PAPER

Automated Vertical Photography for Detecting Pelagic Species in Multitaxon Aerial Surveys

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ABSTRACT

Marine aerial surveys are designed to maximize the potential for detecting target species. Collecting data on different taxa from the same platform is economically advantageous but normally comes at the cost of compromising optimal taxon-specific scanning patterns and survey parameters, in particular altitude. Here, we describe simultaneous visual and photographic sampling methods as a proof of concept for detecting large whales and turtles from a single aircraft, despite very different sighting cues. Data were collected for fishing gear, fish, sharks, turtles, seals, dolphins, and whales using two observers and automated vertical photography. The photographic method documented an area directly beneath the aircraft that would otherwise have been obscured from observers. Preliminary density estimates were calculated for five species for which there were sufficient sample sizes from both methods after an initial year of data collection. The photographic method yielded significantly higher mean density estimates for loggerhead turtles, ocean sunfish, and blue sharks ($p < 0.01$), despite sampling a substantially smaller area than visual scanning (less than 11%). Density estimates from these two methods were not significantly different for leatherback turtles or basking sharks ($p > 0.05$), two of the largest species included in the analysis, which are relatively easy to detect by both methods. Although postflight manual processing of photographic data was extensive, this sampling method comes at no additional in-flight effort and obtains high-quality digital documentation of sightings on the trackline. Future directions for this project include automating photographic sighting detections, expanding the area covered by photography, and performing morphometric measurement assessments.

Keywords: aerial survey, whale, turtle, vertical photography, density estimate

Introduction

Global marine habitats are governed by multiple policies and management frameworks that rely on accurate wildlife population estimates. Various stages of industrial ocean development can have population-level impacts, and regulatory agencies frequently require environmental-impact assessment surveys. Over the last 30 years, assessment and monitoring efforts have steadily improved wildlife density estimates with the use of new technology, better survey methods, and stringent analytical techniques.

Aerial surveys are often used to assess protected species of sea turtles, dolphins, and whales. However, sightings can be missed by observers. An animal may not be available for detection if it is not at the surface within an observer's visible range (Barlow, 1999). Even available animals can go undetected by inexperienced, fatigued, or distracted observers (Laake et al., 1997) or when sighting cues are less conspicuous (Hain et al., 1999). Major factors contributing to these detection biases are dive times (affecting availability bias) and distance from trackline (affecting perception bias) (Hain et al., 1999; Kenney & Shoop, 2012; Marsh & Sinclair, 1989b). Factors can have detrimental and positive effects on sightability at the same time. For example, increased distance from the trackline reduces the chances of being detected by an observer, yet sightings that are farther away remain available for longer as they pass through the observer's view field (Hain et al., 1999). Other factors such as sea state, sun glare, visibility, and water turbidity impact observer detections. When possible, a survey design should minimize those factors that interfere with detections, as well as consider these variables in analysis.

In general, the probability of detecting available animals is improved with lower altitudes when animals are more visible, yet higher altitudes expand visual coverage hence increasing sighting availability. However, this is limited by conspicuousness of sighting cues. Surveys for larger species that can be seen at greater distances benefit from higher altitudes where wider scanning patterns cover a greater area for the same transect length. When experimenting with the effect of doubling altitude and accompanying transect width, Marsh and Sinclair (1989a) found that in-flight observer detections of dugongs were not affected but that a significantly higher density of turtles was observed at the lower height with a narrower strip width. Sighting cues for large whales could be a splash, blow, or body at the surface that can be seen at a distance, whereas a sea turtle cue tends to be the submerged body, only detected close to the trackline. Hence, a survey design to capture sightings of both taxa presents several challenges.

The extent of bias against sightability is a major consideration in survey design features, such as aircraft type and configuration, flight speed, and altitude. Observers stationed at side windows have a swath of ocean directly under the aircraft that is obscured from view. To compensate, some aircraft have bubble windows to allow observers a wider-angle field of view (Palka, 2005). Belly ports are also used where an additional observer dedicated to downward viewing can cover the trackline directly beneath the plane (Forney, 1995; Laake et al., 1997). The Beechcraft AT-11, used for the Cetacean and Turtle Assessment Program (CETAP) surveys, carried two observers in an acrylic bubble in the nose, providing unobstructed views of the trackline ahead, straight down, and to both sides (Kenney & Scott, 1981). Such aircraft, however, are scarce and tend to be relatively old and expensive to operate and maintain. For surveys that accommodate more than one observer on each side, large airframes are needed, which also drive operation costs up.

Marine surveys use photographic documentation as a method of species identification and to track and assess individuals. When precise survey and camera parameters are known, accurate measurements can be made for population density estimates, morphometric indices, and observer validation. Surveys typically conduct initial broad-scale visual aerial monitoring followed by dedicated photogrammetric image-collection flyovers (Fortune et al., 2012; Perryman & Lynn, 2002; Shelden & Mocklin, 2012), rather than the continuous collection of photographic data (Asselin et al., 2012). We describe automated vertical photography as a sampling method, with potential value added from these other uses of photogrammetry.

In response to an interest in wind energy development off southern Massachusetts, the Massachusetts Clean Energy Center (MassCEC) contracted the New England Aquarium to collect year-round migratory and habitat usage data on large whales and sea turtles. A survey was designed to assess both focal taxa from a single aerial platform, despite dramatic differences in size and sighting cues. Aerial observers following standard line-transect methods primarily collected data on large whales, while automated, high-resolution digital vertical photography with forward motion compensation (FMC) technology was used to collect data on turtles. By adopting this approach, the "blind spot" directly under the survey aircraft was covered by the automated photography method. Also, sightings of the smaller species, typically only detected close to the trackline (e.g., fish, sharks, and turtles), were recorded without affecting large-whale observations by changing altitude or scanning patterns. Line-transect aerial survey methods allow for precise population estimates to be made with continued, multiyear data collection. Here, we discuss automated vertical photography as a supplemental method for multitaxon aerial surveys that can be used in the absence of additional dedicated downward-viewing observers. This technological solution improves density estimates and comes at little extra in-flight operational cost or effort.

Materials and Methods

Data Collection

Standard aerial line-transect data collection procedures were followed (Kenney, 2011), including the use of two visual observers—one on each side of the aircraft—continuously scanning forward and aft of perpendicular with the naked eye (Brown et al., 2007). Binoculars (Nikon, 8 × 42, 6.3°) were used to confirm sighting cues. At large-whale sightings, the survey team broke off from the trackline and circled above a species of interest while observers collected oblique photographs out of open windows for photo-identification.

The survey aircraft used was a Cessna Skymaster 337, military O-2A version. Skymasters have high wings and twin engines that are centerline configured. Surveys were flown at an altitude of 1,000 feet (305 m), and all attempts were made to maintain a groundspeed of 185 km/h (100 knots). The O-2A model had an existing camera port that needed minimal structural modification for the use of vertical photography equipment. An optical glass plate was modified for installation in the preexisting camera port opening of the ventral fuselage. An FMC camera mount designed by Aerial Imaging Solutions was engineered in order for the housing and mechanisms to fit over the opening between the forward starboard seat rails and secured to the floor paneling. The FMC mount was powered using the aircraft's 28-V DC electrical system.

Automated vertical photography in the marine environment is challenged by the low contrast between target objects and the surrounding environment, particularly when the subject is subsurface. In low-contrast situations, especially if the subject is moving, automatic-focus lenses do not function well, so we used a prefocused fixed manual setting. A full-frame, high-performance SLR camera (Canon EOS 5D Mark II) was equipped with a manual-focus Zeiss 85-mm f/1.4 lens. In order to prevent the focus from drifting over time, the focus was set on a point at approximately 305 m (1,000 feet) distance, and the focusing ring was taped in place.

Canon EOS Utility software on a semirugged Panasonic Toughbook laptop was used to remotely change the camera settings and provide live view for image quality control. Camera firing intervals and FMC were controlled by *d-tracker*, an aerial-camera control and data acquisition program that also ran on the laptop. Vertical images were either downloaded directly to the computer's hard drive or to the camera's memory card and backed up to the computer's hard drive simultaneously in flight. In the weeks following a survey, flight observers analyzed images that were taken on-track for detection of marine mammals, sea turtles, elasmobranchs, fish, and fishing gear. During training and validation periods, 5-s intervals between exposures were used, and the entire collection was processed by both analysts as a double-observer method to prevent perception bias. This was abandoned once observers were proved "experienced" based on consistently similar detection rates. Following validation, the camera interval was reduced to obtain 100% coverage along the trackline, i.e., back-to-back frames resulting in an image every 1–2 s. Analysis of this larger data set was divided between two observers with one randomly selected trackline duplicated for continued validation.

Ground coverage with the full-frame sensor (36 mm × 24 mm) using a fixed 85-mm lens at 1,000-feet (305 m) altitude was 129 m × 86 m (423.5 feet × 282 feet).

$$\begin{aligned}&\textbf{Ground coverage} = (\textbf{sensor size}/\textbf{focal length}) \times \textbf{altitude}\\&\text{Ground coverage (side–to–side)} = (36\ \text{mm}/85\ \text{mm}) \times 305\ \text{m} = 129\ \text{m}\\&\text{Ground coverage (forward–aft)} = (24\ \text{mm}/85\ \text{mm}) \times 305\ \text{m} = 86\ \text{m}\end{aligned} \tag{1}$$

Ground resolution is the area of ground covered by the sensor's individual pixels. If all other factors were ideal, any object larger than the ground resolution should be discernible in the image. Optimal ground-resolved distance with the same equipment and altitude was 2.3 cm (0.9 inches).

$$\begin{aligned}&\textbf{Ground resolution} = (\textbf{pixel size} \times \textbf{altitude})/\textbf{focal length}\\&\text{Ground resolution} = (6.4\ \mu\text{m} \times 305\ \text{m})/85\ \text{mm} = 23\ \text{mm}\end{aligned} \tag{2}$$

In our surveys, the vertical field-of-view for rear-seat observers from the eyeline marked on the inside window frame was 77° below the horizontal, omitting from view an area of the trackline 142-m (465-feet) wide. Therefore, automated vertical photography shooting 129-m-wide images compensated for 91% of the obscured area when shooting back-to-back frames.

D-tracker recorded time, latitude, longitude, GPS ground speed, GPS quality, GPS number of satellites, GPS altitude, GPS heading, magnetic heading, lens focal length, ground covered sideways, ground covered forward, picture interval, and picture count to a comma delimited (CSV) text file each time a vertical photograph was taken automatically or when triggered by an observer. The GPS output included a proprietary sentence, in standard National Marine Electronics Association format, that provided estimated horizontal and vertical position error in meters to record accuracy of the data. Each day the program was run, a new file was created, and records were added to that file throughout the day. In flight, the port and starboard observers were able to prompt data records independently using remote keypads mounted beside their viewing windows, so as not to distract from visual scanning or influence each other's sighting records. Similarly, the sighting details were spoken into a digital voice recorder and transcribed after flight, again, so that real-time data entry did not jeopardize detection. The primary data recorder had the ability to start or stop the automated camera intervals and to instantly trigger the vertical camera during a flyover using the remote keypad.

An editing program, *e-tracker*, was used by observers to transcribe sightings into a raw data table after flight. After transcription, KML files were populated to instantly view locations of sightings in *Google Earth*, and a GPX file was produced for georeferencing images using *GPicSync* software. Further editing, proofing, and quality assurance checks were performed to conform to line-transect standards for inclusion in the North Atlantic Right Whale Consortium (NARWC) Sightings Database (Kenney, 2011).

The same parameters used for in-flight sightings (e.g., reliability of species identification, number, and behaviors) were recorded for vertical image sightings and verified by a second observer. Sightings were inserted at the corresponding data record in the CSV file based on time stamp. A unique value distinguished sightings detected visually by observers in flight and those detected in the vertical image database.

Statistical Analysis

The density (**d**, number of individuals per unit area) of animals in a population within a specified region is estimated from the number of animals counted (**n**) within a sample of the region having a known area (**a**) (Eberhardt et al., 1979; Seber, 1982).

$$\mathbf{d} = \mathbf{n}/\mathbf{a} \quad (3)$$

Both photographic and visual sampling methods were used to develop density estimates. For photographic density estimates, the area sampled for a given transect is simply the number of images times the area of a single image. For our camera system, the area covered by an image taken from the defined survey altitude was 11,094 m^2 [119,414 sq. feet; see equation (1)]. The area covered by any given image would be larger for altitudes above 305 m (1,000 feet) and smaller for altitudes below, with the difference proportional to the square of altitude divided by 305, i.e., a doubling of survey altitude to 610 m (2,000 feet) would result in an image covering four times the area. The area of each photo was therefore scaled from the nominal value by the actual altitude recorded at the time it was taken.

A photo-quality code (0 = very poor, 1 = poor, 2 = good, 3 = excellent) was assigned to each vertical image, incorporating factors that influenced sightability, including glare, sea state, and image brightness. For each transect surveyed, the number of individuals counted in good or excellent images was summed [**n** in equation (3)]. Similarly, the area sampled per transect [**a** in equation (3)] was the sum of the individual areas of all the good and excellent images. The density for each species was then calculated by dividing **n** by **a**, then multiplying by 10^8 to convert from animals/m^2 to animals/100 km^2.

Visual surveys are used to estimate density using line-transect (also known as distance) methods (Buckland et al., 1993, 2001; Burnham et al., 1985; Garner et al., 1999; Gates, 1979; Laake et al., 1993; Seber, 1982; Thomas et al., 2010). As a survey aircraft proceeds along a trackline, observers measure right-angle distances (x) to each sighting (we used graduations on the wing strut as a guide). A detection probability function, g(x) (the probability of detection at a given distance from the transect), is derived by evaluating the goodness-of-fit between the distribution of observed perpendicular distances and a variety of alternative statistical models, assuming that the detection probability on the trackline is 100% (or g(0) = 1). This g(x) function in turn is rescaled into a probability density function f(x) that integrates to one over the entire range of x, which is then solved for f(0), or the perpendicular distance probability density function evaluated at zero distance. The reciprocal of f(0) is the effective strip width (ESW) on each side of the transect. The area sampled for a transect of known length (L) can be expressed in two ways.

$$\mathbf{a} = \mathbf{2} \times \mathbf{L} \times \mathbf{ESW} \quad (4)$$

or

$$\mathbf{a} = (\mathbf{2} \times \mathbf{L})/\mathbf{f}(\mathbf{0}) \quad (5)$$

Therefore, sample density can be calculated by either of the two equivalent formulas.

$$\mathbf{d} = \mathbf{n}/(\mathbf{2} \times \mathbf{L} \times \mathbf{ESW}) \quad (6)$$

or

$$\mathbf{d} = [\mathbf{n} \times \mathbf{f}(\mathbf{0})]/(\mathbf{2} \times \mathbf{L}) \quad (7)$$

The value for **f(0)** for a given species, or for a set of species with similar sightability characteristics, is estimated from the distribution of right-angle sighting distances using DISTANCE software (Laake et al., 1993; Thomas et al., 2010) (or its predecessor, TRANSECT). To minimize variance of the **f(0)** estimate, it is necessary to have an adequate sample size—minimally 25–30 sightings per species and ideally 40–100 or more (Eberhardt et al., 1979); our sample sizes were too small for a full line-transect analysis. For comparative purposes, we selected five species with reasonable numbers of both photographic and visual sightings—leatherback and loggerhead sea turtles, basking sharks, blue sharks, and ocean sunfish. For these five, "back of the envelope" visual density estimates were calculated using the formula in equation (7) and values of **f(0)** taken from CETAP (1982, Table 6, p. 54). The **f(0)** value for both turtles was 2.867 km^{-1} (**ESW** = 0.3488 km, 0.1883 nm), which we also used for ocean sunfish, which are about the same size as an adult sea turtle, following previous usage by Kenney (1996). For basking sharks, we used the value for minke whales—3.260 km^{-1} (**ESW** = 0.3065 km, 0.1655 nm)—which are closest in size as well as behavior (usually solitary but sometimes in small groups, presenting a dorsal fin above the surface as a sighting cue and occasionally breaching or splashing). Finally, for blue sharks, we selected the value for harbor porpoise—3.616 km^{-1} (**ESW** = 0.2766 km, 0.1494 nm)—since both species are small, tend to be solitary, and are typically sighted submerged just below the surface. The visual and photographic density estimates were then statistically compared for each of the five species.

Results

Sightings were recorded during 24 flights between October 2011 and September 2012 when 13,155 km (7,103 nm) of trackline was flown. Visual observations yielded a total of 744 sightings of which 690 were animal sightings (excluding vessels and debris or pollution) and 515 were on-track sightings of approximately 3,055 (±696) individuals. The photographic method yielded a total of 427 sightings of which 345 were animal sightings (excluding vessels and fishing gear) and 339 were on-track sightings of approximately 1,025 (±21) individuals (count was not given for all sightings of fish schools). Three levels of confidence in identifications were permissible—definite, probable, or possible. The visual method detected 59%, 7%, and 34% of sightings with definite, probable, and possible identification reliabilities, respectively, from the total of 515 on-track, biota sightings. The photographic method detected 52%, 19%, and 29% of sightings with definite, probable, and possible identification reliabilities, respectively, from the total of 339 on-track, biota sightings. Preliminary results are presented in Table 1 for those taxa that were recorded with "definite" and "probable" identification reliabilities in all sighting conditions for both visual and photographic methods.

Sightings that were recorded as "unidentified" were grouped into the "possible" identification reliability category for the purpose of this review. Of the 172 sightings recorded with "possible" identification reliability from the visual method, there were 132 sightings of 2,089 (±557) unidentified animals detected. Of the 99 sightings recorded with "possible" identification reliability from the photographic method, there were 62 sightings of 82 unidentified individuals detected.

Only sightings that were recorded while on track have been included in the results. Sightings recorded during transit, crossleg, while circling, or after breaking from the trackline to perform a direct flyover were excluded. Observers recorded sightings when abeam of the plane at a point when there is no overlap between observer and automated photography view fields; thus, on-track sightings are unique to each method. It was possible, however, for a sighting to be detected by one method and subsequently recorded on-track by a different method. This only occurred when a sighting was detected by observers some distance ahead or behind of the aircraft's trajectory and was also captured in vertical photography. The only occasions of this were sightings of hauled-out seals (Figure 4); thus, seals were omitted from Table 1.

Two full-time employees performed photo analysis and aerial observing, among other survey-related duties. An average 2,300 unique, on-track, vertical images was collected per flight when using 5-s intervals. Both analysts processed this entire collection. Approximately 6,800 unique images were analyzed when collected back-to-back, approximately 3,800 per analyst, where one randomly selected trackline was duplicated for continued validation. The average number of on-track images collected per flight over all 24 survey flights was 4,138 including 5-s and back-to-back intervals, partial and full flights. A total of 99,321 unique images was analyzed, and 34,083 of those were duplicated by a second analyst for detection validation. The total 427 sightings yielded from the photographic method consisted of approximately 1,194 (± 35) counts of animals, vessels, and fishing gear. This excludes sightings of birds, which were not included in the NARWC data submission but were opportunistically recorded, and images were submitted to MassCEC for analysis by avian research teams.

The primary targets of our visual surveys were large endangered whales. For those species, the number of sightings within the defined conditions needed for inclusion in the line-transect density estimation procedure (during a defined census track, Beaufort sea state of three or lower, clear visibility of at least two nautical miles, species ID reliability "definite" or "probable," and a measured right-angle distance) was far too few; therefore, we have not attempted to run complete line-transect analyses from the initial year of data collection.

During the 24 survey flights, 180 transects were sampled in acceptable sighting conditions for visual density

TABLE 1

Sightings and counts of individuals identified to a reliability of "definite" or "probable" by visual and photographic methods in all sighting conditions.

		Visual				Photographic			
		Definite		Probable		Definite		Probable	
		Sightings	Count	Sightings	Count	Sightings	Count	Sightings	Count
Whales									
Fin whale	*Balaenoptera physalus*	8	9	1	1	0	0	0	0
North Atlantic right whale	*Eubalaena glacialis*	9	14	0	0	1	1	0	0
Humpback whale	*Megaptera novaeangliae*	5	6	0	0	0	0	0	0
Sperm whale	*Physeter macrocephalus*	2	5	0	0	0	0	0	0
Common minke whale	*Balaenoptera acutorostrata*	3	3	3	4	0	0	0	0
	Totals	**27**	**37**	**4**	**5**	**1**	**1**	**0**	**0**
Dolphins + porpoises									
Pilot whale	*Globicephala* sp.	3	24–38	1	10–20	0	0	0	0
Risso's dolphin	*Grampus griseus*	0	0	1	1	0	0	0	0
Bottlenose dolphin	*Tursiops truncatus*	0	0	4	29–49	0	0	0	0
Atlantic white-sided dolphin	*Lagenorhynchus acutus*	0	0	1	50–70	0	0	0	0
Short-beaked common dolphin	*Delphinus delphis*	5	125–265	5	34–64	0	0	1	>10
Harbor porpoise	*Phocoena phocoena*	1	5–9	1	2	1	1	2	2–4
	Totals	**9**	**154–312**	**13**	**126–206**	**1**	**1**	**3**	**12–>14**
Sharks									
Basking shark	*Cetorhinus maximus*	141	206–210	2	2	21	31	4	4
Hammerhead shark	*Sphyrna* sp.	0	0	0	0	3	3	1	1
Thresher shark	*Alopias* sp.	0	0	3	3	0	0	0	0
Dusky shark	*Carcharhinus obscurus*	0	0	0	0	0	0	35	40
Blue shark	*Prionace glauca*	11	11	1	1	60	60	6	6
	Totals	**152**	**217–221**	**6**	**6**	**84**	**94**	**46**	**51**

continued

TABLE 1

Continued

		Visual				Photographic			
		Definite		Probable		Definite		Probable	
		Sightings	Count	Sightings	Count	Sightings	Count	Sightings	Count
Turtles									
Leatherback turtle	*Dermochelys coriacea*	53	57	2	2	18	18	2	2
Loggerhead turtle	*Caretta caretta*	24	24	0	0	21	21	6	6
Kemp's ridley turtle	*Lepidochelys kempii*	0	0	6	6	0	0	4	4
	Totals	**77**	**81**	**8**	**8**	**39**	**39**	**12**	**12**
Fish									
Ocean sunfish	*Mola mola*	25	26	1	1	32	33	2	2
School of fish		12	N/A	0	0	13	N/A	0	0
	Totals	**37**	**26**	**1**	**1**	**45**	**33**	**2**	**2**
Totals (excluding fish schools)		**290**	**515–677**	**32**	**82–132**	**157**	**168**	**63**	**77–>79**

N/A, not applicable.

estimates, and 153 transects were photographically sampled with better-than-poor quality images for photographic density estimates (27 transects yielded no images within our defined parameters of acceptable sighting conditions). The photographic method yielded 58,735 images representing an area of 651.6 km^2 (190.0 nm^2) that was sampled in acceptable sighting conditions. Based on ESWs taken from comparable species in CETAP (1982, Table 6, p. 54), the 11,048-km (5,965-nm) length of trackline visually sampled under standardized conditions represents areas of 6,112 km^2, 6,772 km^2, and 7,707 km^2 (1,782 nm^2, 1,975 nm^2, and 2,247 nm^2) for blue sharks, basking sharks, and ocean sunfish and turtles, respectively. Thus, the photographic method covered approximately 11%, 10%, and 8.5% of the area covered by visual methods for blue sharks, basking sharks, and ocean sunfish and turtles, respectively. Visual and photographic density estimates of the five species with adequate sighting numbers in standardized sighting conditions, which were identified to a higher confidence than "possible," are given in Table 2. A supplementary table is available online with density estimates by survey day and trackline (Table 3).

For all four of the smaller species that are most easily detected from directly overhead, the mean photographic density estimates were higher than the visual density estimates, as we would have predicted (Figure 1). The differences were statistically significant for blue sharks, loggerhead turtles, and ocean sunfish ($p < 0.01$) but not for leatherback turtles ($p = 0.09$). For basking sharks, which can be detected relatively easily by either method, the mean visual density estimate was slightly higher, but the difference was not significant ($p = 0.28$) (Table 2, Figure 1).

Example vertical images of common dolphin, basking shark, and gray seal sightings are shown in Figures 2–4.

Discussion

In our surveys, automated vertical photography enabled effective, simultaneous sampling of multitaxon data from a single platform at a constant altitude. For smaller, solitary species such as loggerhead sea turtles and blue sharks, density estimates yielded from the photographic method were significantly higher than those from visual methods, despite the area sampled being considerably less, approximately 8.5% and 11%, respectively. This confirms our *a priori* expectation that a survey designed primarily to optimize the efficiency of visual detection of large targets (i.e., whales) is seriously biased against effective detection of smaller targets such as turtles and sharks. For a visual survey focusing on sea turtles, the optimum altitude range would be 400–500 feet (120–150 m; Barlow et al., 1988; Bayliss, 1986; Kenney & Shoop, 2012; Marsh & Saalfeld, 1989; Marsh & Sinclair, 1989b; Schroeder & Thompson, 1987). It is likely that, even in an

TABLE 2

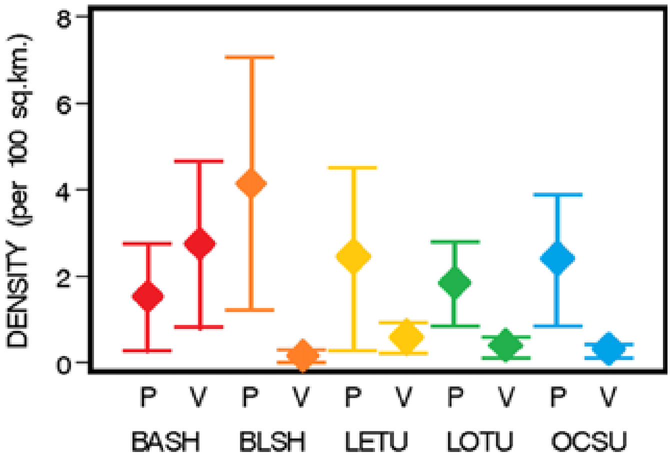
Statistical comparisons of photographic and visual density estimates for five species across all transects sampled, showing the results of a student's T-test for each species, including the Cochran and Cox approximation for unequal variances.

Species	Method	Number of transects	Maximum density per transect	Mean density per transect	Standard Deviation	Standard Error	*P*-value
Basking shark	Photo	153	73.528	1.544	7.618	0.616	0.2825
	Visual	180	116.035	2.772	12.858	0.958	
Blue shark	Photo	153	158.991	4.170	18.085	1.462	0.0071
	Visual	180	7.895	0.175	0.986	0.073	
Leatherback turtle	Photo	153	139.581	2.423	13.107	1.060	0.0917
	Visual	180	18.739	0.599	2.423	0.181	
Loggerhead turtle	Photo	153	33.668	1.848	6.044	0.489	0.0042
	Visual	180	12.506	0.384	1.623	0.121	
Ocean sunfish	Photo	153	81.711	2.3912	9.383	0.758	0.0068
	Visual	180	6.245	0.301	1.035	0.077	

The minimum density per transect for each species and each method was zero.

FIGURE 1

Comparison of mean (±2 standard errors) densities estimated by photographic (P) and visual (V) survey methods for five species: basking shark (BASH), blue shark (BLSH), leatherback sea turtle (LETU), loggerhead sea turtle (LOTU), and ocean sunfish (OCSU).



aircraft with unrestricted downward visibility, photographic sampling of smaller targets would still be more efficient than visual sampling when flying at higher altitudes appropriate for a whale survey. Platforms with obscured downward visibility simply exacerbate the problem by masking the zone of maximum detectability, regardless of altitude. For a multi-taxon survey using visual methods only, the typical solution would be to fly at an intermediate altitude of 750 feet (229 m; CETAP, 1982).

FIGURE 2

Automated vertical photograph of a common dolphin sighting. Image was cropped to 27% of the original diagonal length in pixels. (Color version of figures are available online at: http://www.ingentaconnect.com/content/mts/mtsj/2014/00000048/00000001.)

FIGURE 3

Automated vertical photograph of a basking shark sighting. Image was cropped to 12% of the original diagonal length in pixels.

FIGURE 4

Automated vertical photograph of gray seals sighted hauled out on a sandbar and in surrounding water. Image was cropped to 45% of the original diagonal length in pixels.

The result may be that detection effectiveness for both large and small targets is biased in the attempt at a compromise solution.

The basking shark was the only large species for which the first year of our surveys generated sufficient numbers of both visual and photographic sightings to do the preliminary comparison of density estimates. Mean densities estimated from the two methods were not significantly different. This is an encouraging result, since under ideal conditions with 100% detectability, one would expect equal density estimates from both methods (or any methods) along the same transects. Only time and additional survey data will tell if this holds true for all large species that are sufficiently common so as to have enough samples from both methods. It will also be interesting to see if small animals that occur in larger groups, such as dolphins, follow the same pattern as the basking sharks and large whales.

Perception biases are often reduced by duplicating observer counts on each side of an aircraft (Carretta et al., 1998; Richard et al., 2010). We were not able to duplicate in-flight observations in our Cessna Skymaster due to limited capacity and flight time, but perception biases affecting visual large-whale sighting detections were reduced by alleviating in-flight demands on the observers for recording small species close to the trackline. Sightings at steep angles closer to the aircraft were recorded opportunistically, but overall, observers dedicated their time to wider, more distant scanning patterns. Bubble windows could be used to increase the vertical-angle view field, but without additional observers dedicated exclusively to downward viewing, adjustments to scanning patterns to detect near-trackline turtles may distract from distant large-whale sighting detections.

Visual and photographic methods required different considerations when developing density estimates. Accurate area calculations covered by the photographic method could be obtained by using direct measures of the area captured in digital imagery, whereas it is harder to define an area covered by visual scanning. Having a measurable area for photographic coverage allowed for the assumption that, should an animal be available in that space, the probability of detection is high. However, factors still affect perception bias in photo-analysis sighting detection, in particular; analyst fatigue, and overall image quality. Duplication of photo analysis reduced perception bias during this process. More importantly, density estimates excluded those data collected in poor sighting conditions from area calculations, compensating somewhat for the negative effect that glare, Beaufort sea state, visibility, and image quality had on detection rates. However, approximately 41% of all unique, on-track images were coded "very poor" or "poor," mainly because of glare and Beaufort sea state. Refinements to mitigate glare would considerably increase the area available for detecting sightings. Restricting surveys to time-of-day where glare is less severe is not practical when running visual and photographic methods simultaneously since typically, when glare is worst for one method, it is optimal for the other. However, other options should be further explored such as adjusting the camera angle relative to the solar azimuth and elevation (Normandeau Associates, Inc., 2012).

Our experienced analysts reviewed approximately 400 images per day, which varied widely with sighting conditions and both potential and actual sightings detected. Based on an average of 3,800 images processed per analyst per full flight collecting back-to-back images, the review process should take 9.5 d with two analysts working simultaneously and allowing for duplication. This was true in reality, since data were typically transcribed, processed, proofed, validated, and submitted to the NARWC two to three workweeks following a survey flight. If this process of detecting sightings in vertical photography were automated, it would reduce personnel time and project costs. Technological advancements are being made towards developing software that uses anomaly detection algorithms for detecting biota sightings in digital imagery (Normandeau Associates, Inc., 2012). If the efficiency of automated detection compared with that of manual processing were validated, automation of vertical photography sighting detections would significantly increase the potential processing capacity, thus allowing photographic coverage to be expanded.

Oblique photography has the advantage of covering greater sample areas than vertical photography with the same focal length. Swath width could be expanded by using a multiple digital camera system configured for oblique as well as vertical photography (Fritz et al., 2013). This could be of added benefit for sightings detected in areas where visual and image coverage overlap, by validating observers' perpendicular distance estimates as a quality check for density estimate calculations and improving confidence in species identifications (Asselin et al., 2012). Although multiple camera systems and/or large-format digital mapping cameras (Jacobsen, 2011; Leberl et al., 2003; Neumann, 2008) have the potential to vastly improve coverage at the same altitude, this technology is expensive and may not be feasible with strict budget constraints. Furthermore, both systems would require major structural modifications, or more likely, the use of a larger airframe also bringing costs up. Alternatively, coverage could be expanded by raising altitude, but with the current system, this comes at a cost of reduced ground resolution in vertical images. With advances in digital image technology, future surveys employing these methods need to consider the relationship between the altitude variable and image quality and how this affects identification reliabilities of various-sized target taxa.

Photogrammetry derived from vertical imaging has been used to identify morphologically distinct forms of marine mammals (Gilpatrick & Perryman, 2008; Perryman & Lynn, 1993). This method is used to provide indices for individual health, nutritive condition, allometric growth, reproduction, and stock structure of various cetaceans and sharks (Cole et al., 2007; Durban et al., 2009; Fritz et al., 2008; Hain et al., 1992; Perryman & Lynn, 1994, 2002; Pitman et al., 2007; Ratnaswamy & Winn, 1993; Rohner et al., 2011; Sumich & Show, 2011). Photogrammetry has also proved a viable method for collecting noninvasive measurements of leatherback turtles (Pease et al., 2006). For our surveys, the photographic method improved visual surveys by obtaining photo documentation of sightings, covering an area that would have been obscured from view, reducing perception bias, and improving density estimates. If morphometric indices were yielded from photographic sightings, it would further enhance these multitaxon data.

This study has proved the concept that running simultaneous photographic and visual sampling methods is an effective approach for collecting multiple protected-species data from a single platform. Current aerial surveys could benefit from adopting vertical photography methods to widen the scope of data collection, particularly in the absence of crew solely dedicated to downward viewing. Although vertical photography results in time-consuming postflight data processing, statistically rigorous data can be collected with very little extra operational cost. The viable options for reducing lengthy image processing should be tested, as well as other technological advancements that could further add value from these photographic data. Given the recent increase in energy project development in federal U.S. waters, methods such as these that improve density estimates are vital for better-informed mitigation strategies and management decisions.

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