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# ESTIMATES OF THE ABUNDANCE OF CETACEANS IN THE CENTRAL NORTH ATLANTIC FROM THE T-NASS ICELANDIC AND FAROESE SHIP SURVEYS CONDUCTED IN 2007

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## ABSTRACT

The Trans-North Atlantic Sightings Survey (T-NASS) carried out in June-July 2007 was the fifth in a series of large-scale cetacean surveys conducted previously in 1987, 1989, 1995 and 2001. The core survey area covered about 1.8 million nm² spanning from the Eastern Barents Sea at 34°E to the east coast of Canada, and between 52°N and 78°N in the east and south to 42°N in the west. We present design-based abundance estimates from the Faroese and Icelandic vessel survey components of T-NASS, as well as results from ancillary vessels that covered adjoining areas. The 4 dedicated survey vessels used a Buckland-Turnock (B-T) mode with a tracker platform searching an area ahead of the primary platform and tracking sightings to provide data for bias correction. Both uncorrected estimates, using the combined non-duplicate sightings from both platforms, and mark-recapture estimates, correcting estimates from the primary platform for bias due to perception and availability, are presented for those species with a sufficient number of sightings. Corrected estimates for the core survey area are as follows: fin whales (*Balaenoptera physalus*): 30,777 (CV=0.19); humpback whales (*Megaptera novaeangliae*): 18,105 (CV=0.43); sperm whales (*Physeter macrocephalus*): 12,268 (CV=0.33); long-finned pilot whales (*Globicephala melas*): 87,417 (CV=0.38); white-beaked dolphins (*Lagenorhynchus albirostris*): 91,277 (CV=0.53); and white-sided dolphins (*L. acutus*): 81,008 (CV=0.54). Uncorrected estimates only were possible for common minke whales (*B. acutorstrata*): 12,427 (CV=0.27); and sei whales (*B. borealis*): 5,159 (CV=0.47). Sighting rates from the ancillary vessels, which used a single platform, were lower than those from the dedicated vessels in areas where they overlapped. No evidence of responsive movement by any species was detected, but there was some indication that distance measurements by the primary platform may have been negatively biased. The significance of this for the abundance estimates is discussed. The relative merits of B-T over other survey modes are discussed and recommendations for future surveys provided.

*Keywords: NASS, North Atlantic, cetaceans, abundance, surveys, Balaenoptera, physalus, musculus, borealis, acutorostrata, Megaptera, Physeter, Globicephala, Lagenorhynchus, whales, dolphins, distribution*

## INTRODUCTION

The Trans-North Atlantic Sightings Survey (T-NASS) was the fifth in a series of large-scale cetacean surveys (NASS) conducted previously in 1987, 1989, 1995 and 2001 (Pike, 2009), and was coordinated through the Scientific Committee of the North Atlantic Marine Mammal Commission (NAMMCO). The overall T-NASS project was the largest of the series, with 5 nations (Norway, Faroe Islands, Iceland, Greenland and Canada) participating directly with survey platforms, and Russia providing support in planning, logistics and personnel. The survey was also coordinated with simultaneous cetacean surveys conducted in offshore European waters (CODA survey, Hammond et al., 2009, 2013) and off the northeastern USA (SNESSA survey, NAMMCO, 2009). For the first time, a trans-Atlantic survey was achieved, adding areas to the west of Greenland and the eastern coast of Canada to the core NASS strata areas to the east (NAMMCO, 2016). The 5 vessels and 4 aircraft of the core survey covered over 54,000 nm of on-effort transects in an area of about 1.8 mill. nm², spanning from the Eastern Barents Sea at 34°E to the East coast of Canada, and between 52°N and 78°N in the east and south to 42°N in the west. Over 3,000 cetacean sightings of 18 species were made during the survey. By most measurements the 2007 T-NASS was the largest single wildlife survey ever conducted.

The main purpose of this as well as previous NASS has been to obtain information on abundance necessary to assess the conservation status of cetaceans in the North Atlantic required for effective management relating to direct human impacts such as whaling, fisheries interactions (by-catch, entanglements, *etc.*) and ship strikes as well as noise pollution, chemical contaminants, whale watching and anthropogenic climate change. Whaling is carried out in Norway (common minke whales (*Balaenoptera acutorostrata*)), Iceland (common minke and fin (*B. physalus*) whales), the Faroe Islands (long-finned pilot whales (*Globicephala melas*)) and Greenland (common

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minke, fin, long-finned pilot and humpback (*Megaptera novaeangliae*) whales), making periodic abundance estimates of particular importance for the conservation of these species.

Up to and including the 2001 survey, NASS have shown changes in the distribution and abundance of some species, in particular increases in the numbers of fin and humpback whales in the central North Atlantic (Sigurjónsson, 1992; Paxton et al., 2009; Pike et al., 2019a; Pike et al., 2005; Pike , Paxton, Gunnlaugsson, & Víkingsson, 2009; Víkingsson et al., 2009, 2015). The extensive spatial coverage and time scale (20 years) provided by the NASS and T-NASS present an opportunity to determine if these trends are continuing, and to put them in the context of a larger area of the North Atlantic and ongoing environmental changes.

Here we present design-based abundance estimates from the Faroese and Icelandic vessel survey components of T-NASS for those species with a sufficient number of sightings (>30): fin, humpback, common minke, sei (*B. borealis*) long-finned pilot and sperm whales (*Physeter macrocephalus*), and white-beaked (*Lagenorhynchus albirostris*) and white-sided (*L. acutus*) dolphins. All estimates are corrected for known biases, including visible sightings missed by observers (perception bias) and whales which were submerged and invisible to the primary platform during vessel passage (availability bias) to the extent feasible, and possible remaining biases are identified and discussed. We also present results from associated extension surveys carried out from vessels conducting fisheries research outside of the core T-NASS survey area, in order to assess the distribution of cetacean species in areas that were not covered in the dedicated survey.

## MATERIALS AND METHODS

### <u>Vessels</u>

In the Central North Atlantic component of the T-NASS dealt with in this paper (Figure 1), 4 vessels were employed as dedicated survey vessels (Table 1), each one equipped with 2 observing platforms. Three of these were dedicated solely to the cetacean survey, while a fourth was also engaged in conducting redfish (*Sebastes* spp.) surveys with an additional cetacean survey component. While this latter vessel was equipped and manned for full scale double platform survey it steamed day and night, largely independent of weather conditions, stopping or slowing periodically for trawling and oceanographic operations. The cetacean survey on this ship was conducted during daylight hours when conditions were acceptable and the vessel was moving at survey speed (see below).

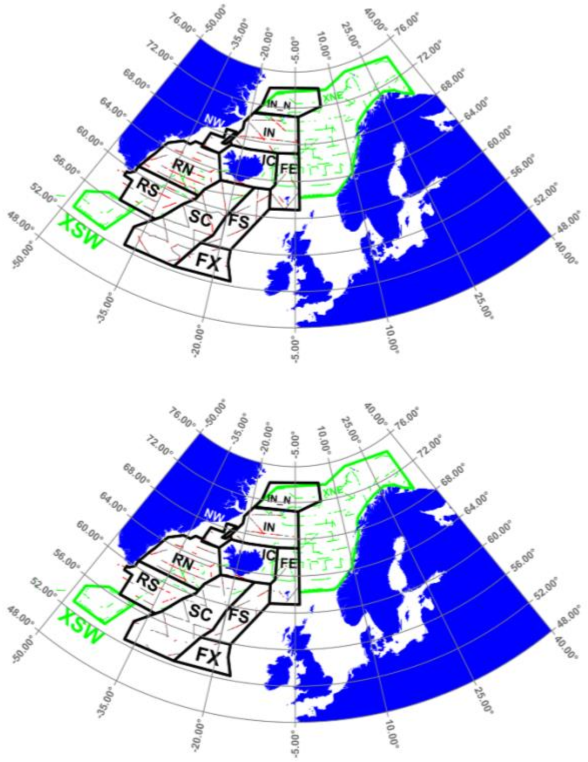


Figure 1. Stratification and realized effort at BSS<6 (top) and BSS<4 (bottom). Effort conducted in B-T mode is shown in red and effort by extension vessels is shown in green. No dedicated survey effort was realized in the planned stratum IN_N.

Five additional vessels were employed as "extension" vessels, each carrying 2 observers operating from a single platform (Table 1). Two of these were part of the redfish survey (a Russian (S in Table 1) and a German vessel), 2 (E and L) were part of an annual Russian-Norwegian pelagic fish survey in the Norwegian Sea, and one was part of the MarEco survey on the mid-Atlantic Ridge. However, the German Redfish and the MarEco survey vessels did not generate data that could be used in this analysis. The 3 remaining extension vessels covered a large area to the northwest and a smaller area to the southwest of the main survey area (Figure 1). They also overlapped with the main survey area in some areas (Table 1).

Table 1. Survey vessels used in the T-NASS dedicated (D) and extension (X) surveys. Platform height (m) (PLAT HT) is given for the tracker (T) and primary platforms. For vessels L and E, observers could be on the bridge or bridge roof, thus 2 heights are given. See Figure 1 for location of strata.

| SURVEY | NAME | PERIOD | ID | OBS | PLAT HT | | STRATA |
|---|---|---|---|---|---|---|---|
| | | | | T/P | T | P | |
| D | JákupB | 0628-0723 | J | 4/2 | 12.2 | 10 | IC, SC |
| D | Venus | 0701-0723 | V | 4/2 | 11.9 | 8.9 | IN, NW |
| D | AF RE200 | 0625-0724 | A | 4/2 | 18.6 | 15.3 | RN, RS |
| D | ThorChaser | 0715-0807 | F | 4/2 | 10.9 | 8.8 | FE, FS, FX |
| X | Libas | 0715-0807 | L | /2 | | 16/19 | XNW, FE, IC, IN |
| X | Eros | 0715-0807 | E | /2 | | 15/17 | XNW, FE, IC, IN |
| X | Smolensk | 0623-0707 | S | /2 | | 8.2 | XNW, XSW, FE, IC, RN, RS, SC |

**Survey design**

Transects for the strata covered by the dedicated vessels, other than blocks RN and RS, were designed using the program DISTANCE (Thomas et al., 2010) (Figure 1). In these blocks a double set of equal-spaced zig-zag transects, starting from a random point along the design axis, was applied. The amount of effort allocated to individual strata was based on the density of target species realized in previous surveys and available ship time. In blocks RN and RS, the redfish survey tracks were designed by the ICES Redfish group in consultation with organizers of the cetacean survey and consisted primarily of equally-spaced parallel east-west transects across the strata.

Transects covered by the extension vessels were designed for their primary purpose as fish surveys, with cetacean observations as a secondary objective. These vessels cruised continuously and stopped or slowed periodically for trawling operations, limiting cetacean observations to periods of suitable weather during daylight hours when the vessel was moving. Strata were mapped post-survey, encompassing the 2 major areas of coverage to the northeast and southwest of the main survey area (Figure 1).

**Field methodology**

For the dedicated survey vessels, the basic methodology followed the Buckland and Turnock (B-T) mode (Buckland & Turnock, 1992) and the operation protocol and guidelines were shared with the simultaneous CODA survey (Hammond et al., 2009, 2013). In this configuration, observers on a "tracker" platform scan ahead of the viewing field of observers on the primary platform, reducing or eliminating correlation in platform detection due to availability and enabling the detection of responsive movement if it occurs after detection by the tracker observers (Burt et al., 2014). On all vessels, observers on the primary platform operated independently of the tracker platform, but made all sightings known to that platform by informing the duplicate identifier situated on the tracker platform of all sightings while they were happening. Therefore, the primary platform operated independently from, but was monitored by the tracker platform, but the converse was not true (1-way independence). The tracker platform did not inform the primary platform of any sighting or tracking activities.

The tracker platform was staffed by 2 observers, a duplicate identifier (who acted as a third observer when not identifying duplicates), and a data recorder who entered sightings data from both platforms and also recorded environmental and survey data. The primary platform was staffed by 2 observers, who relayed their observations to the data recorder and duplicate identifier on the tracker platform.

On the primary platform the general practice was to spot animals with the naked eye, but binoculars were used for identifying animals at long ranges. Observers on the primary platform concentrated their searching effort between ±90° of the bow and within a 500 m radial distance from the ship. One observer on the tracker platform used 7x50 binoculars, scanning the area between ±60° of the bow. The other observer used "Big-Eyes" 25x150 binoculars when conditions were favourable, scanning the area between ±40° of the bow. When conditions were not favourable for Big-Eye use that observer also searched with 7x50 binoculars. Both concentrated their efforts at distances greater than 500 m from the vessel to the horizon. Sightings were tracked until they were observed (duplicated) by the primary platform or until they passed abeam. The purpose of the tracking procedure was to provide trials for mark-recapture distance sampling (MRDS) in order to estimate the proportion of visible sightings missed by the primary platform, and to detect any directed movements by cetaceans in response to the vessel (responsive movement). All species except sperm whales were tracked, but priority was given to tracking common minke whales.

For many sightings there was uncertainty in species identification. Sightings were categorized by the observers according to the degree of identification certainty as High, Medium or Low. Groups were defined as animals that were moving together within 2 to 3 body lengths of one another, and distance was estimated to the geometric centre of the group.

Duplicate identification was performed in the field by the duplicate identifier situated on the tracker platform, based on coincidence in sighting times, angles, species ID and group size. In high density areas, duplicate identification was sometimes performed post-survey based on the recorded data. Duplicate certainty was classified as definite (90% likely), probable (>50% likely) or remote (<50% likely), with only the first 2 categories included as duplicates in the analysis. Whales for which species remained unidentified by either platform were not considered duplicates.

Distance was estimated from the tracker platform primarily using binocular reticle readings of the distance between the sighting and the horizon. On the primary platform, observers used "Distance Sticks" (rulers) to measure the same distance with the stick held at a set distance from the user's eyes. Lateral angle from the bow of the vessel to the sighting was estimated using angle boards. Training exercises in which observers measured distances to a buoy were conducted at the beginning of the survey.

Searching was usually abandoned in poor visibility, in Beaufort Sea state (BSS) 6 or more, or when visibility from the vessel was 1 nautical mile (nm) or less. Operation of the tracking platform ceased at BSS exceeding 4, above which the survey would revert to a combined platform mode, with 2-way communication between the platforms.

When sightings were abeam, the platforms on the dedicated vessels (other than vessel A) could communicate and if identification and/or group size was still uncertain, the vessel could stop and/or approach the sighting for closer inspection, afterwards returning to 45° angle in relation to the track line while off-effort. Otherwise, and for vessel A and the extension vessels, the survey was executed in passing mode.

Data were recorded using the program Logger (International Fund for Animal Welfare, 2010), which integrates vessel GPS data with user-customized data entry forms, as well as audio recordings by observers and webcam images of the angle board readings. Data were validated daily by observers during off-hours. In the event of equipment failure, data were recorded on audio recordings and paper forms.

Observers on the extension vessels operated in a manner identical to those on the primary platform of the dedicated vessels, but sometimes used only a single observer covering both sides of the transect.

**Data treatment**

**Post-stratification**

No dedicated effort was realized in stratum IN_N because of a late start by vessel V. Parts of the survey area off northwest Iceland and near East Greenland were covered in pack ice, precluding survey. Post stratification based on realized effort and ice maps of the area during the survey period reduced the size of blocks NW, RN and IN.

Strata were derived for the extension survey after completion of the survey based on the extent of realized effort and are shown in Figure 1, comprising a large area to the northeast of the main survey area (XNE) and another smaller one to the southwest (XSW). Some effort (70 nm) was realized farther west by vessel S but no sightings were made in this area.

**Species identity**

For those species for which low certainty sightings comprised >10% of the total (fin and sei whales), the sensitivity of abundance to this factor was assessed by calculating separate estimates using: 1. sightings for all 3 certainty levels, the "ALL" estimate; and 2. sightings for the high and medium certainty categories, the "MED" estimate. For other species, only the ALL estimate is presented.

**Data selection**

The analytical procedure used required that all information about a sighting seen by both platforms (i.e., angle, radial distance, group size, species identification) be the same. Measurements from the tracker platform were generally used as this was the higher platform and observers had usually tracked the sighting for longer than the primary platform, and the distance measurement closest to the point of duplication was used in the analysis. For non-duplicated sightings, the last distance before abeam was generally used in the analysis (unless it was considered unreliable by the observer) as these were considered more accurate due to a larger angle to the trackline and larger declination for radial distance reading.

**Beaufort sea state**

Only data recorded in a BSS of 5 or less were used in the analyses for large (fin, humpback, sei and sperm) whales, while data were limited to BSS 4 or less for long-finned pilot whales and BSS 3 or less for common minke whales and dolphins, in conformity with previous analyses of NASS data (Pike et al., 2019a; Pike, Gunnlaugsson, Víkingsson, & Bloch, 2009)

**Analysis**

**Responsive movement**

To determine whether cetaceans reacted to the vessel by moving towards or away from the trackline as it approached, we extracted a sample of sightings by the tracker platform of the same group separated by 2 minutes or more, and duplicate sightings separated by 2 minutes or more. We used multiple linear regression to model last primary (LP) and last tracker (LT) perpendicular distances with independent variables distance at first tracker sighting (FT), time interval between re-sightings (INT), vessel identity and species identity. The best model was chosen as that with the lowest value of Akaike's Information Criterion (AIC). Swimming direction was available for a sub-set of tracker platform sightings. We used Fisher's Exact Test to determine if there was any evidence to suggest that animals swimming towards the trackline were duplicated at a higher rate than those swimming away from the trackline. We also assessed the power of this test using simulation methods

**Combined platform estimates**

For the dedicated survey vessels with 2 platforms, unique and duplicate sightings by the tracker and primary platforms were combined for an uncorrected single platform analysis.

Density and abundance were estimated using stratified line transect methods using the DISTANCE 6.2 software package (Thomas et al., 2010). The perpendicular distance data were right-truncated to include about 90% of sightings to reduce the leverage of distant sightings and in some cases to eliminate the need for adjustment terms. Separate detection functions for the dedicated and extension vessels were developed when the number of sightings allowed this; if not, a combined detection function including a covariate (see below) for survey identity was used to estimate abundance in the extension strata.

The Hazard Rate and Half Normal models for the detection function $f(x)$ were initially considered and the final model was chosen by minimization of AIC (Buckland et al., 2001). Covariates were considered for inclusion in the model to improve precision and reduce bias. Covariates were incorporated into the detection function through the scale parameter in the key function (Thomas et al., 2010). Covariates were retained only if the resultant AIC value was lower than that for the model without the covariate. The following covariates were considered: vessel identity, BSS, cloud coverage (scale 1=0%-24%, 2=25%-69%; 3=70%-89%; 4=>90%), visibility (nm), species identification certainty (0=high confidence; 1=medium confidence; 2=low confidence) and platform making the sighting (primary, tracker or duplicate). In cases where covariates were retained, the detection function was estimated at the stratum level and could therefore vary in scale by stratum depending on covariate levels. Encounter rate was estimated at the stratum level, as was expected cluster size in cases where there were significant differences between strata. Stratum and total variance were estimated using the method of Innes et al. (2002).

The number of sightings of dolphins of genus *Lagenorhynchus* (white-beaked and white-sided) was not sufficient to develop a separate detection function for each species. Therefore, a combined detection function for both species, including species identity as a covariate, was used.

**Double platform analyses**

Due to poor weather conditions, a substantial proportion of effort (28% at BSS<6) was conducted in single platform mode (Table 2), during which both platforms were staffed and in communication. Only effort and sightings realized in B-T mode could be included in this analysis as effort conducted in single platform mode did not use the identical observer configuration (i.e., 1 platform with 2 observers) used on the primary platform in B-T mode.

Density and abundance were estimated using stratified mark-recapture distance sampling (MRDS) techniques (Laake & Borchers, 2004) using the DISTANCE 6.2 software package (Thomas et al., 2010). Because observers on the tracker platform were aware of sightings made by observers on the primary platform, the platforms were not totally independent. Therefore the "trial configuration" (Laake & Borchers, 2004), in

Table 2. Stratification and survey effort at 2 levels of Beaufort sea state for the dedicated (D) and extension (E, shaded yellow) surveys. K = number of transects, TOT = total effort, B-T = effort in Buckland-Turnock mode.

| BLOCK | AREA (nm$^2$) | K | | EFFORT (nm) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | BSS<6 | | | BSS<4 | | |
| | | D | E | D | | E | D | | E |
| | | | | TOT | B_T | S | TOT | B_T | S |
| FE | 61,866 | 5 | 1 | 511 | 448 | 407 | 280 | 269 | 281 |
| FS | 80,255 | 4 | | 865 | 786 | | 647 | 580 | |
| FX | 57,776 | 3 | | 151 | 119 | | 48 | 44 | |
| IC | 0 | 2 | 7 | 106 | 21 | 239 | 106 | 21 | 195 |
| IN | 91,873 | 5 | 10 | 772 | 400 | 278 | 499 | 346 | 273 |
| NW | 17,237 | 4 | | 140 | 109 | | 126 | 95 | |
| RN | 123,981 | 7 | 10 | 1,478 | 790 | 386 | 1,128 | 742 | 308 |
| RS | 91,577 | 5 | 4 | 639 | 273 | 246 | 382 | 220 | 178 |
| SC | 206,706 | 10 | 1 | 2,532 | 2,228 | 110 | 1,405 | 1,325 | 61 |
| XSW | 57,705 | | 11 | | | 311 | | | 227 |
| XNE | 383,486 | | 57 | | | 2,939 | | | 2,457 |
| XW | 0 | | 1 | | | 70 | | | 70 |
| **TOTAL_NASS** | **731,271** | **45** | **33** | **7,192** | **5,175** | **1,666** | **4,621** | **3,641** | **1,295** |
| **TOTAL_EXT** | **441,191** | **0** | **69** | **0** | | **3,319** | **0** | | **2,754** |

which the secondary (tracker) platform serves to generate trials to estimate the proportion of sightings on the trackline that are seen by the primary platform ($p(0)$) was used. Note that the $p(0)$ derived here cannot be applied to the combined platform estimates described above as different platform configurations were used. We initially attempted 2 types of analyses: using the assumption of "full independence" (FI) wherein sightings from the platforms are considered independent at all perpendicular distances, and under the assumption of "point independence" (PI), wherein the probability of detection by the tracker and primary platforms is assumed to be independent only on the trackline (Laake & Borchers, 2004). FI models were selected if responsive movement was suspected. Otherwise the AIC values resulting from both approaches were compared before deciding on a final model. The assumption of point independence requires the estimation of 2 detection functions: one for primary platform detections, and the other for primary platform detections conditional on detection by the tracker platform (conditional detection function), whereas the assumption of full independence requires only the latter detection function.

The detection function for the primary platform only was modelled as described above for the combined platforms. The conditional detection function was implemented as a logistical model with the same covariates (except for platform identity) available as for the primary platform detection function. Again, the final model was chosen by minimization of AIC, after the primary platform detection function had been finalized.

## RESULTS

### Realized survey effort.

Technical difficulties were encountered with the 3 vessels departing from the Faroe Islands. For 2 of the vessels, these were limited to difficulties in setting up and installing the observation platforms, resulting in a departure delay of a few days. The third vessel exhibited such mechanical and technical challenges that it was finally replaced, resulting in a 6-day delay in departure. The delay accumulated at departure, combined with the inclement weather encountered, considerably restricted the effective time available for the survey. Due to this time restriction, block IN_N was not surveyed.

Realized survey effort is summarized in Table 2 and Figure 1. Restriction to effort conducted at BSS<4, required for estimates of common minke whales and dolphins, reduced total available effort by 36% compared to effort conducted at BSS<6 on the dedicated vessels, and 11% for effort conducted in B-T mode. A comparable reduction of 17% was realized on the extension vessels. Realized effort was particularly low on the western side of the survey area near the East Greenland coast, where pack ice and associated fog often precluded completing the survey transects.

There was overlap between the dedicated and extension vessels in 6 of 9 survey strata (Table 2). We compared encounter rate or density (in cases where the number of sightings by extension vessels allowed) between the dedicated and extension vessels in these areas to estimate the sighting efficiency of the extension vessels.

**Sightings and distribution**

Cetacean sightings are illustrated in Table 3 and Figure 2.

As in most previous NASS, fin whales were most commonly sighted to the west of Iceland in block RN. Substantial numbers were also sighted south of Iceland in block SC. In total, 19 fin whales were sighted by the extension vessels, most of these in the large XNE area to the northeast of the core survey area. Most fin whale sightings were of single animals with groups larger than 3 comprising only 2% of the sample. Sightings with low certainty in species identification accounted for 12% of the total but this proportion was higher (19%) for the extension vessels.

Encounter rates for humpback whales were highest in the northwest parts of the survey area, in blocks IN, NW and RN. The extension vessels sighted 8 humpback whales in the T-NASS core area, all but one of them in block IN. These vessels also sighted a few humpback whales in block XNE to the northeast of the main survey area. Groups of up to 5 animals were observed, with groups of 1 or 2 whales comprising 88% of the sample. Humpback whales were identified with relatively high certainty, with only 9% classified as low certainty sightings.

Sei whales were sighted to the south and southwest of Iceland, and none were sighted southeast of Iceland. A large number were sighted at the southern extremity of the survey area in stratum SC. Group size ranged from 1 to 3 but single animals comprised the majority (62%) of the sightings made by the dedicated vessels. The extension vessels sighted 15 sei whale groups, all but one of these outside of the core survey area. Most were sighted in block XSW to the southwest of the core survey area. All but 2 of the sei whales sighted in the extension survey had low certainty species identification.

Common minke whales were most commonly sighted to the north of Iceland in block IN. Several were also sighted off the Faroe Islands (block FE). Few were sighted northwest of Iceland but there was little effort realized in the NW block. In total, 13 sightings of common minke whales were made by the extension vessels in the core survey area, most in block IN. Most sightings by the extension vessels were made in XNE to the northeast of the core survey area. Most sightings (89%) were of single animals and the maximum observed group size was 3. Common minke whales were identified with relatively high certainty, with only 9% classified as low certainty identifications.

Table 3. Sightings of cetaceans by stratum (D = dedicated vessels, E = extension vessels). Strata and sightings by extension vessels are shaded. BP = fin whale, BB = sei whale, MN = humpback whale, BA = common minke whale, PM = sperm whale, LL = white-beaked dolphin, LC = white-sided dolphin, Number of ? indicates the maximum level of uncertainty of species identification included in the sum.

| BLOCK | BP | | | | BB | | | | MN | | PM | | BA | | LC | | LL | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BP? | | BP?? | | BB? | | BB?? | | MN?? | | PM?? | | BA?? | | LC?? | | LL?? | |
| | D | E | D | E | D | E | D | E | D | E | D | E | D | E | D | E | D | E |
| FE | 1 | | 1 | | | | | | | 1 | 4 | 3 | 7 | 4 | | | | |
| FS | 5 | | 5 | | | | | | 4 | | 6 | | 3 | | 4 | | | |
| IC | | | | | | | | | | | | | 1 | | | | | 1 |
| IN | 10 | 3 | 12 | 3 | | | | | 30 | | 2 | 2 | 15 | 9 | | | 9 | |
| NW | 4 | | 7 | | | | | | 40 | | 2 | | 3 | | | | 13 | |
| RN | 208 | 8 | 228 | 14 | 7 | | 11 | | 9 | | 21 | | 5 | | 7 | | 4 | |
| RS | 23 | | 30 | | 1 | 1 | 3 | 1 | 1 | | 10 | | | | 1 | 1 | 2 | 1 |
| SC | 58 | 2 | 70 | 2 | 29 | | 30 | | | | 28 | | 1 | | 11 | | | |
| XSW | | 3 | | 3 | | 10 | | 13 | | 0 | | 0 | | 0 | | 2 | | 0 |
| XNE | | 10 | | 10 | | 2 | | 2 | | 6 | | 23 | | 15 | | 1 | | 26 |
| **TOT_NASS** | **309** | **13** | **353** | **19** | **37** | **1** | **44** | **1** | **84** | **1** | **73** | **5** | **35** | **13** | **23** | **1** | **28** | **2** |
| **TOT_NASS_ EXT** | **322** | | **372** | | **38** | | **45** | | **85** | | **78** | | **48** | | **24** | | **30** | |

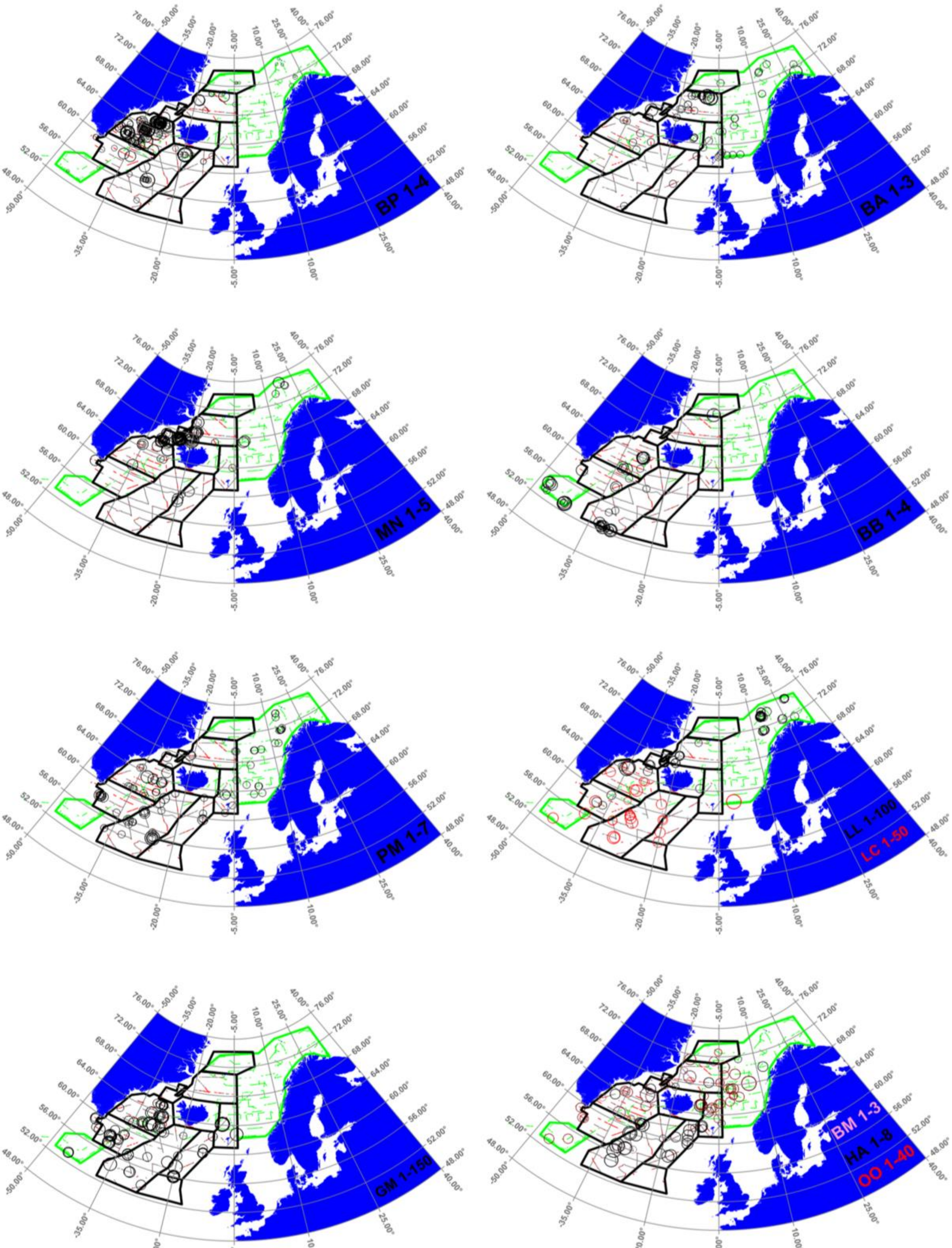


Figure 2. Sightings of cetaceans. Symbol size is proportional to group size indicated on the panels. BP – fin whale; BA – common minke whale; MN – humpback whale; BB – sei whale; PM – sperm whale; LL – white-beaked dolphin; LC – white-sided dolphin; GM – long-finned pilot whale; BM – blue whale; HA – northern bottlenose whale; OO – killer whale.

Sperm whales were found throughout the survey area but were seen in greatest numbers around the Faroes and to the south and west of Iceland. In addition, the extension survey made scattered sightings throughout the central Norwegian Sea. The majority of sightings (78%) were of single animals and the Sperm whales were generally identified with high certainty and only 8% of sightings were classified in the lowest certainty class.

White-beaked dolphins were seen at the western side of the survey area, and in the northern Norwegian Sea and Barents Sea by the extension survey. The modal group size was 7 but groups as large as 100 were rarely observed. Only 6% of sightings were of the lowest species certainty class.

White-sided dolphins were observed south of Iceland, especially in strata FS, SC and RN. Only 2 sightings were made in the extension strata. Group sizes of 2-12 were most common, with occasional sightings of groups of up to 50 in number. Only 6% of sightings were of the lowest species certainty class.

Long-finned pilot whales were sighted south of 65° throughout the core T-NASS strata, but were most frequently sighted to the southwest of Iceland. Group size ranged from 1 to 50 but groups of 10 or less were most common. Long-finned pilot whales were generally identified with certainty, with the least certain category accounting for only 5% of the total.

Other species sighted in the survey by dedicated T-NASS and extension vessels, respectively, included: blue whales (14, 3), northern bottlenose whales (*Hyperoodon ampullatus*) (28, 7), harbour porpoises (*Phocoena phocoena*) (19, 0) and killer whales (*Orcinus orca*) (11, 26) (Figure 2).

**Responsive movement**

Results of the regression analyses of last tracker (LT) and last primary (LP) perpendicular distances for sightings separated by 2 min or more are shown in Table 4 and Figure 3. Using tracker sightings only, for all vessels and species combined (Reg. 1, Table 4), LT was best modelled using first tracker perpendicular distance (FT) only and the slope of the regression was not significantly different from 1 (P>0.05). Restriction to sightings that were duplicated by the primary platform produced a similar result (Reg. 2, Table 2). Regressions restricted to sightings by individual vessels or of single species all had slope terms not significantly different from 1 (Regs. 3-11, Table 4). This provides no evidence for responsive movement by any species; however insufficient trackings (<5) were available for sperm whales, white-beaked dolphins and sei whales to warrant analysis.

LP was also best predicted using FT only for sightings by all vessels and for all species combined (Reg. 12, Table 4), but for this relationship the estimated slope was 0.66 and significantly lower than 1 ($P$<0.05). Regressions restricted to sightings of fin whales, humpback whales or white-sided dolphins produced similar results (Regs. 17-19, Table 4), but there were too few duplicates of other species with >2 min. time separation to warrant analysis. This is suggestive of a measurement bias by the primary platform, but other explanations are possible (see Discussion). Regressions restricted to sightings by individual vessels suggested that the slope was lower on vessel V than on the others, and compared to the combined sightings of vessels A and J, the slope of the regression from vessel V was significantly ($P$<0.05) lower.

Swim direction was recorded for 35% of tracker platform sightings. Of these, 19% were moving approximately parallel to the trackline, either in the same or the opposite direction as the survey vessel.

Of non-duplicated tracker platform sightings, 44% were recorded as moving towards the trackline, while 37% of duplicated sightings were moving towards the trackline (Table 5); however, these proportions are not significantly different (Fisher's Exact Test, $P$=0.30). Simulation indicated that the proportion of whales moving towards the trackline in the duplicated sample would have to approach 70% to be significantly different ($P$<0.05) than the proportion in the non-duplicated sample. This test was repeated for all species with sufficient numbers of tracker sightings with swim direction (>5), and in no case was there evidence that the proportions differed ($P$>0.05).

**Abundance estimates**

Specifications of the models used in estimating abundance are provided in Table 6 and are described by species below. Detection functions are shown in Figure 4. Tabulated uncorrected and corrected abundance estimates are presented by species in Table 7 and in greater detail in Supplementary Files 1-14.

**Fin whales**

Employing a right-truncation distance of 2,500 m, a half-normal function with no adjustment terms provided the best fit for data both excluding and including sightings from the extension vessels, and addition of a covariate for vessel identity with vessels V and F combined improved the fit for data from the T-NASS core survey. Uncorrected density and abundance (Table 7, Supplementary File 1) were highest in block RN, which alone accounted for 53% of the total abundance estimate of 24,824 (CV=0.15, 95% CI: 18,347 - 33,589). Exclusion of the lowest species identification certainty category would reduce this estimate by 12%. Uncorrected abundance in the area covered by the extension vessels was 2,263 (CV=0.46, 95% CI: 943 - 5,434), and stratum XNE accounted for 75% of this total. Encounter rate for the dedicated vessels in the T-NASS blocks where overlap with the extension vessels occurred was 5 (CV=0.46) times greater than that for the extension vessels (Table 8).

Corrected estimate

Observers on the primary platforms duplicated 66% of the sightings made by the observers on the tracker platform while in B-T mode (Table 8). This varied between vessels from 33% on vessel V to 80% on vessel F. The same model described above for the combined data provided best fit for the primary platform data alone. Lowest AIC was realized using a point independence model with perpendicular distance as a covariate in the conditional detection model, which resulted in an estimated $p(0)$ of 0.73 (CV=0.11) for the primary platform. Total corrected abundance for the T-NASS core area was 30,777 (CV=0.19, 95% CI: 21,153 - 44,779) (Table 7, Supplementary File 2).

Table 4. Linear regressions of perpendicular distances to the same sighting separated by 2 minutes or more (FT - first tracker distance; LT – last tracker distance; LP – last primary distance). Upper and lower 95% confidence limits for the slope (LCL and UCL) are given. 1Restricted to duplicate sightings. *** P<0.001, ** P<0.01, NS – P>0.05; BP – fin whale; MN – humpback whale; LC – white-sided dolphin; BA – common minke whale.

| REG. NO. | | X | Y | SPECIES | VESS | n | $R^2$ | SLOPE | LCL | UCL |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *** | FT | LT | ALL | ALL | 83 | 0.79 | 1.03 | 0.91 | 1.15 |
| 2 | *** | FT | LT | ALL[1] | ALL | 42 | 0.76 | 0.95 | 0.78 | 1.11 |
| 3 | *** | FT | LT | ALL | A | 24 | 0.83 | 0.97 | 0.78 | 1.17 |
| 4 | *** | FT | LT | ALL | J | 19 | 0.79 | 1.09 | 0.82 | 1.36 |
| 5 | *** | FT | LT | ALL | V | 37 | 0.77 | 1.05 | 0.86 | 1.24 |
| 6 | *** | FT | LT | ALL | AJ | 43 | 0.81 | 1.02 | 0.86 | 1.17 |
| 7 | *** | FT | LT | BP | ALL | 30 | 0.77 | 1.03 | 0.82 | 1.24 |
| 8 | *** | FT | LT | MN | ALL | 24 | 0.77 | 0.98 | 0.75 | 1.21 |
| 9 | NS | FT | LT | BA | ALL | 6 | | | | |
| 10 | ** | FT | LT | LL | ALL | 5 | 0.92 | 1.35 | 0.79 | 1.91 |
| 11 | *** | FT | LT | LC | ALL | 9 | 0.93 | 0.95 | 0.74 | 1.16 |
| 12 | *** | FT | LP | ALL | ALL | 69 | 0.71 | 0.66 | 0.56 | 0.76 |
| 13 | *** | FT | LP | ALL | A | 33 | 0.83 | 0.82 | 0.69 | 0.95 |
| 14 | *** | FT | LP | ALL | J | 13 | 0.67 | 0.77 | 0.43 | 1.11 |
| 15 | *** | FT | LP | ALL | V | 23 | 0.68 | 0.36 | 0.25 | 0.47 |
| 16 | *** | FT | LP | ALL | AJ | 46 | 0.8 | 0.81 | 0.69 | 0.93 |
| 17 | *** | FT | LP | BP | ALL | 38 | 0.79 | 0.77 | 0.64 | 0.9 |
| 18 | *** | FT | LP | MN | ALL | 17 | 0.65 | 0.59 | 0.36 | 0.82 |
| 19 | *** | FT | LP | LC | ALL | 5 | 0.97 | 0.8 | 0.6 | 1.01 |

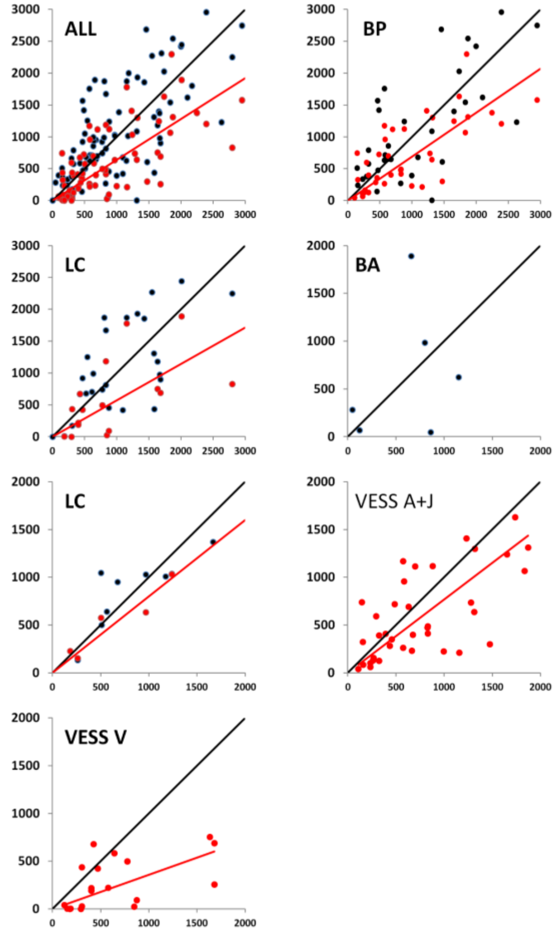


Figure 3. Perpendicular distance (m) at first (x-axis) and last (y-axis) tracker sighting (black symbols) or last (y-axis) primary sighting (red symbols) for duplicates separated by 2 minutes or more. Trendlines are shown for X=Y (black line) and the regression for last primary sightings (red line, regression details in Table 4). ALL – all species; BP – fin whale; MN – humpback whale; BA – common minke whale; LC – white-sided dolphin; VESS – vessel identity.

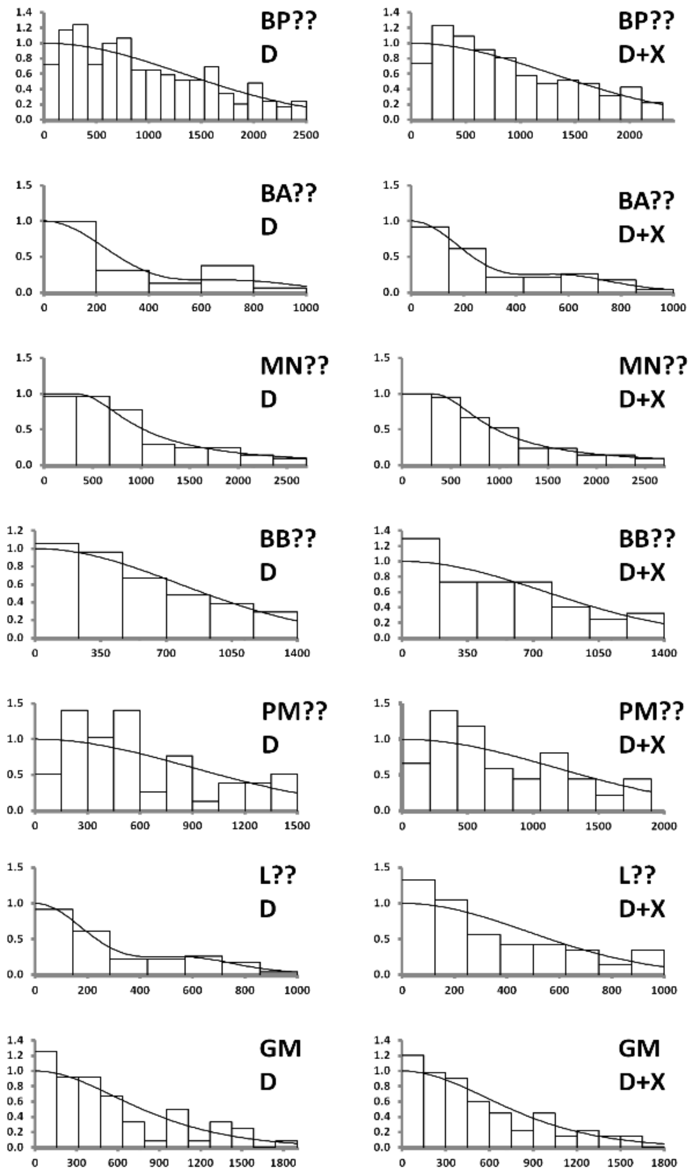

Figure 4. Detection functions for the combined platforms. Number of ?? indicates level of species certainty included. D – T-NASS dedicated; X – extension survey; BP – fin whale; BA – common minke whale; ; MN – humpback whale; BB – sei whale; PM – sperm whale; L – *L.* spp dolphins; GM – long-finned pilot whale.

**Common minke whales**

Detection functions including and excluding extension sightings were quite similar (Figure 4). A truncation distance of 1,000 m was employed and a half normal function with 1 cosine adjustment term and no covariates provided best fit in both cases (Table 6). Density and abundance in the core area were highest in blocks FE and IN which together accounted for 78% of the total uncorrected estimate of 12,427 (CV=0.27, 95% CI: 7,205 - 21,433) (Table 7, Supplementary File 3).

The extension vessels made 11 sightings in areas of overlap with the T-NASS core area, all in blocks IN and FE. Encounter rate in the overlap was 1.3 (CV=0.58) times greater for the extension vessels than the dedicated vessels (Table 8).

Abundance in the extension strata was estimated using the combined dedicated/extension detection function, resulting in an uncorrected estimate of 901 (CV=0.32, 95% CI: 487 - 1,668) for the XNE stratum (Supplementary File 3).

Table 5. Number of tracker platform sightings moving towards or away from the trackline that were duplicated (DUP) or not duplicated (NONDUP) by the primary platform.

| | TOWARDS | AWAY | TOTAL |
|---|---|---|---|
| **NONDUP** | 47 | 59 | 106 |
| **DUP** | 53 | 88 | 141 |
| **TOTAL** | 100 | 147 | 247 |

Table 6. Model specifications for abundance estimates. Species definitions are given in Table 3. SURVEY: D – T-NASS dedicated; E – extension; PLAT: C – combined primary and tracker; P – primary; MODE: C – B-T and combined platform sightings; B-T – Buckland-Turnock mode only; DS MODEL – Distance detection function; MR MODEL – Conditional (mark-recapture) detection function HN – half-normal; HZ – hazard rate; adj – adjuncts, cosine (cos); *SPEC* – species identity; *VIS* – visibility; *SURVEY* – dedicated or extension; *BSS* – Beaufort sea state; *CLUS* – group size.

| SPECIES | SURVEY | PLAT | MODE | TRUNCATION | | DS MODEL | | MR MODEL | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | L (m) | R (m) | Key | Covariates/Adj. | Type | Covariates |
| BP?? | D | C | C | | 2500 | HN | *VESS2* | | |
| BP?? | D+E | C | C | | 2300 | HN | *SURVEY* | | |
| BP?? | D | P | B-T | | 2500 | HN | *VESS2* | Trial PI | *DIST* |
| BB?? | D | C | C | | 1400 | HN | | | |
| BB?? | D+E | C | C | | 1400 | HN | | | |
| MN?? | D | C | C | | 2700 | HZ | | | |
| MN?? | D+E | C | C | | 2700 | HZ | *SURVEY* | | |
| MN?? | D | P | B-T | | 2700 | HZ | | Trial PI | *DIST* |
| BA?? | D | C | C | | 1000 | HN | | | |
| BA?? | D+E | C | C | | 1000 | HN | *SURVEY* | | |
| PM?? | D | C | C | | 1500 | HN | *BSS* | | |
| PM?? | D+E | C | C | | 1900 | HN | *SURVEY* | | |
| PM?? | D | P | B-T | 100 | 1400 | HN | | Trial PI | *DIST+CLUS* |
| LC+LL | D | C | C | | 1000 | HN | *SPEC+VIS* | | |
| LC+LL | D+E | C | C | | 1000 | HN | *SURVEY+SPEC* | | |
| LC+LL | D | P | B-T | | 800 | HZ | | Trial PI | *DIST+VIS* |
| GM?? | D | C | C | | 1900 | HN | *BSS* | | |
| GM?? | D+E | C | C | | 1800 | HN | /cos | | |
| GM?? | D | P | B-T | | 1500 | HN | | Trial PI | *DIST+BSS* |

Table 7. Abundance estimates for the T-NASS survey area covered by the dedicated vessels. Uncorrected estimates using sightings from the combined tracker and primary platforms, and corrected estimates using sightings from the primary platform corrected for perception bias ($p(0)$), are provided. Species definitions are given in Table 3. LCL and UCL – lower and upper 95% confidence limits. Further details are provided in Supplementary Files 1-14.

| | UNCORRECTED | | | | CORRECTED | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SPECIES | ESTIMATE | LCL | UCL | CV | $p(0)$ | CV | ESTIMATE | LCL | UCL | CV |
| BP | 24,824 | 18,347 | 33,589 | 0.15 | 0.73 | 0.11 | 30,777 | 21,153 | 44,779 | 0.19 |
| BA | 12,427 | 7,205 | 21,433 | 0.27 | | | | | | |
| MN | 12,078 | 5,879 | 24,814 | 0.34 | 0.78 | 0.13 | 18,105 | 7,226 | 45,360 | 0.43 |
| BB | 5,159 | 1,983 | 13,423 | 0.47 | | | | | | |
| PM | 6,429 | 3,412 | 10,007 | 0.28 | 0.57 | 0.28 | 12,268 | 6,386 | 23,568 | 0.33 |
| LL | 86,255 | 30,512 | 243,835 | 0.47 | 0.70 | 0.27 | 91,277 | 32,351 | 257,537 | 0.53 |
| LC | 32,396 | 14,609 | 71,838 | 0.40 | 0.70 | 0.27 | 81,008 | 27,993 | 234,429 | 0.54 |
| GM | 92,880 | 57,226 | 150,747 | 0.24 | 0.52 | 0.44 | 87,417 | 41,783 | 182,891 | 0.38 |

Table 8. Ratio of mean encounter rate realized by extension and dedicated survey vessels (E/D) in the areas where they overlapped. Species definitions provided in Table 3.

| SPECIES | E/D | CV |
|---|---|---|
| BP | 0.20 | 0.46 |
| BA | 1.29 | 0.58 |
| MN | 0.10 | 1.13 |
| BB | 0.01 | 1.04 |
| PM | 0.15 | 0.75 |
| LC | 0.21 | 1.09 |
| LL | 0.42 | 0.80 |
| GM | 0.42 | 0.70 |

Corrected estimate

Observers on the primary platform re-sighted 26% of the common minke whales seen by the tracker platform, and all 5 duplicate sightings were within 150 m of the trackline (Table 8). A severe truncation to 250 m was required as the primary platform made only 1 sighting at a distance greater than this, reducing the total number of sightings to 13. As this is insufficient to derive a detection function, a corrected estimate cannot be obtained from these data.

**Humpback whales**

Detection functions including and excluding the extension vessel sightings are shown in Figure 4. A truncation distance of 2,700 m was used and a hazard rate function with no adjustment terms or covariates provided the best fit for both cases. Uncorrected density and abundance in the T-NASS core area (Table 7, Supplementary File 4) were highest in blocks IN and NW which together accounted for 88% of the total estimate of 12,078 (CV=0.34, 95% CI: 5,879 - 24,814).

Uncorrected abundance in the extension stratum XNE, estimated using the combined detection function, was 118 (CV=0.59, 95% CI: 39 - 352). Encounter rate for the dedicated vessels in the T-NASS blocks where overlap with the extension vessels occurred was 10 (CV=1.13) times greater than that for the extension vessels (Table 8).

Table 9. Sightings of cetaceans by vessel and platform for effort conducted in B-T mode in the Beaufort Sea state range and truncation distance used in the analysis. Non-duplicate sightings only are given for each platform, and duplicate sightings are enumerated separately. See Table 3 for species definitions, LAG = LL+LC. Platform 1: primary; Platform 2: tracker; DUP: Duplicate sightings; %DUP: percentage of tracker sightings duplicated by primary.

| VESSEL | PLATFORM | BP?? 2,500 | BB?? 1,400 | MN?? 2,700 | BA?? 1,000 | PM?? 1,500 | LL+LC 1,000 | LL?? 1,000 | LC?? 1,000 | GM?? 1500 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 87 | 9 | 2 | 2 | 9 | 3 | 3 | 0 | 13 |
| | 2 | 18 | 0 | 2 | 0 | 1 | 1 | 0 | 1 | 9 |
| | DUP | 41 | 0 | 4 | 0 | 5 | 3 | 0 | 3 | 8 |
| | **%DUP** | **69** | **0** | **67** | **0** | **83** | **75** | **0** | **75** | **47** |
| F | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 2 |
| | 2 | 1 | 0 | 2 | 6 | 3 | 1 | 0 | 1 | 12 |
| | DUP | 4 | 0 | 0 | 3 | 5 | 1 | 0 | 1 | 2 |
| | **%DUP** | **80** | **0** | **0** | **33** | **63** | **50** | **0** | **50** | **14** |
| J | 1 | 7 | 20 | 0 | 0 | 7 | 2 | 0 | 2 | 5 |
| | 2 | 1 | 3 | 0 | 0 | 9 | 5 | 0 | 5 | 4 |
| | DUP | 1 | 5 | 0 | 0 | 8 | 2 | 0 | 2 | 2 |
| | **%DUP** | **50** | **63** | **0** | **0** | **47** | **29** | **0** | **29** | **33** |
| V | 1 | 7 | 0 | 17 | 3 | 0 | 7 | 7 | 0 | 0 |
| | 2 | 2 | 0 | 21 | 8 | 0 | 8 | 8 | 0 | 0 |
| | DUP | 1 | 0 | 19 | 2 | 1 | 4 | 4 | 0 | 0 |
| | **%DUP** | **33** | **0** | **48** | **20** | **100** | **33** | **33** | **0** | **0** |
| ALL | 1 | 131 | 29 | 20 | 6 | 17 | 13 | 10 | 3 | 20 |
| | 2 | 32 | 3 | 25 | 14 | 13 | 15 | 8 | 7 | 25 |
| | DUP | 62 | 5 | 23 | 5 | 19 | 10 | 4 | 6 | 12 |
| | **%DUP** | **66** | **63** | **48** | **26** | **59** | **40** | **33** | **46** | **32** |

Corrected estimate

Using only dedicated vessel effort conducted in B-T mode, observers on the primary platform duplicated 48% of the humpback whale sightings by the tracker platform (Table 8).

The same detection function described above for the combined data provided best fit for the primary platform data, and the lowest AIC was achieved with a conditional detection function incorporating only perpendicular distance as a covariate, which resulted in an estimate of $p(0)$ for the primary platform of 0.78 (CV=0.13) (Table 7, Supplementary File 5). The total corrected estimate for the T-NASS core area was 18,105 (CV=0.43, 95% CI: 7,226 - 45,360).

**Sei whales**

A half-normal key function with no adjustment terms or covariates provided the best fit for the detection function for data both including and excluding sightings from the extension vessels. Density was highest in block RN but block SC accounted for 62% of the total estimated abundance in the T-NASS core area of 5,159 (CV=0.47, 95% CI: 1,983 - 13,423) (Table 7, Supplementary File 6).

The extension vessels made only 1 sighting within the T-NASS core area, and their encounter rate was 1% (CV=1.04) that of the dedicated vessels in the same area. Abundance in the extension strata, estimated using a detection function combining dedicated and extension vessel sightings, was 4,578 (CV=0.60, 95% CI: 1,381 - 15,172), almost all (97%) of which came from block XSW to the southwest of the core survey area. Total estimated abundance for the core and extension strata combined was 9,737 (CV=0.38, 95% CI: 4,189 - 19,665) (Supplementary File 6).

Corrected estimate

Observers on the primary platforms re-sighted 63% of sightings made by observers on the tracker platforms. However, all of these re-sightings were at perpendicular distances greater than 350 m and the response to distance was contrary to expectations, with the proportion of duplicates increasing with distance. Lowest AIC in the conditional detection function was achieved using only perpendicular distance as a covariate, however this resulted in an unrealistically low and imprecise estimate of $p(0)$ of 0.12 (CV=2.59). We therefore chose not to present a bias-corrected estimate for this species.

**Sperm whales**

The frequency distribution of perpendicular distances to sperm whale sightings was depressed within about 200 m of the trackline, rising to a maximum between 300 m and 600 m and decreasing rapidly thereafter. The relative paucity of sightings within 100 m of the trackline was due primarily to the low number of sightings there by the primary platform, which had 4 sightings in this interval compared to 7 by the tracker platform. Sightings by the tracker platform in this interval were generally made farther ahead of the vessel than were those by the primary, suggesting that sperm whales may have dived before being sighted by the primary platform, however we have no tracker data to confirm this.

The data from the dedicated vessels were truncated at 1,500 m to obviate the need for adjustment terms to fit the long tail of more distant sightings. A half-normal function with the covariate BSS provided best fit to the data from the dedicated vessels (Figure 4). Density and abundance in the T-NASS core area was highest in blocks SC and RN, which together accounted for 65% of the total uncorrected estimated abundance of 6,429 (CV=0.28, 95% CI: 3,412 - 10,007) (Table 7, Supplementary File 7).

Abundance in the extension strata was estimated using a detection function combining sightings from the extension and dedicated vessels, as there were too few sightings from the extension vessels alone. A truncation distance of 1,900 m was employed, and the distribution was similar in form to that for the dedicated vessels alone. A half-normal function with no covariates provided the best fit to the data (Figure 4), however a covariate for survey type (dedicated/extension) was included in the model.

There were only 2 sightings by the extension vessels in the T-NASS core strata. Encounter rate in the strata where there was overlap between the 2 surveys was 6.7 (CV=0.75) times higher for the dedicated vessels than for the extension vessels (Table 8). Estimated uncorrected abundance in the XNE stratum was 276 (CV=0.38, 95% CI: 134 - 572) (Supplementary File 7).

Corrected estimate

On the T-NASS dedicated vessels, observers on the primary platform duplicated 59% of the sightings made by the tracker platform while in B-T mode (Table 8). Sightings data from the primary platform were left-truncated within 100 m of the trackline due to a paucity of sightings in that interval. The resultant uncorrected estimate for the primary platform alone was 7,534 (CV=0.27, 95% CI: 4,353 - 13,040) (Supplementary File 8). Best fit of the conditional detection function was achieved with perpendicular distance and group size as covariates, resulting in an estimated proportion of sperm whale groups detected on the trackline by the primary platform ($p(0)$) of 0.57 (CV=0.28) and a corrected abundance of 12,268 (CV=0.33, 95% CI: 6,386 - 23,568) (Table 7, Supplementary File 8).

**White-beaked and white-sided dolphins**

The numbers of sightings of each species were insufficient to derive individual detection functions, so a combined detection function was fitted. A covariate for species identity was included to account for any differences in scale due to species identity. A half-normal key function including covariates for species identity and visibility provided the best fit to the data from the dedicated vessels (Figure 4).

Density of white-beaked dolphins was highest in stratum NW, but stratum RN accounted for over half the total estimated abundance of 86,255 (CV=0.47, 95% CI: 30,512 - 243,835) (Table 7, Supplementary File 9). Two of the 3 sightings in RN had group sizes of 80 and 100 animals, resulting in a very high estimate for that block.

Density and abundance of white-sided dolphins was highest in stratum SC to the south of Iceland, which contributed 55% of the total estimated abundance of 32,396 (CV=0.40, 95% CI: 14,609 - 71,838) (Table 7, Supplementary File 10).

Abundance in the extension strata for both species was estimated using a detection function pooling sightings from both the extension and dedicated surveys, as there were too few sightings in the extension survey alone. Data were right-truncated at 1,000 m. A half-normal function with no covariates provided the best fit (Figure 4), however covariates for survey (dedicated/extension) and species were included.

There was only 1 sighting of white-beaked dolphins in the overlap area between the dedicated and extension surveys, and encounter rate was 4.2 (CV=0.80) times higher for the dedicated vessels in the same area (Table 9). White-beaked dolphins were sighted in extension stratum XNE only, resulting in an uncorrected abundance estimate of 20,662 (CV=0.51, 95% CI: 7,896 - 54,070) for that block (Supplementary File 9).

There was 1 sighting of white-sided dolphins by the extension vessels in the T-NASS core strata, and encounter rate was 4.8 (CV=1.09) times higher for the dedicated vessels in the same area (Table 9). White-sided dolphins were sighted in both extension strata, resulting in a total uncorrected abundance estimate of 23,287 (CV=0.61, 95% CI: 7,671 - 71,629) for the area (Supplementary File 10).

Corrected estimates

Observers on the primary platforms on the dedicated vessels re-sighted 40% of the *L*. spp. dolphins seen by the tracker platform observers (Table 9), and numbers were generally too low to determine if this rate varied by vessel or species. For primary platform sightings only, a hazard-rate function with no covariates provided the best fit for the detection function, and PI models were selected over FI models. The best fit of the conditional detection function was achieved with perpendicular distance and visibility as covariates, resulting in an average value of $p(0)$ for the primary platform of 0.70 (CV=0.27) for both species. Total corrected abundance of white-beaked dolphins was 91,277 (CV=0.53, 95% CI: 32,351 - 257,537) while that for white-sided dolphins was 81,008 (CV=0.54, 95% CI: 27,993 - 234,429) (Table 7, Supplementary Files 11 and 12).

**Long-finned pilot whales**

The detection functions for this species for sightings with and without the extension data were best modelled using a half-normal key function with a single covariate for BSS (Table 6, Figure 4). Density and abundance were greatest to the southwest of Iceland in strata RN and RS, which together accounted for 52% of the total estimated abundance of 92,880 (CV=0.24, 95% CI: 57,226 - 150,747) in the T-NASS core area (Table 7, Supplementary File 13).

Density in the extension strata was estimated using a detection function combining both the extension and dedicated vessel data (Table 6, Figure 4). With only 2 sightings in the XSW stratum, abundance there was estimated with very poor precision (Supplementary File 13). Encounter rate by the extension vessels in the T-NASS core strata was 0.42 (CV=0.70) that of the dedicated vessels in the same strata, suggesting again that observers on the extension platforms missed a greater proportion of sightings.

Corrected estimate

Observers on the primary platforms re-sighted 32% of long-finned pilot whale groups sighted by the tracker platform (Table 9) in B-T mode, but this varied among vessels to as low as 14% on the Faroese vessel F. The best fit of the conditional detection function was achieved with perpendicular distance and Beaufort Sea state as covariates, with increasing sea state reducing the proportion of duplicates. The estimated $p(0)$ of 0.52 (CV=0.44) increased the primary platform estimate to 87,417 (CV=0.38, 95% CI: 41,783 - 182,891) (Table 7, Supplementary File 14).

## DISCUSSION AND CONCLUSIONS

### Potential biases

**Coverage**

Poor weather, ice cover and other factors conspired to reduce coverage of some areas, particularly the western part of block RN, near the East Greenland ice edge, and blocks NW, RS, FX and the northern part of FE. The IC block around coastal Iceland was also poorly covered, but this area was covered by a concurrent aerial survey (Pike et al., in press). Pack ice in the western parts of blocks RN, NW and IN precluded survey and required post-stratification of these areas. No dedicated effort was realized in the northern block IN_N, although there was some effort by extension vessels in the area. The effect of low coverage in these areas will vary by species, depending on their expected distribution and whether density is correlated with realized effort (discussed below).

**Species identification**

In this survey, observers recorded 3 levels of certainty in species identification. The proportion of very uncertain sightings ranged from 2% to 15%, and was generally higher for species such as fin, blue and sei whales which are easily confused with one another. However, it was surprisingly low (2%-4%) for white-beaked and white-sided dolphins, species which can be difficult to discriminate at sea.

We chose to include all certainty classes in our final abundance estimates, while assessing the sensitivity of the estimates to the exclusion of the least certain classification in cases where these sightings exceeded 10% of the total. While it is likely that some of the less certain sightings were mis-identified and their inclusion could therefore lead to positive bias, it is also likely that some uncertain sightings of similar species were mis-identified, potentially leading to the opposite bias. The problem is likely most severe for blue and sei whales, which are outnumbered by more than an order of magnitude by fin whales in the survey area. It is highly likely that some proportion of uncertain fin whale sightings were actually blue or sei whales, which could then lead to negative bias for estimates of those species. While the converse is also true, the potential bias for the fin whale estimate is proportionally less severe.

**Responsive movement**

Some cetaceans, particularly some dolphin species, may be attracted to vessels (attractive movement), while others may move away from approaching vessels (aversive movement) (Palka & Hammond, 2001). Such movement may severely bias abundance estimates because it can affect both the shape of the detection function and the encounter rate. The B-T methodology is intended to detect such movement and collect data for bias correction by having the tracker platform search for sightings far ahead of the vessel and track them until they may be seen by the primary platform observers or pass abeam (see Figure 5). If responsive movement is detected, analytical approaches are available to correct for the resultant bias (Buckland & Turnock, 1992; Canadas, Desportes, & Borchers, 2004; Palka & Hammond, 2001).


Figure 5. Platform setup on survey vessel. The tracker platform on top is staffed by 4 people , from right to left: observer with "Big-Eye" binoculars, duplicate identifier, observer with the 7x50 binoculars and the data recorder. The lower primary platform is staffed by 2 observers searching by naked eye only. (Photo: C. Pampouline, MFRI, Iceland).

If responsive movement was occurring, we would expect to see a net movement towards or away from the trackline, resulting in smaller (attractive movement) or larger (aversive movement) perpendicular distance estimates for sightings of the same group measured some time after an initial sighting. For measurements taken by the observers on the tracker platform , we saw no such net movement, as illustrated in Figure 3 and Table 4. As these measurements were taken using binocular reticles and usually by the same observer within a series of sightings of the same group, we consider these measurements to be the most reliable for detecting responsive movement. While no evidence of responsive movement was found for any species, there was an insufficient number of tracking events (<5) for sperm, sei, and common minke whales and white-beaked dolphins to reach any conclusions for these species.

Conversely, the relationships of first tracker to last primary distances does suggest attractive movement for all species. However, given that such movement was not detected from measurements by the tracker platform alone, even for the same sightings, we believe there may be an alternate explanation for this (see below).

Evidence for responsive movement by baleen whales in general is equivocal. Macleod et al. (2009) found evidence that fin whales were attracted to the survey vessels used in the CODA survey conducted in European waters in 2007, whereas no evidence for responsive movement was found in the 2016 SCANS III survey, which used identical methodology in parts of the same area (Hammond et al., 2017). Similarly, Palka and Hammond (2001) found that while the response of common minke whales to approaching survey vessels was generally aversive, it differed substantially between the Gulf of Maine, the Northeast Atlantic and the North Sea. The properties and intensity of noise varies among vessels and this likely also affects the response of cetaceans.

No indication of responsive movement by sperm whales was found in either the CODA or SCANS III surveys (Hammond et al., 2017; Macleod et al., 2009).

Some species of dolphins respond strongly to vessels, even approaching them closely to bow-ride. However, the response varies among species and even areas. Palka and Hammond (2001) found that white-sided dolphins exhibited aversive movement while white-beaked dolphins approached vessels, although in both cases the response was complex. Short-beaked common dolphins (*Delphinus delphis*) approach vessels to bow-ride in most areas (Canadas, Desportes, & Borchers, 2004; Macleod et al., 2009), but this response was not detected in the SCANS III survey (Hammond et al., 2017). While we found no evidence of responsive movement for white-sided dolphins, we can reach no conclusions with regard to white-beaked dolphins. If, as in the Gulf of Maine, they approach survey vessels from a distance greater than that from which they would first be detected by observers, our estimates will be positively biased for that species.

**Bias in distance estimation**

Bias in distance measurement can be a serious problem in distance sampling surveys because it affects the detection function and the estimation of effective strip width, and thereby leads directly to bias in abundance estimation (Buckland et al., 2001). Negative bias in distance estimation leads to negatively biased estimates of *esw* and positive bias in abundance estimates, and vice versa.

Distance estimation experiments, in which observers made observations of objects (usually buoys) at a known distance from the vessel, were conducted before or during the survey. While the results varied by vessel, they generally indicated that distances estimated using binocular reticles were unbiased, while those estimated using distance sticks had a slight negative bias (unpublished data). However, these were regarded as training exercises, and the observers were expected to learn from the experiments and adjust their procedures accordingly. Leaper, Burt, Gillespie, and Macleod (2010) found that measurements of distance to fixed objects such as buoys, during which the observers are necessarily aware that they are being tested, were not predictive of the error patterns and biases found in measurements to cetacean groups while on survey effort.

As explained above, comparing distances to sightings of the same group made over 2 minutes apart by the tracker platform shows no indication of net movement towards or away from the trackline, while distances measured by primary platform observers were generally lower than those measured by the tracker platform to duplicate sightings for all species for which sufficient data are available (Figure 3, Table 4). While vessel identity was not selected as a covariate in the regressions, examination of individual vessel regressions suggested that the between-platform difference was greatest on vessel V. As noted above we regard the within-platform comparison as evidence that there is no net movement towards or away from the trackline by those cetaceans for which sufficient tracked sightings are available. The interpretation of the between-platform difference is less certain, but we suggest the following hypotheses:

1. *Distance measurements by the tracker platform were positively biased*. This would lead to negative bias in the uncorrected abundance estimates, which use sightings from the tracker platform in the detection function. We consider this unlikely because no bias was found for tracker platform measurements in the distance estimation experiments noted above. The tracker observers used binocular reticles to estimate distance, which should be more accurate than using distance sticks under most conditions. Leaper et al. (2010) found that distances measured using binocular reticules were less biased than naked eye estimates or those made using distance sticks;
2. *Observers on the primary platform were more likely to duplicate cetacean groups that were moving towards the trackline, and hence tracked whale groups tended to be closer to the trackline by the time they were sighted by the primary.* This would not bias the corrected estimates, as the missed sightings would be incorporated into the estimate of *p*(0). If the primary platform had a higher probability of detecting cetaceans that were moving towards the trackline, we would expect the difference in tracker and primary measurements to be positively correlated with the time interval between the measurements. However, we did not observe this. In addition, for some tracker platform sightings, observers noted the direction of travel of the cetacean group. We examined these data to determine if groups moving towards the trackline were preferentially re-sighted by the primary, but the observed proportion was not significantly different (*P*=0.30) from that for non-duplicated sightings (Table 5). This also suggests that the primary platform was not more likely to duplicate sightings of groups moving towards the trackline. However, this test is relatively weak in that it would require a proportion of about 70% to be moving towards the trackline among the duplicated sightings to reach statistical significance;
3. *Distance measurements by the primary platform were negatively biased.* This would lead to positive bias in the abundance estimates. Although no definite conclusion can be drawn, we consider this more likely than the other 2 explanations.

If distance measurements taken from the tracker platform are assumed to be unbiased, the regression of primary platform measurements against those of the tracker platform for duplicate sightings indicates that primary platform measurements should be increased by about 50% (Reg. 12 Table 4). We conducted sensitivity analyses to determine what effect such a bias would have on estimates of abundance. For most (but not all) duplicate sightings, the measurements from the tracker platform were used, and tracker platform measurements were not changed. Abundance estimates using the adjusted distance measurements from the primary platform were from 12% to 28% lower than those using the unadjusted values.

However, we cannot assume that tracker platform measurements are unbiased. Using data from several ship surveys, Leaper et al. (2010) compared distance measured using video, which were determined experimentally to be unbiased, to distance measurements to the same cue while on survey effort using binocular reticles and naked eye/distance sticks. Over the entire range of measured distances, both reticle and naked eye estimates were negatively biased, with the latter having a more severe bias. However, the relationship was not linear, with observers tending to overestimate distances closer than 1,000-3,000 m (depending on the survey) and underestimate greater distances. Using this error pattern to correct distances resulted in a lowering of *esw*, and therefore an increase in estimated abundance, compared to that using the uncorrected data. This contrasts with decrease in estimated abundance that would result from using the simple regression slope to correct primary platform measurements as noted above. Unfortunately, we lack known unbiased distance measurements to cetacean groups made under survey conditions that would enable us to correct unambiguously for measurement bias. In addition, we cannot exclude the possibility that there was a somewhat higher probability that the primary platform would detect groups moving towards the trackline. Therefore, we retain the abundance estimates using the uncorrected data as the best that can be realized from this survey.

The 2001 NASS used a similar methodology but the data have not been analysed in this manner, so we do not know if they exhibit similar features. Prior to that, NASS used a combined platform, usually with at least 2 observers on the bridge roof and 1 in a higher barrel. These observers usually measured distances using sticks as did the primary observers in this survey.

In future surveys, a way to estimate measurement bias directly should be developed. More emphasis should be put on distance estimation experiments, conducted before and at intervals throughout the survey. Video recording systems to measure radial distances, which have been shown to be unbiased (Leaper et al., 2010), should be included on at least one platform. Another possibility is to use an unmanned aerial vehicle to measure distance directly for a subset of observations. In addition, a greater effort should be made to record swimming direction for a larger proportion of tracker and primary sightings.

**Perception and availability bias correction**

One purpose of operating in B-T mode is to provide sight-resight data with which to correct for the proportion of visible cetacean groups missed by the primary (Buckland & Turnock, 1992; Burt et al., 2014). If the viewing fields of the tracker and primary platforms are sufficiently separated such that the tracker can detect surfacings that are not visible to the primary, the procedure should also largely correct for availability bias (Burt et al., 2014). This will vary between species, with long-diving cetaceans such as beaked and sperm whales being more problematic in this respect.

As responsive movement was not detected for any species (see above), we used point-independence (PI) models in most cases, in which the probability of detection by the tracker and primary platforms is assumed to be independent only on the trackline (Burt et al., 2014; Laake & Borchers, 2004). We also trialled full-independence (FI) models, but in all cases, these were not selected using AIC and produced estimates substantially lower than those produced under the assumption of PI. This was not unexpected, as FI models tend to generate negatively biased estimates unless covariates are included to account for all sources of heterogeneity in detection probability between the 2 platforms, as detection probability between platforms tends to be positively correlated (Burt et al., 2014).

Only one previous NASS (2001) has used B-T mode, and bias was estimated only for fin whales from that survey (Pike, Gunnlaugsson & Víkingsson, 2006). Our estimate of $p(0)$ for fin whales of 0.76 (CV=0.10) is not significantly different ($P$>0.05) from to that from 2001 of 0.81.

Surveys carried out in coastal and offshore European waters in 2007 (Hammond et al., 2009, 2013) and 2016 (Hammond et al., 2017) used essentially identical methodology to that used in this survey, so we might expect their perception/availability bias estimations to be similar for the same species. Bias estimations are not provided explicitly by MacLeod et al. (2009) but can be approximated from their Figure 4 as 0.5 for pilot whales and 0.6 for large baleen and sperm whales, slightly lower than our estimates of $p(0)$ for these species. For white-sided dolphins, the SCANS III survey estimated a value of $p(0)$ of 0.46 (CV=0.33), which is less than our value of 0.74 (CV=0.21) for white-sided and white-beaked dolphins combined. Similarly, the SCANS III estimate for large baleen whales, which should be roughly equivalent to ours for fin whales, is less at 0.61 (CV=0.07) compared to our estimate noted above. We can only offer conjectures as to the reasons for these differences, such as possible differences in how the B-T mode was implemented, observer differences, weather conditions and possibly the way duplicates were identified.

**Extension survey**

The main purpose for including the extension survey in the overall T-NASS project was to obtain information on the distribution and relative abundance of cetaceans outside of the core area covered by the dedicated survey vessels. It was recognized from the outset that it would not be feasible to obtain estimates of absolute abundance directly from this component of the survey, because the vessels carried only 2 observers on a single platform, and their sighting efficiency was expected to be lower than that for the dedicated vessels. However, because there was some overlap between the extension and core strata, it was thought the magnitude of the bias could be estimated by the ratio of estimated densities or encounter rates in the overlap area between the dedicated and extension vessels. These were generally quite low, ranging from 0.01 for sei whales to 0.42 for white-beaked dolphins, with very high variance in every case. The exceptional species was the common minke whale, for which encounter rate was actually higher for the extension vessels than for the dedicated vessels in the overlap area. The apparent low sighting efficiency of the extension vessels for most species is probably due to the low number of observers on each vessel: 2 compared to 5 on the combined platforms of the dedicated vessels.

Lacking sufficient numbers of sightings by the extension vessels alone for most species, we used detection functions combining sightings from the extension and dedicated vessels to estimate abundance in the extension strata. However, these estimates should be considered to be negatively biased, likely severely so, for all species other than common minke whales because of the low sighting efficiency of this survey for most species as noted above.

The main value of the extension survey is that it provided some information on the distribution of cetaceans outside the core T-NASS survey area, especially to the east and northeast. It is apparent that the distribution of white-beaked dolphins, common minke and sperm whales does extend into this area, while sightings of other species were rare. However, we must question the value of the extension survey in this case because it cannot produce unbiased estimates of density, and the magnitude of the bias, while apparently severe, cannot be quantified with sufficient precision. In addition, the area to the east and northeast of the survey area (XNE) that was covered by the extension vessels is surveyed regularly by dedicated survey vessels, and estimates for several species are available (Øien, 2009). Our extension survey results do not add much of value to our previous knowledge of the area. However, the extension survey did reveal a concentration of sei whales to the south of Greenland (XSW), confirming that the NASS do not fully cover the range of this species in the central North Atlantic.

**Comparison to previous estimates**

Pike et al. (2019b) compare estimates of abundance for all species covered in this paper to earlier estimates, including those in this paper.

**Survey mode**

This was the second NASS (along with 2001) to use the B-T survey mode. There are 2 main reasons to use this mode as opposed to symmetrical independent platforms (Independent Observer, IO mode). Firstly, tracking animals provides information on behaviour in relation to the vessel, and therefore whether responsive movement is occurring. If so, methods are available to correct for this bias (Buckland & Turnock, 1992; Burt et al., 2014; Palka & Hammond, 2001). Secondly, because the tracker platform searches far ahead of the vessel using binoculars, while the primary platform uses naked eye searching only, the viewing fields of the 2 platforms are separated in space and time. Sighting events should therefore be largely uncorrelated between platforms except for tracker sightings tracked into the search field of the primary. The estimation of $p(0)$ will therefore encompass both perception bias and availability bias, the extent of the latter depending on the dive cycle of the species and the separation of the viewing fields in space and time (Burt et al., 2014).

The decision as to whether B-T or IO is the more appropriate mode for a survey therefore depends primarily on whether or not responsive movement is expected, and on whether availability bias will be of significance. The NASS are multi-species surveys, but the Icelandic and Faroese components place target priority on fin and long-finned pilot whales, with common minke whales as a secondary target species. Of these, responsive movement is not suspected for fin whales (but see Macleod et al., 2009) or long-finned pilot whales, but may be a factor for common minke whales (Palka & Hammond 2001). Availability to shipboard observers is expected to be high for fin and common minke whales, which typically have dive times of less than 2 min (Croll et al., 2001; Stockin et al., 2001). Long-finned pilot whales perform dives of up to 18 minutes in length (Heide-Jørgensen et al., 2002), making availability bias a greater concern. Availability bias is of greatest concern for long-diving non-target species such as northern bottlenose (Hooker & Baird, 1999) and sperm whales (Whitehead et al., 1992).

B-T mode is not without disadvantages for ship surveys. It is more demanding on observers, particularly those on the tracker platform, who must scan far ahead of the vessel using high-powered binoculars and track animals until they are sighted by the primary platform or pass abeam. This requires careful training, ideally conducted onboard before the survey commences. Generally, more observers are required: 4 on the tracker platform, including the duplicate identifier and data recorder, as opposed to 2 on the primary platform and on IO platforms. In practice, tracking could not be conducted at BSS exceeding 4, while combined platform observations continued to BSS 5. A survey in B-T mode will generally result in fewer sightings than one conducted in IO mode in the same area, because the effort spent in tracking detracts from making new sightings. This can be a concern for rarely sighted species. Finally, because the platforms are not fully independent, fewer duplicate "trials" are conducted compared to IO mode, which can affect the precision of the estimate of perception bias.

In this survey, frequent failure of equipment used for B-T mode data recording, likely due to the weather conditions at high latitudes, caused interruptions and temporary shifts to single platform mode. One advantage of B-T over other survey modes is that it is not necessary for the tracker platform be operational at all times to obtain a valid estimate of $p(0)$ for the primary platform, as long as the configuration of the primary platform remains unchanged. The tracker platform provides trials for the primary platform, but not vice versa. In this survey, when tracking was discontinued, the 2 platforms remained staffed and were combined into 1 platform. Unfortunately this meant that the estimate of $p(0)$ developed for the primary platform could not be applied to effort conducted in single platform mode as the platform configurations were not identical. If future surveys are conducted in B-T mode, single platform operations should be done using a primary platform only, configured the same way as in B-T mode.

Given the species mixture observed in NASS and their prioritization as target species, the mode utilized in future surveys should be carefully considered. While IO mode may be more efficient and easier to implement, and provide adequate results for most species, bias due to responsive movement or availability cannot be detected or addressed. The former can be substantial for some species, particularly dolphins (Canadas, Desportes, & Borchers, 2004) but also for common minke whales in some areas (Palka & Hammond, 2001). If B-T mode is used in future surveys, the importance of tracking all species should be emphasized. Similarly, observers should be required to record swim direction for all sightings, especially from the tracker platform. If tracking all species is too onerous or time consuming, a simplified tracker protocol for species for which responsive movement is not suspected could be developed.

## ADHERENCE TO ANIMAL WELFARE PROTOCOLS

The research presented in this article has been done in accordance with the institutional and national laws and protocols for animal welfare applicable in the jurisdictions where the work was conducted.

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