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Methods of Determining Towfish Location for Improvement of Sidescan Sonar Image Positioning

Anna M. Crawford

Defence R&D Canada

Technical Memorandum

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METHODS OF DETERMINING TOWFISH LOCATION FOR IMPROVEMENT OF SIDESCAN SONAR IMAGE POSITIONING

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Abstract

New methods for improving the positioning of post-processed sidescan sonar seabed imagery have been developed and evaluated. During sea-trial Q260, July 2001, Trackpoint-determined sonar towfish position and ship position data were recorded in several configurations in the sonar data files and in accompanying log files. The Trackpoint system uses a ship-mounted receiver to determine range and bearing to a transponder on the sonar towfish. In post-processing of the sidescan sonar data to obtain geo-referenced seabed imagery, various methods of using this towfish position information have been developed. Varying degrees of conditioning of the Trackpoint position data were required, as well as some recoding of the in-house sonar data mosaicking software. A method for determining towfish position from the cable length entries in the sonar operators' logbook was also developed and used with reasonable success. Resulting positioning errors were estimated from the separation between multiple images of targets in seabed mosaics made from several survey swaths, as well as between geological features appearing in the images. It was found that use of the Trackpoint system for towfish location did improve positioning of the resulting sidescan sonar seabed images, as well as helping to resolve some apparent inconsistencies in positioning caused by unpredicted towfish ship-following behaviour.

Résumé

De nouvelles méthodes visant à améliorer le positionnement d'images du fond marin fournies par le sonar à balayage latéral et ayant subi un post-traitement ont été élaborées et évaluées. Dans l'essai en mer Q260, effectué en juillet 2001, des données relatives aux positions du sonar remorqué et du navire déterminées à l'aide du système Trackpoint ont été enregistrées avec diverses configurations dans les fichiers de données sonar et dans les fichiers journaux d'accompagnement. Le système Trackpoint utilise un récepteur installé à bord d'un navire pour déterminer la distance et le relèvement par rapport à un transpondeur placé sur le sonar remorqué. Dans le post-traitement des données du sonar à balayage latéral effectué en vue d'obtenir des images géoréférencées du fond marin, diverses méthodes d'utilisation des données de position du sonar remorqué ont été élaborées. On a dû soumettre les données de position du système Trackpoint à différents degrés de conditionnement et on a dû reprogrammer dans une certaine mesure le logiciel interne de mosaïquage des données sonar. On a également élaboré une méthode permettant de déterminer la position du sonar remorqué à partir des valeurs de longueur de câble consignées dans le journal de l'opérateur, et l'utilisation de cette méthode a donné des résultats assez concluants. Les erreurs de positionnement résultantes ont été estimées à partir du décalage entre plusieurs images de cibles contenues dans des mosaïques du fond marin obtenues pour différents couloirs explorés, de même qu'entre des caractéristiques géologiques figurant dans les images. On a constaté que l'utilisation du système Trackpoint pour la localisation du sonar remorqué permettait réellement d'améliorer le positionnement des images résultantes du fond marin obtenues avec le sonar à balayage latéral et aidait à corriger certaines incohérences apparentes de positionnement causées par un comportement imprévu de suivi du navire par le sonar.

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Executive summary

Introduction
In order to produce quality geo-referenced seabed imagery from sidescan sonar survey data, accurate sonar towfish positioning is necessary. In the past, towfish position has been determined from sonar operator log entries of the length of cable between the ship and towfish (layback), with generally a single value used per survey track in post-processing. This introduces positioning error in the resulting seabed images (mosaics) if the layback was changing significantly during a survey leg. This work deals with methods for improving the positioning precision in this situation, based on sidescan sonar data collected during the Q260 sea-trial (July 2001) using an acoustic towfish locating system (Trackpoint II) or the logged cable length entries.

Principal Results
The estimated positioning error, determined from offsets between multiple images of the same target on different survey swaths, was improved using the Trackpoint system. Swath-to-swath registration errors of similar magnitude were obtained across a large area survey mosaic using towfish positions determined from the recorded cable length. Analysis of the positioning errors has shown there was unpredicted towfish ship-following behaviour which contributed to positioning uncertainty when not using the Trackpoint system.

Significance of the Results
The methods presented here apply to survey data collected while the towfish layback was changing over the course of the tracks, as is often the case over varying bathymetry. Previously, in order to improve positioning above using an average layback value for an entire survey leg, the leg would have to be segmented in processing, which increases time and effort significantly, as well as introducing discontinuities into the resulting seabed mosaic.

Future Plans
Improvements to the in-house Sidescan Image Processing System (SIPS) software suggested by this work will be integrated with the existing software and user interface so that these methods can become options in the regular sonar data post-processing procedure.

Crawford, A.M. 2002. Methods of Determining Towfish Location for Improvement of Sidescan Sonar Image Positioning. DREA TM 2002-019. Defence R&D Canada - Atlantic

Sommaire

Pour obtenir des images géoréférencées du fond marin de qualité, à partir des données de levé fournies par le sonar à balayage latéral, il faut un positionnement précis du sonar remorqué. Par le passé, on déterminait la position du sonar remorqué à partir des valeurs de longueur de câble entre le navire et le sonar consignées dans le journal de l'opérateur sonar, en utilisant généralement une seule valeur par trajet de levé dans le post-traitement. Cette façon de procéder créait des erreurs de positionnement dans les images résultantes (mosaïques) du fond marin lorsque la longueur de câble variait de façon appréciable sur un segment de levé. Le présent travail porte sur des méthodes visant à accroître la précision de positionnement dans cette situation, en se basant sur des données de sonar à balayage latéral recueillies dans l'essai en mer Q260 (juillet 2001) à l'aide d'un système de localisation à sonar acoustique remorqué (Trackpoint II) ou en se basant sur les valeurs de longueur de câble consignées.

L'erreur de positionnement prévue, déterminée à partir des décalages entre plusieurs images de la même cible obtenues pour différents couloirs explorés, a été réduite grâce à l'utilisation du système Trackpoint. On a obtenu des erreurs d'enregistrement de même grandeur de couloir à couloir sur l'ensemble d'une mosaïque de levé de grande étendue en utilisant les positions du sonar déterminées à partir des valeurs consignées de longueur de câble. L'analyse des erreurs de positionnement a révélé un comportement imprévu de suivi du navire par le sonar qui contribuait à l'incertitude de positionnement lorsqu'on n'utilisait pas le système Trackpoint.

Les méthodes décrites dans le présent document s'appliquent aux données de levé recueillies lorsque la longueur de câble du sonar remorqué variait sur les trajets, comme cela se produit fréquemment dans les levés bathymétriques en conditions variables. Auparavant, pour obtenir un positionnement meilleur que le positionnement obtenu en utilisant une valeur moyenne de longueur de câble pour un segment entier de levé, il fallait diviser le segment au cours du traitement, ce qui nécessitait beaucoup plus de temps et d'effort et créait des discontinuités dans la mosaïque résultante du fond marin.

Les améliorations nécessaires du logiciel interne SIPS (Sidescan Image Processing System, c.-à-d. système de traitement des images obtenues par balayage latéral) révélées par le présent travail seront intégrées au logiciel et à l'interface utilisateur actuels, afin que ces méthodes puissent devenir des options de la procédure normale de post-traitement des données sonar.

Crawford, A. M. 2002. Methods of Determining Towfish Location for Improvement of Sidescan Sonar Image Positioning (Méthodes de localisation de sonar remorqué permettant d'améliorer le positionnement des images fournies par le sonar à balayage latéral). CRDA TM 2002-019. Recherche et développement pour la défense Canada - Atlantique.

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1. Towfish positioning information used in post-processing Q260 sidescan data

During joint DREA/SACLANT sea trial Q260 in July 2001, sidescan sonar surveys of four areas near Halifax were carried out using a Klein 5500 system [1]. All four sites were surveyed at low resolution (~20 cm along- and acrosstrack), and at high resolution (~10 cm along- and acrosstrack) following deployment of mine-shaped targets at two of the sites. All of the sidescan sonar data that was collected has been subsequently processed into mosaics of the seabed using several methods for determining towfish position. Most of the post-processing was done using in-house software, SIPS (Sonar Image Processing Software [2]), with some modifications as will be described. Some additional supporting software was written for Matlab (version 6.1, The Mathworks, Inc.).

In order to obtain accuracy in geo-referencing sidescan imagery, the position of the sonar towfish must be determined accurately. Traditionally, towfish position is calculated from the ship's position and the known amount of cable between the ship and the towfish (layback), assuming the towfish follows the ship in some predictable manner. This is subject to a number of sources of error, particularly in the case of interest here in which the cable length is changing over the course of a survey leg, as when following varying bathymetry.

With the aim of improving towfish positioning, some of the surveys during Q260 were completed using a Trackpoint II Ultra-short Baseline acoustic tracking system (Ocean Research Equipment International Inc.). This consists of a transponder unit fixed to the towfish and a short-baseline receiver mounted on the ship (in this case, at the bottom of a pole deployed from the starboard aft deck). In addition to the deck-unit real time display, the Trackpoint system provides towfish position at ~1 Hz in the form of range and bearing as a serial output, or can be configured to give the latitude and longitude of the towfish. Over the course of the trial, various combinations of ship and towfish position outputs were recorded in the Klein sidescan sonar data files and in log files. In all cases, the sidescan sonar operators manually recorded the amount of cable out in a logbook while surveys were underway.

The four sites that were surveyed during Q260 are shown in gray on a map of the Nova Scotia coast in Figure 1. The various combinations of the methods that ship and towfish position information were recorded during the surveys are summarized in Table 1. More detailed descriptions of the three sources of positioning information available for post-processing of the sidescan sonar data follow.

1.1 Klein data file ping headers

Each ping return recorded in a Klein data file (proprietary "5kd" format) has a header containing the time, ship position, towfish attitude, altitude and depth and other system settings for that ping. The ping header fields identified as "ship latitude" and "ship longitude" usually contain information obtained through a serial line from a GPS positioning system with receiver located somewhere onboard. At some times during Q260 (July 15-17), this information was replaced in the ping headers by towfish position (as latitude and longitude)

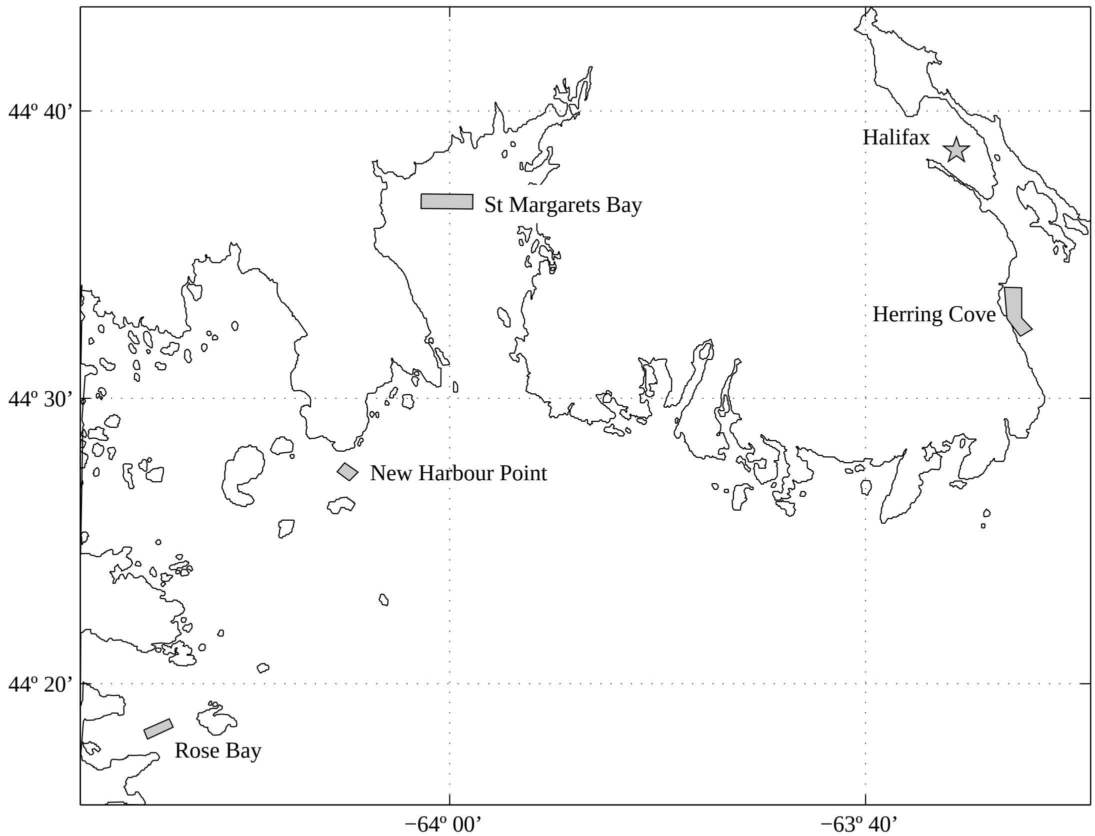


Figure 1: Map of the central Nova Scotia coast showing the four survey areas (in gray).

determined by the Trackpoint system. The towfish position is calculated from the measured range, bearing and depression angle to the towfish from the Trackpoint receiver, the offsets between the receiver and a shipboard GPS receiver (user input) and the ship heading (see Section 5).

1.2 Log file

One of the navigation software packages used during Q260, Aldebaran (International Communications and Navigation Ltd.), can be configured to output serial positioning information it receives (as NMEA-0183 standard character strings through an RS-232 interface) as an ASCII log file. In general, while the Klein acquisition system was running, the navigation software was generating a log file containing either or both of the ship position obtained from GPS and the towfish position obtained as range and bearing from the Trackpoint system, though there were times during the trial when no accompanying log file was recorded (July 4-6 and 16).

1.3 Logbook

As sidescan operations are underway, it has been customary for one of the operators to manually record the amount of cable out in a logbook. In the case of changes in cable length, these should be recorded as they occur. Of course, this is subject to many sources of error, such as in timing or the winch operator's estimate of how much cable is out. In the worst case, no information was recorded at all. The operators have no knowledge of the bearing to the towfish. Finally, there is no way of assessing the quality of this data after the fact. This case, being the usual mode of operation during Klein sidescan sonar surveys, also represents the situation for a large amount of historical sidescan data collected before the Q260 trial.

Table 1: Summary of ship and towfish position data recorded during Q260.

Day	*Location*	*Ping header*	*Log file*	*Comment*
4	Herring Cove	ship	-	low resolution, area survey
5-6	Herring Cove	ship	-	high resolution, mine survey
8	St Margarets Bay	ship	ship, towfish*	low resolution, area survey
14	Rose Bay	ship	ship, towfish	low resolution, area survey
15	St Margarets Bay	towfish	ship	high resolution, mine survey
16	St Margarets Bay	towfish	-	high resolution, mine survey
17	St Margarets Bay	towfish	ship	high res., mine & photo line survey
19	St Margarets Bay	ship	ship, towfish	high resolution, photo line survey
19	New Harbour Pt	ship	ship, towfish	low resolution, area survey

Day is the calendar day in July, *Ping header* is the type of position information (ship or towfish) recorded in the Klein data file ping headers, *Log file* is the type of position information (ship or ship and towfish) recorded in an accompanying log file (if any).
*Towfish position was only recorded during part of the last survey leg of 8 done that day.

2. Overview of strategies for post-processing Q260 sidescan data

Up to this point, the in-house sidescan sonar data processing software, SIPS (Sonar Information Processing System), is written to handle a single value of layback for a series of files. Given the various combinations of available towfish positioning data, several alternate approaches were developed for post-processing the Q260 sidescan data to generate mosaics. These can be summarized as follows:

1) When the towfish position was recorded in the Klein ping headers (July 15 to 17), this information was used directly. SIPS was modified to sidestep the calculations that normally determine towfish position from ship position, layback and offsets.

2) When towfish range and bearing were recorded in a log file (July 14, 19 and part of July 8), this information was used to calculate towfish position. A subroutine was written for SIPS that reads the ASCII log file and converts ship position and towfish range and bearing to towfish position (latitude and longitude). These values were then used in generating the mosaics.

3) When there was no other record of towfish position (July 4 to 6, and part of July 8), this was determined from the logbook entries. In cases where layback was not changing significantly over a survey leg, the old procedure (one value of layback) was used. In most cases, however, layback changed significantly over the course of a single leg as the operators attempted to maintain a constant towfish altitude over shoals and other changes in bathymetry. A file of the same format as the ASCII files output by Aldebaran (entries containing time, towfish range and bearing) was generated from logbook cable entries, and this was used in the same manner as log files which had been generated during the trial (approach 2 described above).

3. A sample of Trackpoint towfish position data

Before discussing methods of post-processing the sonar data, an example of the Trackpoint-determined towfish position data will be shown. A large potential difficulty in dealing with this data is that it is quite noisy, perhaps due in part to the short baseline of the receiver. Figure 2 illustrates an example of the raw data (plotted in blue with red dots) along with conditioned data such as might be used in post-processing to generate a seabed mosaic (in green). The upper plot shows the Trackpoint-measured bearing to the towfish (in degrees from ship heading) and the lower plot, the range (in meters), both as functions of sample number in the ASCII position log file generated by Aldebaran software. There are several dropouts (zeros in both range and bearing) and though the scatter in the bearing data appears to be considerably larger than that of the range data, the y-axis scaling of the two plots should be considered. There is some variation in bearing due to changes in layback (see Figure 6 for a diagram of the relevant geometry) and due to changes in ship heading, which the towfish roughly follows but with a lag. The towfish is being recovered at the end of this time series, where range is reduced to 20 m and the bearing has larger variability as the towfish enters the ship wake and nears the ship hull.

Figure 3 illustrates the scatter in the Trackpoint-determined towfish positioning data. The smoothed data that was shown in Figure 2 (green curves) have been subtracted from the raw data, leaving mostly the noise variation in both range (R) and bearing (θ). There is no discernable range dependence. The standard deviation in each case is shown by a dashed

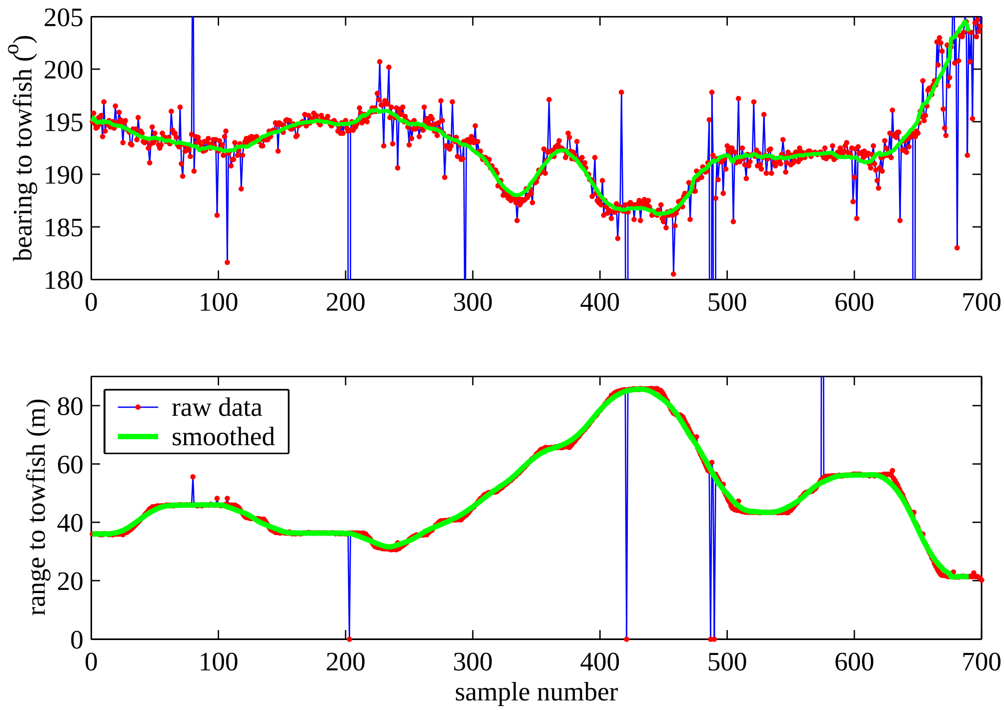


Figure 2: Trackpoint-determined towfish position as range and bearing from the receiver.

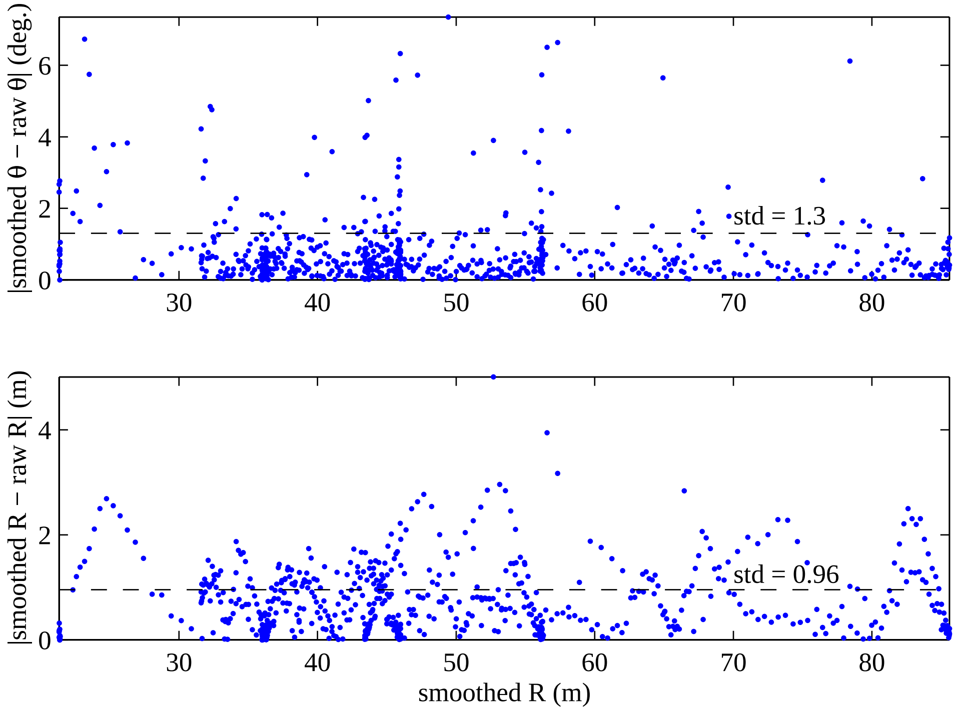


Figure 3: Scatter in the Trackpoint-determined towfish position data shown in Figure 1.

horizontal line ($\sigma(\theta) = 1.3^o$ and $\sigma(R) = 1.0$ m). A bearing variation of 1 standard deviation then equates to an acrosstrack variation in position of +/- 2.3 m at 100 m range, or alternately, the resulting variation in acrosstrack position surpasses the range (alongtrack) variation at a range of 44 m. As a positioning uncertainty, this constitutes quite reasonable accuracy. If not conditioned, however, the spikes (dropouts) in the raw Trackpoint navigation data would lead to discontinuities in the sidescan mosaics generated using this data.

Figure 4 shows the same data as was shown in Figure 2 plotted in plan view as along- and acrosstrack position (in meters) relative to the Trackpoint receiver at the origin. In this co-ordinate system, the center of the ship is to the right and above the position of the Trackpoint

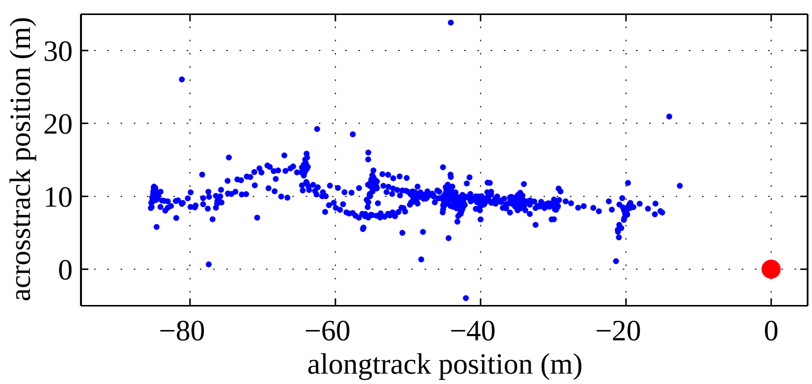


Figure 4: Trackpoint determined towfish position in plan view as across- and alongtrack position (same data as shown in Figure 2).

receiver, and heading to the right. The towfish is following the ship at a mean acrosstrack position (about 8 m from the receiver) that is farther to port than directly behind the towpoint amidships, considering that the ship is about 11 m wide across the aft deck. This will be discussed further later (see sections 4.3 and 7).

When post-processing sidescan sonar data to produce seabed images, it has always been necessary to smooth the associated navigation data. The refresh interval of the GPS ship position varies from approximately once a second to several seconds, slower than the Klein sonar sample rate of several Hz, so the apparent ship track recorded in the sonar data file ping headers has artificial steps. Without smoothing, this would leave regularly spaced gaps in the resulting mosaic, giving it a comb-like appearance. These artifacts have typically been removed by smoothing (usually a 100-sample boxcar average) which turns out also to be adequate for conditioning the Trackpoint navigation data, though the occasional dropouts would introduce large irregularities, so these must be removed prior to smoothing.

4. New strategies for post-processing sidescan data

In the past, part of the procedure for post-processing Klein sidescan sonar data into mosaics using SIPS involved a layback position adjustment to calculate towfish position from the ship navigation data recorded in the sonar data files and then smoothing of the resulting navigation data. Modifications to one or both of these processing steps are required when using alternate methods for determining towfish position. These were briefly outlined previously (section 2) and will now be described in more detail.

4.1 Towfish position in the Klein ping headers

This is the simplest case to deal with, as the only change to the existing post-processing procedure is a slight modification to SIPS to accept the towfish position directly from the Klein data file ping headers, side-stepping the calculation of towfish position from ship position and layback. This method applies to the sidescan data collected on July 15, 16 and 17 at the St Margarets Bay site, while high-resolution surveys were being done over mine-shaped targets and along a line where stereo photos had been collected during Q260 by collaborators on NRV Alliance.

4.2 Towfish position in a log file

This case was handled by writing add-on software for SIPS that reads the ASCII log file and compiles a list of times, towfish ranges and bearings. The range and bearing at the nearest previous time to that of each Klein ping header is then used to calculate towfish position for that ping. The resulting navigation time series is then smoothed. The post-processing proceeds as it normally would from that point. The new subroutine takes the place of the layback adjustment and navigation smoothing steps in the old processing procedure. This method applies to the sidescan data collected on July 14 (at the Rose Bay site) and July 19 (the New Harbour Point site).

Some conditioning of the raw position data in the log files was necessary. It was found that there were offsets in timing between the Klein system computer and the Trackpoint system, and both differed from GPS time. These offsets varied over the duration of the trial and were from on the order of 10's of seconds to more than 2 minutes, determined from the sequence of the time stamped ship and Trackpoint entries in the position logs and correlation between ship position in the logs and in the Klein ping headers. All log file times were adjusted to match the Klein computer time, which is the time recorded in the sidescan sonar data files. Note that this was not a problem when the towfish position was entered directly into the Klein ping headers since the Klein recording software disregards the timestamps on the incoming position data (ship or towfish). Another consideration was that the Trackpoint position data were particularly noisy during the Rose Bay survey (for unknown reasons), so entries containing spikes or dropouts were removed from the log file prior to processing. This did not leave any overlarge gaps in the navigation data, which were subsequently smoothed in any case.

4.3 Towfish position determined from logbook entries

This situation applies to the surveys on July 4 to 6 (at the Herring Cove site) and July 8 (St Margarets Bay site), though there are log file entries for the end of the final leg of the St Margarets Bay survey. This is the most challenging case, particularly while the operators were attempting to have the towfish follow varying bathymetry at a constant altitude. This approach has been tried on the survey data from July 8 at the St Margarets Bay site. The layback was not changing significantly during the earlier survey legs at the Herring Cove site so a single value was used for each leg.

In this case, the manually recorded logbook entries were used to generate a log file of the same format as those generated by the Aldebaran navigation software. During the St Margarets Bay survey, the operators were particularly careful in recording cable length (in light of the experimentation with Trackpoint positioning, it was thought this information would be useful). Digital Trackpoint information from other days was analyzed to determine mean cable payout and reel-in rates, assuming these were roughly consistent over the trial. These rates were used to calculate time series of range and bearing to the towfish based on the times and values of cable length entered in the logbook and towfish depth (from the ping headers). In the calculations, it has been assumed that the towfish followed behind the ship as if on a stiff cable extending directly backward from the ship. The ship survey tracks where this technique has been applied were generally straight, so this is a reasonable assumption most of the time. Once a log file was generated, processing proceeded in the same manner as described in the previous section.

Examination of the Trackpoint towfish position data collected through the trial shows that the towfish was apparently not following directly behind the towpoint, but on average had an offset of several meters to the port side (see Figure 5). Compensation for this in the calculations was attempted by increasing the acrosstrack offset between the towpoint and Trackpoint receiver. This will be discussed again in Sections 5 and 7.

Figure 5 illustrates a comparison between the calculated towfish range and bearing and measurements by the Trackpoint system (during the last part of the final leg of the survey on July 8). The differences in range are less than 10 m, and in bearing, less than 2 degrees. The acrosstrack offset that has been applied seems to be justified by the results shown here (affecting the bearing more than the range). The largest difference in bearing is during a ship course correction (around 16.3 hours) where the towfish was apparently not following the ship heading through the maneuver as has been assumed in the calculation. As expected, there are timing inconsistencies in the log entries, such as just before 16.25 hours where the calculation lags the measurements slightly through a shortening and lengthening of the cable, seen in both range and bearing. The assumed rates of cable payout and reel-in are not always followed in the measured data. On the whole, however, the approximation is close.

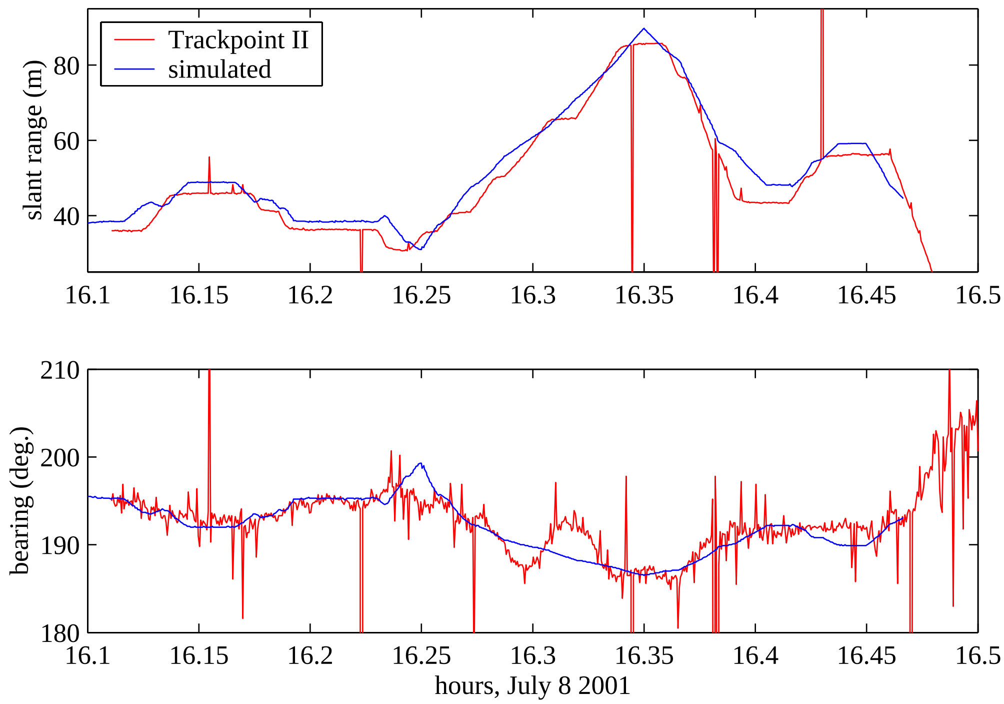


Figure 5: Simulated towfish range and bearing, compared to Trackpoint measurements.

5. Calculation of towfish position

The object is to determine the horizontal position of the towfish ($X_{towfish}$, $Y_{towfish}$) in an East-North co-ordinate system given the position of the ship, the Trackpoint measured towfish range and bearing and the ship geometry, which is shown in Figure 6. Ship position (also in an East-North co-ordinate system) is defined as the location of the GPS receiver (X_{GPS}, Y_{GPS}), which is forward of the position of the Trackpoint receiver (X_{TP}, Y_{TP}). Horizontal offsets are determined relative to the GPS receiver position, relative to the ship heading (across- and alongtrack). Referring to the diagram in Figure 6, the across- and alongtrack offsets to the Trackpoint receiver are ΔX_{TP} and ΔY_{TP}. The across- and alongtrack offsets to the towpoint on the ship's A-frame are ΔX_A and ΔY_A (note that both ΔY_A and ΔY_{TP} are <u>negative</u> values). Vertical offsets are measured relative to the sea surface. The depth of the Trackpoint receiver is ΔZ_{TP} (< 0) and the height of the towpoint is ΔZ_A (> 0). *Cable* is the length of cable between the towpoint and the towfish (assuming it has no curvature), and the *towfish depth* is the vertical distance between the towfish and the water surface (< 0). The Trackpoint system measures the slant range from the receiver to the towfish (R) and bearing (θ) from a line parallel to the ship track. The *ship heading* is the direction of the ship track relative to North. *Layback* has been referred to and is the horizontal alongtrack distance between the ship and towfish positions. Second-order effects, such as changes in the horizontal offsets between the GPS and Trackpoint receiver positions as the ship pitches or rolls, are not considered.

The problem of determining towfish position from the Trackpoint-measured range and bearing can be summarized as follows. Starting from the position of the GPS receiver (the ship's position), the position of the trackpoint receiver in an East-North co-ordinate system is

$$(X_{TP}, Y_{TP}) = (X_{GPS} + \Delta X_{TP} \cos(\text{ship heading}) + \Delta Y_{TP} \sin(\text{ship heading}),$$
$$Y_{GPS} - \Delta X_{TP} \sin(\text{ship heading}) + \Delta Y_{TP} \cos(\text{ship heading}))$$

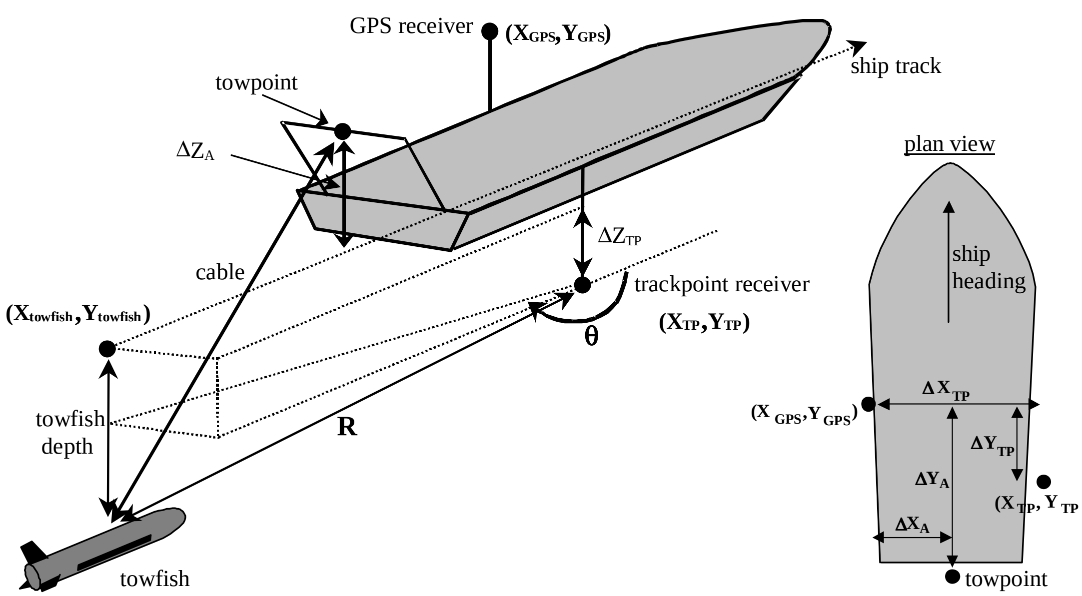


Figure 6: Geometry of the positions of the towfish, GPS receiver and Trackpoint receiver.

The horizontal distance D from the Trackpoint receiver to the towfish is determined from

$$D = \sqrt{R^2 - (\text{towfish depth} - \Delta Z_{TP})^2}$$

The position of the towfish is then determined from the position of the Trackpoint receiver, D and the ship heading by

$$(X_{towfish}, Y_{towfish}) = (X_{TP} + D\sin(\theta)\cos(\text{ship heading}) + D\cos(\theta)\sin(\text{ship heading}),\\ Y_{TP} - D\sin(\theta)\sin(\text{ship heading}) + D\cos(\theta)\cos(\text{ship heading}))$$

When generating a log file from the logbook cable entries, it is necessary to calculate towfish slant range and bearing from the cable length, given the geometry shown in Figure 6. The alongtrack horizontal distance L between the Trackpoint receiver and the towfish is given by

$$L = \sqrt{\left|\Delta X_{TP} - \Delta X_A + \text{offset}\right|^2 + \left(\left|\Delta Y_A - \Delta Y_{TP}\right| + \sqrt{\text{cable}^2 - (\Delta Z_A - \text{towfish depth})^2}\right)^2}$$

where it is assumed that the towfish follows behind the ship (as if on a rigid cable extending behind) with an acrosstrack offset "offset", as discussed in Section 4.3. The slant range and bearing to the towfish from the Trackpoint receiver are then given by

$$R = \sqrt{L^2 + (\text{towfish depth} - \Delta Z_{TP})^2}$$

$$\theta = \pi + \tan^{-1}\left(\frac{\left|\Delta X_{TP} - \Delta X_A + \text{offset}\right|}{L}\right)$$

The horizontal and vertical offsets (ΔX_{TP}, ΔY_{TP}, ΔZ_{TP}, ΔX_A, ΔY_A, ΔZ_A) are determined from the ship geometry and generally do not change during a survey. The measured range and bearing to the towfish (R and θ) change with time as the layback and towfish depth vary, and are subject to noise in measurement as well. Values for the various geometric parameters in the position calculation are shown in Table 2 - these are typical for towfish deployment from CFAV Quest in water depths less than about 50 m (the deepest point of the four survey areas covered during Q260). The observed off-center following behaviour of the towfish was simulated with an offset of 4.6 m (to port), i.e. $|\Delta X_{TP} - \Delta X_A + \text{offset}| = 10$ m.

Table 2: Values of the ship geometric parameters during the Q260 deployment.

Parameter	*Value or Range* (m)	*Parameter*	*Value or Range* (m)
ΔX_{TP}	11.8	ΔY_A	-14.1
ΔY_{TP}	-4.6	ΔZ_A	6.1
ΔZ_{TP}	-7.75	cable length	20-105
ΔX_A	6.4	towfish depth	-10-40

6. Samples from Q260 sidescan mosaics and positioning uncertainty

Any of the full mosaics generated from the survey data are too large to be included here. Following are several samples that have been cropped from the larger images showing the results of post-processing by the various methods described in Section 4. All of the large mosaics are geo-referenced and the samples are shown with North up on the page. Where applicable, positioning uncertainties have been estimated.

6.1 Towfish position in the Klein ping headers

The surveys using this method of recording towfish position were high-resolution surveys over mine-like target objects. Examples of some of the images of two of the mine-shaped targets are shown in Figure 7 - a cylinder in the upper images and a suspended tethered sphere in the lower. The target images from the individual survey swaths making up the two composite mosaics are shown (five in the upper mosaic, and three in the lower), each with a diagram indicating the respective towfish heading and whether the target was to port or starboard of the track. The resulting seabed mosaics are geo-referenced averages of the spatially overlapping survey swaths, so the contrast of the individual target images is reduced by the processing. The average position of each of the targets (from which positioning errors are determined) is also indicated. It is not generally intended that survey data of this type be made into mosaics of the seabed, though it is obviously desirable to be able to accurately determine the positions of targets in sidescan sonar data. The positioning errors are clearly evident in the composite images, and are summarized in Table 3. Individual image positions were taken as the approximate midpoint of the highlight (the cylinder was 1.5 m long by 0.5 m in diameter and the sphere was about 0.5 m in diameter). For each target, the mean position was calculated by averaging the East-North co-ordinates of the individual images of that target. For individual images then, the positioning error, Δr, is determined as the range between its position and the average position for that target. Across and alongtrack errors were determined by rotating the co-ordinates to the survey track heading. The overall mean positioning error is also shown for all images with well-defined mean target positions (if determined from more than 3 images) appearing in the July 15, 16 and 17 survey data.

The positioning error results shown in Table 3 for the images in Figure 7 show positive acrosstrack and negative alongtrack errors. This is coincidental as the mean along- and acrosstrack errors for all 70 of the target images from that survey are small (less than 2 meters) and are distributed evenly around the mean (standard deviation is about 5 m in both directions). The images shown in the figure (a subset of the total number in both cases) were chosen for clarity. As mentioned, the averaging of overlapping swaths when compiling a mosaic leads to reduction in contrast of the target images, so image quality is lost in this processing.

The estimates of positioning uncertainty represent a measure of consistency - the absolute positions of the targets would ideally be very close to the average position over a number of realizations, excluding the possibility of gross systematic error. The true target positions were not determined during the trial (how would this be done?).

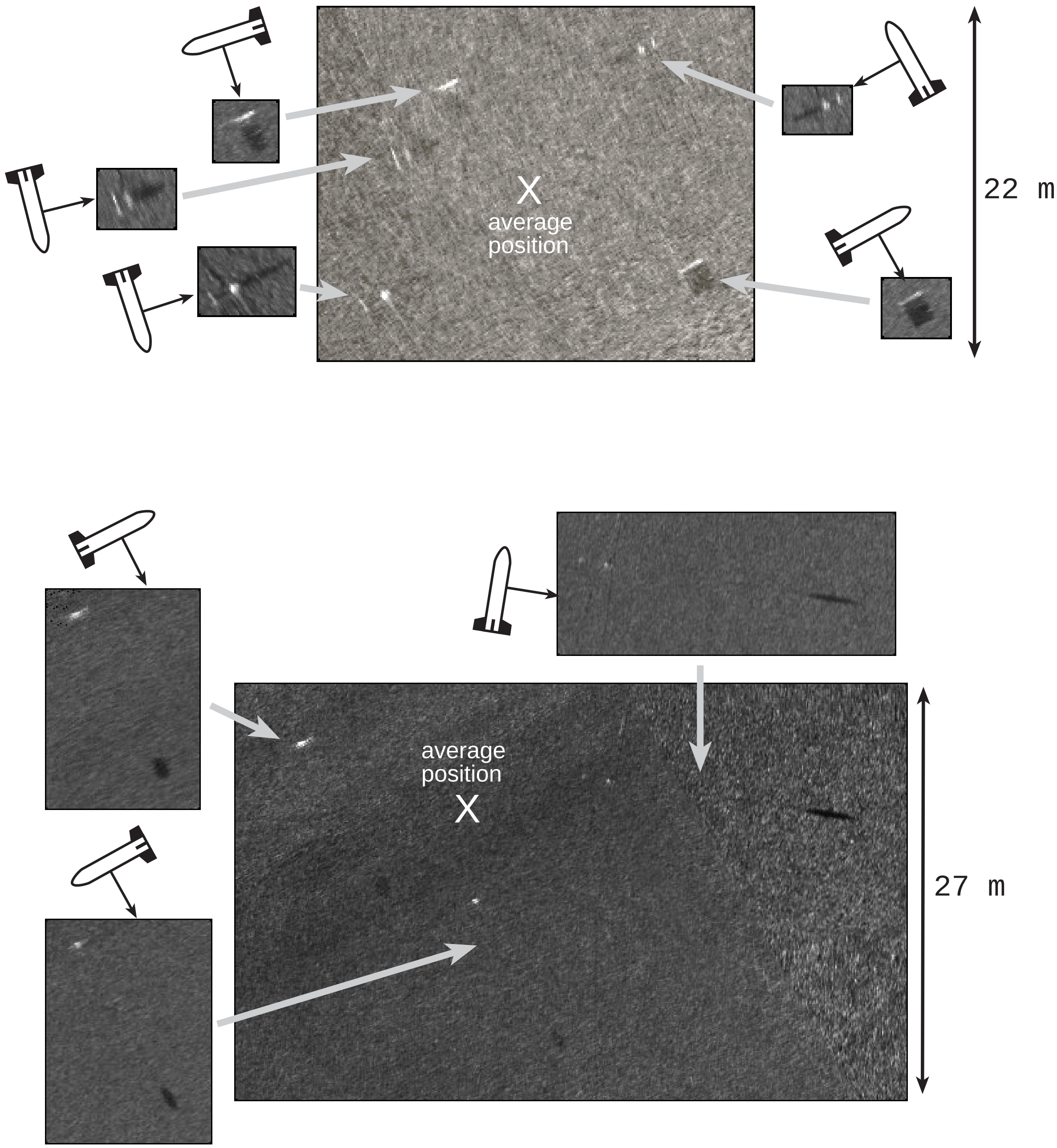


Figure 7: Samples from two mosaics made using towfish position written to the Klein data file ping headers (St Margarets Bay survey).

Table 3: Positioning errors of the images in the samples shown in Figure 7 and for all images with well-defined mean target positions surveyed on July 15, 16 and 17.

image	Δr	$\Delta across$	$\Delta along$
A	9.1	8.5	-3.4
B	3.8	2.4	3.0
C	2.6	0.6	-2.5
D	5.8	4.4	-3.7
E	9.0	7.6	-4.8
F	5.8	3.3	-4.7
G	5.2	4.9	-1.7
H	13.0	9.6	-8.9
all (70)	6.3	1.3	-0.1

Δr is the range of each image to the mean position of all images of that target; $\Delta across$ and $\Delta along$ are across- and alongtrack error relative to the ship heading (all in meters).

6.2 Towfish position in a log file

This method of post-processing has been applied to the low resolution area surveys of the Rose Bay and New Harbour Point sites. Small clips from each of the two resulting mosaics are shown in Figure 8 and Figure 9. A feature of the New Harbour Point site is the interesting geology of the layered bedrock, while the Rose Bay site has well formed ripples on a sandy bottom. The white double-ended arrows in both figures indicate the extent of the overlap of the neighbouring survey swaths. In Figure 9, the alongtrack positioning error visible along the edge of the area of larger scale ripples in indicated between arrows.

In both, the position registration between swaths seems to be quite good, though it is difficult to determine the acrosstrack error in either case, as well as alongtrack error in the New Harbour Point mosaic. The edge of the area of rippled sand in the clip from the Rose Bay mosaic shows an alongtrack positioning error of about 5 m (+/- 2.5 m).

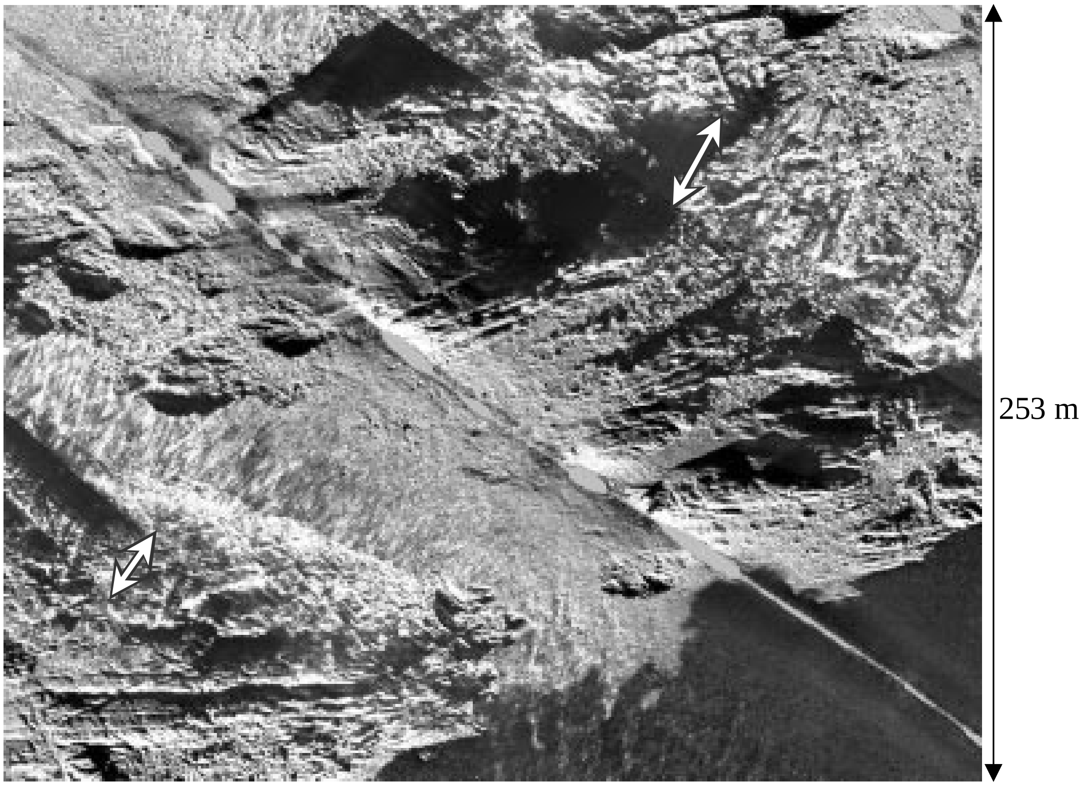


Figure 8: Clip from the New Harbour Point mosaic showing bedrock and a sandy area.

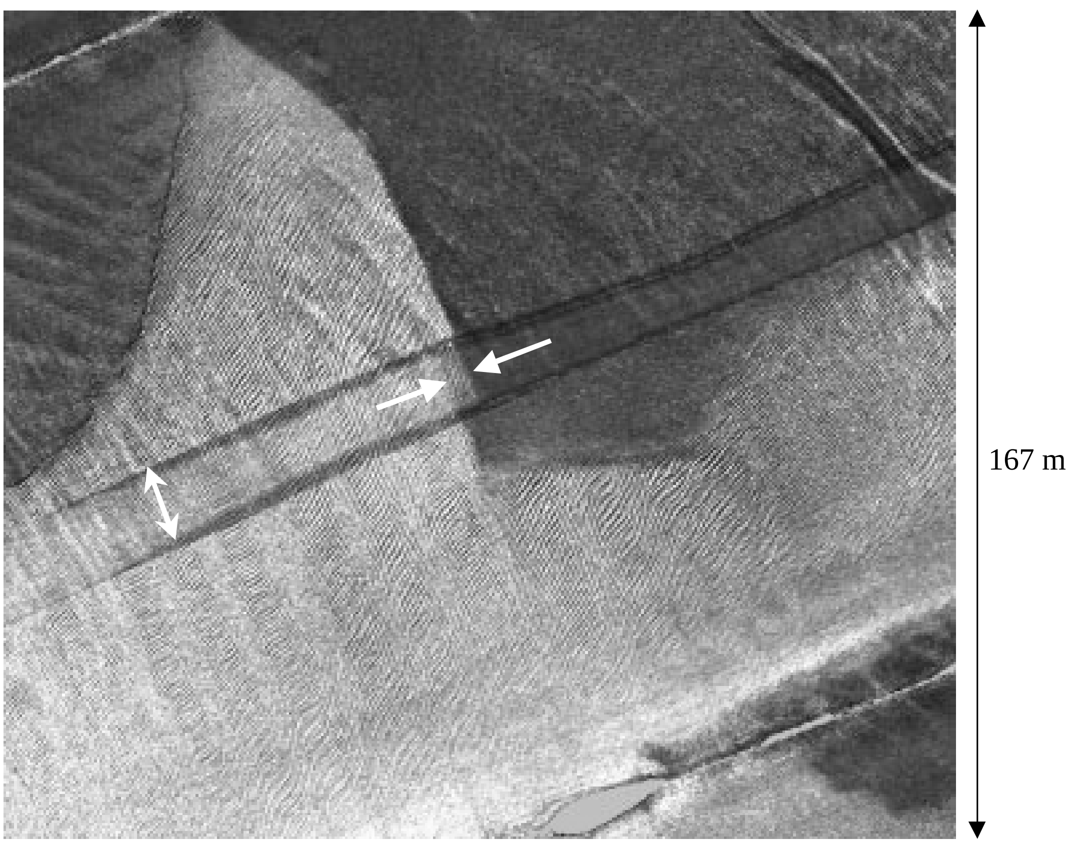


Figure 9: Clip from the Rose Bay survey mosaic showing sandy seabed and the alongtrack registration error on the edge of an area of larger-scale ripples.

6.3 Towfish position determined from logbook entries

This method was applied to the low resolution survey of St Margarets Bay site (July 8). This survey covered a large area - about 3.5 km east-west by 1.75 km north-south, in 7 legs. Figure 10 shows two samples from the large mosaic showing across- and alongtrack offsets between images of a group of rocks and an anchor drag mark and rock. The dashed white lines in (a) denote the grouping of rocks and the solid white segment in both indicates the displacement between the overlapping swaths. In (a), the alongtrack offset between the two swaths is about 10 m and 8½ m acrosstrack, and in (b), about 8½ m in both directions. It is important to note that the cable length was changing between 25 m and up to 100 m over the course of some of these survey legs and that adjacent swaths were surveyed in opposing east-west directions. Typical alongtrack misalignments between objects in a mosaic generated from this data using an average layback value for each leg were between 20 and 50 m. Previously, a strategy for minimizing the layback error would be to segment the survey legs where layback was changing and process shorter pieces separately. This not only increases processing effort, but also introduces discontinuities into the resulting mosaic. As well, the changes in layback are not instantaneous and are certainly unlikely to coincide with the transitions between consecutive data files. The acrosstrack positioning errors show that during this survey the towfish was more often even farther to port of center than accounted for by the extra acrosstrack offset included in the range and bearing calculations (described in Section 5).

When post-processing the high resolution mine survey data from the Herring Cove site (July 5 and 6), cable length was entered as a constant value for each survey leg. This is an example of the historical method of determining towfish position. Samples from that data set are shown in Figure 10. In both images, four overlapping swaths show the same mine-shaped target at different positions (a truncated cone in (a) and in (b), a cylinder). The positioning errors of the target images are summarized in Table 4. Similar to Figure 7, the images have low contrast due to the large number of survey swaths that overlap in the mosaics. In (b), target images E and F almost overlap, and H is very faint (to the right of its label).

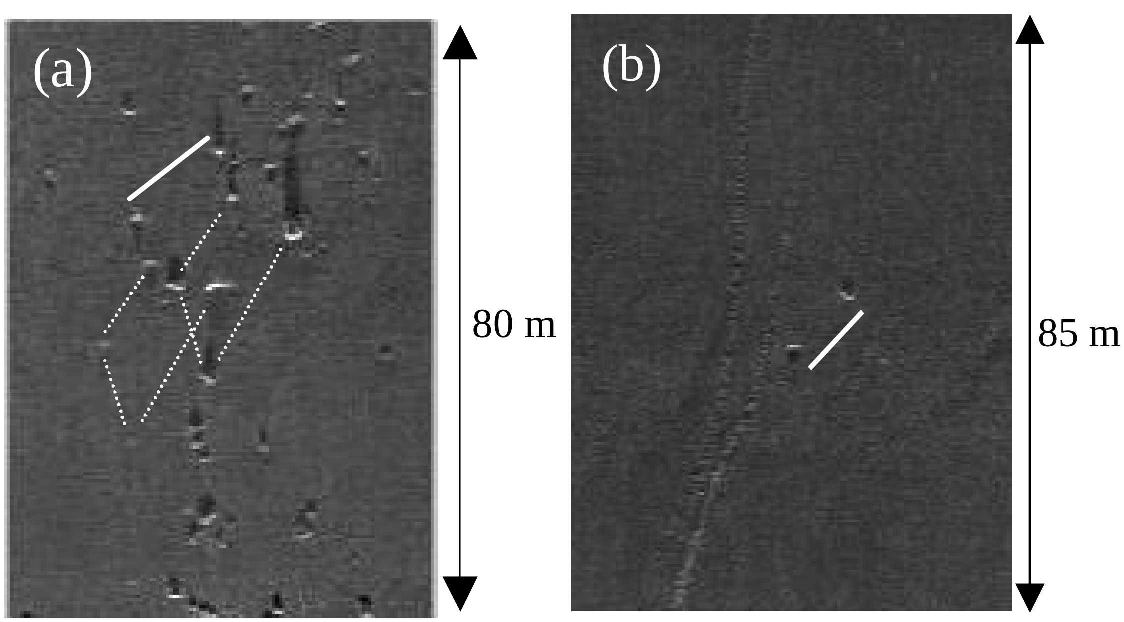


Figure 10: Samples from the low resolution mosaic of the St. Margarets Bay site, showing a group of rocks in (a) and an anchor drag mark and rock in (b).

Compared with the positioning error results shown in Table 3, the mean range error (Δr) for all target images in the Herring Cove survey is larger (11.0 m vs. 6.3 m). As well, the across- and alongtrack positioning errors are larger (between 5 and 10 m vs. less than 2 m), though the widths of the error distributions for this survey are about the same as for the St Margarets Bay survey (about 5 m standard deviation). A positive acrosstrack error implies that the towfish is traveling to port of the assumed track, which is at the centerline of the ship, and a positive alongtrack error implies that the towfish is behind its assumed position.

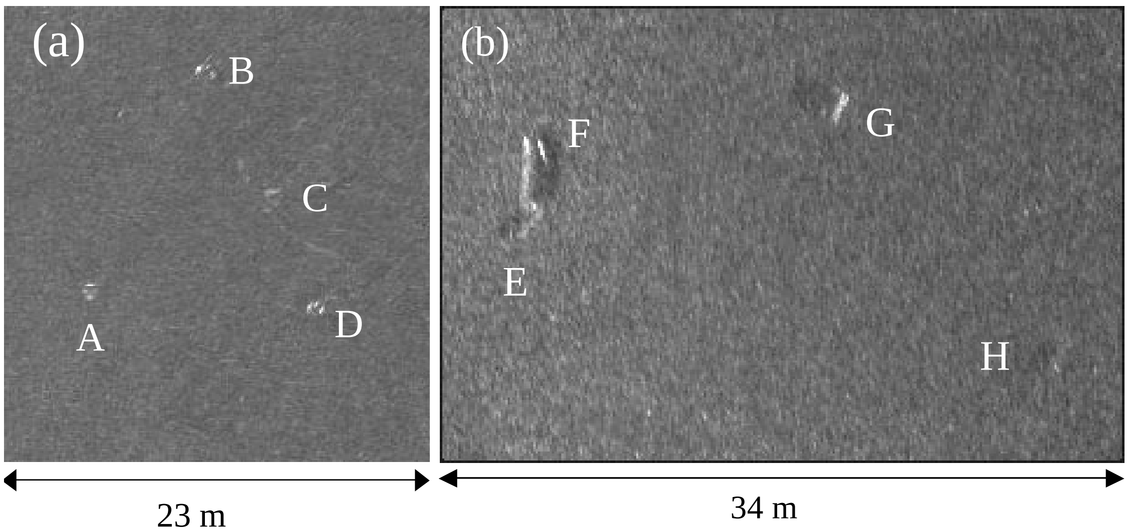


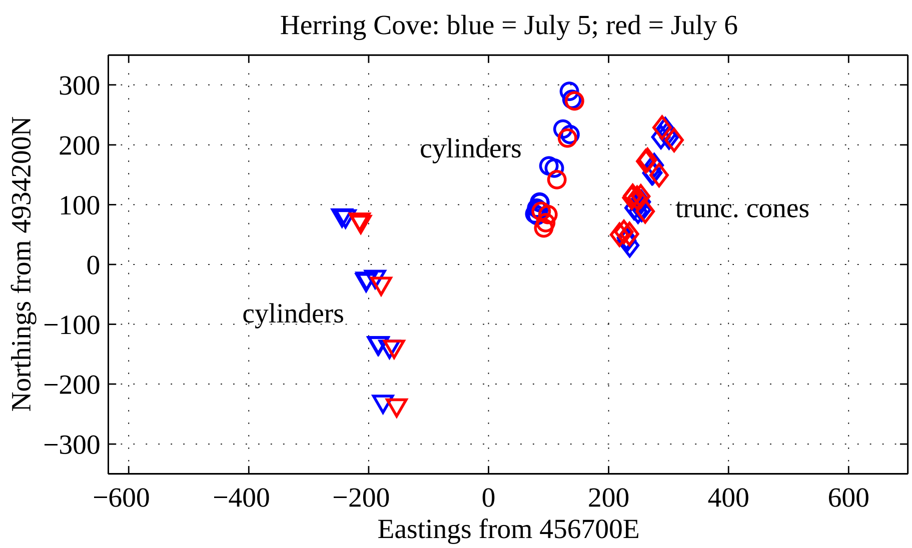
Figure 11: Sample target images from the Herring Cove high resolution survey, showing a truncated cone in (a) and a cylinder in (b).

Table 4: Positioning errors of the images in the samples shown in Figure 11 and for all images with well-defined mean target positions surveyed on July 5 and 6.

image	*Δr*	*Δacross*	*Δalong*
A	10.4	4.6	9.3
B	8.6	5.9	6.2
C	2.0	-0.1	2.0
D	7.0	5.9	3.8
E	10.3	10.0	2.1
F	9.7	8.7	4.3
G	7.0	4.3	-5.5
H	16.4	13.1	9.9
all (40)	11.0	8.3	5.6

7. Discussion of positioning performance

Figure 12 shows the target image positions determined from the processed sidescan sonar data for all days at the two sites where the targets were deployed. The clustering of the locations is somewhat tighter for the St Margarets Bay survey results. This illustrates the difference in positioning repeatability between calculating the towfish position from layback values (the Herring Cove survey results) and real-time measurement of towfish position using the Trackpoint system (the St Margarets Bay survey results). The Herring Cove survey data was processed using a single value of layback for each survey leg since layback was not changing over the parts of the survey tracks where the mine targets were located. This represents the optimal condition for positioning accuracy using the traditional post-processing method built into the processing software SIPS.



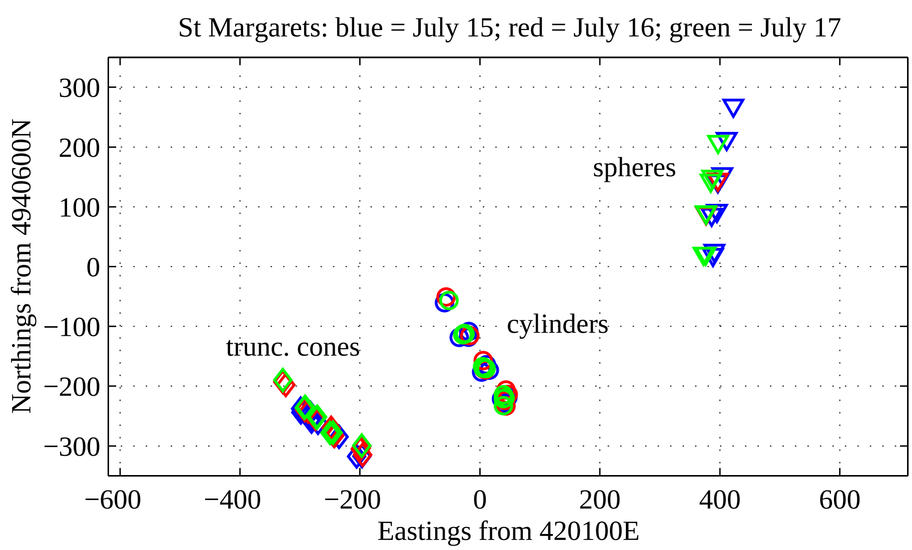


Figure 12: Locations of target images in the processed Herring Cove (upper plot) and St Margarets Bay (lower plot) high resolution survey data. Axes are in meters.

On the whole, the positioning repeatability is quite good using either method, with only marginally better consistency using the Trackpoint system. The mean value of Δr for the Herring Cove survey mine positions (Table 4) is larger than for the St Margarets Bay survey (Table 3): 11.0 m vs. 6.3 m. In either case, a positioning error of approximately 10 m represents reasonable accuracy.

Examining the clustering of target image locations in the Herring Cove survey results (Figure 12), there is some evidence of systematic error in acrosstrack position, most clearly in the target positions along the more westerly line of cylinder targets. The mean acrosstrack positioning error for this survey indicates a positive offset of several meters. As has been mentioned, this would be explained if the towfish was following the ship several meters to port of its assumed position along the ship centerline. This is confirmed by the Trackpoint towfish position measurements (an example is shown in Figure 4). This is a good example of a limitation of calculating towfish position from the layback alone - this type of towfish ship-following behaviour cannot be accounted for in the calculation if not predicted. The positive alongtrack positioning error found in the Herring Cove survey results suggests that the layback was greater than the values recorded in the logbook. Perhaps the length markers on the towfish cable should be examined. Figure 13 illustrates the across- and alongtrack positioning errors for the two sets of survey results. The mean positioning errors for each survey are shown by the red dots and the ellipses have semi-axes equal to one standard deviation in the across- and alongtrack directions.

The relative positioning between overlapping swaths in the Rose Bay and New Harbour Point surveys (where towfish position was recorded in a log file) also seems to be quite good, but it is difficult to estimate the accuracy in the absence of specific targets in the images. The alongtrack positioning has estimated error of about 5 m. There should be little difference in positioning performance between using this method and when the towfish position was recorded in the sonar data files since the source of the positioning information (the Trackpoint system) is the same. A systematic difference could arise in the setup of the Trackpoint system to output towfish latitude and longitude, which requires operator input of the spatial offsets to the Trackpoint receiver. The Trackpoint position data recorded during the Rose Bay survey

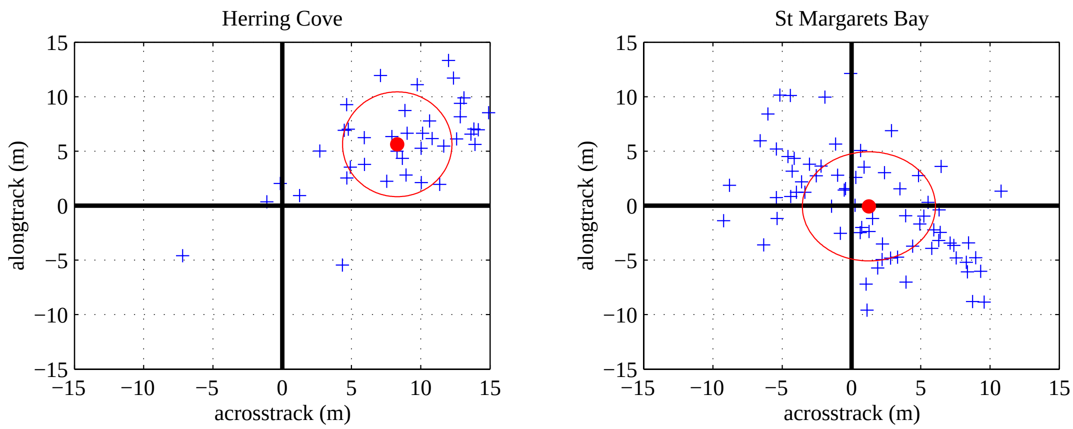


Figure 13: Across- and alongtrack target positioning errors for the two sets of survey results.

was noisier than on other days perhaps due to interference by multiple returns to the receiver or surface reflection (multipath) effects, but it was possible to condition the data adequately.

The mosaic of the low resolution survey data from St Margarets Bay, processed using towfish position determined from logged cable length entries, has registration errors between neighbouring swaths of about the same size as the positioning error in the Herring Cove mine surveys. This is a favourable result, but relies on the care taken in recording the cable length changes during the survey. Obviously this method may not be helpful in processing historical sidescan survey data (even for other surveys during trial Q260) where less thorough record keeping was done.

The horizontal positioning accuracy of the GPS receiver system in use during these surveys (CSI Wireless GBX-Pro, in differential mode) is quoted as 0.9 m [1]. The horizontal dilution of precision (HDOP) values recorded in the GPS position entries in the log files between July 8 and 19 have a mean value of 1.1, or had a value of 1 for 91.4% of the time HDOP was recorded. There were 8 or 9 satellites in view 80.3% of that time. These statistics indicate that the highest quality GPS positioning solutions were possible during this time. The average of the 95% global average horizontal positioning performance statistics supplied by the US Department of Defence GPS Support Center for the month of July 2001 is 3.6 m [4]. This estimate is purposefully large, representing an absolute maximum positioning error, since these were calculated from 4-satellite solutions - the realized error would be significantly less than this. GPS operators routinely quote 1 or 2 m positioning accuracy in differential mode.

The positioning accuracy of the Trackpoint II acoustic tracking system, operating in transponder mode, is quoted as +/- 0.3% RMS of slant range for repeatability accuracy and +/- 0.5% RMS of slant range for absolute accuracy. Slant range accuracy is listed as +/- 1 m, assuming a correct sound speed setting, with a resolution of 0.3 m [5]. The sound speed setting (1458 m/s) was based on with water column sound speed calculated from measurements of temperature and salinity made during the trial [1], though there was a near-surface layer of warmer water giving higher sound speed (~1490 m/s) in the upper 7 to 10 m. The favourable positioning repeatability results for targets in the St Margarets Bay survey, discussed in Section 6.1 and illustrated in Figure 12, do not indicate gross sound speed error, or bearing error due to uncompensated mounting misalignment of the receiver. A comparative study of the Trackpoint II system with other similar acoustic systems (Honeywell Hydrostar and Nautronics ATS) and laser range-bearing measurements found the Trackpoint system gave a mean range error of 0.4 m and bearing error of 0.9 degrees [6]. It is interesting to note that the Trackpoint II system is intended to operate in an essentially downward looking geometry (within a 45 degrees-from-vertical cone of operation), though it appears to function adequately almost horizontally. The Trackpoint II system has more recently been used for towfish location during a Remote Minehunting System Technology Demonstrator (RMS TD) Build trial [7]. During that trial, it was found to give accurate towfish range ("within meters") but very poor bearing measurements. These were compressed to a 2-degree band with a 6-degree offset. This was thought to be due to shielding by the vessel hull or multipath effects caused by hull protrusions or perhaps due to problems with the receiver. In any case, problems of this nature were not encountered during use of the system during Q260, though the bearing data were quite noisy as discussed previously. The Trackpoint system performance during the Q260 trial is also comparable to results from trials conducted by DREP in the early 90's [8].

The surveys conducted during Q260 were in relatively shallow waters (<50 m) with cable length limited to a maximum of 105 m. Compared with operations in deeper water, there should be less potential here for factors such as acrosstrack mean current or curvature of the tow cable to introduce errors into the position calculations involving layback, and the Trackpoint system signal-to-noise situation is optimal. Even in this case, however, there was an unexpected tendency for the towfish to follow the ship at an off-center position. In deeper water, where longer cable lengths are required, less accurate towfish positioning might be expected by either method.

8. Closing Remarks

New methods for handling towfish position information, either from Trackpoint-determined range and bearing measurements or from logged cable length entries, have been developed for use with the in-house sonar image processing software SIPS. The intention has been to improve the positioning accuracy of geo-referenced sidescan sonar seabed images, particularly in the case that the layback was changing over the course of the survey legs.

For cases where the Trackpoint system was used to measure towfish position, SIPS was modified so that this information can be used. Estimates of the positioning precision determined from repeat surveys over the same targets show that the positioning error is on average about 6 m. This is an improvement over results obtained using the traditional processing method on survey data collected during the same trial, which gave an average positioning error of about 11 m. Some of this larger error can be attributed to unpredicted off-center following behaviour of the towfish behind the ship - a good example of how a real-time acoustic locating system can be valuable.

Where there has been careful record keeping of the cable length during a survey, software was developed that uses this information to determine towfish position. A wide-area mosaic of Saint Margarets Bay processed using this technique shows positioning errors of between 5 m and 10 m where layback varied between 20 and 100 m over the course of some of the tracks. This is a substantial improvement in positioning accuracy over the case of using single layback values, or alternately, represents a significant saving in processing effort if tracks had to be broken into segments where layback was changing.

Currently some of the supporting software that has been written as part of this work is not integrated with SIPS. Ultimately there will be a new version of SIPS incorporating these improvements, with appropriate additions to the user interface.

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List of symbols

(X_{GPS}, Y_{GPS})	GPS receiver horizontal position, ship's position [m]
$(X_{towfish}, Y_{towfish})$	towfish horizontal position [m]
(X_{TP}, Y_{TP})	Trackpoint receiver horizontal position [m]
$\Delta X_{TP}, \Delta Y_{TP}, \Delta Z_{TP}$	across-, alongtrack and vertical offsets to Trackpoint receiver [m]
$\Delta X_A, \Delta Y_A, \Delta Z_A$	across-, alongtrack and vertical offsets to towpoint [m]
R, θ	range and bearing from Trackpoint receiver to towfish [m, degrees]
D	horizontal distance from Trackpoint receiver to towfish [m]
L	horizontal alongtrack distance from Trackpoint receiver to towfish [m]
Δr	horizontal (range) of image to average target position [m]
Δacross, Δalong	across- and alongtrack distance to average target position [m]

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New methods for improving the positioning of post-processed sidescan sonar seabed imagery have been developed and evaluated. During sea-trial Q260, July 2001, Trackpoint-determined sonar towfish position and ship position data were recorded in several configurations in the sonar data files and in accompanying log files. The Trackpoint system uses a ship-mounted receiver to determine range and bearing to a transponder on the sonar towfish. In post-processing of the sidescan sonar data to obtain geo-referenced seabed imagery, various methods of using this towfish position information have been developed. Varying degrees of conditioning of the Trackpoint position data were required, as well as some recoding of the in-house sonar data mosaicking software. A method for determining towfish position from the cable length entries in the sonar operators' logbook was also developed and used with reasonable success. Resulting positioning errors were estimated from the separation between multiple images of targets in seabed mosaics made from several survey swaths, as well as between geological features appearing in the images. It was found that use of the Trackpoint system for towfish location did improve positioning of the resulting sidescan sonar seabed images, as well as helping to resolve some apparent inconsistencies in positioning caused by unpredicted towfish ship-following behaviour.

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sidescan sonar data processing, geo-referencing, seabed imaging

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