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Abstract

Radar and satellite global positioning system-platform transmitter terminal (GPS-PTT) transmitters provide complementary information on the movements and behaviors of individual birds. The GPS-PTT tag provides a snapshot of altitude and location of a specific individual of an identified species at predefined intervals. The history of the individual is known because each transmitter has a unique identification code. The radar cannot identify individuals or even species but it provides continuous position reports (altitude and location) of birds within its detection range. By integrating data from the two sources, the behavior and movements of identified individuals (not possible with radar) can be continuously monitored (not possible with satellite tags). In this study the radar detected 40% of the locations of vultures carrying GPS-PTT tags that were within 5 km of the radar. Most (75%) of the locations that were not detected were calculated to be above or below the radar's antenna beam. Speed and direction values recorded by the GPS-PTT tags and the radar were poorly correlated because the vultures were soaring and circling, which produced rapid changes in both azimuth and ground speed of the targets. Nevertheless, our findings show that combining these two techniques can allow monitoring of species that are of conservation concern where it is otherwise difficult to follow identified individual birds.

Introduction

Many conservation efforts require researchers to monitor the location and movements of animals in situations where it is difficult to detect and monitor individuals visually. Satellite transmitters have been commonly used to study migratory movements, especially of large birds (e.g. osprey *Pandion haliaetus*; Weimerskirch *et al*., 1993, 2002; Alerstam, Hake & Kjelle, 2006; Thorup *et al*., 2006*a*,*b*; wandering albatross *Diomedea exulans*; Jouventin & Weimerskirch, 1990). The newest platform transmitter terminal (PTT) devices incorporate global positioning system (GPS) technology and can report altitude, speed, and heading in addition to position (latitude and longitude). By updating the data at hourly intervals, the investigator can coarsely sample a bird's behavior and locations. For example, Mandel *et al*. (2008) examined turkey vulture *Cathartes aura* migratory decisions but were unable to obtain a finer resolution than 1 h in their analysis. From their data they inferred that vultures depend on and use atmospheric turbulence to minimize metabolic costs but could not determine how closely the birds tracked the turbulent layer. Because of their size these transmitters are not suitable for small birds. On an even coarser scale, movements of small birds can be tracked using geolocators to estimate latitude (Stutchbury *et al*., 2009).

Digital avian radars, on the other hand, can detect and continuously track birds with a temporal granularity of about 2.5 s (depending on the antenna rotation speed). However, the technology also has its limitations; radar cannot be used to identify species of birds let alone distinguish individuals from one another. The identification of the species and individuals being observed must be obtained from other sources.

The objective of this study was to determine whether a digital avian radar and satellite transmitters could provide complementary information on freely moving, individual GPS-PTT-equipped black vultures *Coragyps atratus* and turkey vultures. Additional objectives include identifying the conditions and variables that resulted in coincident radar and PTT records. This combination of techniques to verify these two remote sensing techniques with one another has never been accomplished before.

Methods

Study site

The turkey and black vultures were captured using a baited walk-in trap (Humphrey, Avery & Mcgrane, 2000) at the

Marine Corps Air Station (MCAS), Beaufort, SC, USA. The radar was installed centrally on the MCAS Beaufort, SC airfield (32.4735°N, 80.7194°W). The runways and taxiways are surrounded by mown grass to the edge of the aircraft movement area (hangars, parking ramps, safety areas). The surrounding habitat is conifer and mixed conifer-hardwood forest, predominately longleaf *Pinus palustris* and slash pine *Pinus elliottii*, and tidal marsh.

GPS-PTT satellite tags

As part of a long-term study PTT satellite units (PTT-100, Microwave Telemetry Inc., Columbia, MD, USA) were attached using a Teflon tape backpack harness (Humphrey *et al*., 2000) to 8 turkey and 8 black vultures captured between 9 October 2006 and 10 April 2007. The transmitters recorded the GPS location, altitude, heading, and speed hourly, and these data were downloaded via ARGOS satellite services every 2–3 days. The GPS unit turns on at the hour and obtains a fix as soon as sufficient satellite coverage is available to calculate 3D location, heading, and speed (based on data from Microwave Telemetry Inc.). This may take from a few to several seconds. Based on the manufacturer's technical specifications, the devices had a horizontal spatial accuracy of 15 m radius under the best conditions. The duty cycle changed with the season to encompass the local dawn–dusk period. During May, coverage was 11:00–24:00 Greenwich Mean Time (GMT). In June the coverage shifted to 09:00–02:00 GMT.

Digital avian radar

The radar was an Accipiter® eBirdRad (Accipiter Radar Technologies, Inc.; Fonthill, ON, Canada). This system consisted of a Furuno® 2155BB (Furuno Electric Co. Ltd., Nishinomiya City, Japan) front-end housed in a small cargo trailer. A dish antenna that produced a 4° conical-beam pattern and elevated 5° was mounted on the roof of the trailer, about 2.5 m above the ground. The back-end was a commercial, off-the-shelf Dell® tower computer running WINDOWS XP® operating system. The computer clock was synchronized with the time from the system's GPS receiver. Thus, the radar computer's time-stamp and those of the GPS–PTT tags were closely synchronized. The radar software was Accipiter Tracker® (DRP; version 6.7.6.3; Accipiter Radar Technologies Inc.) software described by Nohara *et al*. (2005); digitization range was limited to 5 km from the radar. The system was operated almost continuously from 9 May through 1 July 2008 at MCAS Beaufort, with two short gaps when thunderstorms caused loss of power. The extracted detections and tracks data were automatically saved onto the internal hard drive for subsequent analyses.

The tracks were computed by the software to be a series of detections that are caused by the same radar target and assigned an identification number. The database entry of each detection of a track contained complete information on time, location (lat, long), altitude (of the beam's center at that location), speed, heading, and distance and direction from the radar. Ancillary software (TRACKVIEWER) (Accipiter Radar Technologies Inc.) was used to playback and view the recorded detections and tracks (see Fig. 1).

Side-lobe and multi-path detections were present to 1 km from the radar but were mostly limited to within 0.5 km. These were caused by taxing aircraft and ground vehicles. They did not interfere with data interpretation because all but one of the GPS locations were beyond 1 km.

Data extraction

All satellite GPS fixes that were within the 5 km digitization range of the radar were tabulated and individually located on the radar display (Fig. 1). The extracted radar data (detections and tracks) were played back and, using the time-stamp from the satellite position fix and the radar's time-stamp for each antenna frame, examined for detections and tracks that corresponded to the location reported by the satellite tag. The software's algorithms required specific detection frequency (i.e. three detections in six antenna revolutions) to classify a set of detections as a Track. Birds that were near the edge of the antenna pattern or near the sensitivity threshold often produced an erratic pattern of intermittent detections but not a continuous Track (Fig. 1). Such patterns were classified as probable confirmations but no information on speed and heading could be determined.

Altitude information

To determine whether a bird was within the radar's beam pattern we compared its altitude from the PTT tag with that calculated for the radar's upper and lower pattern boundaries. The PTT tag uses GPS technology to determine altitude, which has an accuracy uncertainty that depends on the number of satellites in view and their locations in the sky. When comparing the PTT altitude with the radar's altitude value, we used an uncertainty of ± 25 m for the PTT altitude value. This is slightly greater than the 18 m listed by the manufacturer (Microwave Telemetry Inc.) for times with maximum satellite coverage and better reflects field conditions.

The radar antenna we used produces a circular cross-section beam that is 4° diameter. We calculated the upper and lower edges of the antenna's coverage based on the distance of each bird from the radar and allowed for a $\pm 0.5°$ beam-width uncertainty for the antenna. The radar's vertical beam width uncertainty is based on several potential causative factors: (1) it was impossible to determine, with the equipment available, whether the antenna was level to within $<0.5°$; (2) although the calculated beam at 3 dB down is 4° across, the antenna pattern is not a sharp cut-off; (3) imperfections in the antenna could result in a wider beam pattern; (4) the measurement of the antenna's elevation angle might not be precise enough to be accurate to within $<0.5°$.

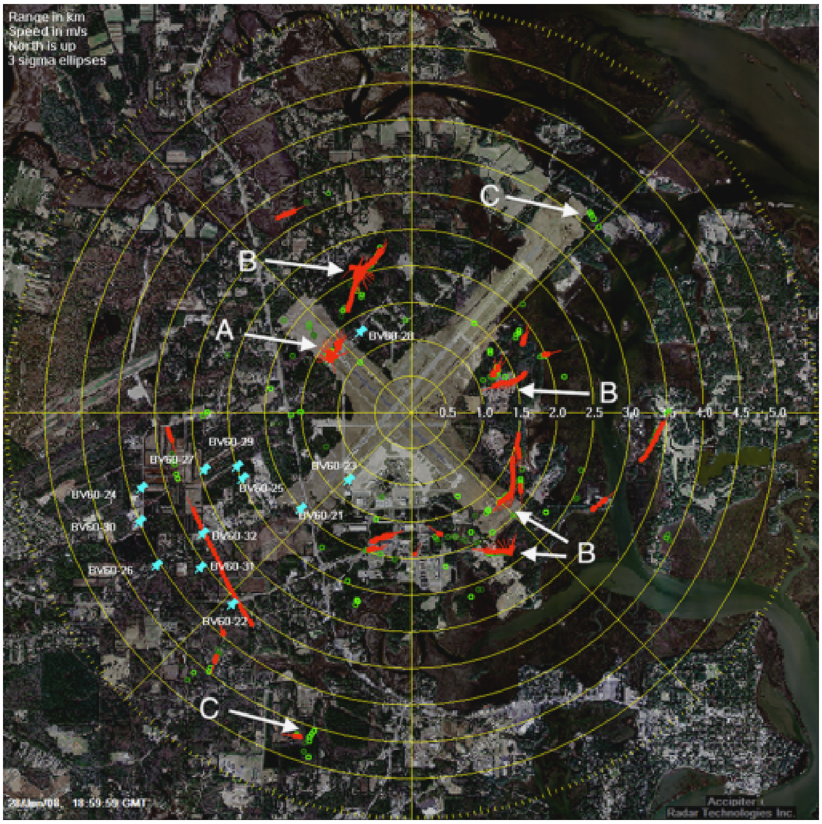

Figure 1 Radar display illustrating the locations (indicated by the 'pushpins' and text labels) of a black vulture carrying a global positioning system-platform transmitter terminal (GPS-PTT) tag. The series of square symbols (A, B) denote the tracks of a GPS-PTT vulture (A) and unidentified birds that appear to be vultures (B). The change in direction of the heading markers (line emanating from the Track symbols) in the examples indicate that the birds are circling at that point and are almost stationary over the ground. The series of open circles C indicates detections of birds that were too infrequent to generate tracks.

Results

One hundred and eighty-two GPS-PTT locations were within the 5 km digitization range of the radar. Two reports were excluded because the radar was not operating when the reports were taken. Of the remaining 180 reports, 13 were from three black vultures and 167 were from two turkey vultures.

Of the 180 PTT locations within 5 km of the radar, 70 positions were reported by the radar software as Tracks ($n = 48$; Fig. 1) or as sporadic detections but not consistent enough for the software to compute a Track ($n = 22$; Fig. 1). Twenty-eight additional locations were computed to be within the radar beam but were not detected by the radar (Fig. 2a). Of the 70 locations confirmed by radar detections, 22 were calculated to be above or below the antenna beam by a mean of 72 m ($\pm$11.6 SE, range 1–181 m). Almost three-fourths (15 of 22 targets) of those were within 80 m vertically of the calculated coverage of the radar beam. Beyond 4.5 km only two birds were detected by radar, and only intermittently (detections too inconsistent to produce a track). Beyond 4.5 km two additional birds were calculated to be within the beam but were not detected.

The most common (45 of 48 Tracks) behavior observed based on the radar tracks was soaring (speed $< 7\,m\,s^{-1}$). Circling behavior (22 of 48 Tracks) could be easily identified by the rapid changes in headings and ground speeds of the birds. In other cases (three of 48) the birds moved rapidly ($> 10\,m\,s^{-1}$) in a more-or-less straight path and, based on their speeds, probably employed flapping flight as opposed to soaring.

Because of the circling paths the birds often followed, we found a poor correlation between the speeds ($r = 0.010$; $P > 0.05$) and headings ($r = 0.117$; $P > 0.05$) reported by the PTT tags and those calculated by the radar.

Within 1-km intervals from the radar, the proportion of the targets within the radar beam increased up to 3 km, but then declined sharply. The percentage of the targets detected by the radar declined steadily with distance from the unit (Fig. 2b). As distance from the radar increased, the height of the lower edge of the beam increased, and as a result greater proportions of vultures were below the beam at greater ranges.

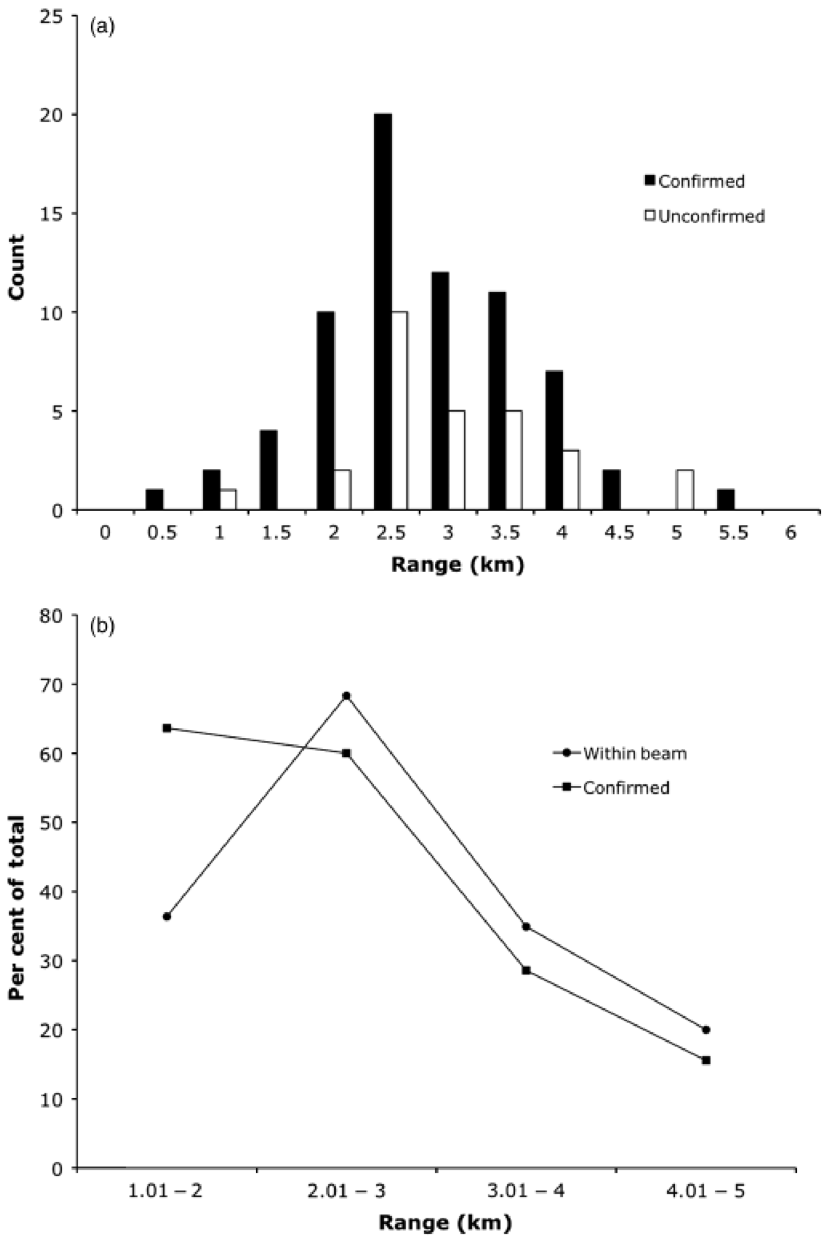

Figure 2 (a) The distribution of the number of global positioning system-platform transmitter terminal (GPS-PTT) locations that were calculated to be within the radar beam and were confirmed by radar data (solid bars) or were not confirmed (open bars). (b) The percentage of GPS-PTT reports that were confirmed and the percentage of reports that were calculated to be within the radar beam with respect to range.

Discussion

Our results indicate that satellite GPS-PTT tags and radar provide complementary information on the movements of individually identified birds on a fine temporal scale. Almost 40% (70 of 180 records) of the birds' PTT location reports were detected by the radar. Of the remaining 110 reports, 82 (75%) were calculated to be above or below the radar's beam pattern and would not be expected to be detected. Of the 28 reports that were calculated to be within the antenna pattern's coverage but were not detected, 23 (82%) were at least 2.5 km away from the antenna (Fig. 2). At this range the returned signal from a single vulture (2 kg; Kirk & Mossman, 1998; Buckley, 1999) would be weak because of its small radar cross-section. This radar cross-section would be further reduced by the orientation of the bird's body relative to the radar, which greatly affects the strength of the reflected signal (Edwards & Houghton, 1959). The theoretical maximum range for detection of a 2 kg bird by this radar in the absence of clutter is 6 km (P. Weber, pers.

comm. based on Blacksmith Jr & Mack, 1965). The presence of clutter within the same resolution cell would be enough, in most cases, for the clutter rejection algorithms in the radar software to cancel the weak return from a vulture along with the clutter's signal (Nohara *et al*., 2005). Although clutter from side-lobe returns can obscure weak returns from birds, such clutter was all within 1.0 km and mostly within 0.5 km of the radar. We had only one GPS-PTT record within 1 km and that bird was detected by the radar.

Most of the birds that were calculated to be within the beam pattern were within the 2–4 km range and, therefore, within an altitude band of 100–350 m above the ground. This altitude range is a function of the radar antenna's angle of elevation and the proximity of the birds to the radar. The distribution of vultures within the beam coverage was the same for birds that were detected (66 ± 8 SE m from nearest edge of beam) as for those that were not (68 ± 9 SE m from nearest edge). Therefore, location within the beam pattern does not appear to influence detection as much as distance.

Twenty-two radar detections were recorded for PTT locations that were calculated to be above or below the radar's beam pattern (Table 1). Most of these were near the edge of the beam pattern where they might have been detected because the antenna's sensitivity is not a sharp cut-off. Birds that were below the beam pattern and not detected were significantly ($t = 2.55$, $P < 0.01$, d.f. = 92) farther below the beam than birds that were detected (means: 74 vs. 43 m). Likewise, birds that were above the beam and were not detected were significantly ($t = 2.71$, $P = 0.01$, d.f. = 8) farther above the beam than those that were detected (means: 441 m versus 121 m). Apparent detections of a PTT-equipped bird calculated to be outside the beam might also have been the result of several birds flying in close proximity and one or more others of the group flying at an altitude within the antenna's coverage pattern. This scenario is highly likely based on the behavior of both species of vultures when soaring.

Comparisons between the speeds and directions recorded by the GPS-PTT tags and the individual radar Tracks can be misleading. In some cases, the match between the PTT speed and heading and the radar's values is poor because the birds were soaring and circling (as determined from their radar tracks); in other individual cases there is a reasonable match. The closeness of the values depends on exactly when the values are recorded relative to one another. On the radar side, a contributing factor is that the antenna requires 2.5 s for each revolution. The time difference would be twice that if a bird was not detected on each scan. On the satellite side, there is delay from when GPS unit turns on until it obtains the fix from sufficient satellites. This typically requires no more than several seconds because the birds are above the trees and other structures that might block view of the sky. Spurious values can be generated by GPS measurement and produce errors when the bird is moving slowly over the ground (Hurford, 2009). These errors also could contribute to the poor correlations, especially in heading. Some speed values, as well as headings, change rapidly for a track from a circling bird because the speeds are ground speeds. When a circling bird turned into the wind, we noted that its ground speed decreased $10\,\mathrm{m\,s^{-1}}$ or more.

Table 1 The number of GPS-PTT locations detected by the radar software that were calculated to be above or below the radar beam by specific distances

Distance (m)	Count
25	7
50	2
75	6
100	2
150	3
200	2

Occasionally, a GPS reported $0\,\mathrm{m\,s^{-1}}$ speed but simultaneously recorded an altitude up to 475 m. We examined 21 records with $0\,\mathrm{m\,s^{-1}}$ in which the bird was calculated to be within the radar's beam (Table S1). In 13 cases (62%), the radar data corresponded to the GPS location report, with associated speeds of $5–15\,\mathrm{m\,s^{-1}}$ calculated by the radar. Circling flight might produce a momentary ground speed of $0\,\mathrm{m\,s^{-1}}$, but more than half of such cases involved birds moving in a linear track, not circling. These situations illustrate the benefits of using multiple sensing techniques to monitor movements of avian species. Applying a combination of sensors can help researchers investigate and explain the challenges faced by birds during migration (Robinson *et al*., 2009).

We have illustrated a unique combination of complementary remote sensing techniques; each provides information not available from the other and each can be used to verify the data from the other. This combination can be used to monitor many avian species of conservation interest on land, lakes, or oceans. Issues that can benefit from the application of these techniques include pre-installation evaluation and post-installation monitoring of wind turbine farms, assessment of bird strike hazards near airports, and continuous monitoring of contaminated sites (mine tailings, waste effluent, oil spills). In each of these instances it is important to keep birds away from hazardous situations. Radar allows continuous monitoring at a specific locale and the satellite tags identify individual birds. This combination provides much finer temporal resolution than integrating satellite tracking and banding (ringing) data (e.g. Strandberg, Dlaassen & Thorup, 2009).

Many shipboard radars, especially those on larger vessels, provide access to the radar signals needed by radar-computer interfaces. A digital computer with the necessary interface and software can be attached to existing radars and birds carrying satellite transmitters can be monitored far from shore. The radar would provide the fine temporal resolution needed to monitor behavior and a satellite transmitter would provide the identity of the animal being observed. Such a capability would be invaluable for studying foraging or navigation of far-ranging species such as albatrosses and other procellariiforms (Weimerskirch *et al*., 1993, 2002; Bonadonna *et al.*, 2005; Nevitt, Losekoot & Weimerskirch, 2008).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Details on the GPS-PTT records of birds with zero airspeeds but non-zero altitudes.

Table S1. Details on the GPS-PTT records of birds with zero airspeeds but non-zero altitudes above the ground that were calculated to be within the radar beam. Date and time values are GMT. TV = turkey vulture, BV = black vulture, Confirmed = radar Track produced, Probable = multiple radar detections but no Track, Not = no radar detections at the location.