Trackline detection probability of Antarctic minke whales: analyses of the BT mode experiments conducted on the IWC-SOWER cruises 2005/06–2007/08

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ABSTRACT

IWC sightings surveys to obtain abundance estimates of cetaceans have taken place in the Antarctic since 1978/79. In order to interpret the minke whale abundance from these surveys and trial different search protocols for future cruises, Buckland-Turnock (BT) search mode experiments were conducted during the IWC-SOWER 2005/06, 2006/07 and 2007/08 cruises. BT search mode is a particular configuration of a double-observer survey and two configurations of BT mode were implemented on the SOWER cruises; BT-NSP mode and BT-option 2. Normal standard passing (NSP) mode is a standard search mode for SOWER vessels and in BT-NSP mode, the observer located on the barrel became the primary and searched as usual in NSP mode with 7×50 binoculars; the observers on the upper bridge became the tracker and used big eye binoculars mounted on the upper bridge. Thus, the probability of detection for the observer in the barrel can be estimated which can help inform interpretations of abundance estimates of SOWER data. For BT-NSP mode, the estimates of detection probability on the trackline for the observer in the barrel ranged between 0.35 (CV = 0.57) to 0.69 (CV = 0.23) for the different years and combinations of data and models. In BT-option 2, the observer on the barrel (searching with 7×50 binoculars) acted as tracker and the observer on the independent observer (IO) platform acted as the primary (searching with naked eye). For this configuration, the estimates of primary detection probability on the trackline were 0.25 (CV = 0.59) and 0.28 (CV = 0.50) for two different models.

KEYWORDS: SOUTHERN HEMISPHERE, SURVEY-VESSEL, SOWER, MINKE WHALE, g(0), MARK-RECAPTURE

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 Antarctic minke whale (*Balaenoptera bonaerensis*) abundance between CPII and CPIII (Branch and Butterworth, 2001). Two key assumptions of conventional distance sampling (DS) 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. To ensure these assumptions were valid on the standard Southern Ocean Whale and Ecosystem Research (SOWER) cruises, observers searched with 7×50 binoculars and there were observers searching from either two or three different platforms on the ship depending on the choice of selected survey mode. In conventional DS analyses of the SOWER data (Branch and Butterworth, 2001), sightings from all platforms were combined and treated as though they were made from a single platform. Despite these measures, differences in cetacean cue size and behaviour may still have resulted in DS assumptions being violated. It has been suggested that estimates of $g(0)$ from standard SOWER search modes may be positively biased because, although observers were acting independently, they tended to search the same area of the sea and the resulting dependence of detection probability on unmodelled variables can induce correlation in the detection probabilities (IWC, 2006). Methodology which combines both mark-recapture and distance sampling (MRDS) overcomes these difficulties (see Laake and Borchers, 2004, for an overview) and, in particular, MRDS methods allow the probability of detection on the trackline to be estimated, rather than assuming $g(0)$ is one.

A series of experiments using MRDS methods were conducted on the 2005/06, 2006/07 and 2007/08 IWC SOWER cruises in order to:

(a) help interpret abundance estimates obtained from previous analyses of data from SOWER cruises by providing independent estimates of detection probability on the trackline; and

(b) assess alternative search protocols that could be used on future cruises.

The particular implementation used on the SOWER vessels was the Buckland Turnock (BT) survey method (Buckland and Turnock, 1992). In BT mode, observers are generally located on two separate platforms and act as either 'tracker' or 'primary' observers. The tracker scans 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 searching closer to the vessel and if the primary subsequently detects the same group as the tracker, this is termed a duplicate sighting. With this setup, duplicates can only occur if the tracker sees the animal first because the tracker is generally aware of any sightings made by the primary.

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Sightings made by the tracker thus serve to set up binary trials for observations made by the primary (the outcome of each trial is either 'seen' or 'not seen' by the primary). Analysis of these trials and duplicate sightings allows the probability of an animal being detected by the primary to be estimated. Provided that the tracker searches sufficiently far ahead of the vessel that animals have not responded to the vessel by the time they are detected by the tracker, this survey method can implicitly incorporate the effect of responsive animal movement in the estimation of detection probability using appropriate analysis options.

BT MODE IMPLEMENTATION ON SOWER VESSELS

Standard SOWER search modes

Prior to 2005/06, minke whale research was conducted on the SOWER vessels using two principal search modes; closing mode and passing with independent observer (IO) mode (Table 1a). In closing mode, observers were located on the barrel (19m above sea level) and upper bridge (10.5masl) and sightings were approached in order to determine species and school size more accurately. In IO mode, observers were located on the barrel, upper bridge and the independent observer platform (IOP; 14masl) and the vessel did not deviate from the trackline. Normal standard passing (NSP) mode was identical to IO mode except that the independent observer was not in place. All observers searched with handheld 7×50 binoculars and, as a consequence, there was no separation of search areas. Comparing the number of detections made by each platform, Table 2 indicates that during closing mode, the barrel and the upper bridge each contributed approximately 50% of sightings. In NSP mode, the barrel contributed over 50% of sightings and the upper bridge only 25% of sightings. During IO mode, when there are three main platforms in operation, the observers in the barrel contributed approximately 45% of sightings with the upper bridge and IOP contributing to the remaining 65% of sightings more or less equally (Table 2).

BT mode searching

In 2005/06, the BT mode experiment was conducted in both NSP and IO modes (Table 1b). In BT-NSP mode, the observers in the barrel acted as usual in NSP mode (i.e. searching with 7×50 binoculars) but were considered to be the primary observers. One observer on the upper bridge acted as the tracker and, to achieve a separation of search areas, used higher powered (×25) big eye binoculars (BE). 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). The other upper bridge observers assisted with tracking and duplicate identification. In BT-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 a detection probability for both 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 and so the majority of the BT mode experiment was conducted in BT-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 previously and so could be used in a greater range of weather conditions (Ensor *et al.*, 2007). The protocol 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.

A trial of BT-option 2 was carried out in 2006/07 and this involved a different platform configuration to that of BT-NSP. In BT-option 2, observers in the barrel acted as trackers

Table 1

Platform configuration for the different search modes: (a) standard SOWER modes with all observers using 7x50 binoculars; and (b) BT modes. Although there were always five observers on the upper bridge, the level of search effort was variable as data recording, tracking and assessment of duplicate status was also undertaken from this platform.

Trial	Platform	Number of observers on platform
(a) Standard SOWER modes		
Closing/NSP mode	Barrel	2
	Upper bridge	5
IO mode	Barrel	2
	IOP	1
	Upper bridge	5

Trial	Years implemented	Platform	BT configuration	Binocular type	Number of observers on platform
(b) BT mode					
BT-IO	2005/06	Barrel	Primary	7×50	2
		IOP	Primary	7×50	1
		Upper bridge	Tracker	×25 Big eyes	1
		Upper bridge	Tracking assistance	7×50	5
BT-NSP	2005/06	Barrel	Primary	7×50	2
	2006/07	Upper bridge	Tracker	×25 Big eyes	1
		Upper bridge	Tracking assistance	7×50	5
BT-option 2	2006/07	Barrel	Tracker	7×50	2
	2007/08	IOP	Primary	Naked eye	2

Table 2
Percentage of sightings recorded by each platform during full search modes from SOWER surveys 1985/86–2004/05.

Platform	Closing mode		IO mode		NSP mode		All search modes	
	All species	Minke	All species	Minke	All species	Minke	All species	Minke
Barrel	49	48	45	44	56	56	47	47
IO	–	–	28	27	–	–	17	16
Upper bridge	46	46	25	27	25	24	32	32
Other	5	6	2	2	19	20	4	5

and searched with 7×50 binoculars. The primary observers were located on the IOP and searched with naked eye. The upper bridge observers assisted with tracking and duplicate identification. BT-option 2 was implemented as a standard search mode for the second half of the 2007/08 cruise to evaluate its utility as a potential replacement for IO mode, which was becoming increasingly problematic due to higher sightings rates of humpback whales in some regions in the Antarctic, and also a detection probability for the IOP could be estimated using mark-recapture methods.

The 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. The estimation of the intercept of the detection function for the primary observer given the tracker detections is then a binary regression problem with explanatory variables y_i and $\underline{z}_i$ for the ith detection ($i = 1,...,n$), where y_i is perpendicular distance, $\underline{z}_i$ is a vector of other explanatory variables associated with the ith detection and n is the number of tracker detections. The detections by the tracker serve as a set of binary trials in which success corresponds to detection by the primary. The probability that a group i at perpendicular distance y_i and with other explanatory variables $\underline{z}_i$ is detected by the primary, denoted by $p_1(y_i,\underline{z}_i)$, is modelled as a logistic function;

$$p_1(y_i,\underline{z}_i)=\frac{\exp\left\{\beta_0+\beta_1 y_i+\sum_{j=1}^{J}\beta_{j+1}z_{ij}\right\}}{1+\exp\left\{\beta_0+\beta_1 y_i+\sum_{j=1}^{J}\beta_{j+1}z_{ij}\right\}} \quad (1)$$

where $\underline{\beta} = (\beta_0,\ldots,\beta_{J+1})$ is a vector of parameters to be estimated. Setting $y = 0$ will provide an estimate of the detection function intercept for other variable values. We use Equation 6.51of Laake and Borchers (2004) to estimate overall detection probability at perpendicular distance zero: $\hat{p}_1(0) = \hat{E}_{\underline{Z}}[\hat{p}_1(0,\underline{z})]$. We refer to this as the mark-recapture (MR) model.

With the BT-NSP configuration, an estimate of the detection probability for the observers in the barrel can be obtained and since the primary observers were acting in BT-NSP mode as they would in standard SOWER search modes, this will provide insight into the detection probability (and abundance) estimates obtained from SOWER data. BT-option 2, will provide an estimate of detection probability for the observers in the IOP searching with naked eye. However, since this is not a standard SOWER survey protocol, it will not help with interpretation of past estimates.

The explanatory variables considered for inclusion in the models, in addition to perpendicular distance, were school size, weather code, Beaufort sea state and sightability (a subjective impression of the conditions for spotting whales). Akaike's Information Criterion (AIC, Akaike, 1973) and χ^2 goodness of fit tests were used to choose which variables were included. School size was included as both recorded school size (and treated as a non-factor variable) and as a factor variable with large sizes grouped together.

Of particular interest in the analyses of SOWER data was the detectability of single animals compared to animals in groups of two or more. To investigate this, an additional factor variable was created which indicated whether the school size was one or more than one. Estimates of the detection probability for these groups sizes were easily obtained by incorporating school size into the MR model, for example:

$$p_1(y_i,sf_i)=\frac{\exp(\beta_0+\beta_1 y_i+\beta_2 sf_i)}{1+\exp(\beta_0+\beta_1 y_i+\beta_2 sf_i)} \quad (2)$$

where sf_i is school size for group i (here used as a factor with two levels to represent school sizes of 1 and ≥2). By substituting distance $y = 0$, the probability of detection on the trackline for different school sizes can be estimated. After preliminary results were obtained, additional analyses were performed which included recorded school size and Beaufort sea state into the model as explanatory variables (see later).

Independence of detections

The binary regression method outlined above is based on the assumption that detections by the primary observers were independent of those by the tracker. It is referred to as a 'full independence' model here. Although the primary observers act independently of the trackers, the detection probabilities can still be correlated, for example because they both preferentially see large schools. While school size (and all other recorded variables thought to affect detection) can be incorporated into the model via the vector $\underline{z}$, dependence of detection probability on unmodelled variables can still induce correlation in detection probabilities (termed unmodelled heterogeneity). Innes *et al.* (2002), Laake and Borchers (2004) and Borchers *et al.* (2006) developed estimators based on the assumption that detections were independent at zero perpendicular distance only (called a point independence model). This estimator is more robust to violation of the assumption of no unmodelled heterogeneity than a full independence model which assumes that detections are independent at all distances. The point

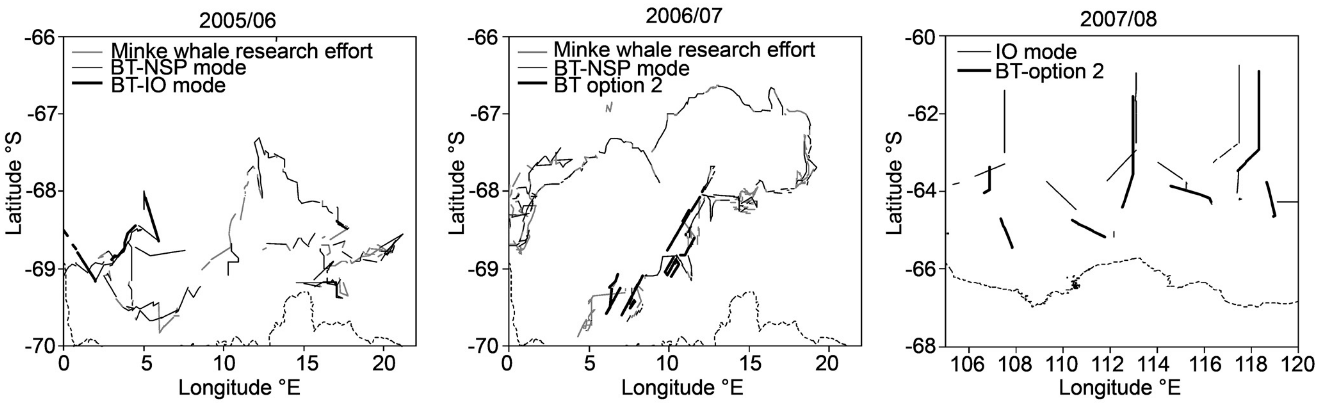

Fig. 1. Plot of search effort in BT mode during 2005/06, 2006/07 and 2007/08. During 2005/06 and 2006/07 research was conducted in the vicinity of the ice-edge which changed substantially during the duration of the cruises; an approximate position of the ice-edge is indicated by the tracklines. The dashed grey line at the bottom of the plots indicates the coast of Antarctica.

independence model uses the shape of the DS detection function (with intercept equal to 1) that incorporates perpendicular distance as well as other covariates, together with the intercept of the MR model (Eqn. 1) to model detection probability. To fit the DS detection function, both hazard rate and half normal forms were considered with AIC used to choose between models. A full independence model uses the MR model to estimate both the intercept and the shape of the detection function.

When animals move in response to the vessel between detection by the tracker and detection by the primary, this affects the shape of the observed perpendicular distance distribution and the effects of unmodelled heterogeneity and responsive movement cannot be separated (Borchers *et al.*, 2006; Cañadas *et al.*, 2004). Therefore, if animal movement is anticipated, the point independence model may be unreliable and a full independence model may be preferable.

Full independence and point independence models both assume independence at distance zero and both models will give the same estimates of detection probability conditional on $\underline{z}$ if both use the same functional forms and explanatory variables. Differences in estimates of mean detection probability at distance zero, not conditional on $\underline{z}$, arise because the two models lead to different estimates of the probability distribution of $\underline{z}$ in the population and estimating the unconditional mean detection probability at distance zero involves estimating the expectation of the conditional probability over $\underline{z}$. Full independence and point independence models will, in general, give different estimates of density, abundance and mean detection probability over all perpendicular distances. We estimate mean detection probability in this paper using both full and point independence using Equation 6.50 from Laake and Borchers (2004).

RESULTS

Search effort

In order to maximise the sighting rate (and hence the number of duplicate detections) in 2005/06 and 2006/07, the BT-NSP 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 (Fig. 1; Ensor *et al.*, 2007). In 2007/08, when BT-option 2 was implemented as a standard method, a pre-defined cruise track covering the southern stratum was used. In BT-NSP mode, 1,385n.miles of trackline were covered in 2005/06 and 1,196 n.miles in 2006/07. In BT-option 2 mode, 275 n.miles of trackline were covered in 2006/07 and 564 n.miles in 2007/08 (Table 3).

Search regions of observers

The separation of search regions is an integral part of the BT method. Examining the angles and radial distances to sightings of all species gives an insight into the search regions for the different platforms. Angle and distance estimation experiments were performed to assess any bias in the sighting angles and radial distances recorded from the various platforms. Analyses indicated there was significant bias in a few cases and the recorded angles and distances were corrected using the bias factors shown in Table 4.

In BT-NSP mode, the trackers were instructed to search an area no more than 45° either side the trackline and ahead of the area searched by the primary, who searched as usual (IWC, 2006). Fig. 2 shows that the BE observer clearly searched

Table 3

Search effort and numbers of minke whale schools sighted (by both tracker and primary observers including duplicates).

			Numbers of schools			
Survey	Search mode	Effort (nm)	Minke	Undetermined minke	Like minke	Total
2005/06	BT-IO	127.4	22	8	–	30
	BT-NSP	1,385.3	258	10	15	283
2006/07	BT-NSP	1,195.9	226	36	31	293
	BT-option 2	275.4	118	21	23	162
2007/08	BT-option 2	564.2	11	1	5	17

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	Barrel	42	–	1.047
	BE	12	–	1.090
2006/07	Barrel	36	0.944	–
	BE	12	–	1.137
2007/08	Barrel	36	0.934	1.056
	IOP (7×50 bins.)	36	–	1.045
	IOP (naked eye)	30	1.066	1.084

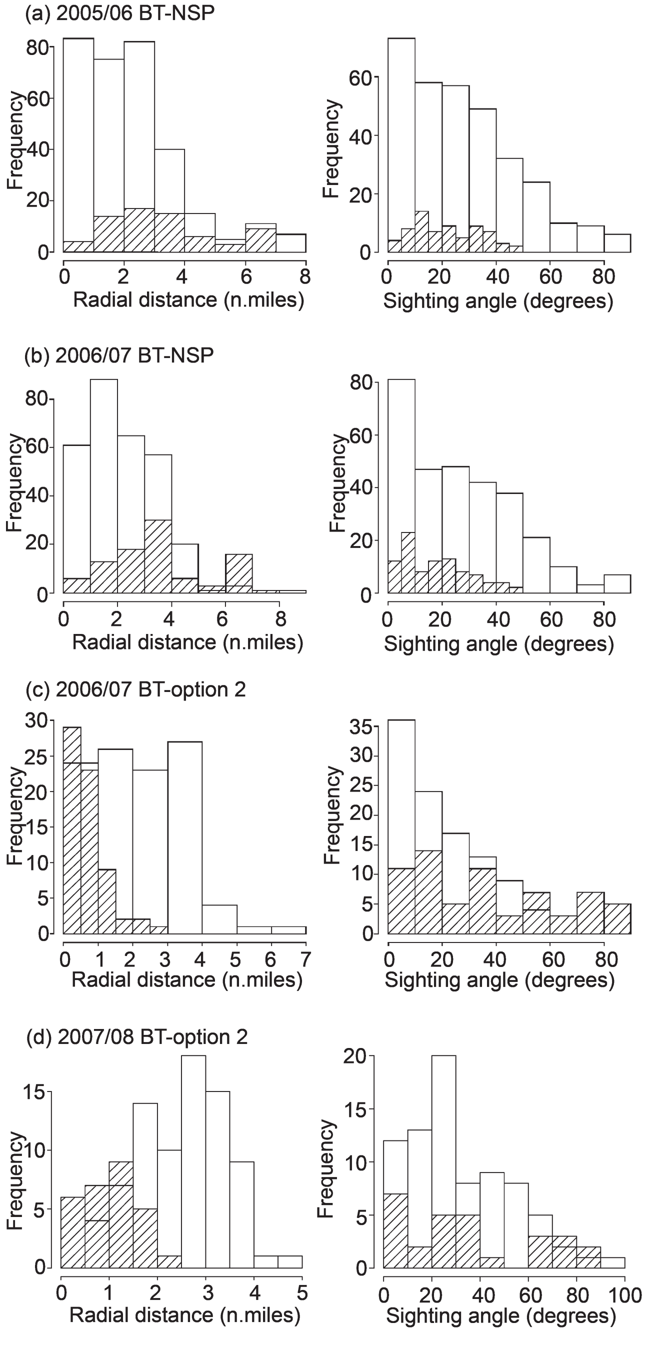

Fig. 2. Distributions of radial distances (left column of plots) and sighting angles (right column) for all sightings from all the platforms used in BT modes. In (a) and (b) the shaded regions are tracker (BE) sightings and unshaded are primary (barrel) sightings. In (c) and (d) the shaded regions are the primary (IOP) sightings and the unshaded regions are the tracker (barrel) sightings.

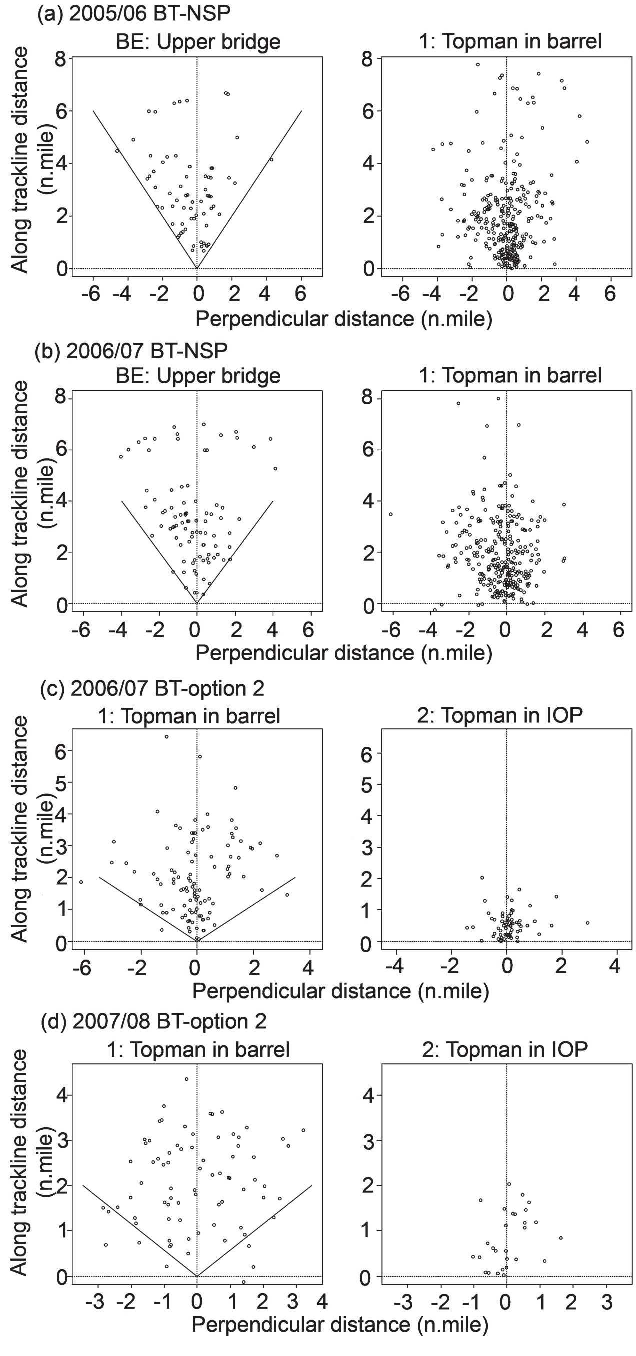

Fig. 3. Relative locations of detected sightings (all species) to the vessel (at point 0,0) by platform. Lefthand column are trackers and the righthand column are primary observers. The lines on the tracker plots indicate 45° either side the trackline for BT-NSP model and 60° for BT-option 2.

within 45° 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 radial distance distribution (in Fig. 2) and Fig. 3 show that there was considerable overlap between the region searched by the tracker and the region searched by the primary.

In BT-option 2, the trackers were instructed to focus their searching far ahead of the vessel and up to 60° either side of the trackline and the primary observers searched with naked eye up to 90° either side of the trackline (IWC, 2007). Figs 2c and 2d show that there was much more of a separation of search regions in BT-option 2 than in BT-NSP mode since the distances the primary observers were able to see was necessarily limited due to searching with naked eye.

Responsive movement

Fig. 4 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 and this plot can generally only provide an indication of responsive movement if the reaction is severe. Errors in sighting angles and radial distances can also mask any reactions. In this case, Fig. 4 is inconclusive with respect to responsive movement.

School size

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 and primary observers recorded school size independently and trackers were thought to estimate school size more accurately. In the SOWER surveys the 'best' estimate (usually made by observer in the barrel) is assigned to both records in the duplicate pair thus a correction factor similar to that of Borchers *et al*. (1998) cannot 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 these sightings had confirmed school sizes. Table 5 shows that approximately half of all groups detected were either single animals or in groups of two, however, the proportion of single animals was substantially lower in 2006/07, when school sizes were confirmed, than in 2005/06.

Detection functions

To estimate the detection function, sightings of minke whale schools (species code 04), 'undetermined minke' (91) and 'like minke' (39) have been used. These are all referred to as minke whales (see Table 3 for the numbers in each species code) and only sightings classified as 'definite' duplicates were considered to be duplicates. Table 6 shows the number of minke whale sightings recorded by the different observers and the perpendicular distance distributions are shown in Fig. 5. In 2005/06 BT-NSP mode, there were 41 tracker sightings of minke whale and the primary saw 21 of them. In 2006/07 BT-NSP mode, there were 65 tracker sightings and 31 duplicate sightings. In BT-option 2, there were 101 tracker sightings of minke whales schools and 27 duplicates. In 2007/08, BT-option 2 mode generated 10 tracker sightings and only 2 duplicates – too few to be able to fit the models reliably and so this data is not pursued further.

As mentioned already, an important consideration during analysis is whether to fit a point or full independence model and this depends in part on responsive movement of the animals. 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, the hazard rate form was found to be preferable in nearly all cases. The most important explanatory variable was school size and this was included in nearly all models in some form with Beaufort sea state and sightability also included in some models. The chosen models are given in Table 7, the fitted MR models are shown in Fig. 6 and the final detection functions of the primary observers are shown in Fig. 7.

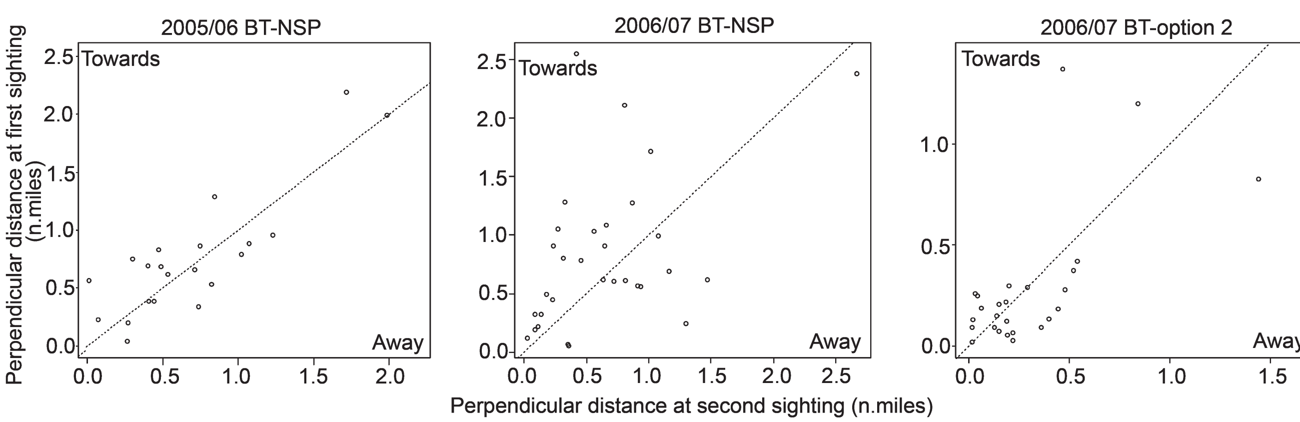

Fig. 4. Perpendicular distances of duplicates at the time they were detected initially by the tracker (*y*-axis) and then by the primary (*x*-axis). The dotted diagonal line corresponds to no movement. Points below the line correspond to movement away from the transect line, while those above correspond to movement towards it.

Table 5

Numbers of minke whale sightings seen by each platform and school size. The numbers in parentheses in (a) are the numbers of schools with confirmed school sizes.

	2005/06			2006/07		
	Tracker	Primary		Tracker	Primary	
School size	BE	Barrel	Duplicates	BE	Barrel	Duplicates
(a) BT-NSP						
1	17	98	6	15 (10)	80	3
2	8	57	3	15 (14)	56	6
3	8	42	6	8 (8)	34	4
4	3	12	3	8 (6)	22	6
5	3	12	2	9 (7)	14	4
6–9	1	14	1	6 (6)	11	5
≥10	1	7		4 (2)	11	3
All	41	242	21	65 (55)	228	31
	2006/07			**2007/08**		
	Tracker	Primary		Tracker	Primary	
School size	Barrel	IOP	Duplicates	Barrel	IOP	Duplicates
(b) BT-option 2						
1	36	19	2	2	3	–
2	22	14	8	2	–	–
3	19	14	9	1	–	–
4	2	3	–	2	2	2
5	4	3	2	–	–	–
6–9	5	3	2	2	–	–
≥10	13	5	4	1	–	–
All	101	61	27	10	5	2

Table 6

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

		Platform			Number of duplicates		
Survey	Search mode	Barrel	IOP	BE	BE:Barrel	BE:IOP	Barrel:IOP
2005/06	BT-IO	13	11	4	2	2	–
	BT-NSP	242	–	41	21	–	–
2006/07	BT-NSP	228	–	65	31	–	–
	BT-option 2	101	61	–	–	–	27
2007/08	BT-option 2	10	5	–	–	–	2

Table 7

Summary of models (a) point independence models and (b) full independence models.

In the DS model column, HZ indicates that a hazard rate form was used and HN indicates a half-normal form. 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), Beaufort sea state (B) and sightability (SG); the subscripts indicate the variable has been included as a factor variable and indicate the number of factor levels. Coefficients of variation are given in parentheses.

Survey	Search mode	Primary	Tracker	DS model	MR model	$\hat{p}(0)$	Average p
(a) Point independence models							
2005/06	BT-NSP	Barrel	BE	HZ: D + S_4+ B_3	D + S_4 + B_3	0.688 (0.23)	0.166 (0.24)
2006/07	BT-NSP	Barrel	BE	HN: D + S_6	D + S_2	0.399 (0.36)	0.144 (0.37)
	BT-option 2	IOP	Barrel	HZ: D	D + S_2	0.283 (0.50)	0.026 (0.53)
(b) Full independence models							
2005/06	BT-NSP	Barrel	BE	–	D + S_4 + B_3	0.660 (0.30)	0.222 (0.30)
2006/07	BT-NSP	Barrel	BE	–	D + S_6 + SG_3	0.352 (0.57)	0.163 (0.57)
	BT-option 2	IOP	Barrel	–	D + S_4	0.245 (0.59)	0.038 (0.59)

Detection probability of the primary observer

Using the point independence model, estimates of average probability of detection on the trackline for the primary observer were for BT-NSP mode, 0.69 (CV = 0.23) in 2005/06 and 0.40 (CV = 0.36) in 2006/07; for BT-option 2, it was 0.28 (CV = 0.50). The same estimates from the full independence model were very similar, but slightly lower (with coefficients of variation that were higher)

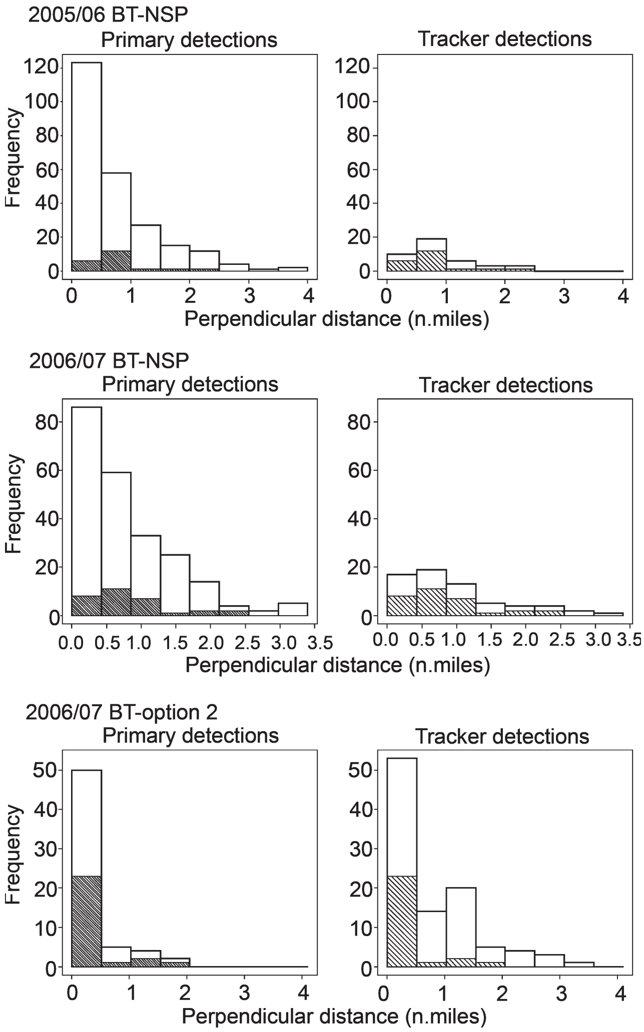

Fig. 5. Distribution of the perpendicular distances for the primary (left column) and tracker (right column) observers where the shaded regions indicate the number of the duplicates. Distances are in nautical miles and have not been truncated.

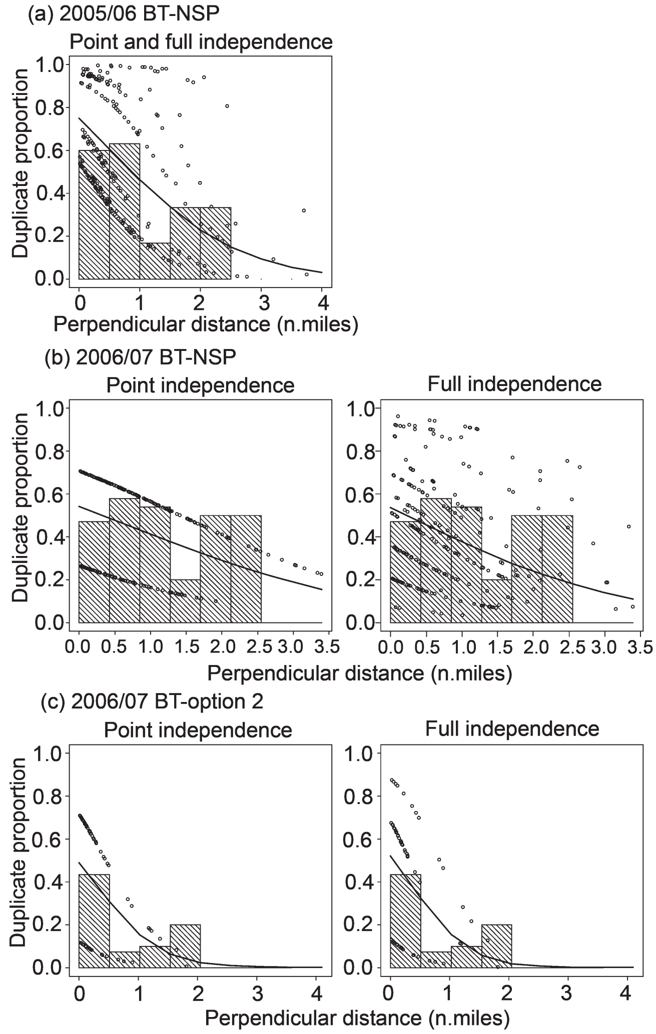

Fig. 6. Histograms of the proportion of duplicates to tracker sightings (see Fig. 5) and the fitted MR models.

than estimates from the point independence model (Table 7).

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. Assuming point independence, these average probabilities of detection are determined from the DS model and this function tends to decline more rapidly as perpendicular distance increases than the MR model on which the full independence model is based (Fig. 7).

Detection probability estimated by school size

After fitting the model shown in equation 2 to the 2006/07 BT-NSP data, the probability of detection on the trackline for single animals was 0.27 (CV = 0.42) and for schools of two or more animals the detection probability increased to 0.71 (CV = 0.15).

To investigate the effect of school size further, two additional models were fitted. Firstly, recorded school size (as a non-factor variable) was included into Equation (2) as well as the factor school size variable, *sf*. Fig. 8a indicates that there is a substantial difference in the detection probability between a single animal and a school of at least two animals; this can be seen by looking at the proportions of the number of duplicates to tracker sightings for the different school sizes in Table 5a. Secondly, Beaufort sea state (divided into two factor levels, ≤ 3 and >3) was included into the model described above as both a main effect and in an interaction term with *sf*. Fig. 8b indicates that Beaufort sea state substantially affects the detection of single animals. Somewhat surprisingly, the probability of detection is slightly better in poorer conditions for groups of greater than two animals but this difference is negligible compared to the difference Beaufort sea state makes on the detection probability of single animals.

The probability of detection on the trackline of the primary observer using naked eye (i.e. using the BT-option 2 data) for single animals and groups of two or more was 0.12 (CV = 0.57) and 0.72 (CV = 0.06), respectively.

DISCUSSION AND CONCLUSIONS

The main aims for performing the BT mode experiments were to obtain an independent estimate of the probability of detection on the trackline for the different platforms used on the SOWER vessels and to evaluate BT mode as a potential survey methodology for future SOWER cruises. Independent estimates of the probability of detection on the trackline, in

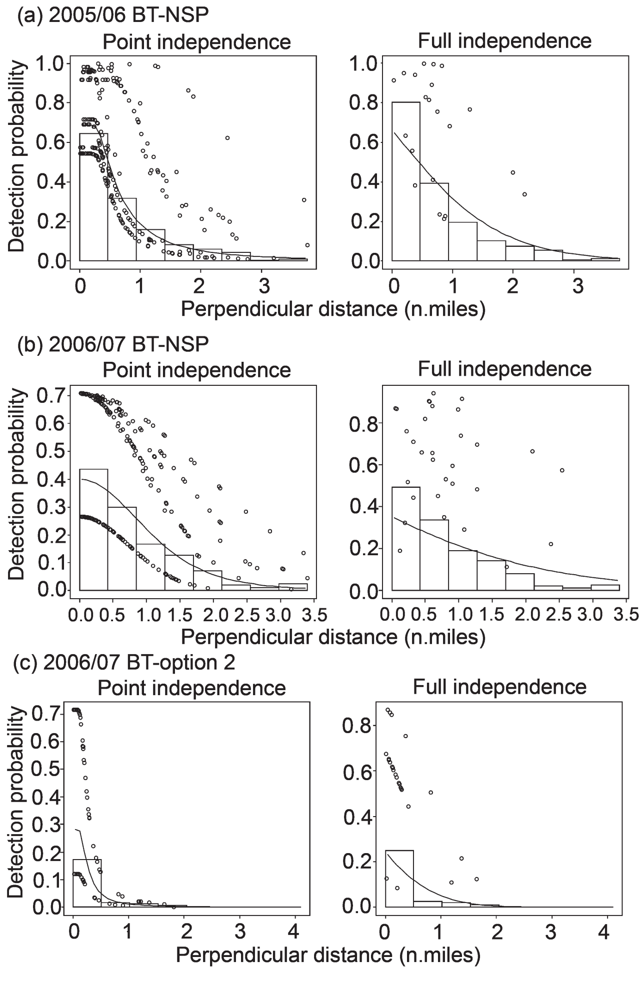

Fig. 7. Fitted detection functions of the primary observer. The point independence models are the scaled DS models fitted to the primary detections. The full independence models are the MR model fitted to the duplicates.

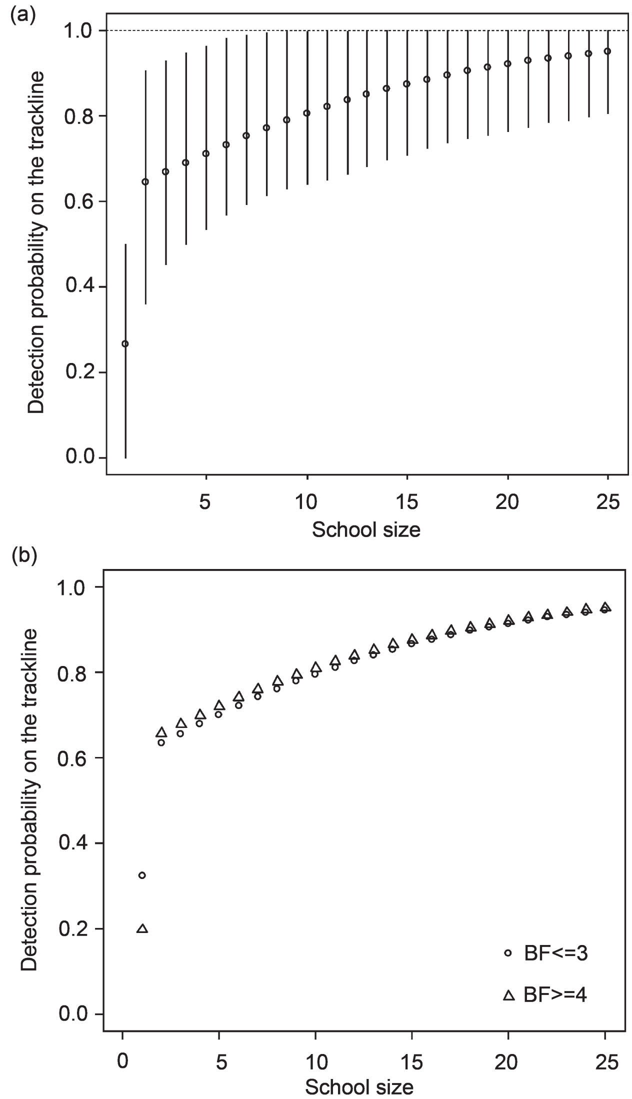

Fig. 8. Estimated probability of detection on the trackline for different school sizes estimated from two MR models fitted to the 2006/07 data (see text). The lines in (a).are the 95% 'percentile' confidence limits (excluded from (b) for clarity).

particular for the barrel and IOP, would help in the interpretation of minke whale abundance estimates obtained from analyses of SOWER survey data. The probability of detection on the trackline for the barrel was estimated to be 0.69 (CV = 0.23) and 0.66 (CV = 0.30) in 2005/06 for the point and full independence models, respectively. In 2006/07, these probabilities were substantially lower; 0.40 (CV = 0.36) and 0.35 (CV = 0.57), respectively. This inter-year difference may be a reflection of the better weather conditions experienced in 2005/06 and the higher quality BE binoculars used in 2006/07 which facilitated survey in poorer weather conditions than in the trials performed the previous year. It was found to be infeasible to implement BT-IO mode and so an estimate for the IOP, searching as per standard SOWER IO mode protocol, could not be obtained.

In BT-option 2, for the 2006/07 trials, the probability of detection on the trackline for the IO searching with naked eye (primary) was estimated to be 0.28 (CV = 0.50) and 0.25 (CV = 0.59) for the point and full independence models, respectively. The evaluation of BT-option 2 during 2006/07 and 2007/08 as a potential survey method for future cruises identified distinct practical advantages over standard IO mode survey as tracking and assessment of duplicate status for large baleen whales was also less problematic in BT-option 2 mode. As large baleen whale cues can be detected at long radial distances, the duration of tracks can be long and this can make assessment of duplicate status difficult in IO mode. In recent years the substantial increase in sighting rates for humpback whales in some regions of the Antarctic has made IO mode problematic and this important aspect of IO mode is likely to become even more problematic in the future (Ensor *et al.*, 2008).

School size is an important factor affecting detectability and the probability of detection on the trackline was estimated for different school sizes. As expected, detection probability on the trackline increased with school size, with single animals having a substantially lower probability of detection than groups of two or more animals; 0.27 (CV = 0.42) for single animals and 0.71 (CV = 0.15) for schools of two or more animals. Beaufort sea state also affects detectability, particularly for single animals. However, as noted above, in order to maximise the sighting rate (and hence the number of duplicate detections) for this experiment, all the trials of BT-NSP mode in 2005/06 and 2006/07 were carried out near the ice edge where school sizes would be expected to be larger than average and Beaufort sea states generally lower. Therefore, away from the ice edge the average probability of detection may be lower than found here.

An important consideration in an MRDS analysis is whether to assume point or full independence. Point independence is to be preferred but is not tenable if there is responsive movement and deciding if there has been responsive movement can be difficult unless it is severe. Although it is a weak diagnostic tool, Fig. 4 does not suggest responsive movement. The differences in the shape of the BT-NSP detection function for the primary observer (indicated by the histogram of perpendicular distances – Fig. 7) and the fitted MR model (right hand column) is typical of (a) increasing unmodelled heterogeneity with increasing distance and/or (b) attractive movement between detection by 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 to several factors: all observers were using binoculars; good weather was experienced, particularly in 2005/06; and although the trackers were using BE, the tracker platform was considerably lower than the primary platform. The effects of unmodelled heterogeneity can be alleviated by separation of the search regions of the tracker and primary observers, however, the results of the BT-NSP trials suggest that there was considerable overlap of search regions and that using BE binoculars on the upper bridge did not demonstrate a substantial improvement in terms of detecting minke whales further away compared with standard SOWER methodologies. In view of the lack of evidence of responsive movement and the overlap in primary and tracker search regions, the estimates from the point independence model are preferable. The BT-option 2 configuration encourages 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 was reduced.

BT-NSP mode has provided an estimate of probability of detection on the trackline for the barrel. However, these trials have not provided an estimate of the probability of detection on the trackline for the other platforms which are also used during the standard SOWER search protocols. In closing mode, the upper bridge is also on search effort and sees a similar number of sightings as the barrel (Table 2). Therefore, assuming that the upper bridge has the same probability of detection as the barrel and is acting independently, then the probability of detection by either the barrel or upper bridge will be 0.9 using the results from the 2005/06 data and 0.6 from 2006/07 (p(seen by barrel or upper bridge) = p(seen by barrel) + p(seen by bridge) – p(seen by barrel)*p(seen by bridge)). Including the IOP is likely to increase these probabilities, although any increase in detection due to the IOP may be tempered by a reduction in the effectiveness of the upper bridge due to tracking animals in order to assess duplicate status. Nevertheless, these results suggest that the probability on the trackline for the SOWER vessels may be close to one in good weather but nearer to half that in poorer weather conditions.

These BT mode trials have proved to be a successful series of experiments, shedding light on both the probability of detection on the trackline of minke whales, which can help to interpret data collected on past SOWER surveys, and also trialling survey methods to be used on future surveys. Notwithstanding some practical advantages over standard SOWER methods, the fact that BT search modes, and other double observer configurations (Laake and Borchers, 2004), allow density to be estimated without assuming $g(0) = 1$ make these methods worth considering for future surveys where detection on the trackline is uncertain.

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