Wiig *et al. Anim Biotelemetry (2017) 5:9*
DOI 10.1186/s40317-017-0124-0

Animal Biotelemetry

TELEMETRY CASE REPORT

Open Access

# Performance and retention of lightweight satellite radio tags applied to the ears of polar bears (*Ursus maritimus*)

Øystein Wiig[1*], Erik W. Born[2], Kristin L. Laidre[2,3], Rune Dietz[4], Mikkel Villum Jensen[5], George M. Durner[6], Anthony M. Pagano[6], Eric Regehr[7], Michelle St. Martin[7], Stephen Atkinson[8] and Markus Dyck[9]

## Abstract

**Background:** Satellite telemetry studies provide information that is critical to the conservation and management of species affected by ecological change. Here we report on the performance and retention of two types (SPOT-227 and SPOT-305A) of ear-mounted Argos-linked satellite transmitters (i.e., platform transmitter terminal, or PTT) deployed on free-ranging polar bears in Eastern Greenland, Baffin Bay, Kane Basin, the southern Beaufort Sea, and the Chukchi Sea during 2007–2013.

**Results:** Transmissions from 142 out of 145 PTTs deployed on polar bears were received for an average of 69.3 days. The average functional longevity, defined as the number of days they transmitted while still attached to polar bears, for SPOT-227 was 56.8 days and for SPOT-305A was 48.6 days. Thirty-four of the 142 (24%) PTTs showed signs of being detached before they stopped transmitting, indicating that tag loss was an important aspect of tag failure. Furthermore, 10 of 26 (38%) bears that were re-observed following application of a PTT had a split ear pinna, suggesting that some transmitters were detached by force. All six PTTs that were still on bears upon recapture had lost the antenna, which indicates that antenna breakage was a significant contributor to PTT failure. Finally, only nine of the 142 (6%) PTTs—three of which were still attached to bears—had a final voltage reading close to the value indicating battery exhaustion. This suggests that battery exhaustion was not a major factor in tag performance.

**Conclusions:** The average functional longevity of approximately 2 months for ear-mounted PTTs (this study) is poor compared to PTT collars fitted to adult female polar bears, which can last for several years. Early failure of the ear-mounted PTTs appeared to be caused primarily by detachment from the ear or antenna breakage. We suggest that much smaller and lighter ear-mounted transmitters are necessary to reduce the risk of tissue irritation, tissue damage, and tag detachment, and with a more robust antenna design. Our results are applicable to other tag types (e.g., iridium and VHF systems) and to research on other large mammals that cannot wear radio collars.

**Keywords:** Ear satellite transmitters, Performance, Retention, Platform transmitter terminal, PTT, Polar bear, *Ursus maritimus*

## Background

Climate change, natural variation, and human activities in the Arctic present challenges for polar bear conservation and management [1]. Increased monitoring has been recommended to track polar bear subpopulation responses to environmental change [2]. Satellite tracking has been a standard ecological and conservation tool, providing data on a range of vertebrate species over broad spatial and temporal scales [3, 4]. While the movements of individual polar bears have been studied using satellite telemetry for decades (e.g., [5–9]), these studies have almost exclusively collected data from adult female polar bears wearing radio collars. This sex bias in the collection of movement data stems from the challenges of

*Correspondence: oystein.wiig@nhm.uio.no
[1] Natural History Museum, University of Oslo, P.O. Box 1172, Blindern, 0318 Oslo, Norway
Full list of author information is available at the end of the article

BioMed Central

© The Author(s) 2017. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http://creativecommons.org/publicdomain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

instrumenting adult males. The neck diameter of adult male polar bears exceeds that of their head and therefore radio collars slip off [10]. Tracking of subadult polar bears is problematic because the collar circumference is fixed upon application, meaning that collars could become constrictive as the bear grows. Preliminary studies involving satellite telemetry [10] and capture–recapture [11] suggested that the size of activity areas of males and females did not differ. However, a recent study found that movements for male and female polar bears differ during the spring [7]. Also, estimates of apparent survival rates, which can reflect emigration from the study area, often differ between subadult and adult bears [12], suggesting that spatial patterns for polar bears may be related to age (e.g., that subadult bears are more likely to disperse to new areas). Given these potential sex- and age-related differences in movement, there is a need for more information on movement of adult male polar bears and subadults of both sexes, to accurately document the ecology of this species and its response to environmental change. There is also a continuous interest in developing satellite tracking devices that are smaller, less visible, and potentially less cumbersome than radio collars [4, 13].

Previous studies have used alternative attachment methods for satellite transmitters, with generally short duration. These methods include surgical implants [10], ear-mounted tags [7], and glue-on tags [14, 15]. In Alaska, seven adult male polar bears with implanted subcutaneous satellite tags were tracked for an average of 97 days (range 30–161 days) during 1996 and 1997 [10, 13]. Subsequent studies in Canada where satellite tags were attached to the ear of bears had limited success (I. Stirling, personal communication, 2015). However, polar bears have received small, inert ear tags since the 1960s for individual identification during capture–recapture studies [16] and these tags have exhibited generally high retention rates lasting for many years (Ø. Wiig, personal observation). This suggests that ear-mounted satellite transmitters, if sufficiently small and durable, could be used to track the movements of adult male and subadult polar bears.

Starting in 2007, small satellite transmitters were attached to the ear of adult and subadults of both sexes during polar bear research in Greenland [14], and similar transmitters were attached to adult and subadults of both sexes in the USA starting in 2009 [15]. In this paper, we present information on the performance and retention of these transmitters attached to the ears of polar bears across five subpopulations in Greenland, Canada, and the USA during spring and autumn 2007–2013. We discuss possible reasons for tag failure and make recommendations for improving the transmitters and attachment systems.

## Methods

### Field work

Bears were live captured and released in the Greenland Sea and Denmark Strait (East Greenland) in 2007, 2008, and 2011; in Baffin Bay (West Greenland) in 2009, 2010, 2011, 2012, and 2013; in Kane Basin (Eastern Ellesmere Island in Canada and Northwest Greenland) in 2012 and 2013; in the southern Beaufort Sea in 2009, 2010, and 2011; and in the Chukchi Sea in 2010 and 2011 (Fig. 1). Polar bears at all sites were darted and immobilized from an Ecureuil AS350 (Greenland and the southern Beaufort Sea), or a Bell 206 LR (Kane Basin and the Chukchi Sea) helicopter and then handled according to standard procedures [17]. Ages of polar bears were determined either from previous capture as a dependent young or from reading the cementum growth layers of a pre-molar extracted during the immobilization [18]. Adult females were defined as bears ≥5 years old and adult males were ≥6 years old [19].

### Transmitters

We tracked polar bears using two types of ear-mounted satellite transmitters (hereafter referred to as platform transmitter terminals, or PTTs): the SPOT-227 and the SPOT-305A (Wildlife Computers, Redmond, WA, USA). Three slightly different models of the SPOT-227 (i.e., SPOT-227B, SPOT-227C, and SPOT-227D) were used (Table 1 and Additional file 1: Table S1). All PTTs, including the SPOT-305A used only in Kane Basin and Baffin Bay in 2013, were cast in epoxy and based on the SPOT5 generation PTTs.

The three SPOT-227 (Fig. 2a) models deployed in 2007–2012 were of similar size and weighed 60–70 g including the attachment system (Table 1). The total mass depended on model and antenna reinforcement. The SPOT-305A (Fig. 2b) was smaller, more elongated and weighed about 40 g including the attachment system. All models had a 17.5-cm-long, and ca. 1-mm-wide, flexible "whip" antenna made of stainless steel (ca. 2 g). On the SPOT-227s the antenna was positioned at the center (SPOT-227B), half-way between the center and the distal end (SPOT-227C), or at the distal end (SPOT-227D) of the flat upper side of the PTT so that the antenna protruded perpendicular to the back side of the ear when attached (i.e., pointing away from the bear's head; Fig. 2a). On the SPOT-305A, the antenna was attached at the distal end so that it protruded parallel to the long axis of the earlobe toward the bear's neck when attached (Fig. 2b). The PTT included a temperature sensor that measures the temperature inside the tag. The temperature measured is usually higher than the external temperature due to heating of the PTT by the bear's body temperature.

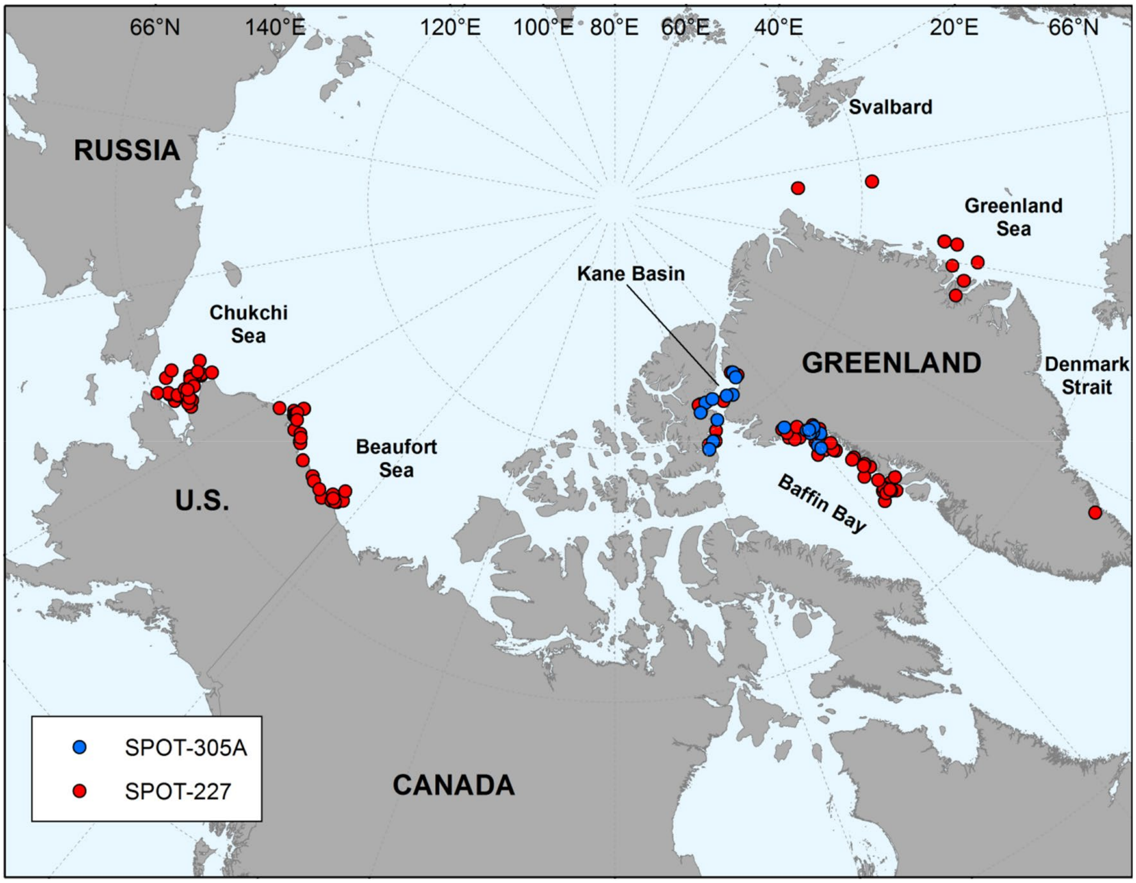


**Fig. 1** Study area and tagging locations where 145 ear satellite transmitters (PTTs) were mounted on polar bears. See also Additional file 1: Table S1 for further information on number of PTTs mounted in each area

**Table 1 Model and dimensions of ear satellite transmitters (PTT) mounted on polar bears**

| PTT model | PTT size without attachment system (mm) | PTT weight without attachment system (g) | Total weight (g) |
|---|---|---|---|
| SPOT-227B | 41.0 × 30.0 × 17.5 | 42 | Ca. 60 |
| SPOT-227C | 43.5 × 30.0 × 22.3 | 48 | Ca. 70 |
| SPOT-227D | 45.1 × 30.0 × 20.0 | 45 | Ca. 70 |
| SPOT-305A | 51.0 × 23.0 × 15.0 | 35 | Ca. 40 |

The bears were tagged in East Greenland, Baffin Bay, Kane Basin, the southern Beaufort Sea, and the Chukchi Sea, 2007–2013

Temperature measurements were made immediately prior to each transmission and sent to the satellite.

In 2007, we used an attachment system for the SPOT-227B that consisted of a stainless steel base plate with a soldered 4-mm-wide stainless steel pin glued with two-component epoxy to the transmitter base. The pin was mounted through a hole in the earlobe of the bear and secured with a steel washer that sat on the inner side of the earlobe. A nut was screwed onto the pin to hold the washer in place (Fig. 3a). The base plate and washer were covered with about 1.0 mm rubber coating to prevent direct contact between metal and skin. From 2008 to 2012, the attachment system of SPOT-227 models was modified to a male screw inserted into a female end of the pin (Fig. 3b). The attachment system of the SPOT-305A consisted of a 4-mm-wide epoxy pin as a fixed part of the PTT. This pin went through the earlobe and was held fast by a plastic washer inside the ear orifice (Fig. 3c).

The SPOT-227B and D models had two M3 batteries (capacity 1500 mAh) that theoretically allowed for 50,000 transmissions, the SPOT-227C had two 7PN batteries (capacity 1500 mAh) that allowed for 40,000 transmissions, and the SPOT-305A had a single M1 battery (capacity 1000 mAh) that allowed for 33,000 transmissions. When operated in low temperatures, these estimates should be reduced by around 25% (Wildlife Computers, personal communication) giving maximum number of transmissions of 37,500, 30,000, and 24,750,

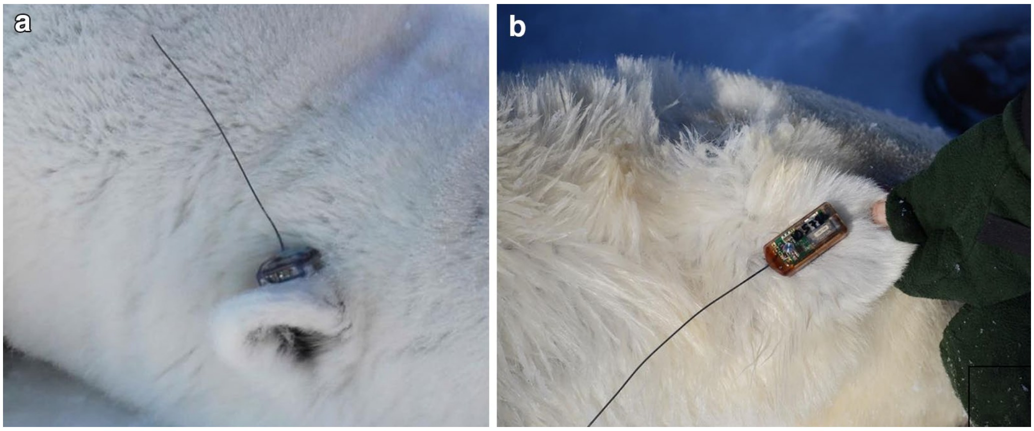


**Fig. 2** Ear satellite transmitter (PTT) mounted on polar bears. **a** SPOT-227. Note the antenna is protruding perpendicular to the ear. **b** SPOT-305A. Note the antenna is protruding along the ear and neck

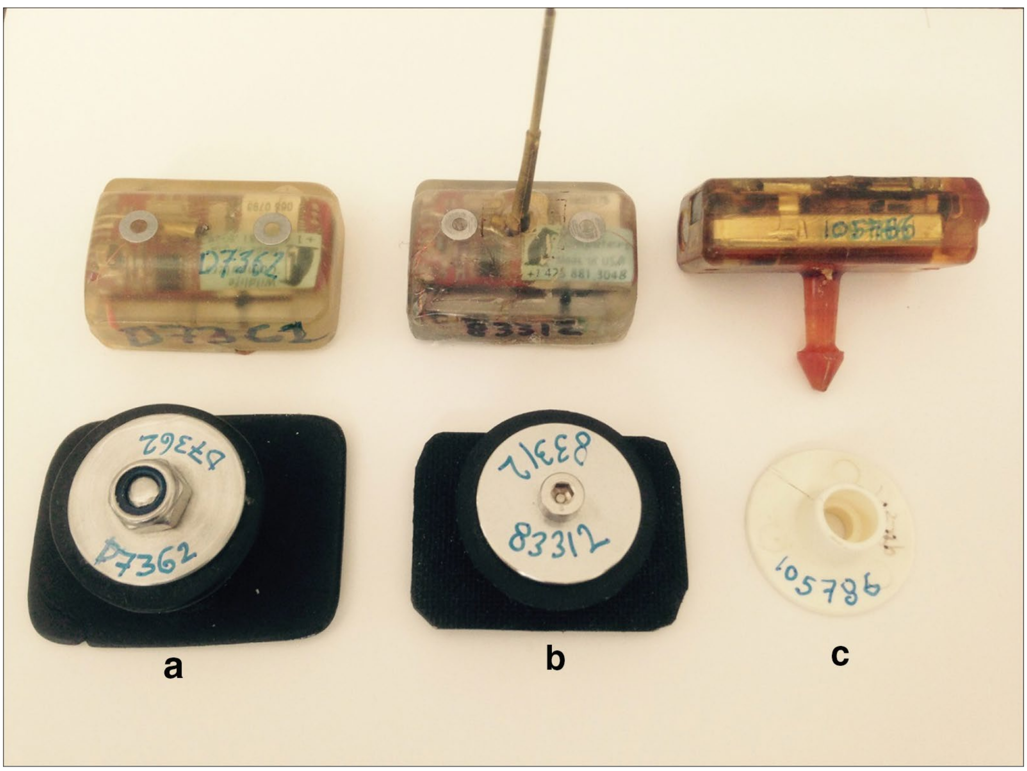


**Fig. 3** Attachment system for ear satellite transmitters (PTTs) mounted on polar bears. **a** SPOT-227B used in 2007. A pin was mounted through a hole in the earlobe of the bear and secured with a steel washer that sat on the inner side of the earlobe. A nut was screwed onto the pin to hold the washer. **b** SPOT-227B in 2008–2012. A male nut was screw into a female end of the pin to hold the washer. **c** SPOT-305A. A plastic pin was held fast by a plastic washer inside the ear orifice. Transmitters **a** and **c** were retrieved from polar bears in Greenland both with antennas broken at base

respectively. All PTTs were programmed to transmit daily during field activities (about 1 month after deployment) which allowed researchers to relocate tagged bears. For the months following field activities, PTT duty cycles [i.e., the time a PTT is transmitting (e.g., 4 h) during a given period of time (e.g., 24 h)] and transmission frequency varied depending on research objectives, from 4 to 24 h per day, every day to every 4th day, and 140–250 transmissions per day (Table 2). Transmissions not used during 1 day were allowed to be transferred to the next day; that is, the normal ceiling of daily transmissions was increased by the addition of unused transmission from the previous day. Within their normal duty cycle, PTTs were programed to not transmit when a wet–dry sensor indicated the PTT was submerged. Repetition rates (number of seconds between each transmission) varied between 43.5 and 90 s (Table 2). For the PTTs deployed in Greenland and Canada, the repetition rate was decreased if the animal was at sea to increase the probability of a good transmission reaching the satellite, while the USA PTTs had a fixed repetition rate.

PTTs were attached to an ear on adult and subadult (including 2 years old) polar bears of both sexes. We considered bears ≥2 years of age to have earlobes thick and sturdy enough to carry a PTT. Transmitters were placed on the caudal, convex aspect of ear pinnae to prevent potential irritation of the auricular cartilages and external ear canal and to minimize potential for hearing impairment.

### Data analysis

Data on locations and PTT status were collected via the Argos Location Service Plus system (Argos, Toulouse, France). Information on PTT status was extracted from the data by the Wildlife Computers Data Analysis Programs 3.0 (www.wildlifecomputers.com). To assess PTT status, we used the following parameters from that program: (1) transmits: the total number of transmissions generated by the PTT at any time, (2) BattVoltage: voltage generated by battery (or batteries) during transmission, and (3) temperature: external temperature measured by the PTT just prior to transmission.

We calculated the total transmission life of PTTs as the number of days between deployment and the last location of any class calculated by Argos for that transmitter. Possible battery exhaustion was assessed in two ways. First, we used the number of transmissions generated by the PTT during its total life and compared that to the manufacturer's theoretical maximum. Second, we used the last battery voltage received from the PTTs as a measure of performance and compared that to 2.7 V, which is the lower limit for the PTT to function (i.e., battery exhaustion) (Wildlife Computers, personal communication). When new, PTTs had a transmission output voltage greater than 3.0 V (Wildlife Computers, personal communication). A last battery voltage less than 2.9 was taken as an indication that the battery was close to exhaustion.

We examined the temperature data given by PTTs for sudden drops that could indicate that the PTT had detached from the bear and was transmitting from the ground or sea ice. If temperature decreased suddenly to below +5 °C and remained low, we investigated the data further. If the temperature was low until end of transmissions, we assumed the PTT had been detached (example readings in Additional file 2: Fig. S1). We also performed a

**Table 2 Duty cycle protocol of ear satellite transmitters (PTT) mounted on polar bears**

| Area | Year | Every day | Every 2nd day from | Every 4th day from | Working hours per day | Maximum daily transmissions | Repetition rate (s) |
|---|---|---|---|---|---|---|---|
| East Greenland, Baffin Bay, and Kane Basin SPOT-227B | 2007 | 1 March–31 May | | 1 June | 16 | 150 | 45/90[b] |
| | 2008 | | | 1 March | 16 | 140 | 42.5/87.5[b] |
| | 2009 | 1 April–31 May | | 2 June | 14 | 150 | 56/86[b] |
| | 2010 | 22 March–19 April | | 23 April | 14 | 150 | 45/90[b] |
| | 2011 | 1–30 April | | 2 May | 13 | 150 | 90 |
| | 2012 | 4–20 April | | 24 April | 13 | 150 | 43.5/88.5[b] |
| Baffin Bay and Kane Basin SPOT-305A | 2013 | 5–19 April | | 23 April | 13 | 150 | 44.5/89.5[b] |
| Southern Beaufort Sea SPOT-227B | 2009 | Deployment date–[a] | | – | 4 | 200 | 56 |
| | 2010 | Deployment date– | | – | 4 | 200 | 56 |
| Southern Beaufort Sea SPOT-227C | 2011 | Deployment date– | | – | 4 | 200 | 90[c] |
| Chukchi Sea SPOT-227B/SPOT-227D | 2010–2011 | March–June | 1 July | – | 4 | 250 | 90 |

The bears were tagged in East Greenland, Baffin Bay, Kane Basin, the southern Beaufort Sea, and the Chukchi Sea, 2007–2013

[a] Three PTTs transmitted every second day

[b] Repetition rate in water/on land

[c] One PTT had repetition rate 60

visual assessment of position data (i.e., whether the tag was moving in a manner suggesting it was attached to a bear or drifting on sea ice) to refine our assessment. A PTT was classified as being on a bear from the day of deployment to the day with reception of data just prior to the date the PTT was classified as being detached from the bear.

Performance of PTTs attached to bears was explored in two ways. First, by functional longevity defined as the number of days PTTs transmitted while still attached to polar bears. Second, performance was also measured by the percentage of high-quality positions generated by the Argos system (http://www.argos-system.org/manual/), calculated as: (number of locations with location class ≥1) * 100/(all locations; location class 3 + 2 + 1 + 0 + A + B + Z).

We pooled the data from the SPOT-227B, SPOT-227C, and SPOT-227D models which were similar in size (denoted SPOT-227) and used a three-way ANOVA to explore difference in performance between SPOT-227 and SPOT-305 PTTs taking possible sex and age variation into consideration. We excluded PTTs deployed in the USA (SPOT-227: $n = 58$) from these analyses because they were programed differently (i.e., with a higher number of maximum daily transmissions and lower repetition rates) than the PTTs applied in Greenland and Canada. We explored seasonal differences in performance of SPOT-227 PTTs deployed during spring and autumn using the US PTTs, because 9 of 10 of the autumn PTTs were deployed in the USA. For statistical tests, we analyzed the percentage variable untransformed and transformed by the logit transformation ($\log(y/(1 - y))$ to improve normality [20]. The two methods gave the same results, and we report only the untransformed data under "Results" section.

To evaluate possible effects of the ear-mounted PTTs on the condition of the ear, and to help determine reasons for PTT failure, we compiled and summarized all available information from bears that were fitted with ear tags and subsequently killed by subsistence hunters or recaptured during fieldwork.

Statistical analyses were performed by SPSS version 21.0.0.0.

## Results

A total of 145 polar bears were instrumented with ear-mounted PTTs during this study. Eighty-six PTTs were deployed in East Greenland, Baffin Bay and Kane Basin in 2007–2013, 30 were deployed in the southern Beaufort Sea in 2009–2011, and 29 were deployed in the Chukchi Sea in 2010–2011 (Additional file 1: Table S1). All PTTs were deployed during spring except nine which were deployed in the Southern Beaufort Sea during August–October 2009 and one which was deployed in East Greenland in August 2011.

### Performance of PTTs during their total transmission life

Three PTTs (all SPOT-227) were excluded from the analysis because they lasted for less than 24 h, likely due to electronic failure. The remaining 142 PTTs had a mean transmission life (i.e., from deployment until last location received) of 69.3 days (median = 56.5, SD = 60.7, range = 5–515). The mean number of transmission for SPOT-227 PTTs was 8681 ($n = 123$, median = 5888, SD = 9048, range = 1024–55,552) and for SPOT-305 PTTs was 3948 ($n = 19$, median = 3072, SD = 4784, range = 2014–23,040). Both mean values were considerably less than the theoretical maximum number of transmissions according to the manufacturer, although several individual tags approached or exceeded the theoretical maximum (four SPOT-227 with >30,000 transmissions and one SPOT-305 with >23,000 transmissions).

Four PTTs had battery voltage less than 2.8 V at the last transmission and five PTTs had battery voltage between 2.9 and 2.8, indicating they were all close to battery exhaustion. These last five PTTs also provided close to the maximum number of transmissions (see above), indicating that battery exhaustion might have caused these to stop. Voltage below 2.9 occurred 106–515 days after deployment. The mean number of transmissions for SPOT-227 was 32,864 ($n = 8$, median = 34,176, range = 7424–55,552, SD = 17,963). One SPOT-305A had 23,040 transmissions. Three of these PTTs were still on the bear when they stopped. The other 133 PTTs (94%) had a voltage between 2.9 and 3.8 V at last transmission, suggesting that the majority of PTTs failed for reasons other than battery exhaustion, including loss of the tag and antennae breakage.

Of the 142 PTTs, 34 (24%) demonstrated a decrease in temperature before they stopped transmitting which, combined with position data, indicated that they had likely detached from the bear (Additional file 3: Table S2). Thirty-one of these were SPOT-227 (25% of 123 SPOT-227) and three were SPOT-305A (16% of 19 SPOT-305A). There was not a significant difference in frequencies of the two types of tags that apparently detached from bears (Yates' $X^2 = 0.108$, $df = 1$, $P > 0.05$). The period between the assumed PTT detachment and the end of transmissions varied between 0 and 409 days (see Additional file 4: Fig. S2).

### Performance of PTTs when attached to polar bears

The 123 SPOT-227 PTTs had a mean functional longevity (i.e., number of days from deployment until the last location received while the PTT was still attached to a bear) of 56.8 days (median = 50.0, SD = 34.2). The 19

SPOT-305A PTTs had a mean functional longevity of 48.6 days (median = 38.0, SD = 32.6). A distribution plot of the functional longevity is shown in Additional file 5: Fig. S3).

Comparing the performance of the SPOT-227 and SPOT-305A (Table 3), we found no effects of sex ($F = 0.761$, $df = 1, 76$, $P = 0.386$) but a possible effect of age ($F = 4.101$, $df = 1, 76$, $P = 0.046$) on functional longevity, with PTTs on subadults transmitting for a shorter time than adults. No difference between the two PTT types was detected ($F = 0.169$, $df = 1, 76$, $P = 0.682$). We found no effects of sex or age for the proportion of high-quality positions ($F = 0.018$, $df = 1, 76$, $P = 0.894$ and $F = 2.517$, $df = 1, 76$, $P = 0.117$, respectively). However, the SPOT-227 PTTs gave a higher proportion of high-quality positions than the SPOT-305A PTTs ($F = 9.490$, $df = 1, 76$, $P = 0.003$).

We found no difference ($F = 1.357$, $P = 0.249$) in the functional longevity of SPOT-227 PTTs deployed in spring ($n = 49$, mean = 55.4 days, SD = 32.5) and autumn ($n = 9$, mean = 41.3 days, SD = 38.2).

Twenty-six bears that were instrumented with ear-mounted PTTs were recaptured during tagging operations during subsequent years ($n = 21$) or were killed by subsistence hunters ($n = 5$) (Additional file 6: Table S3). Six of these bears (23%) still had the PTT in the ear [recapture or kill dates were 54–1120 days after deployment (mean = 529, SD = 365)]. The antenna was broken off at its base on all six tags that were recovered (five SPOT-227 and one SPOT-305A).

The ear-mounted PTT had been detached for 19 of the recaptured or killed bears, and no information on the PTT was available for one bear. For three of these recaptures, the hole in the ear where the PTT had been attached had healed (two of them had only a small scar). In 10 other bears (nine recaptured and one killed), the ear was split but healed. In eight cases (seven reported by scientists and one reported by hunter), there was no apparent injury to the ear and in two cases no information on possible injury was reported by the hunter. In three of the six cases where the PTT was still attached, the ear was inflamed (all harvested bears, of which one also was inspected by a scientist).

## Discussion

Satellite tagging studies provide critical data, which often cannot be obtained in any other manner, on the movements, habitat use, and life history of many free-ranging wildlife species [4, 21]. These data are particularly important to the conservation and management of species such as polar bears that are experiencing rapid environmental change. Diagnosing tag performance and retention is necessary to improve the transmitter technology and attachment systems [3]. In the present study, the performance of ear-mounted PTTs designed for polar bears was poorer than the theoretical life time of batteries and the assumed total number of transmission specified by the manufacturer. Factors accounting for this performance may be grouped into three categories: (1) loss of the PTT from the bear, (2) antenna failure, and (3) battery life.

**Table 3 Performance of SPOT-227 and SPOT-305A of ear satellite transmitters (PTTs) mounted on subadult, adult, male and female polar bears**

| Transmitter | N | Functional longevity (days) | | | Percentage of high-quality locations (LQ ≥ 1) | | |
|---|---|---|---|---|---|---|---|
| | | Mean | Median | SD | Mean | Median | SD |
| *SPOT-227* | | | | | | | |
| Subadult males | 14 | 52.4 | 42.0 | 22.9 | 67.25 | 71.86 | 11.25 |
| Subadult females | 9 | 43.2 | 45.0 | 20.1 | 68.32 | 69.77 | 11.78 |
| Adult males | 39 | 68.6 | 63.0 | 39.5 | 63.07 | 64.96 | 11.83 |
| Adult females | 3 | 33.0 | 38.0 | 8.7 | 62.73 | 64.06 | 5.71 |
| *SPOT-305A* | | | | | | | |
| Subadult males | 5 | 25.4 | 22.0 | 16.1 | 55.70 | 57.89 | 7.39 |
| Subadult females | 2 | 22.0 | 22.0 | 17.0 | 58.26 | 58.26 | 7.29 |
| Adult males | 10 | 61.1 | 59.0 | 31.0 | 49.87 | 48.52 | 14.25 |
| Adult females | 2 | 70.5 | 70.5 | 50.21 | 48.71 | 48.71 | 11.31 |
| *Total* | | | | | | | |
| SPOT-227 | 65 | 60.0 | 52.0 | 34.9 | 64.68 | 66.48 | 11.50 |
| SPOT-305A | 19 | 48.6 | 38.0 | 32.6 | 52.17 | 53.10 | 11.64 |

The bears were tagged in East Greenland, Baffin Bay, and Kane Basin in the period 2007–2013. Differences in functional longevity and percentage of high-quality locations were not significant for age and sex groups pooled ($P > 0.05$, see text)

We evaluated the functional longevity of ear-mounted PTT tags, defined as the number of days that tags provided location data while attached to bears. The mean functional longevity of 56.8 and 48.6 days for the SPOT-227 and the SPOT-305A PTTs, respectively, was too low for ecological studies that require data on the movement of individual animals across seasons or years. A drop in temperature before the tag stopped transmitting was observed in 24% of PTTs. This suggests that some PTTs were dropped from the bears and continued to transmit from the ground or sea ice. Differences in PTT functional longevity between age groups might indicate that PTTs on subadult bears, which have smaller ears, had a tendency to fail earlier than those deployed on larger bears. This suggests that larger tag-to-ear size ratios might be associated with reduced PTT attachment times, which emphasizes the importance of developing smaller tags. However, shorter functional longevity in subadults than in adults could also be related to differences in behavior.

While the causes of tag detachment in these cases are unknown, several lines of evidence provide insight into this question. Inflammation was noted in the ear pinnae of three of the six polar bears that still had an attached transmitter when they were harvested by subsistence hunters. Although we were not able to obtain a veterinary assessment of these cases, we note that the three tags had been on the bears for 416, 483, and 745 days, values that are well above the average duration of tag retention (Additional file 6: Table S3). These findings suggest the importance of (i) continued assessment of the tag attachment system, to reduce the potential for inflammation; and (ii) development of an attachment system that will cause the tag to detach after a predetermined period. The relatively high proportion of recaptured bears with an ear pinna that was split (10 with split ear of a total of 26) suggests that some transmitters were detached by force causing trauma to ear pinna. We speculate that the bears tore the transmitters from the ear using their paws or the transmitters became caught on objects in the bears' surroundings. For example, in Svalbard bears have been observed on two occasions with their plastic ear tags attached to discarded fishing nets on the beach (Ø. Wiig, personal information). In spring, polar bears often plunge head first into seal breeding lairs to catch ringed seals [22], or put their head into ringed seal breathing holes, which can be surrounded with sharp ice. This behavior might tear the PTT out of the ear. Also, during spring adult males engage in fights for mating partners and often inflict severe wounds on each other [14, 23]. Hence, it is possible that PTTs could have been damaged or torn from the earlobe during such fights.

Polar bears move in and out of water and often experience humid condition at subfreezing temperatures during spring. This may cause a buildup of ice around the PTT, on the whip antenna or on the stainless steel post, making the PTT more likely to fall off or be an irritant to the bear. The use of metal ear tags in polar bears for identifying individuals had previously been suggested as the cause of infection as a result of freezing/irritation [16]. SPOT-227 PTTs deployed in spring did not have different longevity than those deployed during the ice-free season in the autumn. However, a separate study reported that 5 SPOT-227 ear PTTs that were attached to adult male polar bears in the Foxe Basin in August 2008 ($n = 4$) and 2009 ($n = 1$) had a retention rate of 97.6 (SE = 11.2) days (V. Sahanatien, University of Alberta, personal information). This is more than twice as long as the 9 PTTs deployed in autumn in East Greenland ($n = 1$) and southern Beaufort Sea ($n = 8$). The importance of icing and feeding behavior on tag functional longevity is uncertain.

It is important to note that all the 19 bears that were recaptured without the PTT had an ear that was completely healed, including the 10 bears that had incurred a split in their ear pinna. Such injuries have rarely been observed for polar bears marked with inert plastic identification ear tags, suggesting that PTT size and weight are likely a contributing factor to the shedding. One would expect that a heavier PTT (SPOT-227) would cause greater irritation to the bear's ear and therefore be shed earlier than a lighter PTT (SPOT-305A). However, we found no difference in the functional longevity of the two PTT types and no difference in frequency of detachment. It is also important to note that inert plastic ear tags, which weigh only about 6 grams, have exhibited generally high retention rates on polar bears, often lasting for many years and rarely causing injury (Ø. Wiig, personal observation). We therefore conclude that the weight of ear-mounted PTTs must be considerably less than 40 g, the lightest tag deployed in the current study, to improve retention and avoid irritation to the bear.

Antenna breakage is proposed as a second important contributing factor in early failure of the PTTs. Loss of the whip antenna means the PTT can no longer transmit data to the satellites. Although our ability to assess antenna function was limited by the relatively small number of PTTs that were recovered after deployment on a bear, in this study all six PTTs that were still on a bear at recapture had lost the antenna. Comparison between PTT types was not possible due to small sample sizes (five SPOT-227 and one SPOT-305A were recovered). The flexible whip antenna is subject to various physical impacts including icing. The movement of the bear's head when walking and running makes the antenna prone to flexing, which at low temperature may cause metal fatigue and increased risk of breakage at the base. We hypothesize that ice buildup on the antenna can exacerbate this effect. Also, the feeding and breeding behavior as described above might contribute to antenna breakage.

The percentage of high-quality positions from the SPOT tags in the present study was about twice as high as the percentage of high-quality positions received from similar SPOT tags used on walruses as reported by [24]. The SPOT-227 PTTs provided a higher percentage of high-quality positions than the SPOT-305A. The quality of estimated positions in the Argos system is partly dependent on the number of uplinks made and on the signal strength of those uplinks [25]. In turn, the signal strength is dependent on the battery performance as well as the quality and position of the antenna. The antenna on the SPOT-227 was attached centrally or laterally on the flat upper ("outward facing") side of the PTT so that it was protruding perpendicular to the back side of the earlobe and therefore pointing away from the bear's head, whereas the SPOT-305A antenna was attached at the distal end of the PTT so that it was protruding parallel to the long axis of the earlobe and the neck. Thus, the antenna of the SPOT-305A was in closer proximity to the bear's body. One reason the antenna position was moved from the flat upper side on the SPOT-227, to the distal end on the SPOT-305A, was to "hide" the antenna along the ear and neck of the bear, potentially affording better protection for the antenna when a bear drove its head into seal lairs or breathing holes. Therefore, lower performance of the SPOT-305A could be due to the voltage standing wave ratio effect, which leads to a reduction in effective radiated power from the antenna due to the antenna's close proximity to a large conductive mass [26–28]. Jay et al. [24] noted that misalignment of the antenna along the body of the walrus of their "tether tag" may have been responsible for poor transmission performance in relation to "post tags" and "implant tags," which had antennae that protruded almost perpendicular to the surface of the animal.

We used the data from the total duration of PTT transmissions, independent of whether the tags were attached to bears, to analyze the role of battery life in determining tag performance. Only nine of the 142 PTTs (6%) had a final voltage reading close to the lower voltage needed for transmission. We therefore conclude that battery exhaustion is not a major reason for failure of ear-mounted PTTs in polar bears. We can only speculate that the wide range of dates before the indication of battery exhaustion was reached may reflect variability in performance of the battery/electronics. A study investigating the performance of small, externally positioned PTTs on walruses similarly found that battery exhaustion was not the likely cause for early failure [24, 29]. Due to lack of recaptures, however, these studies were not able to distinguish between failures that may have been caused by antenna breakage, transmitter damage, or tag loss.

## Conclusions

Based on a sample of 145 ear-mounted PTT tags deployed on free-ranging polar bears, factors accounting for failure of the transmitters were grouped into three categories: (1) loss of the transmitter from the bear, (2) antenna breakage, and (3) battery life. Thirty-four PTTs showed signs of being detached from the bears before they stopped transmitting, indicating that detachment was an important aspect of failure. All six PTTs that were still on the bear at recapture had lost the antenna, which indicates that antenna breakage was a significant contributor to PTT failure. Finally, we conclude that battery exhaustion was not a major reason for failure as only three of 142 PTTs showed signs of low battery voltage while still attached to bears.

The average functional longevity of ear-mounted PTTs in our study was 55.7 days. Our findings may be used to target the most important factors contributing to early tag failure. We suggest that much smaller and lighter ear-mounted transmitters are necessary to reduce the risk of tissue irritation, tissue damage, and tag detachment. A more durable antenna is needed to reduce breakage, likely caused by repetitive flexing and potentially exacerbated by ice buildup. Use of solar cells for power could potentially reduce size and weight, and allow for tracking bears during spring and summer where sunlight prevails for nearly 24 h per day in the Arctic. We also recommend development of a non-permanent attachment system that is durable but, when subjected to direct force (e.g., when a bear pushes its head into a seal breathing hole), is designed to cause the tag to detach without causing tissue damage to the ear. New ear tag technology could be tested out on captive polar bears. Although bears in captivity will not endure similar climate and habitat conditions as bears in the wild, tests with captive bears could be insightful to better evaluate a suitable weight, size, and attachment system. With the improvements outlined here, we believe that ear-mounted PTT tags have the potential to provide critical data on the movements, habitat use, and life history of all sex and age classes of polar bears, with the additional benefit of being less visible and less cumbersome than radio collars. Although the current study focused on tags that use the Argos system, many of our recommendations likely apply to tags that use other radio-tracking technologies (e.g., iridium or VHF). Furthermore, our general findings are likely applicable to any research using ear-mounted satellite tags to track animals that cannot accommodate radio collars.

## Additional files

**Additional file 1: Table S1.** Number of four different models of ear satellite transmitters (PTTs) mounted on polar bears.

**Additional file 2: Fig. S1.** Temperature reads from PTT-ID 105790 mounted on a polar bear.

**Additional file 3: Table S2.** Ear satellite transmitters (PTTs) mounted on polar bears interpreted as being detached from the bear.

**Additional file 4: Fig. S2.** Days between assumed detachment and end of transmissions for ear satellite transmitters (PTTs) mounted on polar bears.

**Additional file 5: Fig. S3.** Functional longevity for ear satellite transmitters (PTTs) mounted on polar bears.

**Additional file 6: Table S3.** Recaptures of polar bears that were fitted with an ear satellite transmitter (PTT).

### Abbreviations
Iridium: satellite constellation providing voice and data coverage to satellite phones, pagers, and integrated transceivers; PTT: platform transmitter terminal; SPOT: satellite transmitter; VHF: very high frequency.

### Authors' contributions
EWB, MVJ, and RDI conceived and designed the experiment and developed transmitters. EWB, KLL, ØW, RDI, GMD, AMP, ER, MS, SA, and MD performed the experiment. ØW, EWB, and KLL analyzed the data and wrote the paper. ØW, EWB, KLL, RDI, SA, MD, MVJ, GMD, AMP, ER, MS, SA, and MD provided expertise and editing. All authors read and approved the final manuscript.

### Author details
[1] Natural History Museum, University of Oslo, P.O. Box 1172, Blindern, 0318 Oslo, Norway. [2] Greenland Institute of Natural Resources, P.O. Box 570, 3900 Nuuk, Greenland. [3] Polar Science Center, Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105-6698, USA. [4] Department of Bioscience, Arctic Research Center, Aarhus University, P.O. Box 358, 4000 Roskilde, Denmark. [5] Mikkels Værksted, Højskolevej 7B, 4534 Vallekilde, Denmark. [6] U.S. Geological Survey, Alaska Science Center, 4210 University Drive, Anchorage, AK 99508, USA. [7] Marine Mammals Management, U.S. Fish and Wildlife Service, 1011 E. Tudor Rd., Anchorage, AK 99503, USA. [8] P.O. Box 19, Group 7, RR2, Dugald, MB X0E 0K0, Canada. [9] Wildlife Research Section, Department of Environment, Government of Nunavut, P.O. Box 209, Igloolik, NT X0A 0L0, Canada.

### Acknowledgements
We thank the technicians Hans Christian Schmidt and Peter Hegelund (Greenland Institute of Natural Resources), Dennis Andriashek (Environment Canada), Kristin Simac and Geoff York (USGS), Paul Frame and Jon Neely (Government of Nunavut), Jopee Kigutak and Mark Akeeagok (Iviq Hunters and Trappers Organization), pilots Sebastian Holst, Geir Akse and Snorre Wigdahl (AirGreenland), Bjørn Frode Amundsen and Roger Eide (Airlift, Norway), and Joseph Fieldman and Doc Gohmert (Prism Helicopters, USA), Howard Reed (Maritime Helicopters, USA), John Innes, Jim Berry and Steve Lodge (Universal Helicopters Nfld). We also thank Inge Mortensen (Chief pharmacian, Nuuk, Greenland), Rigmor Bruhn (Hospital in Upernavik), and subsistence hunters and local people in the settlements Niaqornat, Upernavik, Kullorsuaq, Savissivik, and Grise Fiord for invaluable help and great hospitality during the field work. Fernando Ugarte (GINR) and Sigga Joensen (Department of Bioscience, Arctic Research Center, Aarhus University) are thanked for various help in the laboratory. Wildlife Computers are thanked for help in developing the transmitters and providing additional technical information on the transmitters during the writing process. We thank Vicki Sahanatien for giving us information on retention rates of five ear PTTs attached to polar bears in Foxe Basin in 2008 and 2009. We also wish to thank Norwegian Polar Institute and Institute of Marine Research (both in Tromsø, Norway). The USGS thanks the US Fish and Wildlife Service, Marine Mammals Management and the Arctic National Wildlife Refuge, and the North Slope Borough, Department of Wildlife Management, for their support of polar bear research in the southern Beaufort Sea. The Government of Nunavut thanks P. Frame, S. Lodge, and the hunters from the community of Grise Fiord for their field support. Use of trade names is for descriptive purposes only and does not imply endorsement by the US Government. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the US Fish and Wildlife Service. This report was approved under USGS Fundamental Science Practices.

### Competing interests
MVJ runs a private company that modifies and produces wildlife tagging equipment including attachment system for transmitters. The other authors declare that they have no competing interests.

### Availability of data and materials
The USGS datasets used and/or analyzed during the current study are available http://dx.doi.org/F7057D4R. The remaining datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Ethics
All capturing, handling, and treatment of the polar bears were made with specific permissions from the respective national authorities. In Greenland, the Greenland Government's Department of Veterinary, Department of Health, the Departments of Fishery, Hunting and Agriculture and the Department of the Environment granted permission for all operations according to the official regulations [30]. Research in Nunavut (Kane Basin) was reviewed and approved by affected communities and under Government of Nunavut Wildlife Research Permits (2012-010, 2013-011, 2014-007). Research in the Beaufort Sea was led by US Geological Survey, Alaska Science Center (USGS): US Fish and Wildlife Service research permit MA 690038 and followed protocols approved by Animal Care and Use Committees of the USGS (assurance no. 2010-3). Research in the Chukchi Sea was led by the US Fish and Wildlife Service (USFWS) under the Marine Mammal Protection Act and Endangered Species Act research permit MA-046081, and was approved by the USFWS Region 7 Institutional Animal Care and Use Committee under protocol 2009015.

### Funding
This study was funded by the Danish Ministry of Environment (DANCEA), Bureau of Mineral and Petroleum (Greenland), Vetlesen Foundation, the Greenland Institute of Natural Resources, US Fish and Wildlife Service, University of Washington, University of Oslo, Government of Nunavut (Dept. of Environment), the Nunavut Wildlife Management Board (Nunavut Wildlife Research Trust), Environment Canada, World Wildlife Fund (Canada). In-kind funding and logistical support in Kane Basin was provided by the Polar Continental Shelf Program (Project Numbers 302-12, 310-13, 313-14). Primary funding for the USGS was provided by the US Geological Survey, Ecosystems and Climate and Land Use Change Mission Areas, with additional support from the US Bureau of Land Management, the US Bureau of Ocean Energy Management, and a National Science Foundation Grant (OPP 0732713) to the University of Wyoming.

## Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 17 January 2017 Accepted: 27 March 2017
Published online: 13 April 2017

### References
1. Atwood TC, Marcot BG, Douglas DC, Amstrup SC, Rode KD, Durner GM, et al. Forecasting the relative influence of environmental and anthropogenic stressors on polar bears. Ecosphere. 2016;7(6):1–22.
2. Vongraven D, Aars J, Amstrup S, Atkinsons SN, Belikov S, Born EW, et al. A circumpolar monitoring framework for polar bears. Ursus Mon Ser. 2012;5:1–66.
3. Hays GC, Bradshaw CJA, James MC, Lovell P, Sims DW. Why do Argos satellite tags deployed on marine animals stop transmitting? J Exp Mar Biol Ecol. 2007;349(1):52–60.

4. Kays R, Crofoot MC, Jetz W, Wikelski M. Terrestrial animal tracking as an eye on life and planet. Science. 2015;348(6240):1222.
5. Amstrup SC, Durner GM, Stirling I, Lunn NN, Messier F. Movements and distribution of polar bears in the Beaufort Sea. Can J Zool. 2000;78(6):948–66.
6. Wiig O, Born EW, Pedersen LT. Movements of female polar bears (*Ursus maritimus*) in the East Greenland pack ice. Polar Biol. 2003;26(8):509–16.
7. Laidre KL, Born EW, Gurarie E, Wiig Ø, Dietz R, Stern H. Females roam while males patrol: divergence in breeding season movements of pack-ice polar bears (*Ursus maritimus*). Proc R Soc B. 2013. doi:10.1098/rspb.2012.2371.
8. Laidre KL, Born EW, Heagerty P, Wiig O, Stern H, Dietz R, et al. Shifts in female polar bear (*Ursus maritimus*) habitat use in East Greenland. Polar Biol. 2015;38(6):879–93.
9. Durner GM, Douglas DC, Nielson RM, Amstrup SC, McDonald TL, Stirling I, et al. Predicting 21st-century polar bear habitat distribution from global climate models. Ecol Monogr. 2009. doi:10.1890/07-2089.1.
10. Amstrup SC, Durner GM, McDonald TL, Mulcahy DM, Garner GW. Comparing movement patterns of satellite-tagged male and female polar bears. Can J Zool. 2001;79(12):2147–58.
11. Taylor MK, Akeeagok S, Andriashek D, Barbour W, Born EW, Calvert W, et al. Delineating Canadian and Greenland polar bear (*Ursus maritimus*) populations by cluster analysis of movements. Can J Zool. 2001;79(4):690–709.
12. Bromaghin JF, McDonald TL, Stirling I, Derocher AE, Richardson ES, Regehr EV, et al. Polar bear population dynamics in the southern Beaufort Sea during a period of sea ice decline. Ecol Appl. 2015;25(3):634–51.
13. USFWS. New radio telemetry tags. In: Polar bear news. Anchorage: U.S. Fish and Wildlife Service; 2010. https://www.fws.gov/alaska/fisheries/mmm/polarbear/pdf/newsletter_2010.pdf. Accessed 02 Sept 2016.
14. Born EW, Sonne C, Dietz R. Research on polar bears in Greenland, 2005–2009. In: Obbard ME, Thiemann GW, Peacock E, DeBruyn TD. editors. Occasional Papers of the IUCN Species Survival Commission, vol 43. 2010. p. 135–48.
15. Rode KD, Pagano AM, Bromaghin JF, Atwood TC, Durner GM, Simac KS, et al. Effects of capturing and collaring on polar bears: findings from long-term research on the southern Beaufort Sea population. Wildl Res. 2014;41(4):311–22.
16. Larsen T. Capturing, handling, and marking polar bears in Svalbard. J Wildl Manag. 1971. doi:10.2307/3799868.
17. Stirling I, Spencer C, Andriashek D. Immobilization of polar bears (*Ursus maritimus*) with telazol in the Canadian Arctic. J Wildl Dis. 1989;25(2):159–68.
18. Calvert W, Ramsay MA. Evaluatio of age determination of polar bears by counts of cementum growth layer groups. Ursus. 1998;10:449–53.
19. Rosing-Asvid A, Born EW, Kingsley MCS. Age at sexual maturity of males and timing of the mating season of polar bears (*Ursus maritimus*) in Greenland. Polar Biol. 2002;25(12):878–83.
20. Warton DI, Hui FKC. The arcsine is asinine: the analysis of proportions in ecology. Ecology. 2011;92(1):3–10.
21. Cooke SJ. Biotelemetry and biologging in endangered species research and animal conservation: relevance to regional, national, and IUCN Red List threat assessments. Endanger Species Res. 2008;4(1–2):165–85.
22. Gjertz I, Lydersen C. Polar bear predation on ringed seals in the fast-ice of Hornsund, Svalbard. Polar Res. 1986;4:65–8.
23. Derocher AE, Andersen M, Wiig O, Aars J. Sexual dimorphism and the mating ecology of polar bears (*Ursus maritimus*) at Svalbard. Behav Ecol Sociobiol. 2010;64(6):939–46.
24. Jay CV, Heide-Jorgensen MP, Fischbach AS, Jensen MV, Tessler DF, Jensen AV. Comparison of remotely deployed satellite radio transmitters on walruses. Mar Mamm Sci. 2006;22(1):226–36.
25. CLS. Argos user's manual. 2016. http://www.argos-system.org/manual/. Accessed 12 Dec 2016.
26. Harris RB, Fancy SG, Douglas DC, Garner GW, Amstrup SC, McCabe TR, et al. Tracking wildlife by satellite: current systems and performance. Anchorage: U. S. Fish and Wildlife Service; 1990.
27. Born EW, Knutsen LO. Satellite-linked radio tracking of Atlantic walruses (*Odobenus rosmarus rosmarus*) in Northeastern Greenland, 1989–1991. Mamm Biol. 1992;57(5):275–87.
28. Fuller MR, Fuller TK. Radio-telemetry equipment and applications for carnivores. In: Boitani L, Powell RA, editors. Carnivore ecology and conservation: a handbook of techniques., [Techniques in ecology & conservation series]Oxford: Oxford University Press; 2012. p. 152–68.
29. Dietz R, Born EW, Stewart REA, Heide-Jørgensen MP, Stern H, Riget F, et al. Movements of walruses (*Odobenus rosmarus*) tracked with satellite transmitters between Central West Greenland and Southeast Baffin Island 2005–2008 In: Kovacs K, Acquarone M, Stewart REA, editors. Studies of the Atlantic walrus (*Odobenus rosmarus rosmarus*) in the North Atlantic Arctic. NAMMCO Special Publication; 2013. p. 53–74.
30. Anonymous. Greenland home rule executive order no. 21 of 22 September 2005 on the protection and hunting of polar bears. Greenland Home Rule; 2005. p. 4.

Submit your next manuscript to BioMed Central and we will help you at every step:

- We accept pre-submission inquiries
- Our selector tool helps you to find the most relevant journal
- We provide round the clock customer support
- Convenient online submission
- Thorough peer review
- Inclusion in PubMed and all major indexing services
- Maximum visibility for your research

Submit your manuscript at
www.biomedcentral.com/submit

BioMed Central