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STABILITY OF TOWFISH AS SONAR PLATFORMS AND BENEFITS OF THE TWO-PART TOW

by

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STABILITY OF TOWFISH AS SONAR PLATFORMS AND BENEFITS OF THE TWO-PART TOW

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ABSTRACT

Stability is a very important characteristic of the vessel or body on which a sonar is mounted. With normal tow configurations, stability requirements are often not met by a towfish in moderate sea states, particularly with short cable lengths. The trial described here demonstrates that the two-part tow, which uses a down weight and a neutrally buoyant towfish, significantly reduces towfish motion. In particular the two-part tow effectively suppressed pitch and accelerations. However towfish yaw, which was shown to be caused by lateral motions of the ship's stern, was still significant, and yaw is particularly important to sonar image quality.

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INTRODUCTION

To be useful, a sonar platform has to have a stable attitude. A full analysis of the stability criteria for side-scan sonars is a complicated matter which we are currently addressing. Regardless of criteria, all experienced sonar operators will attest that the necessary stability is not always present in some sea states and with some towing vessels. This memorandum describes a trial in which stability criteria were not satisfied using normal towing methods, because of moderate waves and a very short towing cable. Stability was considerably increased, in the same conditions, by using a two-part tow, which consisted of a down-weight plus a secondary cable to the neutrally buoyant sonar platform.

The two-part tow is one technique which can be used to improve the stability of towed bodies, without employing active control surfaces. This system replaces the direct cable between the tow point on the ship and the top of the towfish (close to the centre of gravity) with two cables: the normal tow cable between the tow point and a down weight, and a neutrally buoyant cable from the downweight to the nose of the towfish. The direct tow method requires a negatively buoyant towfish, while the towfish in the two-part tow must be neutrally buoyant. To conduct the trials described here, this change was effected by adding flotation cylinders. The two configurations are shown in Figures 1 and 2.

Thus the primary aims of the trial described here were to investigate towfish stability in moderate seas, using a ship as large as would normally be used for sonar searches, and to quantify the benefits of the two-part tow.

One secondary aim of this trial was to characterize the sensor package which would be adequate at recording towfish attitude data. This is of interest not only for future stability trials, but also because many applications of sonar images depend on knowing the coordinates of objects found on the sonar records. The required accuracy and the associated requirements for the various types of survey data were analyzed recently (Reference 1). The data which must be recorded for this purpose are generally the same data needed to characterize towfish stability. In designing the sensor package for the work reported here, a gyroscopically stabilized system and a high sampling rate were chosen in order to exceed the specifications of a sensor package suitable for more general work. Thus the third aim of this work was to provide data on which the design of a sensor package could be based.

Because the attitude changes of the towfish were significant even with the two-part tow, some data from another trial are presented. The purpose of so doing is to address the issue of inherent stability of the towfish, that is, was this motion with the two-part tow due to wave-driven vessel motion or to inherent oscillations of the towfish (e.g. from shedding of eddies)? Thus the data selected were from measurements in almost calm conditions and with a long tow cable.

TOWFISH ATTITUDE USING DIRECT AND TWO-PART TOWS IN MODERATE SEAS

The purpose of these trials, which were conducted off the west coast of Vancouver Island aboard the CFAV Endeavour, was to investigate the benefits of a two-part tow in suppressing the effects on the towfish of wave-driven motion of the ship. To do so required first characterizing the towfish motion with a direct tow, and then using a two-part tow in the same wave conditions. Finally, the effects of varying the lengths of the two cables were studied.

Procedure

The towfish used in these trials was designed and built at DREP (Figure 1). This towfish was an evolution from the Klein towfish which we had used previously, with the main change being a much enlarged pressure vessel to house the attitude-sensing package. The upper cylinder, a pressure case which contained the sonar circuitry, the instrumentation suite with the associated digital systems, and the support circuits for the acoustic baseline transducer, was 22 cm in diameter and 78 cm long, with a total fin area of 0.8 m^2. The sonar transducers, which had been removed from our Klein 500 towfish, were suspended in a small free-flooding cylinder beneath the upper cylinder. The lowest cylinder, whose axis was 33 cm from the axis of the main cylinder, was hollow and contained a cylinder of lead whose size and fore-aft position were adjusted to give the desired buoyancy and zero-pitch trim in still sea water.

A key aspect of the design was that the towfish could be towed directly or in a two-part tow. As built, the towfish was negatively buoyant

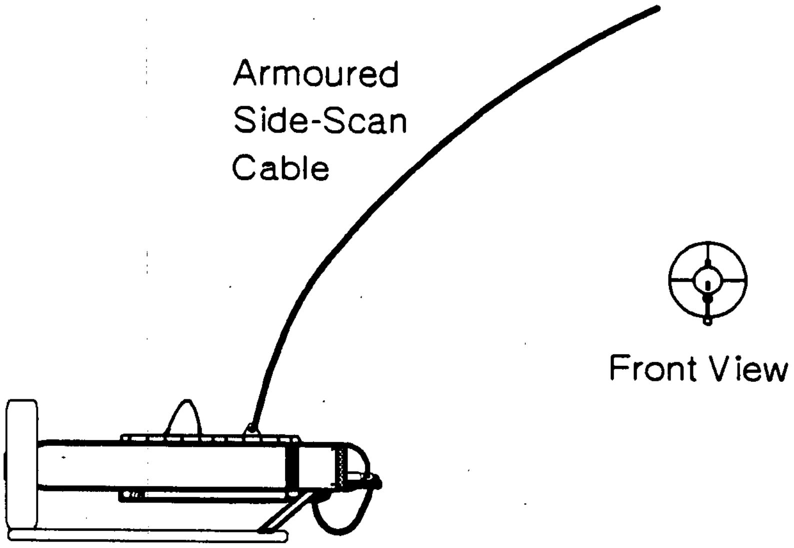

Figure 1. The DREP towfish shown in the heavier-than-water configuration, with the tow cable fixed atop the case and without the cylindrical top floats.

by close to 15 kg. Thus the direct tow was very similar to normal practice, with the normal Klein cable connected atop the large cylinder, a short distance ahead of the centre of gravity. A Kellums grip and the standard Klein shackle were used. This configuration is illustrated in Figure 1.

The two-part tow (Figure 2) requires a neutrally buoyant towfish and a down weight. The former was achieved by strapping appropriate aluminium cylinders to the main cylinder of the towfish, and the buoyancy was adjusted in a test tank of sea water. The down weight was a 32-kg lead sphere attached to a triangular flange by wire. The normal tow cable was connected to the upper leading corner of the flange, while a length of Klein lightweight cable was used to tow the towfish from the trailing corner of the flange. The cable was fixed to the center of the front hemispherical face of the main cylinder of the towfish. This lightweight cable was taped to polypropylene line so as to be approximately neutrally buoyant, and was 14.5 m long. During the trial it was shortened to 12.2 m and to 9.4 m by forming bights of cable and taping them together. The primary tow cable was usually 30 m long, although 61 m and 122 m were used in some trials;

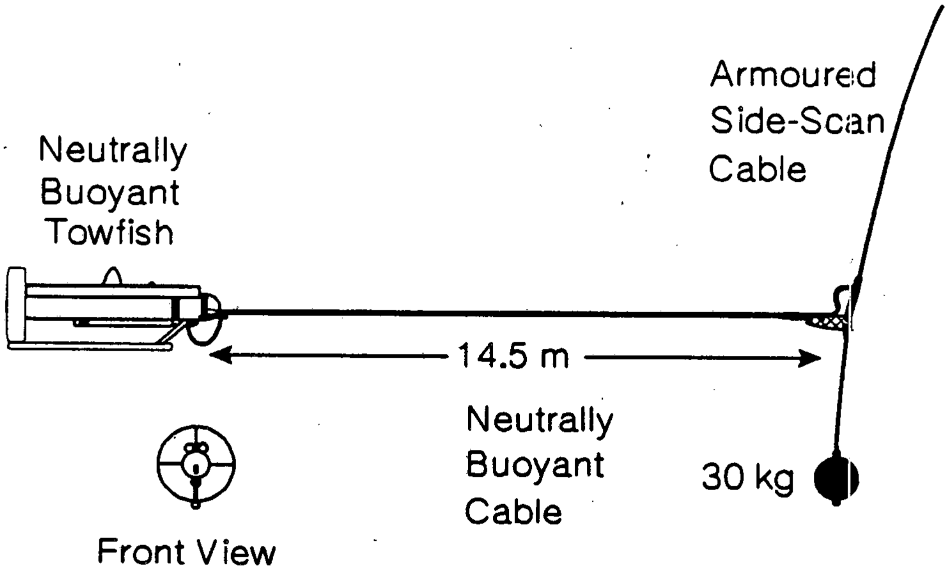

Figure 2. The neutrally buoyant towfish and the towing configuration used. Flotation cylinders were added to the towfish, and the nose became the towpoint.

these lengths refer to the amount of tow cable paid out from the winch after the triangular flange was awash just astern of the ship.

The towfish sensor package consisted of a Digicourse Underwater Heading Sensor (magnetic card compass) to measure towfish heading, a Humphrey Vertical Stabilized Accelerometer package with gimbal pickoffs to measure pitch and roll (the accelerometers were not operational), a Donner Accelerometer mounted fore-aft, and a Sensometrics pressure gauge. The analog values were filtered, amplified, sampled, and converted to a digital data stream in the towfish. This stream was buffered for transmission up the Klein towing cable.

Aboard the ship, a second Vertical Stabilized Accelerometer package, with working accelerometers, was deployed close to the towing point. Unfortunately, the instrument in the towfish failed early in the trial, after which the shipboard unit was used in the towfish. Thus it was necessary to assume that the ship data recorded in that early portion was representative of conditions throughout the trial. Observations from the ship and of its behaviour confirmed that this assumption was very reasonable. Ship heading and speed were entered manually at regular intervals. Also recorded were cable tension and cable angle at the aft end of the sheave.

The towfish and ship data streams were recorded simultaneously in a Compaq computer, resulting in a multiplexed file with a sampling frequency of 14 Hz. At least six minutes of data were recorded for each trial. Back at DREP the files were demultiplexed, analyzed, and plotted using primarily the MAGnetics Interactive Commands (MAGIC) graphics package. Further details on the data collection and manipulation are contained in Reference 2.

To conduct the trials, the ship traversed an octagon, as shown in Figure 3. Changes to the towing configuration were made at the mid-point of the 1-mile legs, and thus two complete trials were conducted on each circuit, each including head, bow, beam, quarter, and stern seas (these terms are illustrated in Figure 3). The ship speed was typically 4 knots, representative of typical towing speeds for side-scan surveys with single-beam-per-side sonars.

The wave conditions consisted of swell from a gale occurring several hundred miles north-west of our area. The wave heights were not measured, but were estimated as sea state 4. All the trials were completed within 9 h. During this time the waves did not decrease, and probably built slightly. Since the trials show improved stability for the two-part tow, and since that configuration was used in the second part of the trial, it can conservatively be assumed that the comparison was made in unchanging waves.

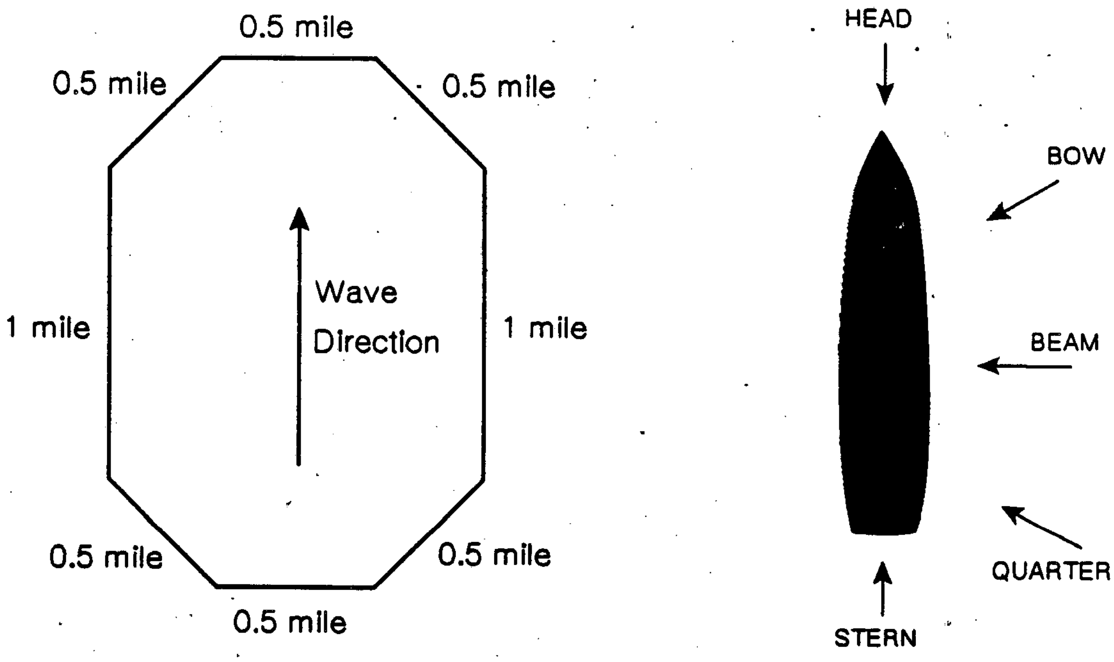

Figure 3. The "octagonal" course followed by CFAV Endeavour during these trials, with dimensions in nautical miles, is shown on the left. A circuit constitutes two trials, with changes made in the middle of the long legs. Wave directions with respect to the ship are described in the text using the terms illustrated on the right.

Ship Motion

The important frequencies of ship motion in those waves are illustrated in Figure 4, which shows power spectra of ship pitch in the wave directions encountered. It can be seen that the frequency of the pitch increases slightly with the velocity of the ship with respect to the waves. Typical ship motion is shown in Figure 5, which shows pitch and vertical acceleration of a point near the towing davit, with a following sea. The spectra of the vertical acceleration of the stern were very similar to those of pitch. Ship roll was found to be important only with waves at or abaft the beam, and its frequency content changed little in those cases. Lateral acceleration of the stern was seen to differ from the roll by the appearance of power at higher frequencies and by having less dependence on the direction of the waves; unlike roll it was significant even in a head sea.

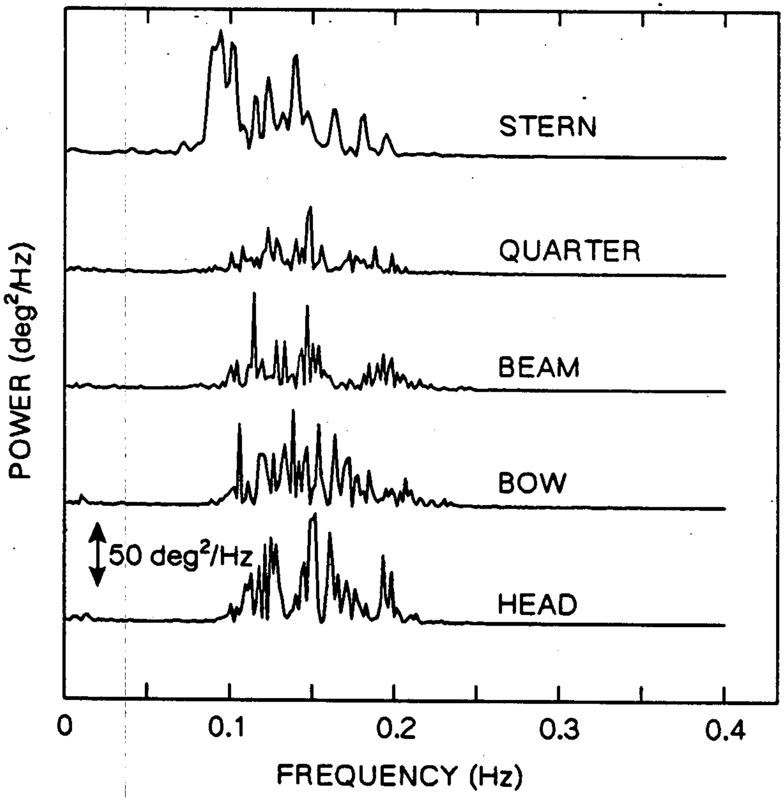

Figure 4. Power spectra of ship pitch with wave directions as shown.

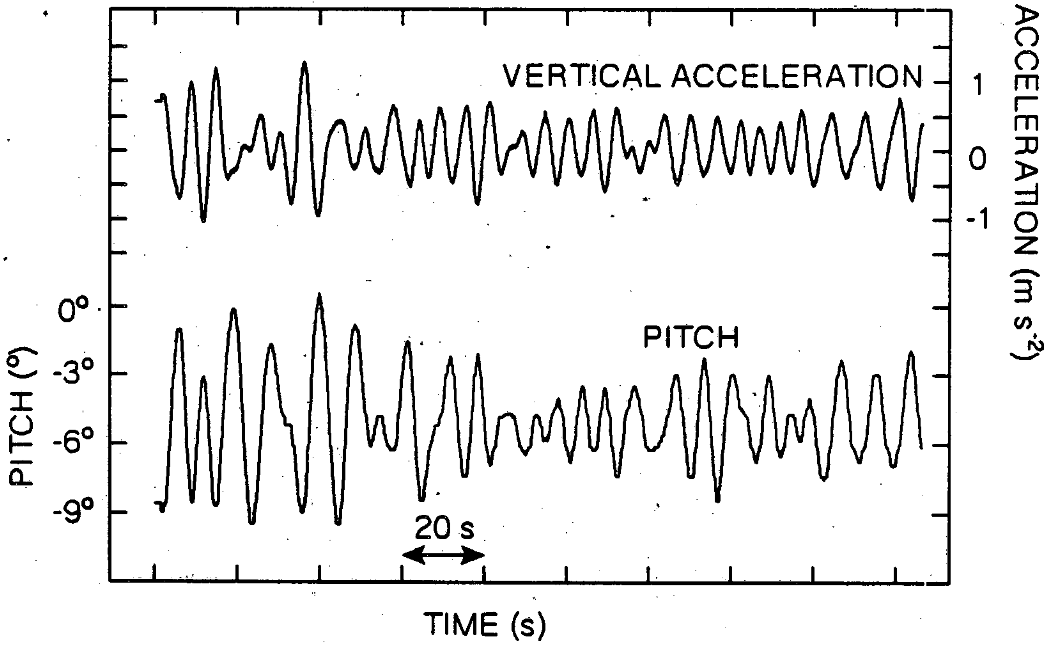

Figure 5. Pitch and vertical acceleration of the stern with a following sea during the first trial of this series. Negative pitch denotes bow downward.

TABLE 1

RMS Amplitudes of Ship Pitch, Roll, and Accelerations

	Wave Direction				
	Head	Bow	Beam	Quarter	Stern
Roll (°)	0.043	2.1	2.8	3.6	1.9
Pitch (°)	2.3	2.3	1.9	1.6	2.9
Vertical Acc. (m s^{-2})	0.58	0.56	0.58	0.46	0.28
Lateral Acc. (m s^{-2})	0.20	0.22	0.27	0.28	0.14
Fore-Aft Acc. (m s^{-2})	0.11	0.10	0.085	0.085	0.10

The observed rms amplitudes of the angular variations and the accelerations are given in Table 1. The trends in these data are largely as expected; for example there is less roll and lateral acceleration with head seas than with beam seas. Note, though, that the largest values of roll and lateral acceleration were found with quartering seas, and that all five values were significant with stern seas. Lateral acceleration might, possibly, be nulled on a ship proceeding directly into very uniform waves, but this does not seem to be observed with normal helming and real waves.

Towfish Motion with Direct Tow

The behaviour of the towfish in head seas with a 30-m tow cable is displayed in Figure 6, which shows the power spectra of towfish accelerations and in Figure 7, which contains a sample of depth, pitch, and acceleration data. The dominant frequencies were between 0.11 and 0.22 Hz for these waves, which is essentially the same range as for ship pitch. The

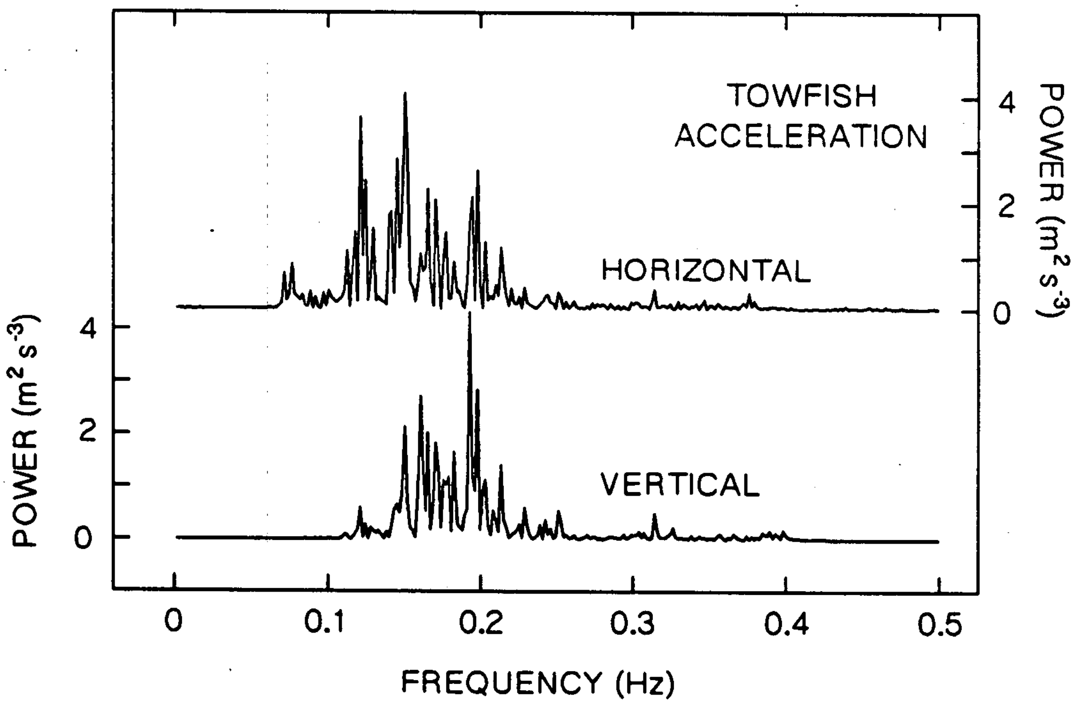

Figure 6. Power spectra of the vertical and horizontal accelerations of the towfish with a head sea, using the direct-tow configuration.

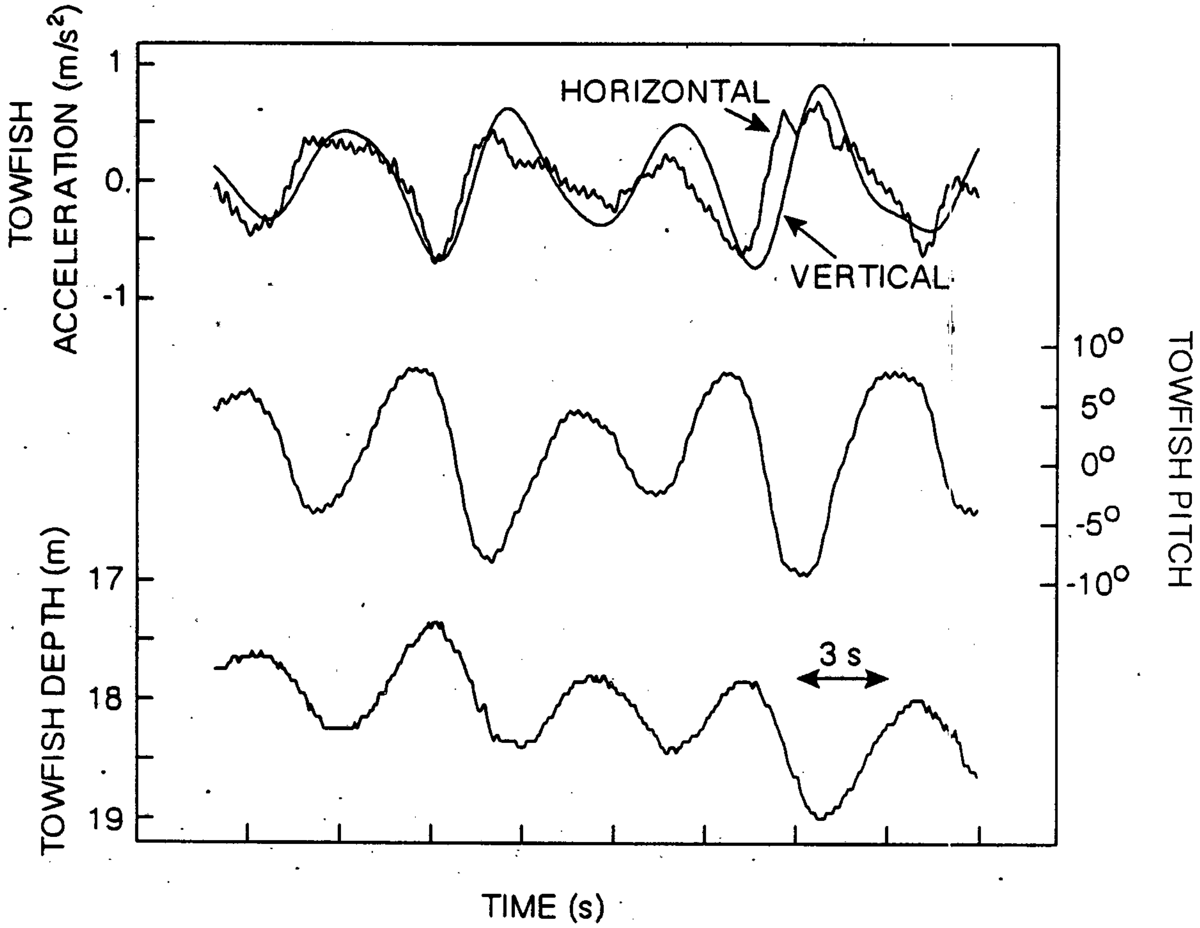

Figure 7. Towfish depth, pitch, and accelerations with a head sea. The vertical acceleration as shown is the second derivative of the depth.

depth, pitch, and acceleration records can be analyzed in the case of head seas, because the ship's motion is largely pitch, as shown above. Taking a cycle as starting when the tow cable tightens due to the ship pitching stern up, the first effect is that the towfish accelerates upward and forward. The towfish soon pitches nose-up, because of the tail fins. The towfish rises until the cable tension at the towfish is less than its weight whereupon it starts to sink, nose downward, again because of the tail fins. The two accelerations are tightly correlated, with little phase difference; and the depth and pitch records are also very similar, with pitch slightly ahead in phase.

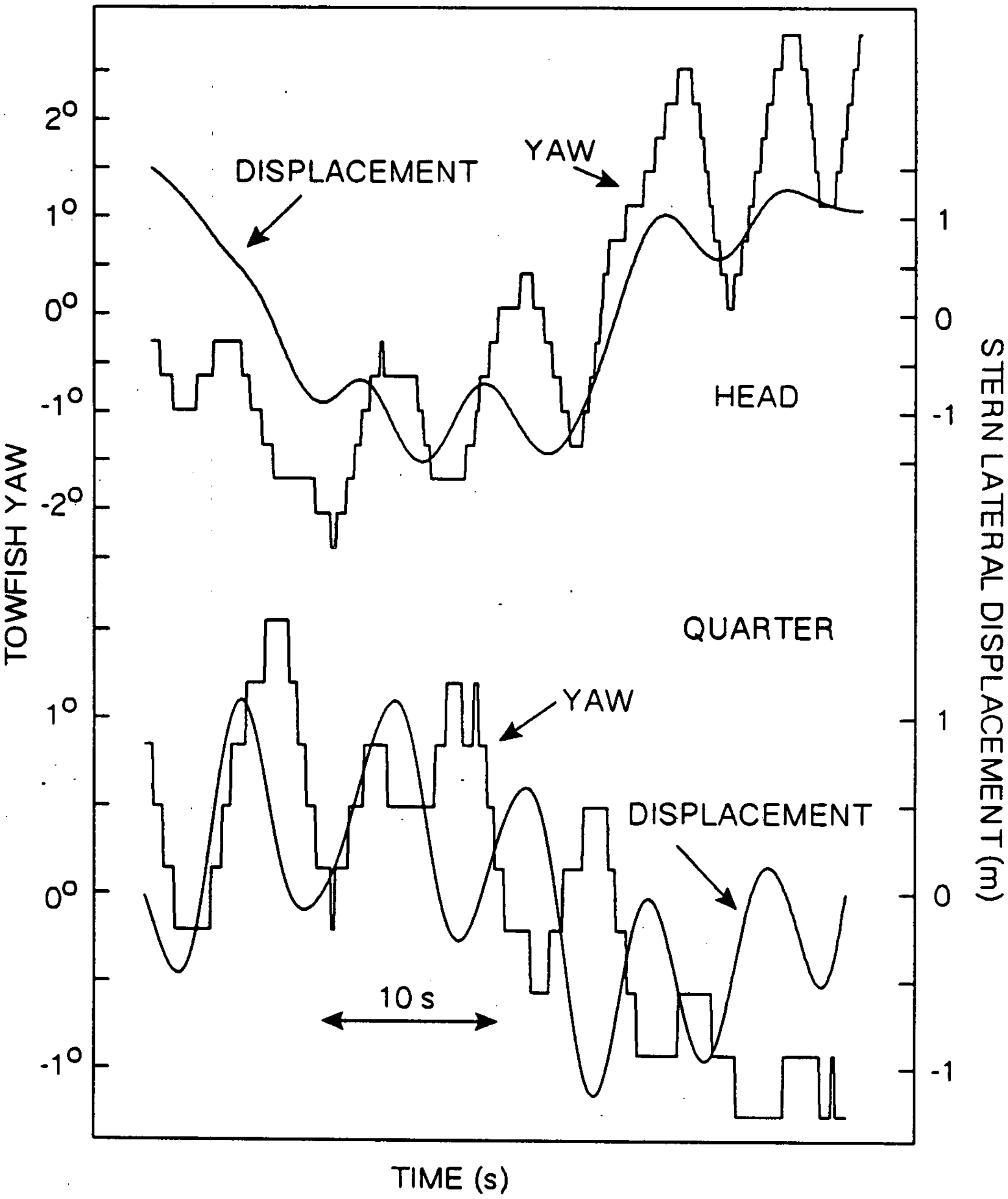

Figure 8. Lateral displacement of the stern of the ship and towfish yaw measured during runs with head seas and quartering seas. The towfish yaw is the towfish heading with the mean removed; the lateral displacement is the second integral of the acceleration with the mean acceleration, velocity, and displacement each removed in turn.

The stern of the ship undergoes significant lateral displacement, as shown by the data in Table 1. This causes towfish yaw. A simple model for the magnitude of the yaw is to assume that the cable is straight when viewed from above, in which case the tangent of the yaw is the amplitude of the displacement divided by the cable length (actually the horizontal component of cable length). For a cable length of 30 m, the amplitude of the yaw in degrees should be about twice the amplitude of the displacement of the stern in metres. Figure 8 shows towfish yaw and lateral displacement of the stern for selected portions of the runs with head and quartering seas. It can be seen that towfish yaw is strongly correlated with motion of the stern, and lags about one-quarter cycle. However it should also be pointed out that many other motions are occurring simultaneously, and other samples of yaw and displacement data do not show clear correlations.

The towfish accelerations for the five wave directions are shown in Figures 9 and 10. Lateral acceleration of the towfish was always very small, and was not plotted in this memorandum. The significant components of acceleration were the fore-aft and vertical components and, in general, they were of comparable size.

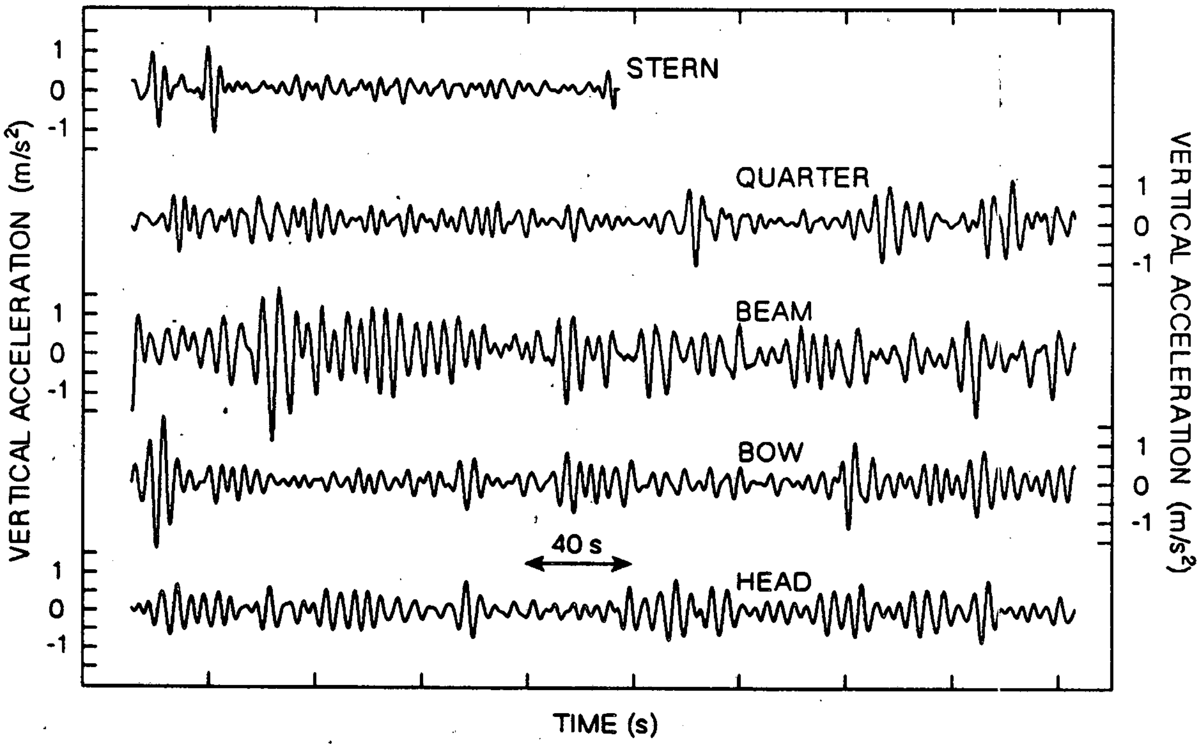

Figure 9. Vertical acceleration of the towfish with the ship encountering the wave directions shown. These data were calculated by finding the second derivative of the depth.

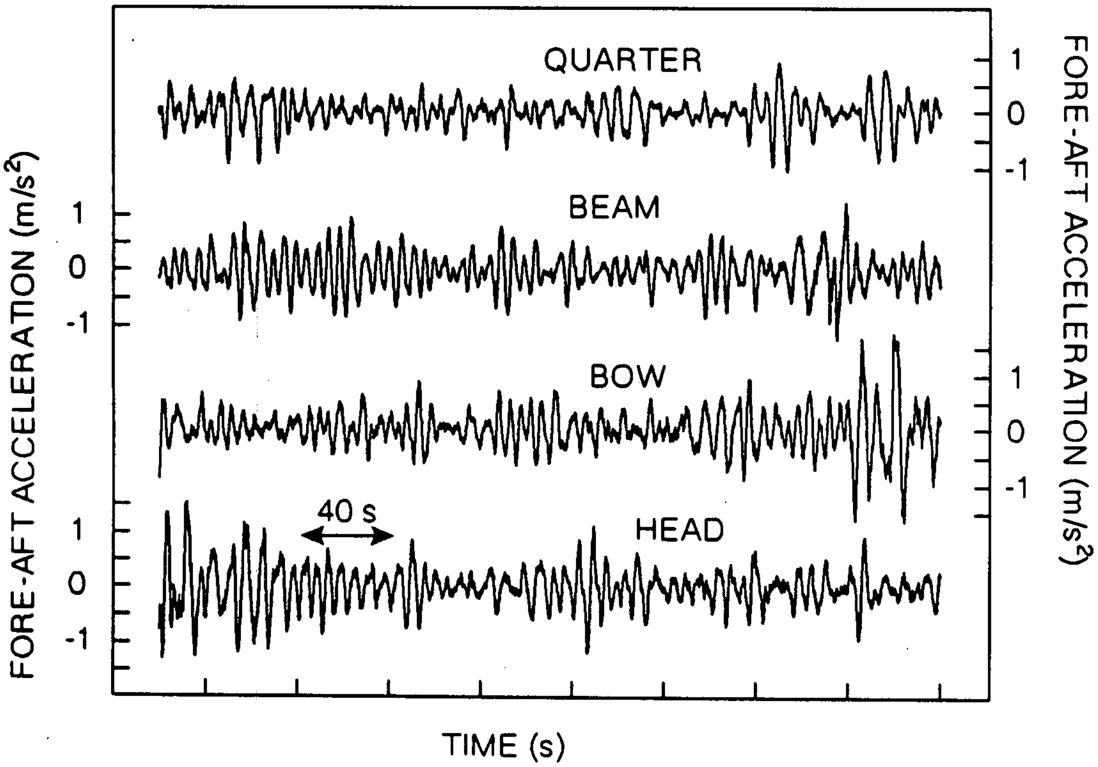

Figure 10. Horizontal component of the fore-aft acceleration of the towfish, with the ship encountering the wave directions shown. The acceleration was calculated by subtracting the component of gravity along the towfish fore-aft line from the output of the accelerometer mounted on that line. No data from the trial with stern seas was available because the accelerometer package failed before that trial.

It is not our purpose here to explain the details of the towfish motion. One approach to analyzing towfish motion may be found in Reference 3, and a complete physical analysis is clearly a significant challenge. Here we present samples of data on attitude and accelerations to show their magnitudes and typical frequencies, and to illustrate very simple physical models where appropriate.

Towfish Motion with a Two-Part Tow

The two-part tow, as described above and illustrated in Figure 2, consisted of the same winch and tow cable towing a triangular flange to which the down weight and the towfish were attached, the weight with 2 m of wire rope and the towfish with neutrally buoyant line. The length of the primary tow cable was either 30 or 122 m. The two-part tow was used very soon after the trial with the direct tow, in essentially the same wave conditions and using the same procedures. An additional variable was available with the two-part tow, namely the length of the flange-to-towfish neutrally buoyant cable. Three lengths were used: 17, 12, and 9.4 m.

The rms amplitudes of the observed motions are given in Table 2 for the three lengths of flange-towfish cable, with the corresponding values from the direct-tow trials included for comparison. The towfish attitude and acceleration show variations at wave frequencies and at much slower frequencies. These slower frequency variations, which are probably due primarily to changes in ship speed, are a real effect but must be eliminated for purposes of calculating the amplitudes of wave-driven oscillations. Thus the data were high-pass filtered, in the MAGnetics Interactive Commands (MAGIC) graphics package, with a cut-off frequency of 0.07 Hz, before the rms amplitudes were calculated.

The variance in the amplitudes of the towfish motion is a reflection of the natural variance in wave heights. Typically, the standard deviation was found to be about 40% over a 6-min sample. Thus when the mean amplitudes of five such samples are averaged, the standard deviation is about 18%.

The two-part tow dramatically reduces the pitch and vertical acceleration (Figures 11 and 12), noticeably reduces fore-aft acceleration (Figure 13), and slightly reduces roll (Figure 14), but has little effect on the yaw (Figure 15). The significance of these observations will now be discussed.

TABLE 2

RMS Amplitudes of Towfish Motion with Direct and Two-Part Tows for Five Wave Directions

	Direct Tow	Two-Part Tow with Flange-Towfish Distance:		
		17 m	12 m	9.4 m
Towfish Pitch (°)				
Head	4.06	0.54	0.49	0.88
Bow	4.40	0.88	0.57	0.72
Beam	4.07	0.74	0.63	1.15
Quarter	3.42	0.58	0.86	1.16
Stern	N/A	0.64	1.02	0.98
Towfish Roll (°)				
Head	0.87	0.89	0.62	0.65
Bow	0.68	0.57	0.72	0.63
Beam	0.69	1.03	1.22	1.14
Quarter	0.60	0.72	0.79	0.81
Stern	N/A	0.91	1.09	0.83
Towfish Yaw (°)				
Head	0.86	0.91	0.95	0.69
Bow	0.93	0.38	0.74	0.54
Beam	0.82	0.60	0.63	0.59
Quarter	0.52	0.42	0.51	0.52
Stern	0.59	0.45	0.66	0.45
Towfish Vertical Acceleration (m/s^2)				
Head	.29	.035	.025	.044
Bow	.28	.036	.027	.029
Beam	.35	.031	.047	.060
Quarter	.32	.037	.045	.050
Stern	.22	.043	.048	.047
Horizontal Component of Towfish Fore-Aft Acceleration (m/s^2)				
Head	.36	.11	.11	.17
Bow	.37	.21	.11	.18
Beam	.32	.16	.15	.28
Quarter	.28	.13	.18	.30
Stern	.21*	.16	.23	.22

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* Estimated in absence of pitch data for this run.

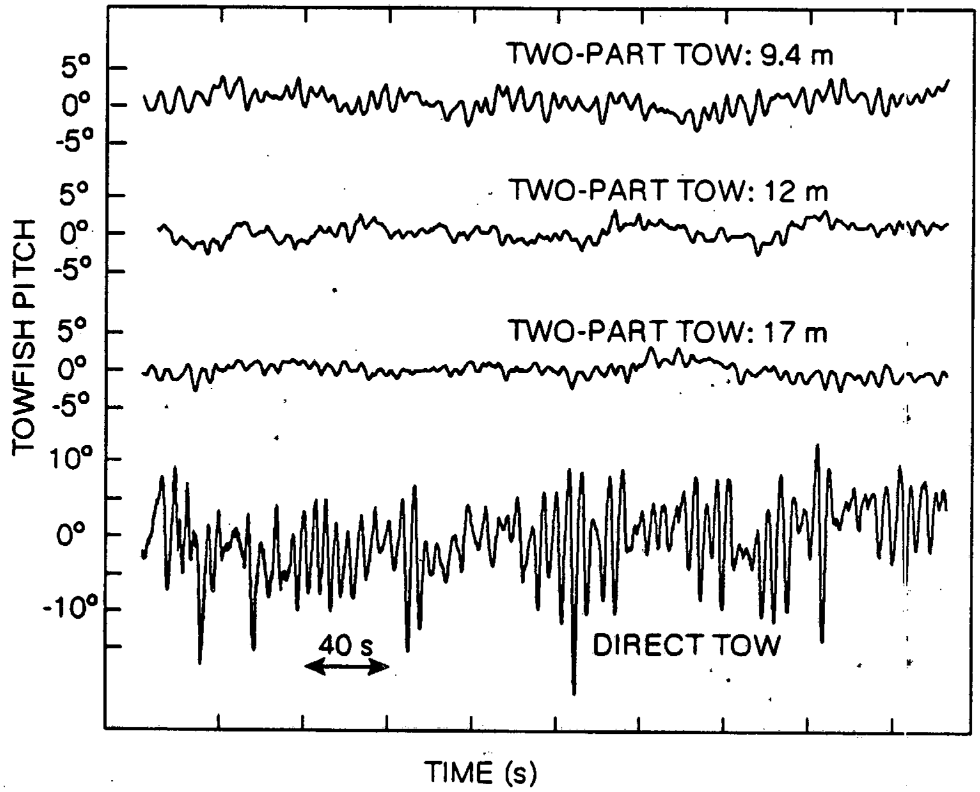

Figure 11. Towfish pitch in head seas with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances.

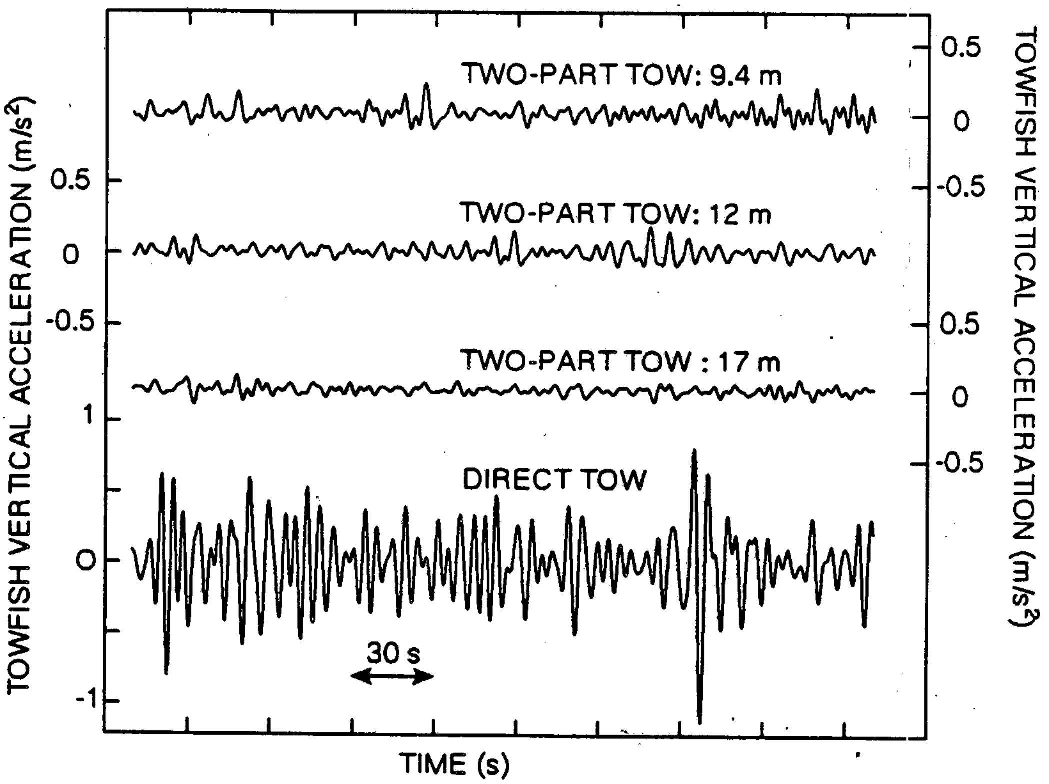

Figure 12. Towfish vertical acceleration in quartering seas with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances.

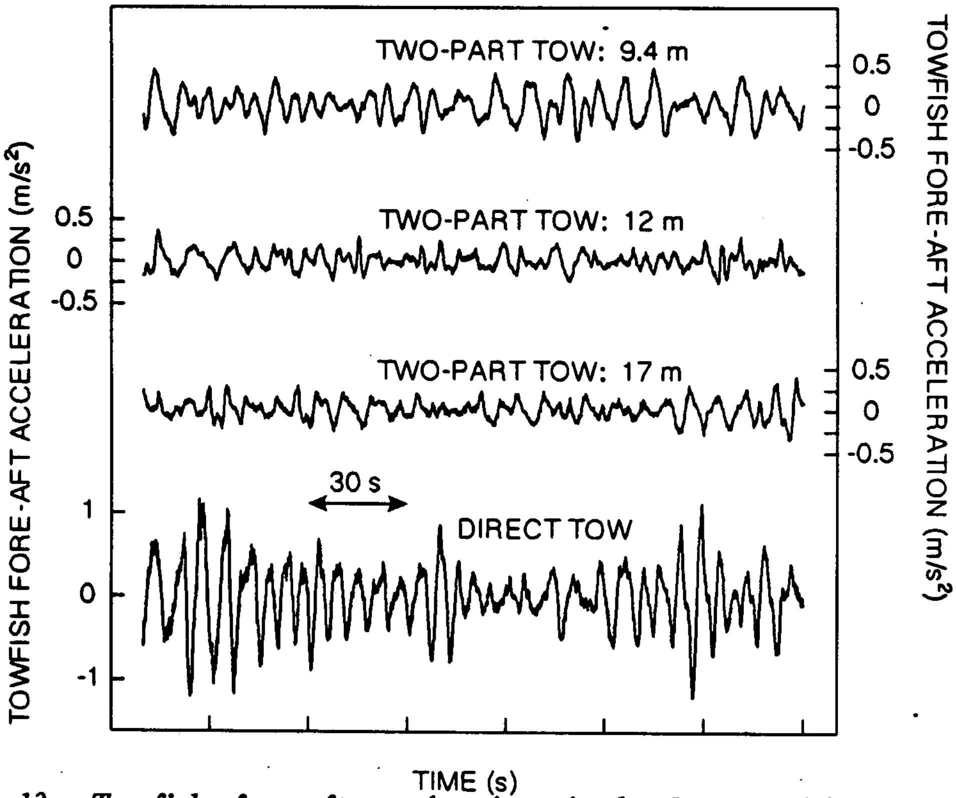

Figure 13. Towfish fore-aft accelerations in head seas with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances.

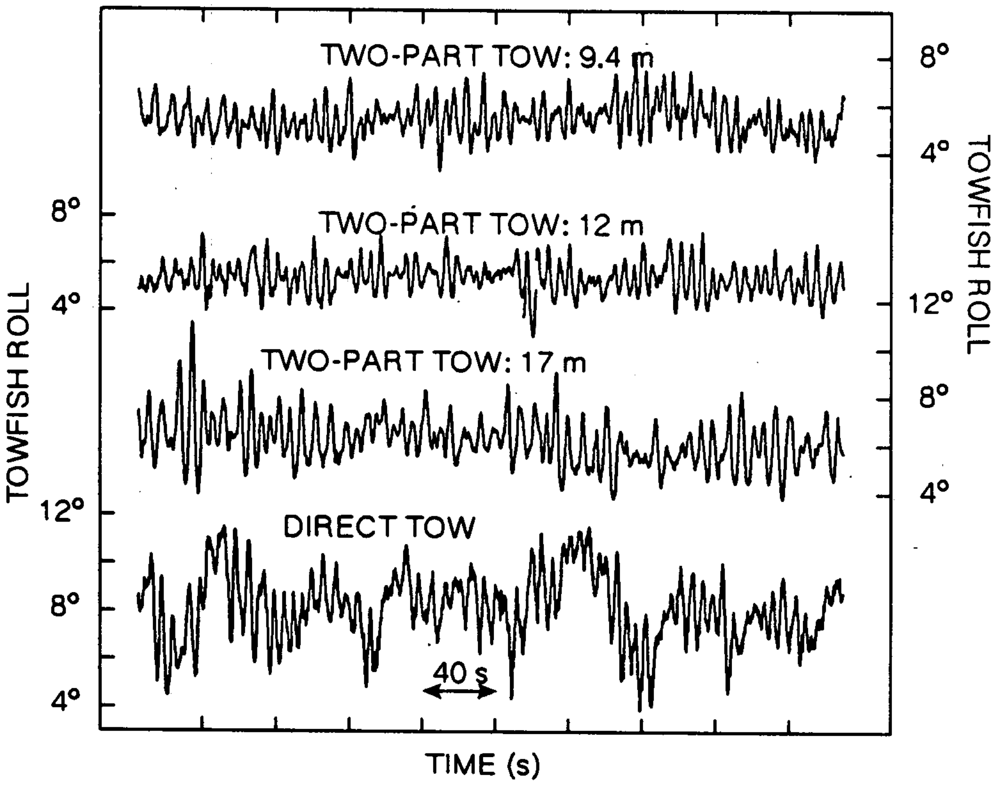

Figure 14. Towfish roll in head seas with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances.

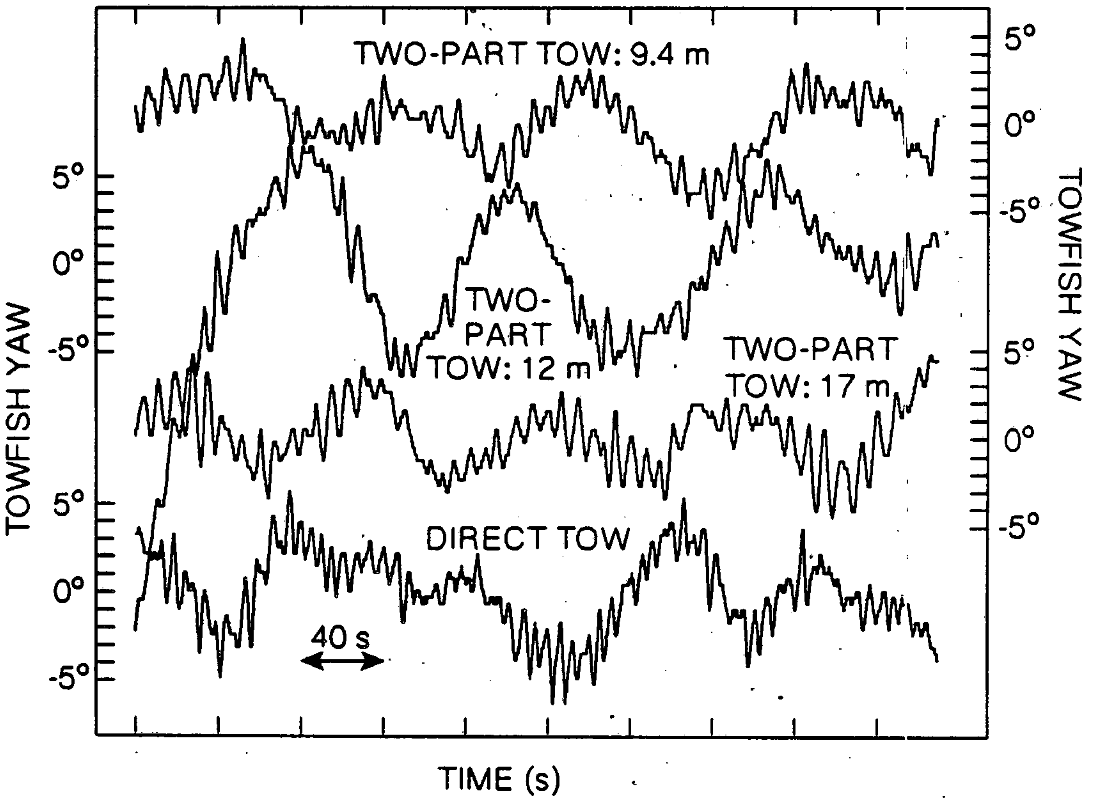

Figure 15. Towfish yaw in head seas with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances. The yaw was calculated as towfish heading minus the mean heading.

One would expect towfish yaw to decrease as the length of the tow cable is increased. Very short cables, 30 m ship-to-flange plus 17, 12, or 9.4 m flange-to-towfish, were used to collect the data shown so far. The final trial was done with 122 m of cable between the ship and the flange, plus 9.4 m between the flange and the towfish. Comparison (Table 3) with the previous trial with 9.4 m of cable between the flange and the towfish does show a general decrease in mean amplitudes, but the individual changes are not statistically significant. Thus it appears that towfish yaw due to lateral motion of the stern is a significant factor in towfish stability even with fairly long cables.

TABLE 3

RMS Amplitudes of Towfish Motion with a Two-Part Tow*

	Pitch (°)		Roll (°)		Yaw (°)	
Tow-Cable Length:	30 m	122 m	30 m	122 m	30 m	122 m
Head	0.88	0.83	0.65	0.70	0.69	0.59
Bow	0.72	0.88	0.63	0.62	0.54	0.40
Beam	1.15	0.91	1.14	0.64	0.59	0.35
Quarter	1.16	0.88	0.81	0.65	0.52	0.73
Stern	0.98	N/A	0.83	N/A	0.45	N/A
Mean	0.98	0.88	0.81	0.65	0.56	0.52

	Vertical Acceleration (m/s^2)		Horizontal Acceleration (m/s^2)	
Tow-Cable Length:	30 m	122m	30 m	122 m
Head	.044	.051	0.17	0.18
Bow	.029	.042	0.18	0.22
Beam	.060	.047	0.28	0.21
Quarter	.050	.038	0.30	0.19
Stern	.047	N/A	0.22	N/A
Mean	.065	.063	0.32	0.28

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* The distance between towfish and flange was 9.4 m.

INHERENT TOWFISH STABILITY

A relevant question, in view of the considerable towfish motion observed with the two-part tow, is whether that motion is caused by wave-driven motion of the ship or is inherent to the towfish. By inherent motion, we mean the motion which the towfish would undergo if towed under steady conditions in placid water. While it might be possible to separate the two causes on the basis of the expected frequencies, a direct test is available by examining stability data from trials in very calm conditions with long tow cables.

The most constant conditions in which we have towed was probably on one particular long pass in a trial conducted in Sept 88. Ship motion was very modest throughout this run, and the depths were such (73 m typical) that we used about 200 m of cable (typical layback of 175 m). The towfish used in these trials differed from the one used earlier only in having thinner walls and thus not requiring strap-on tubes to achieve neutral buoyancy. While the absence of these tubes might contribute marginally to stability, the effect would have to be very small since these tubes were only a small fraction of the frontal area, and thus the drag, of the towfish (Figure 2).

Typical ship motions during a portion of this run are displayed in Figure 16. These data are the fore-aft and lateral accelerations of the stern, near the towing davit, as measured by the same gyro-stabilized accelerometer package. These amplitudes are at least an order of magnitude less than on the towing trial described elsewhere in this memorandum. Towfish yaw and pitch (Figure 17 - note the technical limitations described in the caption) recorded simultaneously with this ship data, show very small amplitudes. This proves that the towfish yaw and pitch measured with the two-part tow and described earlier (Figures 11 and 15), which had amplitudes of several degrees, were caused by ship motion.

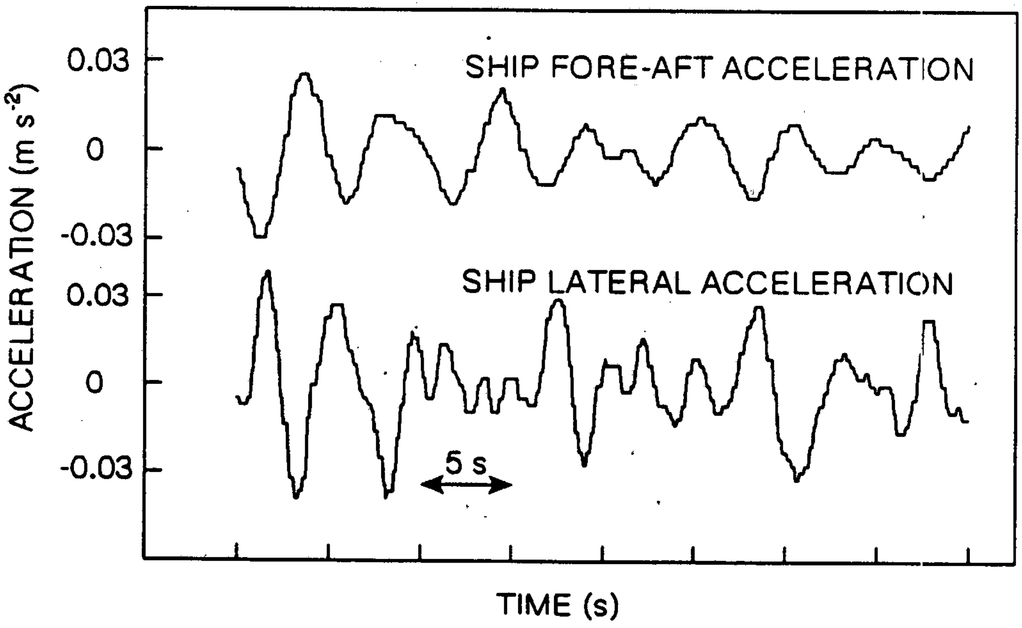

Figure 16. Ship accelerations in very modest waves. The accelerations were measured with a Humphrey gyro-stabilized three-axis accelerometer package located close to the towing davit.

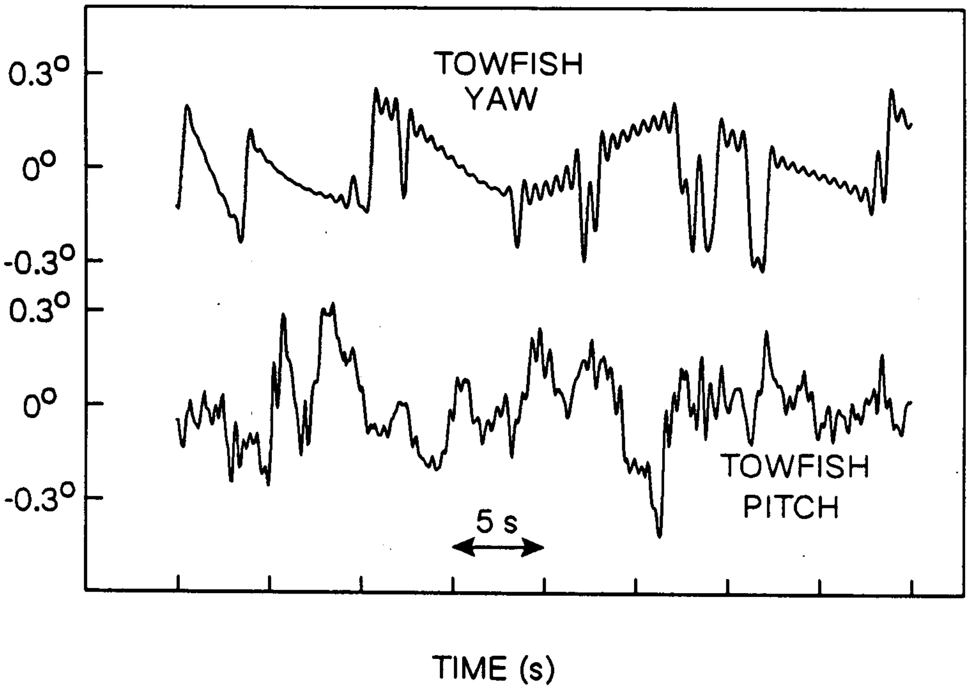

Figure 17. Towfish yaw and pitch during a long run in very modest waves. Yaw was available only from a compass with resolution of 0.35°, thus before filtering contained steps of that size. The ringing was caused by the filtering process which removed variations of 0.07 Hz or less. Pitch was measured with an inclinometer and was thus actually a linear combination of pitch angle and forward acceleration.

EFFECTS OF TOWFISH MOTION ON SIDE-SCAN SONAR IMAGES

In normal side-scan surveys, the sonar image is displayed on the shipboard recorder with each trace parallel to the previous trace. The resulting image (which we will here call an immediate-display image) is an accurate and useful representation of the bottom if the towfish followed a straight trajectory at constant speed. However towfish pitch and yaw will cause the beam to wander, resulting in a distorted image. Speed variations (short-term variations are called surge) will also distort an image, as will sway and heave. The motion of the centre of the footprint of the beam can be calculated from the expressions in Reference 1, and the details of this are presented in Appendix 1. The relationship between this motion and the distortion depends on the beam pattern, the range, and the target, while the amount of distortion which would be acceptable depends on the target and the application. Criteria will not be presented here, but the amount of motion will be calculated in some cases as an indication of the acceptability of those sonar images.

Image processing is of growing importance in sonar applications. One processing technique, called geocoding, is being developed at DREP and under contract (Reference 4). The geocoding technique involves considerable post-processing. Each trace is tagged with the towfish attitude and position (TAP) data for the instant at which it was acquired, and the traces are then overlaid, with averaging as necessary. Towfish motions which would result in immediate-display images containing effects such as duplicated returns, thus apparent lengthening of targets, can often be corrected in preparing the geocoded image. For geocoding to be possible, it is clearly essential that at least some of the sonar return be recorded. No return will be recorded if the towfish is so unstable that its angular motion exceeds the beamwidth, or, if different systems are in use, the larger of the transmit and receive beamwidths. An expression for the angular motion during a round trip of the sound pulse is given in Appendix 1. Comparison of this angular motion with the beamwidth will indicate whether or not a geocoded image could have been produced with that towfish motion.

In terms of the physics of the sonar beam, the stability requirements can be understood by considering the effects of towfish yaw and pitch. The effects of towfish yaw and pitch depend on their rates of change. If the attitude is nearly constant over the time required to image an object, the only effect is that the location of the object may not be where the operator believes it to be if he assumes yaw and pitch to be zero. If attitude changes significantly while imaging an object, the image will be distorted and possibly unrecognizable. These distortions may be removable by geocoding. If attitude changes significantly during the round trip of a single ping, there will not be enough overlap between the transmitted and received beams and the echo will not be recorded. Note that the towfish roll plays no part due to the broad vertical beamwidth.

If the sonar employs beamforming, it would be possible to dynamically correct for attitude changes by altering the time or phase delays in accordance with measured pitch and yaw. With careful design, the wander of the receive beam of such a sonar could be virtually eliminated.

Calculations

Beam wander was calculated from Equation 2 of Appendix 1, as described there and in the following pages. The time period over which wander was calculated was taken to be 1 s, since this is the time required to image a 2-m mine at 2 m/s. Comparisons between wander and the diameter of a typical mine provide an indication of the acceptability of the distortion in an immediate-display image recorded in those circumstances.

Beam rotation was calculated from Equation 7 of Appendix 1. The time period over which beam rotation was calculated was taken to be 1/15 s, since this is the round-trip transit time of the sonar pulse at a range of 50 m. Comparisons between rotation and typical beam widths provide an indication of whether it would be possible to geocode an image recorded in those circumstances.

Neither wander nor rotation required any additional data beyond that described earlier. However yaw rate is important in these calculations, and one problem encountered was that of obtaining a yaw rate, when only magnetic heading was recorded. The difficulty arose from the coarse resolution of the heading data. Each bit of heading data represents 0.35°, thus when a transition occurred during a sampling period of 1/14 s the apparent derivative was 5 deg/s, which was large compared to actual yaw rates. This instrumental artifact can be suppressed by smoothing the heading data before taking the derivative, but only at the risk of suppressing real variations. The data shown in this memorandum were calculated by interpolating the heading data to one point per second, which is sufficient to sample the fastest variations observed and which gives yaw rate essentially free of this artifact. However in the future it would clearly be desirable to measure the yaw rate independently using a rate sensor. Note that the resolution of the pitch data was fine enough that a good estimate of its derivative was available from the point-to-point increments.

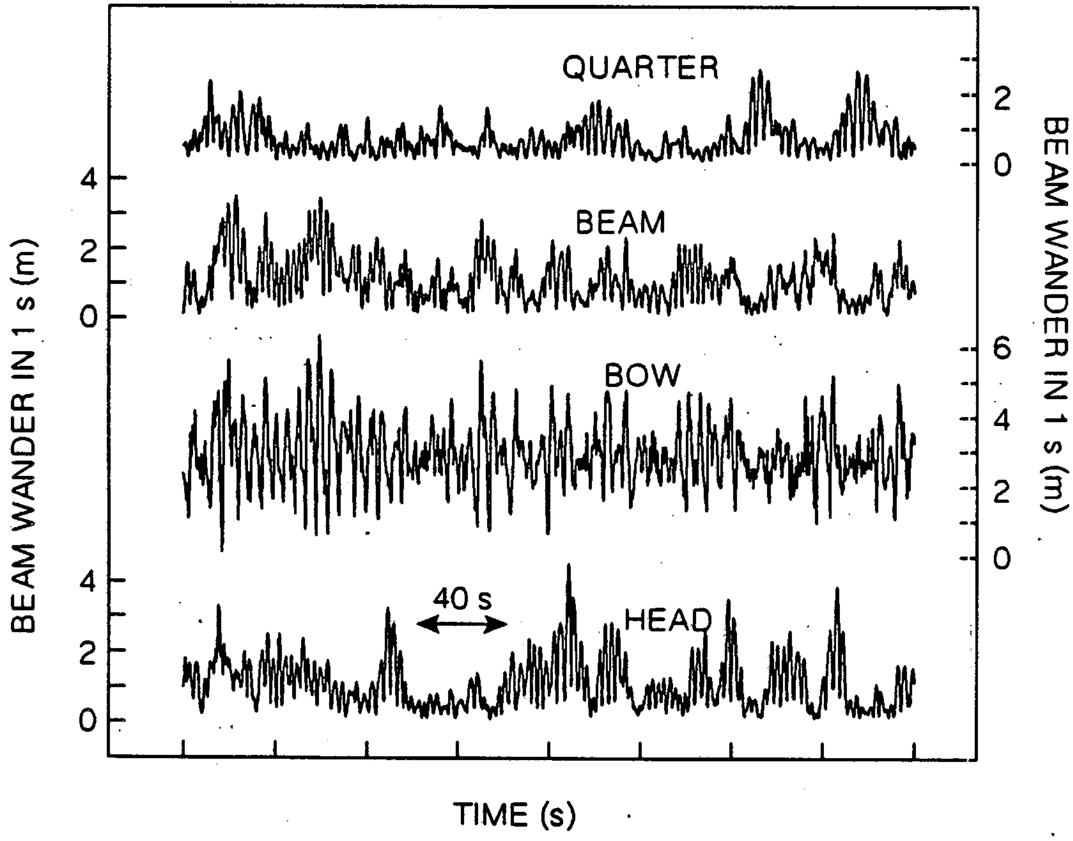

Figure 18. Calculated wander of the beam of a sonar at 50-m range, for a towfish using direct tow, with the ship encountering wave directions as shown. This motion would occur in a 1-s period centered on the time shown, 1 s being representative of the time required to image a mine. No towfish-attitude data were available from the trial with stern seas.

Image Quality with Direct Tow

As an aid in appreciating the magnitude of the towfish motions observed in this trial, the calculated movement of the hypothetical sonar beam is plotted in Figures 18 and 19 for four of the five wave directions (no pitch data were available with stern seas). As discussed above, the wander is relevant to the immediate-display (i.e. non-geocoded) image and indicates the distortion of such an image, while the rotation is relevant to

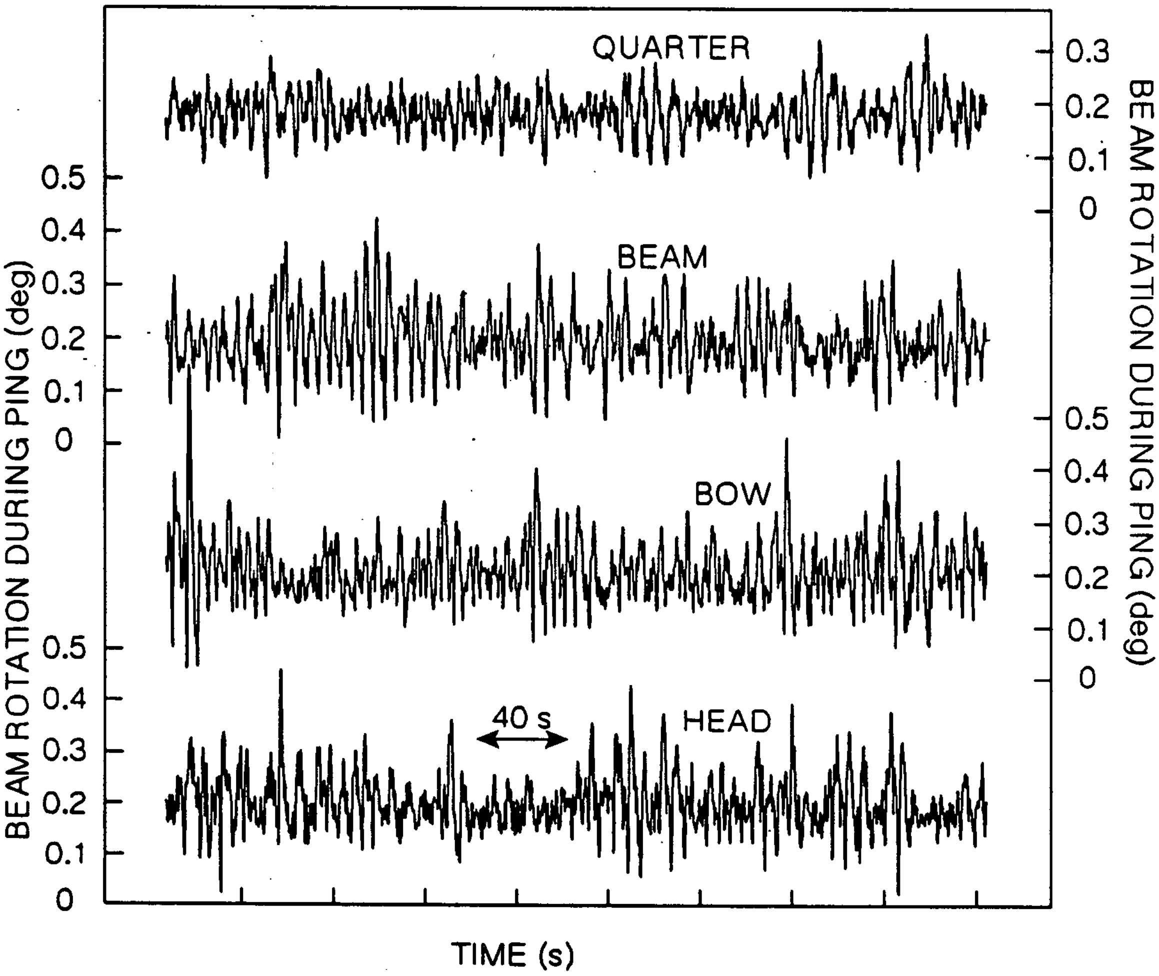

Figure 19. Calculated rotation of the centre of the beam footprint of a sonar at 50-m range for a towfish using direct tow, with the ship encountering wave directions as shown. This motion would occur during the round-trip travel time of the ping. No towfish-attitude data were available from the trial with stern seas.

a geocoded image and indicates how much (if any) of the sonar echo would be captured. In both cases, a sonar operating at 50 m has been used as the example. Since the wander is often larger than the largest dimension of a mine, and since the rotation is occasionally almost as large as the beamwidth of a high-resolution side-scan sonar, it appears that the directly towed towfish is unsuitable as a sonar platform for both immediate-display and geocoded images under these conditions.

Image Quality with Two-Part Tow

The next four figures (Figures 20, 21, 22, and 23) give the calculated wander and rotation of the footprint of the hypothetical beam, for trials in bow and quartering seas with 30 m of towcable and the two-part tow. The wander is that which would occur in the time required to image a mine, and comparison with the dimensions of a mine indicates the distortion which would be seen on a directly displayed image. The rotation is that which would occur during the round trip of a ping to 50-m range, and comparison with the beam width indicates how much of the echo would be lost. No sonar images were actually recorded on the trial.

Since the two-part tow reduces pitch substantially and yaw noticeably compared to the direct tow, it is not surprising that it reduces the distortion in images which are for immediate display (i.e. without geocoding). This can be seen in both Figures 20 and 22. However comparing this wander with a typical mine diameter shows that the distortion in a hypothetical immediate-display image would still have been unacceptable when searching for metre-sized objects.

The quality of hypothetical geocoded images is indicated by the beam rotation during the round-trip travel time of a ping (Figures 21 and 23). The two-part tow reduces this calculated rotation somewhat, which would result in an image with less intensity variation, thus easier to interpret.

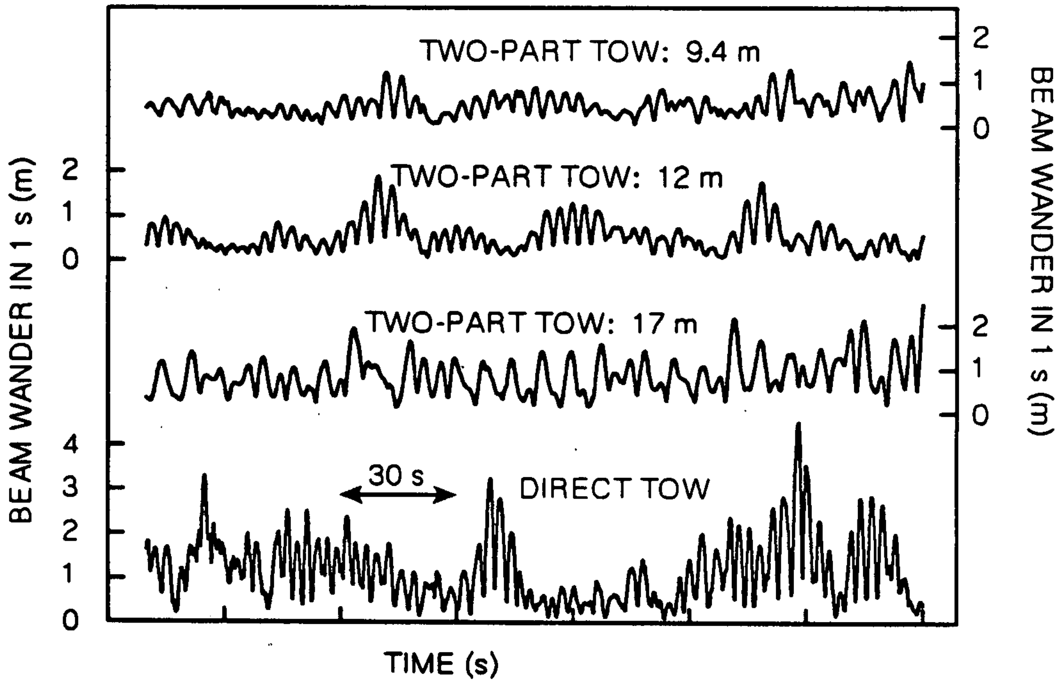

Figure 20. Calculated wander of the centre of the beam footprint of a sonar at 50-m range, with seas on the ship's bow, 30 m of towcable, and with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances This motion would occur in a 1-s period centered on the time shown, 1 s being representative of the time required to image a mine.

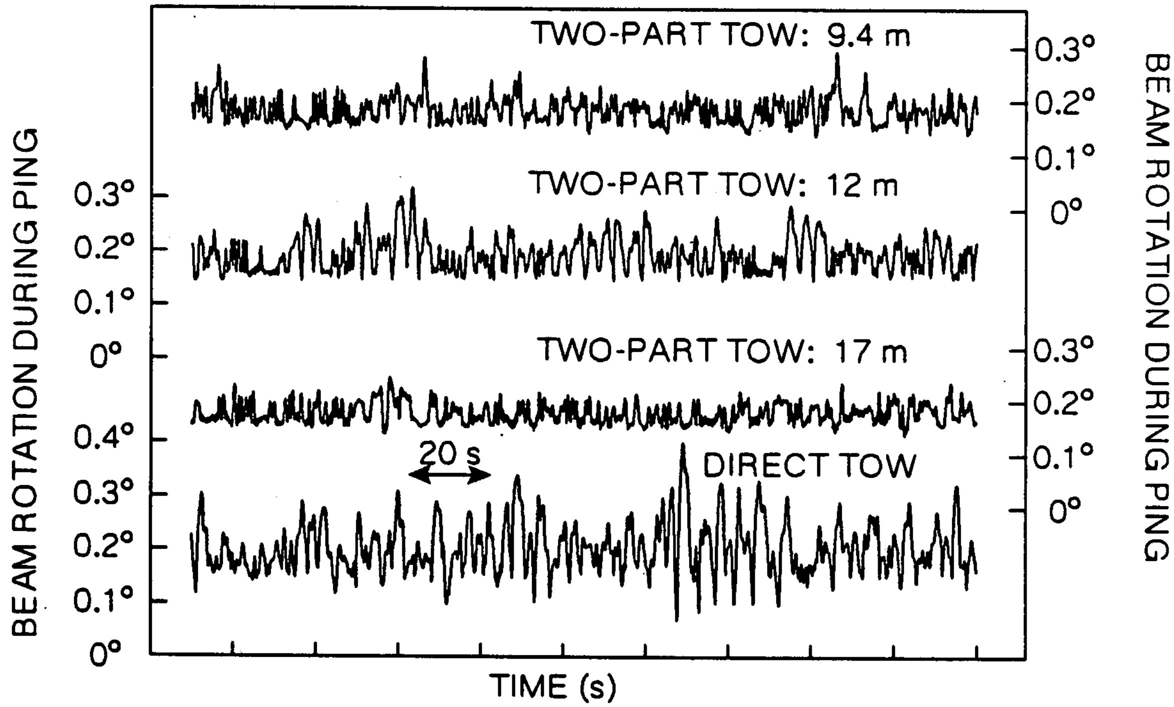

Figure 21. Calculated rotation of the beam of a sonar at 50-m range, with seas on the ship's bow, 30 m of towcable, and with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances. This motion would occur during the round-trip travel time of the ping.

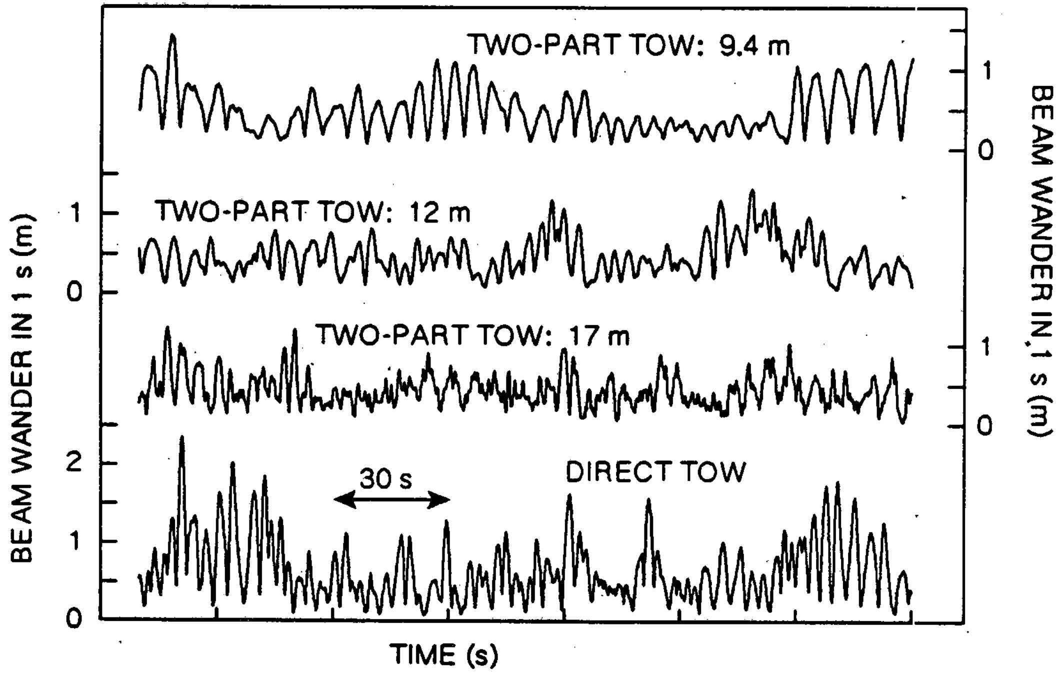

Figure 22. Calculated wander of the centre of the beam footprint of a sonar at 50-m range, with seas on the ship's quarter, 30 m of towcable, and with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances This motion would occur in a 1-s period centered on the time shown, 1 s being representative of the time required to image a mine.

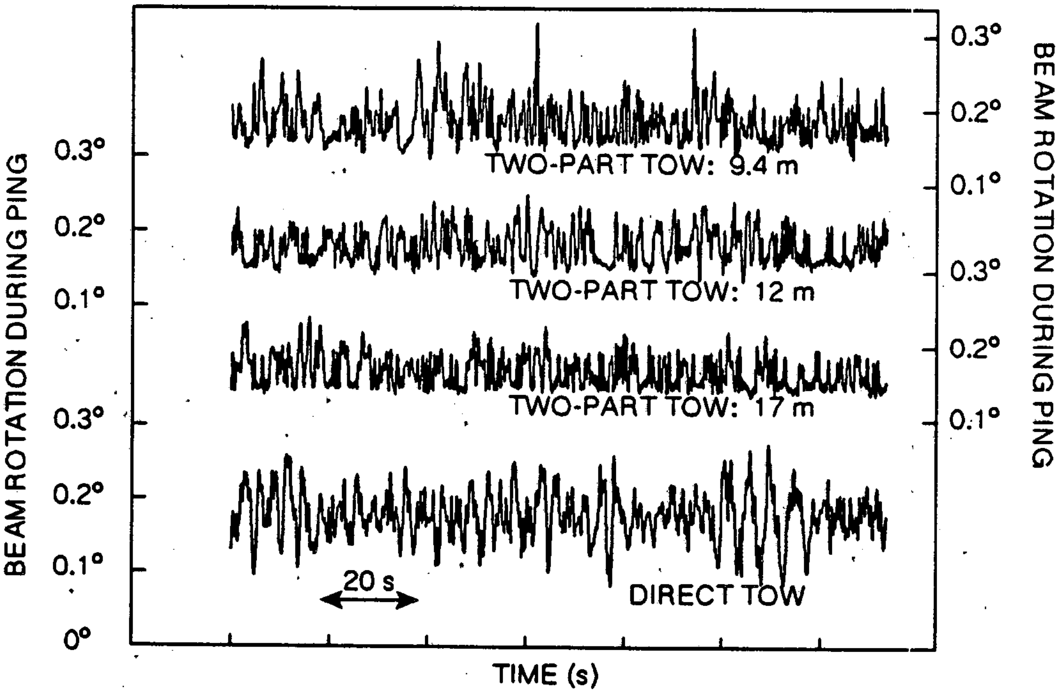

Figure 23. Calculated rotation of the beam of a sonar at 50-m range, with seas on the ship's quarter, 30 m of towcable, and with the direct tow configuration and with two-part tows with the indicated flange-to-towfish distances. This motion would occur during the round-trip travel time of the ping.

The calculated beam rotations are rarely less than 0.13°. This is due to the term 2v/c in Equation 7 (Appendix 1), where v is the towfish speed and c the speed of sound. The physical meaning of this term is that the overlap between transmitted and received beams is reduced by the normal advance of the towfish - clearly if the towfish advanced during the round-trip of the ping by more than the diameter of the insonified area, there would be no overlap. It would have been possible to tow more slowly, and we would have done so if actual images were being collected. Had we done so, all values of beam rotation would have been reduced accordingly.

Geocoding is an expensive process, but these data illustrate its valuable ability to correct an image for distortion caused by waves. The wander shown in Figures 20 and 22 is often larger than even the largest dimension of a mine, and thus a non-geocoded image of a mine collected under these conditions would be broken up, making the mine and its shadow very

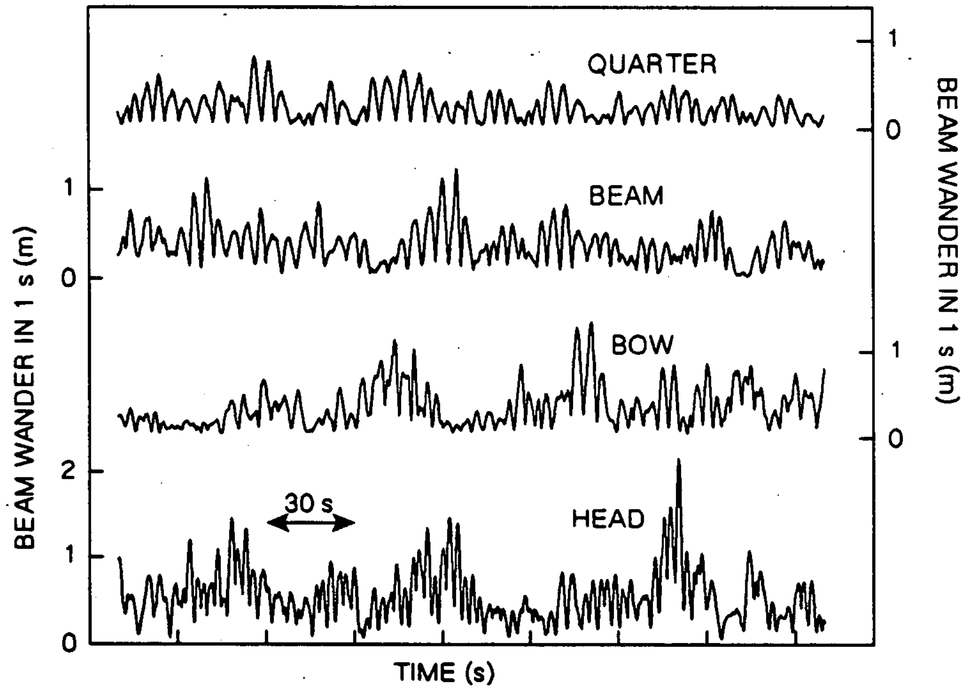

Figure 24. Calculated wander of the centre of the beam footprint of a sonar at 50-m range, for a towfish towed with a two-part tow consisting of 122 m of towcable and 9.4 m of cable between the flange and the towfish. The ship encountered wave directions as shown. This motion would occur in a 1-s period centered on the time shown, 1 s being representative of the time required to image a mine.

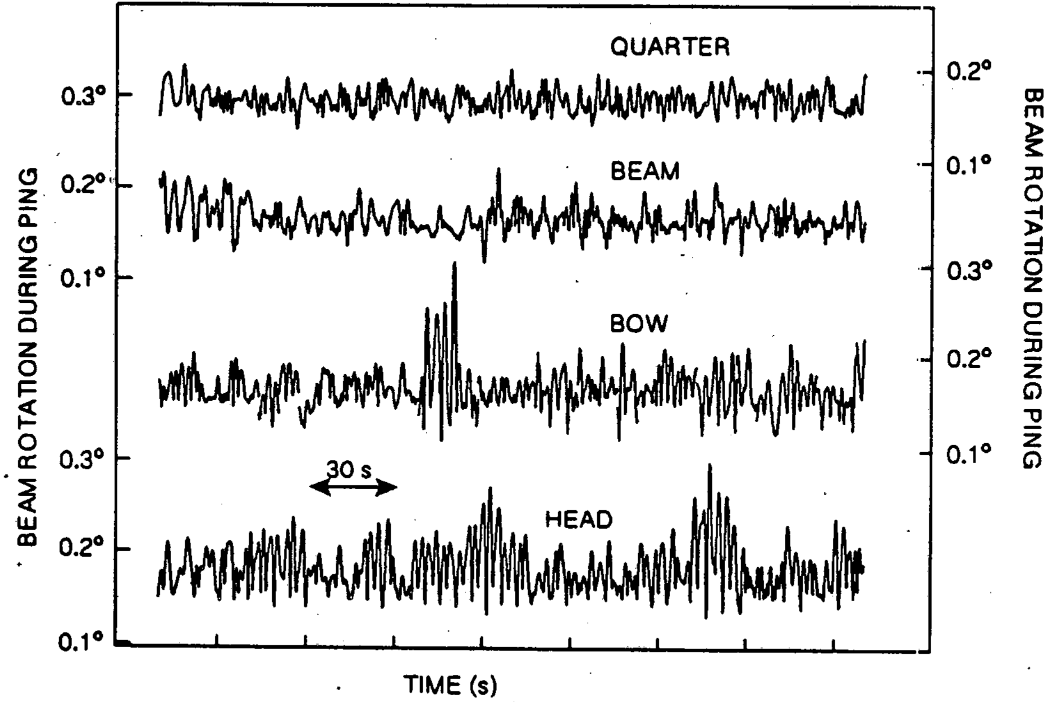

Figure 25. Calculated rotation of the beam of a sonar at 50-m range for a towfish towed with a two-part tow consisting of 122 m of towcable and 9.4 m of cable between the flange and the towfish. The ship encountered wave directions as shown. This rotation would occur during the round-trip travel time of a ping.

difficult to recognize. However the rotation shown in Figures 21 and 23 is smaller than the beamwidth of at least some high-resolution side-scan sonars, and could have been less had we reduced the tow speed. Thus, in some cases, the recorded sonar returns could have been geocoded to produce generally workable images, particularly with the longer lengths of neutrally buoyant cable.

The estimates of beam wander (Figure 24) and rotation (Figure 25) are both reduced even further in the trials with the longer cable between the ship and the downweight. Even in this trial, though, the wander is often comparable to the diameter of a typical mine, and thus the immediate display images would be of little value for minehunting. The calculated values of beam rotation show, as with the 30-m towcable, that geocoding would be possible in at least some cases.

DESIGN OF FUTURE INSTRUMENTATION PACKAGES

One aim of the work reported here was to gain experience on which to base the design of future towfish attitude and position (TAP) instrumentation packages. To this end, the sampling rate was chosen to exceed the expected requirement, and the package which was used contained a costly gyroscopically stabilized acceleration and attitude sensor package.

Figures 4 and 6 are typical power spectra of ship and towfish motion. They show very little power above 0.25 Hz. Power spectra from other trials, such as those described in Reference 2, show only slightly faster variations. While the period between waves could be slightly less in some circumstances, it is clear that filtering TAP data to exclude variations faster than 1 Hz would discard very little, if any, wave-driven effects. Thus we conclude that filtering with a corner frequency of 1 Hz is a reasonable recommendation for a TAP instrumentation package for measurement of wave-driven effects.

Yaw rate is not, of itself, required for image processing. However it is the most important variable in studies of towfish stability. Deducing yaw rate from magnetic heading sensors is inaccurate, because the limited resolution of their output means that it cannot be differentiated accurately. Thus a yaw rate sensor is highly advisable in trials of towfish stability.

CONCLUSIONS

Trials designed to investigate the improvement in stability arising from the two-part tow were done in a moderate sea. Ship motion and towfish motion were both measured, although not simultaneously, but the entire trial was completed within 9 h in very similar wave conditions. Two tow configurations were used: the normal direct tow and a two-part tow with a down weight and a neutrally buoyant towfish.

With the direct tow, it was found that ship pitch couples directly into towfish pitch and acceleration, and a typical towfish pitch amplitude was 4°. Also, large towfish accelerations were found with all wave directions, and it was clear that with the short tow cable used the towfish was quite unsuitable as a sonar platform. Even in head seas, the ship yawed sufficiently that there was significant lateral motion of the stern, and this caused significant towfish yaw.

Towfish pitch and vertical acceleration were found to be dramatically reduced by use of the two-part tow. Horizontal forward acceleration was noticeably reduced, and roll slightly improved. Towfish yaw, however, was essentially unchanged by the switch to the two-part tow. The tow cable was far shorter than would normally be used in surveys, and there was some indication that the use of a longer cable reduced towfish yaw.

Nonlinear towfish motions cause the sonar beam to wander, causing image distortion, and, in more extreme situations, to rotate such that only a reduced fraction of the echo energy is received. Expressions were provided which enable these motions of the beam to be calculated for comparisons with the dimensions of the target and the beamwidth.

The power spectra from this trial showed that filtering at 1 Hz would not exclude any significant amount of wave-driven motion. This observation reduces the data-handling requirements of future instrumentation packages.

Because the yaw rate is so important in assessing stability, a significant improvement in further studies of platform stability would be to use a yaw rate sensor rather than to differentiate the compass reading.

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APPENDIX 1

MOTION OF SONAR BEAM ACROSS BOTTOM

A better appreciation of plots of towfish attitude and acceleration can arise from considering the effects these motions would have on sonar images taken from that towfish. This appendix contains calculations of the motion of the beam footprint due to towfish attitude and position (TAP) changes. Unfortunately, the situation is too complex for these motions to be used to generate criteria for towfish stability, although work toward that goal is underway. Here the complications will be avoided by ignoring both the beam pattern and human perception of the images, and concentrating on the motion of the axis of the beam. The results will not be criteria, but will permit comparisons between beam motion and the dimensions of the object, and between beam rotation and beamwidth.

Both motion and rotation of the beam need to be considered. Motion is essential to the imaging process, in which an image of the target is built up from several pings. Ideally this motion is at a constant velocity, v, but TAP variations cause the beam footprint to wander. The amount of wander determines the distortion in the image, and the first aim of this appendix is to relate TAP variations to the wander. Under more extreme conditions, TAP may change so quickly that by the time an echo returns to the towfish, its receive beam pattern is no longer oriented to receive it, or receives only part of it. Thus the second aim of this appendix is to relate TAP to the overlap between the transmitted and received beams. This is perhaps best pictured as a beam rotation, even though the overlap can be small if even a completely stable towfish is simply towed too quickly.

Beam Wander

Beam wander is best calculated in a coordinate frame which is moving with the towfish at the mean velocity, v. The process is to calculate the coordinates (x,y) at which the beam axis meets the bottom, which is assumed to be flat. In this moving coordinate frame, (x,y) would be constant if there were no variations in towfish attitude or position.

Consider the coordinate frame to have its x-axis along the towfish course, the z-axis vertically downward, and the origin at the towfish position at the mid-point of the period under consideration. This frame is identical to that used in Reference 1, and the coordinates at which the beam axis meets the bottom, from that reference, are:

$$\begin{aligned} x &= x_t - k \sin\alpha \left[r^2 - h^2 \sec^2\gamma\right]^{1/2} + h \cos\alpha \tan\gamma \\ y &= y_t + k \cos\alpha \left[r^2 - h^2 \sec^2\gamma\right]^{1/2} + h \sin\alpha \tan\gamma \end{aligned} \qquad (1)$$

where (x_t, y_t) are the x-y coordinates of the towfish, both with values of zero in the middle of the period, in this case. The towfish yaw is α, the pitch is γ, the height above bottom is h,and the index k can have only two values, +1 for the starboard side and -1 for port.

The wander of the beam during the time required to image an object, depends on the changes in the TAP variables, during that period, not on their actual values. For example, there could be significant crab, i.e. yaw, which would not cause beam wander unless it changed during the imaging period. To calculate wander, the direct approach seems to work best. This approach is to calculate (x,y) for each set of values of TAP, and then to calculate a wander, Δ, as

$$\Delta^2 = \left[x_{max} - x_{min}\right]^2 + \left[y_{max} - y_{min}\right]^2 \qquad (2)$$

This calculation was done in macros in DREP'S MAGnetics Interactive Command language (MAGIC) for both port and starboard ($k = \pm 1$), where max and min denote the extreme values over a time period centered on that observation time. The value of k was then selected to maximize the wander, and this maximum excursion was then plotted against time.

Unfortunately, the calculation was not quite as straightforward as this. The required values are towfish pitch and yaw, towfish position in the coordinate frame, and range to the target. In the trials discussed here, the pitch and yaw were measured. If sonar images were being recorded, the range and height could be taken from those records; in this case the calculations were done for a range of 50 m and a height of 7 m, since those are typical conditions for our trials. However x_t and y_t, the coordinates of the towfish in the moving frame, cannot be directly measured to the required accuracy without very sophisticated instrumentation.

Surge is the periodic fore-aft motion of the towfish. Here, however, we use surge to mean that component parallel to the x axis, that is, parallel to mean course. The two are related by $\cos\alpha \cos\gamma$, where α is the yaw and γ the pitch. An estimate of along-towfish surge is available from the accelerometer mounted on the fore-aft axis of the towfish. After subtracting the component of gravity along the fore-aft axis ($g \sin\gamma$) the acceleration data were integrated twice. Filtering to remove instrumental drifts and multiplication by $\cos\alpha \cos\gamma$ gave an estimate of along-towfish surge.

Because of its substantial surface area when viewed from the side, the towfish undergoes negligible sway. Here, however, we use sway to mean periodic motion along the y axis, the horizontal axis perpendicular to the average course. There are two motions which contribute to sway in this sense. First and usually more important is that when the towfish yaws it continues to move at a speed close to its mean speed of advance. To calculate the resultant motion, a suitable approximation for periods typically required to obtain a single image would be to write $\alpha(t) = \alpha_0 \sin(2\pi\omega t)$ and $v_y = v \sin\alpha = v\,\alpha$ (to first order). Then

$$y_t = -\frac{v}{\omega}\,\alpha\left[\,t - \frac{1}{4\omega}\,\right] \qquad (3)$$

This approximation will serve adequately even in cases in which the yaw is not sinusoidal, provided a reasonable frequency can be assigned. The second component arises from variations in speed and is calculated similarly to surge. Again the fore-aft acceleration is integrated twice to give the fore-aft periodic displacement, and in this case the desired component is $\sin\alpha \cos\gamma$.

To summarize, the wander has here been calculated directly from Equations 1 and 2 above, with the yaw and pitch measured during the trial, a typical height, and the maximum range at which that sonar would be operated. Also, x_t (surge) and y_t (sway) have been calculated using yaw and fore-aft acceleration data, as described above.

Beam Rotation

The rotation of the beam pattern between transmit and receive of the sonar ping is calculated here so that it can be compared with the beam width. If rotation is excessive, an inadequate fraction of the echo energy would be received (i.e. there would be limited overlap of the beam patterns at the transmit and receive times).

Beam rotation is due primarily to towfish yaw and pitch. However a high towing speed could cause poor overlap even in a completely stable towfish. Rather than deal with this complexity here, it will be assumed that the distance travelled between pings is less than a third of the transducer length, so that even in the near field there would be reasonable overlap in the absence of yaw and pitch. Typically, on our trials, we have used $v = 2$ m/s, which satisfies this assumption for Klein 500 transducers.

In this calculation we use a coordinate system aligned as above, but stationary, with its origin at the location of the towfish when the sound is reflecting from the target. The horizontal angle through which the beam moves during a round trip to range r is

$$\theta = \frac{1}{r} \int_{-r/c}^{r/c} \mathrm{MAX} \left[\left| \frac{dx}{dt} + v \right| \right] dt \qquad (4)$$

where x is the displacement parallel to the x-axis due to yaw, pitch and surge, c is the speed of sound, and MAX means to select the port or starboard side to maximize the integrand. Note that because of the large vertical extent of the side-scan beam, overlap perpendicular to the towfish axis is assured, and we are concerned only with overlap parallel to the towfish.

High-resolution sonar imagery is characterized by short ranges and thus round-trip transit times of less than 1 s. Wave-driven motions have periods exceeding 1 s, and thus it is reasonable to assume constant rates of change of towfish yaw, pitch, and surge during a round trip. Thus

$$x = x(0) + \frac{2r}{c}\frac{dx}{dt} = x(0) + \frac{2r}{c}\left[\frac{\partial x}{\partial \alpha}\frac{d\alpha}{dt} + \frac{\partial x}{\partial \gamma}\frac{d\gamma}{dt} + \frac{\partial x}{\partial t}\right] \qquad (5)$$

where all the derivatives are evaluated at t=0 and the last term is the surge. Equation 5 applies in a coordinate frame which is yawed and pitched from the towfish by the angles α and γ, but since we are considering here only the motion of the beam over a short time, we will choose the orientation of the frame so that $\alpha = \gamma = 0$ at t=0, and therefore x(0) = 0. The partial derivatives have simple forms under these conditions:

$$\frac{\partial x}{\partial \alpha} = -k\left[r^2 - h^2\right]^{1/2} \qquad \frac{\partial x}{\partial \gamma} = h \qquad (6)$$

The beam rotation is thus

$$\theta = \frac{2}{c}\left[r^2 - h^2\right]^{1/2}\left|\frac{d\alpha}{dt}\right| + \frac{2}{c}\left|h\frac{d\gamma}{dt} + v + \frac{\partial x}{\partial t}\right| \qquad (7)$$

since MAX(|a+kb|) = |a| + |b|. This angle was calculated and plotted in a similar fashion to the beam wander.

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Stability is a very important characteristic of the vessel or body on which a sonar is mounted. With normal tow configurations, stability requirements are often not met by a towfish in moderate sea states, particularly with the short cable lengths used here. In the trial described here it was shown that the two-part tow, which used a down weight and a neutrally buoyant towfish, significantly reduced towfish motion. In particular the two-part tow effectively suppressed pitch and accelerations. However towfish yaw which was shown to be caused by lateral motions of the ship's stern, was still significant, and yaw is particularly important to sonar image quality.

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Towed Bodies
Ship Towed Sonar
Towed Sonar
Towed Vehicles
Stability Criteria
Attitude
Towfish

All except "towfish" are from TEST