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Application of Airborne Thermal Imagery to Surveys of Pacific Walrus

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Abstract

We conducted tests of airborne thermal imagery of Pacific walrus to determine if this technology can be used to detect walrus groups on sea ice and estimate the number of walruses present in each group. In April 2002 we collected thermal imagery of 37 walrus groups in the Bering Sea at spatial resolutions ranging from 1–4 m. We also collected high-resolution digital aerial photographs of the same groups. Walruses were considerably warmer than the background environment of ice, snow, and seawater and were easily detected in thermal imagery. We found a significant linear relation between walrus group size and the amount of heat measured by the thermal sensor at all 4 spatial resolutions tested. This relation can be used in a double-sampling framework to estimate total walrus numbers from a thermal survey of a sample of units within an area and photographs from a subsample of the thermally detected groups. Previous methods used in visual aerial surveys of Pacific walrus have sampled only a small percentage of available habitat, resulting in population estimates with low precision. Results of this study indicate that an aerial survey using a thermal sensor can cover as much as 4 times the area per hour of flight time with greater reliability than visual observation. (WILDLIFE SOCIETY BULLETIN 34(1):51–58; 2006)

Key words

Odobenus rosmarus divergens, *Pacific walrus, remote sensing, thermal imagery.*

The last population survey of Pacific walrus (*Odobenus rosmarus divergens*) was jointly conducted by the United States and the Soviet Union in 1990 (Gilbert et al. 1992) and, after nearly 15 years, the current population size is unknown. The technique used at that time, a visual aerial survey, is now considered to be inadequate for measuring the size of the population with acceptable levels of accuracy and precision (Hills and Gilbert 1994, Gilbert 1999). Drawbacks to a visual aerial survey include narrow survey swath width, observer bias and fatigue, lack of a permanent data record, and safety concerns associated with low-level flight in remote areas. Of these, narrow survey swath width is considered to have the greatest impact on the precision of the resulting population estimate due to the large geographic area that must be surveyed in a short time period (Estes and Gilbert 1978, Gilbert 1999). At an international workshop of walrus biologists held by the United States Fish and Wildlife Service (USFWS) and the United States Geological Survey (USGS), the consensus opinion was that remote sensing techniques capable of collecting data over large areas should be investigated and developed as an alternative to visual surveys (Garlich-Miller and Jay 2000).

The history of aerial surveys of Pacific walrus has been reviewed by Hills and Gilbert (1994), Gilbert (1999), and Udevitz et al. (2001). In the autumn season when most of the previous surveys were conducted, the walrus population is segregated, with some animals associated with the ice edge in the Chukchi Sea, while others make use of terrestrial haulouts along the coast of Bristol Bay, Alaska in the United States, and the Chukotka and Kamchatka peninsulas in Russia. Fewer surveys have been conducted in winter and early spring, when the entire walrus population occurs almost exclusively on the pack ice of the Bering Sea with concentrations in the Gulf of Anadyr, south and west of St. Lawrence Island, and south of Nunivak Island (Fay 1982).

At any time of year, some or all of the walrus population is associated with sea ice, where animals haul out of the water and rest in large aggregations on ice floes (Fay 1982). Within minutes of leaving the water, their skin temperature becomes noticeably warmer than the background environment (Ray and Fay 1968), which provides excellent thermal contrast. In the mid-1970s, Wartzok and Ray (1980) experimented with a variety of aerial photography and remote sensing techniques, including thermal imagery, to detect marine mammals in the Bering Sea. While their results were promising, the development of a survey method using thermal imagery was not feasible due to limitations of existing technology. Over a decade later, Barber et al. (1991) used a forward-looking infrared system (FLIR) to demonstrate that groups of Atlantic walrus (*Odobenus rosmarus rosmarus*) can be detected by their signatures in the 8–12µm thermal infrared (IR) band. In addition to FLIR systems, there are other types of thermal imagery systems available for survey applications. In contrast to the video image of FLIR systems, across-track thermal scanners are capable of producing a continuous vertical photo-like digital image in the thermal IR band. Regardless of the collection system used, thermal imagery can be analyzed using commercial image analysis software to detect and classify thermal signatures of walrus groups and the application of these techniques to survey the population warranted further examination.

It is vitally important to monitor the status and trend of the Pacific walrus population. Walruses are an important part of Alaska Native subsistence culture and economy of coastal communities throughout the Bering and Chukchi seas region (Fay et al. 1997). In addition, the Pacific walrus population is shared with Russia and also is harvested by subsistence hunters in that nation (Garlich-Miller and Burn 1999). To manage the Pacific walrus effectively, population estimates from recurring joint United States - Russian surveys are required to determine population status and trends (Hills and Gilbert 1994, Gilbert

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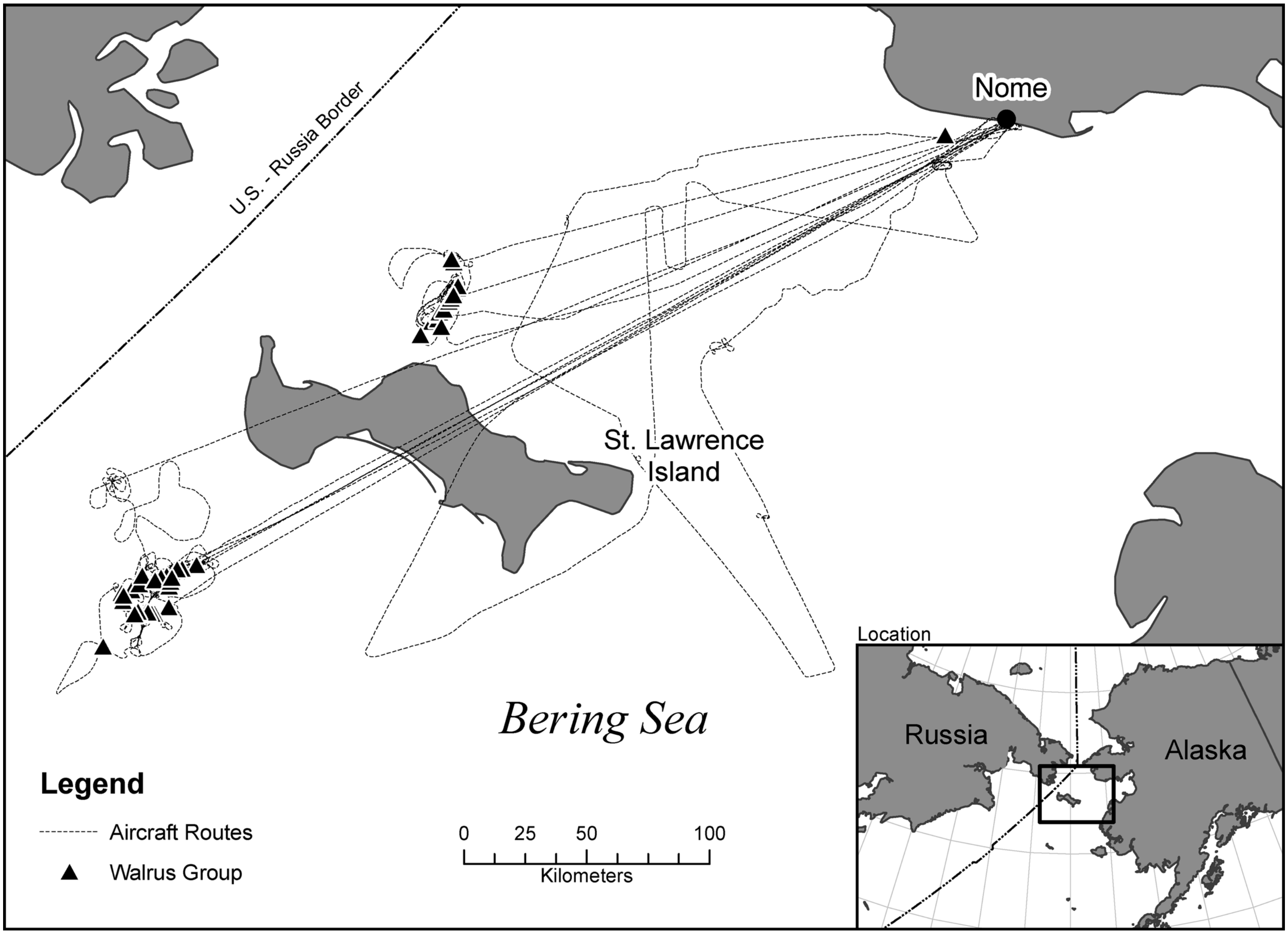

Figure 1. Study area for field data collection of AMS thermal imagery and digital aerial photography indicating aircraft routes and location of walrus groups in the Bering Sea in April 2002.

1999). The purpose of this study was to evaluate the use of an airborne thermal imaging system to detect and quantify walrus groups, and to develop a practical method for using this technology to survey a walrus population that is distributed over a large geographic area.

Methods

Study Area and Survey Dates

The study area consisted of the Bering Sea pack ice in the vicinity of St. Lawrence Island, Alaska (Fig. 1). While based out of Nome, Alaska, we conducted flight operations on clear weather days from 2–16 April 2002.

Remote Sensing Systems

The primary remote sensing system used in this study was a Daedelus Airborne Multispectral Scanner (AMS), built by SenSyTech Inc. (now Argon ST) of Ann Arbor, Michigan. The system had a 1.25 milliradian instantaneous field of view (IFOV) and collected imagery across a sensor array 1,440 pixels wide; when the data are imported to a computer, the resulting image is 1,493 pixels wide (B. Swift, SenSyTech Incorporated, personal communication). The AMS system recorded a thermal infrared channel (8.5–12.5 μm) with 12-bit radiometric resolution. All scanner data were recorded on an Exabyte internal 8-mm tape drive. Spatial resolution of the system was a linear function determined by the altitude of the survey aircraft (Table 1).

In addition to the AMS, we also used a Nikon D1X digital camera to collect high-resolution vertical photographs of walrus groups. This 5.47 megapixel camera produced images with dimensions of 3,008 × 1,960 pixels. Depending upon the altitude of the survey aircraft, we used either a 105- or 180-mm lens for photographing walrus groups. We connected the camera to a notebook computer via an IEEE 1394 (firewire) port and loaded images directly to the hard drive using Nikon Capture software.

Survey Aircraft

We used an Aero Commander 690B turbine engine aircraft for our survey flights. The 690B is a high-wing, twin-engine aircraft equipped with bubble windows allowing excellent lateral and downward visibility for walrus observations on both sides of the aircraft. The digital camera and AMS control panel were mounted

Table 1. Combinations of altitudes, pixel sizes, and swath widths used to collect airborne multispectral scanner imagery of walrus groups in the Bering Sea in April 2002.

Altitude (above ground level)		Pixel size	Swath width
(meters)	(feet)	(meters)	(kilometers)
800	2,625	1.0	1.49
1,600	5,250	2.0	2.98
2,400	7,875	3.0	4.48
3,200	10,500	4.0	5.97

within the cabin of the aircraft and the AMS scan head was mounted in the tail section.

Flight Operations

When weather permitted, we flew at an altitude of 457 m above ground level (AGL; all altitudes reported are AGL) while visually searching for walrus groups along open leads in the pack ice. When we observed walrus groups, we marked their locations as waypoints with a Global Positioning System (GPS) that also recorded the aircraft's flight track. Once we had recorded the location of 3–4 walrus groups, we began collection of aerial photography and AMS thermal imagery.

We initially collected aerial photography at 457 m AGL using a 105-mm camera lens. The resulting images had a pixel size of 3.5 cm, which was sufficient to resolve and count individual walruses. After we observed signs of disturbance in some walrus groups from overflights at that altitude, we increased our altitude to 800 m AGL and used a 180-mm camera lens. Images collected at this combination of altitude and focal length had 3.4-cm pixels. When collecting photography at the 800 m AGL, we also collected 1-m AMS thermal imagery simultaneously. Even at this greater altitude, a few minor disturbance events of walruses occurred. Once we had collected photographs of each walrus group, we collected AMS thermal imagery at altitudes that produced spatial resolutions ranging from 1–4 m (Table 1). In some instances we returned to take additional photographs of some groups after collection of AMS thermal imagery at either 457 or 800 m AGL.

Analytical Methods

At the end of each flight day, we archived the digital photographs on compact disc (CD) media. After the data collection portion of the study was complete, we imported the digital photos of each walrus group into Earth Resources Data Analysis System (ERDAS) Imagine (Leica Geosystems, Atlanta, Georgia) software. To count the number of walruses in each group, we created annotation layers and manually marked each walrus with a colored symbol. We counted each walrus group 3 times on different dates (without referring back to previous counts) using a different colored symbol each time. Finally, we simultaneously displayed all 3 group counts to compare the individual counts and arrive at a final, rectified count for each group.

We imported the AMS imagery directly from 8-mm tape into Imagine software using the Daedelus import module which corrects for tangential distortion in the final image. To determine the threshold temperature value between walruses and the background environment, we examined the frequency histogram of temperature values in the entire image. Within each image, the point at which the histogram rapidly decreased from thousands of pixels at each temperature value to fewer than 10 pixels was chosen as the temperature threshold value (Fig. 2). Pixels with temperatures warmer than the threshold value were, therefore, classified as having some portion of their area covered by walrus. After determining the threshold temperature for each image, we calculated an index of the total amount of heat produced by each walrus group as

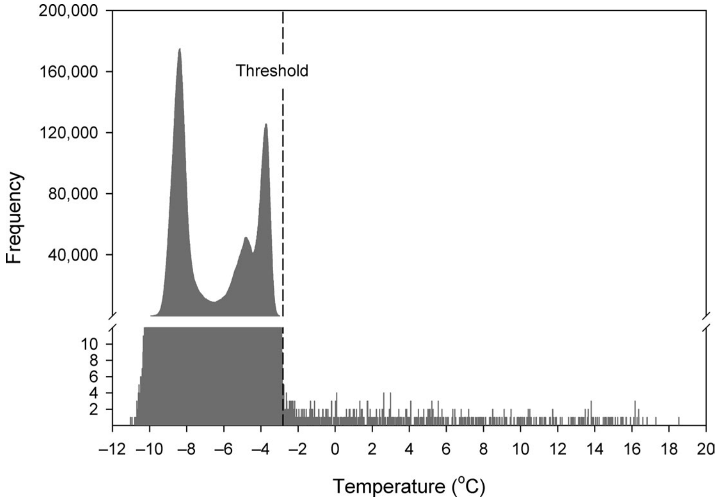

Figure 2. Example of frequency histogram of AMS thermal imagery showing temperature threshold between the background environment and walrus that occurs at –2.81° C. Pixels to the right of the threshold value have some portion of their area covered by walrus.

$$h_i = a\sum(t_{ij} - T_i)$$

where h_i was the index for group i, a was the pixel area (m^2), t_{ij} was the temperature for pixel j of group i, T_i was the threshold temperature for group i, and the summation was over all pixels with temperature values above the threshold (i.e., pixels with $t_{ij} > T_i$).

After matching the walrus groups in the AMS thermal imagery and digital photos, we used generalized linear models (McCullagh and Nelder 1989) to examine the relationship between the number of walruses and the index of total walrus heat at each level of spatial resolution. We used identity links with gamma distributions for the models because variances were approximately proportional to the squares of the mean functions. Models were of the form

$$E(y_i) = \alpha + \beta h_i \ , \qquad Var(y_i) = \varphi(\alpha + \beta h_i)^2$$

where y_i was the photographic count for group i, and α, β, and ϕ were parameters estimated by maximum likelihood. We assessed the fit of models using deviance and deviance residuals and used likelihood ratio tests to assess parameters in the mean functions.

We excluded from our analysis instances where obvious changes in walrus group size or distribution occurred. For example, 1 ice floe split into several smaller pieces during the collection of AMS thermal imagery at increasing altitudes and we did not include these images in the regressions.

Table 2. Summary of walrus counts and AMS thermal imagery for walrus groups observed in the Bering Sea in April 2002.

				Index of total walrus heat			
Walrus group	**Date**	**Photo time**	**Walrus count**	**1-m**	**2-m**	**3-m**	**4-m**
1	9 Apr 2002	13:08:46	8			33.77	25.22
2	9 Apr 2002	13:17:51	40			267.29	457.01
3	9 Apr 2002	14:08:24	103			1,030.09	879.83
4	9 Apr 2002	15:45:10	41			823.49	
5	10 Apr 2002	13:06:24	111	1,663.78	1,612.36	1,647.93	1,968.76
6	10 Apr 2002	13:11:03	8				10.39
7	10 Apr 2002	12:41:45	32	484.92	423.97	408.23	257.68
8	10 Apr 2002	13:32:33	77	865.92	835.15	720.30	745.05
9	10 Apr 2002	12:55:36	12	202.84	138.89	153.93	66.96
10	10 Apr 2002	14:10:05	18	212.01	293.66	232.36	159.01
11	10 Apr 2002	13:39:16	15	107.14	93.45	124.12	178.17
12	10 Apr 2002	14:06:11	8	58.75	181.99	75.64	56.36
13	10 Apr 2002	13:12:57	256	3,457.05	3,729.66	4,329.81	4,198.86
14	10 Apr 2002	13:23:13	6	123.10	161.96	24.56	61.51
15	10 Apr 2002	14:25:51	11	100.67	176.15	104.74	81.91
16	10 Apr 2002	14:25:54	17	195.72	245.65	92.55	125.74
17	10 Apr 2002	14:43:30	21	326.16	312.72	241.60	218.20
18	10 Apr 2002	15:23:27	43	629.53	627.26	438.43	586.11
19	10 Apr 2002	14:37:56	10	88.61	41.25	57.77	70.26
20	10 Apr 2002	14:37:57	57	661.57	644.99	358.94	438.25
21	10 Apr 2002	14:32:54	32	255.38	268.67	249.72	191.42
22	10 Apr 2002	15:18:24	176		2,327.41	2,708.79	1,951.48
23	14 Apr 2002	15:50:22	22	759.55	547.55	588.45	428.12
24	14 Apr 2002	16:01:24	16	559.62	408.87	344.69	145.41
25	14 Apr 2002	15:36:32	10	185.47	87.36	67.10	47.84
26	14 Apr 2002	15:36:33	23	467.92	356.38	269.68	195.83
27	14 Apr 2002	15:38:03	14			45.26	15.52
28	14 Apr 2002	15:41:17	21	287.32	381.80	319.67	
29	14 Apr 2002	15:52:42	21	640.39	597.83	584.24	232.46
30	14 Apr 2002	16:03:34	7	293.85	305.36	99.47	90.29
31	14 Apr 2002	16:44:45	8	173.01	107.14	31.44	131.67
32	14 Apr 2002	16:45:12	13	83.96	22.09	61.00	
33	14 Apr 2002	17:42:53	64	1,393.75	1,302.01	955.96	1,173.89
34	14 Apr 2002	17:00:41	43	664.72	670.09	365.24	286.68
35	14 Apr 2002	16:46:30	6	165.72	99.94	72.40	201.84
36	14 Apr 2002	16:52:24	1	5.3			
37	14 Apr 2002	16:45:21	11	176.99	201.13	147.22	
Sample Size			37	29	30	35	33

Results

During the 2-week field period, we conducted flight operations on 7 separate days, flying a total distance of approximately 7,650 km. We encountered walrus groups in 2 general areas: 1) 70 km southwest of St. Lawrence Island on 9–10 April 2002, and 2) 20 km north of the village of Savoonga on St. Lawrence Island on 14 April 2002. We searched the first location based on sighting information collected in previous years during aerial surveys and research cruises aboard icebreaking ships (Fay 1982, Fay et al. 1984, Simpkins et al. 2003). The second location was purely fortuitous; heavy cloud cover south of St. Lawrence Island prevented us from returning to the first location so we searched open leads to the north of the island.

We collected digital photographs and AMS thermal imagery of 37 different walrus groups over 3 days (Table 2). A sample photograph of 1 group and corresponding AMS thermal imagery are presented in Fig. 3. It was not always possible to collect AMS thermal imagery of each walrus group at all 4 spatial resolutions. In order to minimize the amount of time between collection of photographs and AMS thermal imagery, we concentrated on only a few walrus groups at one time. In some areas where walruses were particularly abundant, it became difficult to keep track of which groups we had already photographed and scanned. In addition to these limitations, on our first day of data collection (9 April 2002), we experienced technical difficulties recording AMS thermal imagery at 1- and 2-m resolutions and recorded only 3- and 4-m resolution imagery for that date. We corrected the problem and successfully recorded 1- and 2-m resolution AMS thermal imagery on subsequent flights.

We were able to detect walrus groups as small as 6 animals in AMS thermal imagery at all resolutions. We detected the single animal photographed as group 36 in the 1-m AMS thermal image, but not at lower resolutions. While we would expect that it might be difficult to detect an individual walrus at the 3- or 4-m resolutions, a close inspection of this location in the 2-m AMS thermal image also did not show any signature of this walrus. The digital photograph of this animal showed another walrus swimming only a few meters away. These circumstances suggest that the single walrus may have entered the water at some time between the collection of the 1- and 2-m AMS imagery.

There was a strong linear relation ($\chi_1^2 > 44.13$, $P < 0.01$) between the numbers of walruses in a group and the index of total

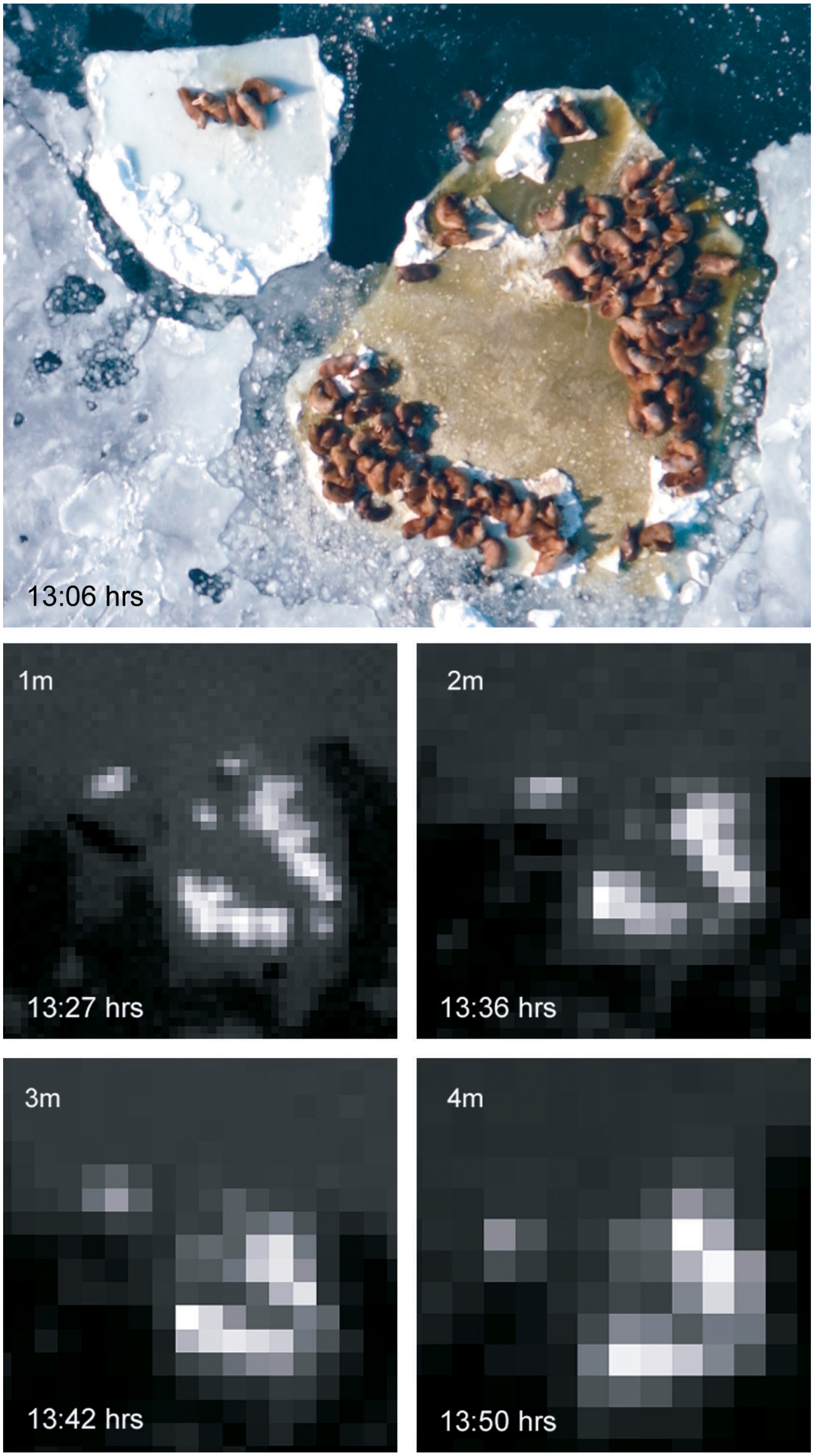

Figure 3. Example of digital photography and matching AMS thermal imagery at 1–4-m spatial resolutions of walrus group 5 collected on 10 April 2002. Photo courtesy of United States Fish and Wildlife Service.

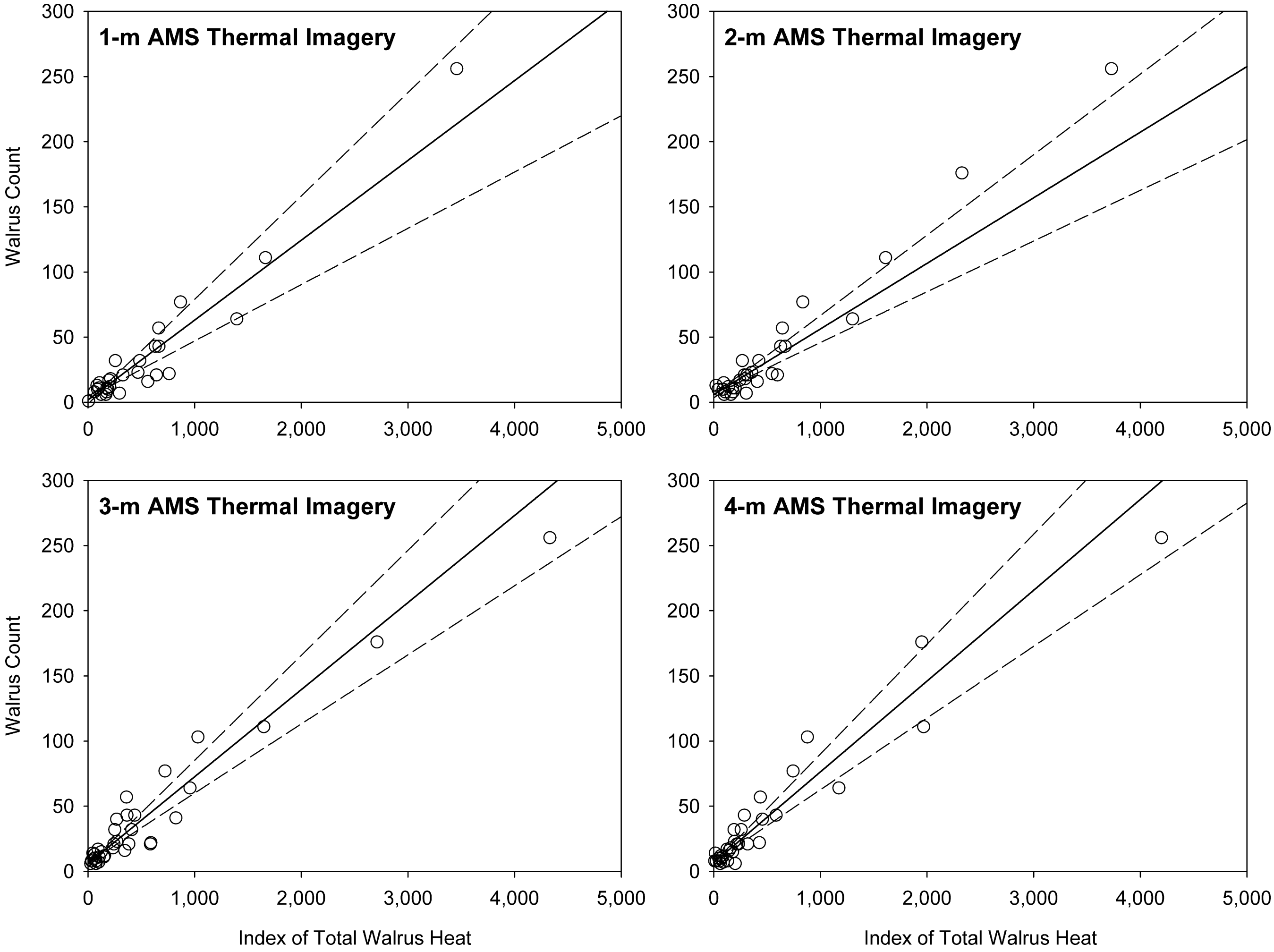

Figure 4. Gamma regressions of walrus count as a function of total heat index for AMS thermal imagery at 1–4-m spatial resolutions. Dashed lines represent 95% confidence intervals.

walrus heat at all spatial resolutions of the AMS thermal imagery (Fig. 4). Plots of deviance residuals did not show any lack of fit to the linear model or the gamma variance function. Deviance values were similar at all resolutions (Table 3), indicating that precision of estimating group sizes from AMS thermal data did not decrease with decreasing spatial resolution of the imagery.

Discussion

The results of this study indicate that AMS thermal imagery can be used to detect walrus groups at spatial resolutions up to 4 m. Several factors may account for variance in the relationship between walrus group size and the amount of heat they produce. When a walrus initially hauls out of the water, its skin temperature is near water temperature and warms over time after emergence and drying (Ray and Fay 1968, Barber et al. 1991). Walrus skin temperature is influenced by environmental conditions such as ambient temperature, wind speed, and insulation, as well as behavioral responses such as huddling (Fay and Ray 1968). The total amount of heat produced by a group is likely to be more a function of surface area than numbers of walruses. If there are differences in the age–sex composition between groups, these differences in surface area likely would result in different amounts of heat produced. For example, 10 adult females with calves would cover a smaller area and produce less heat than 20 adult males. Differences in age and sex may result in differences in individual skin temperatures as well (Fay and Ray 1968).

Changes in the size of walrus groups also could account for differences in the number of walruses present in the digital photographs and the amount of heat measured in the AMS thermal imagery. We generally collected photographs first, followed by the AMS thermal imagery at 1-, 2-, 3-, and 4-m resolutions. Although we collected all photographs and thermal imagery for each group in <1 hour of elapsed time, any addition or removal of walruses after the photograph was taken would affect the amount of heat measured in the AMS thermal imagery. If this had occurred in our study, we would expect the greatest variability at the 4-m resolution, as that was the last imagery collected; however, the model fit was comparable across all resolutions.

We were able to detect walrus groups as small as 6 animals at all spatial resolutions. Our results appear similar to Barber et al. (1991) who were able to detect single animals at altitudes ranging from 500–1,000 m AGL and groups of 6–7 animals at 2,500–3,000 m AGL. Walruses range in size from 1–3 m in length (for

Table 3. Parameter estimates (and standard errors) for gamma regression models of walrus group size as a function of total heat index derived from AMS thermal imagery at various spatial resolutions observed in the Bering Sea in April 2002.

Spatial resolution	n	Parameter α	Parameter β	Parameter φ	Deviance
1-m	29	1.92 (1.45)	0.061 (0.0092)	5.23 (1.33)	5.72
2-m	30	5.95 (1.25)	0.050 (0.0058)	6.43 (1.62)	4.78
3-m	35	5.87 (1.11)	0.067 (0.0070)	8.30 (1.95)	4.30
4-m	33	6.60 (1.09)	0.070 (0.0075)	7.78 (1.88)	4.33

calves and adult males, respectively [Fay 1982]). Therefore, it seems likely that 1-m resolution would be capable of detecting all walruses present within the scanned area. Conversely, we would expect that single walruses or small groups may not be detectable in 3- or 4-m AMS thermal imagery. In our study the median group size was 18 walruses, yet groups with more than 18 individuals accounted for 86% of the total walruses. Results of previous visual aerial surveys also indicate that the vast majority of walruses occur in groups that would be detectable at these spatial resolutions (Estes and Gilbert 1978, Garlich-Miller and Jay 2000); therefore, the magnitude of any bias due to undetected groups would be relatively small.

The use of larger pixel sizes minimizes the likelihood of false positives, as there are no other natural sources of heat capable of generating such large thermal signatures. Other large wildlife species, such as bearded seals (*Erignathus barbatus*) and polar bears (*Ursus maritimus*) can reach lengths over 2 m but do not aggregate in large groups and would not be expected to raise the temperature of one or more pixels above the threshold value. We also believe that the thermal signature of man-made objects such as ships or boats would be readily distinguishable from the irregular shapes exhibited by walrus groups.

When ambient temperatures are below freezing, the warmest nonliving substance in the environment is seawater, which freezes at approximately −2° C. Ice floes that have been abandoned by walruses typically are stained by feces and often appear to have walruses present when viewed from a distance. During examination of our AMS thermal imagery, this "dirty walrus ice" often was warmer than adjacent clean ice, but in no instance was it warmer than the threshold temperature separating walruses from the background environment. In addition, during a pilot survey conducted in April 2003 at 3,200 m AGL with 4-m spatial resolution, all of the thermal signatures subsequently examined and photographed were, in fact, walrus groups (USFWS, unpublished data).

Management Implications

The development of an aerial survey method using thermal imagery would address many of the shortcomings of visual aerial surveys as described by Gilbert (1999). Visual surveys historically have been flown at relatively low altitudes (150–300 m AGL) and airspeeds (250 km/hr) that allowed for both detection and counting of walrus groups in a relatively narrow swath, usually 1.86 km or less. The proportion of the study area that could be searched by visual methods typically was low, resulting in population estimates of low precision (Estes and Gilbert 1978, Gilbert 1999). By flying at a faster airspeed (370 km/hr) at 3,200 m AGL using a thermal sensor to detect walrus signatures, the 6-km survey swath would make it possible to sample over 400% more area per hour of flight time.

Based on the relationships between the size of walrus groups and the amount of heat they produce, it appears that 4-m resolution imagery is no less precise than 1-m imagery, while covering over 4 times the area per unit of effort and missing fewer than 5% of the walruses present on ice floes (Garlich-Miller and Jay 2000). Theoretically, the system could be flown at even larger spatial resolutions, covering an even greater area, however the proportion of walruses that would likely be missed would also increase. Alternatively, as systems with smaller IFOVs and larger pixel arrays become available, it would be possible to survey larger areas with the same 4-m resolution.

In addition to covering a larger area per unit time, the thermal sensor is more reliable than visual observations. For example, observer bias and fatigue are not issues, as the sensor is calibrated to record data consistently and can continue to function at the same level of efficiency during extended flights. The resulting imagery serves as a permanent data record that can be re-examined at any time in the future. Actual animal counts from high-resolution aerial photography are more precise than rapid estimates made during visual surveys. And lastly, flight safety is greatly improved by only flying at higher altitudes on clear-weather days.

Most of the previous aerial surveys of Pacific walrus were conducted in the autumn of the year. We recommend conducting surveys using a thermal imagery system during the spring for several reasons. First, during the autumn season when the walrus population is segregated, 2 methods are needed to survey the entire population. In the early spring season, however, (March–April), the walrus population can be found almost exclusively on the pack ice of the Bering sea; therefore, only 1 survey method is needed. Second, thermal imagery systems are incapable of seeing through clouds and fog, so clear weather is necessary during survey operations. During the autumn season, southerly winds typically result in fog and low clouds along the ice edge in the Chukchi Sea, which would make the use of thermal imagery impractical at that time of year. In the spring season, stable high-pressure systems and northerly winds create periods of clear weather between storms when a thermal imagery system could be flown at any altitude.

Based on the results of this study, we believe thermal imagery system can be an effective tool to survey large areas of sea ice habitat in the spring. We recommend flying the current AMS system at 3,200 m AGL, as the 6-km survey swath of the AMS would make it possible to survey over 10,000 km^2 in an 8-hr flight. In addition to thermal imagery, high-resolution digital photographs, suitable for counting individual walruses, would need to be obtained to allow estimation of group sizes from the thermal data. Given the relative importance of large groups to the overall number of walruses observed, it would be important to photograph the full range of walrus group sizes. We recommend a double-sampling design (Thompson 2002) in which a random sample of survey transects would be scanned using the AMS and the location of thermally detected groups transmitted to a second aircraft that would then be used to obtain photographs for a random sample of those groups. A regression-type estimator (Thompson 2002) could be used to estimate the total number of walruses in the survey area.

To minimize the effect of sea ice and walrus movements within the study area, the survey should be conducted over as short a period of time as practicable. Estimating the size of the Pacific walrus population also would require an estimate of the proportion of the population hauled out on ice and available for detection during the survey, as well as international coordination with Russian scientists.

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