Analysis of the BT mode experiments conducted on the IWC-SOWER 2005/06 and 2006/07 cruises

ML BURT AND DL BORCHERS
RUWPA, University of St Andrews, The Observatory, Buchanan Gardens, St Andrews, Fife, KY18 9LZ, UK
louise@mcs.st-and.ac.uk

ABSTRACT

IWC sightings surveys 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 and 2006/07 cruises. The BT mode combines mark-recapture and distance sampling methods to overcome two 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). This report describes the search protocol, analysis and results from these BT mode experiments.

The BT method allows the probability of detection on the trackline for the 'primary' observer to be estimated. Two configurations of BT mode were implemented; BT-NSP and BT-option 2. In BT-NSP mode, the primary observer was the topman in the barrel who searched as on a standard SOWER cruise. The estimates of $g(0)$ for the topman for the different years and combinations of data and models, ranged between 0.39 (%cv=32) to 0.69 (%cv=23). In BT-option 2, the primary observer was on the independent observer platform and searched with naked eye. The estimates of $g(0)$ for two different models were 0.25 (%cv=59) and 0.32 (%cv=49).

One of the requirements for a BT mode survey to succeed is a separation of search regions between the different observers. This seemed to be more successfully achieved in BT-option 2.

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 distance sampling (DS) 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 was conducted on the 2005/06 and 2006/07 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 (Buckland and Turnock, 1992) experiments that were conducted. The purpose of these experiments was to evaluate BT mode and estimate the probability of detection rather than to estimate abundance.

Two key assumptions of conventional line transect 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 result in these assumptions being violated. A variety of methods combining mark-recapture and distance sampling (MRDS) methods have been developed to overcome these difficulties (see Laake and Borchers, 2004, for an overview).

It has been suggested that estimates of $g(0)$ from standard SOWER search modes may be positively biased because although observers are acting independently they are searching the same area of the sea and the resulting dependence of detection probability on unmodelled variables can induce correlation in the detection probabilities. The BT mode separates the search regions of the observers which should reduce the bias due to this unmodelled heterogeneity.

BT mode (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 observer (referred to as the primary) searches close to the vessel. The second observer (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. 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. Detections by the tracker serve as a set of binary trials in which a success corresponds to detection by the primary. Analysis of these trials and duplicate sightings allows the probability that an animal is detected by the primary observer to be estimated.

SURVEY METHODS

Search mode and platform configuration

Prior to 2005/06, the standard methodology was conducted on the SOWER vessels using two principal search modes; closing mode and passing with independent observer (IO) mode. In closing mode observers were located on the barrel and upper bridge and animals were approached in order to determine more accurately species and school size. In IO mode, observers were located on the barrel, upper bridge and the independent observer platform (IOP) and animals were not approached. Normal standard passing (NSP) mode was identical to IO mode except that the independent observer was not in place. All observers searched with handheld 7x50 binoculars and there was no separation of search areas. In order implement BT mode and achieve a separation of search areas, higher powered (x25) big eye binoculars (BE) were introduced on the upper bridge. Although the upper bridge was the lowest platform, it was chosen as the tracker platform because it was the only practical location where the BE could be installed and isolated from ship vibration (Ensor *et al*. 2006).

In 2005/06 the BT mode experiment was conducted in NSP mode and in IO mode. In IO mode, an observer on the IOP operated as an additional primary observer but acted independently of the observer 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 and thus estimate $g(0)$ for the observers in the barrel and IOP. However, 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).

BT-NSP mode was again used in 2006/07. The BE were larger, heavier and of higher optic quality than those used in the 2005/06 survey and thus could be used in a greater range of weather conditions (Ensor *et al*. 2007). The procedure was also modified so that closure to all minke sightings initially detected by the BE was attempted after tracking and when the sightings were judged to be abeam of the vessel (and therefore no longer able to be detected by the primary observers). The purpose was to obtain accurate school size information of BE sightings.

Also in 2006/07, BT-option 2 was introduced and this involved a different platform configuration to that used in the NSP configuration. In BT-option 2, the primary observers were located on the IOP and searched with naked eye and the trackers were located in the barrel and searched with 7x50 binoculars. The upper bridge observers again assisted with tracking and duplicate identification.

Configuration of the three platforms for all the search modes is shown in Table 1.

ANALYSIS METHOD

Detection function

The analysis is based on methodology developed by Borchers *et al* (1998; 2006). In BT mode, the role of the tracker is to generate detections of animals before they have responded to the vessel. Estimation of the intercept of the detection function for the primary observer is then conditioned on these detections. The detections by the tracker serve as a set of binary trials in which success corresponds to detection by the primary. Note that data from the primary cannot be used to estimate the detection function for the tracker because there may have been responsive movement after detection by the tracker and the tracker is not isolated from the primary. The probability that an animal, at a given perpendicular distance x and covariates $\mathbf{z}$, is detected by the primary is denoted by $p_p(x,\mathbf{z})$ and is modelled as a logistic function;

$$p_p(x,\mathrm{z}) = \frac{e^{\left(\theta_{10}+\theta_{11}x+\sum_{r=1}^{R}\theta_{1(r+1)}z_r\right)}}{1+e^{\left(\theta_{10}+\theta_{11}x+\sum_{r=1}^{R}\theta_{1(r+1)}z_r\right)}} \tag{1}$$

where $\left(\theta_{10},\theta_{11},...,\theta_{1(R+1)}\right)$ represent the parameters to be estimated and R the number of covariates. Thus, by appropriately weighted averaging over all covariates an estimate of the detection function intercept, $p_p(0)$, can be obtained. In this application, an estimate of the detection probability on the trackline for the topman in the barrel from the BT-NSP mode data and the topman in the IOP from the BT-option 2 mode data can be obtained.

Independence of detections

Although the primary observers act independently of the trackers, dependence of detection probability on unmodelled variables (e.g. Beaufort sea state or school size) can induce correlation in detection probabilities (termed 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 (called a point independence model). These estimators were more robust to violation of the assumption of no unmodelled heterogeneity than a full independence model which assumes no unmodelled heterogeneity at any distance. The point independence method uses the difference between the shape of the conventional DS detection function estimated from the primary observer data only (called the DS model) and the mark-recapture detection function estimated from duplicates (MR model; see eqn. 1) 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). Therefore, if animal movement is anticipated, then a full independence model is preferable.

RESULTS

Search effort and number of sightings

In order to maximise the sighting rate (and hence the number of duplicate detections), the BT experiments were conducted in the vicinity of the ice edge, a flexible cruise track was adopted and regions with higher sightings rates were covered more than once (Figure 1; Ensor *et al*. 2007). In BT-NSP mode, 1,385 nm of trackline were covered in 2005/06 and 1,196 nm in 2006/07. In BT-option 2 mode, 275 nm of trackline were covered.

To examine search regions of the observers, sightings of all species have been included. To estimate the detection function, only sightings of minke whales (species code 04), 'undetermined minke' (91) and 'like minke' (39) have been used. These are all referred to as minke whales (see table 2 for the numbers in each species code). Only sightings classified as 'definite' duplicates were considered to be duplicates. Table 3 shows the number of minke whale sightings recorded by the different observers.

Measurement error

Angle and distance experiments were performed to assess any bias in the sighting angles and radial distances recorded from the various platforms. Analyses indicated there was only significant bias in a few cases and the recorded angles and distances were corrected using the bias factors shown in Table 4. Neither the BE in 2005/06 nor the IO searching with naked eye in 2006/07 were tested.

Search regions of observers

Search regions are an important consideration in the BT method and ideally the search regions of the two observers should be separated. Examining the angles and radial distances gives an insight into the search regions for the different platforms (Table 5 and Figure 3) although caution must be exercised when interpreting these figures because the distribution of recorded values may not entirely represent the search pattern of observers. In BT-NSP mode, the trackers searching with BE were instructed to search an area no more than 45^o either side the trackline and ahead of the area searched by the primary observers (topman in barrel). The BE observer clearly searched within 45^o of the trackline, although the distribution of sighting angles indicated that they appeared to have concentrated more off to the sides and not so much on the trackline; the majority of sightings were seen between 1 and 7 nm. Although the majority of sightings from the primary observer were seen with a radial distance of 0-4 nm from the vessel, there was considerable overlap between the region being searched by the tracker and the region searched by the primary. There does not appear to have been a separation of search regions between the primary observer and the upper bridge observer, but since all these observers were using 7x50 binoculars this is not surprising even though there was a considerable height difference (8.5m) between the two platforms.

In BT-option 2, the trackers were instructed to focus their searching far ahead of the vessel and up to 60^o either side of the trackline (Anon, 2006). Figure 3 shows that the majority of sightings seen with naked eye (platform code 2: topman in IOP) were within 1.5 nm of the vessel and for the tracker searching with 7x50 binoculars the vast majority of sightings were within 4 nm. Again there is overlap of the search regions but because the radial distances of the primary observer is necessarily limited due to searching with naked eye, the proportion of the tracker region searched by the primary is much less in BT-option 2 than in BT-NSP mode.

Responsive movement

Figure 2 shows the perpendicular distances of duplicate sightings at the time they were initially detected by the tracker and then subsequently by the primary. One needs to be cautious about interpreting responsive movement from 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. Thus, observing more duplicates moving towards, rather than away from, the vessel is not necessarily an indication of attractive movement. However, this information can give an indication of responsive movement, although in this case, Figure 2 does not suggest much, if any, responsive movement.

School size

The distribution of school sizes is shown in Table 6. Errors in school size can have an impact on the abundance estimate. Borchers *et al*. (1998) estimated a correction factor for school sizes recorded by primary observers using the school size estimates from duplicate detections only; in that analysis, trackers were thought to estimate more school size accurately and trackers and primary observers recorded school size independently. In the SOWER surveys the 'best' estimate (usually made by topman in the barrel) is assigned to both records in the duplicate pair thus a correction factor similar to that of Borchers *et al*. (1998) can not be estimated. Dedicated experiments to assess school size error were conducted during the 2006/07 survey but the results from that experiment have not been included in this analysis. However, as noted previously, the search protocol for BT-NSP mode was changed in 2006/07 so that all minke whale sightings made by the BE were approached to obtain more accurate school size estimates and 85% of BE sightings had confirmed school sizes. In this case, nearly half of all animals sighted were either single animals or in groups of two and the maximum school size observed was 40 animals. In 2006/07 the proportion of single animals was lower than in 2005/06.

Detection functions

For analysis of the BT-NSP mode data, two analyses are performed: firstly using only BE sightings as tracker sightings and then, to boost the number of duplicates, both BE and 7x50 sightings were used as tracker sightings.

In 2005/06 BT-NSP mode there were 41 BE sightings of minke whale schools and 42 7x50 sightings; the primary saw 21 and 16 of these sightings, respectively. In 2006/07 BT-NSP mode there were 65 BE sightings and 39 7x50 sightings; the primary saw 31 and 12 of these sightings, respectively. In BT-option 2, there were 101 tracker sightings of minke whales schools and 27 duplicates (Table 3).

All available explanatory variables (to model heterogeneity) were considered for inclusion in the model and Akaike's Information Criterion (AIC, Akaike 1973) was used to choose which variables were included. The explanatory variables considered, in addition to perpendicular distance, were school size, weather code, Beaufort sea state and sightability (a subjective impression of the conditions for spotting whales).

An important consideration during analysis is whether to fit a point or full independence model. If responsive movement is suspected then a full independence model is preferable, otherwise a point independence model is preferable given the strong assumption in the full independence model that detections are independent at all distances. Although Figure 2 does not suggest much, if any, responsive movement both point and full independence models have been fitted. A point independence model requires that both a DS model and an MR model are specified. For the DS model, both hazard and half-normal forms were considered; the hazard rate model was preferable in all cases. The best models, according to AIC and χ^2 goodness of fit tests, were selected. The most important explanatory variable was school size and this was included as either a factor or non-factor variable. Beaufort sea state was also included in two models. The chosen models are given in Table 7 and the detection functions are shown in Figure 5.

Probability of detection on the trackline by the primary observer

Using the point independence model, estimates of probability of detection on the trackline for the primary observer were for BT-NSP mode, 0.69 (%cv=23) using BE only and 0.50 (%cv=18) for both BE and 7x50 sightings in 2005/06; and 0.51 (%cv=21) using BE only and 0.44 (%cv=19) for both BE and 7x50 sightings in 2006/07. For BT-option 2 it was 0.32 (%cv=49). Estimates probability of detection on the trackline for the primary observer from the full independence model were very similar, if slightly lower (and coefficients of variation higher) than estimates from the point independence model.

In Table 7a, two models are given for the 2005/06 BT-NSP BE + 7x50 data: the model given in italics has been included as a comparison to the model fitted to the BE data only; the best model includes school size only in the MR component. Including the 7x50 tracker sightings has decreased the estimated probability of detection on the trackline for the primary observer, substantially so in 2005/06 but less so in 2006/07. This is contrary to expectation since observers searching in the same region as the trackers would tend to increase the probability of detection.

The estimated average probabilities of detection for the primary observer (averaged over all explanatory variables including perpendicular distance) are also given in Table 7 and these are higher for the full independence models than for the point independence models, as would be expected. These average probabilities of detection are determined from the detection function of the primary: in BT-option 2 mode, the detection function of the primary drops off quickly resulting in a very low average probability of detection; in BT-NSP mode the primary detection function drops off more quickly resulting in a higher average probability of detection (Figure 5).

It was recommended that estimates of $g(0)$ from these BT experiments be reported for different school size categories (IWC 2008). The estimates of $g(0)$ for different school sizes on the trackline are found from the MR model only. Therefore, using the MR model with explanatory variables distance and school size, s (as a continuous variable, not a factor), the probability of detection can be estimated using

$$p(x,s) = \frac{\exp\{\beta_0 + \beta_1 x + \beta_2 s\}}{1+\exp\{\beta_0 + \beta_1 x + \beta_2 s\}}.$$

By substituting distance x=0, the probability of detection on the trackline for different school sizes was estimated for the point and full independence models fitted to the 2006/07 BT-NSP BE only data (since the BE had confirmed school sizes) and the BT-option 2 data (Table 8). Using the model fitted to the 2006/07 BT-NSP BE only data where school size was fitted as a continuous variable, the probability of detection on the trackline for solitary animals was 0.46 (%cv=29); for schools of size 5 and 10, the probabilities of detection increased to 0.64 (%cv=21) and 0.82 (%cv=14), respectively (Fig. 6a). Fitting school size as a factor variable, the probability of detecting a solitary animal was 0.29 (%cv=38) and detecting a group of 10 or more animals was 0.90 (%cv=8). The maximum group size recorded in BT-NSP model was 40 animals. Using the model fitted to the 2006/07 BT-option 2 data, the estimated probability of detection on the trackline for solitary animals was 0.14 (%cv=66) (Fig. 6b). The probability increased to 0.70 for animals in groups of two or three (%cv=12 and 18, respectively) and for groups of 4-9 animals, the probability was 0.83 (%cv=26) and for groups of 10 or more animals, the probability was 0.96 (%cv=31). The maximum school size recorded in BT-option 2 mode was 29 animals.

DISCUSSION AND CONCLUSIONS

One of the primary aims for performing the BT mode experiments was to obtain an estimate of the probability of detection on the trackline for the Topman in the barrel and the Topman in the IOP which would help in understanding the minke whale abundance estimates obtained from the IWC-SOWER survey data. It was found to be infeasible to implement BT-IO mode and so an estimate for the Topman in the IOP searching as per standard SOWER protocol could not be obtained. The probability of detection on the trackline for the Topman in the barrel ranged from 0.39 (%cv=32) to 0.69 (%cv=23) depending on model fitted. The highest probability of detection occurred with the 2005/06 data using only the BE sightings and it is not clear why these estimates should be so different from the other estimates.

To highlight the importance of school size on detectability, the probability of detection on the trackline for different school sizes was estimated. Using the 2006/07 BE only data, for which there were confirmed school sizes, detection on the trackline for solitary animals was 0.46 (%cv=27) fitting school size as a continuous variable model and 0.29 (%cv=38) fitting school size as a factor variable. As expected, detection increased with school size.

In an MRDS analysis, the type of model is an important consideration and deciding between the full and independence model is not straightforward unless there is clear evidence that animals are moving in response to the survey vessel. Although the point independence model is preferable to the full independence model because of the strong assumptions of the full independence model, the point independence model is not tenable if there is responsive movement. Figure 2 does not suggest much, if any, responsive movement. However, the differences in the shape of the BT-NSP detection function for the primary observer (indicated by the histogram of perpendicular distances – left hand column in Figure 5) and the fitted MR model (right hand column) is typical of a) increasing unmodelled heterogeneity with increasing distance and /or b) attractive movement between the tracker and the primary. The unmodelled heterogeneity may occur because the primary and trackers were searching the same region. This lack of separation of search regions may be due in part to the good weather that was experienced, particularly in 2005/06, but also the location of the BE which were considerably lower than the primary platform. The effects of unmodelled heterogeneity can be alleviated by separating the search regions of the observers. The BT-option 2 configuration enforces a clearer separation of search regions and the similarity of the DS plot and the MR plot for this data indicates that the effects of any unmodelled heterogeneity has been reduced.

It was important that the observers designated as ‘primary’ searched using the standard SOWER methodology and hence they used 7x50 binoculars. In order to achieve a separation of search regions between the tracker and primary observers, trackers used BE assisted by observers using 7x50 binoculars. The BE used in 2006/07 were better quality than those used previously, however, the search profiles of the observers suggested that in practise it was difficult to achieve a separation of search regions when all observers were using binoculars.

The BT mode has provided an estimate of probability of detection on the trackline for the topman in the barrel. The analysis does not give an indication of the probability of detection on the trackline for the other platforms which are also used during the standard SOWER search protocols. For previous conventional DS estimates of minke whale abundance, the probability of detection on the trackline for all platforms combined was assumed to be one (Branch and Butterworth, 2001). An analysis of duplicate sightings recorded on previous SOWER cruises may provide an insight into the probabilities of detection on the trackline for other platforms.

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REFERENCES

Akaike, H. (1973) Information theory and an extension of the maximum likelihood principle. In *International Symposium on Information Theory* 2nd edition (eds Petran BN and Csàaki), Akadèemiai Kiadi, Budapest, Hungary, pp267-81

Anon (2006) *IWC SOWER cruise 2006/07 Information for researchers*. Available from the IWC Secretariat, Cambridge, UK

Borchers, D.L., Buckland, S.T., Goedhart, P.W., Clarke, E.D. and Hedley, S.L. (1998) Horvitz-Thompson estimators for double-platform line transect surveys. *Biometrics* 54: 1221-1237

Borchers, D.L., Laake, J.L., Southwell, C. and Paxton, C.G.M. (2006) Accommodating unmodelled heterogeneity in double-observer distance sampling surveys. *Biometrics* 62: 372-378

Branch, T.A. and Butterworth, D.S. (2001) Southern hemisphere minke whales: standardised abundance estimates from the 1978/79 to 1997/98 IDCR-SOWER surveys. *Journal of Cetacean Research Management* 3(2): 143-174.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. and Thomas, T. (2001) *Introduction to Distance Sampling*. Oxford University Press, Oxford

Cañadas, A., Desportes, G. and Borchers, D.L. (2004) The estimation of the detection function and *g*(0) for short-beaked common dolphins (*Delphinis delphis*), using double-platform data collected during the NASS-95 Faroese survey. *Journal of Cetacean Research and Management* 6: 191-198.

Ensor, P., Komiya, H., Beasley, I., Kukutome, K., Olsen, P. and Tsuda, Y. (2007) 2006-2007 International Whaling Commission-Southern Ocean Whale and Ecosystem Research (IWC-SOWER) cruise. Unpublished. Presented to the IWC SC meeting, Anchorage, document SC/59/IA1.

Ensor, P., Komiya, H., Olsen, P., Sekiguchi, K. and Stafford, K. (2006) 2005-2006 International Whaling Commission-Southern Ocean Whale and Ecosystem Research (IWC-SOWER) cruise. Unpublished. Presented to the IWC SC meeting, St Kitts, document SC/58/IA1.

IWC (2008) Report of the SOWER Abundance Workshop. Seattle May 2008.

Laake, J.L. and Borchers, D.L. (2004) Methods for incomplete detection at distance zero. In Buckland, S.T., Anderson D.R., Burnham, K.P, Laake, J.L., Borchers, D.L. and Thomas, L. (eds) *Advanced Distance Sampling*. Oxford University Press, Oxford.

Table 1 Platform configuration for the different search modes; a) standard SOWER modes and b) BT modes. Platform height is in metres above sea level.

a) Standard SOWER modes

Trial	Observer code	Platform description	Binocular type	Platform height (masl)	No. of observers on platform
Closing/NSPmode	1	Topman in barrel	7x50	19.0	2
	3	Upper bridge, main observer	7x50	10.5	2
	4	Upper bridge, secondary observer	7x50	10.5	2
IO mode	1	Topman in barrel	7x50	19.0	2
	2	Topman in IOP	7x50	14	1
	3	Upper bridge, main observer	7x50	10.5	2
	4	Upper bridge, secondary observer	7x50	10.5	2

b) BT mode

Trial	Observer code	Platform description	BT configuration	Binocular type	Platform height (masl)	No. of observers on platform
BT-IO mode	1	Topman in barrel	Primary	7x50	19.0	2
	2	Topman in IOP	Primary	7x50	14	1
	3	Upper bridge, main observer	Tracker (assistant)	7x50	10.5	2
	4	Upper bridge, secondary observer	Tracker (assistant)	7x50	10.5	2
	BE	Upper bridge	Tracker	x25 Big eyes	10.5	1
BT-NSPmode	1	Topman in barrel	Primary	7x50	19.0	2
	3	Upper bridge, main observer	Tracker (assistant)	7x50	10.5	2
	4	Upper bridge, secondary observer	Tracker (assistant)	7x50	10.5	2
	BE	Upper bridge	Tracker	x25 Big eyes	10.5	1
BT-option 2	1	Topman in barrel	Tracker	7x50	19.0	2
	2	Topman in IOP	Primary	Naked eye	14.0	2

Table 2 Search effort and numbers of minke whale schools sighted (by all observers and including duplicates) in BT mode.

Survey	Search mode	Effort (nm)	Numbers of schools			
			Minke	Undetermined minke	Like minke	Total
2005/06	BT-IO	127.4	22	8		30
	BT-NSP	1 385.3	300	12	17	325
2006/07	BT-NSP	1 195.9	255	43	34	332
	BT-option 2	275.4	118	21	23	162

Table 3 Number of minke schools sighted by each platform and number of duplicates. The duplicate columns are denoted by Tracker:Primary.

Survey	Search mode	Platform				Number of duplicates between platforms				
		1	2	3 + 4	BE	3+4:1	BE:1	BE:2	3+4:2	1:2
2005/06	BT-IO	13	11	2	4	1	2	2	1	
	BT-NSP	242		42	41	16	21			
2006/07	BT-NSP	228		39	65	12	31			
	BT-option 2	101	61							27

Table 4 Bias correction factors for each platform. A dash indicates no correction was necessary.

Survey	Platform	Number of trials	Angle bias factor	Distance bias factor
2005/06	1: Topman in barrel	42	-	1.047
	2: Topman in IOP	42	-	-
	3+4: Upper bridge	48	-	1.059
2006/07	1: Topman in barrel	36	0.944	-
	2: Topman in IOP	30	-	-
	3+4: Upper bridge	30	-	1.059
	BE: Upper bridge	12	-	1.137

Table 5 Search effort for each BT mode and the number of sightings (all species) and mean and maximum radial distances and estimated sighting angles for each platform. Standard deviations are given in parentheses.

Survey	Search mode	BT configuration	Platform	Number	Radial distance (nm)		Sighting angle (degrees)	
					Mean	Maximum	Mean	Maximum
2005/06	BT-NSP and BT-IO	Tracker	Upper bridge, BE	72	3.50 (1.9)	7.5	22.0 (12.2)	46
		Tracker (assistant)	Upper bridge	62	2.40 (2.0)	7.2	25.1 (24.1)	90
		Primary	Barrel	334	2.24 (1.7)	7.9	28.4 (20.7)	90
		Primary	IOP	13	2.11 (1.7)	6.5	37.4 (17.9)	70
2006/07	BT-NSP	Tracker	Upper bridge, BE	93	3.22 (1.7)	6.6	18.4 (12.0)	46
		Tracker (assistant)	Upper bridge	49	1.65 (1.2)	6.6	26.4 (19.5)	80
		Primary	Barrel	297	2.24 (1.4)	8.2	28.8 (21.9)	94
	BT option 2	Tracker	Barrel	106	2.26 (1.3)	6.5	22.1 (17.6)	74
		Primary	IOP	66	0.75 (0.6)	3.0	37.1 (27.4)	90

Table 6 Numbers of minke whale sightings seen by each platform and school size. Duplicates sightings are indicated by platform codes Tracker:Primary. The numbers in parentheses in b) are the numbers of schools with confirmed school sizes.

a) 2005/06

School size	BT-NSP mode			Duplicates	
	Tracker		Primary	BE:1	3+4:1
	BE: Upper bridge	3+4: Upper bridge	1: Topman in barrel		
1	17	21	98	6	6
2	8	11	57	3	5
3	8	6	42	6	3
4	3	1	12	3	
5	3		12	2	
6-9	1	2	14	1	1
≥10	1	1	7		1
All	41	42	242	21	16

b) 2006/07

School size	BT-NSP mode			BT option 2		
	Tracker	Primary	Duplicates BE:1	Tracker	Primary	Duplicates 1:2
	BE: Upper bridge	1: Topman in barrel		1: Topman in barrel	2: Topman in IOP	
1	15 (10)	80	3	36	19	2
2	15 (14)	56	6	22	14	8
3	8 (8)	34	4	19	14	9
4	8 (6)	22	6	2	3	
5	9 (7)	14	4	4	3	2
6-9	6 (6)	11	5	5	3	2
≥10	4 (2)	11	3	13	5	4
All	65 (55)	228	31	101	61	27

Table 7 Summary of a) point independence models and b) full independence models. The parameter $\hat{p}(0)$ is the estimate of the average probability of detection on the trackline for the primary observer. 'Average *p*' refers to the average probability of detection averaged over all explanatory variables. The variables are perpendicular distance (D), school size (S) and Beaufort sea state (B); the subscripts indicate the variable has been included as a factor variable and indicate the number of factor levels. Percentage coefficients are given in parentheses.

a) Point independence models

Survey	Search mode	Primary observer	Tracker	DS model	MR model	$\hat{p}(0)$	Average *p*
2005/06	BT-NSP	1: Topman in barrel	BE	$D + S_4 + B_3$	$D + S_4 + B_3$	0.688 (22.7)	0.166 (24.2)
			BE + 7x50	$D + S_4 + B_3$	$D + S_4 + B_3$	0.480 (19.7)	0.116 (21.4)
			BE + 7x50	$D + S_4 + B_3$	$D + S_4$	0.505 (17.6)	0.122 (19.4)
2006/07	BT-NSP	1: Topman in barrel	BE	D + S	D + S	0.509 (21.4)	0.172 (22.9)
			BE + 7x50	D + S	D + S	0.437 (18.5)	0.148 (20.2)
	BT-option 2	2: Topman in IOP	1: Topman in barrel	D	$D + S_5$	0.317 (48.6)	0.029 (51.4)

b) Full independence models

Survey	Search mode	Primary observer	Tracker	DS model	MR model	$\hat{p}(0)$	Average *p*
2005/06	BT-NSP	1: Topman in barrel	BE	-	$D + S_4 + B_3$	0.661 (29.7)	0.231 (29.6)
			BE + 7x50	-	$D + S_4 + B_3$	0.479 (30.2)	0.255 (30.0)
2006/07	BT-NSP	1: Topman in barrel	BE	-	$D + S_6$	0.430 (40.9)	0.231 (40.8)
			BE + 7x50	-	$D + S_6$	0.390 (32.2)	0.240 (32.0)
	BT-option 2	2: Topman in IOP	1: Topman in barrel	-	$D + S_5$	0.253 (59.0)	0.082 (58.3)

Table 8 Probability of detection on the trackline by school size fitted to 2006/07 BT-NSP BE only data and BT-option 2 data. In the full independence model fitted to BT-NSP BE data and the model fitted to the BT-option 2 data school size has been fitted as a factor variable.

School size	BT-NSP BE only		BT-option 2
	Point independence	Full independence	
1	0.460 (28.5)	0.293 (38.4)	0.139 (64.7)
2	0.506 (25.6)	0.609 (21.1)	0.699 (11.8)
3	0.552 (23.8)	0.660 (29.1)	0.696 (17.9)
4	0.597 (22.6)	0.925 (9.39)	0.833 (25.8)
5	0.641 (21.4)	0.772 (20.7)	
6	0.682 (20.0)		
7	0.721 (18.3)		
8	0.757 (16.7)		
9	0.789 (15.2)		
10	0.818 (13.7)	0.900 (7.72)	0.957 (30.6)
20	0.966 (5.36)		

Fig. 1. Plot of search effort during the minke whale research component. 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 dashed grey line at the bottom of the plot indicates the coast of Antarctica.

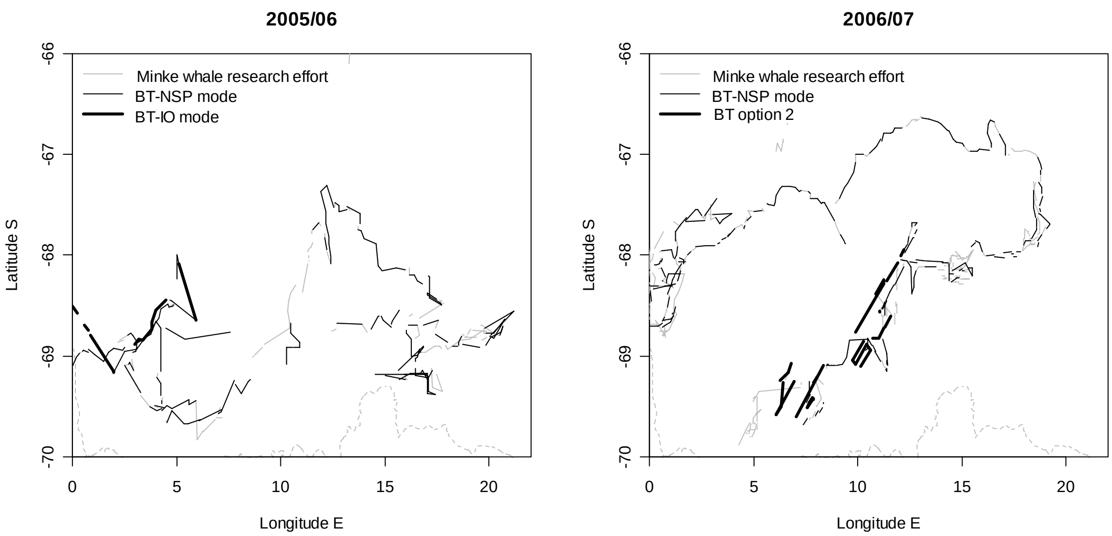


Fig. 2. Perpendicular distances of duplicates at the time they were detected initially by the tracker (*y*-axis) and then by the primary (*x*-axis). The dotted diagonal line corresponds to no movement. Points below the line correspond to movement away from the transect line, while those above correspond to movement towards it. In the BT-NSP mode plots, circles indicate duplicates between the trackers using BE and the primary; triangles indicate duplicates between the assistant trackers (using 7x50 binoculars) and the primary.

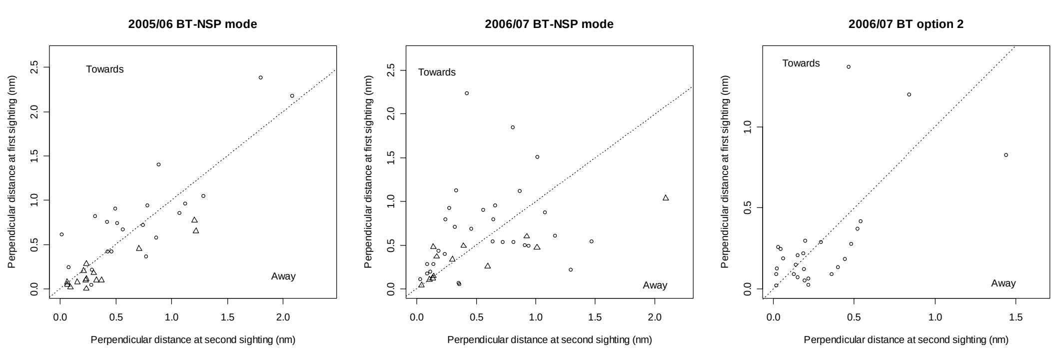
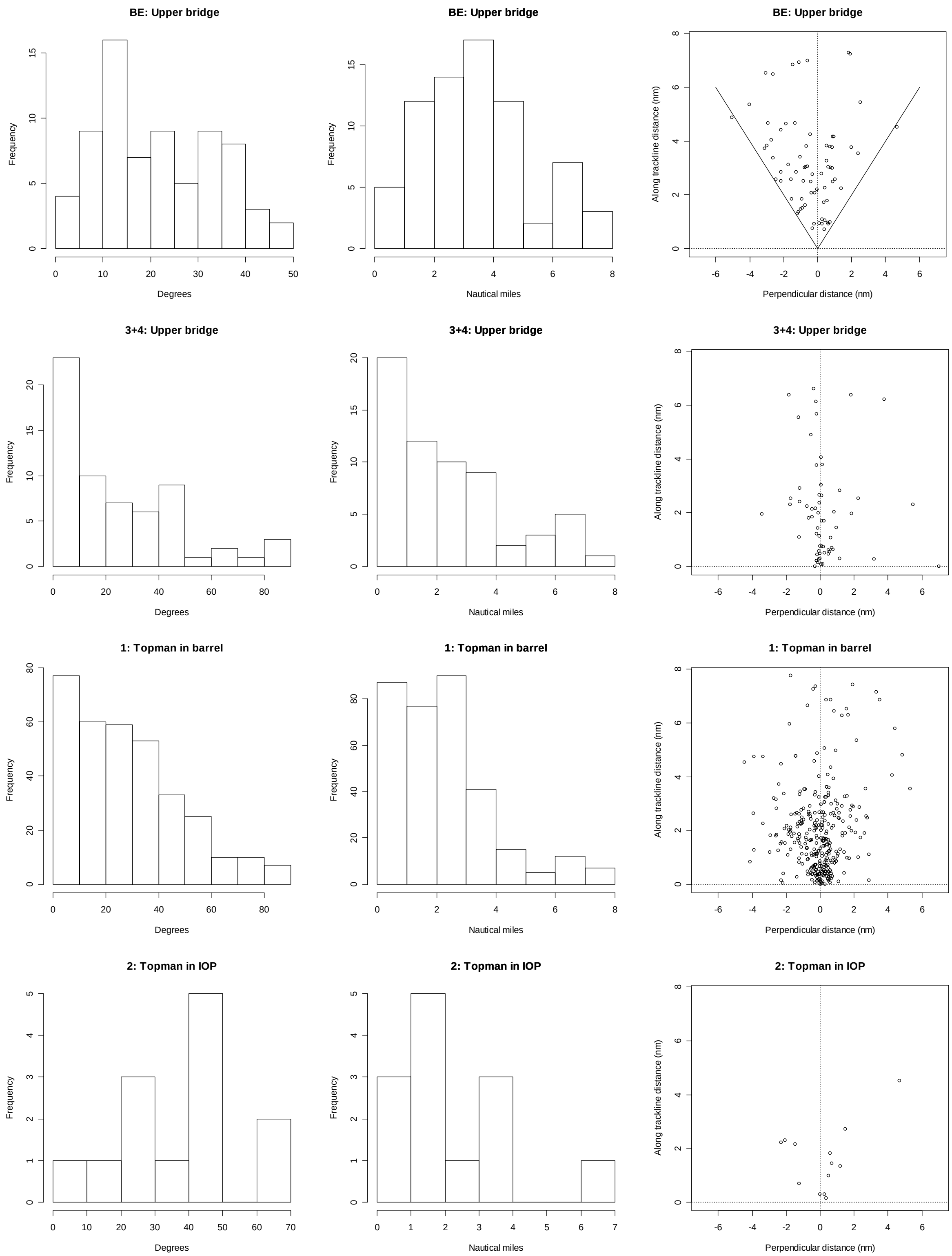
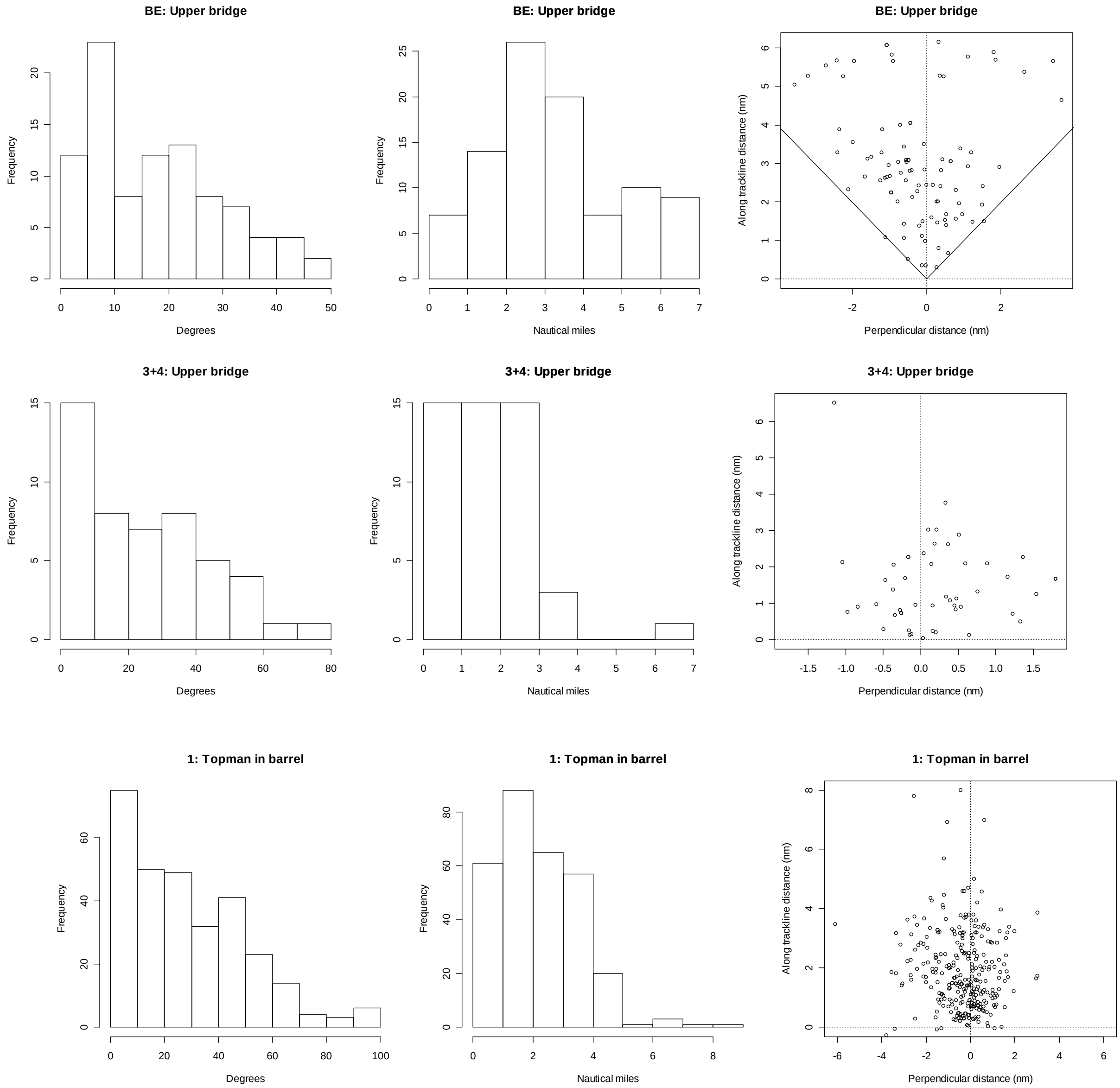


Fig. 3. Distributions of the sighting angles (left column of plots), radial distances (middle column) and locations (right column) for all sightings from all the platforms used in BT mode. The location plots show the position all sightings relative to the vessel at (0, 0); the lines on the plots for the BE indicates 45^{o} either side of the trackline for BT-NSP mode (plots a and b) and 60^{o} for BT-option 2 (plot c).

a) 2005/06 BT-NSP and BT-IO



b) 2006/07 BT-NSP



c) 2006/07 BT-option 2

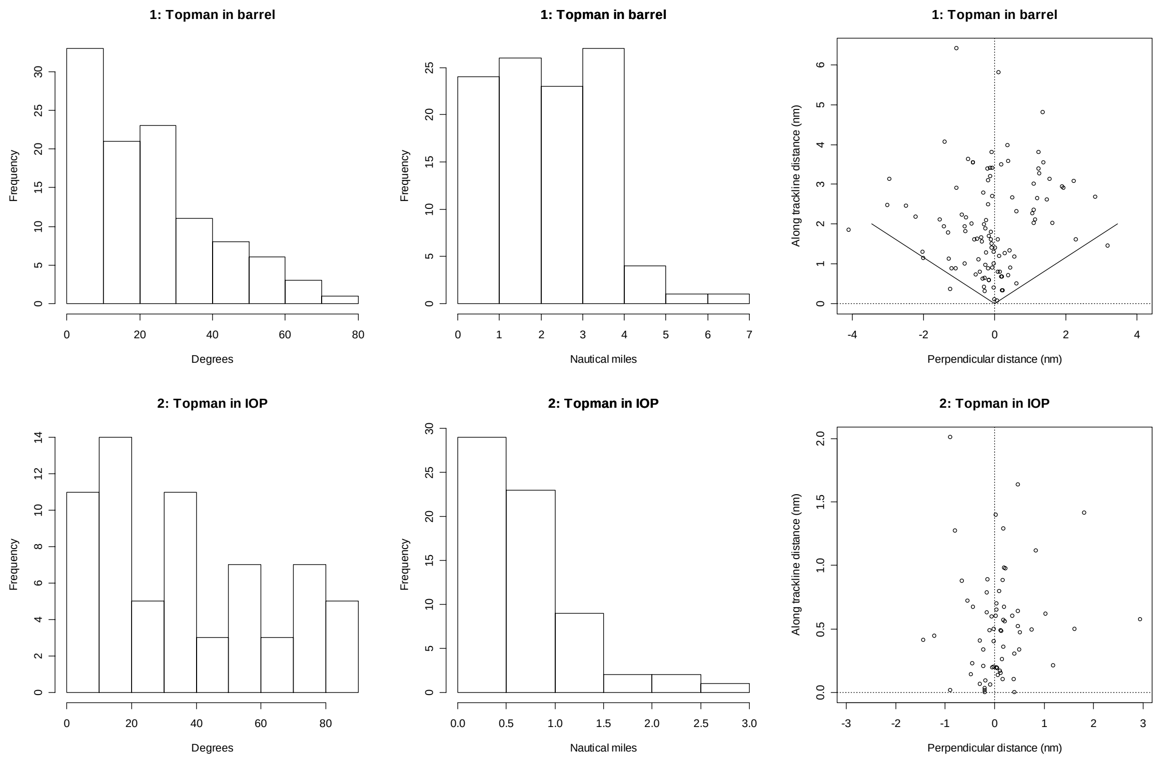
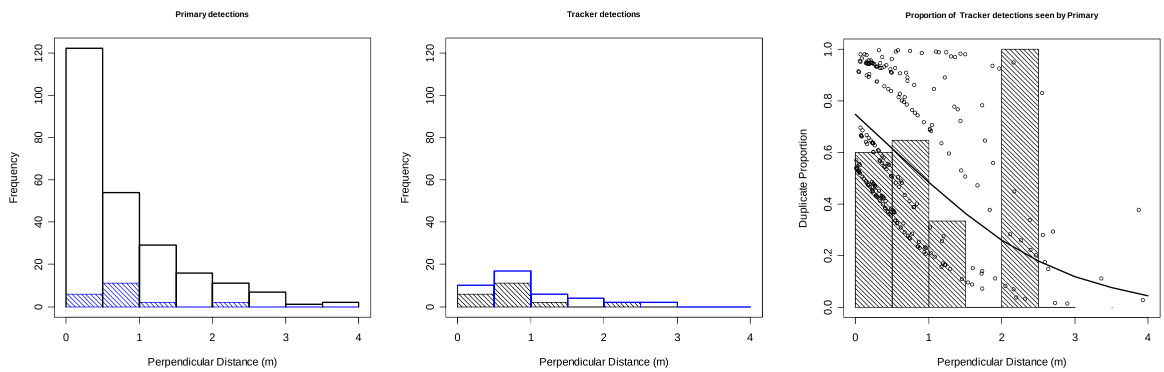


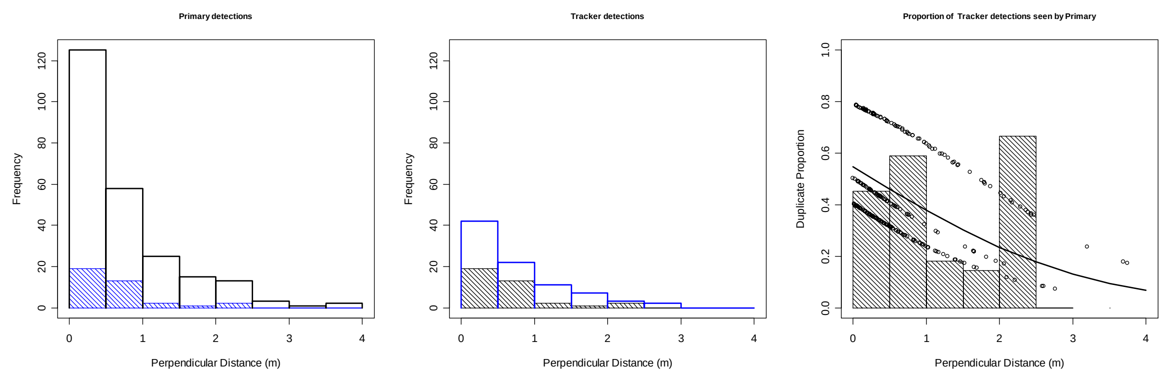
Fig. 5. Distribution of the perpendicular distances for the a) primary and b) tracker observers. The shaded regions indicate the number of the duplicates. Plot c) shows the proportion of duplicates to tracker sightings and the fitted MR model (point independence model). The points are the estimated probability of detection for each observation (given its perpendicular distance and other explanatory variables). Distances are in nautical miles and have not been truncated.

a) b) c)

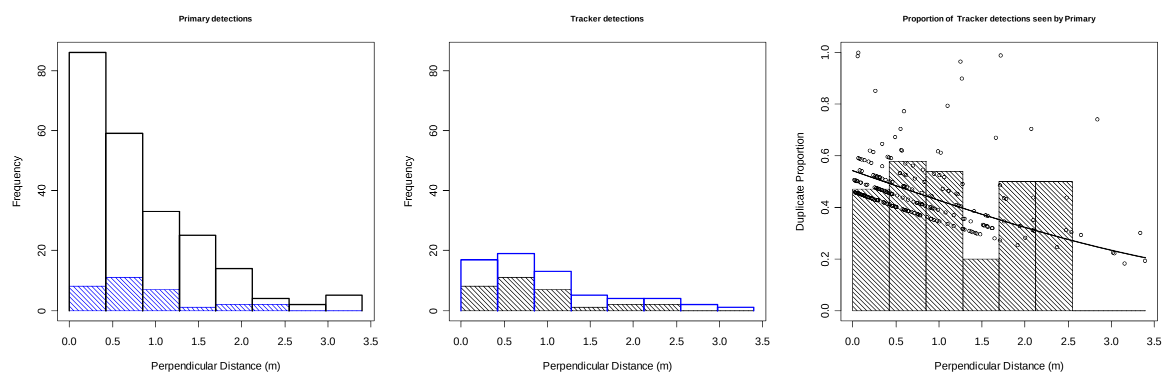
2005/06 BT-NSP BE only used as tracker sightings



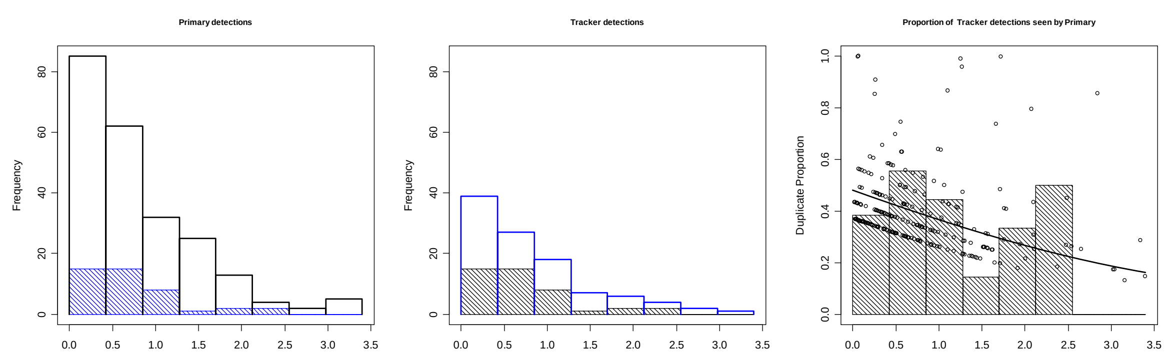
2005/06 BT-NSP Both BE and 7x50 used as tracker sightings



2006/07 BT-NSP BE only used as tracker sightings



2006/07 BT-NSP BE and 7x50 used as tracker sightings



2006/07 BT-option 2

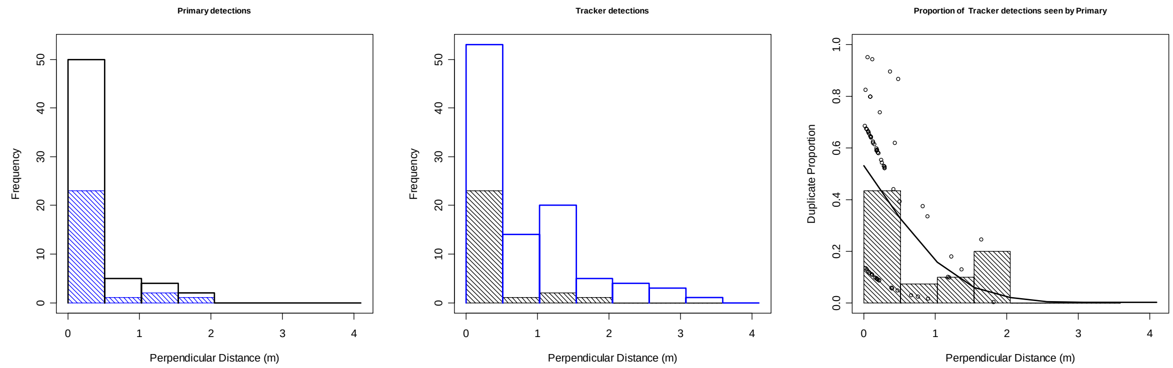
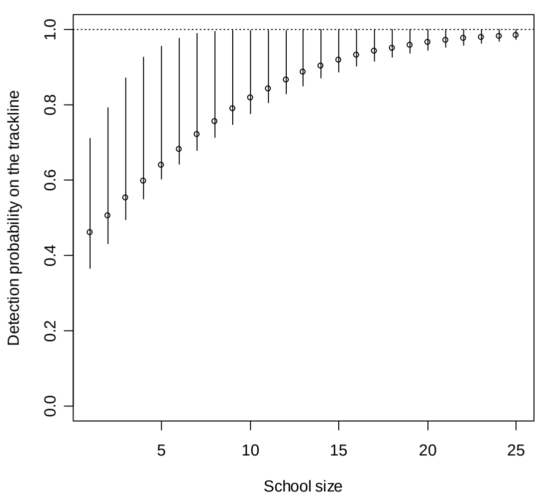
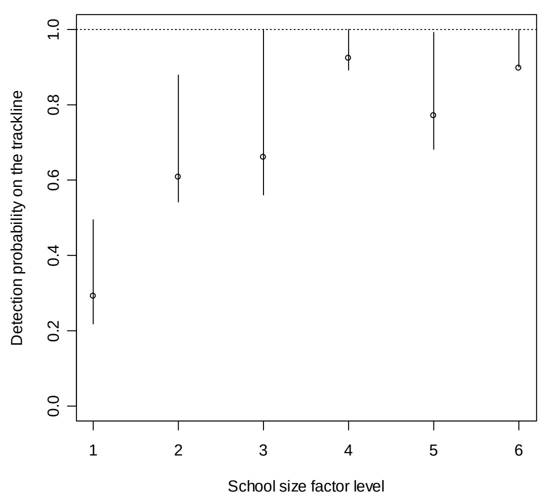


Fig. 6. Probability of detection on the trackline for different school sizes using the MR model fitted to the 2006/07 data: a) BT-NSP data using BE sightings only, point independence model; b) BT-NSP data using BE only, full independence model and c) BT-option 2. The lines are the 95% ‘percentile’ confidence limits. In b) the six factor levels relate to school sizes of 1, 2, 3, 4, 5-9 and ≥10 animals; in c) the five factor levels relate to school sizes of 1, 2, 3, 4-9 and ≥10 animals.

a) BT-NSP BE only, point independence model



b) BT-NSP BE only, full independence model



c) BT-option 2