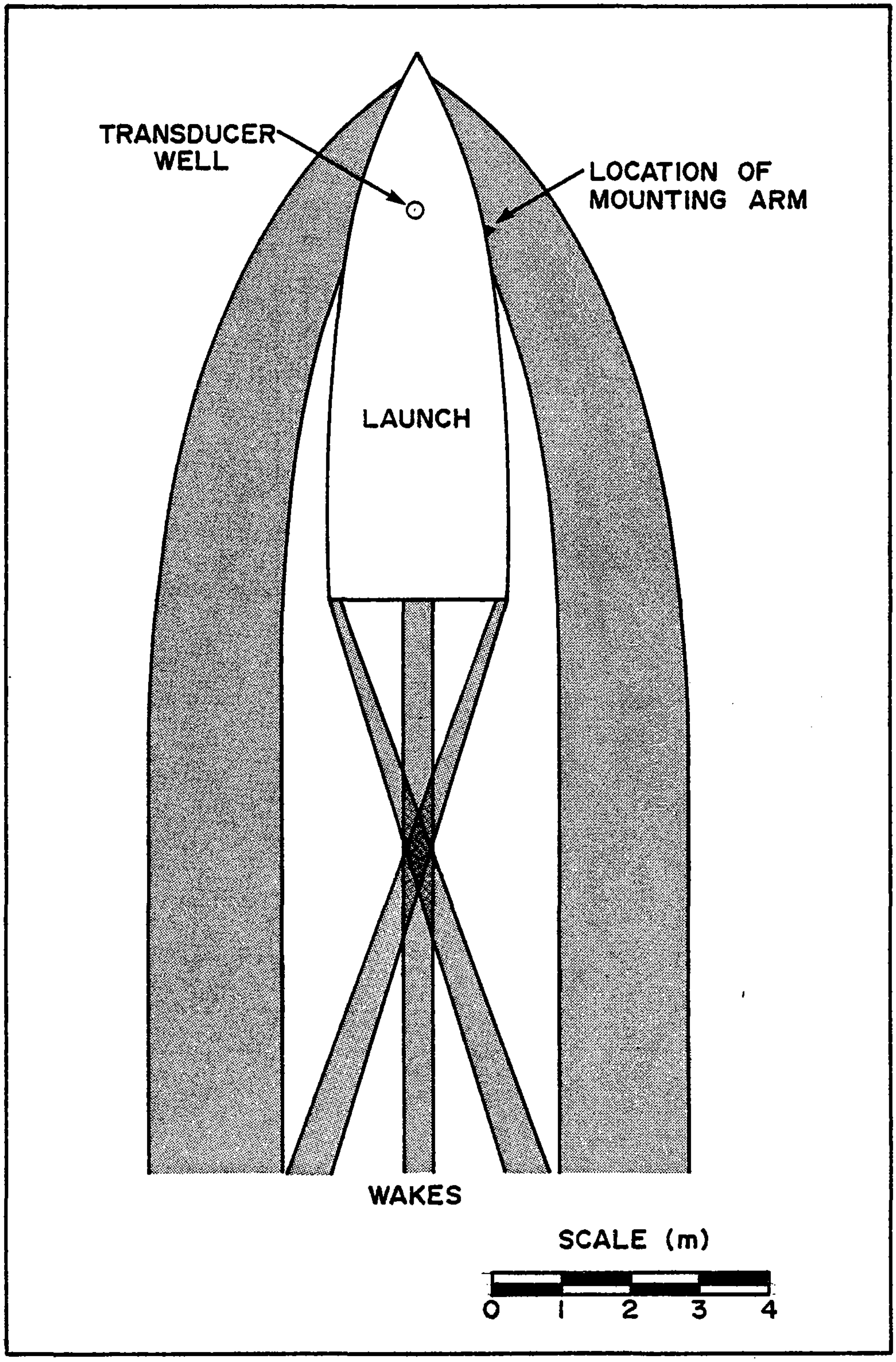

Figure 5: Plan view of the vessel wake at full speed, as visually estimated from the C.S.L. Petrel.

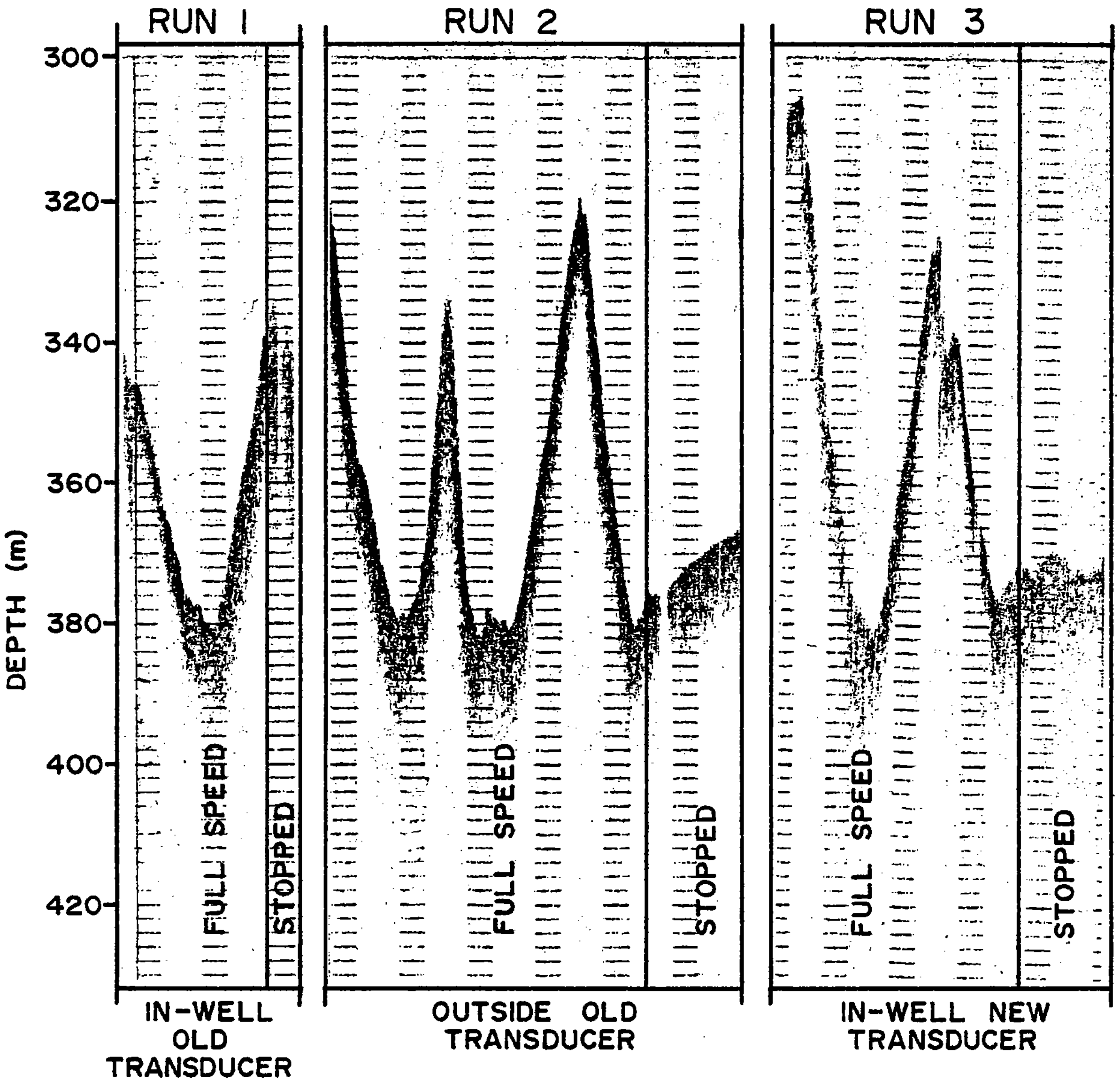

Figure 6: Results obtained on March 7, 1984 at the Haro Strait test range on C.S.L. Petrel. See text for description of Runs 1, 2 and 3.

speed obtained was reduced by an estimated 1 to 1.5 knots). The sounder electronics/chart unit was a new Simrad model on loan to the CHS.

The best results, as judged qualitatively from the chart recorded output (Figure 6), were obtained with the transducer mounted away from the hull (Run 2). With the transducer in the well, the results from both runs (1 and 3) were inferior; however, a large difference was apparent between these two cases. The difference between Run 1 and Run 3 may have been caused by the difference in the transducers.

In all of the runs, no deterioration in bottom returns was evident when running at full speed as compared to the returns received when drifting. Such a speed-dependent reduction in signal would have been expected if a bubble layer beneath the transducer well was causing significant attenuation of the acoustic signals. The differences between the three runs suggested that the problems were more likely associated with signal losses in the well.

4.2 TEST OF MARCH 21, 1984

On March 21, further testing was carried out from the C.S.L. Petrel at the Haro Strait test range. During these tests, winds were light with choppy seas in the morning, gradually subsiding through the day. An older transducer, marked 23-041, was used in all test runs. This time, the sounder electronics unit was the Model 802 Skipper Sounder (Serial No. 233, calibrated for 1463 m/s sound speed), used on most hydrographic surveys. In addition, a Tektronix 2445 oscilloscope (150 MHz bandwidth) was used to monitor the signal levels and waveforms of the return pulse. The oscilloscope was attached to the 'video out' connection of the sounder unit.

By comparing the 'video out' voltage levels to those measured at preamplifier input from the transducer, the electronic gain was determined to be 2640 or 68.4 dB. Relating electrical output of the transducer to sound pressure levels proved to be much more difficult. The transducer sensitivity to incoming pressure amounts to -108.5 dB relative to 1 watt per microbar (Giske, 1984) or -208.5 dB relative to 1 watt per micro Pascal (the equivalent pressure units used in this study). The electrical impedance of the transducer is 45j + 5.8 ohms; however, approximately 88% of the transducers deviate by varying (and unknown) amounts from this nominal value (Giske, 1984). Based on this nominal value, the conductance G (real part of the reciprocal of impedance) is 0.0028. Thus, the preamplifier voltage V can be related to sound pressure levels by expressing electrical power, V^2G as

$$10 \log (V^2G) = 20 \log V + \log G = -208.5$$

$$20 \log V = -208.5 + -25.5 = -183$$

$$\log V = -9.15$$

$V = 7.08 \times 10^{-10}$ RMS volts/micro Pascal re 1 m.

For example, for an echo level of 140 dB, i.e. $20 \log (P/P_o) = 140$ dB, then $P/P_o = 10^7$ and V = 7.08 millivolts.

Throughout all tests on March 21, the settings on the sounder display were: gain-minimum; fine line-off; TVG at 5 (middle position); pulse width-middle position, chart intensity-8.

Test 1

In the first sequence of operations, the launch was allowed to drift while the transducer was located in different positions within the vessel: in the well, outside suspended from midway along the vessel in 2 m of water, and against the hull through the bilge water approximately 0.5 m aft of the transducer well. With the transducer in the well, bottom returns were markedly reduced in amplitude by comparison with the received signal with the transducer off the side of the launch (Figure 7). Even returns obtained through the hull aft of the well were larger in amplitude than most of those obtained from the well. In addition to the lower amplitudes, bottom returns through the well tended to be highly variable; repositioning the transducer would noticeably change the returns. Another interesting characteristic of the returns through the well was the long pulse width of the returned signal, as indicated by the greater length of the vertical traces shown in Figure 7.

Using the oscilloscope, the signals received through the well had mean peak-to-peak voltages (visually averaged over approximately 10 returns) of 3.3 volts, with a pulse width of 50 msec. By comparison, with the transducer outside the hull the voltage levels and widths averaged 5.9 volts and 30 msec.

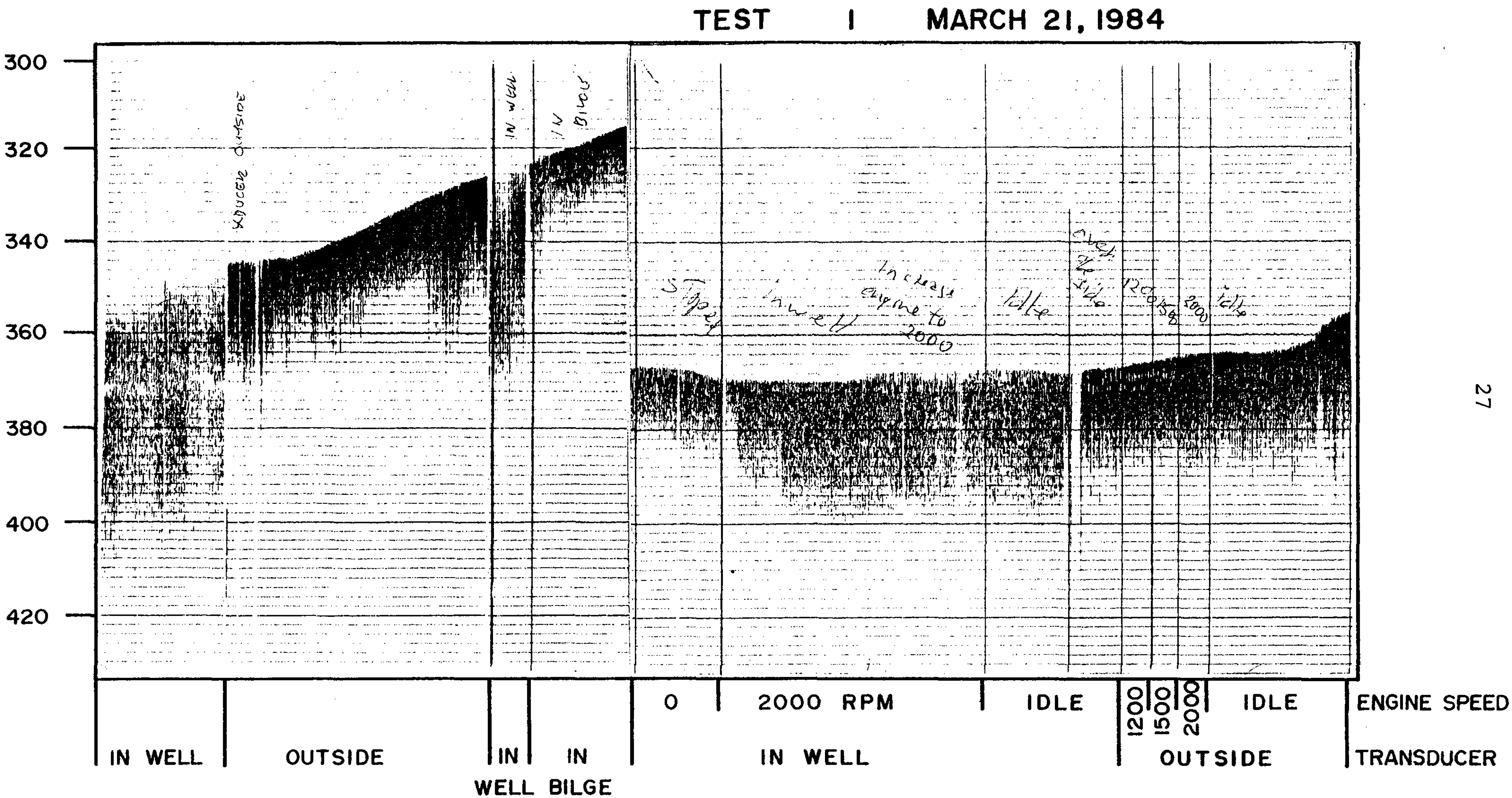

Figure 7: Results obtained during Test 1 at the Haro Strait test range from C.S.L. Petrel.

With the propeller drive disengaged, the engine was operated at different speeds up to 2000 RPM, with the transducer in the well and then outside the hull. The returns, both as seen on the chart and the oscilloscope, did not change significantly with the engine running.

Test 2

During this sequence of tests, the transducer was placed in the well, and the launch was powered through the water at a range of engine speeds, from 800 RPM (idle) to 2600 RPM (full speed). The results as recorded by the sounder deck unit are shown in Figure 8. The return signal characteristics, as visually observed on the oscilloscope,are summarized below:

Table 4: Summary of voltage levels and pulse widths of the bottom return signal measured during Test 2 (transducer in the well) on March 21, 1984 at the Haro Strait test range.

Launch Speed	Peak-to-Peak Voltage Level (Volts)	Pulse Width (msec)	Comments
1200 RPM	3.2	40	
2000 RPM	3.2	50	leading edge of lower amplitude
2600 RPM	3.5	50	noise level of 1.4 volts; pulse size difficult to determine due to high noise levels
2300 RPM	3.3	52	noise level of 0.45 volts
800 RPM	3.5	32	engine off
	3.4	33	

The noise observed at 2600 RPM, and at much reduced levels at 2300 RPM, occurred throughout the sweeps of the oscilloscope (i.e. before and after the return pulse from the bottom). Background noise levels at launch speeds of 2000 RPM or less, were generally less than 0.15 volts. At these higher launch speeds, the bottom return signal did not appear to diminish

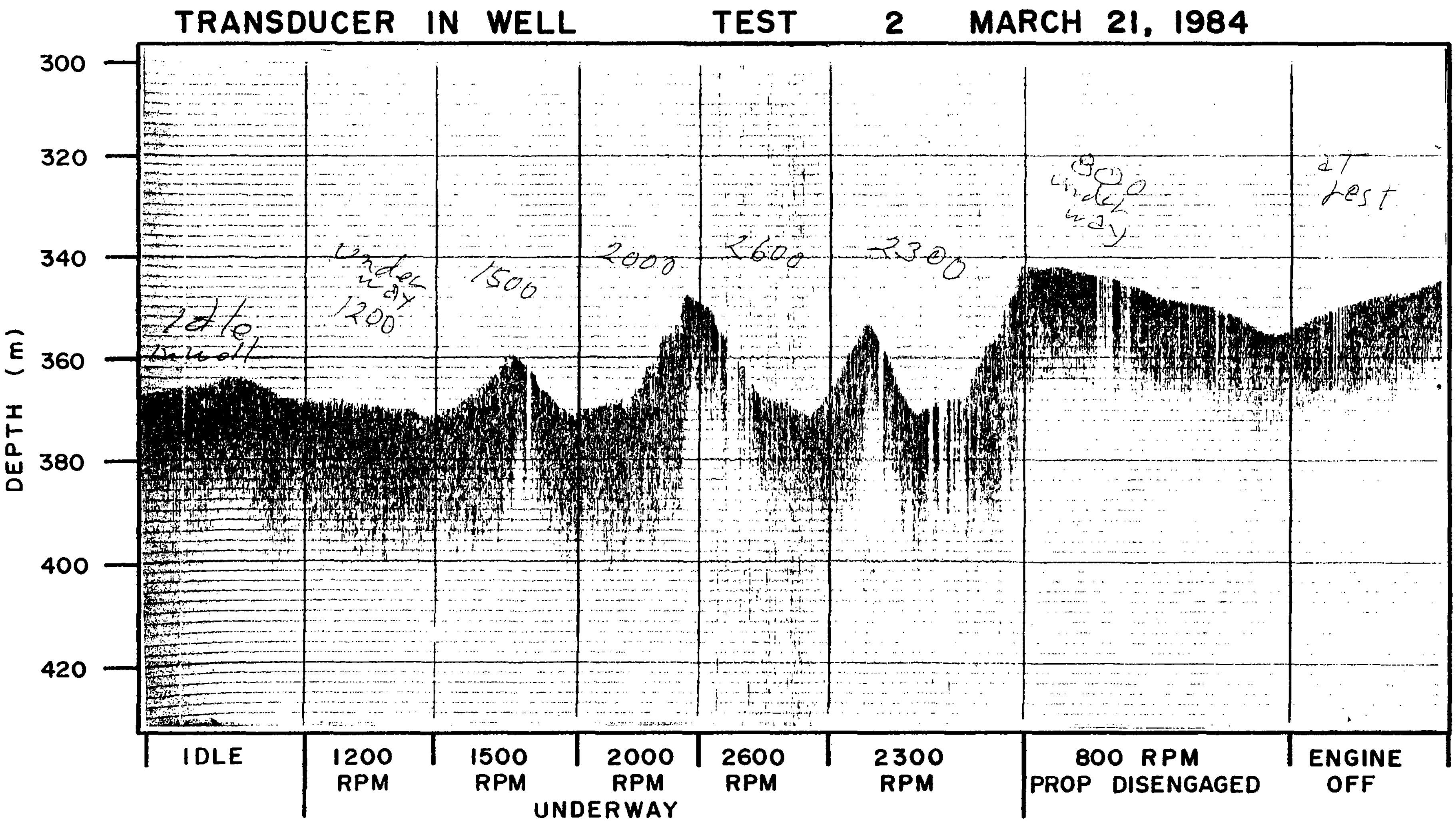

Figure 8: Results obtained during Test 2 at the Haro Strait test range from C.S.L. Petrel.

significantly in voltage level or pulse width, although measurements were more difficult to visually estimate due to the higher background noise levels.

Test 3

After the transducer was mounted on the starboard arm, outside the hull, the same operations as those of Test 2 were carried out. The sounder chart output is displayed in Figure 9. The bottom return signal characteristics, as observed on the oscilloscope, are summarized below:

Table 5: Summary of voltage levels and pulse widths of the bottom return signal measured during Test 3 (transducer mounted outside hull) on March 21, 1984 at the Haro Strait Test range.

Launch Speed	Peak-to-Peak Voltage Level (Volts)	Pulse Width (msec)	Comments
engine off	6.4	24	
1200 RPM	6.0	28	pulse more decayed on falling edge
2000 RPM	6.0	28	pulse more decayed on falling edge
2600 RPM	5.8	31	distinct background noise of 1.34 volts; envelope very spikey
800 RPM	6.0	23	drive disengaged engine off
	6.0	23	

The results of Test 3, like that of Test 2, show the bottom return signal to be independent of launch speed and the background noise levels to increase markedly at full speed. Outside the hull, the voltage levels of the noise are nearly identical to those measured within the well, while the bottom return levels are twice those measured in the well. When the transducer is outside the well, pulse widths of the return signal are significantly reduced by comparison to the pulse widths measured through the well.

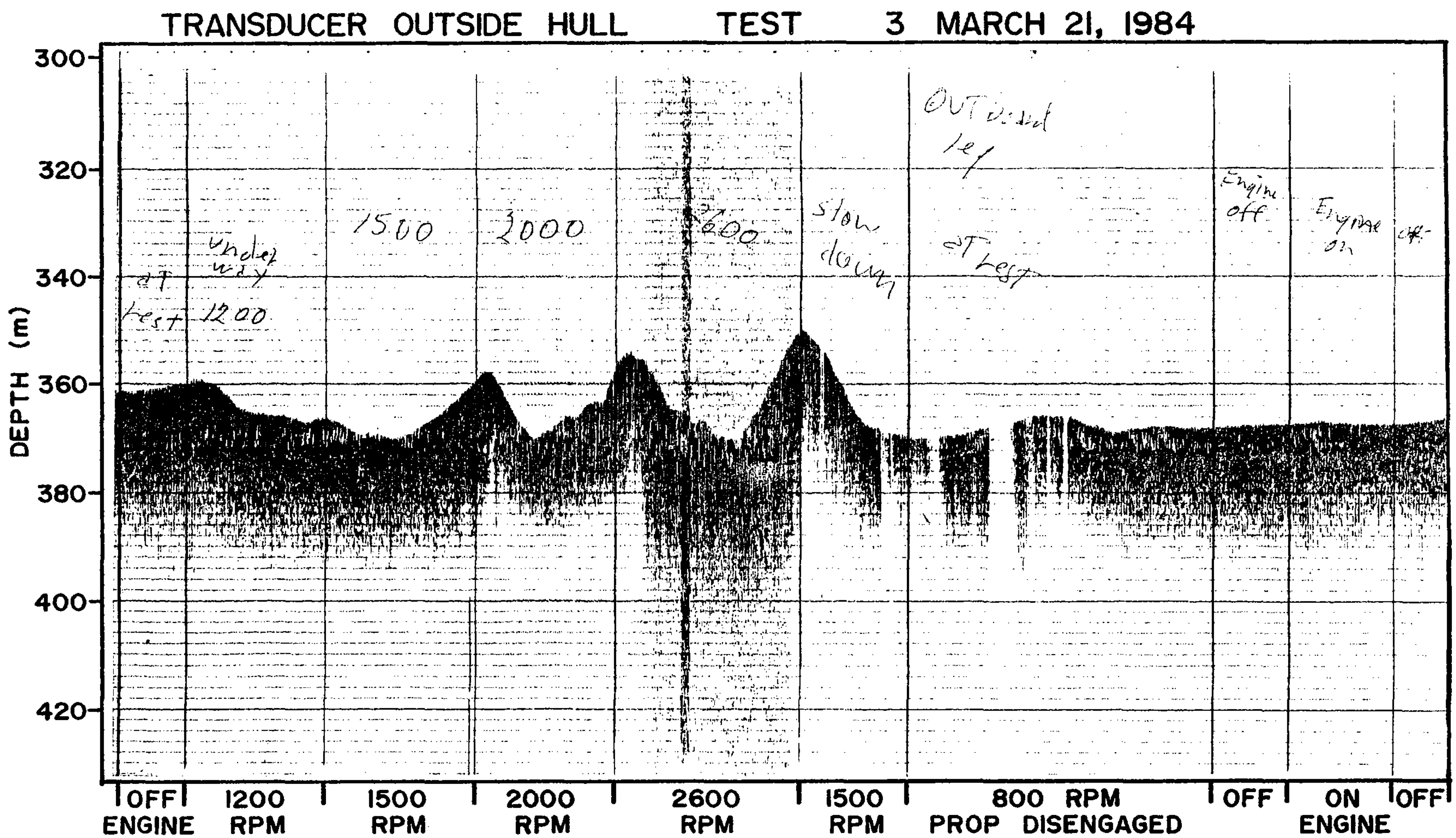

Figure 9: Results obtained during Test 3 at the Haro Strait test range from C.S.L. Petrel.

Test 4

The transducer was returned to the well; however, a marked improvement was immediately evident in the bottom returns (Figure 10) over those measured through the well in Tests 1 and 2. Voltage levels reached 5.8 volts with pulse widths reduced to 26 msec. Experimentation with various transducer positions in the well indicated the optimum transducer location to be flush against the well. To achieve good returns, it seemed to help by applying pressure to the transducer and horizontal movements along the face of the hull. There is a possibility that the acoustic coupling is reduced by the presence of a thin film, possibly consisting of bubbles between the transducer and the hull. Application of pressure or horizontal movements may reduce or eliminate this film. By repositioning the transducer within the well, the return signals could easily be reduced to the previous low levels of Test 1 and 2.

Finally, the transducer was placed along side the V-drive against the hull in the bilge water. With the launch underway, high noise levels and reduced signal levels (2.4 volts) were measured.

4.3 SUMMARY

The results of the launch tests in the Haro Strait range indicate two major problems exist in the echo sounding systems on the launch.

Considerable signal losses can occur within the well. Signal levels were often reduced by a factor of 2, equivalent to a loss of 6 dB in acoustic intensity. Given that reductions in amplitude are accompanied by a nearly proportional gain in pulse width, it appears that the problem is due to reverberation of the transmitted pulse within the well, arising from poor coupling of the transducer output through the hull. As a result, the outgoing pulse leaves the well with approximately half the signal strength over a time of twice the usual pulse width.

However, on some occasions, the return signal obtained through the well reached at least 95% of the value attained outside the hull (losses of less than -0.5 dB). Thus, by carefully and consistently mounting the transducer in the well, the problem of losses in the well can be virtually eliminated.

The strength of the bottom signal, at 6.0 volts peak-to-peak (equivalent to an RMS voltage of 0.80 millivolts at the preamplifier), indicates that the bottom returns had a strength

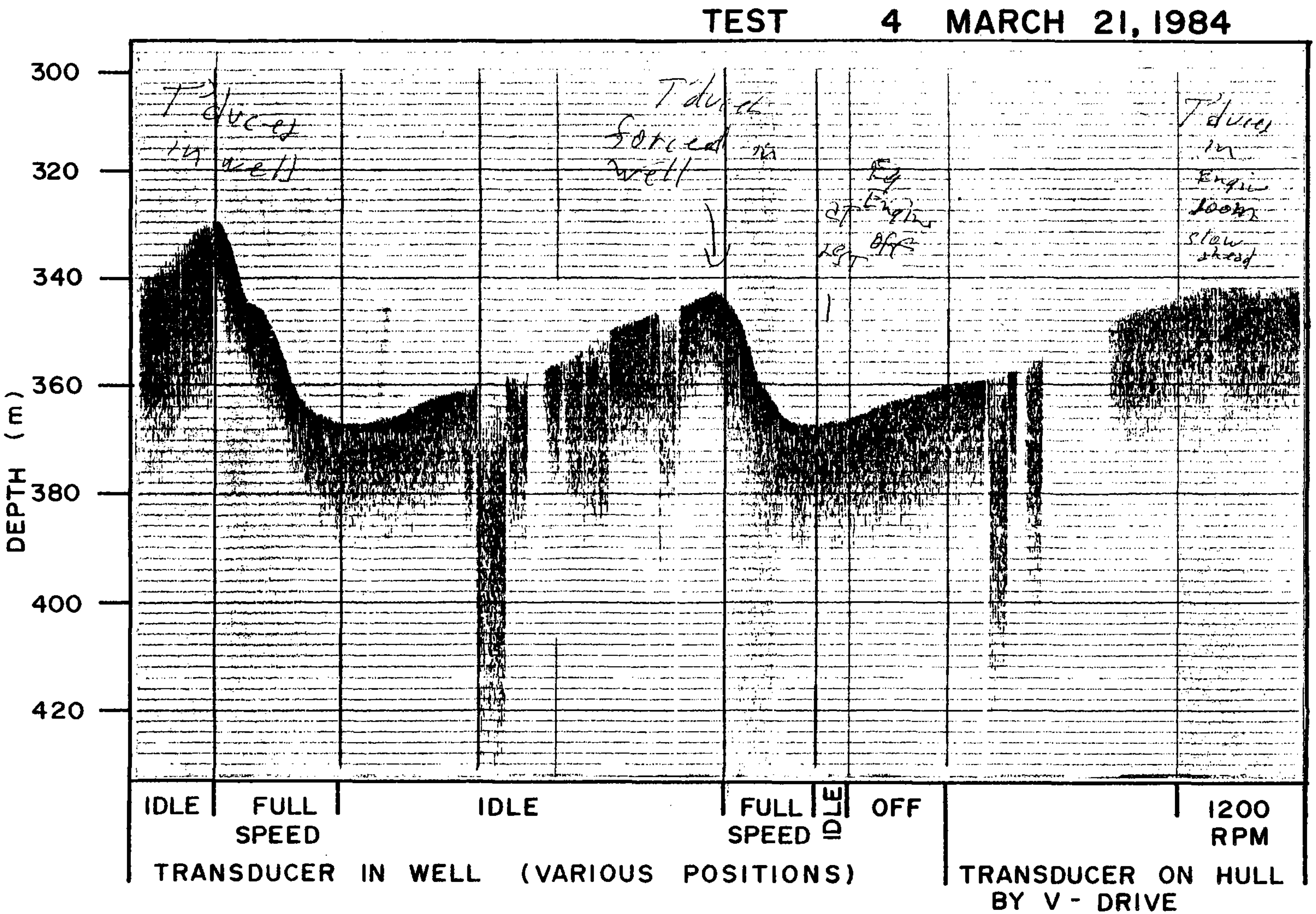

Figure 10: Results obtained during Test 4 at the Haro Strait test range from C.S.L. Petrel.

of 121 dB, using the nominal receiver sensitivity. In a depth of 360 m, the expected bottom return (see Section 3.6) would amount to 136-TS. For a bottom of high reflectivity (TS = 5) as expected for the test range (Section 3.4), the expected bottom return would be approximately 131 dB. The difference between the absolute values computed for the echo level on the basis of theoretical (Section 3) and empirical (Section 4) methods likely reflects uncertainties in the assumed transducer transmission and receiving characteristics.

The major source of noise in the echo sounding system occurs at high launch speeds. Given the sudden onset of this noise as a function of engine speed (over speeds from 2000 to 2800 RPM) the source of the noise is likely due to propeller cavitation, a process inherently non-linear as a function of engine speed (see Section 3.5.1). At full speed, the noise levels are reduced by approximately 13 dB from the bottom returns in 370 m water depth in Haro Strait. In absolute terms, the noise level amounts to 108 dB, computed from the nominal calibration values discussed above. Because both the sound pathway from the propeller to the transducer and the receiver sensitivity at such low grazing angles are not known, the actual sound levels at the source cannot be computed by this method.

The results of the field tests provided no evidence of speed dependent attenuation of the bottom return signal. In all trials, the signal return measured at full launch speed was equal, within measurement uncertainty, to the signal measured when the launch was stopped. This finding clearly demonstrates that signal losses due to a bubble layer beneath the hull is not a significant factor in echo sounding operations from the launches. Only under rough seas conditions, when the launch bow is periodically pitched out of the water, could bubble layer attenuation play a role in limiting sounder operations.

While differences between the theoretical calculations of Section 3 and the field test results are evident, the relationship of signal to noise level is reasonably consistent. With better calibration information (and improved signal measurement techniques), more reliable estimates of absolute sound levels could be attained.

5. CONCLUSIONS

The results of both the theoretical treatment (Section 3) and empirical field tests (Section 4) indicate that sounding operations at high speeds are limited by noise generated by the launch (primarily due to propeller cavitation) which exceeds the bottom return signal. The limiting depth appears to be significantly less (by perhaps 150 m) in the coastal inlets than in other coastal areas (e.g. Haro Strait) due to a reduced degree of bottom reflectivity in the inlets.

A necessary prerequisite for improved launch operations is ensuring that the transducer is mounted in such a way that minimizes return signal losses. These losses can be substantial, amounting to as much as 6 dB. However, they can be virtually eliminated by devising a careful, consistently followed procedure for reliable acoustic coupling of the transducer within the well. O'Connor (1980, p.19) presented one approach to mounting the transducer. The results of this study indicate that mounting of the transducer flush to the hull may provide the required optimum acoustic coupling.

To improve the present operational capabilities at high launch speeds, three general approaches are possible:

1) **Reduction in the source noise levels:** Improvements have been achieved in the past (Naval Engineering Unit, 1978); O'Connor suggested that replacement of the propeller drive by water jet drive system as the next logical step but this was not considered a practical alternative due to the high costs.

2) **Increase in signal strength:** The signal strength return could be increased in two ways, either by increasing output power or increasing the efficiency of the transducer. In the former case, the improvement that can be achieved is limited since even doubling the output power would improve the signal strength by only 3 dB, equivalent to extending operational depths by 35 m. Possibly, a greater improvement could be realized through the use of more efficient transducers; transducers of 50% efficiency over the current level of 21% would result in a gain of 5 dB, equivalent to a 60 m

extension in operating depth. Ultimately, the possibilities will be determined through the increased costs of achieving greater transducer efficiency.

3) **Improvement in the signal to noise ratio:** This could be achieved in two ways:

   a) The use of transducers having better directionality characteristics would serve to reduce input received through the side lobes (primarily noise) and increase the output and input of the downward looking main beam (the signal). The use of acoustic insulator materials around the side of the transducers could achieve similar results. Unfortunately, available information on such materials for this application is limited, although manufacturers of transducers would likely have considerable information and experience which could be applied to this problem. As a prerequisite to efforts along this line, the directional pattern of noise propagation within and beneath the launch needs to be determined to assess the improvements which could be attained and the directionality of the transducer must be properly measured.

   b) More sophisticated methods of bottom detection could yield major improvements. Recent work (May, 1983), applying specialized digital correlation techniques to sonic signals suggest that improvements in signal to noise ratios of 100 (20 dB) are possible, equivalent to a extension of 240 m in operating capability. In principle, the digital techniques could be incorporated into the existing echo sounding systems on the launches through the use of additional digital circuitry placed between the power amplifier and sounder chart display.

In summary, the most promising means of significantly improving the operational performance of the the hydrographic launches at high speeds, over that attained by O'Connor (1980), is offered through enhancement of the signal-to-noise ratio. With the introduction of digital correlation techniques in detecting the bottom returns, major improvements are possible. In addition, the use of transducers offering better directional sensitivity characteristics by discriminating against noise received through side lobes may also provide significant gains, although a better understanding of the acoustic pathways of the noise is required to assess the amount of possible improvements.

Improvement of the output efficiency of the transducer would yield moderate gains over present performance, while the possibilities for the application of more power to the transducers or the reduction in acoustic noise levels appear to offer comparatively small increases in performance.

6. RECOMMENDATIONS

A variety of approaches, as discussed in Section 4, offer the possibility of improving the operational capabilities of high speed launches in hydrographic surveying:

1) Devising the optimum mounting arrangement, in order to eliminate signal losses within the well on transmission. As well as the physical mounting arrangement, the type of fluid used in the well and possible use of 'wetting' agents should be considered. This would require tests in local waters to evaluate and verify the best procedure. A test to be used routinely in surveying operations (e.g. examining the length of the return trace on the sounder's chart recorder) should be implemented.

2) Tests to provide a better understanding of the directional patterns of acoustic noise propagation within the launch are required. This could be achieved through operational tests using hydrophones mounted at various positions and depths outside the hull and bottom-mounted hydrophones over a test range. The results would determine the extent to which improvements in performance can be achieved by the reduction of receiver sensitivity through side lobes. If these results demonstrated sufficient potential for improvement, the use of a transducer having better directionality (in conjunction with part 3 below) or the use of acoustic insulation materials around the sides of the transducer should be examined.

3) Examination of the published performance of commercially available transducers, in terms of transmission efficiency, directional patterns and costs, to assess the improvements which could be achieved through the use of better transducers. If warranted, a trial of improved transducers should be carried out to assess the actual performance and degree of enhanced capabilities before a final decision is taken on such improvements.

4) A feasibility study of the use of pulse coded digital techniques for sounding. As noted in Section 5, this approach offers the greatest potential for improvement (up to 240 m) of operational performance. This would involve an analysis of the capability of such techniques for the bottom sounding application. Emphasis should be

placed on assessing the practicality of incorporating this technique into existing sounder electronics, with the capability of returning to conventional operation in order to assess the characteristics (e.g. layering) of the bottom. The costs of such an approach should be estimated in order to determine the cost effectiveness of conversion of the sounding systems on the high speed launches to incorporate this digital sounding technique.

In the course of this study, the relevance of regional differences in acoustic reflectivity of the seafloor bottom within B.C. coastal waterways was identified. Such differences could result in sounding operations from high speed hydrographic launches being curtailed by depths of approximately 150 m within the B.C. inlets as compared to the connecting passages (e.g. Haro Strait, Boundary Passage) of the inland waterways. Therefore, it is further recommended that:

6) A systematic survey of acoustic bottom reflectivity within B.C. coastal waterways be undertaken to assist in planning hydrographic surveying operations. Emphasis should be placed on comparing direct measurements of bottom reflectivity with bottom sediment samples. Comparison of these two types of measurements would be used to develop an empirical relationship which, if successful, could then be applied to estimating bottom acoustic properties from the large bottom sediment data base for the region.

7. REFERENCES

Aleksandrov, I.A., 1962. Physical nature of the "rotation noise" of ship propellors in the presence of cavitation. Soviet Physics-Acoustics, 8(1), pp. 23-28.

Clay, C.S. and H. Medwin, 1977. Acoustic Oceanography: Principles and Applications. John Wiley & Sons, New York.

Cockbain, A.E., 1963. Distribution of sediments on the continental shelf off the southern British Columbia coast. Manuscript Report No. 15. Institute of Oceanography, University of British Columbia, Vancouver, B.C., 7 p.

Day, W.G.J., 1979. Flow observations and speed loss predictions for USNS Wyman (T-AGS-34) with an External Bottom Topological Survey System (BOTOSS). U.S. Government Report DTNSRDC/SPD-0740-02. David W. Taylor Naval Ship Research and Development Center, Bethesda, Md. (Available from National Technical Information Service, Springfield, Va.)

Giske, S., 1984. (Personal communications.) Written and verbal responses to specific questions related to this study. Skipper Electronics A/S, Ensjoveien 18, P.O.B. 6094 Etterstad, 0601 Oslo 6, Norway (Telephone 47-2-67-04-90).

Johnson, B.D. and R.C. Cooke, 1979. Bubble populations and spectra in coastal waters: a photographic approach. J. Geophys. Res. 84(C7), pp. 3761-3766.

Mackenzie, K.V., 1960. Reflection of sound from coastal bottoms. J. Acoust. Soc. Am. 32, pp. 221-231.

May, G.A., 1983. Correlation sonar using pseudo-random noise codes. Can. Contract. Rep. Hydrogr. Ocean Sci. 14: 134 p.

Naval Engineering Unit, Pacific, 1978. Sound Range Report, Launch Petrel. Report Serial No. E120. Department of National Defence, Esquimalt, B.C. 32 p.

O'Connor, A.D., 1980. Improving launch echo sounding graphs. Technical report. Canadian Hydrographic Services, Institute of Ocean Sciences, Sidney, B.C. 20 p.

Pickard, G.L., 1961. Oceanographic features of inlets of the British Columbia mainland coast. J. Fish Res. Board of Can. 18, pp. 907-999.

Pickard, G.L., 1975. Annual and longer term variations of deepwater properties in the coastal waters of southern British Columbia. J. Fish. Res. Board of Can. 32, pp. 1561-1587.

Shumway, G., 1960. Sound speed and absorption studies of marine sediments by a resonance method, Part II. Geophys. 25, pp. 659-671.

Urick, R.J., 1975. Principles Of Underwater Sound, second edition. McGraw-Hill, New York.

U.S. Navy, 1969. Physics of Sound in the Sea. NAVMART P-9675, Department of the Navy, Headquarters Naval Materiel Command, Washington, D.C.

Wang, H.T., C.W. Dawson and N.M. White, 1977. Calculation of streamlines on the USNS Dutton. U.S. Government Report SPD-771-01, David W. Taylor Naval Ship Research and Development Center, Bethesda, Md. (Available from National Technical Information Service, Springfield, Va.)

Watt, J.V., 1978. Extending the bathymetric capability of the M.V. Pandora II. Pacific Marine Science Report 78-25. Institute of Ocean Sciences, Sidney, B.C. (unpublished manuscript). 13 p.