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REMOTE MINE-HUNTING SYSTEMS - VEHICLE STABILITY TRIALS

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Remote Mine-Hunting Systems - Vehicle Stability Trials

Jon M. Preston
Mine Countermeasures Group,
Defence Research Establishment Pacific,
CFB Esquimalt, Victoria, BC V0S 1B0

Landy Shupe
International Submarine Engineering Research Ltd.
1734 Broadway St.
Port Coquitlam, BC V3C 2M8

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Abstract

The Maritime Coastal Defence Vessels (MCDV) will allow the Canadian Navy to perform detailed route survey by acquiring, mosaicing, and cataloguing high resolution sonar images of the coastal sea bottom. The MCDV sonar system will be a side-scan sonar operating from a towfish. Mine hunting, which would be based on comparisons between new and catalogued images, could be done with similar equipment and procedures, except that the MCDV could not safely enter a minefield. A remote system for mine hunting could potentially be faster and more flexible, as well as safer.

An important issue in the design of remote systems for acquiring sonar imagery is that the sonar towfish must be stable, that is, must not respond excessively to the wave-driven motion of the towing vessel. Even modest motions of a sonar platform can distort images and generate coverage gaps. Comparative measurements of the wave-driven motions of a surface drone, of a near-surface drone, and of a ship representative of an MCDV were performed off the west coast of Vancouver Island. The results show that a near-surface drone is as stable as a ship comparable to an MCDV except in surge. The effects of DOLPHIN surge could probably be significantly reduced by driving the winch in opposition to the surge velocity, but this has not been demonstrated.

Background

Mine hunting is the process of finding mines, normally on or close to the sea bottom. An important mine countermeasure, it provides intriguing technical challenges. There are four steps: detection of mine-like objects, classification that they are likely mines, identification to prove that they are mines, and disposal. The first two require sonar, the last two a diver or vehicle. Together with mechanical, electromagnetic, and/or acoustic mine sweeping, mine fields can be cleared to a high level of confidence.

The traditional approach to mine hunting employs a specialized ship, such as the Royal Navy's Single Role Minehunter [1]. Key components of these sophisticated vessels include a complex hull-mounted (or variable- depth) sonar, command and control systems for holding a position or moving the ship in any direction or orientation, and underwater vehicles for identification and disposal. To enable the ships to operate close to live mines, they are designed both to withstand large shocks and for minimal magnetic and acoustic signatures, which implies strongly braced non-metallic hulls, specialized alloys, and careful attention to equipment mounts. The mine hunting procedure is to search ahead of the ship by sonar to detect mine-like objects, then to switch the sonar to higher resolution for classification (often manoeuvring the ship to a different perspective), then to launch the identification and disposal vehicle if appropriate. These ships and procedures have been used and refined for decades, and are of proven effectiveness.

The vessels being built for the Canadian Navy for mine countermeasures, the Maritime Coastal Defence Vessels (MCDV) will also have other missions, such as coastal patrol. They are not designed to enter a minefield safely. Because of this, and for other reasons discussed below, remote mine hunting systems are being considered.

Remote Mine Hunting

Remotely controlled or autonomous mine hunting systems are being considered even by navies

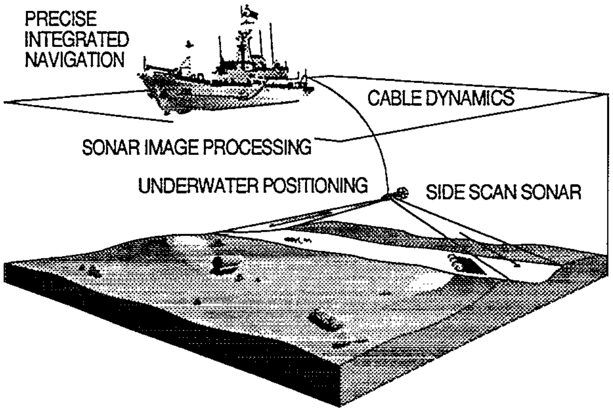

Figure 1: *Equipment and concepts used for route survey at DREP.*

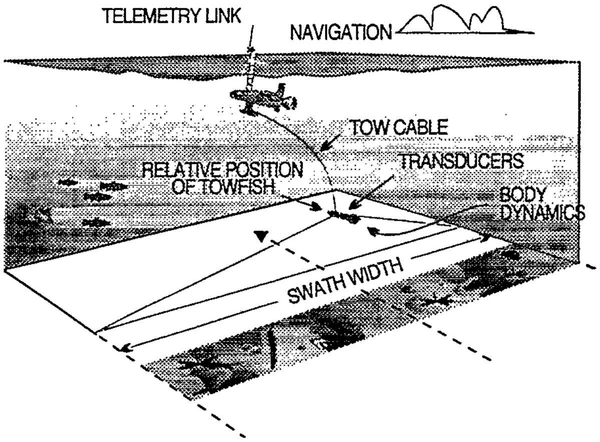

Figure 2: *A concept for minehunting with a drone and a towfish.*

with large commitments to mine hunting ships. The obvious benefit is increased safety. The requirements and costs for signature reduction, blast hardening, and manouverability are far less for a ship which is not designed to enter a minefield. Because unmanned systems could safely pass close to the mine there is another important benefit: the sonar need not be as sophisticated to operate at ranges of about 100 m as it would for about 600 m.

A promising concept for remote mine hunting is similar to the procedures used for route survey. Route survey is the peacetime process of acquiring sonar images of the entire area in which mine hunting is anticipated, to provide a reference against which mine-hunting images can be compared. Figure 1 illustrates acquiring such images with a sidescan sonar on a towfish. The sonar range is typically 100 m, and the towfish altitude is ideally about 15% of the range, so that objects generate clear shadows. Route survey will be a common task on an MCDV [2], and it will be done as shown in Figure 1.

One concept for remote mine hunting is shown in Figure 2, obviously quite similar to Figure 1. The ship has been replaced by a drone, and a high-bandwidth link transmits the sonar images to the command vessel or shore-based command centre. The other concepts for remote minehunting involve powered submerged sonar-carrying vehicles, either swimming ahead of the ship or untethered and with varying degrees of autonomy. All remote mine hunting systems which have progressed beyond the conceptual stage would do only the sonar stages of mine hunting: detection and classification. Unlike ship-based systems, they would continue on their search tracks rather than stop to identify or dispose of a mine-like object. Knowing the coordinates of the classified objects, the MCDV commander would then plan a safe approach to each object for identification and disposal with a remotely operated vehicle.

Several challenges arise in the design of a drone-towed remote mine-hunting system, particularly navigation, the telemetry link, and maintaining towfish altitude and stability. This paper deals with towfish stability, that is, the design of a towfish and tow system to reduce the wave-driven motion of the towfish to acceptable levels.

Stability of Sonar Towfish

The wave-driven motion of the towing ship or drone readily causes towfish motion. Some towfish motions, particularly yaw, markedly degrade the sonar image and can make detection and confirmation impossible [3], [4]. Among the techniques to mitigate this problem are active control surfaces on the towfish [5] (and several commercial towfish), towfish design [6], and different tow configurations such as the two-part tow [3]. This is a particularly relevant question for remote mine hunting systems since the drones will be far smaller than ships, and have very different wave-driven motions.

With a towed system there are only two choices for drones: surface vessels and near-surface vessels. They would be expected to have quite different motions in waves. The only near-surface drone we know of is DOLPHIN (Deep Ocean Logging Platform for Hydrographic Instrumentation and Navigation), developed, manufactured, and operated by International Submarine Engineering Research Ltd, Port Coquitlam, BC. DOLPHIN, shown in Figure 3, is a diesel-powered snorkelling submersible, 7.6 m overall and 3.3 t, which normally travels 3 m below the surface, inhaling combustion air through the snorkel. It was originally developed for hydrographic survey, as a vessel which would be far more stable than a surface launch, because it travels beneath the waves and has active stability control. DOLPHIN's control system is a two-layer hierarchical controller operating at 50 Hz [7]. A small fleet of DOLPHINs is currently performing hydrographic survey off Newfoundland.

Most of the engineering challenges associated with a remote mine-hunting system are the same for surface and near-surface drones. Examples are navigation [7], telemetry, and the sonar system. The most important difference is stability in rough seas. To justify the additional complexity of a near-surface system it would have to be shown that their stability is considerably better.

Measuring Wave-Driven Motion

A trial was conducted to measure the motions of candidate surface and near-surface drones, and a ship. Because of the variability of waves, meaningful comparisons can be made only if all vessels operate simultaneously in the same waves. The ship was the *Vector*, 500 t and 40 m in length, normally used for hydrographic research, and somewhat smaller than an MCDV. Drone vessels have been developed by Germany and Denmark. The German Troika remote-control vessel is 25 m overall and 96 t [8], and the Danish Stanflex system [9] uses vessels 18 m long displacing 32 t. A longstanding concept in MCM is to use craft of opportunity, that is, to requisition available craft. A sensible choice for mine hunting in exposed waters is a commercial fishing vessel, most of which have hull designs which emphasize sea-keeping. To represent a typical trawler, and also to give an indication of the wave-driven motions of the Troika and Stanflex drones, we used a fishing vessel named *Caligus*, 65 t and 15.5 m. Even *Caligus* was unable to put to sea safely on the roughest day of the trial, and a smaller vessel would likely have been even more restricted.

Each of the three vessels was instrumented to measure motion of the tow point, as indicated in Figure 3 for DOLPHIN. As well as its regular suite used for vehicle control, DOLPHIN carried a gyroscopically stabilized package (Humphrey Inc. SA09-0601-1) which measured the three acceleration components plus roll and pitch, to provide improved data. The remotely controlled keel-mounted winch included sensors for revolutions paid out and cable tension. When a depressor was used, either deadweight or hydrodynamic, its depth was measured with a pressure sensor. The DOLPHIN-towed towfish, which was 22 cm in diameter and 1.7 m long, with a total fin area of 0.3 m^2, carried a full instrumentation suite including another Humphrey SA09-0601-1, plus heading, pressure, angular rate, and strapdown acceleration sensors.

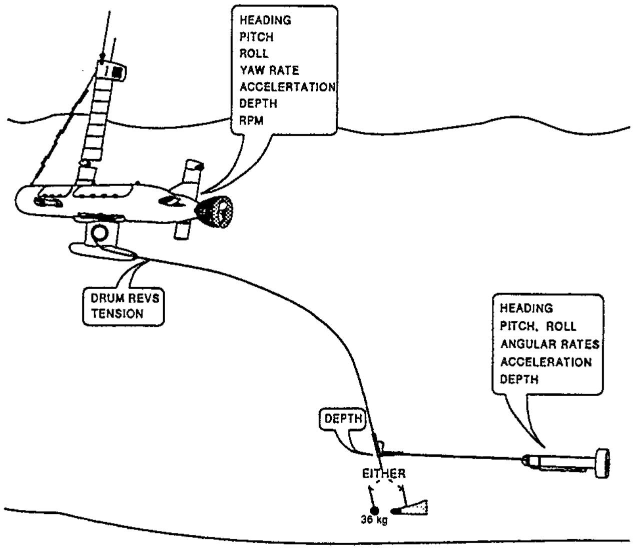

Figure 3: *The DOLPHIN vehicle and its towfish, towed as a two-part tow. On some trials the towfish was ballasted and towed directly, on others either a 36-kg lead ball or a hydrodynamic depressor was used. Sensor locations are indicated.*

Each ship carried, near the tow point, a Ship Motion Sensor System (SMSS), developed and operated by Defence Research Establishment Atlantic (DREA). SMSS is based on a similar triaxial gyro-stabilized accelerometer, plus angular rate sensors. Our only towfish instrumentation suite was on the DOLPHIN-towed towfish, so motions of the ship-towed towfish were sensed only with pressure sensors on their depressors. (Because a depressor and two-part tow significantly increases the stability of ship-towed towfish [10], two-part tows were used throughout the trial with the ships.)

Each day all three vessels left harbour for the trials area, where they followed a race track course as shown in Figure 4. Of the eighteen preprogrammed courses, the one was selected which was best oriented into the swell, to provide the five wave aspects shown in Figure 5. The waverider

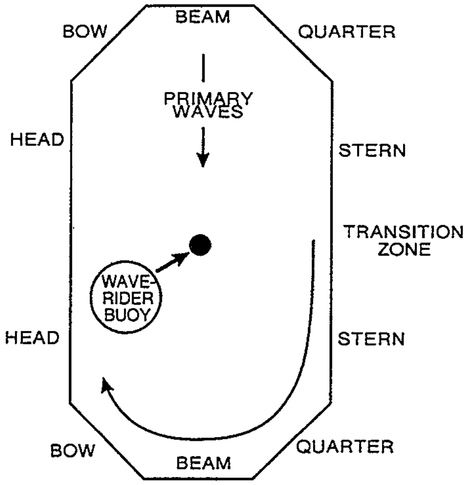

Figure 4: *A race track pattern sailed clockwise by the vessels to generate motion data for five wave aspects. Each circuit produced two sets of aspects.*

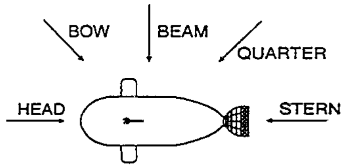

Figure 5: *Definitions of the five wave aspects.*

buoy deployed for the trial reported wave heights and periods; swell was from the west each day with very little wind-driven waves, thus the wave spectrum generally had but one peak. Cable lengths and ship speeds were changed within the transition zone, but the tow configuration could not be changed at sea.

Data Analysis

Each sensor (pressure, pitch, ...) produced a time series for each wave aspect under each condition. The averaging process used to characterise them was the so-called significant average. This average is well established in wave statistics [11], and was calculated each half-hour by the package supplied with the wave-height measuring buoy, the Waverider. It is the mean of the largest one-third of the vertical distances between trough and crest, designated $\overline{H_{1/3}}$. The same mean was calculated for each time series (heave, roll, etc.).

Displacements are more intuitive than accelerations, and can be compared directly with wave heights, therefore the vertical, fore/aft, and lateral accelerations were integrated twice to give heave, surge, and sway respectively. Pitch rate was calculated by numerical differentiation of pitch. Filtering to remove offsets, drifts, and artifacts was a major part of the data processing and required considerable refinement to generate results which were consistent and merited confidence.

The head aspect was selected as the aspect at which the primary inter-vessel comparisons were made. Data from the other aspects have been plotted with respect to the same motion in head seas. The amount of data taken for each speed and wave aspect was about 12 min, in which time an average of 60 waves were encountered (less data were recorded in sea state 6).

Results

Head Seas

It was found that the significant means of the vessel and drone displacements in head seas were nearly proportional to the significant wave height. The same proportionality was found for the products of the significant means of pitch, pitch rate, and roll multiplied by the mean wave period. Figure 6 is a plot against $\overline{H_{1/3}}$ of the significant mean surge divided by $\overline{H_{1/3}}$ and Figure 7 is similar for the product of significant-mean pitch and mean wave period. Over this range of sea states those ratios do not appear to depend on wave height or speed. The vessels surge with very different amplitudes with, surprisingly, *Caligus* far less than *Vector*.

Mean values for all motions are listed in Table I. DOLPHIN's roll, pitch, and sway are notably more stable than either ship, as might be expected for a vehicle with active control [7]. Heave is not as well controlled because DOLPHIN maintains depth rather than minimizes vertical motion, and this distinction is significant in long-wavelength swells. DOLPHIN does not control its surge.

Other Wave Aspects

The aspect dependence of the variables listed in Table I have been calculated and two examples, surge and roll, are shown in Figures 8 and 9. Each data point was calculated by dividing the significant mean of that quantity at that aspect and speed by the significant mean of the same quantity in head seas at the same speed. The curves in these plots are spline curves fitted to mean values at each aspect, and have no theoretical significance. Some comments on the corresponding plots for the other

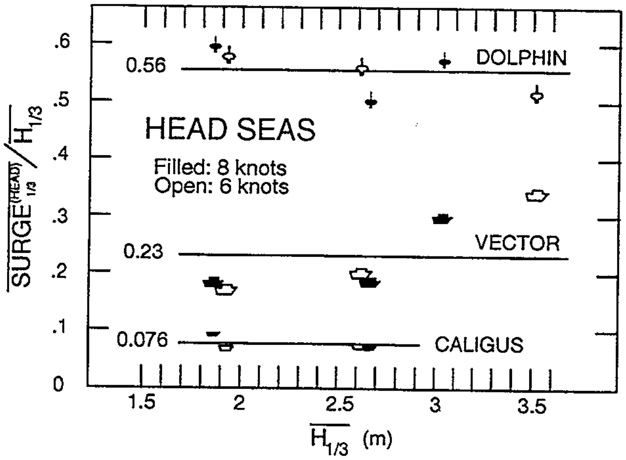

Figure 6: *The ratio of significant-mean surge of the vessels and drone to significant wave height plotted against significant wave height. Vector data are plotted as ship silhouettes, Caligus data as boats, and DOLPHIN data as its distinctive shape.*

Table 1: SHIP MOTIONS IN HEAD SEAS

	DOLPHIN	*Vector*	*Caligus*
Heave	0.78	1.07	0.94
Surge	0.56	0.23	0.076
Sway	0.39	0.56	0.71
Pitch	12.7	25.7	34.4
Roll	10.8	19.2	17.3
Pitch Rate	12.4	32.2	64.4
Yaw Rate		3.6	8.6

Values shown are the average over all trials of the significant mean of that quantity divided by the significant wave height; for angles (deg s/m) and angular rates (deg/m) the significant mean was also multiplied by the mean wave period at the time of the measurement. Yaw rate was not measured on DOLPHIN.

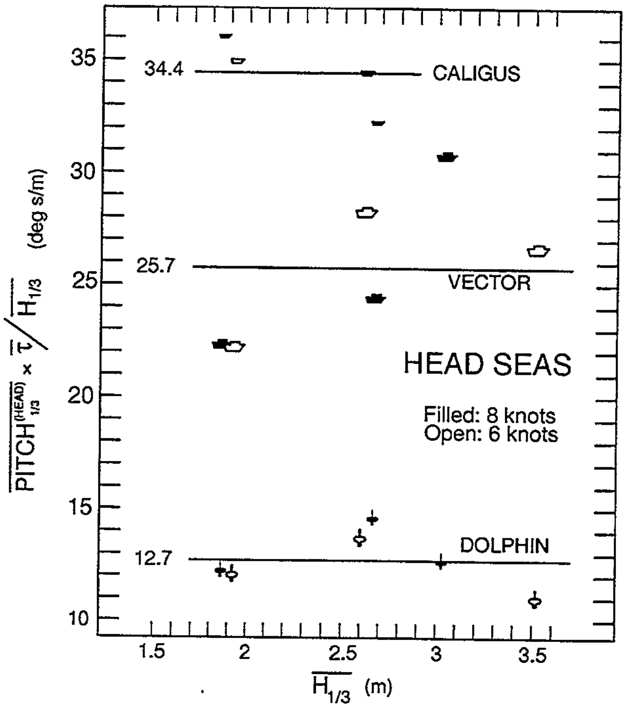

Figure 7: *The ratio of significant-mean pitch of the vessels and drone multiplied by the wave period during that measurement to significant wave height plotted against significant wave height. Symbols as in previous figure.*

motions, listed in Table I, follow, even though their plots are not reproduced here. Heave had the least aspect dependence, for all vessels. Roll and sway were approximately equal for head and stern aspects, and considerably larger at or near beam, particularly for the ships. Surge and pitch showed clear aspect variations between vessels: *Vector* surged most in head seas while the lighter surface vessel, *Caligus*, and DOLPHIN surged far more in stern seas. The ships had maximum pitch in head seas while DOLPHIN pitched most in stern seas, but even in stern seas the ships pitched almost as much as DOLPHIN: *Vector* 67% and *Caligus* 87%.

In these ship motion and attitude results, DOLPHIN is found to be at least as stable as the ships except in surge, and far more stable for some variables. However, as shown in examples such as Figure 10, the DOLPHIN-towed towfish clearly undergoes more vertical motion than those towed by the ships (the three tow configurations were identical, using a downweight and neutrally buoyant towfish).

Consideration of the cable dynamics shows that surge is, for DOLPHIN's cable configuration in this trial, the drone motion which most affects cable tension. Chapman [12] supports the sheath model as an accurate description of cable response to wave-driven motion. In this model, motions of the top of the cable are divided into two components, parallel and transverse to the upper part of the cable. Parallel motions are transmitted down the cable without (in the short term) changing the cable profile, and transverse motions excite waves which become insignificant after only a few tens of metres, thus the cable moves as if it were in a sheath. Furthermore, the cable leaves DOLPHIN

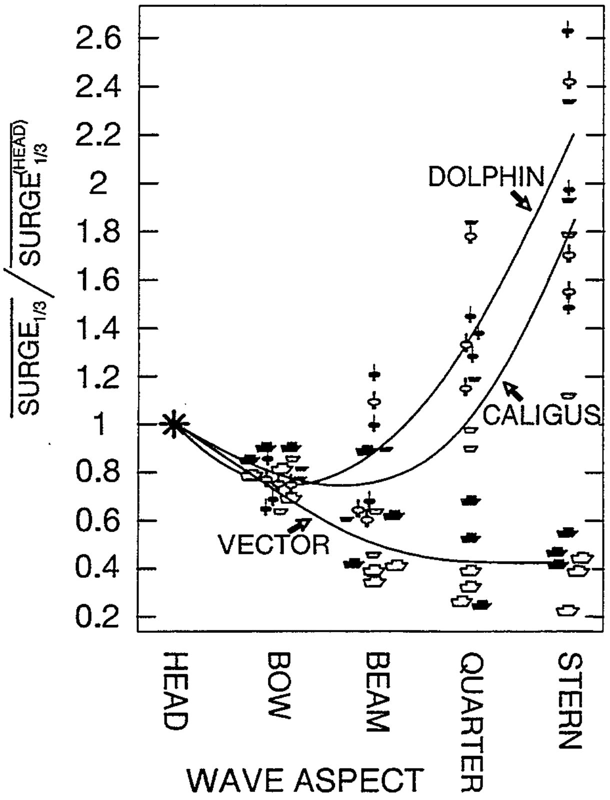

Figure 8: *Significant-mean surge of the vessels and drone at various wave aspects compared to surge in head seas. Curves are spline fits with no theoretical significance. Symbols as in previous figures.*

at no more than 15° below the horizontal, but is close to vertical at the depressor. Thus DOLPHIN surge efficiently drives vertical towfish motion. Figure 11 clearly shows the high correlation between DOLPHIN forward velocity and downweight vertical velocity. Velocities were plotted, rather than motions or accelerations, because cable tension is proportional to velocity squared, and the tension, measured where the cable exited DOLPHIN, is indeed tightly correlated with these velocities.

Ships do not surge nearly as much (Figures 6 and 8), and their tow cables are further from the horizontal because the uppermost parts are in air, making surge not the only important motion.

Thus DOLPHIN was found to be at least as stable as the ships in the motions and attitudes which drive the motions of ship-towed towfish. However it was shown that surge is particularly important for a DOLPHIN-towed towfish, and that DOLPHIN surges considerably more than either ship.

It should be possible to compensate for DOLPHIN surge by sensing DOLPHIN fore-aft acceleration and driving the winch to cancel DOLPHIN's surge velocity. The existing winch is capable of the required speeds.

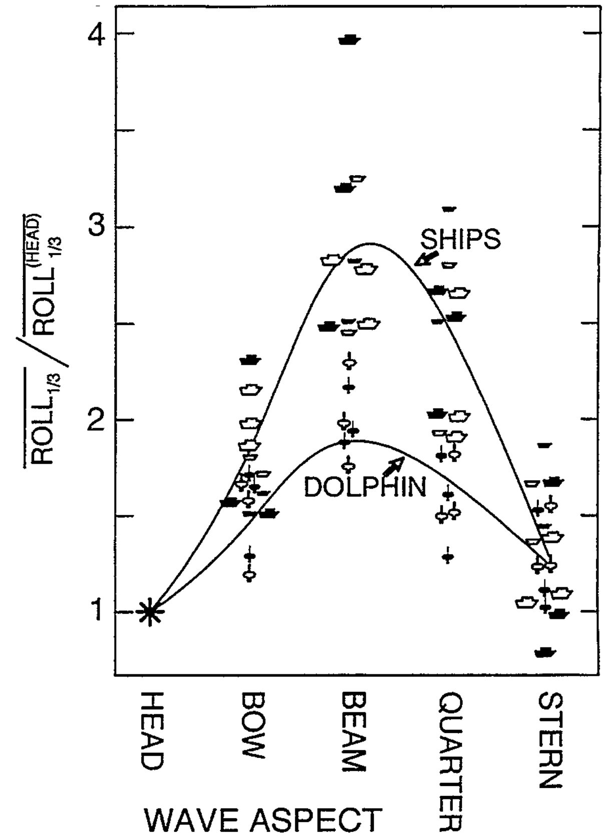

Figure 9: *Significant-mean roll of the vessels and drone at various wave aspects compared to roll in head seas. Curves are spline fits with no theoretical significance. Symbols as in previous figures.*

Conclusions

Wave-driven motions of a towed body can be reduced by compensation for ship motion, by tow configurations such as the two-part tow, by active controls, and by selection of the towing vessel or drone. None of these can eliminate wave-driven motion, so criteria for tolerable motion must be considered. Many factors set these criteria, such as the beamwidth of the sonar, its speed of advance, the target dimensions, and even the intended use of the sonar images. Approximate criteria can be calculated easily but are not generally published, even if they are used for design of towbodies. Reference [4] contains the results of a detailed calculation.

An important decision in the design of a drone-towed remote mine-hunting system is the choice be-

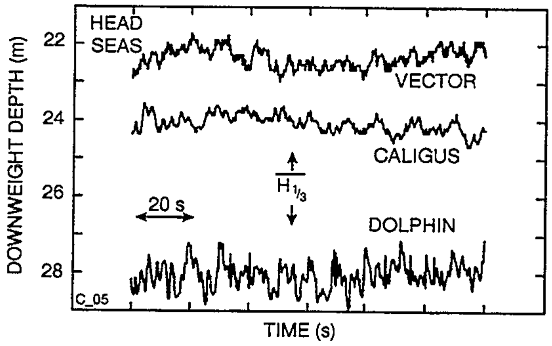

Figure 10: *Depths of the downweights of each two-part tow in head seas. The significant wave height, 1.9 m, is indicated by the labelled vertical arrow.*

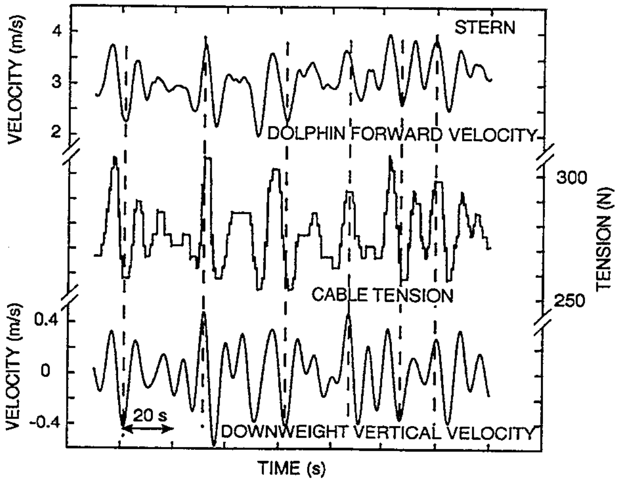

Figure 11: *DOLPHIN speed, cable tension, and downweight vertical speed in stern seas. DOLPHIN speed was calculated by integrating fore/aft acceleration and adding the mean speed. To calculate a credible time derivative of the downweight depth, it was necessary to reduce noise by low-pass filtering below 0.15 Hz. Vertical dashed lines through some extrema of downweight velocity have been added to show correlations.*

tween a surface or near-surface drone. Stability of the towfish against wave-driven motion is a key factor in that decision. Comparative measurements showed that a near-surface drone, DOLPHIN, was at least as stable as much larger surface vessels except in surge. However DOLPHIN's towfish was less stable than the ship-towed fish because the cable dynamics are such that, for a near-surface drone, surge is the wave-driven motion which most effectively drives towfish motion.

While DOLPHIN surge could not readily be controlled, it is likely that the effects of surge could be significantly reduced by driving the winch in opposition to the surge velocity. The winch is capable of the required speeds, but a trial to measure such a reduction has not been done.

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