2013

Evaluation of an Avian Radar System

Michael B. Gerringer
Indiana State University

Evaluation of an Avian Radar System

A thesis

Presented to

The College of Graduate and Professional Studies

Department of Biology

Indiana State University

Terre Haute, Indiana

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

---

by

Michael B. Gerringer

August 2013

Keywords: Avian Radar, Bird Strike, Wildlife Management, Airport, Human-Wildlife Conflict

COMMITTEE MEMBERS

Committee Chair: Steven L. Lima, Ph.D.

Professor, Department of Biology

Indiana State University

Committee Member: William A. Mitchell, Ph.D.

Associate Professor, Department of Biology

Indiana State University

Committee Member: George S. Bakken, Ph.D.

Professor, Department of Biology

Indiana State University

Committee Member: Travis L. DeVault, Ph.D.

Project Leader, Wildlife Service, NWRC Ohio Field Station

United States Department of Agriculture

ABSTRACT

The problem of bird strikes in aviation is becoming an increasing threat, both to aircraft and to human safety. Management efforts have reduced wildlife hazards below 500 feet and within the immediate airport environment, but traditional methods of monitoring bird activity are limited to an observer's field of view. Avian radar systems could potentially be useful in monitoring bird activity at great distances from the airport, at higher altitudes, and at night (Dolbeer 2006), but little work has been done to validate the tracking capabilities of avian radar systems. Thus, the goal of this research is to evaluate the detection and tracking abilities of the Merlin Avian Radar System provided by DeTect Inc. Radio-controlled (RC) aircraft flights were used to systematically test the tracking abilities of the Merlin System with respect to distance and altitude. Transits by free-flying birds provided an equally important test of the Merlin System, allowing for the assessment of tracking performance as influenced by flock size, altitude, and distance from the radar unit. Overall tracking performance regarding the RC aircraft and single large bird targets was poor across all study distances and altitudes. However, flocks of large birds such as geese and cranes were tracked well, even those several miles away from the radar unit. Given these results, avian radar could be a useful tool for monitoring bird flock activity at airports, but less so for single large bird targets such as thermalling raptors.

ACKNOWLEDGMENTS

Many people assisted in the conduct of this research, and I wish to thank them all: Dr. Steven L. Lima offered me a position in his lab at Indiana State University, and mentored me while conducting my research and writing my thesis. My other committee members, Dr. Travis L. DeVault, Dr. William A. Mitchell, and Dr. George S. Bakken, provided help and various important insights. My technicians Jordan Kesner and Jenny Bodwell spent many hours capably operating the radar system and provided flexibility in their work schedules to do so. My lab-mates, Jennie Carr, Jong Koo Lee, and Robert Arndt helped with insight during my research, analysis, and writing. Tim West from DeTect Inc. was patient and instrumental in teaching me how to operate the Merlin System. John Beasley and the rest of the airport police at the Terre Haute International Airport helped immensely in securing a location to set up the radar and in escorting us in and out of the airport on a daily basis. Dennis Griffin (FAA Manager) and Dennis Wiss (A.A.E. Airport Director) at the Terre Haute International Airport approved the radio-controlled aircraft flights. The FAA providing the funding that made this research project possible.

I would also like to thank my parents Bruce and Anne-Marie for all of their support and encouragement over the years and for encouraging me to pursue my career goals and interests, and my friend Monica for her encouragement and support during my research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EVALUATION OF AN AVIAN RADAR SYSTEM

INTRODUCTION

The Bird Strike Problem

My research is motivated by the problem of bird strikes in aviation, which is a serious and growing threat to human safety (DeVault et al. 2013). The recent incident of US Airways Flight 1549 ditching into the Hudson River after striking Canada geese (Marra et al. 2009) was a dramatic example of the consequences of such strikes. Bird strikes are also not a new phenomenon (Dolbeer 2013). The first bird-aircraft collision occurred in 1905 when Orville Wright struck a bird while chasing a flock with his plane (Thorpe 1996). Seven years later, Calbraith Rodgers, the first to fly across the continental US, was the first to die as a result of a bird strike (Thorpe 1996). In 1960, a bird strike in Boston resulted in the complete destruction of a Lockheed L-188 Electra and in the deaths of 62 of the 72 passengers onboard. In 1995 in Alaska, a U.S. Air Force Boeing E-3 Sentry AWACS aircraft crashed shortly after takeoff following multiple engine ingestions of Canada geese, killing all 24 crew members. More recently, bird-aircraft collisions have become an increasing threat due in part to increasing populations of large, flocking bird species (Dolbeer and Eschenfelder 2003; Cleary et al. 2006). Thirteen of the 14 bird species in North America with a mean body mass greater than 8 lbs have undergone significant population growth over the last thirty years (Dolbeer and Eschenfelder 2003), a rather troubling statistic considering that aircraft engines and other components are generally not tested for collisions with birds weighing more than 4 lbs (Dolbeer and Eschenfelder 2002).

Also contributing to the increasing threat of bird strikes is the steady annual 1.3% increase in air traffic (Dolbeer et al. 2009). A further problem is that modern two-engine aircraft, which are quieter and less likely to alarm birds, have essentially replaced noisier and less efficient three and four-engine aircraft (Burger 1983; Kelly et al. 1999). With only two engines, an aircraft cannot afford disabling bird ingestions into more than one engine. Quieter two-engine aircraft have six times as many bird strikes as older noisier aircraft (Burger 1983). Thus, with increasing air traffic, quieter aircraft with fewer engines, and increasing populations of large birds, the risk and frequency of bird strikes along with the potential for loss of human life, property, and birds due to bird strikes will increase (Cleary et al. 2004; Dolbeer 2006).

Aside from threatening human life, bird strikes are costly for the aviation industry in terms of aircraft damage and downtime. In 2011 alone, 10,083 bird strikes were reported in the United States, 541 of which resulted in aircraft damage (Dolbeer 2011). Worldwide, bird strikes have led to the destruction of over 210 civil and military aircraft resulting in more than 229 deaths since 1988 (Richardson and West 2000). Using data from 1999 and 2000, Alan and Orosz (2001) estimated that bird strikes result in an annual cost of over 1.2 billion dollars for commercial airline carriers worldwide. The annual estimated cost of wildlife strikes to the United States civil aviation industry is 592,000 hours of aircraft downtime, 614 million dollars in direct costs, and 144 million dollars in associated costs (Dolbeer 2006). Besides the commercial and private sector, the United States military suffers significant costs as well (Alan and Orosz 2001; Zakrajsek and Bissonette 2005).

My research is focused on the potential use of avian radar in lessening the problem of bird strikes in aviation. Specifically, my project involves the evaluation of the detection and tracking abilities of the DeTect Merlin Avian Radar System, designed and built by DeTect, Inc., of Panama City, FL. This radar evaluation is part of a collaborative effort between Indiana State University (ISU), the USDA National Wildlife Research Center, and the National Center for Atmospheric Research (NCAR). ISU's role in this collaboration is to field-test the radar system, whereas NCAR's role is to examine and characterize the components of the radar system itself.

History of radar use for bird detection

During WWII, radar was developed for the purpose of tracking enemy aircraft. Soon thereafter, it was discovered that some of the puzzling radar echoes observed on radar were birds. Before long researchers found that radar could be used to detect and track bird targets, and thus it became an important tool for monitoring and quantifying bird movements (Lack and Varley 1945). In the early 1970s, when affordable marine surveillance radars became more widely available, a number of researchers began using them to study birds (Nohara et al 2007; Gauthreaux and Schmidt 2013). Further work (Gauthreaux 1972) led to the realization that radar might be used to address the threat of bird-aircraft collisions by serving as early warnings of hazardous bird activity in the airport environment (Blokpoel 1976). There is now a variety of radar systems used for bird detection, each functioning at different spatial scales, and unique in the type of information that they are capable of collecting (Gauthreaux and Schmidt 2013).

Tracking radar, for instance, is capable of locking on to an individual bird target and tracking it out to distance of 4 miles (6 km), yielding specifics regarding its flight speed and trajectory. However, these narrow beam systems have a rather limited sampling range and are only capable of tracking one target at a time (Bruderer et al 1995; Gauthreaux and Schmidt 2013).

Weather surveillance radars (WSR) have been used for over 50 years now to study bird movements. The newest WSR, the WSR-88D, is an advanced sensitive S-band system that is capable of detecting small birds, bats, and insects, and has the ability to detect flocks as far away as 150 miles (240 km) (Larkin 1984; Gauthreaux and Schmidt 2013). Weather surveillance radars have been used to provide general location and directional information for birds (Russell et al. 1998; Gauthreaux et al. 2003), but lack the higher resolution needed for monitoring bird activity at airports (Nohara et al. 2007; Beason et al. 2013). Other disadvantages include a slow update rate and the inability to detect low flying targets.

Avian Radar Systems

Modern avian radars are typically defined as those capable of automatically detecting and tracking birds 360 degrees around an airfield, at distances of up to 6 miles, and at altitudes up to 5000+ feet (Beason et al. 2013). (Note that units of feet and miles will be used throughout this document as per the standards of the aircraft transportation system). Most avian radar systems are capable of providing real-time estimates of target location, altitude, speed, and size, and specialized alerts based upon levels of bird activity (Gauthreaux and Schmidt 2013). Avian radar systems generally use commercial, off-the-shelf marine radar sensors, along with antennas, transceivers, and radar processors that are often customized for bird detection (Beason et al.

2013). Unlike traditional marine radar units, digital avian radars employ clutter suppression, which could result in higher detection rates of birds. Avian radars are typically low-powered systems, ranging in power from 5-60 kW, but most have at least a 25 kW power output. Higher powered systems allow for increased detection rates and improved tracking over lower powered systems (Gauthreaux and Schmidt 2013).

The marine radar sensors in avian radar use either X-band or S-band radar. X-band systems have a wavelength of 3 cm (frequency = 9 GHz), whereas S-band sensors have a wavelength of 10 cm (frequency = 3 GHz). The X-band wavelength is much closer to the peak absorption frequency of rain droplets (1.35 cm) than is the S-band wavelength. Hence, rain droplets result in more attenuation for X-band than for S-band radar, and intense precipitation can decrease the chances of detecting targets when using X-band radar (Schmidt and Gauthreaux 2013). However, the new solid state X-band marine radar sensors with rain clutter suppression capabilities may perform much better during rainfall (Beason et al. 2013). Furthermore, X-band may be more favorable for detecting bird targets because avian radar cross sections are typically larger in X-band than in S-band radar.

There are two main antenna configurations, a dual vertical and horizontal scanning array antenna setup or a rotating parabolic dish antenna. The parabolic dish antenna produces a narrow conical beam (also referred to as a pencil beam or spotlight beam) that scans 360 degrees. The high gain and narrow beam of the dish antenna allows for bird detection at greater ranges, and good azimuth and altitude resolution (Beason et al. 2013). The primary advantage of the parabolic dish is that it allows for near 3D tracking, unlike the array antenna which provides only 2D tracking. The dish antenna also provides estimates of target altitude (within a specific range of altitudes) 360 degrees around the airfield.

A horizontal array antenna, with a 20-24 degree beam width, allows for greater airspace coverage (ground level to 15,000+ feet) than parabolic dish antennas. However, the broad vertical extent of the horizontal array antenna beam leads to poor altitude resolution, making accurate measures of target altitude unattainable. As a result, only 2D tracking is possible with a horizontal array antenna. However, the broad beam coverage theoretically allows for more birds to be detected. The vertically rotating array antenna provides measures of target altitude over a broad range of altitudes, but only along a relatively narrow radius away from the radar system. The parabolic dish antenna thus trades elevation coverage and azimuth resolution in favor of better altitude resolution, whereas the horizontal array trades altitude resolution in favor of greater altitude coverage (allowing for a greater volume of airspace to be sampled).

Avian radar has been used for a number of applications. These include monitoring hazardous bird activity at airports, automatic monitoring of bird activity patterns (habitat use, use of attractants near airports, nocturnal activity), use in the development of airport wildlife hazard assessments, and use in examining trends in flight patterns and altitude distribution at proposed wind farm sites (Cooper 1996; Harmata et al. 1999; Gauthreaux and Belser 2003). Avian radar has also been used to study migration patterns, timing, and passage rates (Gauthreaux and Belser 2003), monitor bird/bat roosts, and to determine spatial and temporal patterns in bird movements between roosting and feeding sites (Beason et al. 2013).

RADAR PROJECT PURPOSE AND OBJECTIVES

Need for validating avian radar in airport environments

Whereas wildlife management efforts at airports have significantly reduced hazards below 500 feet, avian radar is capable of providing information on bird activity and trends at higher altitudes, at further distances from the airport, and at night (Dolbeer 2006). Radar may be more effective at sampling bird activity than visual observers (Beason and Bowser 2009; Brand et al. 2011). Thus, some have proposed, albeit carefully, that information collected by avian radar could also be used to provide airport personnel with near real-time warnings of bird hazards in the airport environment (Nohara 2009; Gauthreaux and Schmidt 2013). Yet, despite the potential of avian radars, there is still much uncertainty concerning their detection and tracking performance, as well as how the information gathered by such systems would be utilized at airports (Weber et al. 2005; Gauthreaux and Schmidt 2013). The 2010 Advisory Circular on Avian Radar (Federal Aviation Administration 2010) set forth general guidelines for the use of avian radar at airports, but states that integration plans should be specific to the needs and organizational structure of each airport. Given that avian radar is not optimized for air traffic use, there are a number of complexities in integrating avian radar with air traffic control (Federal Aviation Administration 2010). According to the Advisory Circular, the FAA is currently assessing these integration issues.

While many claims have been made regarding the detection and tracking capabilities of avian radar systems, few studies have collected the data necessary to confirm such claims. Thus, there is a need for ground-truthed target observations to validate radar returns from birds (Schmidt and Guthreaux 2013) and ultimately to determine the detection and tracking ability of avian radar systems. To our knowledge, the only major avian radar evaluation project conducted and published to date is the IVAR (Integration and Validation of Avian Radar) Project (Brand et al. 2011). The IVAR evaluation demonstrated that (i) some of the objects automatically tracked by avian radar are indeed birds, (ii) avian radar is capable of detecting and tracking birds within the ranges and altitudes where most bird strikes take place, and (iii) avian radar software is capable of placing bird targets within 10 meters of their actual location. Despite the many important accomplishments of the IVAR project, there is still a need for basic detection and tracking performance data regarding avian radar.

The Current Radar Evaluation Project

The primary goal of my radar work is to evaluate the tracking ability of the DeTect Merlin Aircraft Birdstrike Avoidance Radar, provided by DeTect, Inc. of Panama City, FL. Indiana State University, the National Wildlife Research Center (Ohio Field Station), and the National Center for Atmospheric Research (NCAR) collaborated to conduct a comprehensive evaluation of the Merlin System (VIN number 1D9BR2427AP670010; production number Merlin 56). The primary objective of the field testing is to evaluate the Merlin System's ability to accurately detect and track targets as a function of distance, altitude, and various target flight characteristics. Radio controlled-aircraft were used for much of the field evaluation work. Transits by free-flying birds also provided an equally important test of the Merlin System.

The Merlin Avian Radar System

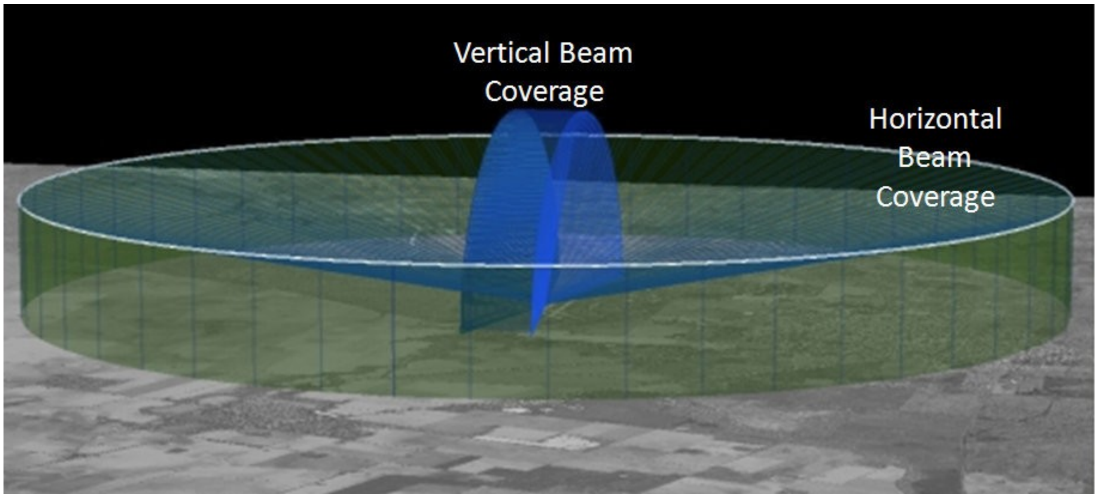
The Merlin System consists of a trailer (Figure 1), a climate-controlled cabin which houses the computer systems (Figure 2), radar processors and other equipment, and two towers on which the dual-scanning array antennas are mounted (Figure 1). The system has both a vertical and a horizontal scanning solid-state S-band radar that provide simultaneous coverage of the airfield, each with an antenna rotation speed of 24 rpm. Both the horizontal and vertical radar have a peak power output of 0.2 kW, but through pulse compression achieve an outcome comparable to a 30 kW magnetron system. The horizontal scanning radar (HSR) has a theoretical detection range of 6 - 8 nautical miles (NM) around the airfield (Figure 3A), 15,000+ feet above ground level, and scans 360 degrees with a 24 degree beam width and a 7 degree upward tilt angle (Figure 3B). The HSR provides latitude/longitude coordinates for each tracked target as well as estimated target size, speed, heading, and a number of other variables. The vertical scanning radar (VSR) also has 24 degree beam width with a theoretical detection range of 3 - 4 NM out and over 10,000 feet above ground level (Figure 3A). The VSR provides specific measures of target altitude and distance (among other variables) centered on a single narrow radius away from the radar unit. Given that the HSR and VSR are not integrated, the altitude of a target in the VSR is not associated with the track of a target in the HSR. The vertical and horizontal radars are displayed on separate monitors located in the cabin (Figure 4).

The Merlin System's radar software is designed specifically for detecting and tracking large birds, and classifies targets into 1 of 4 size categories. The software labels targets as small (e.g. songbird), medium (e.g. American Crow), large (e.g. Canada Goose) or flock, based upon on the number of pixels representing the target in the radar display. This radar system does not provide measurements in standard metric units, thus altitude and distance measurements will be given in feet and nautical miles respectively.

Figure 1. Merlin Avian Radar System at the Terre Haute International Airport.

Figure 2. Radar Computers.

A.



B.

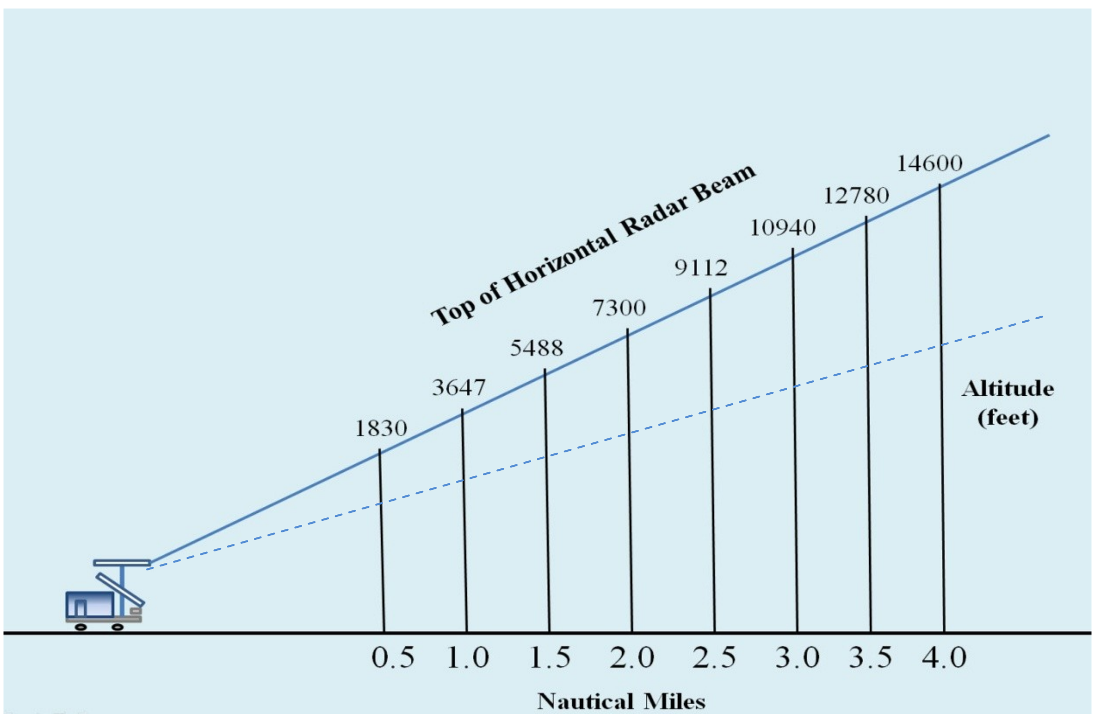


Figure 3. Vertical and Horizontal Beam Coverage (A; from DeTect Inc. website 2013), and altitude coverage of the horizontal scanning radar (B), with the dashed line representing the center of the beam.

Figure 4. VSR and HSR monitors.

STUDY SITE

The radar field evaluation took place at the Terre Haute International Airport in Terre Haute, Indiana. A commercial moving company delivered the radar system to the field site on August 5, 2011, where it was set-up at the edge of a level, asphalt tarmac. The vertical radar was aligned with an east-west road (Swalls Drive) at an angle of 86 degrees, such that the center of the vertical beam crossed Swalls Drive at approximately 2.0 NM (Figure 5). This configuration allowed easy access to the vertical beam from Swalls Drive out to 4 NM. A technician from DeTect Inc. (Tim West) worked with me to optimize the radar system for use at the airport. The optimization process included the creation of static clutter maps of the radar testing area. Clutter maps allow the Merlin System's software to compensate for areas of stable clutter such as buildings or trees. This initial set-up and my task of becoming familiar with the operation of the radar system, took several weeks in late August through mid-September of 2011.

Conducting the radar evaluation in an airport environment was important because (i) this is precisely where such systems are expected to be used and (ii) airport environments yield relatively little ground clutter given that they are generally open in nature. Thus, the selected study site was ideal, as the Terre Haute International Airport is surrounded primarily by crop fields and grassland habitat (Figure 5, 6A-C). It was also important to select a site that was generally flat, given that hills can produce significant radar "shadows" where birds are not detected due to beam blockage. Elevation was nearly the same across the entire study site (roughly 600 ft above sea level).

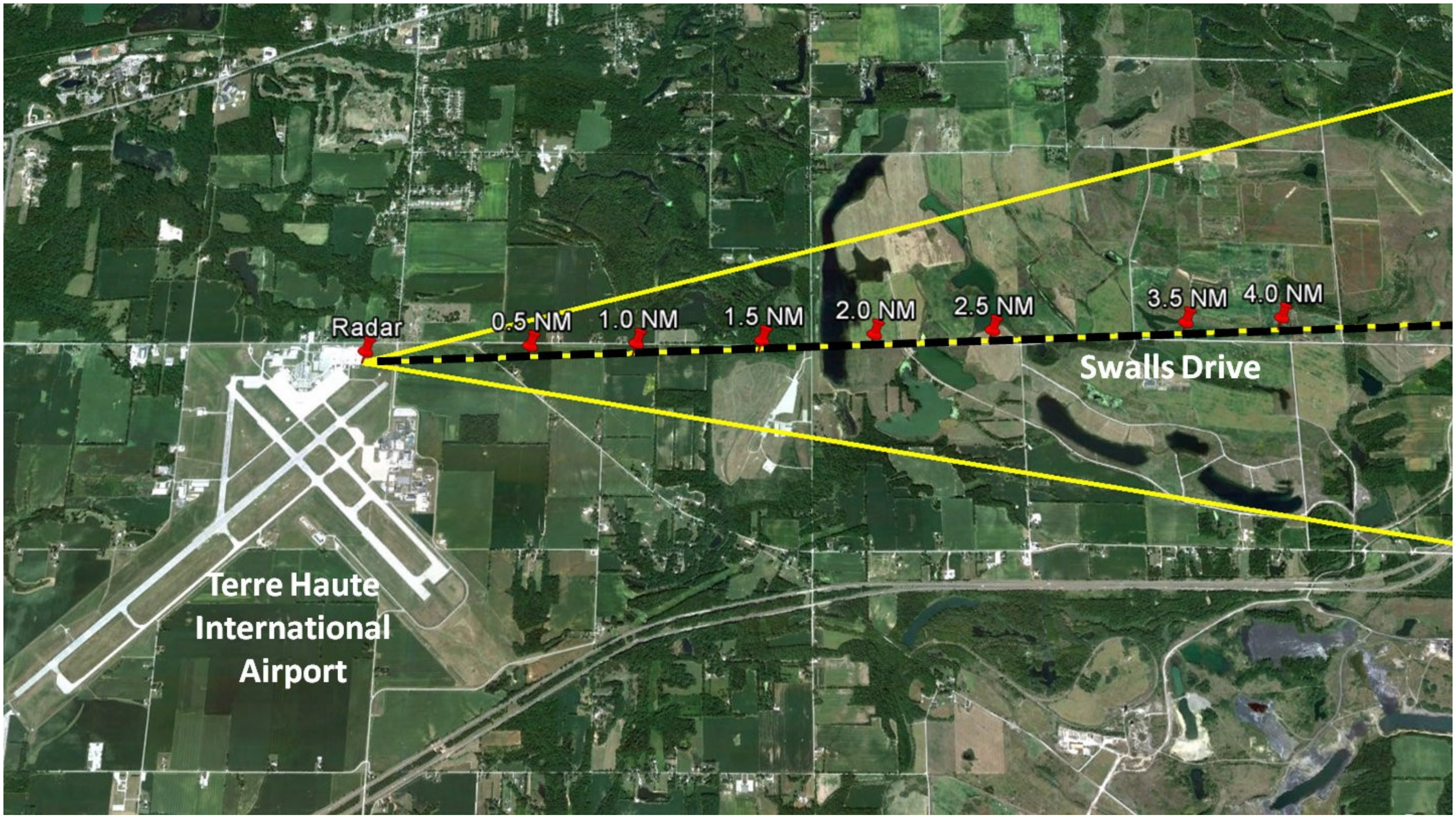


Figure 5. Study Site: The Merlin Radar and each RC flight location are marked with a red push-pin. The dashed black and yellow line represents the center of the vertical beam while the solid yellow lines outline the edges of the vertical beam coverage.

A.

B.

Figure 6. Habitat: Cropland 1.0 NM away from the radar (A), grassland habitat 2.0 NM away from the radar (B), and grassland habitat 3.5 NM away from the radar (C).

C.

Figure 6 Continued.

The grassland habitat and abundance of lakes (Figure 5) within the study site attract a variety of bird species that was ideal for an evaluation requiring the passage of free-flying birds. Bird activity within the study site was largely characterized by thermalling hawks and vultures, migrating waterfowl, and waterfowl moving between lakes or feeding sites. These bird species are among those that present the greatest hazards to aircraft (Kelly 1999; Blackwell and Wright 2006; DeVault et al. 2011), capable of inflicting significant structural damage and rendering aircraft engines inoperable.

RADIO CONTROLLED AIRCRAFT AS THE TARGET

Methods

Radio-Controlled Aircraft

Radio-controlled aircraft were used as easily controlled avian analogs for part of the field evaluation of the Merlin System. The radio-controlled (RC) aircraft used in this study was a Parkzone Radian Pro, which is a 5-channel (aileron, elevator, flaps, rudder, and throttle) electric-powered sailplane with a wingspan of 6.5 feet (Figure 7A). The RC aircraft is primarily constructed of foam with both wings and fuselage reinforced with fiberglass blades to reduce flex. The aircraft has an 87 gram, 960Kv metal brushless motor, a 2.4 GHz Spektrum receiver, and a 9.75 x 7.5 inch folding carbon composite propeller. Given these components as well as the aircraft's electrical wiring and metal pushrods, the RC aircraft has a somewhat greater radar signature than most large birds. The RC aircraft is nevertheless comparable to a large raptor in both area and reflectivity, and is a bit more detectable than bird species such as turkey vultures or red-tailed hawks (see below). Sailplanes are ideal for this work as they can cover a broad range of speeds typical of soaring birds. Given restrictions imposed by the Terre Haute International Airport, our test altitudes were limited to 1,000 feet above ground level, which nevertheless covers the great majority of airspace in which bird strikes are a serious threat; seventy-five percent of all reported bird strikes occur below 500 feet (Dolbeer 2006). Training to fly the RC aircraft took place during the summer of 2010.

The RC aircraft was equipped with an on-board GPS (Eagle Tree System GPS Expander Module) that continuously logs ground speed, altitude, and lat/long (Figure 7B). Information collected by the recorder was continuously transmitted to the pilot providing real-time information concerning aircraft ground speed, altitude, and heading. Data from the onboard barometric altimeter were also transmitted and recorded. After each field session, data stored onboard were downloaded to a laptop for storage and analysis. A GPS time stamp allowed for GPS data to be time synced with the radar data for analysis.

RC Aircraft Flights

The RC aircraft was flown such that the vertical and horizontal radar beams could be evaluated at the same time. This was possible by using the horizontal test radial that is aligned with the center of the vertical beam (Figure 5). The RC aircraft was flown from fixed points (or distance stops) along the radial and at various altitudes out to a distance of 4 nautical miles (NM). The Merlin system can operate at ranges greater than 4 NM, but when operating at such ranges, radar data cannot be recorded and saved because the volume of information is too much for the system to process.

Flights were conducted at 7 distance stops, at roughly 0.5 NM increments along the test radial (see Figure 5) and at 5 altitude levels at each stop. A stop at 3.0 NM was not included as a flight location because I could not obtain permission from local landowners to conduct flights in that region. A stop at 1.5 NM was not included in the HSR analysis given that clutter was a significant problem at this location, but this was not a problem for the VSR. At each distance stop, the aircraft was flown in square patterns (about 800 x 800 ft) for approximately 2 minutes per leg at 200, 400, 600, 800, and 1000 feet above ground level, working upward in a step-like pattern through progressive altitudes. Once this procedure was complete, the aircraft was flown in a circling, “thermalling flight” pattern (diameter 150-200 ft) for approximately 1.5 - 2 minutes per leg from 1000 down to 200 feet above ground level at 200 ft. intervals. The aircraft was flown at a speed of around 20 mph, and always during fair weather with wind under 13 mph.

The ascending square flight patterns yielded perpendicular and radial passes and approximate straight line bird flight, whereas the thermalling flight pattern served to mimic the thermalling behavior of birds such as a raptors, and cranes, which present some of the more serious bird strike problems in aviation.

Each flight at a given altitude level/distance stop combination was taken as an independent estimate of radar performance. A goal of 20 RC aircraft flights was set for each distance/altitude combination, which allowed for a meaningful estimate of the Merlin tracking ability. Given that flight locations were in close proximity to the Terre Haute International Airport, airport police, air traffic control, the air national guard, and the life line helicopter service were each given notice well in advance of each flying session, and were notified after each session was complete. These general operating procedures were approved by Dennis Griffin, the FAA manager at the Terre Haute International Airport. RC aircraft flights were conducted between January, 2012 and May, 2012.

A. B.

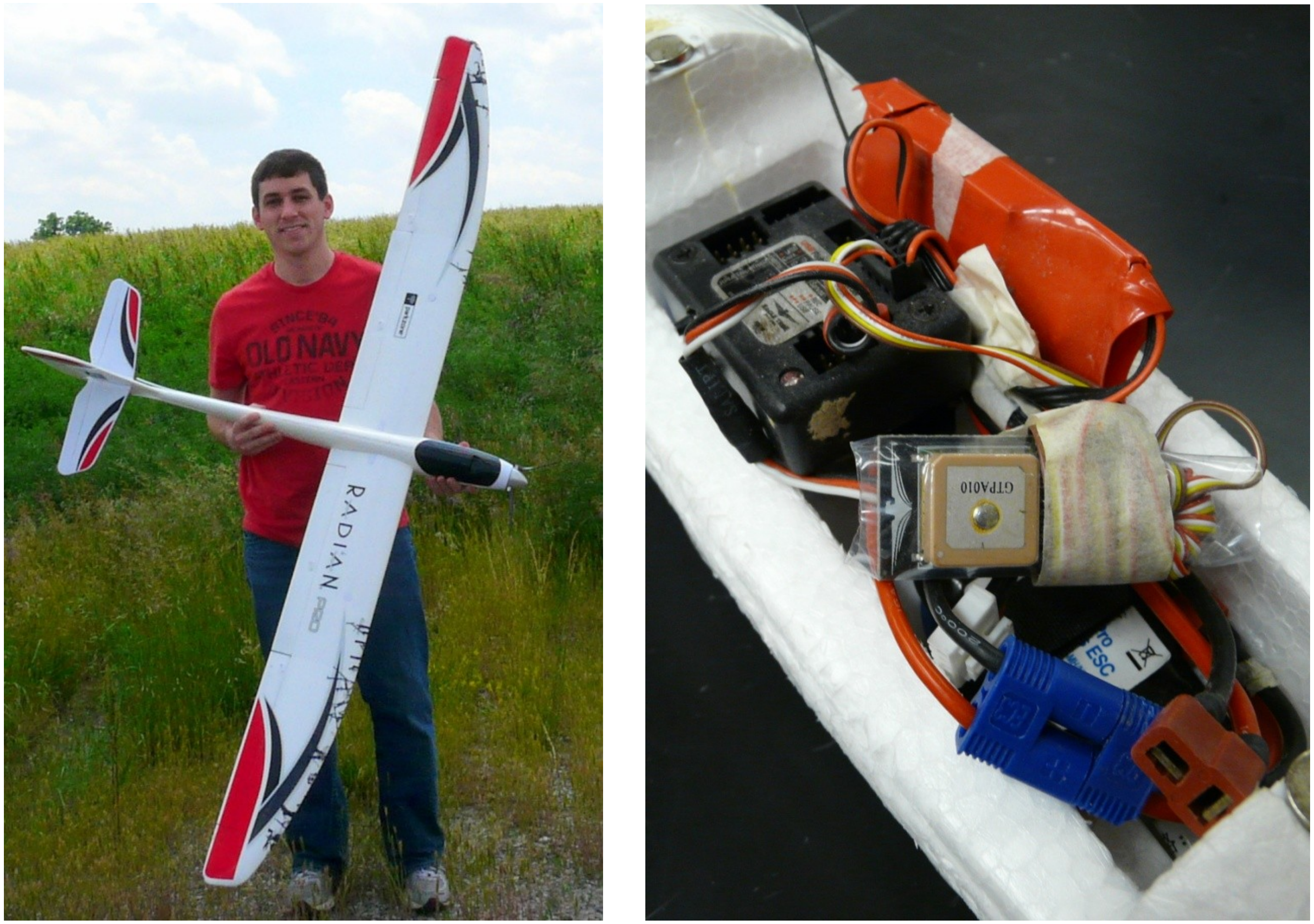


Figure 7. RC aircraft (A), Onboard GPS, recorder, and transmitter (B).

Radar Data Review

In the Merlin Software, a detection (or plot) occurs when, during a given scan, a radar echo is large enough to be recognized by the software as a legitimate bird-sized target. A track begins when enough detections (3 out of 4 consecutive scans) are generated to initiate a track. A track can include "misses" (non-detections or "coasted targets"). The software allows for up to 2 consecutive misses, which are included as part of the track (displayed on the computer screen as a different color). If missed for a third time in a row, the software terminates that track. The tracking software assigns each track a track ID (each of which can be found in an Access database), and so each detection or coasted target that is a part of a given track is labeled under the same track ID. Note that the tracking software underestimates track length (see Tracking Software Algorithm section below): a consistently tracked target may yield numerous track IDs, reflecting the inability of the tracking software to handle thermalling/circling behavior or sudden sharp movements. For purposes of this evaluation, if a target was tracked for multiple consecutive scans, but the radar broke the track up into different track IDs, I considered the series of tracks to be a single effective track.

As long as there was a software-detected target within reasonable distance (0.2 NM or 1200 ft) of the actual RC aircraft location, the former was considered to be the RC aircraft. This liberal criterion reflects a lat/long registration problem with the radar GPS, causing targets to be placed consistently a bit north of their actual location. I do not attribute this to an inherent problem with the radar unit, but rather to a set-up/optimization issue, one which was not resolved, despite repeat requests for technical assistance from DeTect technicians. Nonetheless, the shape of the tracks produced by the radar, target speed, and target altitude closely matched those produced by the aircraft's onboard GPS (although the estimates for coasted targets were much less accurate). Thus, there was rarely any question as to whether a tracked target was the RC aircraft. Unlike other potential aerial targets, the RC aircraft was the only target in that area moving in square-flight patterns, and generally the only target present in that area. When the RC aircraft was flown in a thermalling-flight pattern, it was essentially indistinguishable from a thermalling raptor. If a thermalling raptor approached the flight location and lingered long enough to cause confusion as to which target was which, the flight was excluded from the analysis.

The Merlin Software allows users to select a minimum target size value (number of pixels in radar raster image) which is used by the software algorithms to determine what constitutes a legitimate bird-sized target. The ability to alter minimum target size is very important when collecting data at different ranges. Within 2 NM of the radar unit, a minimum target size of 3 pixels (for the HSR) was selected for this study, meaning that a target must occupy at least 3 pixels in order to be tracked and displayed on the radar computer screen. A more sensitive minimum target size value of 2 pixels was selected for targets observed beyond 2 NM (for the HSR). This more sensitive setting was necessary because at greater range, a setting of 3 pixels would result in few tracked targets. A minimum target size of 2 pixels could not be used within 2 NM given that such a setting results in a considerable number of false tracks produced by ground clutter and small (non-aircraft) targets, making it nearly impossible to distinguish false tracks from the RC aircraft. Both of these standard settings were more sensitive than typically suggested by DeTect (pers. comm. Tim West of DeTect Inc.). A minimum target size of 2 pixels was used across all ranges for the VSR because clutter was not as much of an issue for the VSR.

Measures of Tracking Performance

To determine how well the RC aircraft was tracked by the radar system, several measures of tracking performance were considered. First, for each distance/altitude combination, I calculated the percentage of flights (out of the total number of flights) during which the aircraft was tracked at least one time (i.e. detected during at least 3 out of 4 consecutive scans). In other words, the number of flights during which an aircraft-associated green target appeared on the radar display at least one time.

Second, the average percentage of time that the RC aircraft was tracked was also calculated for each distance/altitude combination as the amount of time that the radar tracked the RC aircraft at a given distance/altitude combination out of the total time that the aircraft was flown at that combination. The amount of time tracked while at each distance/altitude combination includes those instances in which an aircraft-associated green tracked target or yellow target (indicated a coasted scan), was displayed on the screen. As mentioned earlier, coasted scans (non-detections) occur when the radar failed to detect the tracked target during a scan. The radar uses information from previous scans to “guess” where the target should be during that particular missed scan, yielding a yellow (coasted) target. The software allows for up to 2 misses, which I included as time tracked. The time tracked began once enough detections had occurred to generate a track, so the detections required to initiate the track were not counted toward time tracked.

The third measure of tracking performance was average track length, calculated for each distance/altitude combination. Track length is defined as the number of scans that make up an RC aircraft track (as defined earlier). At each distance/altitude combination, the RC aircraft was often tracked multiple (short) times, resulting in multiple tracks of various lengths. Average track length is thus defined as the average number of consecutive scans that the RC aircraft was tracked while at a particular distance/altitude combination. Recall that the radar tracking software underestimates track length, often breaking up a single effective track into several tracks. Average track length was calculated using the effective track length as defined earlier. Mean values and standard errors for average track length are provided below.

Patterns in the percentage of flights detected at least once were analyzed using a generalized linear model (binomial with link = logit) in the statistical package R. The dependent variable was whether or not a flight was tracked, and the independent variables were altitude, distance, and $distance^2$; the $distance^2$ term was used given apparent non-monotonic relationships between distance and this basic measure of detectability. Patterns in the percent time tracked as a function of altitude and distance were analyzed in one of two ways. A general additive model (GAM) in R (Wood 2006) was used to analyze the results of the RC aircraft flights and free-flying raptors, since the many missed targets (concentrated in only a subset of altitude/distance combinations) significantly violated the underlying assumptions of more familiar generalized linear models (GLM). The number of "knots" in the GAM splines (Wood 2006) was set at n-1 where n is the number of levels of altitude or distance under consideration. The GAM analysis results in Chi-squared statistics with non-integer degrees of freedom (limited by the number of spleen knots) as estimated via an iterative procedure. Statistical analyses are not provided for graphs that display only tracked flights given that these results differed little from analyzed graphs that consider both tracked and untracked flights.

RC Aircraft Flight Results and Discussion

Flight Characteristics

Table 1 provides the average length of time that the RC aircraft was flown at each altitude during the square-pattern ascending portion of each flight. On average the RC aircraft was flown for approximately 150 seconds, or about 60 radar scans, per altitude level (recall that the rotational speed of the antenna is 24 revolutions per minute). Average total possible track length indicates the typical number of scans during which the RC aircraft could potentially be tracked for each altitude level. On average, about 90-100 seconds, or about 38 scans, was spent per altitude level during the descending thermalling portion of each flight (Table 2).

Table 1. The average time (seconds and radar scans) spent flying at each altitude for the square pattern portion of a flight (2.5 sec/scan).

Altitude (ft)	Average Time (seconds)	Average total possible track length (scans)
200	136	54
400	142	57
600	160	64
800	166	66
1000	163	65

Table 2. The average time (seconds and radar scans) spent flying at each altitude for the thermalling pattern portion of each flight (2.5 sec/scan).

Altitude (ft)	Average Time (seconds)	Average total possible track length (scans)
200	114	46
400	100	40
600	99	40
800	94	37
1000	88	35

Tracking Performance of Horizontal Scanning Radar

Table 3 provides the percentage of square-pattern RC aircraft flights during which the RC aircraft was tracked at least one time by the horizontal scanning radar (HSR). This measure is given for each distance/altitude combination. The majority of flights resulted in at least one track, and at intermediate distances from the radar, nearly all flights were tracked at least once. A similar pattern was observed in thermalling-pattern flights, but such flight patterns yielded consistently fewer tracked flights than did square flight patterns (Table 4). In both Tables 3 and 4, the percentage of flights in which the aircraft was tracked at least one time peaked around 2.0 NM. There was indeed a significant effect of distance for both square flights (distance: $Z = 5.73$; $P < 0.0001$; distance^2: $Z = -6.47$; $P < 0.0001$) and thermalling flights (distance: $Z = 4.62$; $P < 0.0001$; distance^2: $Z = -4.82$; $P < 0.0001$). This measure of tracking performance varied non-significantly among altitudes for both square ($Z = -0.48$; $P = 0.630$) and thermalling flights ($Z = 1.01$; $P = 0.311$).

Figure 8 provides the average percentage of time that the RC aircraft was tracked during square-flight patterns as a function of both distance and altitude. This measure includes those flights during which the RC aircraft was not tracked at all. Overall, the average percentage of time tracked was well under 50%. The trends observed were broadly similar to those in Table 3. Distance was once again a significant factor ($\chi^2 = 508.3$; df = 4.85; $P < 0.0001$) The average percentage of time tracked tends to peak at about 2 NM. The effect of altitude was significant ($\chi^2 = 10.4$; df = 1; $P < 0.001$), with a tendency for tracking performance to decrease with increasing altitude. Including only those flights in which the RC aircraft was actually tracked (i.e. excluding flights during which the aircraft was never tracked) yielded a similar result (Figure 9).

Tracking performance improved (as expected), but the general trends are the same as in Figure 8. Even those flights that were detected were on average tracked under 50% of the time.

Table 3. The percentage of square pattern flights in which the RC aircraft was tracked at least one time by the HSR.

Distance (NM)	**200 ft**	**400 ft**	**600 ft**	**800 ft**	**1000 ft**	**No. of flights**
0.5	95	91	81	67	57	21
1.0	75	90	95	85	85	20
2.0	100	100	100	100	100	19
2.5	100	90	100	94	100	19
3.5	74	53	58	78	68	19
4.0	40	70	80	60	65	20

Table 4. The percentage of thermalling pattern flights in which the RC aircraft was tracked at least one time by the HSR.

Distance (NM)	**200 ft**	**400 ft**	**600 ft**	**800 ft**	**1000 ft**	**No. of flights**
0.5	76	67	57	48	43	21
1.0	47	53	47	47	29	17
2.0	75	88	75	100	94	16
2.5	67	87	67	87	73	15
3.5	35	53	35	65	71	17
4.0	19	56	69	44	63	16

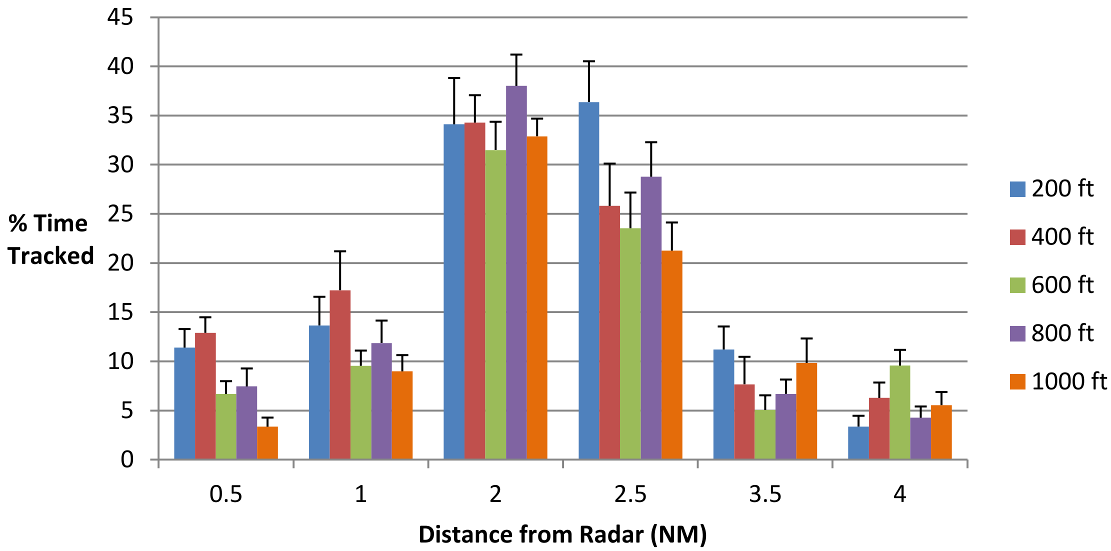


Figure 8. The average percentage of time that the RC aircraft was tracked by the HSR during square flight patterns as a function of distance and altitude. Data are included only for detected flights. Mean values and standard errors are plotted.

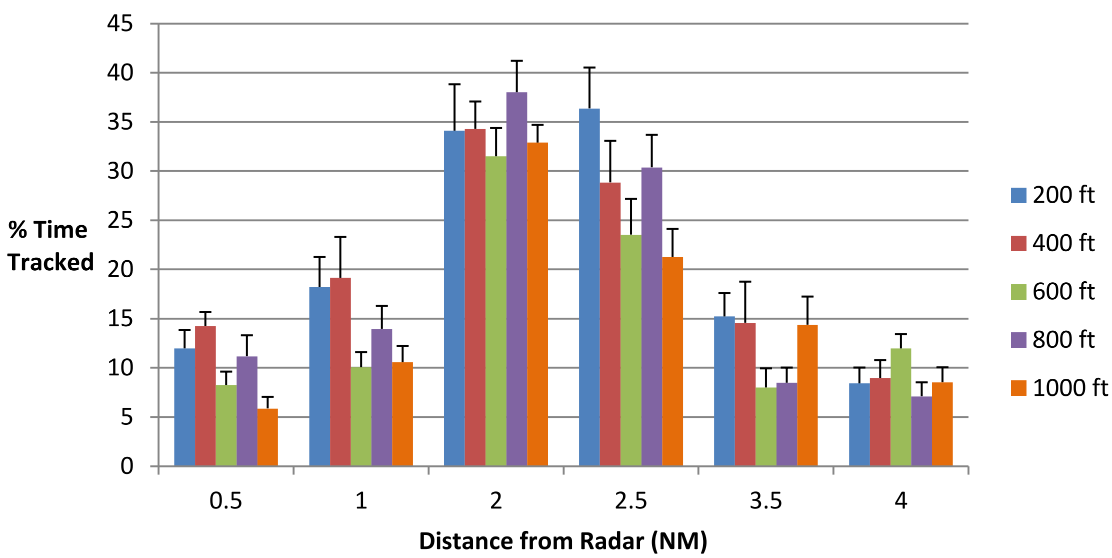


Figure 9. The average percentage of time that the RC aircraft was tracked by the HSR during square pattern flights as a function of distance and altitude, with untracked flights excluded. Mean values and standard errors are plotted.

Figure 10 shows the average percentage of time that the RC aircraft was tracked during thermalling flight patterns as a function of both distance and altitude. As before, the percentage of time tracked was well under 50%, with a peak at 2 NM. The average percentage of time that the RC aircraft was tracked during thermalling flight patterns (Figure 10) was consistently less than that for square flight patterns, and generally under 30%. This result suggests that the radar tracking software is less capable of tracking targets exhibiting circling patterns than those exhibiting straight flight patterns. Distance was a significant factor ($\chi^2 = 186.2$; df = 4.91; $P <$ 0.0001), but altitude was not ($\chi^2 = 1.1$; df = 1; $P = 0.297$). Figure 11 provides the same information as Figure 10 except that this measure excludes completely untracked flights. Even when discarding flights that went untracked, the average percentage of time tracked was usually well under 30%.

Figure 12 displays the average track length for square-pattern RC aircraft flights as a function of distance and altitude, while Figure 13 shows the same for thermalling-pattern flights. In both figures, only detected flights are included. Overall, average track lengths were generally short at under five scans (or about 12.5 seconds). Note that much of the short tracks actually ended with two "coasted scans" during which the aircraft was not actually detected. The average track lengths were consistently longer for square-pattern flights (compare Figures 12 and 13), suggesting again that the tracking software has more difficulty tracking birds that are circling than those on a straighter trajectory. The average track length for square pattern flights (Figure 12) peaked around 2 NM, corresponding to the pattern in the Table 3 and Figures 8 and 9 above. The effect of distance was statistically significant for square flights (F = 15.73; df = 5, 451; $P <$ 0.0001) and thermalling flights (F = 2.52; df = 5.279; P= 0.030). No such 2 NM peak was apparent in the thermalling-pattern flights (Figure 13). There was no obviously consistent effect of altitude for square flight patterns (Figure 12; F = 0.53; df = 4, 451; *P* = 0.716) and thermalling flights (Figure 13; F = 0.77; df = 4, 279; *P* = 0.547).

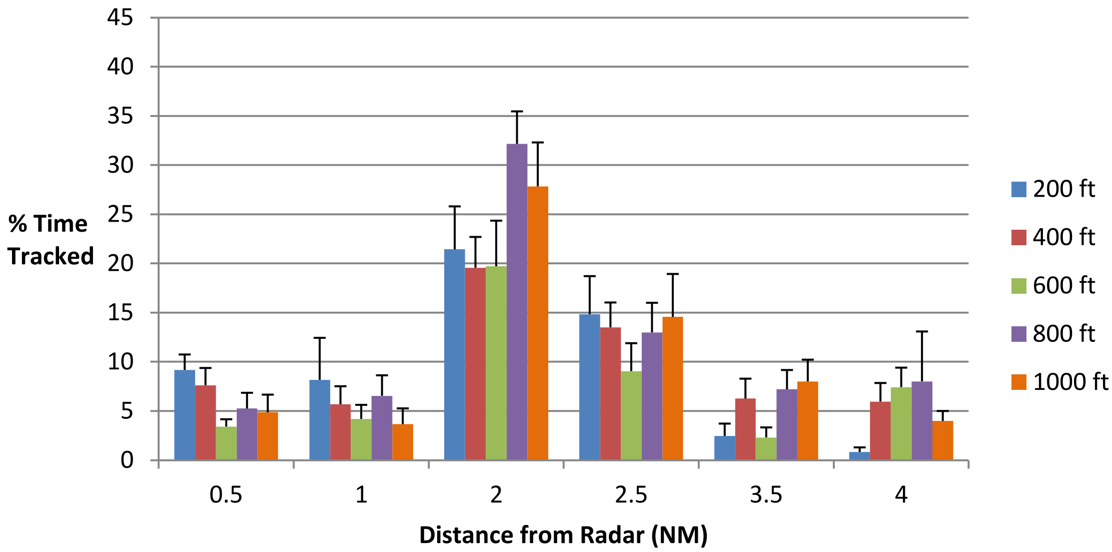


Figure 10. The average percentage of time that the RC aircraft was tracked by the HSR during thermalling pattern flights as a function of distance and altitude. Data are included only for detected flights. Mean values and standard errors are plotted.

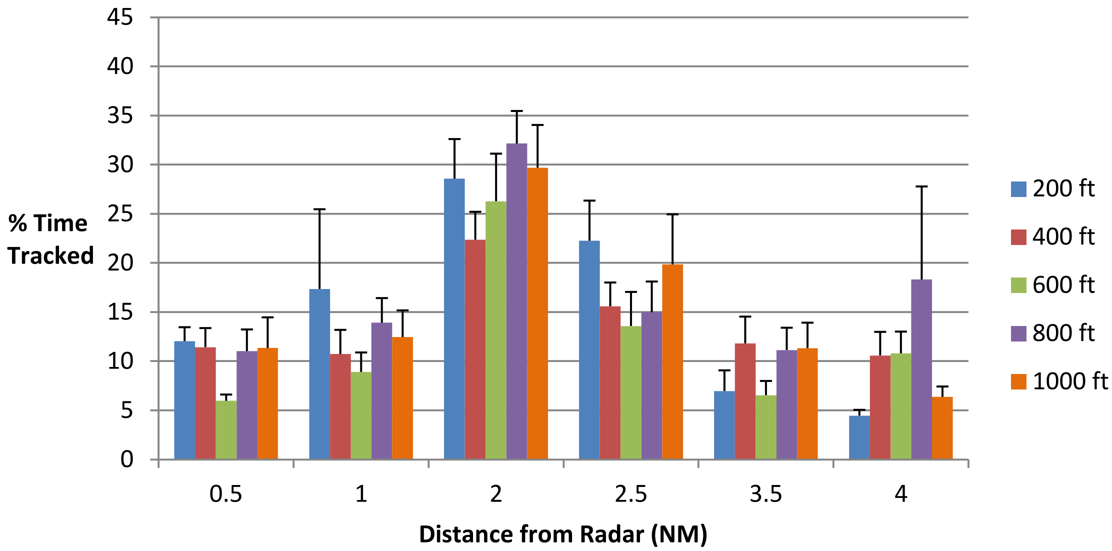


Figure 11. The average percentage of time that the RC aircraft was tracked by the HSR during thermalling pattern flights as a function of distance and altitude, with untracked flights excluded. Mean values and standard errors are plotted.

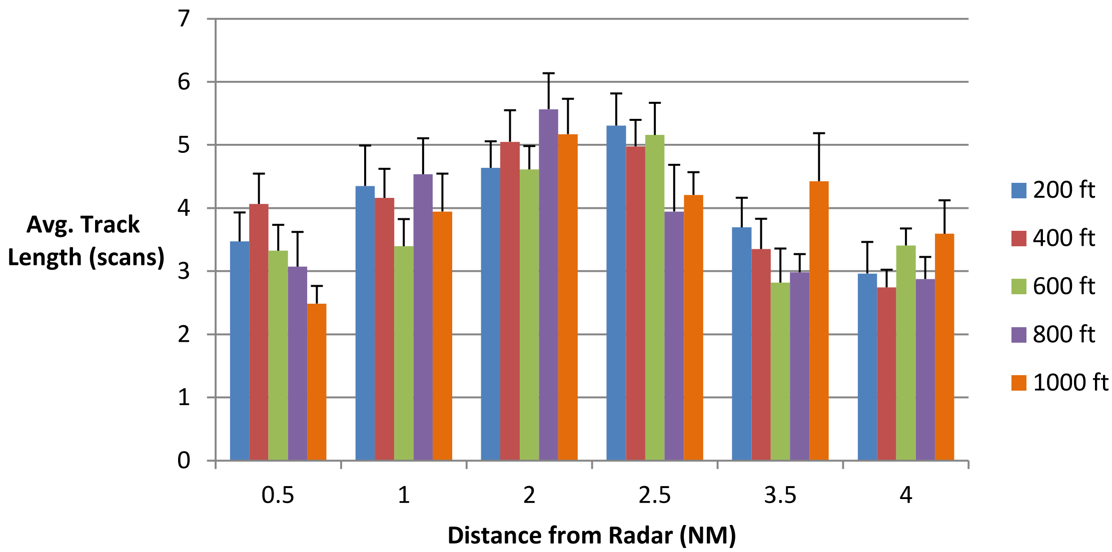


Figure 12. The average track length (# of radar scans) for square pattern flights as a function of distance and altitude (HSR). Data are included only for detected flights. Mean values and standard errors are plotted.

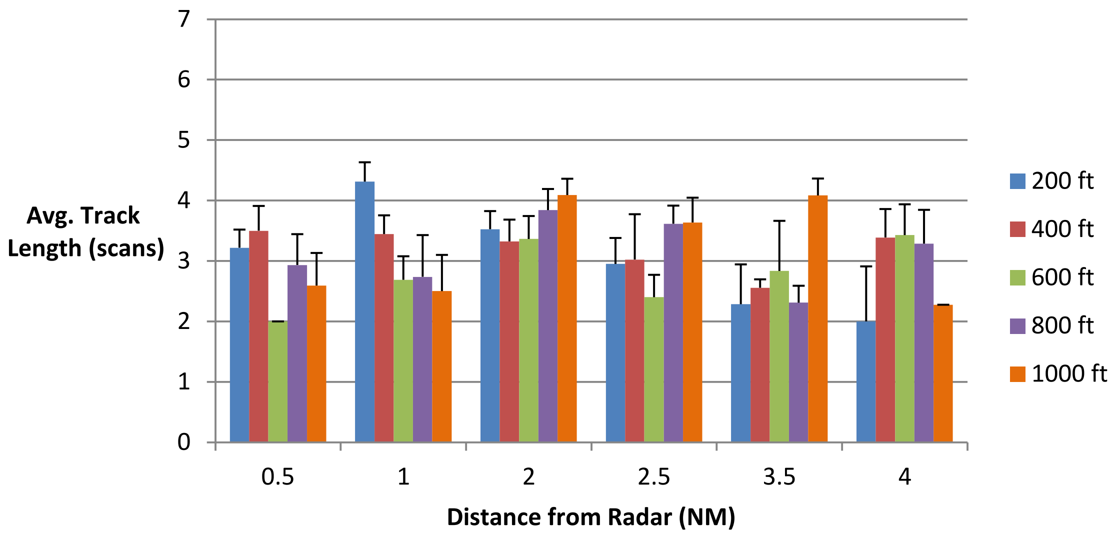


Figure 13. The average track length (# of radar scans) for thermalling pattern flights as a function of distance and altitude (HSR). Data are included only for detected flights. Mean values and standard error bars are plotted.

Overall, there was a consistent peak in tracking performance between 2.0 and 2.5 NM. Beyond 2.5 NM, tracking performance decreases considerably with increasing distance. The fact that tracking performance peaks at this intermediate distance, rather than close to the radar, could be due in part to the fact that more sensitive target filter settings were used beyond 2 NM. Recall that a target filter setting of 3 was used within 2 NM and a setting of 2 (more sensitive) was used beyond 2 NM for reasons stated above. However, even when using a setting of 3 at greater range (2 - 4 NM), tracking performance was still much higher at 2.0 – 2.5 NM than it was closer to the radar unit (results not shown). This suggests that something other than the target filter setting is influencing the intermediate peak in tracking performance.

The increase in tracking performance at intermediate distances may be due in part to a stand of trees between 1.2 and 1.8 NM and the shallow radar shadow that it casts beyond 1.8 NM. Radar shadows eliminate ground clutter, allowing for increased detection of bird targets that are above the beam blockage created by the trees (Beason et al. 2013). The area in which tracking performance is greatest (2.0-2.5 NM) is precisely where the radar shadow begins. Another possible explanation is that ground clutter is often more intense closer to the radar unit, especially for array antennas (Beason et al.2013), and could mask bird targets, potentially resulting in fewer birds detected and lower tracking performance.

Surprisingly, there was often no clear effect of altitude on tracking performance, except where tracking performance tended to decrease with increasing altitude (e.g. Figure 8). Flights conducted at the closest flight location were well below the "cone of silence" (see Figure 3B), thus eliminating such an explanation for the lowered tracking performance with increasing altitude. In fact, these flights should be near the middle of the beam.

The Merlin's HSR is said to have the capability of detecting and tracking bird targets out to a distance of 6 - 8 NM away from the radar unit (DeTect Inc. website 2013). Given that the RC aircraft is similar in radar appearance to a large raptor, the tables presented above demonstrate that a large bird target is indeed capable of being tracked at distances out to 4 NM. However, the frequency with which such targets are tracked and the amount of time that they are tracked is low, particularly for targets exhibiting thermalling flight patterns. Note, however that my data extend only to 1000 feet above ground level, which is perhaps not an important altitude well away from an airport. A more serious problem is that the average track length for thermalling flight patterns was between 2 and 4 scans. So, essentially, a large thermalling raptor track would end soon after it began. Thus, the radar operator would only see a single green circle representing a detection followed by one or two yellow circles representing coasted scans (misses/radar guesses). Given that the radar detects and tracks many targets at once, a radar operator could miss such targets, given their brief appearance on the radar screen.

Tracking Performance of Vertical Scanning Radar

Table 5 shows the percentage of square-pattern RC aircraft flights during which the RC aircraft was tracked at least one time by the vertical scanning radar (VSR). The results were similar to the results from the HSR, except that for the VSR, the tracking performance declines more precipitously with distance. Nearly 100% of flights were tracked at least one time at 1 NM, but very few were tracked at least once at 2.5 NM or farther away. The percent of flights in which the aircraft was tracked at least one time was uniformly lower for thermalling-pattern flights than it was for square-pattern flights (Table 6). Distance was a significant factor for both square (distance: Z = 2.108; $P = 0.035$; distance^2: Z = -4.52; $P < 0.0001$) and thermalling flights (distance: Z = 3.45; $P = 0.0005$; distance^2: Z = -4.65; $P < 0.0001$). Altitude was a significant factor for both square flights (Z = 2.34; P = 0.019) and thermalling flights (Z = 6.36; $P < 0.0001$), with tracking performance generally increasing with increasing altitude (Table 5 and 6).

Figure 14 provides the average percentage of time that the RC aircraft was tracked by the VSR during square flight patterns as a function of both distance and altitude, including those flights during which the RC aircraft was untracked. The VSR out-performed the HSR at the 1 NM flight location (compare to Figure 8), but overall HSR detection and tracking performance was much higher than it was for the VSR, particularly at greater distances (1.5 NM or farther away) from the radar. In fact, beyond 2.5 NM, only a few of flights were detected by the VSR. Distance was indeed a significant factor ($\chi^2 = 890.9$; df = 5.98; $P < 0.0001$) as was altitude ($\chi^2 = 63.6$; df = 2.81; $P < 0.0001$) Overall, tracking performance was generally best between 400 and 800 feet at 1 NM. Figure 15 provides the same information, but with untracked flights excluded. Excluding untracked flights made little difference in the percentage of time tracked, indicating that detected flights were also not well tracked.

Table 5. The percentage of square pattern flights in which the RC aircraft was tracked at least one time by the VSR.

Distance (NM)	200 ft	400 ft	600 ft	800 ft	1000 ft	No. of flights
0.5	57	52	86	52	76	21
1.0	65	100	100	100	100	20
1.5	19	86	91	81	62	21
2.0	79	32	58	68	63	19
2.5	0	5	26	11	16	19
3.5	16	5	0	0	0	19
4.0	10	0	0	0	0	20

Table 6. The percentage of thermalling flights in which the RC aircraft was tracked at least one time by the VSR.

Distance (NM)	200 ft	400 ft	600 ft	800 ft	1000 ft	No. of flights
0.5	5	24	62	57	62	21
1.0	6	88	100	100	82	17
1.5	29	7	36	79	86	14
2.0	19	19	13	31	38	16
2.5	7	7	7	0	0	15
3.5	6	0	6	0	0	17
4.0	0	0	0	0	0	16

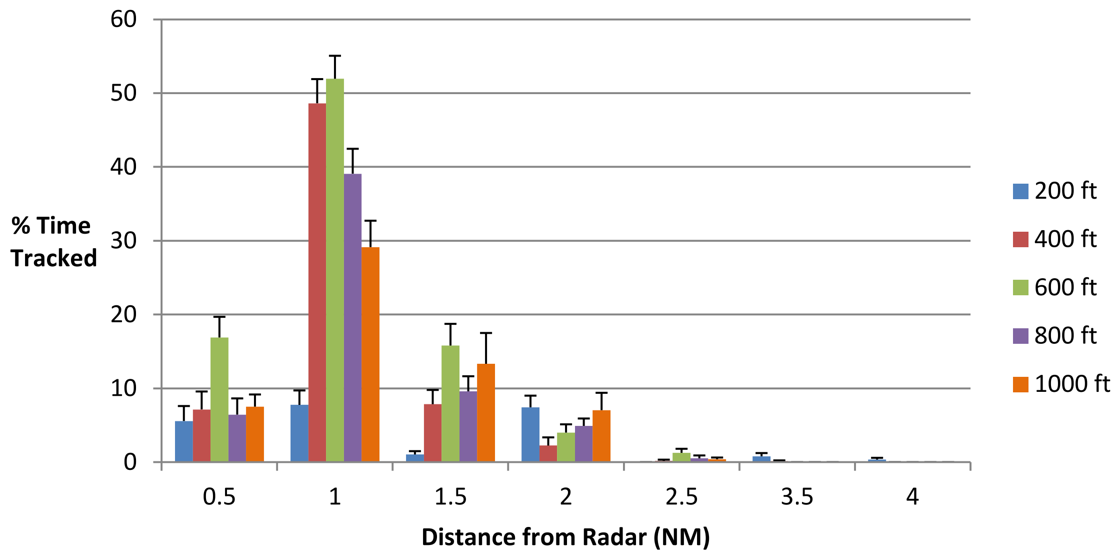


Figure 14. The average percentage of time that the RC aircraft was tracked by the VSR during square pattern flights as a function of distance and altitude. Mean values and standard errors are plotted.

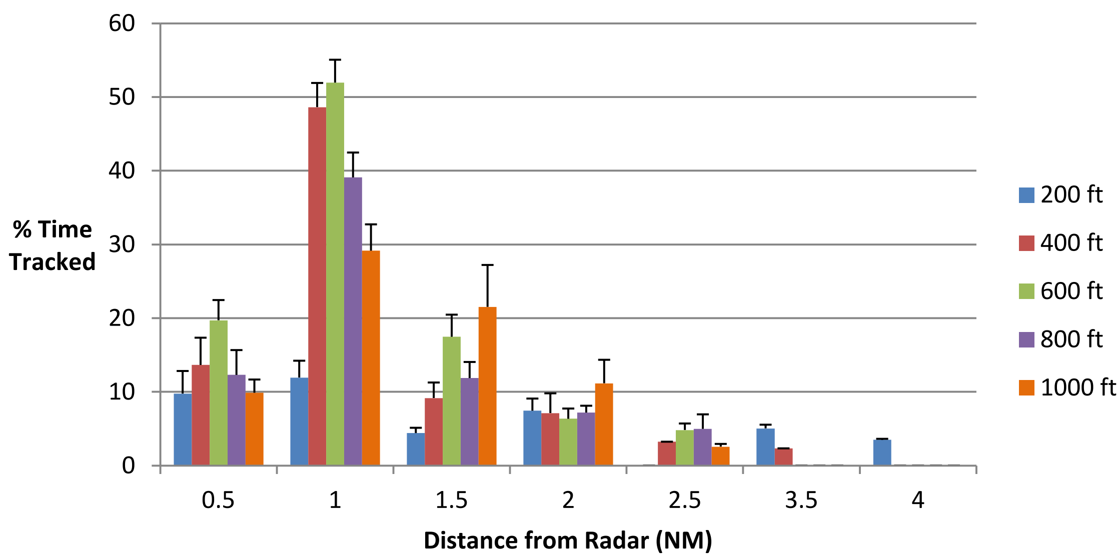


Figure 15. The average percentage of time that the RC aircraft was tracked by the VSR during square pattern flights as a function of distance and altitude, with untracked flights excluded. Mean values and standard errors are plotted.

Figure 16 provides the average percentage of time that the RC aircraft was tracked by the VSR during thermalling-pattern flights as a function of distance and altitude. Tracking performance for thermal-pattern flights also drops off substantially beyond 1 NM. Both distance (χ^2 = 347.9; df = 4.98; P < 0.0001) and altitude (χ^2 = 32.7; df = 2.54; P < 0.0001) were significant factors. Similar to the HSR results, tracking performance for the VSR was lower during thermalling-pattern flights than during square-pattern flights. Excluding untracked flights improved the percentage of time tracked, but distant flights were still poorly tracked (Figure 17).

Figure 18 shows the average track length for square-pattern RC aircraft flights as a function of distance and altitude, while Figure 19 shows the same for thermalling flight patterns. Average track length varied significantly with distance from the radar, and was generally lower for thermalling-pattern flights. Distance had a significant effect on track length for both square (F = 23.38; df = 6, 281; P < 0.0001) and thermalling flights (F = 2.93; df = 5, 140; P = 0.015). Altitude was not a significant factor for square (F = 2.14; df = 4, 281; P = 0.076) or thermalling flights (F = 2.12; df = 4, 140; P = 0.082). Within 1 NM of the radar unit, the VSR outperformed the HSR in track length (compare Figures 12 and 18). In fact, average track length was near 10 scans in some cases for the VSR (Figure 18). However, beyond 1 NM, average track length was higher for the HSR.

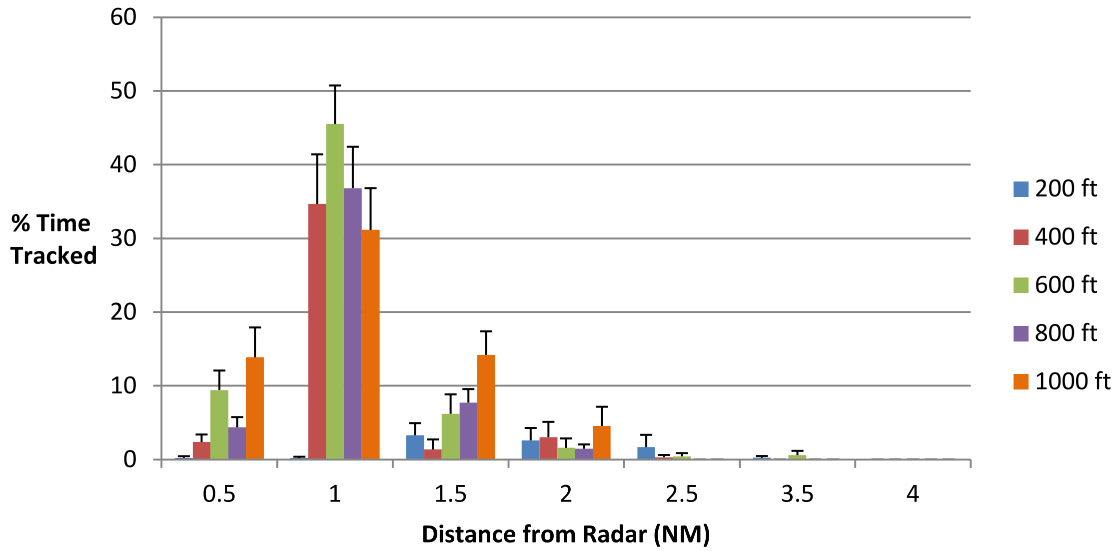


Figure 16. The average percentage of time that the RC aircraft was tracked by the VSR during thermalling flight patterns as a function of distance and altitude. Mean values and standard errors are plotted.

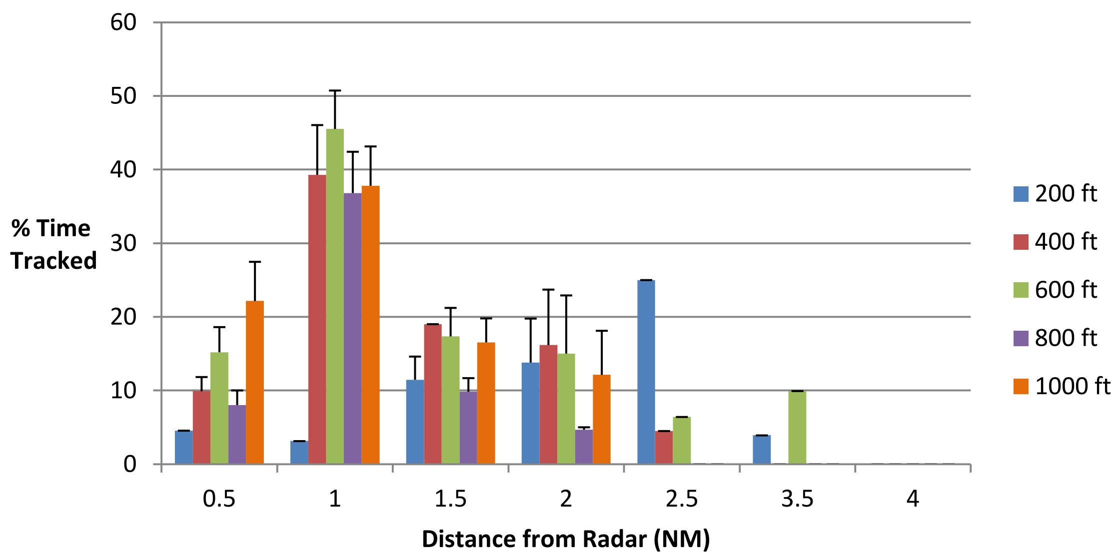


Figure 17. The average percentage of time that the RC aircraft was tracked by the VSR during thermalling flight patterns as a function of distance and altitude, with untracked flights excluded. Mean values and standard errors are plotted.

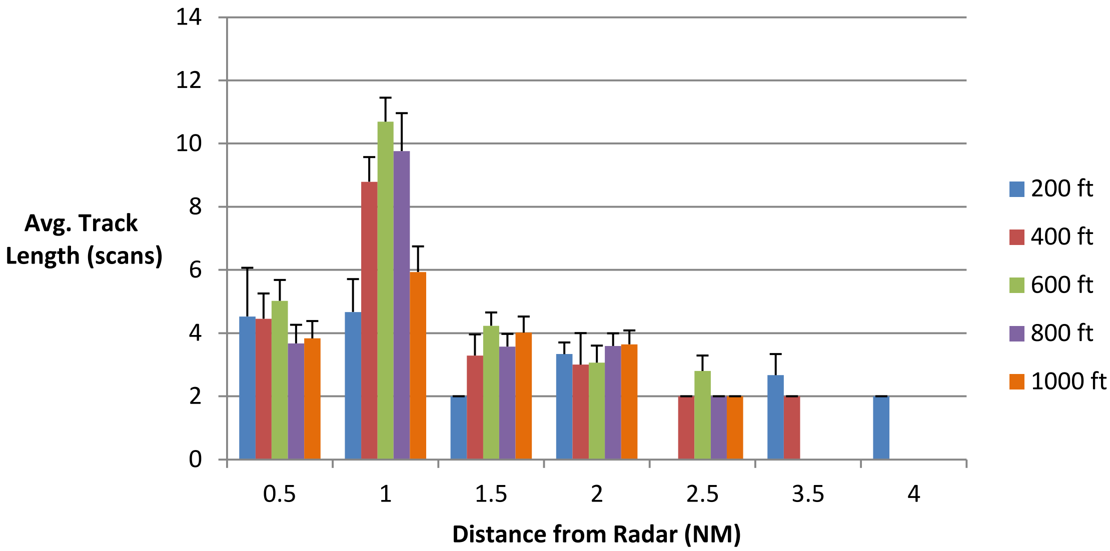


Figure 18. The average track length (# of radar scans) for square pattern flights as a function of distance and altitude (VSR). Data are provided only for detected flights. Mean values and standard errors are plotted.

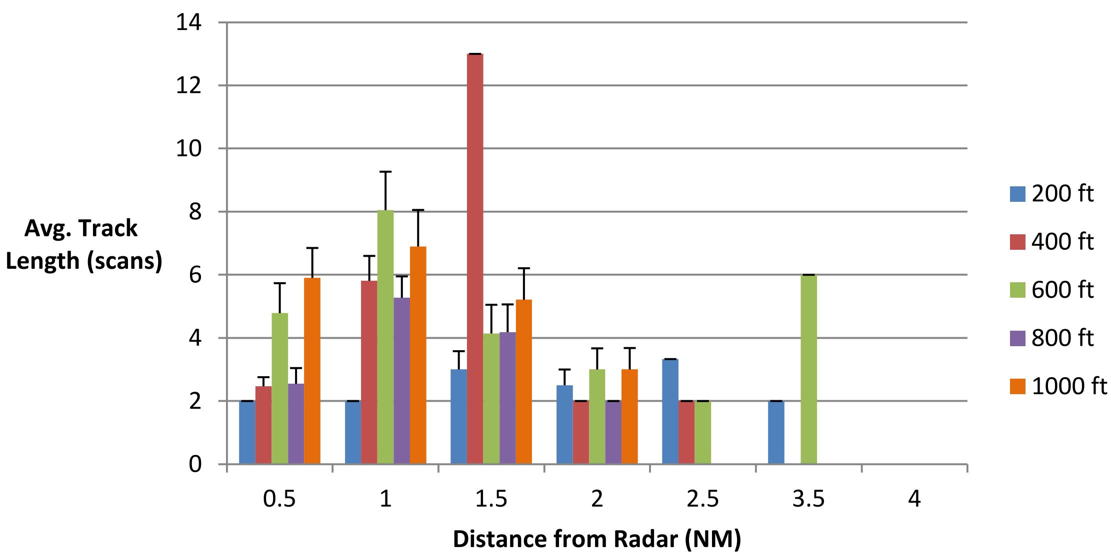


Figure 19. The average track length (# of radar scans) for thermalling pattern flights as a function of distance and altitude (VSR). Data are included only for detected flights. Bars with no errors represent single values. Mean values and standard errors are plotted.

Overall, in the VSR results above, there is a peak in tracking performance at 1.0 NM, after which tracking performance decreased markedly with increasing distance out to 4 NM. There was also a trend for greater tracking performance at higher altitudes. Average track lengths were greatest at the 1.0 NM flight location; average track lengths were much higher than those for the HSR at that distance.

The Merlin's VSR is said to have the capability of detecting and tracking bird targets out to a distance of 3 - 4 NM away from the radar unit (DeTect Inc. website 2013). These results demonstrated that a large bird target flying at or under 1000 feet can indeed be tracked at distances of 3 - 4 NM from the radar unit, but the frequency with which such targets are tracked and the amount of time that they are tracked is low, especially at distances beyond 2.0 NM.

TRACKING PERFORMANCE WITH FREE FLYING BIRDS

Transits of free-flying birds provided the opportunity to test directly how well the Merlin system can track single birds and flocks. DeTect Inc. states that the HSR is capable of detecting birds at distances of 4 - 8 NM and at altitudes of 15,000+ feet, whereas the VSR is capable of bird detection out to 3 - 4 NM and at altitudes of 10,000+ feet (DeTect Inc. website 2013). However, as mentioned earlier, few studies have collected ground-truthed bird observations to assess the performance of avian radars. Here I assess not only whether an avian target can be detected by radar, but more importantly (i) the frequency with which such targets are detected at a given range/altitude, and if detected (ii) how well and for how long they are typically tracked.

As mentioned earlier, the only major avian radar evaluation project reported to date is the IVAR project (Brand et al. 2011), in which a significant number of ground-truth bird target observations were made. During the IVAR project, radar technicians looked for targets on the radar display that appeared to be bird targets, and if a well tracked target was located on the radar display, the radar technicians would inform field observers of the target location. The field observers would then confirm whether or not a bird target was present in that location. In this way, they were able to determine whether the targets being tracked by radar were, in fact, birds. Between 2007 and 2008, 2,632 such targets were identified by radar technicians at military bases in North Carolina, Maryland, Washington, and Alaska. Of these 2,632 targets, 1531 were confirmed to be birds by the field observers. The other 944 targets were either (i) not confirmed because apparently no bird was present, (ii) aborted/called off by the radar technician because the target disappeared from the radar display before the field observer had the chance to locate the target, or (iii) not confirmed because the field observer failed to receive the radar technician's notice. The IVAR report did not specify the number of observations attributed to each of these three categories. Of the 1531 confirmed targets representing 65 bird species, 841 were single targets and 702 were flocks.

On limited occasions, field observers identified targets for radar technicians to confirm, but there were only 30 such observations mentioned in the IVAR report. The limited number of observations was primarily due to the fact that much of the evaluation work was done with a dish antenna. A dish antenna samples a relatively narrow range of altitudes, making it difficult for field observers to determine whether a bird was within the radar beam. However, Beason et al. (2010) demonstrate that one can objectively determine whether a target is within the beam by using birds equipped with global positioning system-platform transmitter terminal (GPS-PTT) transmitters.

Methods

Avian Ground-truthing Protocol

I acted as the field observer, calling out bird targets to the radar technician, who would then confirm whether or not a bird target was being tracked (at that specified location) by the radar (i.e. displayed on the radar computer screen). Given that the Merlin system uses an array antenna, 360 degree coverage is provided by the HSR from near ground level to 15,000+ feet, so there was never a question as to whether a bird target was within the beam or not, except for instances in which a high-flying target was likely within the "cone of silence" close to the radar unit (see Figure 3). For this reason, we excluded targets that may have been within or close to the cone of silence.

The field observer provided the radar technicians, who were recording notes, with updates every few seconds on the location of the bird target(s). After each session, the recorded tracking data and notes were reviewed in detail to both ensure accuracy, and to determine the tracking performance for each observed target as per the criteria established in the RC aircraft portion of the study. This method allowed me to determine (i) the number of instances in which a bird target was present, but was missed by the radar software, and therefore (ii) the likelihood with which an avian target was tracked at least one time as a function distance, altitude, and flock size, (iii) the percentage of time that such targets were tracked over the time which a given bird target was visible to the field observer and (iv) the average track length for such targets as a function of distance, altitude, and flock size. This approach thus addresses errors of omission, or instances in which known birds were not tracked by the Merlin System. Errors of commission (tracking of false targets) could not be assessed because potential targets indentified by radar can be easily missed by field observers. However, although we did not specifically assess errors of commission, numerous false tracks (mainly generated by clutter) occurred on a daily basis, reflecting the sensitivity settings used in this evaluation.

For ease of distance estimation (from the radar unit) for each bird target, the study site in the area of Swalls Drive (Figure 5) to the east of the Terre Haute International Airport was divided into various sections defined by forest edges, fence rows, roads, and lakes, etc. For each bird or bird flock, the location of the target within a given section was noted and updated every 5-30 seconds (depending on how quickly the target was moving through the study site) for as long as the target was visible. Using the location of a bird target within a section, its approximate distance from the radar could be determined using the measuring tool in Google Earth. An associated estimate of a target altitude was recorded, placing each target within broad altitude classes (> 500 feet or < 500 feet). The field observer did not include targets that appeared to be near tree-top level, thus excluding targets likely to be missed by the radar due to beam blockage from trees. When bird targets were tracked by the radar, the estimates of altitude made by the field observer were usually close to the estimates provided by the radar (VSR altitude estimates were also found to be very consistent with target altitudes provided by the GPS onboard the RC aircraft).

Notes on species and general behavior (flight direction, thermalling, etc.) were also recorded for each observed target. If the birds were flying in a group, then the number of individuals and an estimate of inter-bird spacing (dense or loose flock) was recorded. Dense flocks were considered those in which inter-bird spacing was less than 5 body lengths, whereas loose flocks had an inter-bird spacing greater than 5 body lengths. Given that nearly all flocks observed were dense, only dense flocks were considered in the analysis. Flocks that were less than about 1200 feet apart were also excluded from the analysis in order to avoid the possibility of the radar detecting two separate flocks as one target. All remaining observations were pooled into distance and altitude categories as required to obtain reasonable sample sizes. Most of the observations were from low clutter environments.

All bird observations were conducted on fair and relatively calm days. During very windy conditions, few birds were in the air, and very few were at altitudes high enough to be detected by radar. This study covered the period between October, 2011, and March, 2012, and thus focused on species wintering in western Indiana.

Study Species

The focus of this work was on larger wintering birds, including raptors and large flocking waterbirds. Eleven raptor species were observed during the course of the project, with turkey vultures (*Cathartes aura*) and red-tailed hawks (*Buteo jamaicensis*) ranking as the most frequently observed species. These two species were thus selected to represent "large thermalling raptors." Red-tailed hawk and turkey vulture strikes alone account for 93.4% of civilian aircraft downtime due to raptor strikes (Cleary et al 2004; Blackwell and Wright 2006). Red-tailed hawks and vultures also account for 64% of all damaging raptor strikes to US Air Force aircraft (Kelly 1999; Blackwell and Wright 2006).

Twenty-two large, flocking waterbird species were observed during the study, but only those yielding sufficient sample sizes were selected to be included in the study. These included sandhill cranes (*Grus canadensis*), Canada geese (*Branta canadensis*), and ducks (mainly mallards - *Anas platyrhynchos*, ring-necked ducks – *Aythya collaris*, and gadwalls – *Anas strepera*). These flocking bird species are hazardous to aircraft not only because of their large in size, but also because they fly in flocks, thereby increasing the likelihood of multiple strikes to aircraft (Dolbeer and Seubert 2006; DeVault et al. 2011). Waterfowl are also one of the most frequently struck group of birds, responsible for the most strikes involving damage and the most strikes resulting in human injuries and fatalities (Dolbeer 2006). Therefore, the species included in this analysis are among the most hazardous species to aircraft (DeVault et al. 2011).

Turkey vultures and red-tailed hawks observed during the study generally exhibited thermalling flight behavior. Therefore, only those observations where thermalling behavior was exhibited are included in this part of my study. Observations of sandhill crane flocks included in the analysis represent their typical flight pattern in which cranes alternate between straight flight patterns and circling or doubling back to gain altitude. The Canada geese and ducks observed during the study were those traveling between roost lakes and agricultural fields, characteristic of the hazardous bird activity posed by such species. Thus, goose and duck flocks were those following relatively straight or widely circling trajectories.

Analysis Protocol for Bird Data

The majority of the bird data analysis focuses on data collected by the horizontal scanning radar. Although some of the observed bird targets were aligned with the center of the vertical beam (allowing both the vertical and horizontal beams to be evaluated), most fell outside the reach of the vertical scanning radar, particularly within 1 NM of the radar, where the vertical beam is relatively narrow. Measures of tracking frequency, tracking performance, and track length were determined as per the corresponding RC aircraft work (although the aircraft data were more precise). As before, only bird target observations within 4 NM of the radar unit are considered in the analysis.

From time to time, light to moderate wind created clutter over a section of trees between 1.1 and 1.8 NM, so this area was avoided when conducting bird observations during such occasions. Also excluded were any cases in which clutter happened to be a significant issue where a bird target was present. Observations during rain or snowfall were not included due to confusion from tracks associated with precipitation-induced clutter (see below). Few birds were in the air during precipitation events.

Only targets (single targets or flocks) well separated (>1200 feet) from any other targets were included in this study, to avoid mistaking one target for another when multiple bird targets were present. Flocks were defined as two or more birds that were similarly well separated from any other bird targets within the study site. Occasionally, during some radar scans, larger flocks may be tracked as more than one target. As long as at least one target (representing a given flock) was shown on the radar display (at that location) during a given scan, it was counted toward the amount of time that the flock was tracked.

A frame-by-frame analysis of the radar recordings was conducted in analyzing the observed bird tracks. Merlin Radar data can be played back in real-time, but the Merlin System had no pause or rewind options. I thus used a software program called “Debut Video Capture Software“ by NCH Software to record the radar tracking display when playing back radar data, allowing for tracking data to be carefully reviewed frame-by-frame. Playing the data through the Merlin software program also results in an Access Database for each radar recording. This database includes every track that is recorded and provides a number of variables for each detection or coasted scan included in a given track.

The unit of measure is an individual bird observation, which is defined as the length of time that a single bird target or flock was visible to the observer. A detection and track are defined as per the corresponding RC aircraft work mentioned above. Measures of tracking performance were also defined similarly to the work on the RC aircraft. These measures include (i) the percentage of bird observations where a target was tracked at least one time, (ii) the percentage of time that a bird target was tracked out the total time that it was visible to the field observer, and (iii) the average track length for each bird target. Each measure is provided as a function of distance and altitude (above or below 500 feet) for single bird targets and as a function of distance and flock size for flocks. Data for flocks is not presented as a function of altitude given that duck and goose flocks were almost always between 200 and 400 feet whereas cranes were nearly always above 500 ft (usually about 1000 feet). For single bird targets, observations were pooled in 1 NM increments out to 4 NM. For flocks, distance from the radar unit is divided into near (<2 NM) or far (>2 NM) categories and flock size categories, were either small (2 - 10 individuals), medium (11 - 29 individuals), or large (30+ individuals).

Patterns in the percentage of flights detected at least once were analyzed using a generalized linear model (binomial with link = logit) in the statistical package R. For single raptors as the targets, as with the RC flights, the dependent variable was whether or not a target was tracked, and the independent variables were altitude, distance, and distance^2. For flocking birds, the independent variables were flock size and distance, since flocks were usually at a characteristic altitude; distance included only two levels, hence distance^2 was not included as a variable.

Patterns in the percent time that raptors were tracked as a function of altitude and distance were analyzed using a general additive model (GAM) as per the RC data, with the exception that the spline function was applied only to the distance variable; the use of only two levels for the altitude variable precluded the use of a spline function. As such, the results for altitude are expressed via a t-test. The percent time that flocks were tracked was analyzed as a function of flock size and distance (both fixed factors) using a generalized linear model (GLM) rather than a GAM, which reflects (in part) the fact that few flock targets were missed (relative to the situation with the RC aircraft flights or solitary raptors). The small number of flock size and distance categories used for pooling flock data also preclude the efficient use of GAM models (Wood 2006).

Results and Discussion - Horizontal Scanning Radar

Single Targets

Turkey Vultures

A total of 190 turkey vulture observations was included in the radar evaluation. Of the 190 vultures observed, 96 were tracked by the radar at least one time. Within 2 NM, about 75 - 95% of turkey vultures were tracked at least one time (Table 7). The percentage of vultures tracked at least one time beyond 2 NM was quite low, at 10 - 40%. The qualitative relationship between distance and the percentage of vultures tracked matched that observed in the RC aircraft work, with this measure peaking between 1 and 2 NM, and then decreasing considerably between 2 - 3 NM. However, the effect of distance on vulture tracking was marginally insignificant (distance: $Z = -0.33$; $P = 0.740$; distance^2: $Z = -1.77$; $P = 0.076$). There was no obvious relationship between altitude and the percentage of vultures tracked at least one time ($Z = -0.059$; $P = 0.950$).

Table 7. The percentage of turkey vulture observations in which vultures were tracked at least one time by the HSR.

Distance (NM)	Altitude Low (<500 ft) High (>500 ft)	N	Percentage of observations with at least one track
0 - 1	Low	29	79
	High	8	75
1 - 2	Low	21	95
	High	16	81
2 - 3	Low	30	36
	High	38	39
3 - 4	Low	29	10
	High	18	22

Figure 20 displays the average percentage of time that turkey vultures were tracked out of the total time observed as a function of altitude and distance from the radar unit. Overall, vultures within 2 NM of the radar were tracked well under 50% of the time. The highest tracking performance was within 1 NM of the radar, which does not closely match the trend observed in the RC aircraft results, where tracking performance within 1.0 NM was not maximal. The observations with the highest tracking performance were a vulture tracked 74% of the time at 1.1 NM and a vulture tracked 72% of the time at 0.7 NM. Distance ($\chi^2 = 68.8$; df = 1.24; $P < 0.0001$) had a significant effect on tracking performance, but altitude did not (T = 1.14; $P = 0.256$). Removing untracked vultures improved tracking performance considerably at each distance (Figure 21), but average tracking performance was still under 50%.

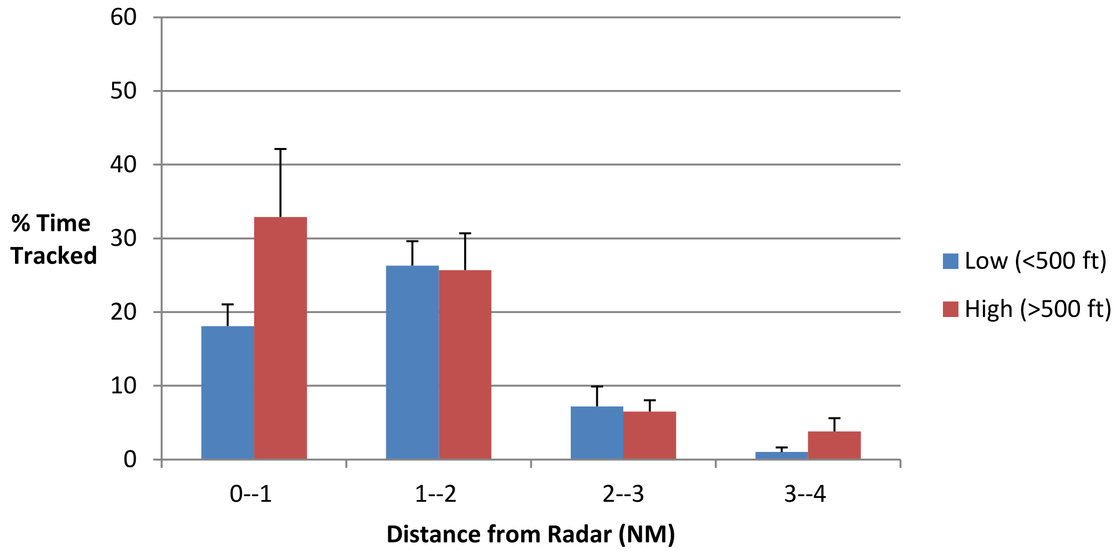


Figure 20. The average percentage of time that turkey vultures were tracked by the HSR as a function of distance and altitude. Mean values and standard errors are plotted.

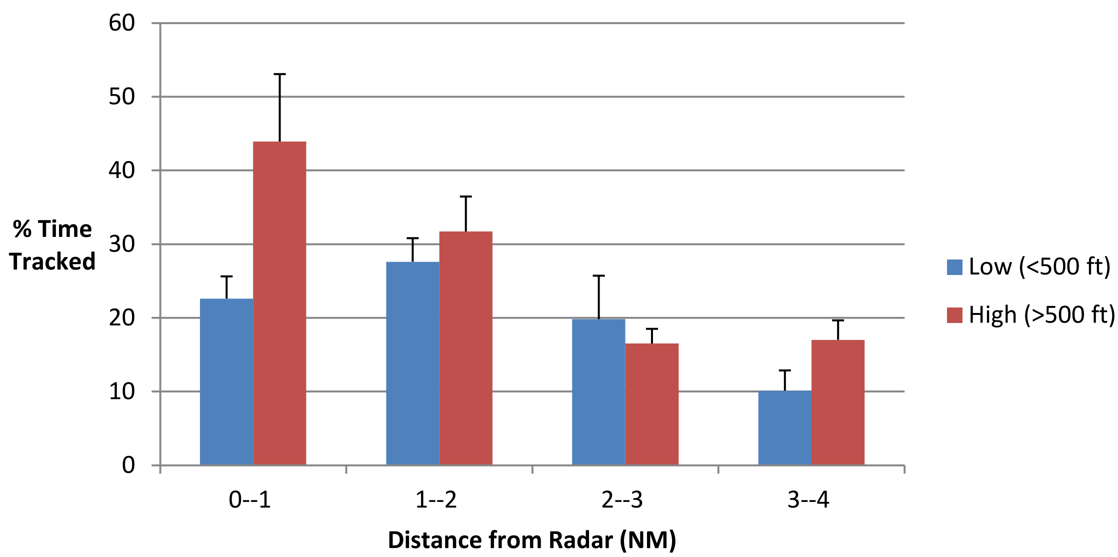


Figure 21. The average percentage of time that turkey vultures were tracked by the HSR as a function of distance and altitude, with untracked vultures excluded. Mean values and standard errors are plotted.

Figure 22 provides the average track length for turkey vultures as a function of altitude and distance from the radar unit. Average track lengths were all much shorter than the potential maximum track lengths, and similar across distances, except for high-flying vultures at close distances. Track lengths observed for turkey vultures were similar to those observed for the RC aircraft during thermalling flights (compare to Figure 13), likely reflecting the thermalling flight behavior of vultures. Overall, neither distance (F = 2.01; df = 3, 86; P = 0.119) nor altitude (F = 2.98; df = 1, 86; P = 0.080) had a significant effect on track length. The longest observed track length for a turkey vulture was 14 scans (35 seconds) for a high vulture observed for about 60 scans (150 seconds) at 2.1 NM. The next highest track length was 11 scans, for a low vulture at 0.8 NM, which was observed for 27 scans (about 70 seconds).

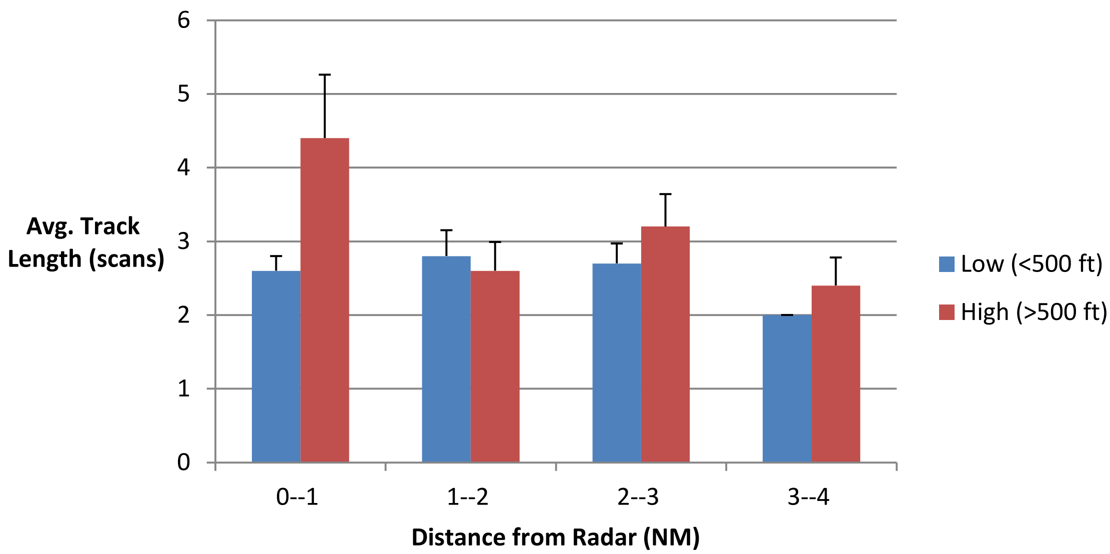


Figure 22. The average track length (# of radar scans) for turkey vultures as a function of distance and altitude. Data are included only for detected vultures. Mean values and standard errors are plotted.

Red-tailed Hawks

A total of 67 red-tailed hawk observations was included in the radar evaluation, of which 33 were tracked by the radar at least one time. The probability of a hawk being tracked at least one time was relatively high within 2 NM (Table 8), except perhaps for hawks that were above 500 feet and within 1 NM of the radar (but note the low sample sizes at close range). Distance, however, was not a significant factor (distance: Z = 1.25; $P = 0.210$; distance^2: Z = -1.95; $P = 0.051$). There also was no obvious altitude trend (Z = 0.703; $P = 0.480$). The overall qualitative trends were similar nevertheless to those observed in the vulture and RC aircraft results.

Table 8. The percentage of red-tailed hawk observations in which hawks were tracked at least one time by the HSR.

Distance (NM)	**Altitude Low (<500 ft) High (>500 ft)**	**N**	**Percentage of observations with at least one track**
0 - 1	Low	13	54
	High	2	100
1 - 2	Low	No Obs.	No Obs.
	High	3	100
2 - 3	Low	13	62
	High	10	60
3 - 4	Low	15	20
	High	11	27

Figure 23 displays the average percentage of time that red-tailed hawks were tracked out of the total time observed as a function of altitude and distance from the radar unit. Overall, tracking performance for red-tailed hawks was less than 20% at most ranges, except between 1 and 2 NM where it was higher (n = 3 hawks). One hawk in particular was tracked exceedingly well at 1.2 NM, at 83% of the time that it was observed. However, even when excluding this well tracked hawk, average tracking performance between 1 - 2 NM is still higher (27%) than that at other ranges. The tendency for tracking performance to peak at intermediate distances from the radar is similar to the trends observed for turkey vultures and the RC aircraft. The effect of distance was statistically significant ($\chi^2 = 13.32$; df = 1.61; $P = 0.002$), and there was no obvious altitude trend (T = 0.06; $P = 0.550$). Excluding untracked red-tailed hawks raised the average percentage of time tracked at each distance range (Figure 24), but tracking performance was still low.

Figure 25 shows the average track length for red-tailed hawks as a function of altitude and distance from the radar unit. Overall, average track length was low and comparable to the average track length observed for vultures and for thermalling-pattern RC aircraft flights. As before, these lower average track lengths likely reflect tracking algorithm limitations in tracking thermalling flight behavior. Neither distance (F = 1.95; df = 3, 26; $P = 0.146$) nor altitude (F = 0.96; df = 1, 26; $P = 0.335$) had a significant effect on track length. The longest observed track length for a red-tailed hawk was 10 scans (about 25 seconds) for a low hawk at 0.5 NM observed for about 106 scans (just under 4.5 minutes).

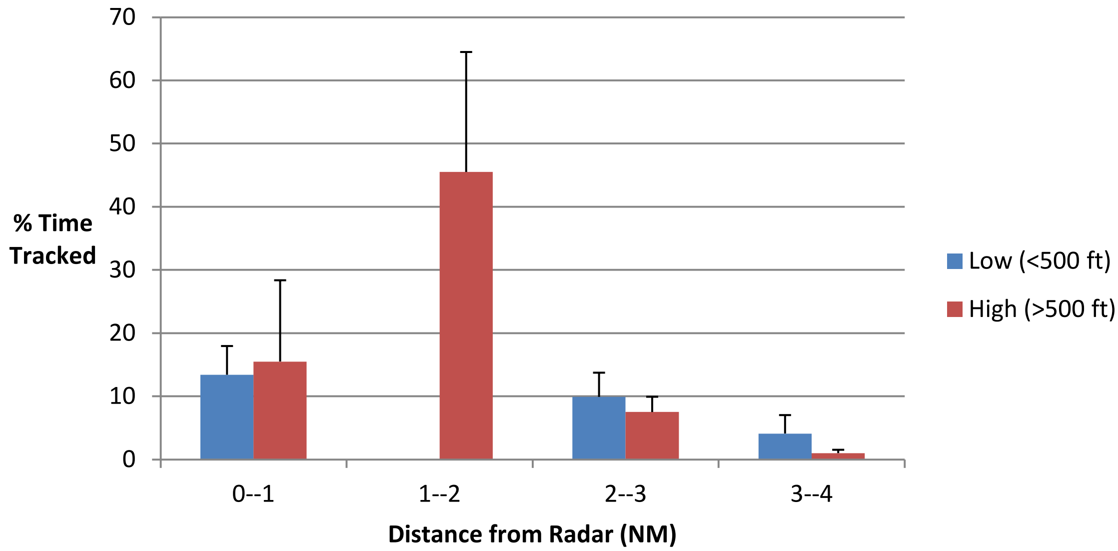


Figure 23. The average percentage of time that red-tailed hawks were tracked as a function of distance and altitude. Mean values and standard errors are plotted.

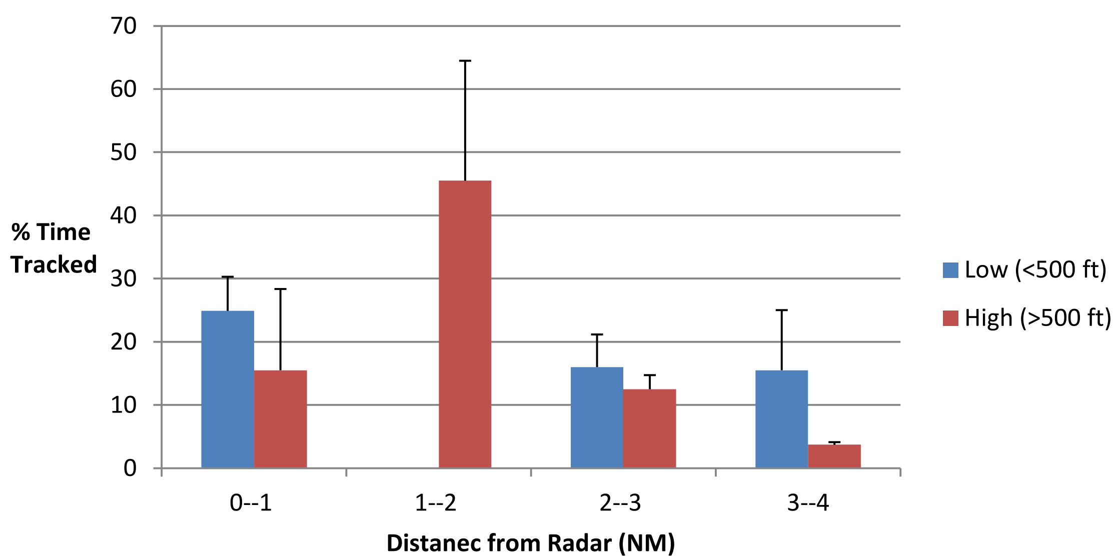


Figure 24. The average percentage of time that red-tailed hawks were tracked as a function of distance and altitude, with untracked hawks excluded. Mean values and standard errors are plotted.

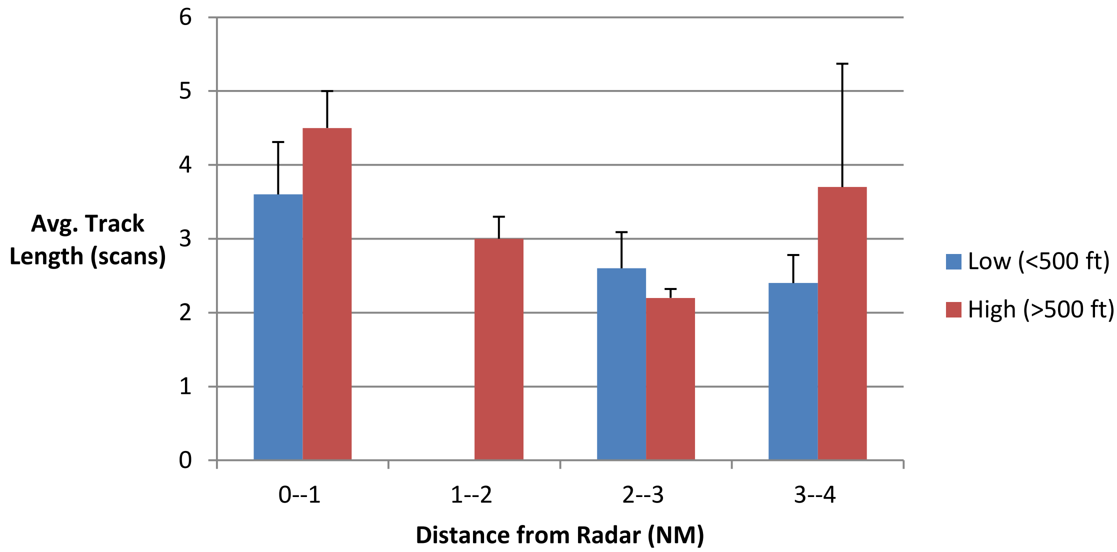


Figure 25. The average track length (# of radar scans) for red-tailed hawks as a function of distance and altitude. Data are included only for detected flights. Mean values and standard errors are plotted.

Overall, raptors (turkey vultures and red-tailed hawks) were often detected when close to the radar unit, but in most cases they were tracked for less than 50% of the time present. There was a tendency for peak tracking performance between 1 and 2 NM. This pattern does not seem to fit the radar shadow hypothesis mentioned in the RC aircraft section above, because peak tracking performance was on the radar side of the forested area in question. Nonetheless, like the RC aircraft work, peak tracking performance occurred at an intermediate distance from the radar unit. As mentioned above, clutter close to the radar unit could potentially mask bird targets close to the radar. The low average track lengths for single bird targets result in targets appearing on the radar screen intermittently and briefly, a trend that was also observed for thermalling RC aircraft flights.

Flocks

Sandhill Cranes

A total of 86 sandhill crane flocks was included in the radar evaluation, most of which (82) were tracked by the horizontal scanning radar at least one time. Only a few smaller flocks went completely untracked (Table 9). There was no apparent drop in performance at far distances (the high detection rate precluded a logistic analysis). This tracking performance far exceeded that associated with the RC aircraft or raptors. Note that all of these flocks were essentially in the high altitude category (>500 feet).

Table 9. The percentage of crane flock observations in which flocks were tracked at least one time by the HSR.

Flock Size	**Distance Near (<2 NM) Far (>2 NM)**	**N**	**Percentage of observations with at least one track**
2 - 10	Near	8	75
	Far	8	75
11 - 29	Near	11	100
	Far	11	100
30 - 100+	Near	18	100
	Far	27	100

Figure 26 displays the average percentage of time that sandhill crane flocks were tracked out of the total time observed. The crane flocks were tracked over 40% of the time on average. The average percentage of time tracked increased with increasing flock size (F = 13.66; df = 2, 77; $P < 0.0001$), and in all cases greatly exceeded that for single turkey vultures, red-tailed hawks, or the RC aircraft. Distance from the radar was not a significant factor (F = 0.24; df = 1, 77; $P = 0.629$). Three crane flocks were tracked 100% of the time that they were observed (recall that the Merlin tracking software allows for misses between detections): a flock of 20 sandhill cranes at 3.3 NM, a flock of 35 at 1.9 NM, and a flock of 80 at 2.9 NM. Two large crane flocks entered the HSR cone of silence, and were thus removed from this portion of the analysis.

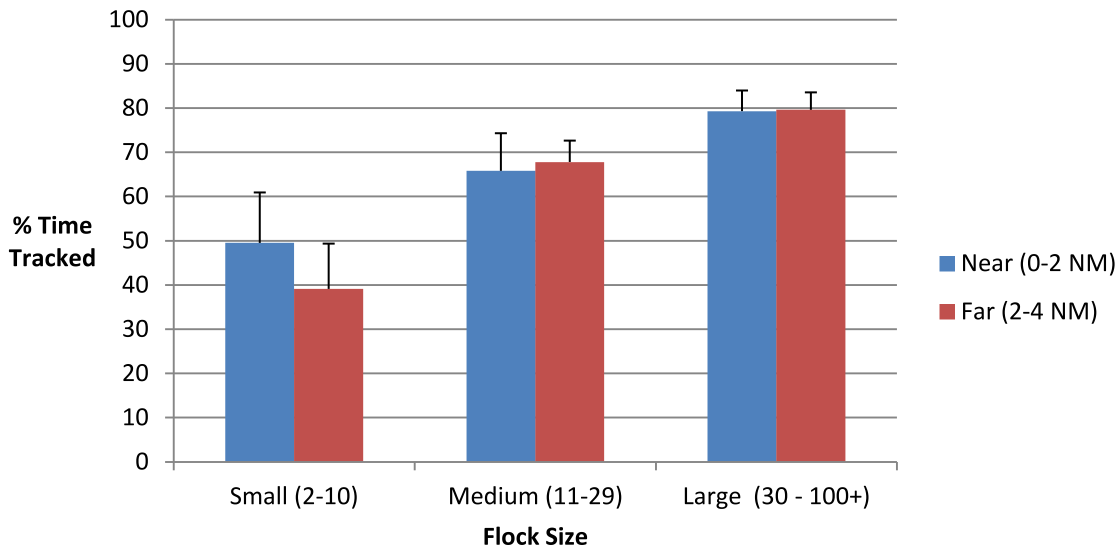


Figure 26. The average percentage of time that crane flocks were tracked as a function of distance and flock size. Mean values and standard errors are plotted.

Figure 27 provides the average track length (in scans) for sandhill cranes as a function of distance and flock size. Average track length increased with increasing flock size, although this effect was not quite significant (F = 3.11; df = 2, 72; $P = 0.051$). There was no clear distance trend observed for this measure (F = 0.80; df = 1, 72; $P = 0.373$). Overall, average track length was relatively high, especially for large flocks (15 - 20 scans, or 40 - 50 seconds). The longest observed track length for a sandhill crane flock was 81 scans (about 3.5 min) for a flock of 100 cranes at 2.8 NM. The next highest track lengths observed were 67 scans (168 seconds) for a flock of 150 cranes at 3 NM, and 57 scans (143 seconds) for a flock of 90 cranes at 3.2 NM.

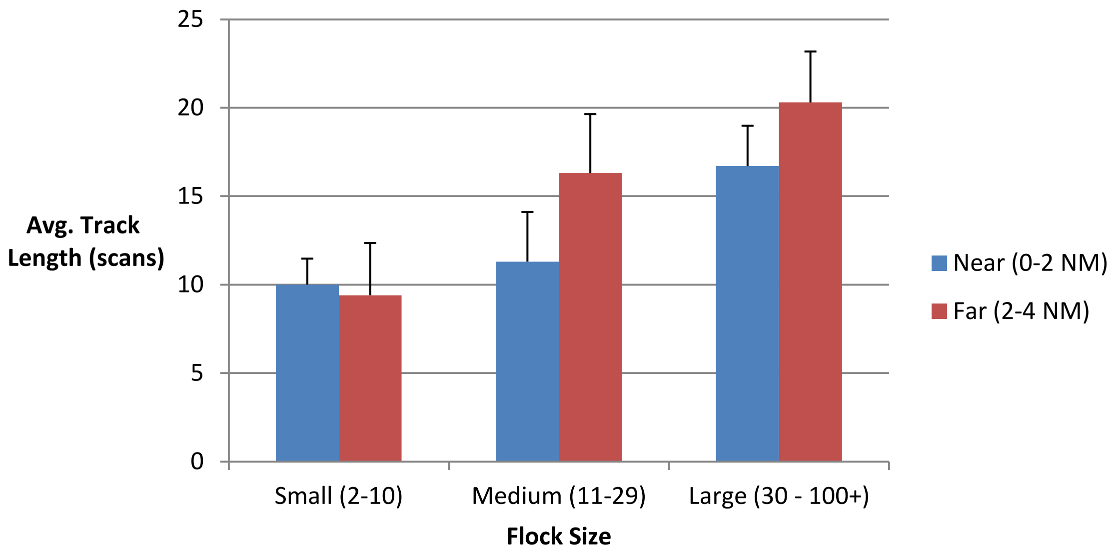


Figure 27. The average track length for crane flocks as a function of distance and flock size. Data are provided only for detected flocks. Mean values and standard errors are plotted.

Canada Geese

A total of 134 Canada goose flocks was included in the radar evaluation, of which 121 were tracked by the HSR at least one time. The percentage of goose flocks that were tracked at least one time increased significantly (Z = 2.42; *P* = 0.025) with increasing flock size (Table 10). Distance also had a significant effect (Z = -2.14; *P* = 0.032), with better tracking at greater distances. Overall, the great majority of goose flocks were tracked at least once, much more often than raptors, but not quite as well as the crane flocks.

Table 10. The percentage of goose flock observations in which flocks were tracked at least one time by the HSR.

Flock Size	Distance Near (< 2 NM) Far (> 2 NM)	N	Percentage of observations with at least one track
2 - 10	Near	36	89
	Far	20	70
11 - 29	Near	25	100
	Far	17	88
30 - 80+	Near	22	96
	Far	14	100

Figure 28 displays the average percentage of time that Canada Goose flocks were tracked out of the total time observed. The average percentage of time tracked increased within increasing flock size ($F = 20.67$; df = 2, 128; $P < 0.0001$). There was no clear effect of distance ($F = 1.56$; df = 1, 128; $P = 0.214$). The average percent time tracked was relatively high at 60-70% for the largest flocks, but under 50% for smaller flocks. Three goose flocks were tracked 100% of the time: a flock of 15 at 0.5 NM, a flock of 30 at 1.8 NM, and a flock of 60 at 2.2 NM. Overall, these trends were similar to those for sandhill crane flocks. The average percentage of time that goose flocks were tracked did not substantially increase by removing untracked flock observations (Figure 29), because most flocks were detected by the HSR.

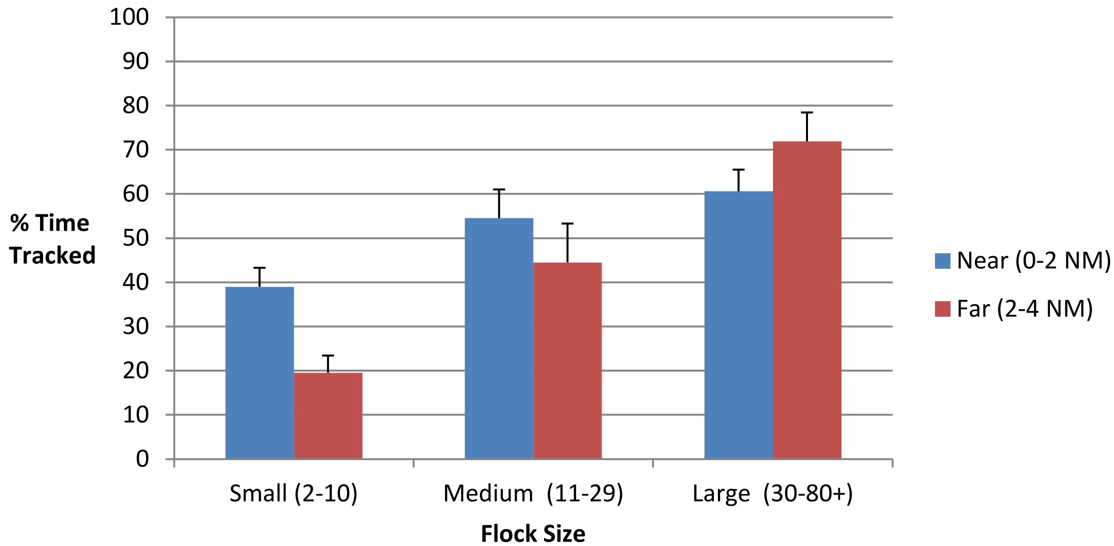


Figure 28. The average percentage of time that goose flocks were tracked as a function of distance and flock size. Mean values and standard errors are plotted.

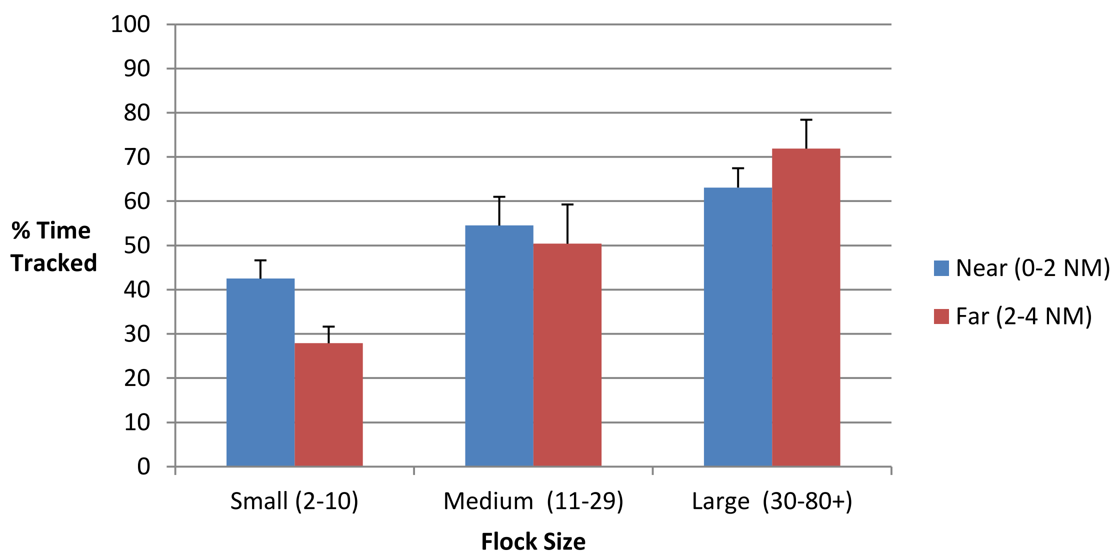


Figure 29. The average percentage of time that goose flocks were tracked as a function of distance and flock size, with untracked flocks excluded. Mean values and standard errors are plotted.

Average track length also increased significantly with increasing flock size (Figure 30; F = 8.61; df = 2, 116; $P < 0.0001$). Distance, however, was not a significant factor (F = 0.36; df = 1, 116; $P = 0.550$). Overall, average track lengths for goose flocks were not as high as those for crane flocks, perhaps reflecting the generally larger size of cranes. The longest observed track length for a Canada goose flock was 66 scans (approximately 2.8 minutes) for a flock of 25 geese at 0.5 NM that circled slowly and broadly many times prior to landing.

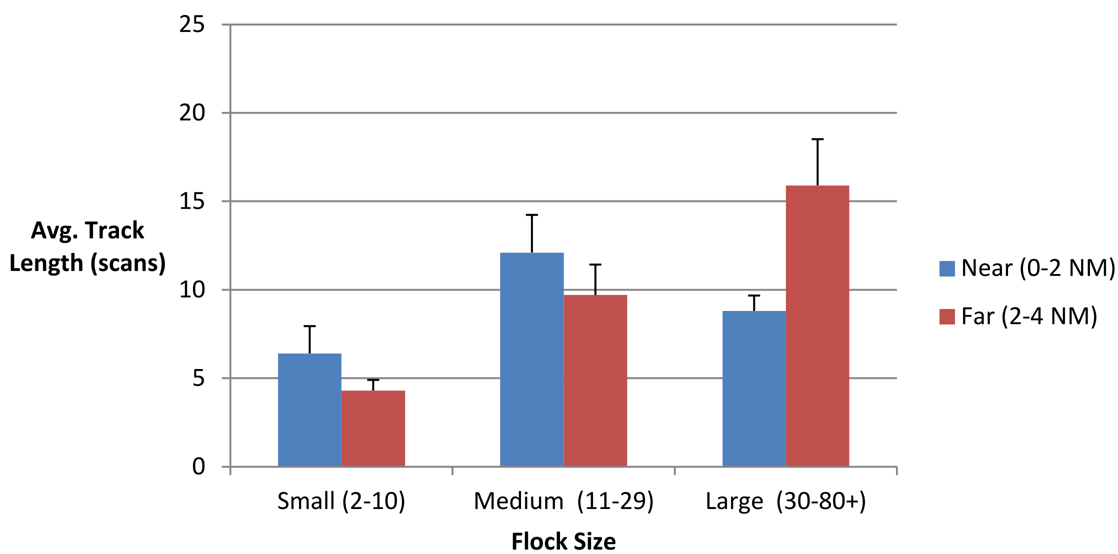


Figure 30. The average track length (# of radar scans) for goose flocks as a function of distance and flock size. Data are provided only for detected flocks. Mean values and standard errors are plotted.

Duck flocks

A total of 126 duck flocks was included in the radar evaluation, of which 85 were tracked by the radar at least one time. Overall, the percentage of duck flocks tracked at least one time increased significantly (Z = 4.11; $P < 0.001$) with increasing flock size (Table 11). The relationship between this measure and distance from the radar was not significant (Z = 1.77; P = 0.077), but showed a tendency to increase at greater distances. Whereas the trends observed for duck flocks largely matched those for crane and goose flocks, the ducks were detected less often than the others, especially in smaller groups.

Table 11. The percentage of duck flock observations in which flocks were tracked at least one time by the HSR.

Flock Size	Distance Near (< 2 NM) Far (> 2 NM)	N	Percentage of observations with at least one track
2 - 10	Near	7	57
	Far	59	53
11 - 29	Near	10	40
	Far	18	83
30 - 50+	Near	13	92
	Far	19	100

Figure 31 displays the average percentage of time that ducks flocks were tracked out of the total time observed. The percentage of time tracked increased with increasing flock size (F = 19.83; df = 2, 120; $P < 0.0001$), and was generally greater further from the radar (F = 4.33; df = 1, 120; P = 0.040). Overall, the average percent of time tracked was lower for duck flocks compared to that for crane and goose flocks (compare Figures 26, 28, and 31), likely reflecting the smaller size of ducks. The faster speed of ducks, compared to geese and cranes, could also influence this measure. Nonetheless, the average percentage of time that duck flocks were tracked was much higher than that for single raptors or the RC aircraft, thus the radar system was able to track these fast birds. Four of the observed duck flocks were tracked 100% of the time: a flock of 18 ducks at 2.9 NM, a flock of 22 at 2.5 NM, a flock of 30 at 2.5 NM, and a flock of 40 at 2.4 NM. Excluding untracked flocks (Figure 32) made a notable difference in the average percentage of time tracked for small and medium flocks, but not for large flocks (most large flocks were well tracked). However, small and medium flocks that were detected were generally tracked under 50% of the time.

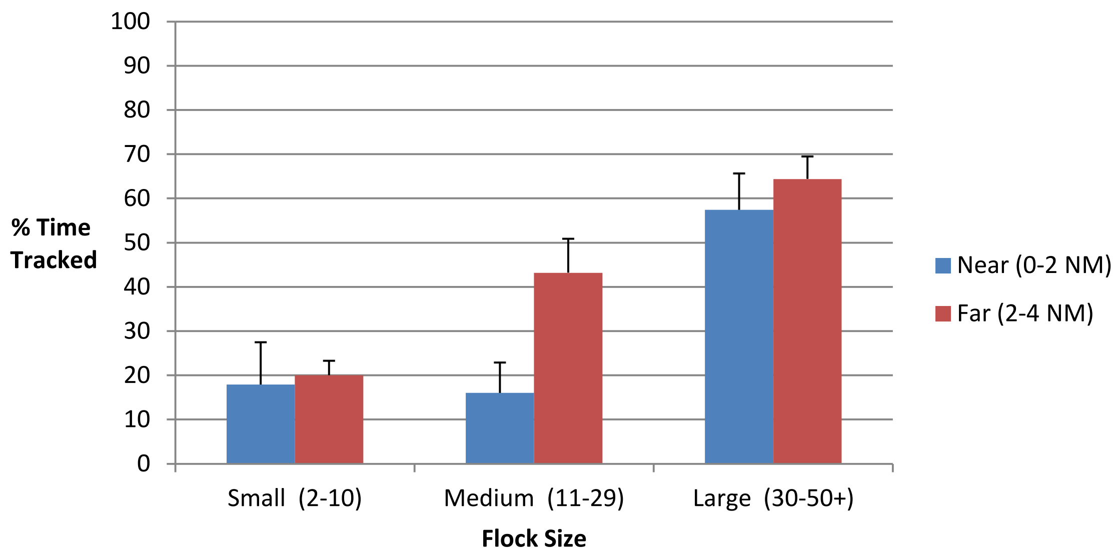


Figure 31. The average percentage of time that duck flocks were tracked as a function of distance and flock size. Mean values and standard errors are plotted.

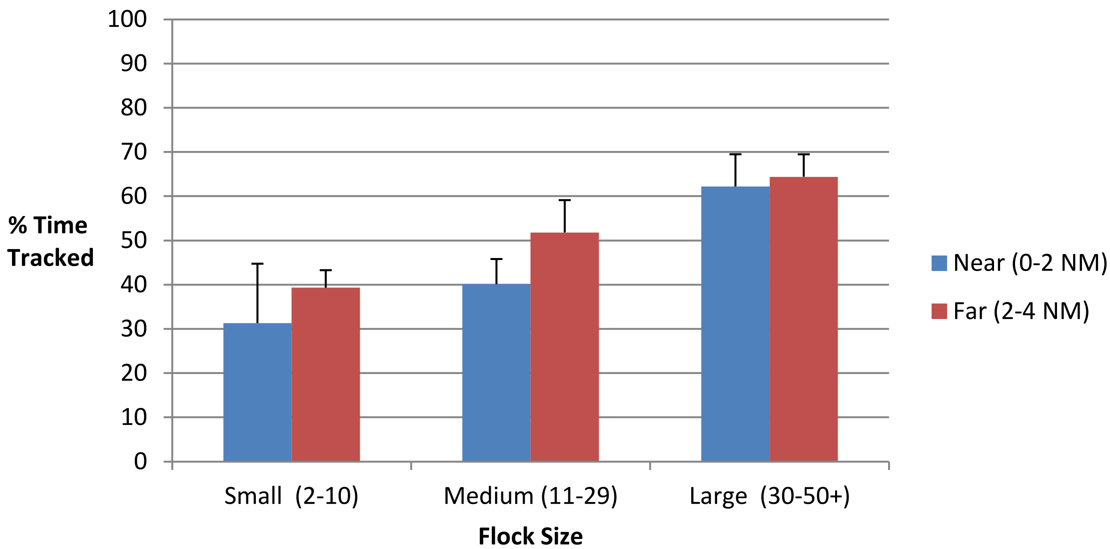


Figure 32. The average percentage of time that duck flocks were tracked as a function of distance and flock size, with untracked flocks excluded. Mean values and standard errors are plotted.

Similar to the trends in average track length for goose and crane flocks, average track length for duck flocks increased significantly with increasing flock size (Figure 33; F = 3.54; df = 2, 77; *P* = 0.034). Distance from the radar was not a statistically significant factor (F = 0.92; df = 1, 77; *P* = 0.340). Overall, average track length for duck flocks was lower than that for crane and goose flocks, yet still much higher than those for single raptors and the RC aircraft. The longest observed track length was 30 scans (approximately 75 seconds) for a slowly circling flock of 45 ducks at 1.3 NM. The next highest track lengths observed were 28 scans (70 seconds) for a flock of 6 ducks at 3.3 NM and 27 scans (about 67 seconds) for a flock of 60 at 2.5 NM.

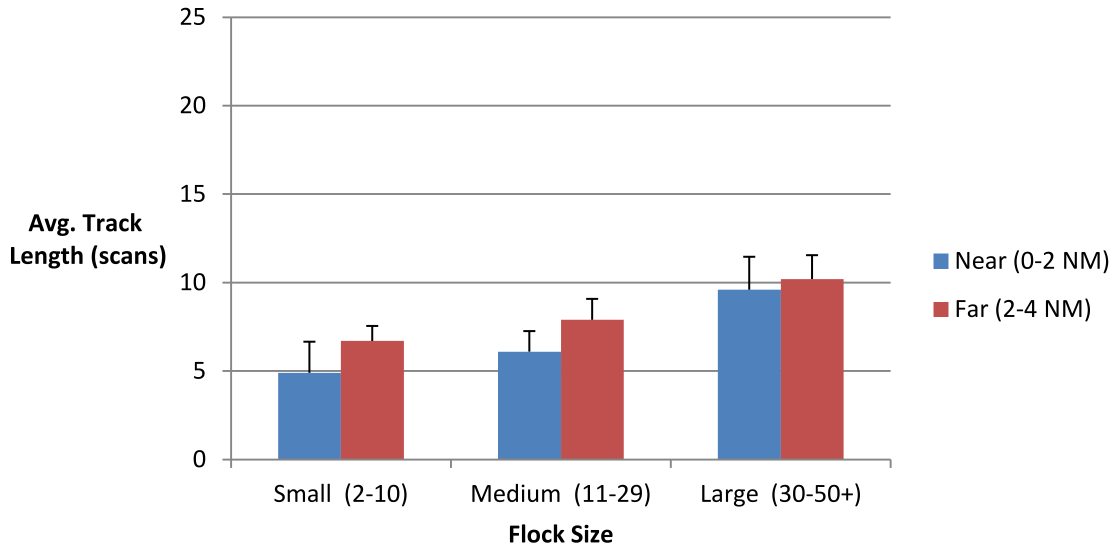


Figure 33. The average track length (# of radar scans) for duck flocks as a function of distance and flock size. Data are provided only for detected flocks. Mean values and standard errors are plotted.

Overall, flocks of relatively large birds were clearly more detectable than single raptors or the RC aircraft. However, it is important to point out, as Tim West of DeTect (personal comm.) put it, that the effective beam width depends upon the size of the target. Thus, flocks were likely much more detectable further from the center of the horizontal beam than were single targets. The percentage of observations with at least one track, the average percentage of time tracked, and the average track length were all greater for flocks, particularly goose and crane flocks. A very noticeable difference between (single) raptor data and flock data was that each of these measures remained high for flocks at relatively great distances from the radar unit.

DeTect, Inc. claims that the HSR is capable of detecting and tracking birds out to a distance of 4 - 8 NM (DeTect Inc. website 2013). These results demonstrate that the Merlin radar system is indeed capable of detecting and tracking large flocking birds (especially cranes and geese) out to a distance of 4 NM, and likely at much greater distances, given that flocks were often tracked from the moment they entered the radar coverage area to the moment they exited. Thus, the HSR could be a useful tool for airports that face daily movements of large flocking birds (e.g. moving from roost lakes to feeding grounds) or for airports that lie in the migration pathway of waterfowl species. The HSR could be used to monitor bird flock activity in the general airport environment, thus this system could effectively serve as an early warning system for bird flock activity hazardous to aircraft. In many cases we were able to anticipate that crane flocks detected 4 NM (5 - 15 min) away were on track to pass over the airport.

Results and Discussion - Vertical Scanning Radar

The nature of the vertical radar beam allows for vertical resolution of targets but does not assess horizontal position. Given that migrating flocks are often followed by additional flocks that tend to follow the same flight path trajectory and altitude, one right after another, it was difficult to distinguish between flocks in the vertical radar display. Assessing tracking performance in the vertical beam is also complicated by the fact that the VSR does not provide lat/long information for targets. However, there were instances in which a single flock cross the vertical beam well ahead of the main migration traffic. For such flocks, it was possible to determine the length of time that they were tracked. A few examples are provided below.

Single, isolated bird targets, on the other hand, were not usually confused with other bird targets. However, evaluating single bird targets in the vertical beam is difficult, because effective beam width depends upon the size of the target. Smaller targets are detected closer to the center of the beam, whereas flocks are often detected over a much wider area. The larger the flock, the further from the center of the beam it can be detected (because larger objects intercept and reflect a greater amount of energy emitted by the radar). Given this information, only single targets that crossed the center of the vertical beam are considered here.

Single Targets

Two species that were frequently observed flying solo were turkey vultures and red-tailed hawks, thus both species are considered in this section. Given the uncertainty regarding how close single targets must be to the center of the vertical beam in order to be tracked, only those observations in which targets clearly crossed the vertical beam were considered. For this same reason, I do not report the percentage of time tracked; rather, I report the percentage of vultures/hawks that were tracked at least one time as they crossed the vertical beam. Of the 190 turkey vultures included in the HSR evaluation, 24 met these requirements for inclusion; 10 of the 67 red-tailed hawks did so. Turkey vulture and red-tailed hawk observations were pooled in order to attain better sample sizes, but there were too few data for statistical analysis. Qualitatively, the percentage of raptors tracked at least one time (Table 12) was greatest (50%) between 1 and 2 NM. Overall, 30 – 50% of raptors within 3 NM were tracked at least one time by the VSR, whereas none were detected beyond 3 NM. There was no clear effect of altitude upon the likelihood of detection, although sample sizes were uneven. Raptors that were tracked by the VSR were tracked for only a short period, unless they lingered relatively close to the center of the vertical beam coverage area. Operating the vertical beam at a shorter range, such as 0.75 NM, or 2.0 NM as opposed to 4 NM could result in improved detection of single bird targets crossing the vertical beam, but may not suit the need of a given application.

Table 12. The percentage of raptors (turkey vultures and red-tailed hawks) tracked at least one time by the VSR, out of the total number of raptors that crossed the vertical beam.

Distance (NM)	Altitude Low (<500 ft) High (>500 ft)	N	Percentage of observations with at least one track
0 - 1	Low	13	23
	High	3	67
1 - 2	Low	1	100
	High	3	33
2 - 3	Low	4	50
	High	3	33
3 - 4	Low	4	0
	High	3	0

Flocks

As mentioned earlier, there were instances where a single flock (well separated from other flocks) passed through the vertical beam, allowing me to determine the length of time that it was tracked from the moment it was first tracked until it was no longer tracked. A few examples are provided in this section: two flocks (one large and one small) at greater ranges, and two (one large and one small) at close range. These flocks consistently traveled in a straight north-south or south-north manner across the study site, and thus clearly passed perpendicular to the vertical beam (see Figure 5).

Of the two isolated flocks considered at greater range, one was a flock of 120 cranes at 2.9 NM and the other, 22 cranes at 2.7 NM. From the moment the flock of 120 cranes entered the approximate beam coverage area, it was tracked consistently until it exited the beam coverage area. At this distance the beam is about 1.2 NM wide, which is roughly the north-south distance that this flock was tracked within the vertical beam. The flock appeared to be within the beam for 386 seconds, 313 of which it was tracked. Therefore, the flock was tracked about 82%

of the time. The flock was not tracked as well at the outskirts of the beam coverage area than it was toward the center of the coverage area.

The other flock at relatively great range involved 22 sandhill cranes at 2.7 NM. This flock was slightly closer to the radar, and so the beam width at this location is approximately 1.1 NM. This flock was not detected until it was well within the beam, but once detected, it was tracked consistently (95% of the time) until it exited the beam coverage area. When considering the amount of time that the flock was within the beam, it was tracked about 66% of the time.

Of the two isolated flocks observed at closer range, one was a flock of 150 cranes at 0.9 NM and the other 45 cranes at 0.3 NM. The flock of 150 cranes was tracked from the approximate moment that it entered the beam coverage area to the moment it that exited the beam (100% of the time over 30 scans). At this distance, the vertical beam is approximately 0.4 NM wide. The flock was within the beam for about 75 seconds. The other flock observed at closer range was a flock of 45 cranes flying north at 0.3 NM away from the radar unit. The flock was detected for only a short period, but at this distance, the width of the beam is only about 0.1 NM (roughly 600 feet). The flock was tracked for 10 scans in a row.

Overall, the VSR was more useful in monitoring flock activity than single raptor activity for two reasons. First, flocks are tracked for longer periods of time and farther from the center of the vertical beam coverage. Secondly, VSR altitude estimates for flocks passing through the vertical beam coverage area provided an indication of the altitude of distant flocks (those visible only on the HSR radar display). Given the good HSR tracking performance for flocks, one could use the VSR in concert with the HSR to anticipate the altitude of approaching flocks (in the HSR) and thus the hazard they might pose to flight activities around an airport.

ADDITIONAL TOPICS

Tracking Software Algorithm

As mentioned earlier, the tracking software often underestimates target track length. Consistently tracked flocks may yield numerous track IDs, reflecting the inability of the tracking software to handle thermalling/circling or sudden changes in direction. This often occurs when crane flocks exhibit thermalling flight behavior before continuing on their original course.

For example, a flock of 40 sandhill cranes 3 NM from the radar unit, alternating between straight and thermalling flight behavior, was tracked for 37 consecutive scans. However, the radar tracking software produced 9 different track IDs for this flock. This occurs because when a flock begins to thermal, suddenly changing direction, the tracking software often marks that track as ended, while at the same time initiating a new track for that same flock. There were several instances where a flock was consistently tracked under the same track ID for many scans, but these typically occurred during long stretches of straight flight behavior.

Given these results, information provided by the radar in the Access database does not provide a reliable indicator of effective track length for some bird targets. However, this is not a functional problem for an operator viewing the radar computer screens. While the track ID may change, the radar operator would see an uninterrupted track displayed on the screen.

Target Classification System

The Merlin System's software classifies targets into 1 of 4 size categories based upon the number of pixels representing the target in the radar software raster output: small (e.g. songbird), medium (e.g. American crow), large (e.g. Canada goose), or flock. The target classification system is based upon an operating range of 0.75 NM, therefore the current target size interpretation is strictly only applicable at this range. However, target size estimates provided by the radar software varied significantly from scan to scan, especially for flocks. Such variation will cause problems for the classification system when operating at any range.

Figure 33 shows the variation in target size estimates from scan to scan for a red-tailed hawk thermalling at 0.6 NM from the radar unit. This observation represents one of the better single bird target tracks, as this particular hawk was detected and tracked several times over the course of 4 minutes. Notice that target size ranges from 3 – 28 pixels. Depending on the classification scheme, this hawk could be classified in 2 or more ways over the course of its passage.

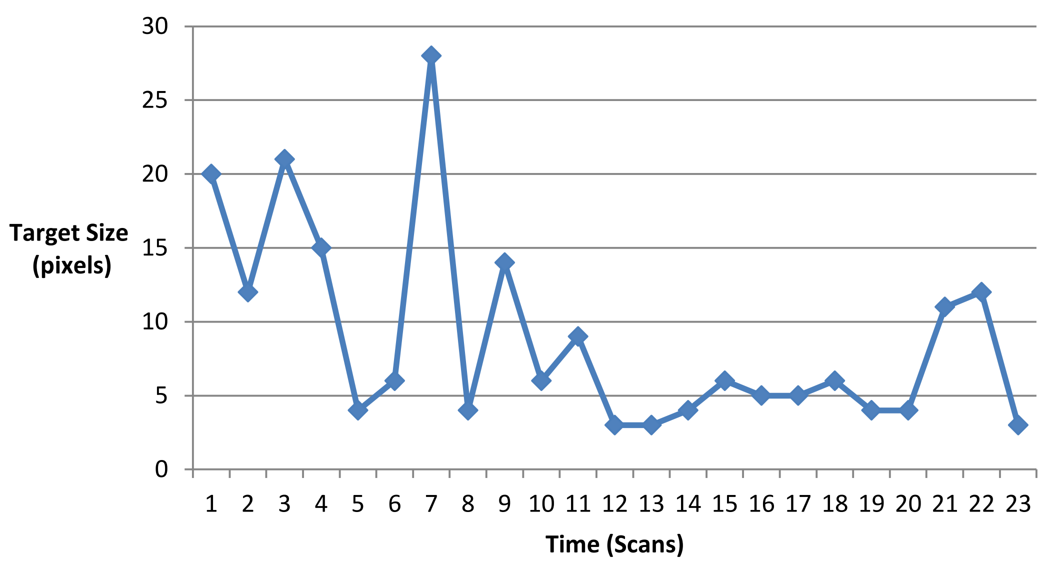


Figure 34. Scan to scan variation in radar estimates of target size for a red-tailed hawk at 0.6 NM. Over the course of 5 minutes, the hawk was tracked multiple times. Shown are consecutive target size estimates from several different tracks, totaling 23 scans.

Figure 34 shows the variation in target size estimates from scan to scan observed from a flock of 40 sandhill cranes that was tracked for 31 consecutive scans at 3.0 NM from the radar unit. Notice that target size for this flock ranges from 2 – 146 pixels, which would probably cover the range from a single bird to a flock in any classification scheme. This variation in target size from scan to scan may be due in part to the circling or thermalling behavior of flocks as they move through the area, causing fluctuations in the amount of surface area facing the radar beam, and therefore differences in the amount of energy reflected back toward the radar (Beason et al. 2013; Gauthreaux and Schmidt 2013). There was probably a similar cause underlying variation in target size estimates for single bird targets, but these variations were not as great as that observed in flocks.

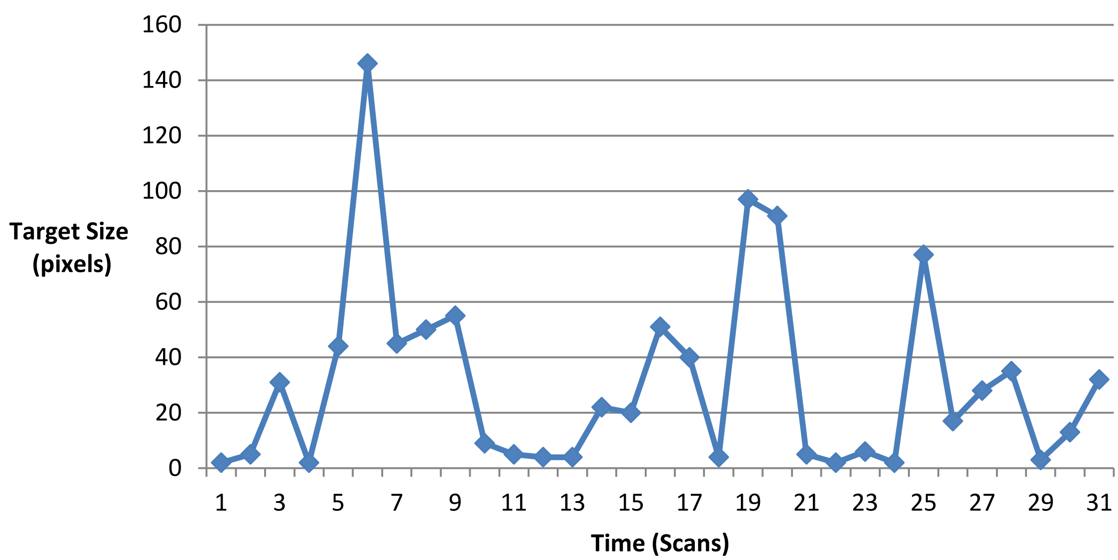


Figure 35. Scan to scan variation in radar estimates of target size for a flock of 40 sandhill cranes at 3.0 NM. Target size estimates are provided for one track that was 31 scans in length.

Given these results, the target classification system, in its present form, is not all that useful because it is only accurate when operating at a 0.75 NM range, and because target size estimates of the same bird target or flock vary considerably from scan to scan. The software may not be capable of providing reliable estimates of target size, which has implications for determining real-time bird hazard levels. This also has implications for other uses of the radar, particularly for projects that attempt to quantify the passage of small, medium, large, and flock sized targets. Further versions of the Merlin System may feature an operating-range-specific classification system (personal comm. DeTect, Inc) which would be an improvement over the current system, but the above target size variation will likely remain a problem for target classification.

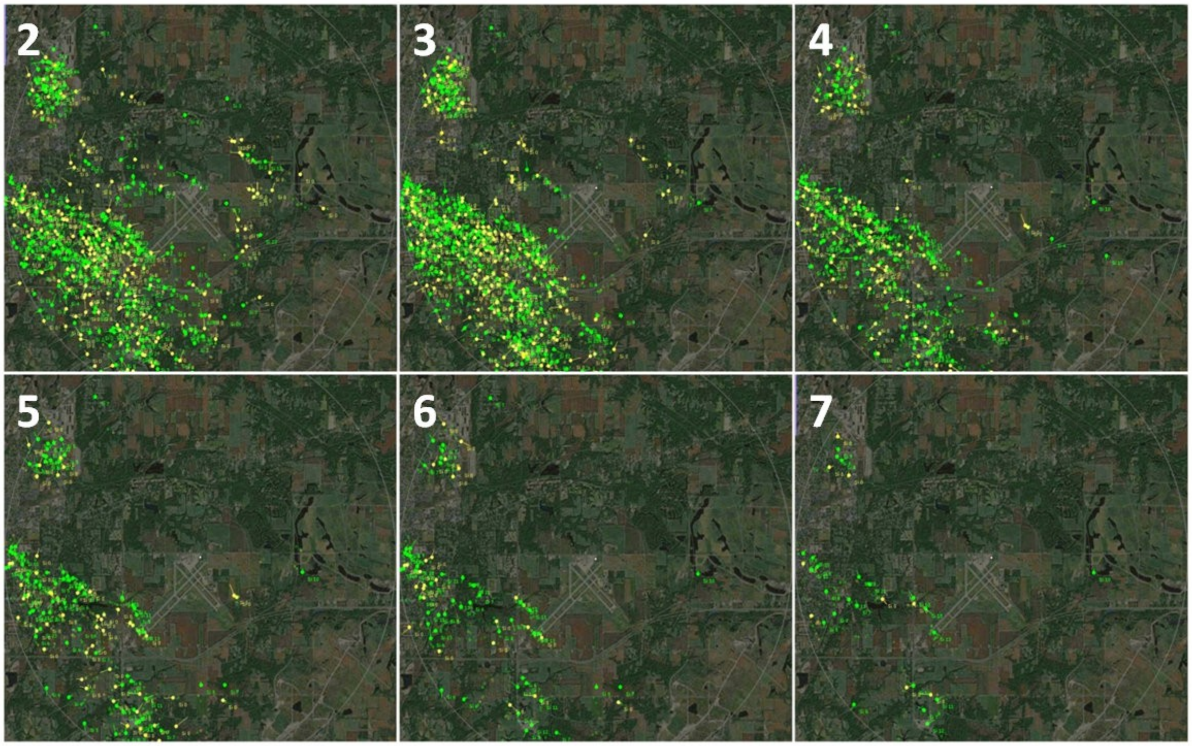
Performance during rainfall events

Precipitation can result in a large number of false detections by radar, which can be problematic for radar systems that use automatic processing algorithms (Gauthreaux and Schmidt 2013). Due to the volume of detections during rainfall events, and the close proximity of such detections to one another, automatic tracking algorithms will often generate numerous false tracks that meet the tracking algorithm requirements (Gauthreaux and Schmidt 2013).

The degree of rainfall tracked by a radar depends both on the intensity of rainfall and on the sensitivity of the selected target filter settings. For the present radar evaluation, minimum target filter settings were set at 2 (pixels) when observing birds within the 2-4 NM range, or 3 (pixels) when observing birds within the 0 - 2 NM range. A significant number of tracks were generated by rainfall clutter when using these filter settings. The less sensitive the filter settings, the fewer false tracks generated by rainfall. However, as mentioned earlier, using settings greater than 2 (i.e. less sensitive settings), would result in many avian targets being completely missed. Large flocks are still detected at lower sensitivity settings, but single targets, small flocks, and sometimes medium flocks, often disappear with decreasing sensitivity in target filter settings.

Figure 35A shows a moderate rainfall event on March 23, 2012, with rain moving in from the southwest. This figure shows the radar display during the same rainfall event at the same point in time for 6 different filter settings, ranging from the most sensitive (top left) to the least sensitive (bottom right). Clutter is a significant issue when operating the radar at the settings necessary to detect single bird targets beyond 2 NM (the top middle and top left screenshots), but not as much of a problem when using less sensitive settings (the bottom middle and bottom right screenshots). Figure 35B shows the same for a very light (drizzle) rain event on November 7, 2011; even these events cause problems at the necessary sensitivity settings. Therefore, moderate to heavy rainfall was a functional problem, even for the S-band radar installed in our Merlin System.

A.



B.

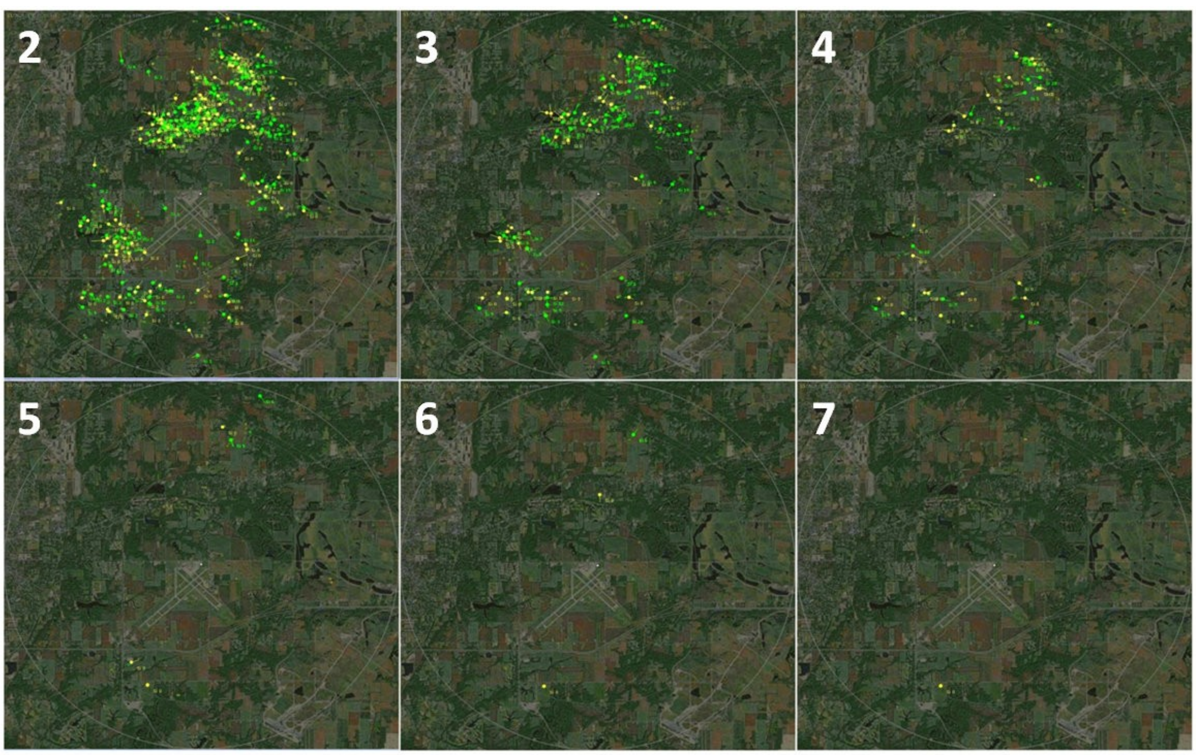


Figure 36. Moderate rainfall event (A) and light rain/drizzle event (B). Numbers indicate the target filter size settings ranging from the most sensitive (2) to the least (7).

Tracking Large Blackbird Flocks

On February 27, 2012, long waves of tens of thousands of red-winged blackbirds were moving south (toward a roost site) between 3 and 4 NM and at altitudes of about 100-200 feet above ground level. Figure 37 displays the radar output of one such wave of blackbirds, numbering in the tens of thousands. As this one-mile-long flocked pushed south, dozens of targets representing the flock were displayed. The radar system did not track this huge flock as one individual unit, but rather as many targets. The tracks yielded a scintillating pattern with many tracks appearing and then disappearing. Events like this are very obvious on radar, hence the horizontal scanning radar could be useful in mapping daily movements of blackbirds moving from feeding to roost locations for wildlife hazard assessments, and in monitoring the activity of large blackbird or starling flocks which pose a substantial threat to aircraft (Dolbeer et al. 2011).

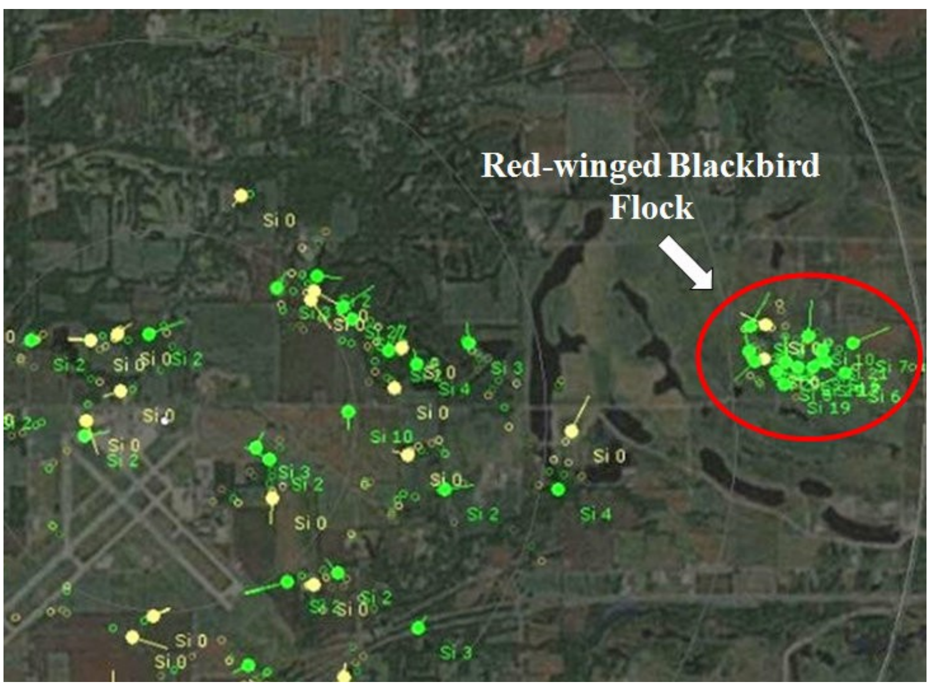


Figure 37. Radar tracks produced for a large red-winged blackbird flock. Many of the tracks concentrated at the center of the figure are false tracks associated with a stand of trees.

SUMMARY

The RC aircraft flights and raptor observations demonstrated that tracking performance for single large bird targets is fairly poor. Thermalling RC aircraft flights and observations of thermalling raptors resulted in lower tracking performance than straight flight patterns, suggesting that the radar tracking software is less capable of tracking targets exhibiting thermalling flight patterns (e.g. turkey vultures and red-tailed hawks). Tracking performance for flocks of waterbirds was good, especially for large birds such as geese and sandhill cranes. Compared to single bird targets, flocks are (i) much more likely to be detected by the Merlin System, (ii) more likely to be detected and tracked at distances farther away from the radar unit, and (iii) tracked far more reliably. Thermalling and circling behavior of single bird targets or flocks resulted in underestimation of effective track length by the tracking software. Target size estimates provided by the radar varied too widely to be of practical use for consistently estimating target size. The target filter settings necessary to eliminate false tracks generated by rainfall clutter caused most single bird targets and smaller flocks to be missed, but larger flocks were still tracked at these settings. Given these results, avian radar could be a useful tool for monitoring bird flock activity at airports, but not so useful for single large bird targets such as thermalling raptors.

REFERENCES

Allan, J. R., and A. P. Orosz. 2001. The costs of birdstrikes to commercial aviation. Pages 218-226 *in* Bird Strike 2001, Proceedings of the Bird Strike Committee-USA/Canada meeting. Calgary, Alberta, Canada: Transport Canada, Ottawa, Ontario Canada.

Beason, R.C., and Bowser, C.O. 2009. Are visual and radar bird sampling techniques correlated? Proceedings of the Bird Strike North America 11:7.

Beason, R. C., J. S. Humphrey, N. E. Myers, and M. L. Avery. 2010. Synchronous monitoring of vulture movements with satellite telemetry and avian radar. Journal of Zoology (London) 282:157–162.

Beason, R.C., Nohara, T.J., and Weber, P. 2013. Beware of the Boojum: caveats and strengths of avian radar. Human-Wildlife Interactions 7:16-46.

Blackwell, B.F., and Wright, S.E. 2006. Collisions of red-tailed hawks (Buteo jamaicensis), turkey vultures (Cathartes aura) and black vultures (Coragyps atratus) with aircraft: Implications for bird strike reduction. Journal of Raptor Research 40:76-80.

Blokpoel, H. 1976. Bird hazards to aircraft. Clark, Irwin, and Co. Ltd., in assoc. with Environment Canada. 235 pp.

Brand, M., Key, G., Herricks, E., King, R., Nohara, J.T., Gauthreaux, S. Jr., Begier, M., Bowser, C., Beason, R., Swift, J., Klope, M., Griese, H., and Dotur, C. 2011. Integration and Validation of Avian Radars (IVAR), ESTCP Final Report for Project SI-200723, Environmental Security Technology Certification Program (ESTCP), SPAWAR Systems Center –Pacific, San Diego, CA.

Bruderer, B., Steuri, T., and Baumgartner. 1995. Short-range high-precision surveillance of nocturnal migration and tracking of single targets. Israel Journal of Zoology 41:207-202.

Burger, J. 1983. Jet aircraft noise and bird strikes: why more birds are being hit. Environmental Pollution (Series A) 30:143-152.

Cleary, E. C., R. A. Dolbeer, and S. E. Wright. 2004. Wildlife strikes to civil aircraft in the United States, 1990-2003. U.S. Department of Transportation, Federal Aviation Administration, Serial Report No. 10, DOT/FAA/AS/00-6 (AAS-310). Washington, DC, USA. 55 pages (http://wildlife-mitigation.tc.faa.gov/).

Cleary, E. C., R. A. Dolbeer, and S. E. Wright. 2006. Wildlife strikes to civil aircraft in the United States, 1990–2005. U.S. Department of Transportation, Federal Aviation Administration, Serial Report No. 12 DOT/FAA/AS/00-6(AAS-310). Washington D.C. USA. 64 pages.

Cooper, B.A. 1996. Use of radar for wind power-related avian research. Pages 58-73 in Proceedings of National Avian-Wind Power Planning Meeting II. Prepared for the Avian Subcommittee of the National Wind Coordinating Committee by RESOLVE Inc., Washington, D.C., and LGL Ltd, Kind City, Ontario.

DeTect Inc. website. 2013. Technical Data Sheet: Merlin Aicraft Birdstrike Avoidance Radars.

DeVault, T.L., Belant, J.L., Blackwell, B.F., and Seamans, T.W. 2011. Interspecific variation in wildlife hazards to aircraft: implications for airport wildlife management. Wildlife Society Bulletin 35:394:402.

DeVault, T.L., Blackwell, B.F., and Belant, J.L., eds. 2013. Wildlife in Airport Environments: Preventing Animal-Aircraft Collisions through Science-based Management. John Hopkins University Press, Baltimore, MD, USA. 200 pp.

Dolbeer, R.A., Wright, S.E., Begier, M.J. & Weller, J. 2009. Wildlife Strikes to Civil Aircraft in the United States 1990–2008. Federal Aviation Administration National Wildlife Strike Database Serial Report Number 15. Washington, DC: Report of the Associate Administrator of Airports Office of Airport Safety and Standards & Certification.

Dolbeer, R., and Eschenfelder, P. 2002. Have population increases of large bird outpaced airworthiness standards for civil aircraft? Proceedings of the 20th vertebrate Pest Conference. University of California, Davis.

Dolbeer, R. A. and P. Eschenfelder. 2003. Amplified bird-strike risks related to population increases of large birds in North America. Pages 49-67 *in* Proceedings the 26th International Bird Strike Committee meeting, Warsaw, Poland (Volume 1).

Dolbeer, R.A. 2006. Height distribution of birds recorded by collisions with civil aircraft. The Journal of Wildlife Management, 70:1345-1350.

Dolbeer, R.A. and Seubert, J.L. 2006. Canada goose populations and strikes with civil aircraft: Positive trends for aviation industry. Poster presentation at 8th Bird Strike Committee USA/Canada meeting, St. Louis, Missouri, USA, 21-24 August 2006.

Dolbeer, R.A., Wright, S.E., Weller, J., and Begier, M.J. 2011. Wildlife strikes to civil aircraft in the United States, 1990-2011. Federal Aviation Administration National Wildlife Strike Database Serial Report Number 18. Washington, DC: Report of the Associate Administrator of Airports Office of Airport Safety and Standards & Certification.

Dolbeer, R.A. 2013. Appendix: Regulations for wildlife management at airports. In: Wildlife in Airport Environments: Preventing Animal-Aircraft Collisions through Science-based Management. T.L. Devault, B.F. Blackwell, and J.L. Belant, eds. Forthcoming from Johns Hopkins University Press, Baltimore, MD, USA. 200 pp.)

Federal Aviation Administration. 2010. Airport avian radar systems. Advisory Circular 150/5200-25. Federal Aviation Administration, Washington, D.C., USA.

Gauthreaux, S.A. Jr. 1972. Radar techniques for Air Force applications in avoidance of bird-aircraft collisions and improvement of flight safety. Interim technical report to Air Force Office of Scientific Research.

Gauthreaux, S. A. Jr., and Belser, C.G. 2003. Overview: radar ornithology and biological conservation. Auk 120:266-277.

Gauthreaux, S.A., Belser, C.G., and van Blaricom, D., Jr. 2003. Using a network of WSR-88D weather surveillance radars to define patterns of bird migration at large spatial scales. In: Berthold, P, Gwinner, E., Sonnenschein E, editors. Avian migration. Berlin: Springer. p. 335-346.

Gauthreaux, S.A. Jr., and Schmidt, P.M. 2013. Application of radar technology to monitor hazardous birds at airports. In: T.L. DeVault, B.F. Blackwell, and J.L. Belant, eds. Wildlife in Airport Environments: Preventing Animal-Aircraft Collisions through Science-based Management. Johns Hopkins University Press and The Wildlife Society.

Harmata, A.R. Podrusny, K.M., Zelenak, J.R., and Morrison, M.L. 1999. Using marine surveillance radar to study bird movements and impact assessment. Wildlife Society Bulletin 27:44-52.

Kelly, T.A. 1999. Seasonal variation in birdstrike rate for two North American raptors: turkey vulture (Cathartes aura) and red-tailed hawk (Buteo jamaicensis). Journal of Raptor Research 33:59-62.

Kelly, T. C., R. Bolger, and M. J A. O'Callaghan. 1999. The behavioural responses of birds to commercial aircraft. Proceedings of Bird Strike 1999:77–82.

Lack, D., and Varley, G.C. 1945. Detection of birds by radar. Nature 156:446.

Larkin, R.P. 1984. The potential of the NEXRAD radar system for warning bird hazards. Pages 369-379 in Proceedings of the Wildlife Hazards to Aircraft Conference and Workshop. Federal Aviation Administration, Charleston, South Carolina, USA.

Marra, P.P., Dove, C.J., Dolbeer, R., Dahlan, N.F., Heacker, M., Whatton, J.F., Diggs, N.E., France, C., and Henkes, G.A. 2009. Migratory Canada geese cause crash of US Airways Flight 1549. Frontiers in Ecology and the Environment 7:297-301.

Nohara, T.J., Weber, P., Ukrainec, A., Premji, and A., Jones, G. 2007. An overview of avian radar developments: Past, present and future. Proceedings of the 9th Annual Bird Strike Committee USA/Canada Meeting, Kingston, Ontario, Canada.

Nohara, T.J. 2009. Could avian radar have prevented US Airways Flight 1549's bird strike? Proceedings Bird Strike North America Conference, Paper 3: unpaged. Victoria, British Columbia, Canada.

Richardson, W. J., and T. West. 2000. Serious birdstrike accidents to military aircraft: updated list and summary. Pages 67-98 *in* Proceedings of 25th International Bird Strike Committee Meeting. Amsterdam, The Netherlands.

Russell, K.R., Mizrahi, D.S., and Gauthreaux, S.A. 1998. Large-scale mapping of purple martin pre-migratory roosts using WSR-88D weather surveillance radar. Journal of Field Ornithology 69:316-325.

Thorpe, J. 1996. Fatalities and destroyed civil aircraft due to bird strikes, 1912-1995. Proceedings of the International Bird Strike Conference 23:17-31.

Weber, P., Nohara, T.J., and Gauthreaux, S. 2005. Affordable, real-time, 3-D avian radar networks for centralized North American bird advisory systems. Proceedings Bird Strike Committee USA/Canada, Vancouver, British Columbia, Canada (abstract only).

Wood. S.N., 2006. Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC, Boca Raton, FL.

Zakrajsek, E.J. and Bissonette, J.A. 2005. Ranking the risk of wildlife species hazardous to military aircraft. Wildlife Society Bulletin 33:258-264.