Analysis of the BT mode experiments from the IWC-SOWER 2005/06 Cruise

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ABSTRACT

IWC sightings surveys which have taken place in the Antarctic since 1978/79. In order to interpret the minke whale abundance estimates obtained from data collected on these surveys and to improve the survey design of future cruises, BT mode experiments were conducted during the IWC-SOWER 2005/06 cruise. The BT mode survey method combines mark-recapture and line transect methods to overcome difficulties associated with conventional distance sampling survey methods (i.e. ensuring that animals on the trackline are certain to be seen and that they are seen before they have moved in response to the vessel). The data was divided according to the type of binoculars used (either 7x50 binoculars or higher powered big eye binoculars) and separate analyses were conducted. The results suggested that there were differences between these two sets of analyses but it was not clear why. Further BT mode experiments and analysis of previous sighting survey data would be required to better understand these results.

INTRODUCTION

Sightings surveys have taken place in the Antarctic under the auspices of the International Whaling Commission (IWC) every austral summer since 1978/79 and there are now three circumpolar (CP) sets of surveys. Abundance estimates, obtained using conventional line transect (LT) distance sampling methods (Buckland *et al*. 2001), have indicated an appreciable decline in minke whale abundance between CP II and CP III (Branch and Butterworth, 2001). A series of experiments were conducted on the 2005/06 IWC Southern Ocean Whale and Ecosystem Research (SOWER) cruise in order to interpret these abundance estimates and also to improve survey design for future cruises. This report evaluates the BT mode experiment. Note that the purpose of this experiment was to evaluate the BT mode survey protocol and not to estimate abundance.

Two key assumptions of conventional LT methods are that animals on the trackline are certain to be seen (denoted by $g(0)=1$) and that they are seen before they have moved in response to the vessel. Cetacean size and behaviour may results in these assumptions being violated. A variety of methods combining mark-recapture and line transect (MRLT) methods have been developed to overcome these difficulties (see Laake and Borchers, 2004, for an overview).

The BT mode survey method (called 'trial configuration' mode by Laake and Borchers, 2004) requires two teams of observers. (The term 'observer' is used here to refer to one or more people performing the same role.) The first team (referred to as the primary) searches close to the vessel. The second team (tracker) searches ahead of the vessel, scanning a region sufficiently far ahead of the vessel that animals are unlikely to have reacted to the vessel's presence before being detected. The scanned region should also be sufficiently wide that animals outside of it would not be able to enter the region searched by the primary. Animals detected in this region are then followed by the tracker. The primary acts independently of the tracker and if the primary sees the same animal as the tracker, this is termed a duplicate sighting. Duplicates can only occur if the tracker sees the animal first; the tracker platform is in contact with the primary platform and is thus aware of animals seen by the primary. In essence, detections by the tracker serve as a set of binary trials in which a success corresponds to a detection by the primary. Analysis of duplicate sightings allows the probability that an animal is detected by the primary observer to be estimated, thus abundance can be estimated without assuming $g(0)=1$.

SURVEY METHODS

Platform configuration
Configuration of the three platforms on the IWC-SOWER vessel during the 2005/06 cruise is shown in Table 1. The primary observers were stationed on the barrel and independent observer platform (observers 1 and 2, respectively) and searched independently of each other and of the tracker platform which was on the upper bridge. An important component of BT survey method is that tracker searches far ahead of the vessel and the primary observers search close to the vessel. In the usual IWC-SOWER methodology all observers searched with handheld 7x50 binoculars and there is no separation of search areas between the platforms. However, in order to achieve a separation of search areas for this survey, higher powered (x25) big eye binoculars (BE) were introduced on the upper bridge. Although the upper bridge is the lowest of the platforms it was chosen as the tracker platform as it was the only practical location where the BE could be installed and isolated from ship vibration. Thus, trackers were using both 7x50 binoculars (observers 3 and 4) and BE.

Search mode

The BT mode experiment was conducted in normal standard passing (NSP) mode and in independent observer (IO) mode. In IO mode, observer 2 operated as an additional primary observer but acted independently of observer 1 in the barrel and *vice versa*. The intention was to conduct most of the BT experiment in IO mode (to be comparable with the standard SOWER methodology). However, during the cruise difficulties were experienced conducting BT trials during IO search mode due to the additional data recording, tracking and duplicate assessment related to the BE sightings. Thus, the majority of the BT mode experiment was conducted in NSP mode (Ensor *et al*. 2006).

ANALYSIS METHOD

Detection function

Although the primary observers (barrel) are acting independently of the trackers (upper bridge observers), dependence of detection probability on unmodelled variables (e.g. Beaufort sea state or group size) can induce correlation in detection probabilities. This is called unmodelled heterogeneity. Since it may not be possible to record all variables affecting detection probability, unmodelled heterogeneity may persist even when the effects of all recorded variables are modelled. Laake and Borchers (2004) and Borchers *et al*. (2006) developed estimators based on the assumption of no unmodelled heterogeneity at zero perpendicular distance only. These estimators are more robust to violation of the assumption of no unmodelled heterogeneity than previous perpendicular distance-based estimators. The methods use the difference between the shape of the conventional LT detection function estimated from the primary observer data only, and the mark-recapture detection function estimated from duplicates, to estimate unmodelled heterogeneity off the trackline. When animals move in response to the vessel between detection by the tracker and detection by the primary observer, the effects of unmodelled heterogeneity off the trackline and responsive movement cannot be separated (see Cañadas *et al*., 2004 and Borchers *et al*. 2006). Because we anticipated animal movement, we assumed no unmodelled heterogeneity at any distance. We considered inclusion of all available explanatory variables (to model heterogeneity) and models were chosen using Akaike's Information Criterion (AIC, Akaike 1973). The explanatory variables considered, in addition to perpendicular distance, were school size, weather code (as a factor variable), Beaufort sea state and sightability.

RESULTS

Data selection

The BT experiments commenced with the intention of using a standard SOWER constructed trackline within the southern stratum (the region up to 60 nmiles from the ice-edge). However, away from the ice-edge, the sighting rate of minke whales was low and as the main aim of the experiment was not to obtain an abundance estimate *per se*, a flexible cruise track was adopted with the aim of increasing the encounter rate (Ensor *et al*, 2006). The search effort is shown in Figure 1 and Table 2.

Angle and distance experiments were performed to assess any bias in the sighting angles and radial distances recorded from the various platforms. Analyses indicated that there was only significant bias for the radial distances of the barrel and the upper bridge (not BE) and that these biases were small (5-6%). Sighting angles did not appear to be biased.

To examine search regions, all sightings (of all species) seen in both NSP and IO mode were included. Subsequent analyses were limited to sightings of minke whale (Antarctic) (species code 04), 'undetermined minke' (91) and like minke' (39). These are all referred to as 'minke' whales. There were no sightings of 'minke, like Antarctic' (92). Only duplicates classified as 'Definite' were considered to be duplicates.

Search regions of observers

Search regions are an important aspect of the BT method and examining the estimated angles and radial distances gives an insight into the search regions for the different platforms. For this analysis, sightings of all species collected during both NSP and IO modes were used. Table 3 and Figures 2 to 4 summarise the distribution of angles and radial distances. Caution must exercised when interpreting these figures because in some cases the numbers of sightings are small and the distribution of recorded values may not entirely represent the search pattern of observers. However, there are a few indications.

The protocol required BE observers to evenly scan a region no more than 45^o either side the trackline and this was followed, although they appeared to have concentrated more off to the sides and not so much on the trackline. The fewer detections at closer radial distances by the BE is to be expected as they were instructed to search as far ahead of the vessel as possible, at least more than 2nm away.

Tracking observers 3 and 4 were instructed to search as usual i.e. scan 90^o either side of the trackline and cover all distances. More than 60% of sightings seen by observer 3 were seen within 2nm of the vessel. The radial distance distribution of observer 4 (upper bridge, secondary observer) may be an artefact of sighting rate: when there was a higher sighting rate of minke whales they were mainly assessing duplicate status and recording data rather than searching; when the sighting rate was lower, observer 4 had time to search but appeared to focus at further distances.

The majority of sightings from observer 1 were seen within a region of 0 - 4nm from the vessel although there were detections out to 8nm. The majority of sightings from the BE were between 1 - 5nm with some sightings out to 8nm. Thus, there was partial separation of search regions between observer 1 and the BE. There does not appear to have been a separation of search regions between observer 1 and the upper bridge (observers 3 and 4), but since these observers were all using 7x50 binoculars, then this may not be expected and the primary platform was considerably higher than the tracker platform (Table 1).

Responsive movement of animals
Figure 5 shows the perpendicular distances of duplicates at the time they were initially detected by the upper bridge (tracker) and subsequently by the barrel (primary). One needs to be cautious about interpreting this figure because animals moving towards the vessel are more likely to become duplicates because they become more detectable to the primary observers. Such animals are therefore more likely to appear in the figure than animals moving away from the vessel, so that observing more duplicates moving towards the than away from the vessel is not necessarily an indication of attractive movement. The number of duplicates is small (Table 4). However, all but one duplicate seen initially by the upper bridge (observers 3 and 4) were seen by the primary when the animals were moving away from the vessel. For animals swimming away from the vessel, there may be more opportunities for them to be seen by the primary (and hence become duplicates) because there may be more resurfacings before they pass abeam. For duplicates seen initially with BE, Figure 5 does not suggest much, if any, attraction since we expect more points above the line, even in the case of no attraction. Although most circles are above the line, the effect of attraction does not look large.

Figure 6 shows the movement of animals between duplicate sightings, taking into account the movement of the vessel between sightings. There are clearly some unlikely speeds as shown in Figure 7 but these occurred with duplicate sightings that were seen close together in time, less than 4 minutes apart, and are likely to be caused by errors in the angle and distance measurements.

Observers using the BE were instructed to track animals and record information about subsequent sightings, or resightings. Figure 8 shows the tracks of minke whales that were resighted during BT/NSP and BT/IO modes. The longest track lasted for 22 minutes although generally tracking lasted, on average, 4.5 minutes. Forty-five minke schools were tracked and 24 of these were definite duplicates of sightings seen by the primary observers and three were possible duplicates.

School size estimates
NSP mode generated very few sightings where school size was confirmed. For observer 1 nearly a quarter of all sightings have confirmed school sizes, although this percentage was much smaller for sightings of minke whales (14%). The mean school size was smaller for sightings with confirmed school size estimates than for both confirmed and unconfirmed. This may be a due to the fact that it is easier to confirm school sizes for schools that are close to the vessel and then preferentially seeing large schools at greater distances so that the number of large schools are overrepresented in the sample (or perhaps a slight tendency to lump 'subgroups' together for more distant sightings whereas for closer sightings they may have been treated as separate sightings). It is clear from Figure 9 that confirmed schools were seen close to the trackline but they were not necessarily initially detected close to the vessel. Groups with confirmed school sizes will usually have surfaced several times and at small perpendicular distances before passing abeam.

There were no differences in the estimates of school size for duplicate sightings between the two platforms since the 'best' estimate was usually made by observer 1, the topmen in the barrel.

Detection function
In order to evaluate BT mode, analyses were conducted separately for duplicates seen initially with BE, duplicates seen initially with 7x50 binoculars (observers 3 and 4) and finally all duplicates combined. The number of duplicates is small, particularly for the 7x50 binoculars, and so simple models, which used perpendicular distance only, were fitted. The AIC clearly showed that the detection function should be estimated for all data combined and given the larger number of duplicates additional explanatory variables were also included in this model. The variable which had the most influence was school size, fitted as a factor variable (with levels 1, 2, 3 and 4 or more animals). The detections functions are given in Figure 10 and results are in Table 6.

A conventional LT analysis using only sightings seen by the primary observer (topman in barrel) is also included for comparison. Note that in all analyses both confirmed and unconfirmed school sizes have been used.

DISCUSSION

The histogram and estimated LT detection function (Figure 10e) and histogram and MLRT detection function for the 7x50 duplicates (Figure 10b) are similar, much more so than the corresponding detection plots for the BE duplicates (comparing Fig. 10a with 10e). For the BE duplicates, the MLRT histogram and detection function are much flatter than the CDS plot. This is typical of a) increasing unmodelled heterogeneity with increasing perpendicular distance from the trackline and/or b) attractive movement between the detection by the tracker and detection by the primary.

One needs to be cautious about interpreting these figures because the sample size is small and the AIC suggests that there is not a substantial difference between the distributions of BE and 7x50 duplicate proportions. However possible interpretations of a) and b) are:

a) Attractive movement between detections for both the BE and 7x50 duplicates. Figure 10a supports the interpretation for attractive movement for the BE duplicates but while Fig. 5 does not contradict this, it does not provide strong support for this idea. Because the 7x50 trackers search in the same place as the primary, Fig. 10b could be consistent with attractive movement occurring before detection by the observers using the 7x50 binoculars.
b) Unmodelled heterogeneity. This would have been expected to be a problem for both the BE duplicates and the 7x50 duplicates, but it only appears to be a problem for the BE.

The results suggest that there is something different between the BE and the 7x50 tracker situations. BE observers had almost continuous search effort while 7x50 trackers had variable search effort since they are also trying to resight animals seen initially by the primary to get species identification and school size estimates. The secondary observer on the upper bridge (platform 4) will often have no search effort for long periods due to data recording. However, although the variable effort of the 7x50 observers is likely to affect the numbers of duplicates it is unlikely to affect detection. The most plausible explanation from the evidence here is responsive movement in the time between detection by the BE and detection by the primary although the evidence is not clear.

The effects of responsive movement and unmodelled heterogeneity can be alleviated by detecting animals before they have responded to the vessel and separating the search areas between the primary and tracker observers, with the trackers searching far ahead and the primary observers searching close to the vessel. Although the BE observers were focusing ahead of the vessel, primary observers were able to detect sightings at distances as far away as the BE observers so that only a partial separation of search areas was achieved. This may be due in part to the good weather that was experienced during the survey but also to the location of the BE which were considerably lower than the primary platform.

CONCLUSIONS AND RECOMMENDATIONS

It seems advisable to do further BT mode experiments using the BE and also consider experiments to distinguish between the possible interpretations outlined above. If understanding the issues raised by this and previous analyses is a priority on the next cruise, rather than estimating abundance, then again a flexible design would be advantageous if it increases the likelihood of duplicate sightings.

The majority of search effort took place in good weather (76% in Beaufort sea states 2 or less) and conducting trials in a wider variety of weather conditions would be useful. The prevalence of good weather may have meant that sighting distances were further than normal, thus increasing the overlap of search regions between the BE and the primary observers in the barrel. An analysis of previous SOWER cruises would indicate whether sighting distances on this cruise were further than normal. Instructing BE observers to search further ahead than specified in this cruise or change the location of the BE may help to separate the search regions. If moving the BE is not possible, then considering experiments where the primary observers searched with the naked eye would be an alternative.

The BT method can provide an estimate of the probability of detection on the trackline for the primary observer and in the SOWER configuration the primary observers are the observers in the barrel. The analysis does not give an indication of the probability of detection on the trackline for all platforms combined which, for previous LT estimates of minke whale abundance, is assumed to be one. However, if the other platforms had a similar probability of detection on the trackline to the barrel, then a combined $g(0)$ will be less than one.

There are clearly differences between duplicates made by the BE and 7x50 observers. An analysis of duplicates from data recorded on previous SOWER cruises may provide an insight into the probability of detection on the trackline for the barrel and whether this has changed overtime.

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Table 1 Platform configuration on IWC-SOWER vessel. Note that platform height is in metres above sea level.

Observer code	Platform description	Binocular Type	Platform height (masl)	No of observers on platform	BT mode configuration
1	Topman in barrel	7x50	20	2	Primary
2	Topman in IOP	7x50	14	1	Primary
3	Upper bridge, main observer	7x50	11.0	2	Tracker (assistant)
4	Upper bridge, secondary observer	7x50	11.0	2	Tracker (assistant)
BE	Upper bridge	x25 Big eyes	11.0	1	Tracker

Table 2 Search effort and numbers of sightings in BT search effort (nm).

		Numbers of sightings		
Search mode	Effort	Minke	Undetermined minke	Like minke
BT/IO	127.4	22	8	
BT/NSP	1 310.2	282	12	17
BT/NSP with ice navigation	75.2	18		
Total	1 512.8	323	20	17

Table 3 The number of sightings and mean sighting angle, radial distance for all sightings seen in both BT/NSP and BT/IO modes. Standard deviations are given in parentheses.

Observer and Platform	Number	Estimated angle (degrees)	Radial distance (nm)
1: Topman in barrel	334	28.3 (20.7)	2.23 (1.65)
2: Topman in IOP	13	37.4 (17.9)	2.11 (1.68)
3: Upper bridge, main observer	33	24.9 (21.9)	1.72 (1.54)
4: Upper bridge, secondary	29	25.3 (26.7)	3.24 (2.18)
BE: Upper bridge	72	22.0 (12.2)	3.50 (1.88)
All[1]	489	27.1 (20.2)	2.44 (1.78)

[1] Includes 7 sightings classified as BE but simultaneously seen by other platforms.

Table 4 Number of duplicate sightings that were initially seen by the tracking observer, mean time between duplicate sightings, mean distance travelled by the animals between duplicate sightings and mean speed of the animals. Standard deviations are in parentheses.

Tracking observer	Number	Time (minutes)	Distance (nm)	Speed (knots)
3: Upper bridge, main observer	10	2.86 (3.25)	0.35 (0.37)	16.4 (18.0)
4: Upper bridge, secondary observer	6	5.02 (3.90)	0.52 (0.35)	12.9 (12.5)
BE: Upper bridge	21	4.36 (4.31)	0.69 (0.76)	20.0 (22.7)
All	37	4.06 (3.96)	0.57 (0.63)	17.9 (19.9)

Table 5 Best school size estimates recorded by observer 1 (topman in barrel) in BT/NSP mode. Standard deviations are given in parentheses.

	Confirmed		Confirmed and unconfirmed	
Species	Number	Mean (sd)	Number	Mean (sd)
All sightings	77	1.97 (1.81)	317	2.49 (2.26)
Minke	33	2.18 (1.83)	241	2.53 (2.17)

Table 6 Results from the different MRLT models. The parameter $\hat{p}_1(0)$ is the probability of detection on the trackline for the primary observer (1: topman in barrel). Estimated density, $\hat{D}$, is given for minke whale schools, *s*, and individuals *i*. $\hat{E}[s]$ is the estimated school size. The last row shows the results of a conventional LT analysis fitted to observer 1 sightings only and estimated school size is obtained from a size-bias regression. Percentage coefficients of variation are given in parentheses.

Platform	Variables in model	$\hat{p}_1(0)$	$\hat{D}_S$	$\hat{D}_i$	$\hat{E}[s]$
3 + 4: Upper bridge	Distance	0.45 (31.2)	0.278 (38.3)	0.758 (42.7)	2.73 (14.0)
BE: Upper bridge	Distance	0.29 (34.8)	0.077 (41.7)	0.210 (45.7)	2.73 (14.0)
All	Distance	0.52 (27.2)	0.079 (35.5)	0.215 (40.2)	2.73 (14.0)
All	Distance + school size	0.50 (28.8)	0.100 (36.3)	0.198 (35.8)	1.98 (16.6)
1: topman in barrel	Distance (LT model)		0.096 (26.0)	0.207 (26.5)	2.16 (5.21)

Figure 1 Plot of cruise effort in BT/NSP mode (including ice navigation) and BT/IO mode (thick black lines). The research was conducted in the vicinity of the ice-edge which changed substantially during the duration of the cruise. An approximate position of the ice-edge is indicated by the tracklines. The grey line in the south indicates the coast of Antarctica.

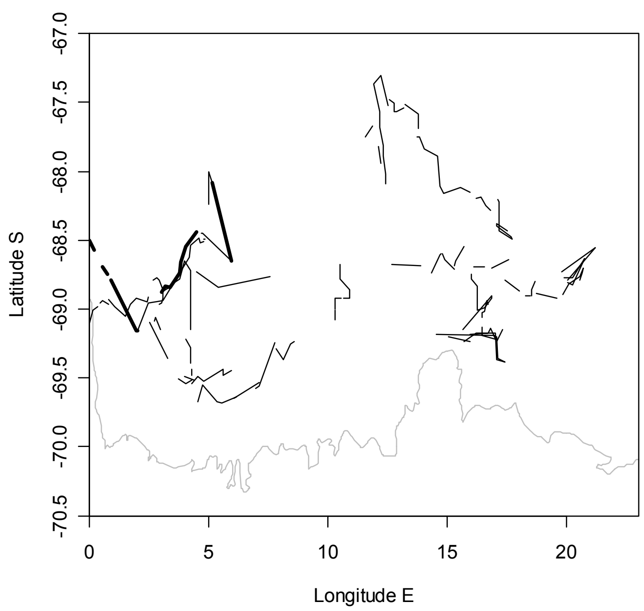

Figure 2 Histograms of estimated sighting angles for all sightings detected in BT/NSP and BT/IO search mode by observer.

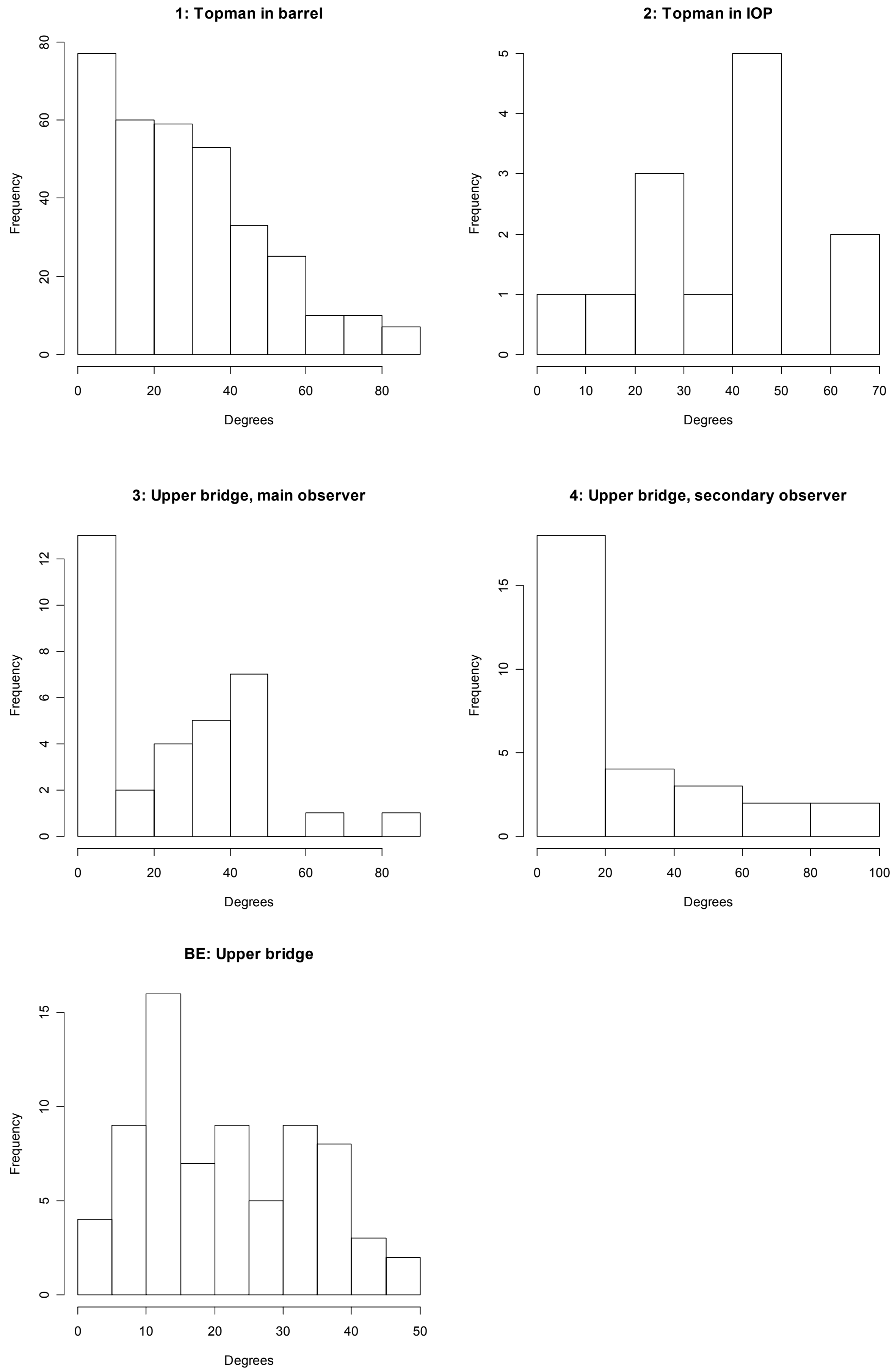

Figure 3 Histograms of radial distances for all sightings detected in BT/NSP and BT/IO search mode by observer.

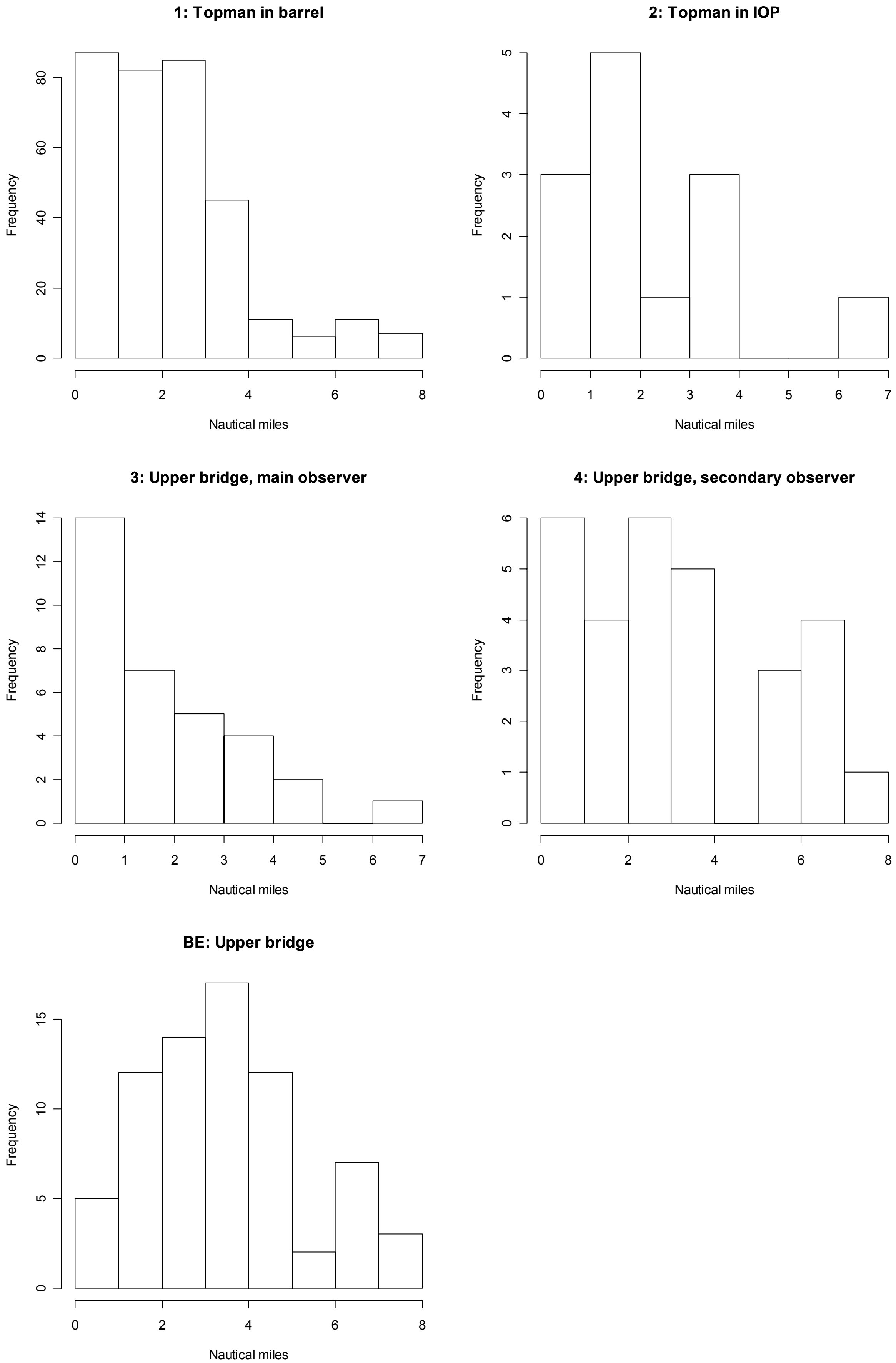

Figure 4 Location of the all sightings detected in BT/NSP and BT/IO search mode relative to the vessel which is at (0, 0).

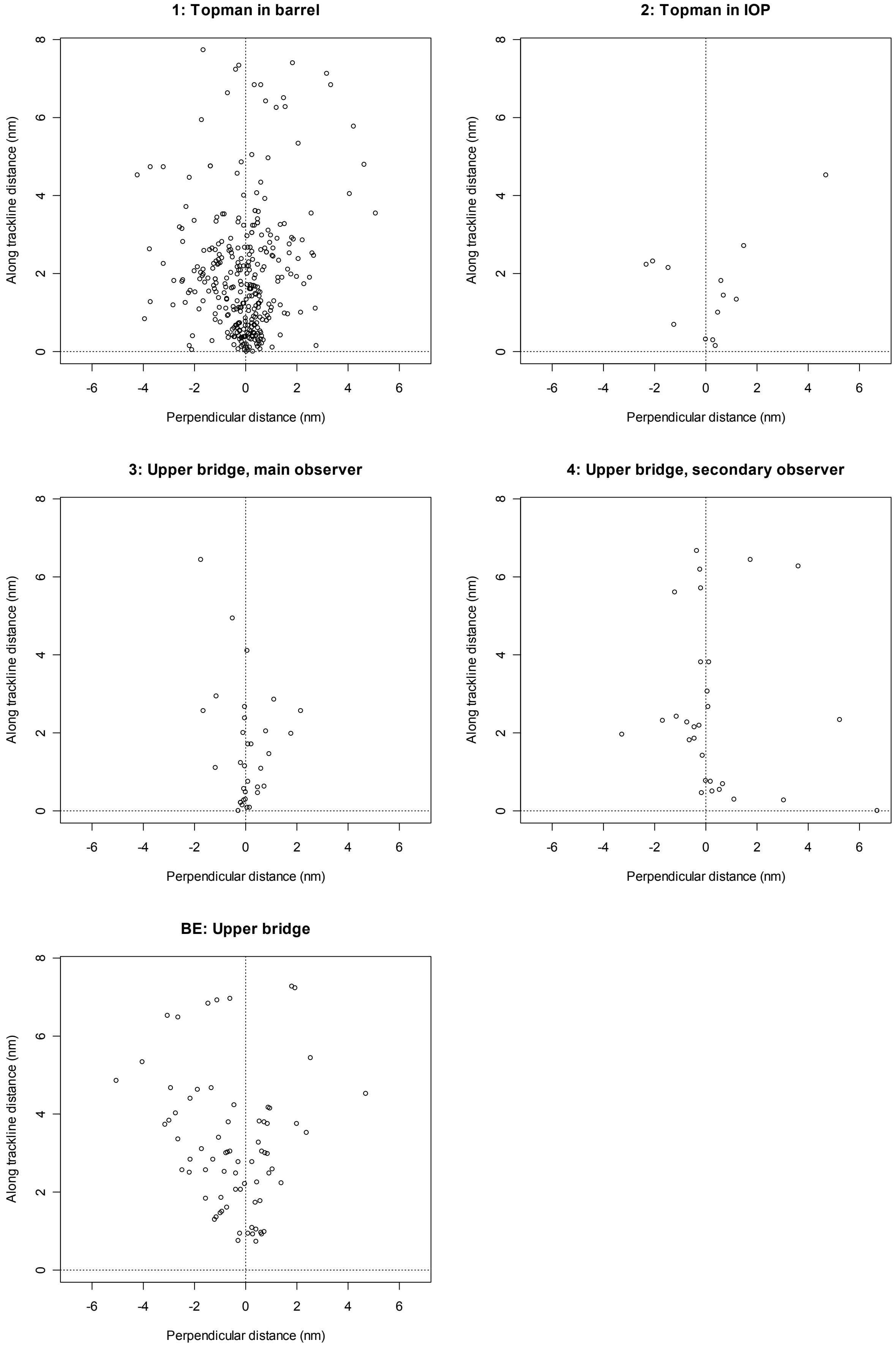

Figure 5 Perpendicular distances of duplicates at the time they were detected initially by the upper bridge (*y*-axis) and then by observer 1 (topman in the barrel; *x*-axis). The symbols indicate which upper bridge observer made the sighting: o = BE, + = observer 3 (upper bridge, main observer) and triangle = 4 (upper bridge, secondary observer). The dotted diagonal line corresponds to no movement. Points below the line correspond to movement away from the transect line, while those above correspond to movement towards it.

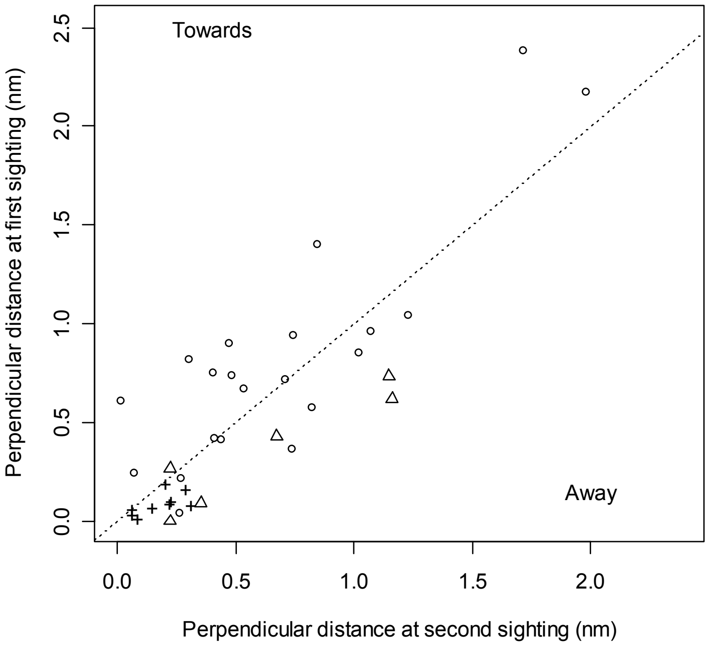

Figure 6 Plot showing the movement of animals between duplicate sightings relative to the vessel. Circles indicate the location of the tracker sightings in relation to the vessel (BE sightings indicated by solid circles): the vessel is at (0,0) at the time of the tracker sighting. The location of the primary sightings in relation to the vessel at the time of the primary sighting are indicated by a '+'. The movement of the ship along the trackline between the tracker and primary sighting has been taken into account. The lines link the duplicate pairs.

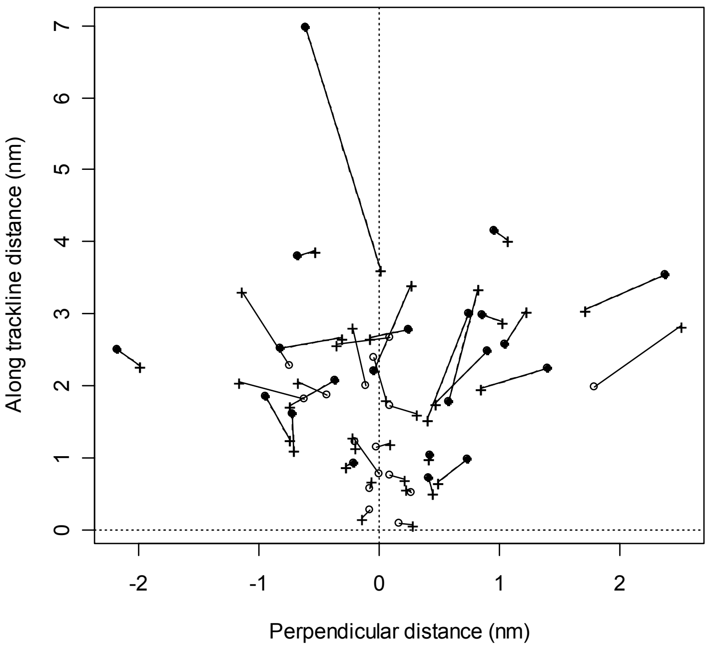

Figure 7 a) Histogram of speed of animals travelled between duplicate sightings. b) Plot of speed against the time between duplicate sightings. Solid circles indicate duplicate sightings initially seen by BE and open circles indicate 7x50 duplicate sightings.

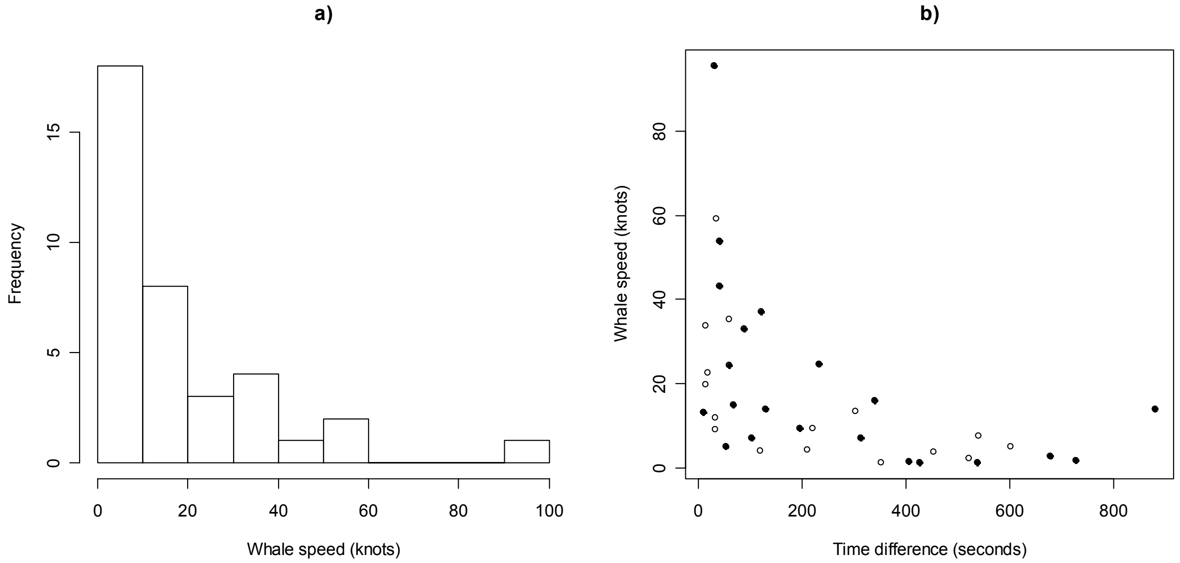

Figure 8 Plot of the tracks of minke whale sightings that were seen by the BE during BT/NSP and BT/IO modes. The vessel at first sighting is at (0,0) and the dots indicate the first sighting relative to the vessel. Lines link the subsequent resightings and movement of the vessel along the trackline has been taken into account.

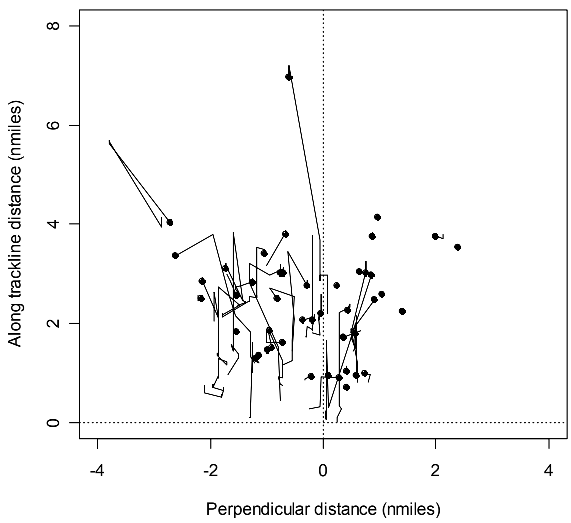

Figure 9 Plots of minke whale school size recorded by observer 1 (topman in barrel) against perpendicular distance from the trackline (top) and radial distance (bottom).

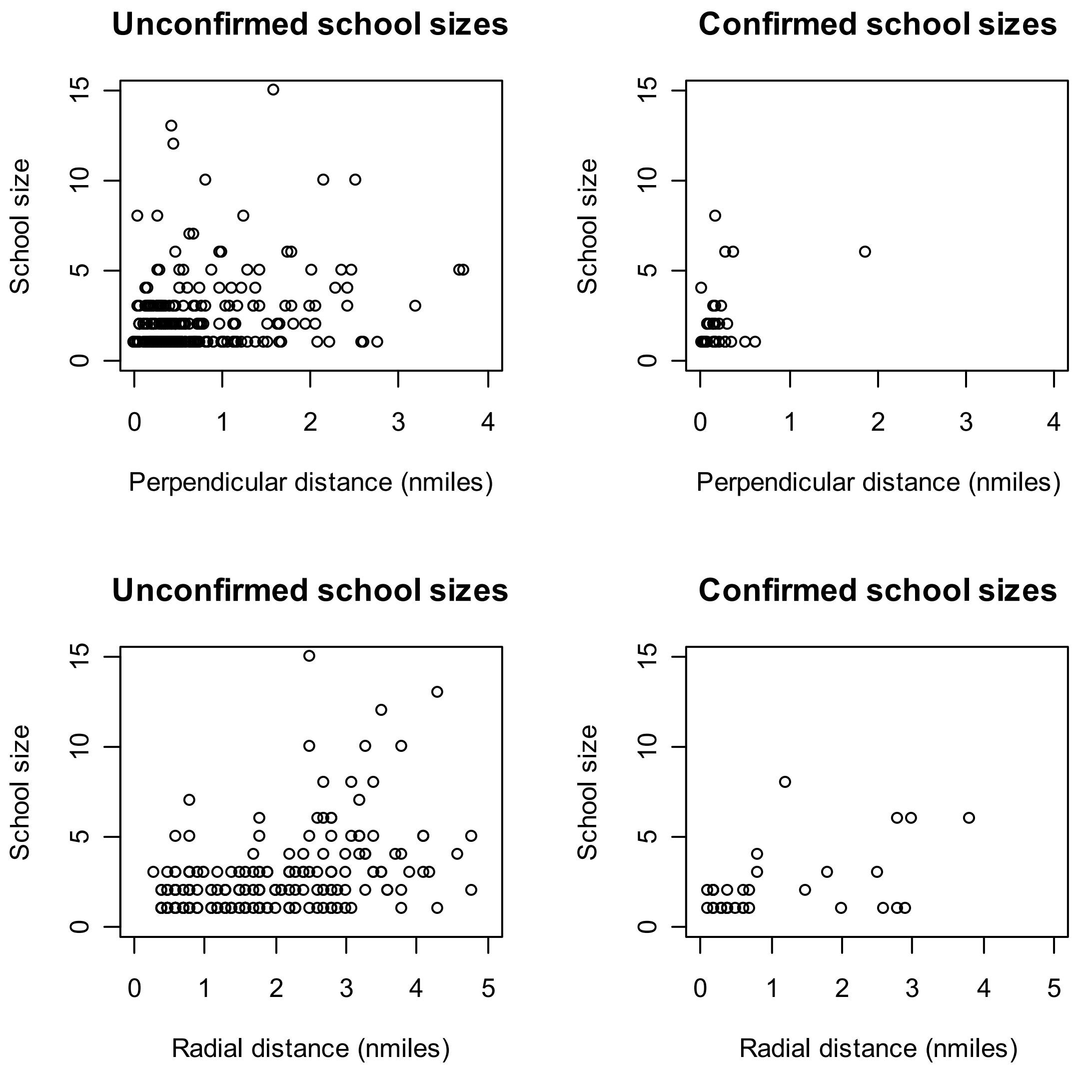

Figure 10 Detection function plots using the MRLT approach (a-d). The histogram shows the proportion of tracker detections that were seen by the primary. The line is the average fitted detection function. The points are the estimated probability of each observation (given its explanatory variable values and perpendicular distance) for the primary observer. Distances are in nmiles. In plots a., b. and c. only perpendicular distance has been used, whereas in d. school size (as a factor with 4 levels) has also been included in the detection function. e) Distribution of perpendicular distances and fitted detection function for primary (barrel) sightings only using a conventional LT approach.