Mark-Recapture Distance Sampling Estimate of Minke Whales from the Icelandic, Faroese and Russian components of T-NASS.

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INTRODUCTION

The Trans North Atlantic Sightings Survey (T-NASS) was a multinational synoptic survey undertaken in June/July 2007 (Figure 1 for Faroese, Icelandic and Russian regions only). Here we combine survey data collected under different observer configurations (hereafter "modes") to estimate minke whale (*Balaenoptera acutorostrata*) numbers for the Faroese, Icelandic and Russian regions of the study. An aerial survey was conducted during the same period in the CIC (Costal Icelandic Central) block and gave an estimate corrected for availability at the surface of 15,055 (95% CI 6,357, 27,278) (CV 0.36, (Pike *et a*l. 2008). Duplicate data showed that this estimate was likely little affected by perception bias. The vessels had little effort and no predesigned tracks in this area so no estimate is produced here.

Two important forms of bias associated with marine mammal surveys are availability bias (i.e. the bias caused by the animals not being present at the surface) and perception bias (caused by animals being missed even when at the surface). Perception bias can be overcome by the use of mark-recapture methods (Laake and Borchers 2004) which allow estimation of the probability of detection on the trackline ($g(0)$). The double platform BT survey mode adopted during this survey is intended to compensate for the perception and at least partly for the availabilitybias by having trackers on a higher platform scanning the trackline ahead and setting up trials for the primary observers. Here, because some of the data was collected using such a double platform configuration, g(0) could be estimated for the primary platform, thus allowing correction for perception bias for animals at the surface in estimates based on the primary sightings. Minke whales on average dive for about a minute but generally a long dive lasts 2 – 4 minutes followed by 2 -4 surfacings (blows) at shorter (10 -30 sec) intervals. At the last surfacing before a deep dive the animal curls up more but does not lift its tail. Deep dives rarely last more than 6 minutes. The blows of North Atlantic minke whales are not very visible unless in exceptional conditions so the cue is usually the back. Minke whales are generally hard to detect if the sea is not calm and not at distance of more than a

few hundred meters, but are occasionally observed jumping out of the water and may then be detected at great distances but identification may then be problematic from a passing sighting survey vessel. The heterogeneity in the detectability of whales/schools, where some sightings are easily spotted by both platforms, while others are likely to go undetected by both, still leaves an unknown negative bias in the g(0) corrected estimates.

Another source of bias can be caused by the animals avoiding or actively approaching the research vessel. Minke whales have not been observed to adversely react to vessels passing, whale watching or even hunting at a distance. Some minke whales however appear to be curious and may slowly approach a vessel in the area but likely not with speed that would be of significance here.

MATERIAL AND METHODS

The data analysed here comes from three dedicated survey vessels (J, V and F) (Gunnlaugsson 2008, Desportes and Halldórsson 2008, Mikkelsen 2008). The fourth vessel (A) while participating in the international Redfish survey, coordinated by ICES, covered the Denmark Strait and the Irminger Sea with also full cetacean survey effort (Víkingsson et. al. 2008). These surveys were conducted from the 26th of June to the 22nd of July. These vessels surveyed mainly in BT-mode. In addition there were three platforms of opportunity (Fisheries research vessels referred to here as Extension vessels) with two primary observers each. Data from the extension vessels was intended to be used to extend the coverage to areas not surveyed by the dedicated survey vessels. The extension vessels were two Norwegian vessels (E and L) in the Norwegian Sea (The pelagic Norwegian/Russian fish survey) in the period mid July to early August. The third extension vessel (S) was Russian and also surveying in the International Redfish survey but made no minke whale sightings while on full primary effort.

Survey regions and data

Realised search effort and block boundaries are given in Figure 1 with the different survey modes shown in different colours. The CIC (Coastal Icelandic Central) block was not systematically surveyed by the vessels but there is some effort there during transit. Table 1 gives the sizes for each block and the different amounts of effort conducted under each survey mode. Only effort undertaken in Beaufort Sea State less than 4 (0 to 3.5) was used. This excluded one sighting in BSS 4.5.

Species Identification

All sightings identified as most likely minke whales were included. Definite and probable duplicates were considered but not remotely likely duplicates. One distant sifghting where the primary platform did not identify the sighting to be of a minke whale was excluded.

Survey modes

The three modes of survey were Buckland-Turnock (BT) mode (Buckland *et al.* 2001, Buckland and Turnock 1992), single platform mode and combined mode. The most complex survey mode was BT mode. In this mode observers were located on two different platforms. On the higher platform two trackers were looking far forward of the vessel searching for animals prior to any potential responsive movement aided by a duplicate identifier and data recorder (in total four observers) on detecting a group it was tracked until it was either observed by the primary platform (known as a duplicate) or until it was observed or believed to have passed abeam. On a lower platform, two primary observers scanned closer to the vessel generally not using binoculars and were not informed of what was seen by the trackers. Any information flow was from primary to trackers only. Thus, trackers set up trials for the primaries.

Combined mode was used when there was a break down of recording or communication equipment, or the computer had to be closed down due to wet, or weather was to poor to do tracking. The two platforms then cooperated in identifying and confirming sightings. During these periods the tracker platform may not have been fully manned or some of the observers there engaged in addressing equipment problems.

In BT mode, trackers set up trials for the primary observers and a 'success' corresponds to detection by the primary. Analysis of these trials can be used to obtain a $g(0)$ (i.e. probability of detection on the trackline) for the primary observer which can be used to correct for perception bias. Thus an unbiased estimate of the population of minke whales available at the surface may be obtained.

In BT mode, trackers detected 24 pods of minke whales and of these, 5 were subsequently detected by the primary observers. One primary sighting was subsequently also recorded by the trackers providing their independent distance estimate. In addition, the primary observers detected a further 6 sightings in BT mode (total 11), 20 sightings in single platform mode and 7 sightings in combined mode. The furthest perpendicular distance a minke whale was seen by the trackers was 3,101 m and the furthest distance a minke whale was seen by a primary observer (under all modes) was 1,200 m. Due to the few sightings and very few duplicates the overall approach used in this analysis was to combine all the shipboard survey data collected by all the vessels under the three different observer configurations, or survey modes, to produce an estimate of minke whale abundance based on the primary platform sightings and detection function corrected for g(0) which was obtained from the tracker data and duplicates (trials). All but one of the primary sightings was estimated to be within 250m perpendicular from track. The four tracker sightings within this distance were duplicated and one in high Beaufort (so not included in the analysis) was missed. One of these minke tracker sightings was duplicated only as an unknown medium whale by the primaries and should on hindsight not have been treated as a duplicate. The BT mode vessels A and J made most sightings from the primary platform (2/3) and this was so also for the larger whales on vessel V, but reversed in case of medium and smaller whales and in general for all species on the vessel F.

Detection function estimation

There are two approaches to analysis of BT mode data depending on the underlying assumptions made about the collection process (Borchers *et al*. 2006, Laake and Borchers, 2004, Burt *et al*. in prep.). If whales show responsive movement, then it is better to assume that detections from the two platforms are independent at all distances – known as full independence (FI). If no movement can be assumed, point-independence (PI) offers a more robust approach to dealing with the data – detections are assumed to be independent on the trackline only. To test for the responsive movement between detection by the tracker and detection by the primary, both duplicates sightings and independent data from one platform only records from BT mode and sightings collected in single platform mode were compared.

With a FI approach, a single mark-recapture model is constructed. With a PI approach, a two component model is constructed with discrete mark-recapture (MR) and conventional distance sampling (DS) components. Data were considered both in FI and PI configurations because of ambiguity as to whether the animals showed responsive movement (see results). The primary observations from the BT mode data were augmented with the single platform mode data to provide a robust estimate of unadjusted detection probability (i.e. the conventional distance sampling component).

Distance v6 (Thomas *et al.* 2002) using the mrds engine (Burt *et al.* in prep.) was used for model selection of detection functions and thereafter the models were implemented in the statistical package *R* (R Developmental Core Team). Because all tracker sightings should be considered as potential trials no right truncation of the data was undertaken (i.e. all distances were considered). Variables considered for inclusion in the models were *Visibility, Weather, Beaufort sea state* and *group size.* Model selection was by minimisation of *Akaike's Information Criterion* (AIC). The estimated probability of detection for each sighting was then used to create a Horvitz-Thompson-like estimator for each sighting (which represented a correction for imperfect detection). These could readily be applied to the primary sightings. Then, estimated numbers were summed for each block and a density was calculated based on the estimated searched area for a block (calculated as twice the truncation distance multiplied by the total length of effort for that block). Block abundances could then be estimated.

The g(0) associated with combined mode was unknown, but could reasonably be assumed to be higher than $g(0)$ for primary observers in BT mode and single platform mode (because there are more observers). Thus, combined mode sightings and effort were treated in two ways: either the combined mode data were simply omitted from the analysis or it was treated as single platform mode data. In this latter case, combined mode data were used to obtain encounter rates but were not used in the MRDS analysis. Because g(0) should be higher in combined mode than for the other survey modes, using a $g(0)$ correction obtained from the BT mode data with combined mode sightings over compensates and thus could lead to an inflated estimate of abundance, all other factors being constant. Therefore, abundance estimates were initially calculated under four scenarios

a) responsive movement (assuming FI) with no combined effort (Table 2a)

b) responsive movement (assuming FI) with additional combined platform effort (Table 2a)

c) assumed no movement (assuming PI) with no combined effort (Table 2b)

d) assumed no movement (assuming PI) with additional combined platform effort. (Table 2b)

Additional scenarios also considered included

e) assumed no movement (assuming PI) with no combined effort, and no sightings and effort from the extension vessels E, L and S. (Table 3a)

f) assumed no movement (assuming PI) with combined effort, and no sightings and effort from the extension vessels E, L and S. (Table 3a)

g) assumed no movement (assuming PI) with no combined effort but primary radial distances corrected by a factor of 1.34 to investigate how biases in naked eye distance estimation would affect the estimates (Table 3b)

h) assumed no movement (assuming PI) with combined effort but primary radial distances corrected by a factor of 1.34 to deal with biases in naked eye distance estimation(Table 3b)

i) assumed no movement (assuming PI) with combined effort but no sightings and effort from the extension vessel S. (Table 4)

j) assumed no movement (assuming PI) with combined effort but g(0)=1 (Table 5)

Variance estimation

The whole process was then was then repeated as a non-parametric bootstrap, generating the bootstrap sample by sampling, with replacement, transect legs (within each block to ensure good coverage). The above process repeated 1000 times to obtain a distribution of abundance estimates which could then be used to obtain confidence intervals.

RESULTS

Responsive movement and distance estimation

Because there were only 4 duplicate sightings (albeit 5 independent distance estimates) available, no meaningful paired comparison of distances could be made. The number 1.34 used here in the sensitivity tests for bias in distance estimation by naked eye was based on observed differences in the distances estimated to fin whale sightings (Pike *et al.* 2008b). This number was larger than that obtained from the distance estimation experiments. In a comparison of non-paired tracker and primary platform distances a significant difference was confirmed (Mann-Whitney Test: W = 1942 P<0.001, median primary distance = 309 m, median tracker distance = 637 m). However because of the different platform heights and searching strategies of the two observer groups (i.e. tracker searching further away) this could not necessarily be seen as evidence of aversive movement. Therefore, both FI and PI assumptions were considered for the BT mode data.

Sightings and detection functions

In the case of both FI (Figure 2) and the mark-recapture component of PI (Figure 3a), model selection in *Distance* suggested the best model included perpendicular distance only. In the case of conventional DS component (Figure 3b) for the PI-mode analysis, *Visibility* improved the fit but fitting a multiple-covariate detection function proved problematic in the bootstrap and so this model was not finally implemented and *distance* only was used. The estimate of $g(0)$ from the FI configuration (using all data) was 0.950 (CV 0.318) leading to an overall probability of detection of 0.0476 (CV 0.281). The estimate of $g(0)$ from the PI configuration (using all data) was also 0.950 (CV 0.090) leading to an overall probability of detection of 0.120 (CV 0.240). The low overall probability of detection across both configurations is caused in part by the large truncation distance of 3104 m

Abundance estimates

The final abundance estimates are given in Table 2 for FI and PI configurations with and without combined data. Tables 3,4 and 5 give the estimates from the additional scenarios. Including the combined mode data with increased number of observers should cause estimates to be biased upwards, but in fact caused a small lowering of the overall estimates, implying that combined mode was implemented in regions of low minke abundance or when sighting conditions were poor.

A best estimate for the entire T-NASS region derived not including the extension vessels E, L and S and so not including the CL block, but with the addition of the CL block estimate from the entire data set, including combined effort and assuming point independence was 10,900 (6,600 30,000). A best estimate of minke whales for the surveyed part of the IWC central region (with the same approach as above) would give an estimate of 11,100 (6,400 30,600)

DISCUSSION

The extension vessels in general had considerably lower sighting frequency than the dedicated vessels (primary platform only) in the areas where there is overlap in effort. An exception is minke whales in the survey block north of Iceland (NI) where the extension vessel (L) has 316 miles on effort and 9 minke sightings. One is of two animals and 4 of three animals. These are the only sightings in this survey of more than one minke whale. These sightings were lumped at Jan-Mayen and 7 were seen in one day (28th July). Apparently the vessel hit a high density spot there. The dedicated survey vessel (V) during 500 miles on effort in this block made 15 sightings but only 6 were seen by the primary platform. There was no dedicated survey effort north and east of the NI block in 2007 and the extension vessels made only 4 sightings of minke whales during 600 miles on effort there, but in 2001 during also 600 miles on effort 28 sightings were made there. In the area east of 4°E the extension vessels made 5 sightings during 865 miles on effort. This area has been surveyed periodically bitwise during Norwegian minke whale sighting surveys but there was no overlap with that effort in 2007.

Limited comparison can be made with densities in earlier surveys due to the low number of sightings in general in these blocks. The highest densities have been seen at the coast of Greenland in earlier surveys but during this survey there was almost no effort there due poor sighting conditions. This is the main reason for a lower estimate from this survey than in 2001 and that in 2001 an area was covered farther to the east by dedicated vessels.

Heterogeneity due to school size is negligible for minke whales in this area as most of the animals are single, but there will always be heterogeneity in the distinctiveness of cues and the sighting conditions, although here we have limited the analysis to the data collected in low Beaufort. Also for some minke whales several cues are likely to be visible while for others there may be only one and as this data/analysis is not cue based, this will cause heterogeneity in the likelihood of animals being detected. This will result in too many duplicates and the g(0) correction inherently underestimated (Skaug *et al*. 2004).

When the trackers do not manage to get a species identification or wrongly assign a minke whale sighting to some other species, then that is not a valid minke whale trial and should not count as a duplicate success if spotted by the primary observers, as it would also never have been considered a minke whale trial miss, had it not been spotted by the primary observers. As the platforms are only one-way independent, it is impossible to say whether in some cases a whale would have been correctly identified by the trackers, had it not been spotted by the primary observers. This is a source of additional negative bias in the g(0) corrected abundance estimates. Due to this inherent weakness of the BT method, great care most be taken in the conduct of such surveys but this had not been identified during the planning of this survey.

In practise, including the combined mode data made little difference to the overall estimates of abundance (Table 2) but as it reduced the overall level of abundance contrary to expectation, combined mode probably provided more coverage in low density areas or when conditions for sighting were poor. A large difference occurred between the PI and FI estimates. Unfortunately the trackers were not instructed to confirm the primary nonduplicate sightings and take independent distance estimates to these sightings, so there is limited data available to compare the platforms. Given the paucity of double platforms sightings it may be premature to reach firm conclusions. The confidence intervals of the estimates do overlap but the point estimates of the PI configuration are substantially lower due to a lower estimated overall probability of detection. The ultimate choice depends on what is known of the behaviour of minke whales. If responsive movement is suspected, then the FI configuration estimates should be preferred.

The g(0) estimate obtained here is at face value negligibly different from 1 and thus an estimate based on this data where both platforms were merged and duplicates ignored is reasonable and would be directly comparable to estimates in this region from earlier surveys, where duplicate data was not collected, in particular if data from all surveys was combined and analysed with the same methods. These data do however not preclude that g(0) in such surveys might be as low as 0.5 and therefore future surveys should consider collecting more and more precise duplicate data. The fact that out of the 4 duplicated sightings one was apparently not correctly identified by the primary platform and a different handling of this

sighting would have significantly changed the results, show the importance of precise recording. There may have been other such cases which are not reflected in the records, as the importance of this had not been sufficiently stressed in advance and the observers were supposed to validate their data, at which point they may have changed their species identification based on subsequent discussions with the other platform.

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Table 1. Size (km^2) of survey blocks and the total length (km) of survey effort for each survey mode (including all realized search effort) within each block for the T-NASS 2007 survey.

Block	**Size (km^2)**	**BT mode (km)**	**Single platform mode (km)**	**Combined mode (km)**	**Total (km)**
CL	129,034	0	391	0	391
IN	328,246	741	516	687	1,944
FE	210,240	830	476	115	1,421
FS	276,515	1,468	35	110	1,614
FX	197,635	216	6	53	275
SC	710,204	4,119	549	118	4,786
RS	316,518	458	440	550	1,448
RN	453,401	1,438	1,307	706	3,451
NW	73,794	199	0	53	251
CIC	198,999	45	461	0	506
Total (T-NASS area)	**2,900,440**	**9,514**	**4,181**	**2,392**	**16,087**
IWC Central Stocks 74˚ N to 52.5˚ N	**2,7234687**	**8,029**	**3,983**	**2,183**	**14,195**
Unblocked effort	**-**	**51**	**3,663**	**91**	**805**

Table 2. *Estimates of abundance by block for 2007 a. full independence, and b. point independence.*

a. **Block**	**Abundance (assuming aversive movement)** **FI. No combined effort.** **Mean (± 95% confidence intervals)**	**Abundance (assuming aversive movement)** **FI. Combined effort considered.** **Mean (± 95% confidence intervals)**
CL	1,400 (0, 7,900)	1,400 (0, 7,500)
IN	21,400 (3,200 56,700)	18,700 (4,200, 53, 200)
FE	1,000 (0, 3,200)	900 (0, 3,000)
FS	2,500 (0, 5,000)	2,300 (0, 4,500)
FX	0 (0,0)	0 (0,0)
SC	0 (0,0)	0 (0,0)
RS	0 (0,0)	0 (0,0)
RN	2,000 (0, 4,800)	2,300 (500, 5,700)
NW	1,400 (0, 4,100)	1,100 (0, 3,700)
Total (T-NASS area)	**29,700 (10,300, 68,300)**	**26,700 (11,100, 63,500)**
IWC Central Stocks 74˚ N to 52.5˚ N	**29,900 (8,700, 83,400)**	**29,900 (10,200, 77,100)**

b. **Block**	**Abundance** **PI mode. No combined effort** **Mean (± 95% confidence intervals)**	**Abundance** **PI mode. Combined effort considered** **Mean (± 95% confidence intervals)**
CL	500 (0, 3,000)	500 (0, 3,100)
IN	8,500 (1,400 23,700)	7,400 (1,700 20,200)
FE	400 (0, 1,800)	400 (0, 1,700)
FS	1000 (0, 2,800)	900 (0, 2,500)
FX	0 (0,0)	0 (0,0)
SC	0 (0,0)	0 (0,0)
RS	0 (0,0)	0 (0,0)
RN	800 (300, 2,400)	900 (100, 2,700)
NW	600 (0, 2,000)	400 (0, 1,800)
Total (T-NASS area)	**11,800 (4,400, 29,500)**	**10,600 (4,500, 26,300)**
IWC Central Stocks 74˚ N to 52.5˚ N	**11,900 (3,600, 31,400)**	**11,900 (4,200, 31,100)**

Table 3. *Abundance estimates by block for 2007 a. not including the extension vessels E, L & S. b. with a correction to primary distances by a factor of 1.34. All estimates derived assuming point independence .*

a. **Block**	**Abundance (assuming aversive movement)** **PI. No combined effort** **Mean (± 95% confidence intervals)**	**Abundance (assuming aversive movement)** **PI. Combined effort considered** **Mean (± 95% confidence intervals)**
CL	-	-
IN	4,800 (0 15,200)	5,000 (1,100, 14,300)
FE	1,000 (0, 5,700)	1,000 (0, 4,900)
FS	1,700 (0, 7,000)	1,600 (0, 5,600)
FX	0 (0,0)	0 (0,0)
SC	0 (0,0)	0 (0,0)
RS	0 (0,0)	0 (0,0)
RN	1,800 (0, 4,800)	2,000 (600, 6,000)
NW	1,000 (0, 3,800)	800 (0, 3,100)
Total (T-NASS area, not including CL)	**10,400 (4,800 29, 600)**	**10,400 (6,100, 29,000)**
IWC Central Stocks 74˚ N to 52.5˚ N	**9,100 (4,200, 24,400)**	**10,600 (5,700, 30,500)**

b. **Block**	**Abundance (assuming aversive movement)** **PI. No combined effort** **Mean (± 95% confidence intervals)**	**Abundance (assuming aversive movement)** **PI. Combined effort considered** **Mean (± 95% confidence intervals)**
CL	500 (0, 2,900)	500 (0, 2,900)
IN	7,600 (1,300 21,400)	6,600 (1,600 18,400)
FE	300 (0, 1,500)	300 (0, 1,500)
FS	900 (0, 2,600)	800 (0, 2,300)
FX	0 (0,0)	0 (0,0)
SC	0 (0,0)	0 (0,0)
RS	0 (0,0)	0 (0,0)
RN	700 (0, 2,200)	800 (100, 2,500)
NW	500 (0, 1,800)	400 (0, 1,600)
Total (T-NASS area)	**10,600 (4,000, 26,700)**	**9,500 (4,200, 23,300)**
IWC Central Stocks 74˚ N to 52.5˚ N	**10,600 (3,200, 27,400)**	**10,600 (4,000, 27,200)**

Table 4. *Abundance estimates by block for 2007 not including the extension vessels S.*

Block	**Abundance (assuming aversive movement PI Mean (± 95% confidence intervals) Combined effort considered**
CL	500 (0, 3,300)
IN	7,400 (1,800 18,800)
FE	400 (0, 1,700)
FS	900 (0, 2,700)
FX	0 (0,0)
SC	0 (0,0)
RS	0 (0,0)
RN	1,200 (300, 3,400)
NW	400 (0, 1,800)
Total (T-NASS area)	**10,900 (4,800, 26,800)**

Table 5. *Abundance estimates by block for 2007 all data assuming g(0)=1*

Block	**Abundance (assuming aversive movement) PI Mean (± 95% confidence intervals) Combined effort considered**
CL	500 (0, 2,800)
IN	7,100 (1,600 18,400)
FE	350 (0, 1,600)
FS	900 (0, 2,700)
FX	0 (0,0)
SC	0 (0,0)
RS	0 (0,0)
RN	900 (200, 2,500)
NW	400 (0, 1,700)
Total (T-NASS area)	**10,200 (4,100, 25,600)**
IWC Central Stocks 74˚ N to 52.5˚ N	**11,400 (4,000, 29,900)**

Fig. 1. *The survey blocks and realised search effort. T-NASS blocks are in solid black. The IWC central Atlantic minke stock boundary down to 52˚N assuming a western boundary equivalent to the western boundary of the T-NASS blocks RN, NW IN and CL is in green. Dotted lines show single platform effort in red. BT mode effort in black and combined mode effort in blue.*

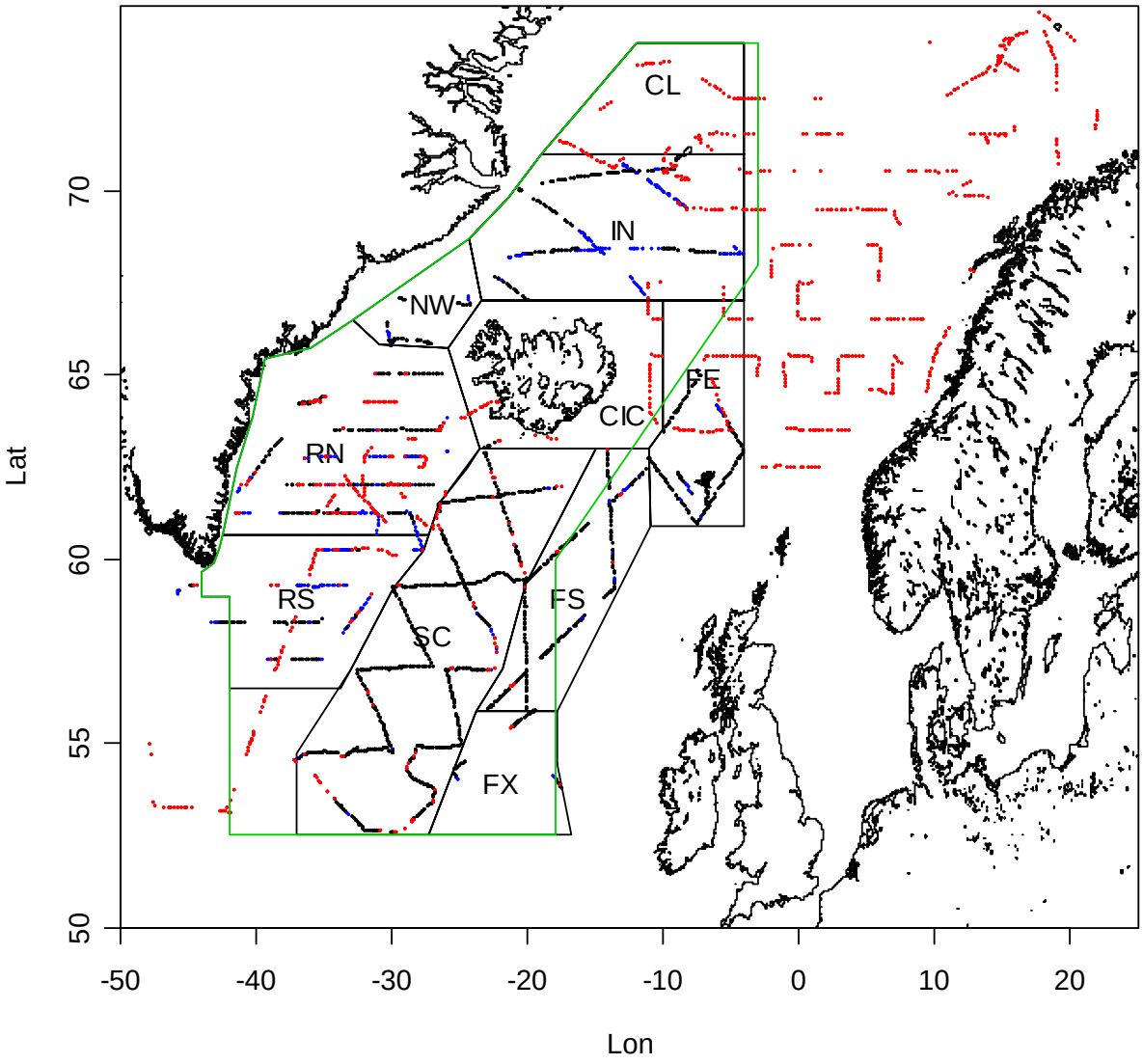

Fig. 2. *Full independence detection function. a. Conditional probability of the primary seeing a group of whales given the whale was seen by the tracker. The bars represent the proportion of trials seen within the binned distances that were seen by primaries and the points represent the conditional probability for the observed distances b. the unconditional detection function. Histogram bars rescaled to reflect the overall detection of probability and g(0). The dots (observed distances) follow the estimated detection function rescaled so that g(0) = 0.950.*

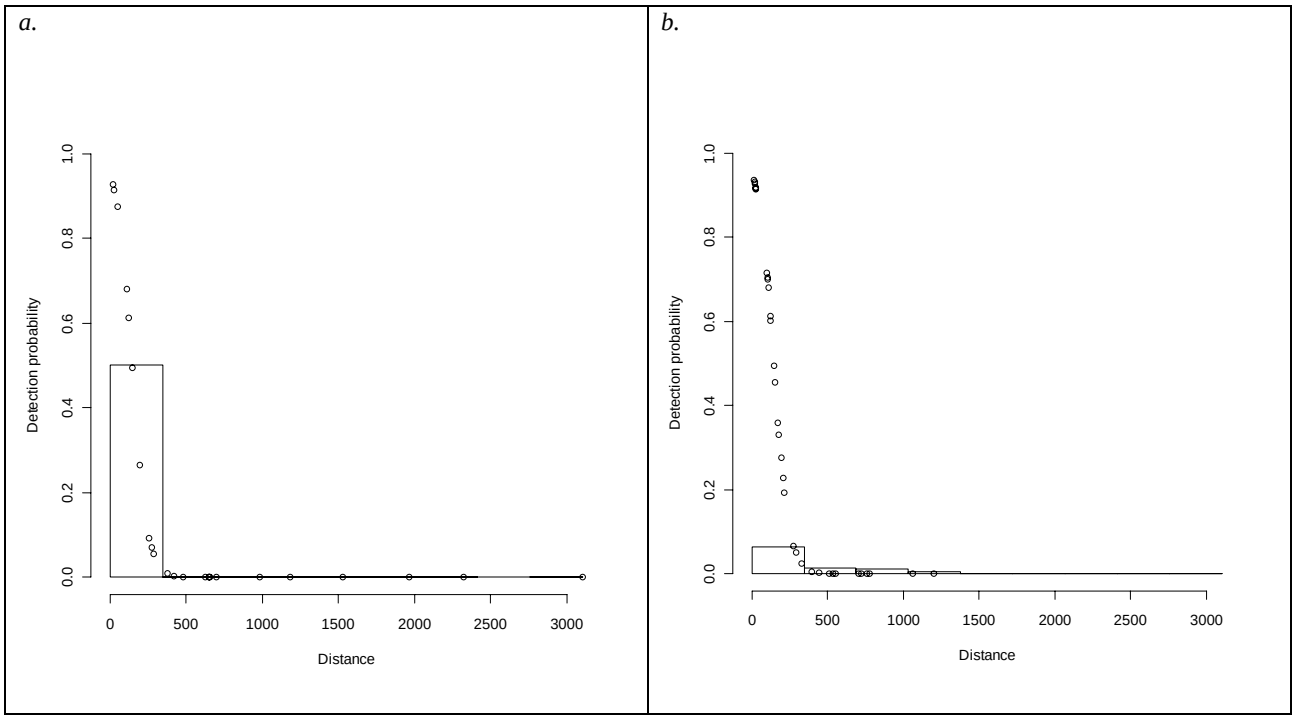
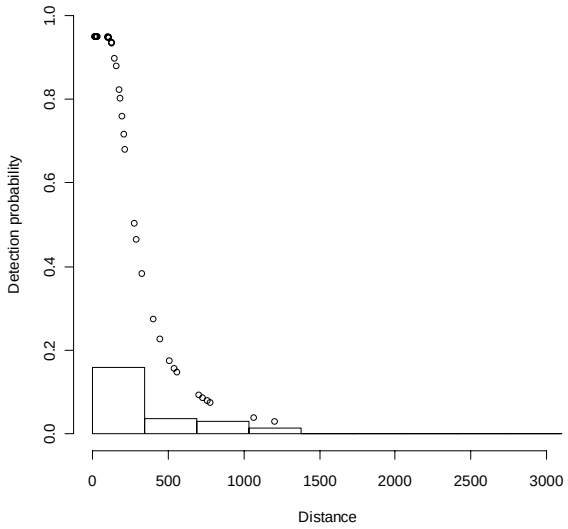
Fig. 3. *The single platform (primary) component of the point independence BT mode model. Mark recapture component is essentially the same as the full independence case. Histogram bars rescaled to reflect the overall detection of probability and g(0). The dots (observed distances) follow the estimated detection function rescaled so that g(0) = 0.950.*