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Beware the Boojum: caveats and strengths of avian radar

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Abstract: Radar provides a useful and powerful tool to wildlife biologists and ornithologists. However, radar also has the potential for errors on a scale not previously possible. In this paper, we focus on the strengths and limitations of avian surveillance radars that use marine radar front-ends integrated with digital radar processors to provide 360° of coverage. Modern digital radar processors automatically extract target information, including such various target attributes as location, speed, heading, intensity, and radar cross-section (size) as functions of time. Such data can be stored indefinitely, providing a rich resource for ornithologists and wildlife managers. Interpreting these attributes in view of the sensor's characteristics from which they are generated is the key to correctly deriving and exploiting application-specific information about birds and bats. We also discuss (1) weather radars and air-traffic control surveillance radars that could be used to monitor birds on larger, coarser spatial scales; (2) other nonsurveillance radar configurations, such as vertically scanning radars used for vertical profiling of birds along a particular corridor; and (3) Doppler, single-target tracking radars used for extracting radial velocity and wing-beat frequency information from individual birds for species identification purposes.

Key words: aircraft, avian radar, BASH, bird strike, conservation, environmental impact assessment, human–wildlife conflicts, mobile radar, marine radar, natural resource management, ornithology

In the midst of his laughter and glee,
He had softly and suddenly vanished away—
For the Snark was a Boojum, you see.
The Hunting of the Snark *by Lewis Carroll*

In his tale of the Snark, Lewis Carroll cautions us not to accept a statement as true simply because it has been repeated frequently. If we accept statements unquestioningly, we position ourselves for failure. Radar is a versatile tool that enhances a biologist's ability to detect, track, and monitor the activity of animals on a scale not possible with other techniques. However, it is not without its limitations, and attempts to extract types of data that are beyond its capability can create methodological traps that result in the Snark being a Boojum, reaching inaccurate conclusions. Both analog and digital avian radar systems require training and experience to interpret the displays correctly. Neither form is user-friendly enough that a naïve researcher can turn the systems on, push a button, then sit in front of a display and immediately interpret the system's output.

Weather radars (Gauthreaux and Belser 2003) and air-traffic control radars (Beason 1978, 1980; Gauthreaux 1991; Troxel et al. 2001, 2002) have been used to monitor the movements of birds, especially during migration (Figure 1). Smaller, lower power, marine radars have been used for basic and applied research applications in (1) locations that are distant from the larger radars, (2) locations where larger radars are shielded in their coverage by terrain, and (3) locations where higher resolution is needed to track movements of small flocks or individual birds. Larkin (2005) reviewed and compared the characteristics and uses of the various types of radars. In this paper, we focus on the strengths and limitations of avian radars. We define avian radars as systems designed for tracking individual or groups of birds out to about 20 km from the radar. Typically, they are based on commercial, off-the-shelf marine radar sensors. The radar's standard or custom-developed antenna and transceiver associated with these sensors provide the signals that are processed by the avian radar's signal processor.

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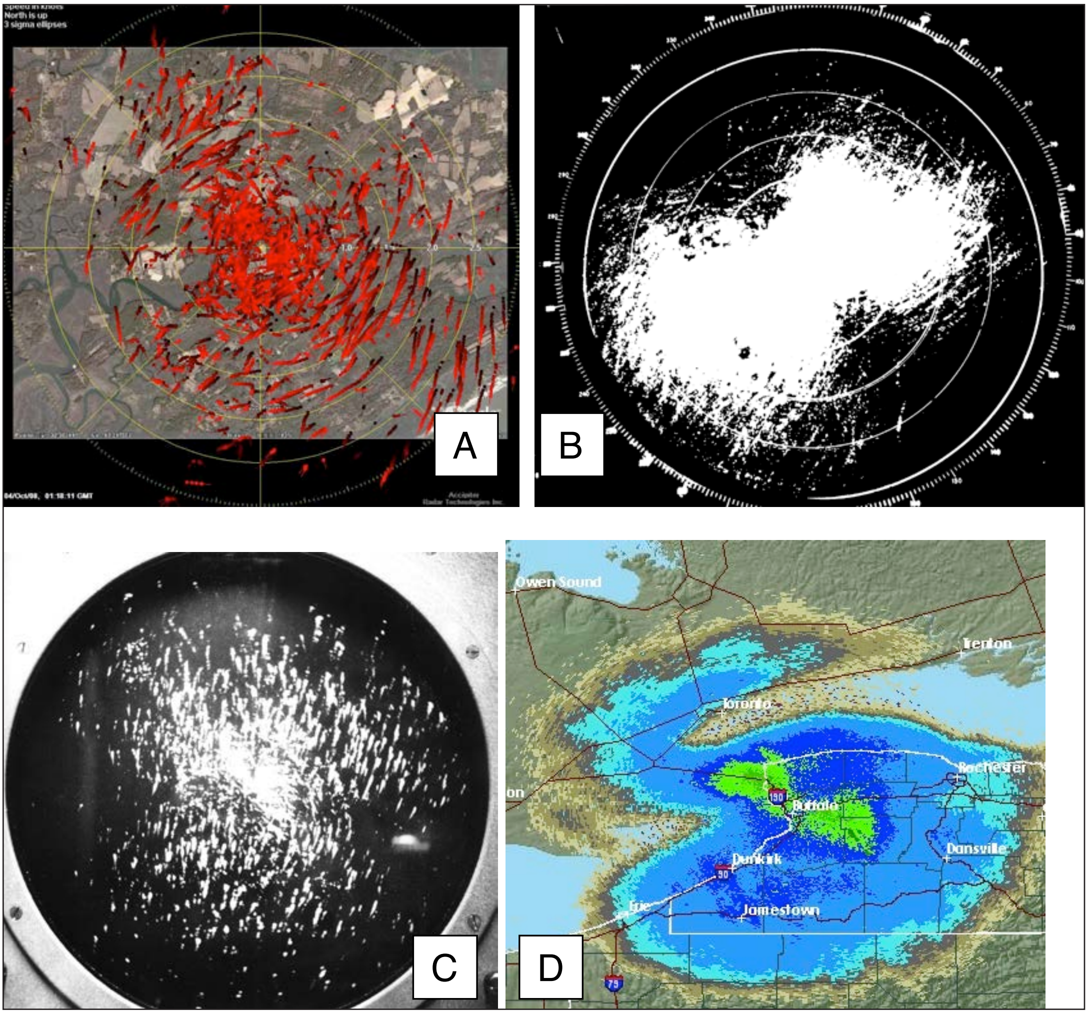

Figure 1. Birds as they appear on different types of radar: (A) digital X-band avian radar; (B) airport surveillance radar; (C) Federal Aviation Administration air route surveillance radar (en route); and (D) WSR-88D weather radar. The white stippling, or streaks, in B and C are produced by radar echoes of birds. Display ranges (distances from the centers of the displays to the edges) are: A = 6.5 km; B = 7 km; C = 70 km; D = 140 km.

The processor can be as simple as a radar plan position indicator (PPI) display, requiring a dedicated operator, or more advanced, incorporating a modern, automatic digital radar processor (DRP). Digital radar processors are typically based on commercial, off-the-shelf computer technology running specialized radar processing software designed for detecting and tracking birds.

Our objective is to provide wildlife biologists and ornithologists with the knowledge and background to select and use analog and digital avian surveillance radars in their investigations. With such knowledge, researchers can accurately interpret their data and draw conclusions that are backed by the physics of the equipment. Avian surveillance radars have benefited from significant technological advances over the past decade. By surveillance radars, we mean those avian radars that provide 360° of continuous, real-time coverage. Hence, they address (1) the general surveillance problems associated with monitoring bird migration and (2) applied management applications, such as population monitoring of endangered and threatened species, natural resources, and bird–aircraft strike hazards. We also review avian radar sensing as a background for understanding the application of the target information they produce.

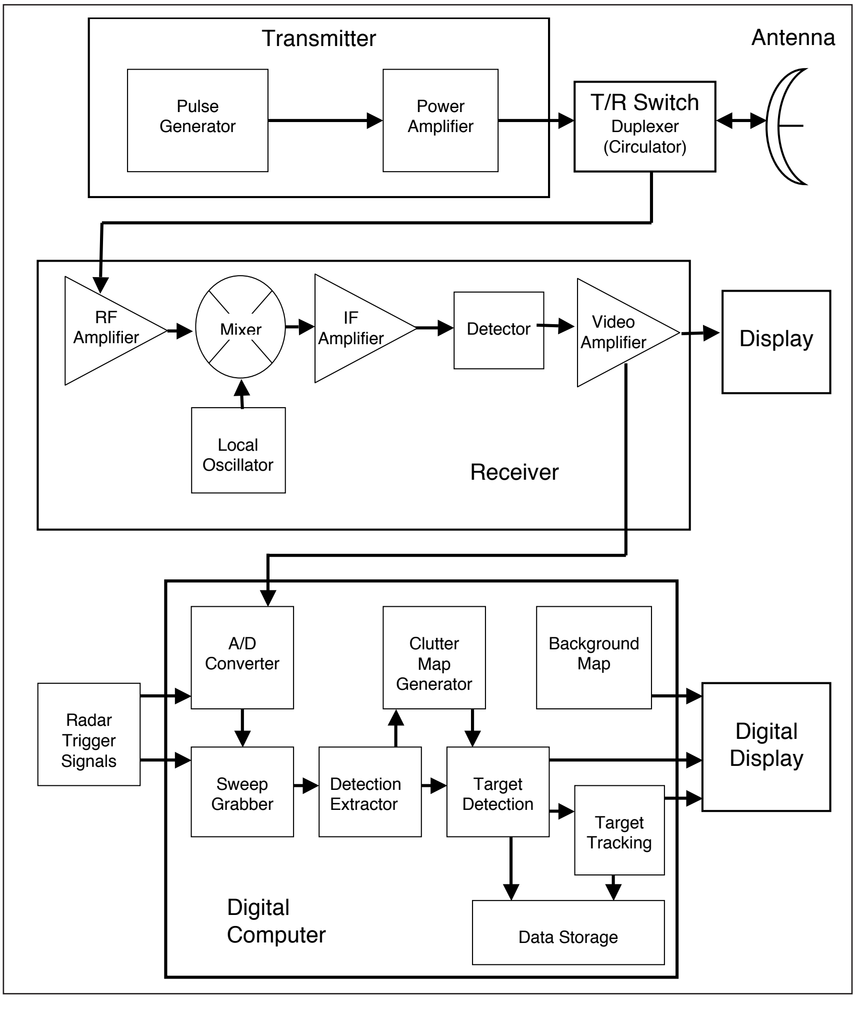

Figure 2. Block diagram of avian radars illustrating analog and digital pathways for radar signals. T/R Switch = transmit-receive switch; RF Amplifier = radio-frequency amplifier; IF Amplifier = intermediate-frequency amplifier; A/D Converter = analog to digital converter.

Radar basics

The acronym RADAR is derived from the term RAdio Detection And Ranging. An avian radar scans a local volume of air above and surrounding its location; typical coverage is limited to 0 to 10 km range, 360° azimuth, and 0 to 1,500 m altitude. The sensor concept is flexible in terms of radar frequency, beam shape, and scanning pattern. These sensors are typically mounted on or near the ground, on a rooftop, or on a short tower. If installed on a trailer or vehicle, the radar system is easily movable.

State-of-the-art digital avian radar systems provide continuous, day-or-night, all-weather, local, and wide-area situational awareness with automated detection, tracking, localization in earth coordinates, and specialized alerts of avian activity. They can be part of a network of radars operating together to increase coverage at a particular location or to provide a composite picture for a local, regional, national, or continental monitoring system (Weber et al. 2005). Such avian radars are also designed to minimize operator interaction and, in so doing, increase the productivity of the biologist.

Marine radar transceivers

Marine (or maritime) radars are produced by several manufacturers worldwide for maritime navigation applications that typically concern the detection of shorelines and tracking vessels. Such sensors are available with a variety of power and antenna options, each of which affects the radar's operational characteristics with regards to detecting birds, which are much smaller than the intended targets of marine radar sensors. The principle of operation for marine radars is similar to larger, more powerful systems, such as air-traffic control or military radars. Radar systems are a combination of a radio transmitter and radio receiver (together termed the transceiver) connected to an antenna (Figure 2). A sequence of pulses of radio frequency (RF) energy is emitted from the radar transmitter and sent to the antenna by way of a hollow, rectangular wave-guide. The antenna directs the pulses (comprising the waveform, described below) away from the unit. The antenna also receives the RF energy, referred to as backscatter radiation, or echoes, that are reflected from objects illuminated by the transmitted pulses. The received echo signal passes through several stages within the receiver, where it goes by different names, depending on its characteristics (Figure 2).

Commercial, off-the-shelf marine radar sensors are available in 2 licensed bands: X-band and S-band. X-band sensors outnumber their S-band counterparts by about 25:1 (Briggs 2004). S-band units have a wavelength of about 10 cm and a frequency of about 3 GHz. The two differ in many ways and require careful selection for use as avian radars (Appendix 1).

One compelling argument cited for using an S-band sensor is its better performance in rain, but this requires careful consideration. Recently introduced, solid-state, X-band marine radar sensors with coherent rain clutter suppression capabilities in their transceivers may negate any theoretical advantage S-band might have had in rain. One factor in favor of X-band is the typically larger avian radar cross-sections (RCS, discussed below) at X-band as compared to S-band radar (Briggs 2004).

As a pulse of RF energy travels away from the antenna, its power density decreases as a function of distance. This means that the farther an object is from the antenna, the less energy that strikes it. Depending on its composition, the object scatters some fraction of the energy back toward the antenna, and we refer to it as the object's echo. The reflected echo similarly suffers from loss of power density as it returns to the antenna. The distance of each object from the radar is determined from the time it takes to receive its round-trip echo; the relationship is a constant ratio of about 150 m μs^{-1}, where μs is microseconds. The direction of each object from the antenna is encoded by circuitry associated with the antenna positioner. In conventional radar systems, the echo signal is presented on a Plan Position Indicator (PPI) display (Figure 2) with the antenna position located at the center of the display. The brightness and extent of the echoes represented on the display are functions of the strength of the reflected echo signal, the beamwidth of the antenna, the range resolution of the waveform, and the physical extent of the target (e.g., single bird versus a large flock).

Radar waveform

Pulsed radars transmit a high-powered signal (e.g., 25 kW) for a short time, then remain silent while the receiver receives echo signals reflected from objects in the outgoing path. The outgoing pulse is termed the pulse waveform. The waveform is approximately rectangular (constant amplitude) and is characterized by the length of time it is on (i.e., the pulse width). The ratio of the on-time to the off-time is referred to as the duty cycle of the waveform and is typically <0.1% for magnetron-based marine radars, producing an average power (duty cycle × peak power) in the range of 10 to 20 Watts. It is average power, not peak power, that determines detectability of targets. Commercial, off-the-shelf marine radars are configured such that specific waveforms are associated with individual range-scale selections. Shorter pulses (<0.1 μs) are associated with shorter range scales (0 to 3 km) and longer pulses (>1 μs) with longer-range scales (5 to 175 km); although ≥1 pulse might be available for an individual range scale. Shorter pulse widths allow the radar operator to discriminate objects that are at slightly different distances from the radar and thus have better range resolution capability. Long pulses, on the other hand, increase the likelihood that a weak, distant target will be detected.

Some recently introduced marine radars use a very long, expanded pulse on transmit combined with a pulse compression technique in the receiver. This process reduces the effective received pulse duration and, thus, achieves comparable range resolution. Pulse compression is commonly used in radar to reduce the peak power requirement of the transmitter while maintaining average power. This allows solid-state amplifiers to be used in place of magnetrons for generating the waveform with greater flexibility in waveform design.

Although most radars that are used to detect biological targets are pulsed, some produce an uninterrupted signal and are called continuous wave (CW) radars. Such radar units (e.g., older-style, traffic radar guns) were originally designed to measure the speed of vehicles, but they have also been used to measure the flight speeds of birds (Evans and Drickamer 1994; Schnell 1965, 1974). However, CW radars have very limited ability in locating targets, while pulsed radars excel at this. CW radars can determine the Doppler frequency shift caused by a moving object that is proportional to its velocity. Traditional magnetron-based, pulsed radars do not have Doppler shift measurement capability but, rather, measure true target velocity (and position) through tracking. Recently introduced solid-state marine radars measure Doppler shift and can filter based on Doppler, but they typically do not output this information for downstream processing.

Antennas

The constraints of the radar antenna prevent the radar from detecting all birds at all altitudes. The volume sampled and its shape are influenced by the antenna and the radiation pattern it produces. Standard marine radar antennas (e.g., 2-m T-bar or slotted-array antenna) provide high gain, good azimuth resolution (~ 1.2° at X-band), and elevation coverage, but poor elevation resolution (~20°) because of the fan beam shape. In the usual horizontal-scanning configuration (referred to herein as a horizontal array) 2-D trajectories of individual birds can be resolved, providing latitude and longitude updates of bird positions about every 2.5 seconds. Altitude is not resolvable due to the poor elevation resolution.

If oriented in a vertical-scanning configuration (referred to herein as a vertical array), 2-D trajectories of birds over the ground are no longer resolvable, because the fan beam is now orientated in the horizontal plane, resulting in poor horizontal resolution. Horizontal coverage is extremely limited, but bird passage rates and flux and altitude distributions (Figure 3) are readily measurable along the bearing line on which the vertical scanning array is oriented.

Parabolic dish antennas reduce instantaneous

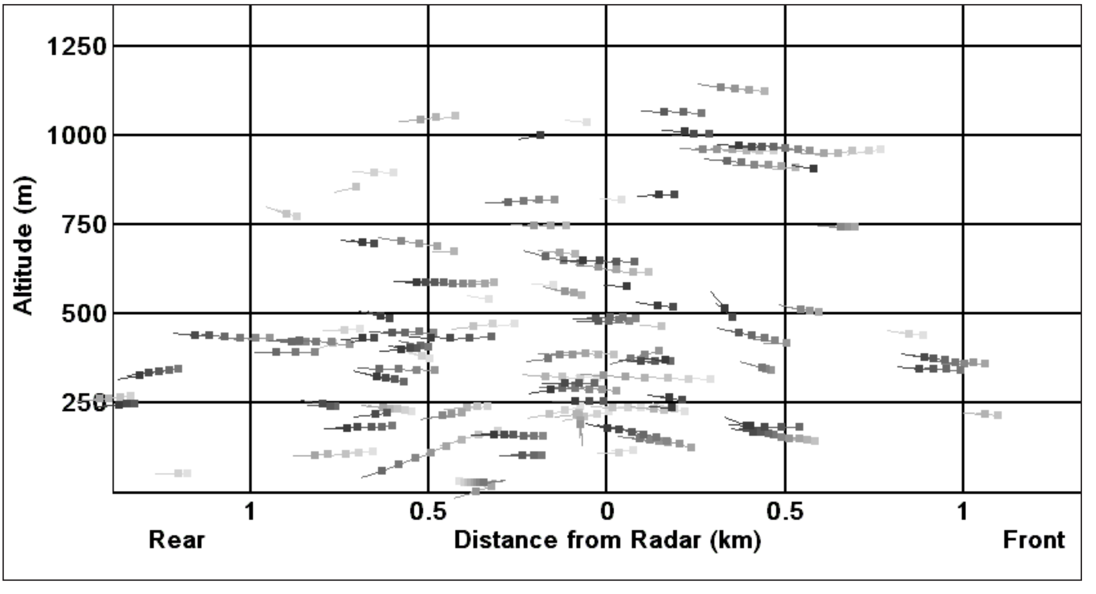

Figure 3. The display of an X-band radar that is modified so that it turns an array antenna in the vertical plane. This results in range and altitude information for the targets but not precise track information. Target track symbols (black and gray symbols) document the altitude of bird targets and show whether the birds are moving more-or-less toward or away from the radar.

Table 1: Avian radar antennas and their characteristics.

Antenna type	Resolvable information	Typical surveillance coverage volume
Horizontal array	2-D trajectories (latitude, longitude)	Azimuth: 0 to 360° Elevation: -10 to 10° or 0 to 20° with up-tilt
Vertical array	Passage rate-flux and altitude distribution along a single bearing line	Azimuth: -10 to 10° and 170 to 190° Elevation: 0 to 90° Aligned to particular bearing
Dish	3-D trajectories (latitude, longitude, altitude)	Azimuth: 0 to 360° Elevation: -2 to +2° from mid-elevation Aligned to particular elevation
Multibeam dish	3-D trajectories (latitude, longitude, altitude)	Azimuth: 0 to 360° Elevation: -4° to +4° from mid-elevation Aligned to particular elevation
Dual-axis scanning dish	3-D trajectories (latitude, longitude, altitude) Passage rate-flux and altitude distributions along all bearing lines.	Azimuth: 0 to 360° Elevation: 0 to 90° Complete coverage of atmosphere

Table 2: Avian radar configurations suitable for various applications.

Application	Data required	System
Airport surveillance, migration study	2D trajectories	Horizontal array
Airport surveillance, migration study	3D trajectories	Horizontal dish
Turbine study	Passage rates; altitude distribution	Vertical array
Migration study	Localized vertical profile	Vertically-pointing dish
Turbine study, airport surveillance	2D trajectories; altitude distribution along single bearing	Horizontal array and vertical array
Migration study, airport surveillance	3D trajectories with full volume coverage	Dual-axis scanning dish
Airport surveillance	3D trajectories with greater instantaneous volume coverage	2 horizontal dish radars at different elevation settings

elevation coverage and azimuth resolution in favor of better elevation (altitude) resolution (Figure 4). Consequently, 3-D trajectories of individual birds can be resolved with dish antennas, providing latitude, longitude, and altitude updates of bird positions about every 2.5 seconds.

Is a parabolic reflector (dish) antenna or a slotted array (T-bar) antenna better for detecting and tracking birds? The answer depends on the user's needs. The antenna's design determines how focused the outgoing pulse of energy is (Figure 4). The typical pattern from an unmodified marine radar antenna is a vertical, ellipsoidal fan-shaped pattern with half-power beam extent from 10° above the horizon to 10° below. This results in half of the transmitter's energy being projected at the ground (i.e., wasted). Fan beam antennas have been modified so that they can be tilted upwards, placing the main beam above the horizontal (Beason 1972). This orientation effectively doubles the detection volume (vertical coverage) of the system without any increase in energy, and reduces the intensity of ground clutter returns only marginally because of the broad shoulders associated with the broad vertical beam pattern. The horizontal beam width and azimuth resolution are dependent on the length of the antenna and the radar's wavelength. A 2-m X-band array antenna will have a horizontal resolution of 1.2°, while a 2-m S-band antenna will have a horizontal resolution of 3.6°, which is similar to a typical X-band dish antenna.

A parabolic dish antenna produces a spotlight type of beam (also referred to as a focused beam or pencil beam) that has the same vertical and horizontal beam widths, with the beam's diameter inversely proportional to the dish's diameter. A smaller diameter beam (from a larger diameter dish) results in detection of objects at greater ranges and with better azimuth and altitude precision. Conventional dish antennas available for X-band operation have mechanically or electronically adjustable mounting hardware that allows the operator to tilt the antenna to a desired elevation angle to provide the volume coverage needed for monitoring specific altitudes. The focused beam allows significant ground clutter reduction when tilting the beam above the horizontal. As a result, X-band dish antennas have been shown to provide excellent clutter rejection. Because of comparatively less ground clutter, a dish antenna is often able to detect birds close to the radar when an array antenna cannot (Figure 5), and a dish antenna usually detects more birds overall when operated on land in comparison to an array when clutter is present. The trade-off is that a 4° dish antenna has a wider horizontal extent than an array antenna with a 1.2° horizontal beam. This reduces the azimuth precision of the targets.

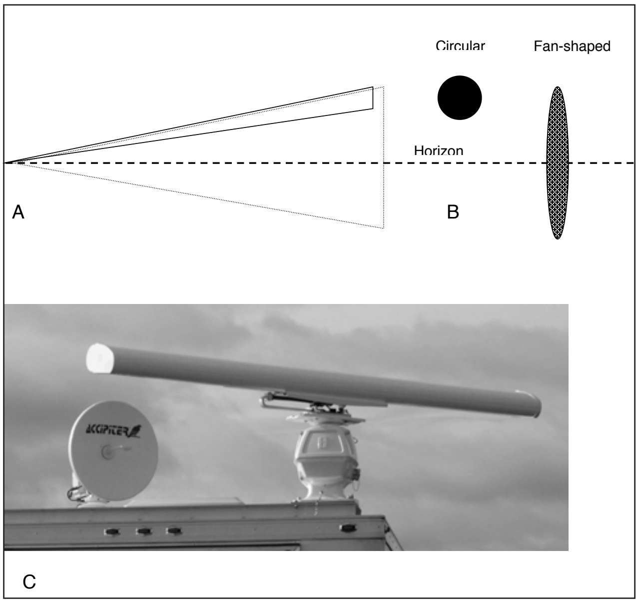

Figure 4. Comparison of the characteristics of parabolic dish (solid line and circle) and slotted array (dotted lines and oval) antennas. The dashed line represents the horizon relative to the beam patterns. The slotted array pattern projects above and below the horizon: (A) Longitudinal section through the beam patterns; (B) Cross-section through the beam patterns; (C) Photograph comparing dish (left) and array (right) antennas.

Next generation antennas that represent variations to the aforementioned pencil-beam pattern have been shown to provide significantly improved capabilities. Multi-beam designs based on the pencil beam (Nohara 2009, Beason et al. 2010*b*) provide about 8° of instantaneous vertical coverage (similar to an array) while improving vertical elevation resolution to better than 1°. A dual-axis scanning dish antenna that rotates horizontally and that also scans vertically at a much slower rate in accordance with a user-specified pattern, provides any desired vertical coverage between 0 to 90° (Table 1).

The differences between antenna types are significant and hence critical to meeting the user's requirements (Tables 1, 2). Therefore, the antenna to select depends on the application of interest. If a study is being carried out, for example, at a proposed wind farm location where all that is required are passage rates and altitude distributions along a particular bearing line, a vertical array will work quite nicely. In airport applications where warning of birds approaching and present in aircraft arrival and departure corridors is a first priority, bird trajectories are needed. Trajectories also provide information on where the birds both are coming from and heading toward. Hence, horizontal arrays and dish antennas are the tools of choice. If only 2-D trajectories are needed, then horizontal arrays work well. If 3-D trajectories are required and if ground clutter is a challenge, then dish antennas will be more suitable. Combinations of antennas can also be used to meet coverage and information requirements.

Figure 5. A comparison of the displays from an array-equipped radar (A, C) co-located with a dish-equipped radar (B, D). The lines of square symbols (arrows) on the digital displays (A, B) represent the tracked locations of birds, with the brightest symbols representing the most recent update and the darkest symbols the oldest. The array-equipped system is more sensitive to ground clutter than the one with the dish antenna, which detects more birds and tracks them farther. The white and gray areas on the analog plan position indicator (PPI) video displays (C, D) represent areas of ground clutter.

Radar echoes from point targets

The strength or amplitude of the reflected signal (echo) is influenced by the radar's wavelength and the object's size, composition, and orientation and its distance from the radar. Larger, discrete targets (e.g., aircraft) will typically produce stronger echoes than smaller, discrete targets (e.g., songbirds) at the same distance. However, as Stealth aircraft demonstrate, the material composing the object greatly influences the intensity of the returned signal. Metal and water are very good reflectors of microwave energy. Because birds are composed of about 90 to 95% water, they reflect microwaves well (Eastwood 1967). Poorly conducting tissue, such as feathers and chitin, are essentially transparent to radar (Edwards and Houghton 1959). Consequently, the radar's view of a biological target would differ from that of a visual observer.

The radar cross-section is a measure of the reflecting size of an object. The RCS for a given target differs for different wavelengths. Physically larger animals do not necessarily generate stronger echoes. The intensity of the reflected signal can be influenced by too many

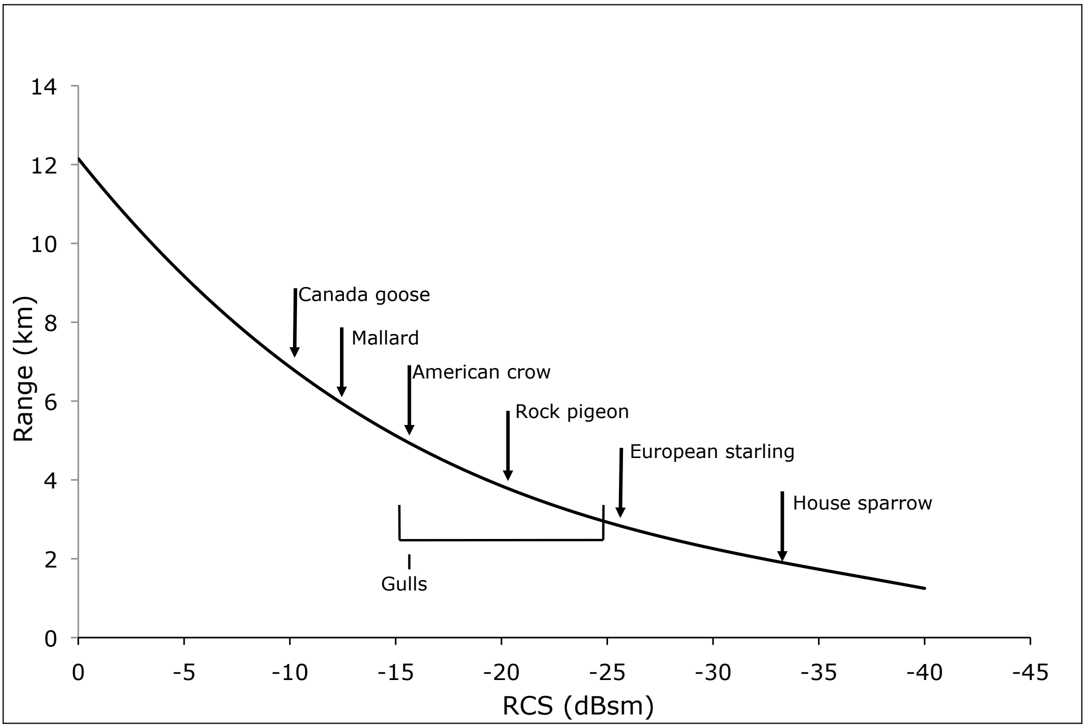

Figure 6. The relationship between bird size and the calculated maximum range at which it can be detected. Radar Cross Section (RCS) is in units of decibels relative to a square meter (dBm^2). An RCS of 0 dBm^2 is equivalent to a target with a surface area of 1 m^2; a target with an RCS of -40 dBm^2 would have a surface area of 1 cm^2. RCS values are from Blacksmith and Mack (1965), Eastwood (1967), Edwards and Houghton (1959), and Vaughn (1985). The range calculations are based on a pulsed X-band radar with 50 kW peak power, 80 ns pulse width, and an antenna gain of 31 dB. Canada goose (*Branta canadensis*), allard (*Anas platyrhynchos*), American crow (*Corvus brachyrhynchos*), rock pigeon (*Columba livia*), European starling (*Sturnus vulgaris*), house sparrow (*Passer domestica*); gulls (*Larus* spp.).

factors to reliably indicate body size. Radar cannot precisely measure the sizes of birds, even within controlled test facilities (Edwards and Houghton 1959), but it can be used to provide a rough estimate of size (Nohara et al. 2011). Factors, such as the orientation of the animal and its appendages to the radar antenna (Dybdal 1987, Edwards and Houghton 1959), and the uncalibrated nature of marine radar receivers preclude the accuracy needed.

The orientation of an object relative to the radar beam (i.e., its aspect angle) influences the amount of the signal that is reflected to the antenna. Other than spheres, most objects have a greater cross-section when viewed from 1 angle than others. Birds have an ovoid shape and have their largest cross-section when they are viewed from the side. The changes in aspect angle as a bird or other object moves through the air accounts, in part, for the changes in reflected signal amplitude from the object from 1 antenna revolution to the next (see Figure 2 in Nohara et al. 2011). On some revolutions, the reflected signal is too weak for the radar receiver to detect, and no echo is displayed. When there are moderate to large numbers of small birds migrating dispersed in the airspace, the radar display shows a scintillation effect that is especially obvious when recorded and then played back at a faster speed.

Is the spatial extent of a target's echo as displayed on a radar PPI display indicative of its physical size? The answer to this question is also complex. First, we need to distinguish between point targets and extended targets. Point targets are small in comparison to the radar resolution cell, which has its size determined by the radar's range and angle resolution capability. Extended targets, on the other hand, are physically larger than the resolution cell in at least 1 dimension. With radar, the width of the beam in space (i.e., the cross-range width) increases linearly with range. Consider a radar with a 10-m range resolution and a 1°-azimuth resolution. At a distance of 1 km from the radar, the cross-range resolution is 1,000 m × tan (1°) = 17.5 m.

Because a single bird, whether a sparrow or goose, is well-contained within the 10- × 17.5-m resolution cell, it would be considered a point target. The echo on the radar display from such a point target will have an extent approximately equal in size to the resolution cell. Therefore, one cannot extract bird size information from the echo extents of point targets. Similarly, 2 birds flying close together within a resolution cell will appear as a single point target. However, a large flock of European starlings (*Sturnus vulgaris*) spanning 100 m would be viewed by the radar as an extended target because it spans several contiguous resolution cells. As a result, there is size information of the flock in the echo extent of an extended target.

The ability of radar to detect birds and the distance (Figure 6) at which they can be detected are described by the Radar Equation (Appendix 2). There are many characteristics of the radar, environment, and the birds that affect a radar's sensitivity. Those unfamiliar with the radar equation are encouraged to read the discussion in Appendix 2.

Confounding factors

Marine radars used to study birds are powerful enough and the receivers sensitive enough that birds would be easily detectable if they were visible and isolated from other objects. What makes detection difficult is the presence of shadowing and clutter. A single radar might not always be able to cover the desired volume. It will have blind regions where targets are not detectable because they are (1) obstructed by closer objects (shadowing), (2) masked by strong reflections from clutter scatterers that appear in the same or nearby resolution cell(s), and (3) too distant to have sufficient energy returned to the radar. One way to mitigate shadowed regions is to deploy multiple radar sensors, each one augmenting the covered area, until the desired total coverage is reached. A means to improve a system that has clutter that obscures targets would be to remove vegetation in selected areas where needed most. Clutter fences, whether natural or artificial, can reduce clutter beyond the fence but will shadow targets near the ground (Figure 7). Natural fences include berms and treelines, while an artificial one could consist of a wire fence of a height slightly greater than the antenna at a distance of about 3 to 5 m. The relative benefits of vegetation removal versus radar fences depends on the user's need to track low-flying targets. As a result of these factors, radar performance is strongly affected by how the radar is configured and sited. For permanent installations, performance can be significantly enhanced by carrying out a site assessment before deployment. During this assessment, the radar itself, with different antennae, is used to map the clutter, coverage, and interference for a number of possible sites. The site and radar configuration can then be selected to best meet local requirements.

Surface clutter

Radars detect many stationary and moving objects in the environment around them. One of the most serious confounding factors to tracking birds is what is referred to as ground clutter. Ground clutter is the result of reflections from stationary or nearly stationary objects on the ground, such as buildings, trees, and the ground itself (hills, mountains, even furrows of plowed fields). The large extent of ground clutter and the strength of the reflected signal can make it difficult or impossible for an operator to discriminate birds moving within the area covered by the clutter (Figure 7).

The extent of ground clutter is influenced by the height of the antenna above the ground, its beam pattern, and its angular elevation. The radar horizon is determined by the height of the antenna and the curvature of the earth. If the center of the antenna is pointed horizontally, ground clutter will be detected out to the radar horizon. Thus, the higher the antenna is, the farther the horizon and extent of clutter. The stationary nature of ground clutter provides an avenue to remove it from the displayed radar image. However, it is often not possible to detect birds flying over the regions where the clutter is removed.

Objects on the ground can also block the radar's signal and generate "radar shadows". These are areas in which an object is shielded from the radar signal, preventing its detection (Figure 7). In this case, there is no opportunity to remedy the effects of the ground obstruction other than to install additional radar sensors. Buildings, water towers, trees, and mountains are the most frequent causes of radar shadows.

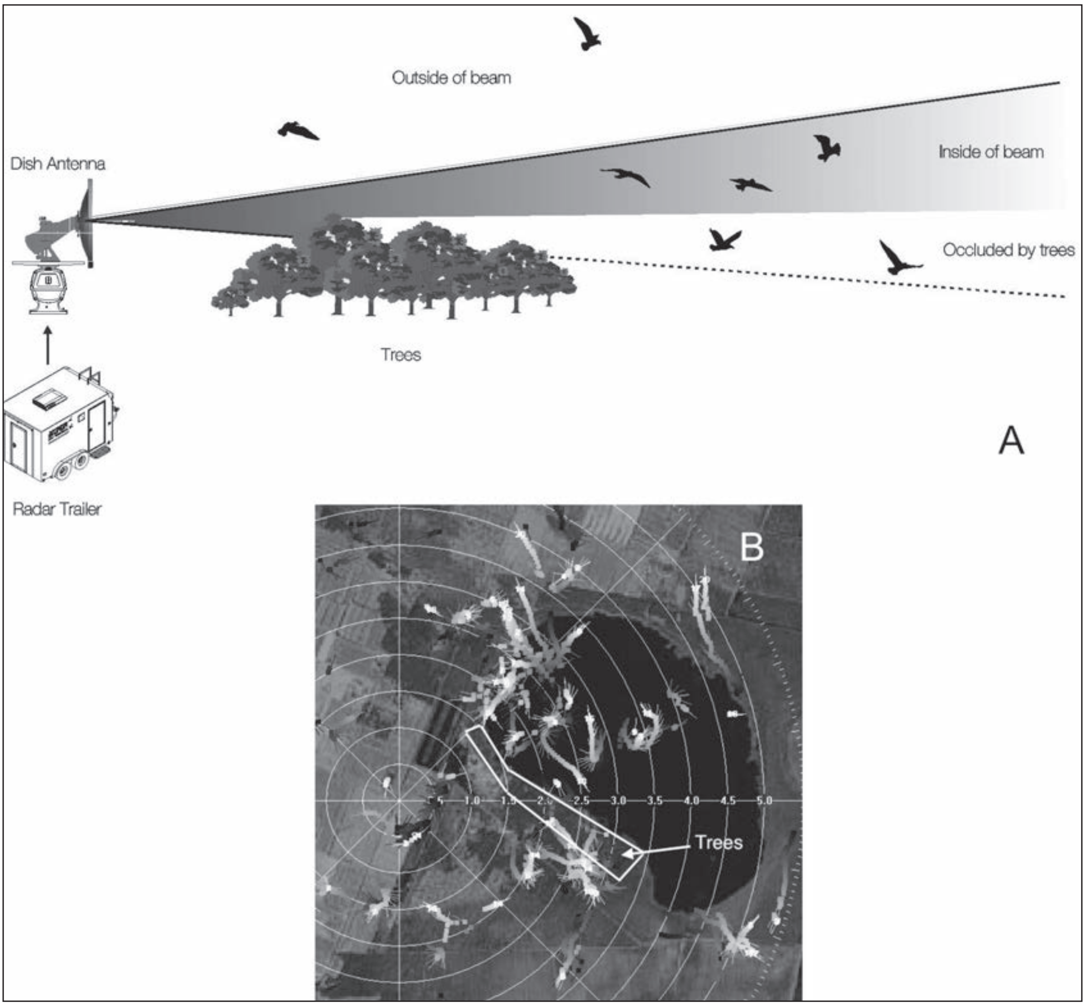

Figure 7. (A) Schematic showing the effects of radar shadows and fences. The lower birds on the right are shadowed by the trees and are not detectable by the radar. The echo from the bird above the trees would be overwhelmed by the strong signal reflected by the trees and, thus, the birds are not detectable. The upper right birds are in a clutter-free area created by the trees shadowing the ground and are, thus, easily detected. (B) A radar display showing the effects of trees shadowing the clutter below birds flying over and around the lake.

If birds are high enough to be above the radar shadow and low enough to still be within the radar beam, they will be more easily detected than without the shadow, because the ground clutter beneath them has been shielded (Figure 7). Clutter fences use this principle to reduce the effects of ground clutter.

Volume clutter

Precipitation can confound the radar display and obscure echoes produced by birds in the same resolution cells. Unlike ground clutter, precipitation echoes move at speeds similar to bird targets and are more difficult to remove without also removing the birds themselves. Precipitation clutter will inhibit detection of birds in the same way that ground clutter does. However, digital avian radar systems that employ adaptive clutter suppression can maintain near-optimum performance levels in those regions of the coverage volume without precipitation (see “Detection processing”, below). Under unusual circumstances, moving localized weather cells can produce long tracks that resemble birds, except that they move at the velocity of the wind. Without knowledge of the wind, an observer might mistake these weather echoes for birds (Figure 8).

There is greater backscatter per-unit-volume of rain at X-band than at S-band. However,

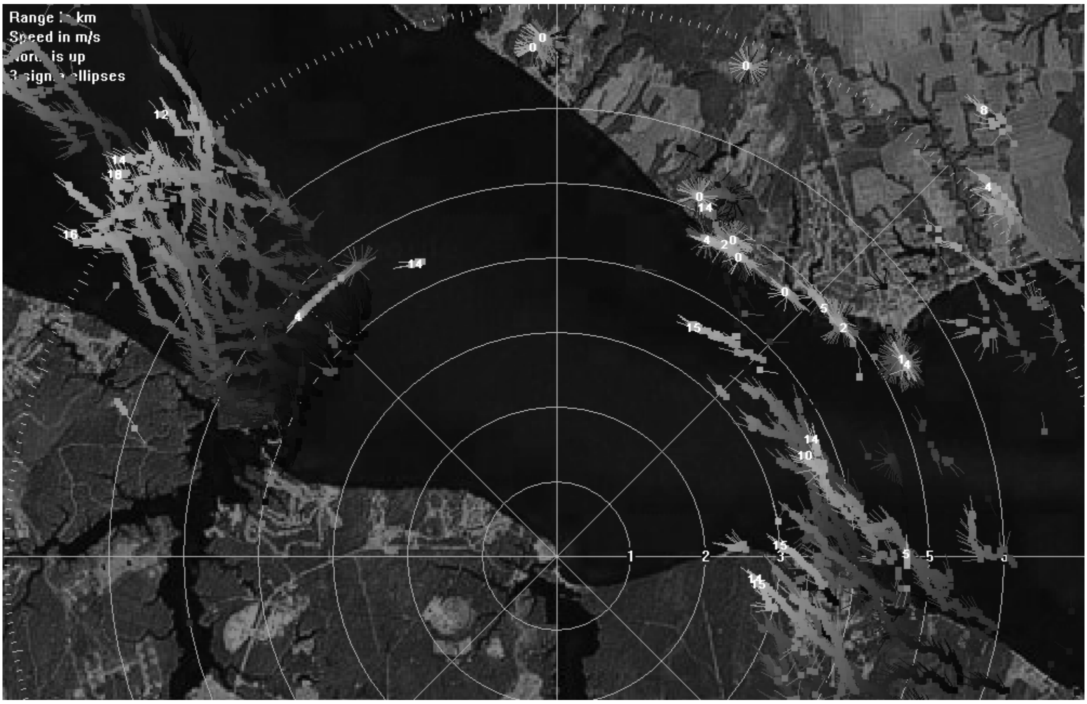

Figure 8. An example of radar echoes that mimic returns from birds. In this example the presumed flocks moving up the river are actually cohesive rain cells that are being tracked by the radar. The numbers at the head of the track are the speeds of each cell in m s^{-1}. Because the echoes move downwind at near the speed of the wind, they cannot be birds. Visual observations confirmed that there were no birds present.

an S-band sensor typically has much larger volume resolution cells to contend with than its X-band counterpart for the antenna-size reasons described above. The 2 effects tend to offset each other, so that rain clutter levels are not that different between X and S-bands (Briggs 2004).

In addition to reflecting radar signals, moisture, especially in the form of precipitation, also attenuates the radar signal. Consequently, strong precipitation diminishes the ability of the radar to detect birds that are beyond the precipitation, especially for wavelengths of 10 cm and shorter. This attenuation is important to keep in mind if there are strong showers scattered over an area and birds are being tracked between the showers. In this situation, birds might appear to vanish behind a rain cell but in fact are shadowed by the rain. Because X-band's 3-cm wavelength is closer to the peak absorption frequency of water (1.3 cm) than S-band's 10-cm wavelength, X-band signals are attenuated more by rain. However, the amount of attenuation is usually minimal at the short ranges used by avian radar operators (Bean et al. 1970). When precipitation is light (e.g., 1 cm/hour) the attenuation is approximately 0.01 dB/km for S-band radar, and 0.15 dB/km for X-band radar. Thus, even for a bird that is 5 km away, the total amount of attenuation is negligible.

Insects also can produce clutter on the display. If they are near enough to the antenna, large insects or high densities of insects will reflect enough signal that the receiver can detect them. Generally, insects move at about the same velocity as the wind. This makes it easy to distinguish them from small birds, which move faster than wind and in directions other than downwind, but it makes it difficult to remove their echoes with ground clutter removal techniques. Post-detection processing techniques can be used to filter out insect tracks (e.g., using RCS estimates). In some locations where clouds of insects span large regions, radar echoes from insects can be large enough to obscure bird echoes, especially those from small birds.

Large numbers of small birds can sometimes appear like volume clutter if the radar resolution cell is large enough and the density of birds is great enough (Figures 1B, 1D). Then, the bird echoes are not isolated and appear like an extended target (see earlier discussion). Replaying the radar PPI display (faster than real time) shows an illusion of drifting snow moving in the direction of migration.

Undesired target clutter

Avian radars designed to track birds will also detect man-made targets, such as vehicles and aircraft. The location and habitat of the radar site have a dramatic impact on the number of these undesired targets. Sites near roadways will have patterns of vehicular traffic unless the radar is shielded by vegetation or a radar fence. Detections from vehicular traffic can result even when the targets are below the beam if they are of high enough RCS to be detected in the antenna side-lobes. The impact of ground vehicles can be reduced by using the radar system's masking capabilities, if available, to define selected regions, such as roadways, and ignore all detections within those regions. Although bird detections also are lost when they enter the masked regions, their tracks can be extrapolated over the masked areas and will continue when they subsequently exit.

Radar locations near general aviation airports will detect small aircraft traveling at speeds near those of fast-flying birds. Although aircraft typically produce a stronger and larger signal than individual birds at the same range from the radar, flocks of waterfowl and shorebirds can produce echoes as large as aircraft, depending on the radar geometry. One technique to distinguish tracked bird flocks from aircraft is that aircraft follow generally straight paths, but birds meander as they travel. An exception is migrating birds flying at high altitudes; these typically produce linear tracks, especially at night. RCS estimators in digital avian radars also can be used to help distinguish general aviation aircraft from bird tracks.

Finally, when large aircraft land and approach the radar, property fences, terminal buildings, and trucks passing on nearby surfaces can each produce multipath echoes. These echoes are caused by multiple radar signal bounces off and among large objects and other ground features. Multipath echoes can produce considerable clutter on a radar display, producing false detections and tracks at ranges beyond the nearby large objects. Although careful siting of the avian radar can reduce the production of multipath echoes, at some airfields there may not be any available sites without multipath problems (Federal Aviation Administration 2010, Herricks et al. 2010). Fortunately, advanced digital avian radar processors have multipath suppression algorithms that can mitigate these issues. The effect of multipath suppression on a radar display is to make tracks from birds more discernable (Figure 9). Similarly, sidelobe echoes from very large targets also can confound a display, producing false detections and tracks at the same ranges as the large targets, but at different bearings. Advanced sidelobe-echo suppression algorithms can mitigate these effects.

Traditional radar processing

Prior to around the year 2000, avian radar systems used commercial, off-the-shelf marine radars, some specialized software, and largely manual methods for target extraction. Cameras and frame-grabbers were used to capture radar video screens. Grease pencils and spreadsheets were used to indicate detected bird targets on the radar PPI display and to record their characteristics, such as their position, heading, speed, and quantity. These manual methods are still in use today and have gained scientific acceptance.

The output from the processing electronics of the radar is a standard PPI display. The position of the radar is at the center of the display, the degrees of azimuth are displayed around the perimeter, and the range rings are displayed outward from the center (Figure 10 A). In more advanced configurations, the output is passed through a video capture board in a desktop computer and then to the computer monitor. This allows the operator to view the PPI display on the computer monitor and, through the use of a companion software product, to save static images of the PPI display as graphic files on the computer's hard disk. These images are digital counterparts to the camera images used by earlier researchers and require similar levels of skill and effort to extract meaningful data.

A useful feature of some marine radars is the user-selectable, true trail display (Figure 10 D). In this mode, returns from the current scan of the radar are displayed in 1 color (e.g., yellow)

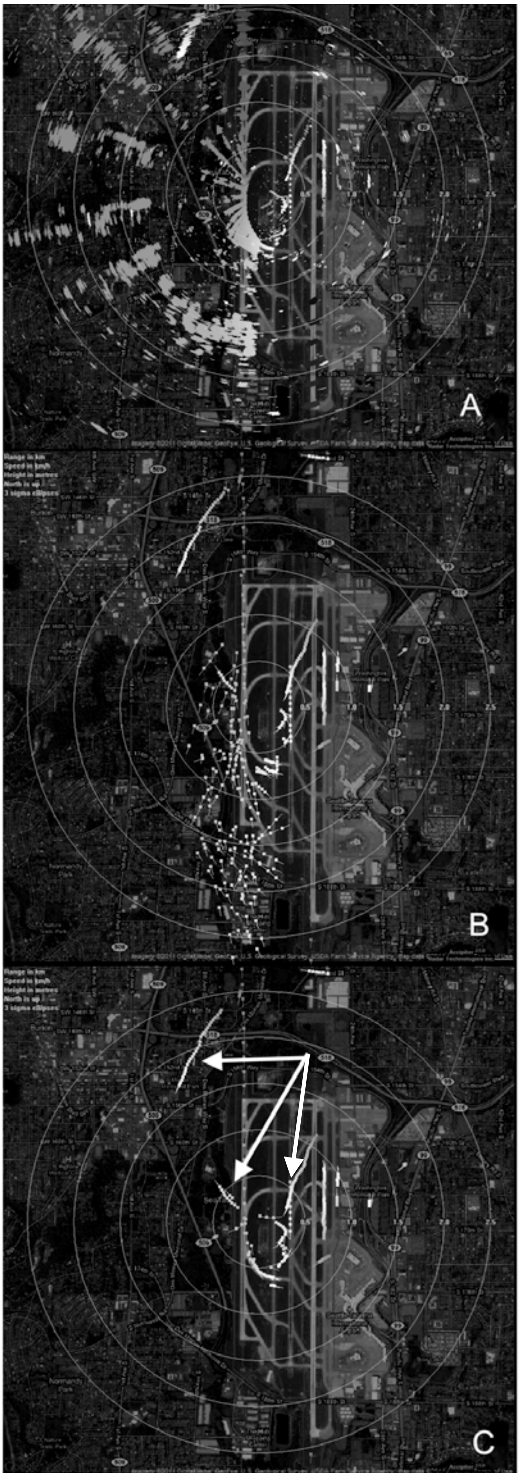

Figure 9. Multipath clutter as it appears on (A) an analog marine radar plan position indicator (PPI) display, (B) a digital avian radar display without multipath suppression, and (C) a digital avian radar display with multipath suppression. In C, the multipath returns from the nearby aircraft are removed and the tracks from birds (arrows) are more distinguishable.

and returns from previous scans of the radar are displayed in graduated shades of another color (e.g., blue). The current yellow returns overwrite any prior blue returns on the screen. Thus, stationary targets, such as buildings and trees, are always displayed in yellow, while for moving targets the current position is displayed in yellow, and its previous positions are displayed in fading shades of blue. Moving targets appear comet-like, with yellow heads and blue tails. The faster the target is, the longer its tail. This effect can be seen quite clearly in Figure 10 C, with many targets around the radar moving in a southerly direction.

It is important to note that the target-trails display is not tracking. The radar processor has no information to connect 1 detection on the screen to another. It is simply displaying a color-coded history of radar returns that provides the human observer with the visual cues to connect the dots, as it were, and more readily recognize moving targets. Although optional tracking modules have been available for marine radars, they are not suitable for avian applications; their capacities are too low for typical bird activity, and they are not suited for small maneuvering targets.

To extract quantitative data about a target from this type of display, the operator first captures a graphic image of the screen and then manually measures the target's bearing and range relative to the radar. Target heading and speed are estimated using trail length and the rotation rate of the radar. When a dish antenna is used, target altitude above ground level can be determined using both its range and the angle of the radar beam. The size of the radar returns (blobs) for extended targets can be measured manually, as well.

There are several technical problems with analog avian radars. First, the large areas of yellow on the display are echoes from ground clutter, received through the main beam and side lobes of the radar antenna (Figure 10; see section above, "Confounding factors"). Any targets moving above or near these stationary objects are hidden from view because they are lost in a sea of yellow. Second, extracting data about a target as described above is a slow, tedious, and largely manual process that cannot be done in real-time, which is a major limitation for many applications. Third, it is

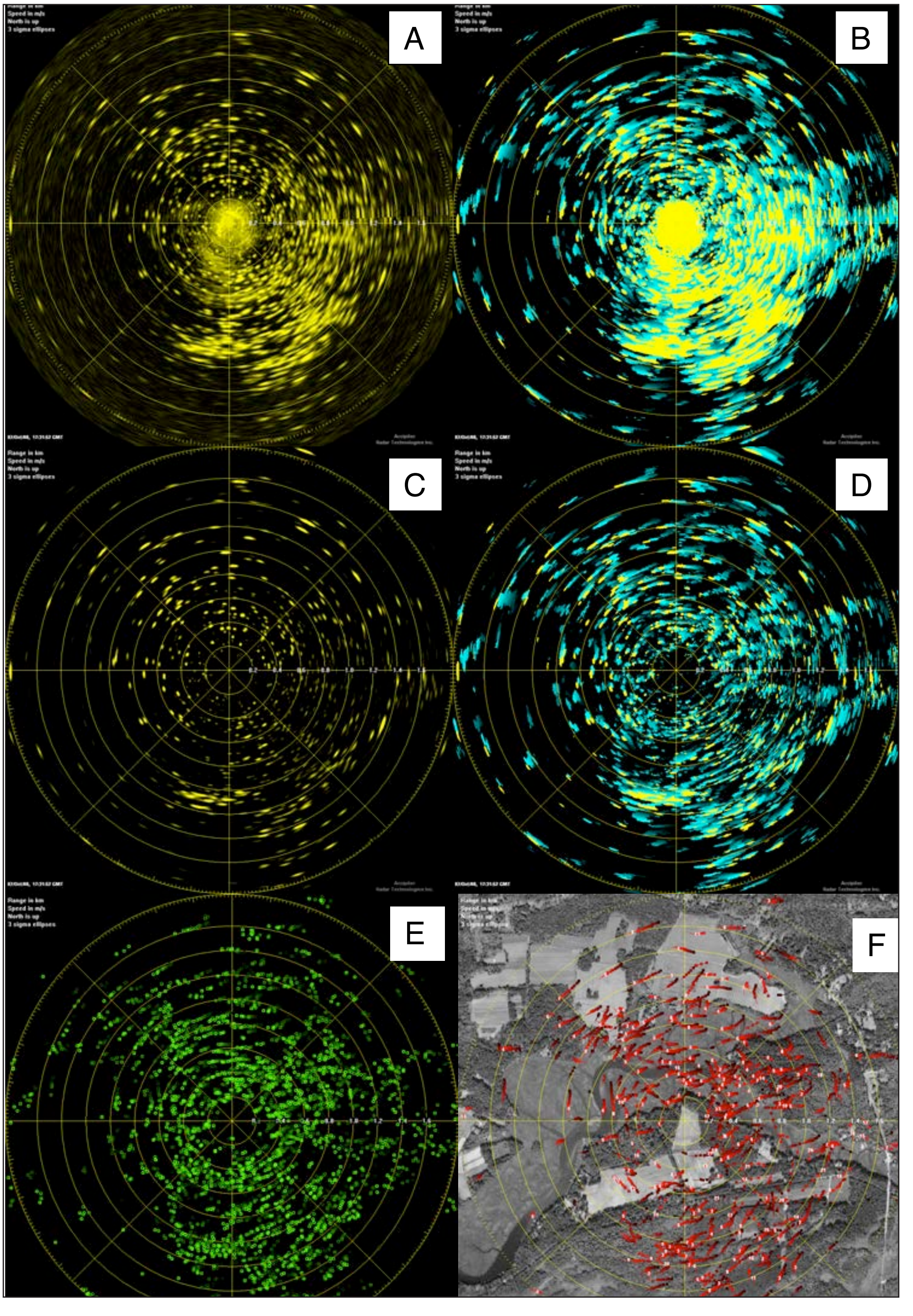

Figure 10. The outcomes of various stages of radar signal processing on received radar echoes, using the same input data. (A) A single revolution of the radar showing raw radar video in a PPI-like mode. (B) Trails mode of display showing the most recent locations of targets (yellow) and their previous positions (blue). (C) Same mode as Figure 10A with the implementation of clutter mapping to remove stationary echoes (clutter). (D) Same mode as Figure 10B, but with clutter removed. (E) Display of moving targets showing the digitized detections (green circles) that correspond to the radar echoes in Figure 10D. The symbols are set to fade to black after 20 seconds. (F) Display of digital radar showing tracks of birds corresponding to the targets in Figure 10D represented by a series of red symbols overlaid onto an aerial map of the location. The tracks have been set to fade to black after 12 antenna revolutions (30 seconds). The fine line emanating from the track symbol indicates the direction of travel. The numbers at the most recent position of the target represent its speed in m s^{-1}.

difficult to relate the target's position on the display to the positions of buildings and land features. Finally, the data from the radar cannot be automatically collected and stored, nor can the radar operation or data analysis be done remotely.

Clutter removal with coherent radar systems

Surface clutter removal with coherent radars is usually accomplished using electronic circuits, such as delay-line cancellers, also called moving target indicators or Doppler processors. This approach filters out all signals that lie within a small band of radial velocities around 0 m/s with respect to the radar. Because surface clutter fits this description, clutter suppression is achieved. However, certain desirable targets also will be cancelled with this approach because their radial velocity (or Doppler shift) is either equal to or ambiguous with respect to zero velocity. For example, targets flying tangential to the radar beam (i.e., circling the radar at a constant range) will have a zero radial velocity and, hence, will be cancelled. Thus, birds disappear as they come abreast of the radar, producing a figure-8 pattern of no targets on the display (Figure 1 B). Further, zero radial velocity as seen by the radar is ambiguous once the target's Doppler shift exceeds one-half the pulse repetition frequency (PRF). For an X-band radar with a PRF of 1 kHz, this occurs approximately every 15 m/s. Thus, a target approaching the radar at 15 or 30 m/s will appear to the radar as having the same radial velocity as fixed ground clutter, i.e., 0 m/s and, hence, will be cancelled.

Radars that are capable of extracting Doppler information (e.g., NEXRAD weather radars, solid-state marine radars) are more complex and expensive than typical pulsed marine radars. However, some recently introduced solid-state marine radars have coherent front-ends with the capacity to perform Doppler processing on the returned signal before passing it on to the digital radar processor. This processing could be used to suppress clutter as described above, but with the consequence of bird-target cancellation, as well. Great care will need to be taken to ensure that targets of interest are not lost at the expense of clutter cancellation. Doppler precipitation suppression is even more challenging, as birds are likely to be moving with similar radial velocities as the precipitation itself. By comparison, when using the clutter map techniques described below, all moving targets are retained regardless of their radial velocity. A combination of these techniques may be the best answer, but this is left for future validation.

Digital radar processing

Overview

Digital avian radar systems are designed to track birds and to provide information about their location, speed, and heading (Nohara et al. 2005). A radar system receives reflected energy from all objects in its field of view, including buildings, the ground, the water surface, and moving targets. For avian study applications, the digital radar processor looks for reflections from the moving objects that cause an observable difference from the ambient picture.

The radar digital interface (Figure 2) digitizes each received radar pulse echo return (sweep) and provides the data to the computer, which carries out the digital radar signal processing, target tracking, data archiving, management, and distribution. The radar signal processing includes functions, such as scan-conversion, adaptive clutter-map processing to remove ground and weather clutter, target detection, numerous operator displays, and post-processing (e.g., generation of automated alerts). As radar data move through the processing chain, the processor first identifies detections and then generates tracks. While the person siting and optimizing the radar system might be interested in the detection data and their statistics, a typical end-user would key on the track data and the tracking performance for various target classes.

Detection processing

On each radar rotation (scan), the radar processor detects the physical locations with stronger-than-average reflections. Such detections can be caused by either the presence of real targets in their respective locations or the variability of the ambient clutter and noise. If the latter, the detection is a false one. On any given scan, there will be a number of detections, both true and false, scattered about the field of view. Depending on the number of birds aloft, environmental conditions, and software settings, there can be anywhere from zero to several hundred detections on any given scan.

The radar software divides its field of view into a large number of resolution cells, which are similar in concept to the pixels of a picture. The 3D extents of a resolution cell are roughly the antenna's beamwidths in azimuth and elevation and the radar's resolution in range, as described above. The software receives the digitized radar echo signal samples, organizes them into a 2D grid for each radar scan, and then filters the data to increase signal-to-noise ratio. The result is a digitized range-azimuth matrix of intensity values for each resolution cell on each radar scan. This format of radar intensities is referred to as B-scan data. PPI displays are generated by passing the B-scan data through a polar-to-Cartesian transformation (scan-conversion) before being rendered as an image on the monitor. Although detection processing is better performed using B-scan data, some digital avian radars still use the lower quality scan-converted signal for detection.

Automatic detection is a nonlinear thresholding or decision process that is ideally applied to the B-scan data. The simplest decision process sets a single fixed threshold that is applied globally across the B-scan data. Detections are declared in all resolution cells with intensity greater than the fixed threshold. One problem with this simple approach is that the intensity of the returned signal is greatly influenced by the target's distance from the radar (Appendix 2), as well the amount of energy reflected from the target. This results in small, nearby targets, such as small birds or large insects, being represented by the same signal strength at the receiver as a large, distant target, such as a flock of waterfowl. Consequently, if the threshold (i.e., the sensitivity) is set so that the system does not detect the weak signals from small, nearby targets, it might also miss large distant targets that are of interest.

Another problem with the fixed-threshold approach is that strong clutter regions will end up impacting the entire field of view. If the threshold is set high enough to reject the strong clutter regions, sensitivity will be reduced everywhere, even in areas that are clutter-free. Small birds will not be detected at all, and medium and large birds will not be detected at greater ranges. On the other hand, if the threshold is set low enough to detect small birds in clutter-free areas, then strong clutter regions will result in numerous false detections.

High-performance detection software applies a different threshold to each resolution cell. Each threshold is adaptively computed, based on the spatial and temporal pattern of clutter in its vicinity. One technique is to create a clutter map that is updated or refreshed periodically (e.g., once a minute) allowing the map to follow changes in environmental conditions, such as wind and precipitation. Once this map is created, it is subtracted from each subsequent B-scan matrix. Figure 10 (A–D) shows radar PPI images before and after clutter removal. What remains after subtraction are residual cell intensities that are above the local clutter level; these would be positive when a detectable target moves through the scene. A fixed threshold is applied to the residual signal and set for a tolerable false detection rate. This provides a spatially and temporally nonhomogeneous detection algorithm that produces (in theory) a constant false alarm rate (CFAR) across the entire field of view. With such CFAR algorithms, digital radars can often detect and track targets that are within or near strong non-homogeneous clutter regions.

Setting a low detection threshold allows weaker targets (i.e., those that are barely above the background noise) to be detected. To maximize detectability of small birds, CFAR detection thresholds are set relatively low, leading to a seemingly large number of false detections. This is not as problematic as first appears, because the downstream track processing eliminates isolated false detections, leaving the tracks from real objects and, possibly, a few false tracks in troublesome clutter areas. Setting too low of a threshold can yield so many false targets that they overwhelm the software's ability to track all of them. Consequently, the selected threshold is a compromise to detect as many targets of interest (i.e., birds) as possible, while not being overwhelmed by false detections from noise or residual clutter.

The clutter removal process is not perfect; some residual clutter will get through, leading to some false detections. Troublesome residual clutter areas often are not those with the strongest average backscatter, but rather those that generate more temporally variable backscatter. For example, clutter returns from a water surface often are spikey in time (i.e., their probability distributions are characterized by long tails). This effect creates greater clutter residuals from water surfaces than from stronger, but more consistent, land clutter. Wind-blown trees and bushes can behave similarly, causing a greater number of false detections than might otherwise be expected. These effects are more severe under windy conditions. Although the rate of change is slower, plant growth, such as agricultural crops, affects the clutter. Static clutter suppression thresholds must be adjusted accordingly. All of these highly variable effects are reasons why, in order to get an acceptably uncluttered display while maximizing bird target sensitivity, site-specific adjustment of the detection parameters is necessary with digital avian radars.

High residual clutter areas can be managed by digital avian radar processors in at least 4 ways: (1) reducing the detection sensitivity globally; (2) using a detection algorithm that applies higher-order clutter statistics to correct for these residuals in a localized manner; (3) allowing the operator to mask out the troublesome clutter areas from detection; (4) relying on downstream processing to produce sufficiently few false tracks from the regions of high false detection rates. This requires sophisticated tracking methods, such as multiple hypothesis tracking-interacting multiple model (MHT-IMM), described below.

Track processing

The tracking process attempts to connect the time series of detections from each individual real target, forming its track. Tracking eliminates most isolated false detections, leaving only the tracks from real objects and few false tracks. The number of false positives, thus, decreases as data move through the processing chain. There are a few high-performance algorithms suitable for tracking small maneuvering targets, such as birds, in the dense target and clutter environments typically encountered with avian radars. One example is the MHT-IMM algorithm (Blackman 2004), which has been tested extensively with birds (Brand 2011). MHT-IMM is capable of dealing in a consistent manner with converging and diverging birds, maneuvering birds, crossing birds, circling birds, and flocking birds.

A track is a set of detections defining a trajectory (path) that is believed to be associated with a specific target. The tracking algorithm employs operator-configurable criteria to classify a time-series of detections as a track. For example, a pair of closely located detections on a respective pair of scans would denote a potential 2-point track, which can be categorized as a tentative track on the next scan. A 2-out-of-5 scan criterion might be used to maintain a tentative track, and a 3-out-of-5 criterion might be used to promote a tentative track to a confirmed track. Confirmed tracks require a certain number of updates (e.g., 4-out-of-8 scans) to be maintained before automatic deletion occurs.

This type of approach is necessary because the radar does not necessarily detect the target on every scan, due to either weak target signal or the object crossing an area that has been masked. If the software were not configured to deal with the problem, multiple broken-track segments and track IDs would result.

Between every scan, all tracks are filtered and predicted forward, so that new detections can be associated properly with the existing tracks. Better-performing track filters are parametric in nature so that target dynamics can be predicted reliably into the future. To handle maneuvering targets, a set of interacting multiple models can be used to compute target accelerations during the filtering process (Blackman 2004).

This process repeats on each scan, with the tracking algorithm trying to ascertain whether each new detection belongs to an existing track. The Multiple Hypothesis Tracking Association algorithm (Blackman 2004) looks at all the new detections and all the existing tracks and makes the optimal assignment *en masse*. Newly assigned detections are then filtered to generate more accurate target trajectories. New detections that are not assigned to tracks are retained for initiating new tracks. The new detection might be the start of a new track or an isolated detection (i.e., a false alarm) for which there will be no future supporting detections. Tracking algorithms retain tracks and assign new detections to them after brief gaps of 1 to a few scans.

Digital avian radars employing tracking

algorithms as described above are capable of detecting and tracking hundreds of birds (and other objects) in real-time. The tracks can then be converted to earth-coordinates on the fly to be immediately plotted in a geographical information system (GIS) format for analysis with third-party GIS software. Digital avian radars can also send tracks, bird densities, and other metrics onto a network in real-time.

Tracks can be plotted live on a background map to provide a real-time user display. In the example shown in Figure 10F, each target's most recent track position is indicated by a red square with a short protruding arm that indicates the target's heading. Previous track positions are represented by squares with increasingly fading shades of red.

Digital avian radar displays

The information produced by the radar software can be presented to the digital avian radar user as a real-time display showing bird targets and their locations. This display can be remote from the radar system (e.g., in the user's office). Such information can include scan-converted video and, more importantly, target data (i.e., detection and track data). An aerial photograph or map can be integrated with the radar display to provide a geo-referenced background for the radar data display. These display features enable bird behavior to be more easily placed in a geographical context. Detection and track symbols indicate past and present locations of birds.

Avian radar users should be able to select from a range of options for displaying detections, tracks, and backgrounds. They could, for example, choose a familiar format that resembles a marine radar display (Figure 10A, C). With flexible display software, however, users can selectively view the display with or without clutter and with or without the detection and track symbols and histories (Figure 10). Other items under user control include display range, PPI video image brightness and contrast, markers, colors, and track labels. The user can specify how long the detection or track histories persist, from only 1 scan (current position) up to several past minutes' worth. Detection and track information can be displayed against a black background, typical of a radar display or overlaid on a locality map (Figure 10). Displaying the current and past locations makes bird radar tracks easily identifiable by an observer. All of the above flexibility allows the creation of a real-time situational awareness picture tailored to the user's preferences.

In addition to the display of target information, the avian radar's user-console also can include operator controls. These provide a graphical user interface to control the operation of the radar, including its hardware and software.

Data recording

In addition to displaying detection and track information on the screen, state-of-the-art digital avian radars can be configured to continuously organize and store their target information. To do so, they use a high-performance database management system configured as a radar data server. The server supports real-time insertions from ≥1 digital avian radars while at the same time providing access to real-time or stored information to remote users for their own unique purposes. The server organizes all target data extracted from the avian radars, including detections and tracks. The track data should typically include at least the following: target identifier, date, time, latitude, longitude, altitude, range, azimuth, speed, heading, RCS, intensity, and covariance. Unique track identifiers are generated automatically and can be used as indices to the tracks in the database. The tracks and their individual detections can be examined using appropriate software, and can be reviewed or replayed for display or analysis. Whereas recording the raw radar video data would require gigabytes of storage every hour, the target information database, which contains all the target data extracted from the raw data, requires only megabytes of storage per hour, a space savings of approximately a thousand fold. This means that a few years' worth of bird target information can be stored on a single computer hard disk.

The software also can distribute track reports in real-time to remote sites using low bandwidth, standard TCP/IP networks, either wired or wireless, including the Internet. Because the track reports contain all of the important target data (i.e., date, time, position, dynamics, and size), remote monitoring of avian activity in real time is achieved.

These tools can be used individually and in various combinations. For example, stored tracks can be reviewed while the user looks for interesting or unusual patterns. When an interesting pattern is found, the targets of interest can be selected and studied in more detail.

Digital avian radar software also can record the unprocessed (i.e., raw) radar signals. Raw data recordings allow for off-line playback, reprocessing, analysis, and parameter testing. The ability to re-process raw radar data allows users and system designers to evaluate avian radar performance with different processing algorithms and parameter settings on real data.

These raw digitized files will be very large. While the actual data rate varies as function of the range and waveform settings, the rate for avian applications could be as high as 5 megabytes per second. Even at this rate, several days' worth of raw data could easily be stored on a 2-TB disk drive. Once files are reviewed, they can either be deleted or archived to another medium.

Networking

The networking capabilities of digital avian radars allow users to monitor single or multiple locations simultaneously in real time. In the case of multiple radar systems, their outputs can be fused or merged into a single presentation that enhances an observer's ability to monitor bird movement over a large area (e.g., a wind turbine farm or airfield). Connectivity permits data sharing and pooling from multiple locations and among multiple researchers. Eventually, such networking could provide an opportunity for an integrated large-scale representation of bird migration, similar to the National Weather Service's national weather radar map, but with much finer detail about the behavior of individual birds and flocks.

Avian target attributes

Once the digital avian radar has detected and tracked the various moving targets within its field of view, there remains the task of identifying each of the tracked objects. Various attributes of the individual tracks, such as speed and location, can help in this task. So can *a priori* information about the site (e.g., locations of roads), knowledge of current environmental conditions, as well as the collective behavior of tracks. The following subsections explain how the various pieces of information collectively can lead to useful interpretation of the radar data.

Target track characteristics

In addition to detecting birds, marine radars also detect other moving targets, biological and nonbiological. Nonbiological targets, such as boats, ships, cars, trucks, trains, and aircraft, typically travel predefined paths or travel much faster than birds and can be eliminated from the category of birds by their speeds and linear tracks.

Nonavian, biological targets more closely resemble birds than do nonbiological targets and, consequently, are more difficult to differentiate. Large insects usually move in the direction of the wind and are typically detected only near the radar. Bats are active at night and potentially can be confused with migrating songbirds, but foraging bats usually have a zigzag flight path on the radar as they chase insects (Figure 11). Their high rates of turning and slow flight speeds permit them to be distinguished from migrating birds. Migrating bats fly at speeds and altitudes similar to migrating songbirds and follow straight paths, again, similar to migrating birds. Consequently, the two cannot be reliably distinguished using their track data alone.

Echo size (extent)

The spatial dimension or lateral extent of a bird echo is not a good indicator of the bird's physical size, because a bird typically is seen as a point target to the radar. A group of birds will produce a slightly larger echo, which will fragment into multiple echoes if the birds separate, then coalesce to a single echo if the birds come together again. These tracks resemble a braided pattern through time. Large groups (i.e., hundreds or thousands) of birds will produce echoes that are hundreds of meters to kilometers across, and they appear to the radar as an extended target. In this latter case, echo size (extent) is indicative of flock extent. Depending on how dense the birds are within the flock, it might show fragmentary structure as gaps appear between subgroups.

One phenomenon to keep in mind is that the

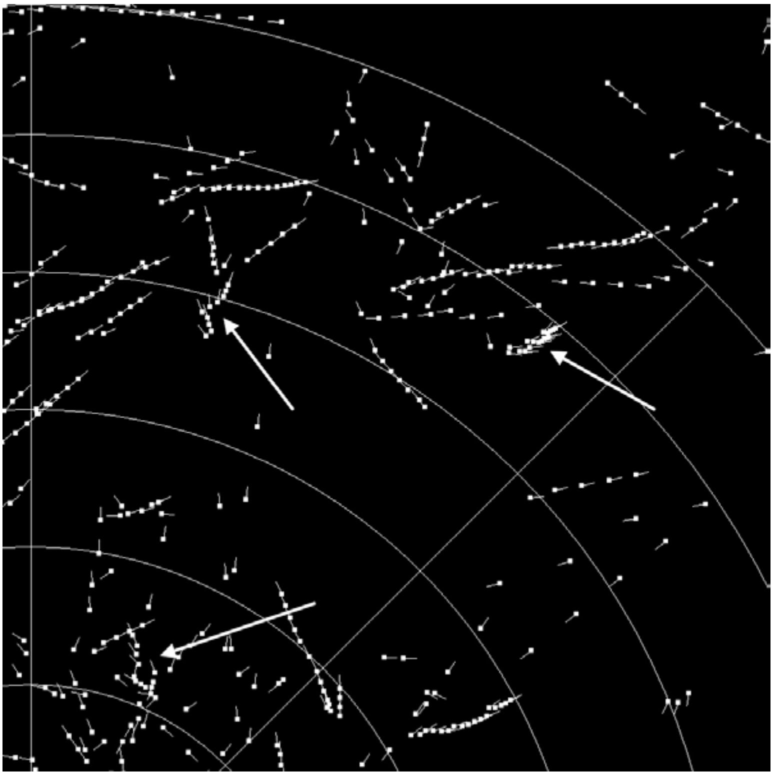

Figure 11. The tracks of foraging bats showing sharp turns as recorded by radar. The tracks of bats are indicated by the arrows. Range rings are 200 m apart.

echo from a target will appear to grow in width on the radar display as it moves farther from the radar. A point target echo (e.g., from a large bird) will subtend an angle determined by the horizontal beamwidth of the radar's antenna. At 0.5 km, a 4° beam will create an echo 35 m wide, while, at 3 km, the echo will be 200-m wide. Consequently, a point target close to the antenna appears smaller than the same target farther away. The video gain selected when displaying target echoes also influences the size of any given echo. A bright echo intensity has the effect of making the echo appear larger.

Strength (amplitude) and radar cross section

The amplitude or strength of the return signal is affected by many characteristics of the target (Appendix 2). If several birds are in the same resolution cell, they will appear as a single target, and the strength of the returned signal will be a composite of all the individual echoes. The physical size and composition of the target, in combination with the radar's frequency determine the target's RCS (i.e., its reflecting size). In general, targets with a large RCS reflect more energy than targets with a small RCS. Because of the energy loss due to spherical spreading (Appendix 2), distant targets are less likely to be detected than equal-sized targets nearby. Unfortunately, the receivers on the small marine radars used in avian radar systems are uncalibrated and nonlinear in their sensitivity. This makes it particularly challenging to determine the RCS precisely, especially for targets, such as birds, that change considerably in RCS with changes in their aspect (Edwards and Houghton 1959, Nohara et al. 2011). However, it is possible to determine the approximate size of the target and from that information determine whether it is composed of a single bird or several (Nohara et al. 2011).

Signal fluctuations

Fluctuations in the amplitude of the returned signal from birds were first reported in 1939 from a Navy VHF radar (Bonham and Blake 1956). Since then, similar amplitude fluctuations have been reported for other radar systems. These amplitude modulations are caused partly by the beating of a bird's wing, but do not necessarily equate to wingbeat patterns in birds (Emlen 1974, Demong and Emlen 1978). The modulation produced by a beating wing is not sinusoidal, but reflects the characteristic upbeat and downbeat pattern of the bird (Demong and Emlen 1978, Cochran et al. 2008). To determine the amplitude signature's spectra, it is necessary to obtain the frequency and amplitude data of the fundamental and harmonic components of the signal (Flock and Green 1974). Most attempts at analyzing amplitude signatures for species identification have dealt only with the signal's fundamental frequency and, therefore, do not represent a wingbeat signature.

Pulsed radars with a rotating antenna, such as the marine radars used for most avian studies, do not spend enough uninterrupted time on a bird to accumulate a sufficient number of echoes to produce an amplitude signature. Only single-target tracking radars, including those specifically modified for studying birds (Bruderer 1997), that use a feedback circuit to lock an antenna onto a bird and follow it are able to accumulate enough returns from a bird that they can develop an amplitude signature.

Breathing also changes the physical size of a bird's body and can affect the reflected signal. The breathing of a flying bird is synchronized with the wingbeats (Boggs 1997), but rarely in a 1:1 relationship, and the contribution of breathing to changes in cross-sectional area is probably integrated with that produced by the moving wing.

A second, often ignored, component of radar amplitude signatures is changes in the orientation (i.e., aspect angle) of birds relative to the radar antenna. This orientation greatly affects the amount of signal reflected, especially within the X-band (Edwards and Houghton 1959). As a bird travels, the amount of RF energy reflected can vary in a pattern reminiscent of wingbeats, but actually results from changes in orientation of the bird to the radar (Figure 12).

Attempts to characterize a bird's species by its amplitude signature or wingbeat signature (Zuagg et al. 2008) can be misleading. The radar amplitude fluctuations are a composite of the bird's moving wings and breathing combined with its changing aspect to the radar. The resulting variations in amplitude do not accurately reflect a wingbeat frequency that can be used to identify a target to a species or species-group of birds.

Doppler signatures (i.e., fluctuations of the reflected signal's frequency; Figure 13), on the other hand, are unaffected by changes in aspect and accurately represent fluctuations caused by wingbeats (Flock and Green 1974, Schnell 1974). Thus, Doppler signatures can be used to accurately assess wing-beat frequencies and patterns, which can allow categorization of targets to species or species-groups. The differences in wing-flapping patterns also can be used to distinguish migrating from nonmigrating birds (Demong and Emlen 1978) and birds from other types of targets, such as insects (Zaugg et al. 2008). Some solid-state marine radars will have the capacity to extract Doppler signals, which might allow the identification of bird echoes to species or other taxonomic groups (e.g., thrushes). However, it is unrealistic to expect to use bird radar echoes to distinguish between similar species (e.g., Swainson's thrush [*Catharus ustulatus*] versus gray-checked thrush [*Catharus minimus*]) based on wingbeat pattern.

Flight speed

Several features of a series of radar echoes can be used in combination to estimate the identity of the echoing object. As discussed above, speed and flight paths can be used to distinguish biological targets from vehicles and aircraft, and among some categories of animals. Insects fly slowly and have flight speeds and directions that differ only slightly from the low-level wind velocities. Small birds and bats have flight speeds that differ significantly from the wind, usually by 10 to 15 m/s, more for larger birds (Green and Alerstam 2000, Bruderer and Boldt 2001, Alerstam et al. 2007). Soaring birds, such as raptors and cranes, have apparent ground speeds of 5 to 10 m/s with circling flight paths that can drift with the wind, faster when moving downwind and slower when moving into the wind (Beason et al. 2010*a*).

The most feasible method of determining the ground speed of a radar target with digital avian radars is to calculate it based on the distance the target travels from one antenna scan to the next. Knowing the distance the target traveled and the antenna rotation rate (rpm), the speed between rotations can be calculated. With successive locations associated with one another via tracking, a more accurate speed can be calculated for the duration of the track over many antenna revolutions. The tracking algorithms employed in digital avian radars can automatically compute accurate ground speed and heading information with each track update. To determine the bird's air speed, the user needs to know the wind velocity and the bird's flight behavior (e.g., level flight, ascending, descending, circling).

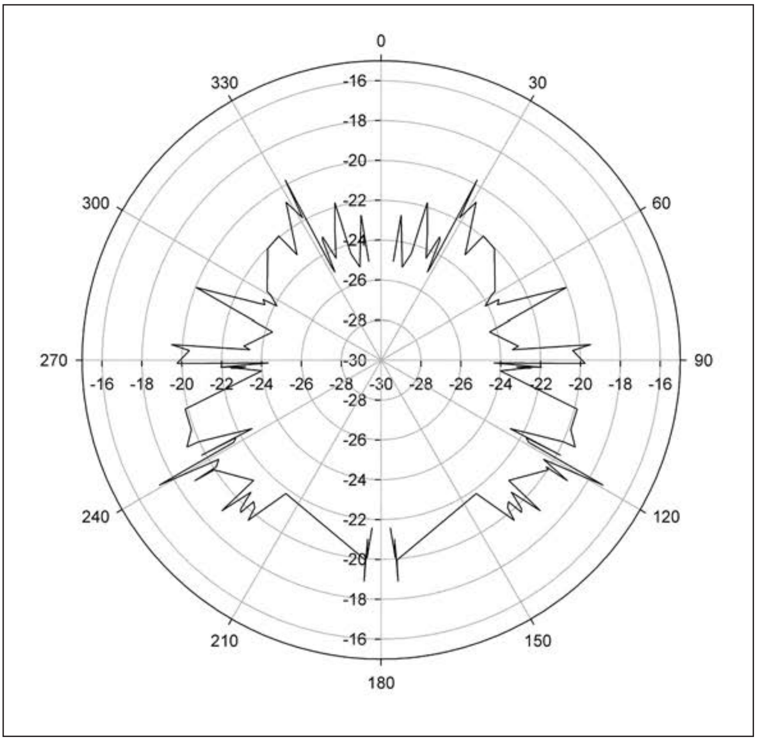

Figure 12. The radar cross-section of a gull as its orientation relative to the radar changes. These changes are the result of the complex interactions of the signal reflected from various parts of the bird's body and the size of the reflecting surface. The top of the circle (0°) represents the target's head or nose, and the bottom (180°) represents the tail. The sides are represented by 90° and 270°. The units are dBm².

Altitude

If the radar antenna produces a narrow, vertical beam pattern, the altitude of tracked bird targets can be estimated using trigonometry: altitude = sin θ * slant range, where θ is the elevation angle of the antenna. The returned signals from the birds will be strongest when the bird is in the center of the antenna pattern, but still is sufficiently strong at the upper and lower edges of the pattern to produce echoes on the display. Although the calculated altitude is usually based on the center of the antenna pattern, the bird might be anywhere within that pattern. An antenna with a 4° vertical beam width, for example, will produce an uncertainty of ±35 m altitude at a slant-range of 1 km and twice that at 2 km. Thus, a bird 2 km from an antenna that is elevated 10° would have a calculated altitude of 350 ± 70 m (280 to 420 m). Greater precision can be obtained with multibeam antennas and with antennas that automatically scan different elevation angles (Beason et al. 2010*a*).

A radar with either a dish antenna pointing vertically or an array antenna mounted to scan vertically can more accurately measure the altitude of a bird than a radar with a horizontally-scanning antenna. The altitudinal uncertainty is then proportional to either the pulse width of the radar waveform (dish pointing vertically) or to the beam width of the antenna (array spinning vertically). The tradeoff is that these systems provide little or no track information and, thus, require a second horizontally-rotating surveillance radar to monitor the directions, speeds, and locations of the birds. Also, it is not possible to directly associate target detections from a vertically-spinning radar with those from a nearby horizontally-spinning radar. Thus, such a combination is not capable of providing full 3D information about targets (i.e., their locations and heights simultaneously).

Future work

The technology for studying and monitoring avian movements using radar has undergone dramatic changes within the past 10 years

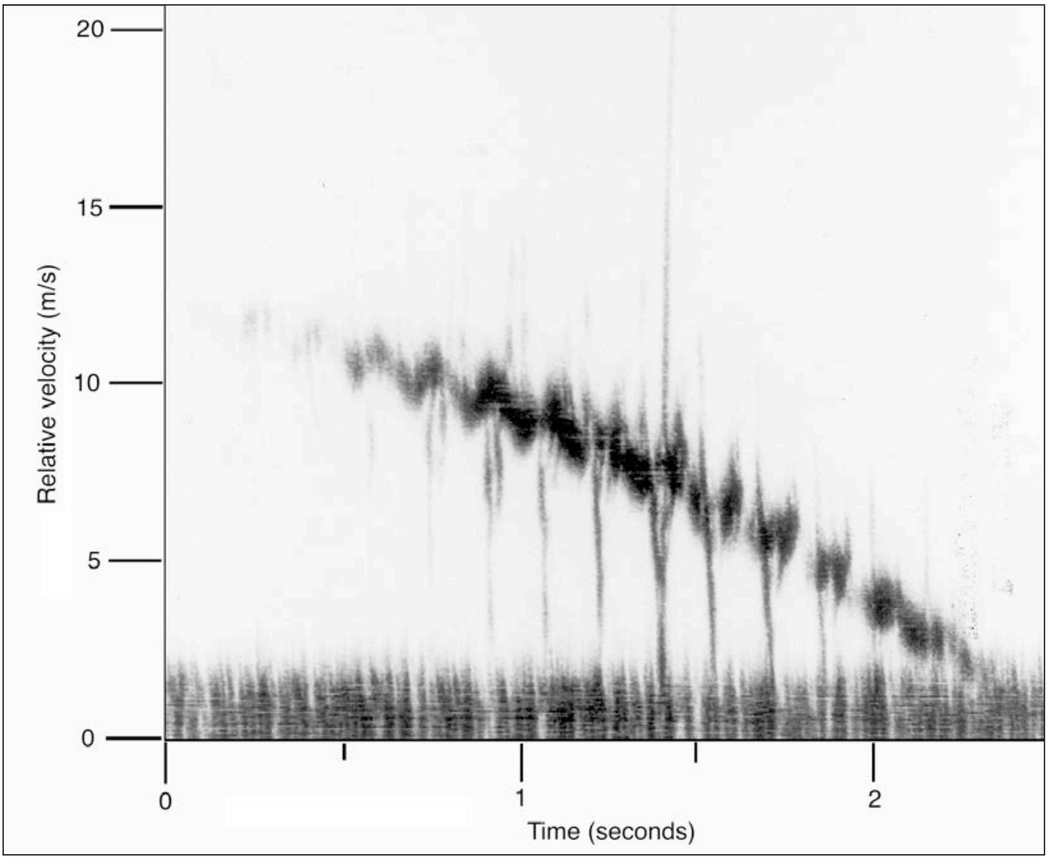

Figure 13. Doppler radar signature of a northern pintail as it passed through the beam of a continuous wave10 GHz radar. The strong curved trace is from the bird's body as it moves to a flight path perpendicular to the radar beam. The perpendicular flight path results in a zero radial velocity at the right end of the graph and no Doppler shift. The Doppler shifts caused by the beating wings are visible as vertical spikes away from the trace of the body.

when digital computers and signal processing software have been developed for the task. One of the results of these changes is that digital avian radars generate tremendous quantities of data, and, thus, any developments to automate data analysis would be beneficial. The abilities to (1) distinguish types of targets (e.g., birds, insects, or aircraft), (2) identify types of birds, and (3) determine flock sizes are important goals for future research and development of avian radars. Although one cannot expect to reliably classify birds to species, the rich target information provided from avian radars can provide the detailed information on individually tracked birds that is necessary for classification to avian guilds.

If reliable classification algorithms are to be developed, then avian radar systems should be researcher-friendly. This means that these systems will make available, in an open and practical manner, both geo-referenced target data (i.e., complete detection data and track data) and free or inexpensive software tools for visualization and data manipulation. Such tools will allow researchers to easily access and review those data and create their own models and algorithms for testing with collected data. The results of these efforts will lead to the development of automatic or operator-assisted classifiers in affordable digital avian radars.

Management implications

Radar is an excellent tool, but it needs to be deployed carefully. Avian radars require training and experience to properly interpret and configure. Analog displays are confusing to an inexperienced researcher because of the clutter, side-lobe detections, multipath detections, and targets other than those of interest. While digital avian radar systems will alleviate the effects of

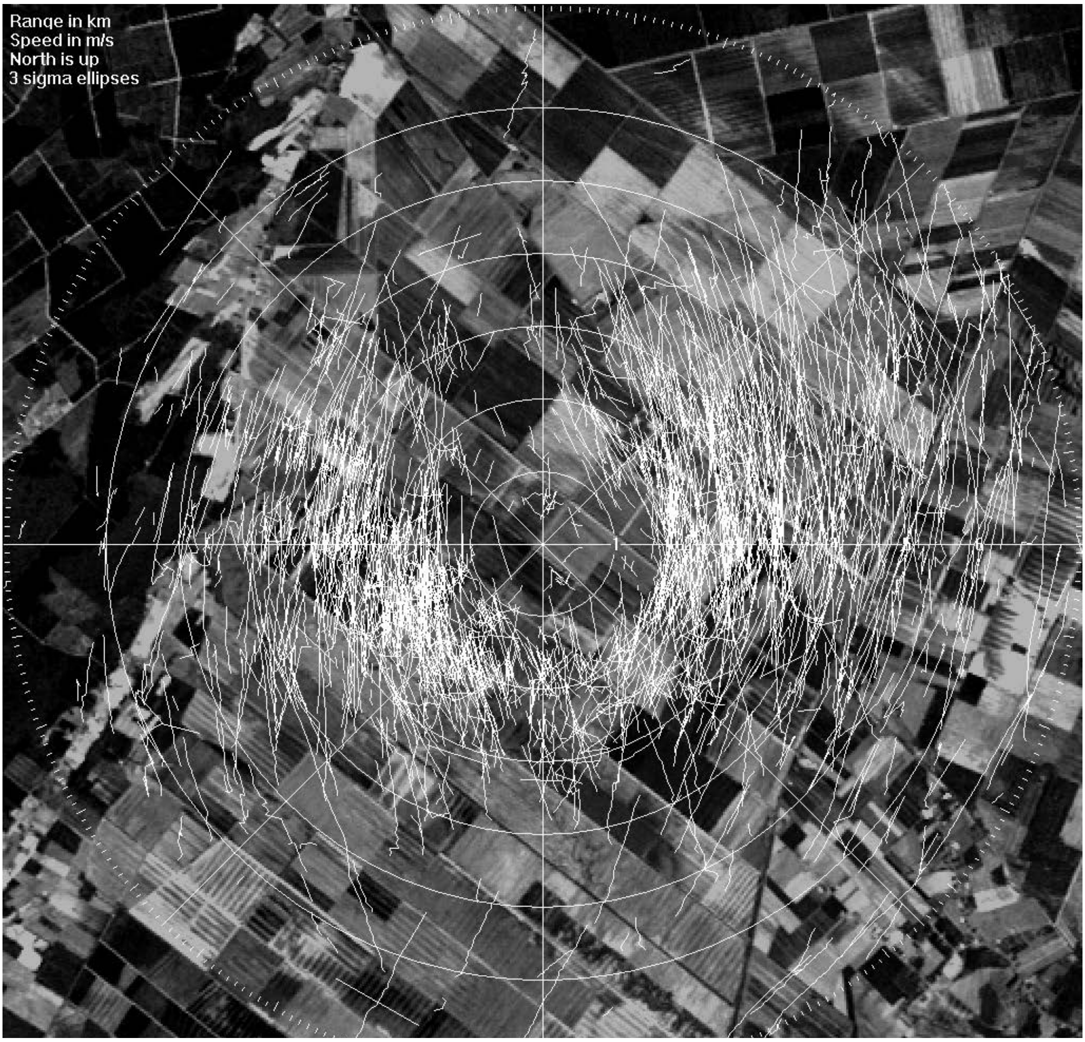

Figure 14. A display showing 2 hours of spring nocturnal migration (from 1 hour to 3 hours after sunset) by tundra swans (*Cygnus columbianus*) and other waterfowl in coastal North Carolina. Each streak is an individual bird or a small flock. Display range is 7.5 km.

clutter and false detections, expertise is needed for their setup and operation.

Because of radar's complexity, wildlife biologists and ornithologists have a special role to play in the use of avian radar; they understand avian behavior and can use that knowledge to properly interpret the radar data. As biologists transition from analog marine radars and the PPI display to digital avian radars, they will need to determine the relationship between the number of birds detected by the digital avian radar and the number detected by the system that they used previously. Digital avian radars use clutter suppression, which results in more birds detected and tracked. Because of the different radar clutter environments at each location, adjustments will need to be made on a site-by-site basis.

Although there are many uses of radar data in ornithological and wildlife studies, 3 categories are the most obvious and frequently pursued: detection and identification of birds that cannot be observed directly, automatically monitoring patterns of activity, and studying migration.

Detection and identification of visually unobservable birds

Categorization of bird echoes to taxonomic groups based on characteristics of the radar tracks can be improved with knowledge of the natural history of the region. Whether observing diurnal bird movements or nocturnal migration, flight speed is 1 characteristic that can be used to distinguish among general categories (Bruderer and Boldt 2001, Alerstam et al. 2007). Correlating visual observations with radar tracks can aid in determining the local speeds of individual species during the day. However, birds have slower optimal flight speeds for local flights compared with migration (Hedenström and Alerstam 1995). These differences must be considered when using speed to help identify the type of bird making a radar track. A second adjustment is that the track speed recorded on the radar must be corrected for the direction and speed of the wind. The radar data can be used only to compute ground speed, which is influenced by the wind's velocity. During migration especially, birds tend to fly more-or-less following winds, resulting in ground speeds that are greater than their air speeds (Richardson 1991).

The intensity and changes in intensity of the returned signal can be used only to approximate the size and hazard of the bird (Nohara et al. 2011). The extent (diameter) of the radar target provides information on whether it is caused by an individual bird or a flock. Knowledge of the flocking behavior, seasonal changes in behavior, and species pool at that time of the year will help with the identification of flocking birds producing a radar track. If birds travel in flocks during nocturnal migration, the individuals are dispersed in the airspace, not congregated as they are during the day (Balcomb 1977).

Daily activities

Avian radar systems typically are used to monitor bird activity on a small scale, often within 5 km of the radar, although flocks have been readily monitored beyond 20 km. Obstructions can block detections in certain sectors, and clutter can reduce detections of targets that are passing over the source of clutter. Except for these blind areas, avian radar can provide and record a high-resolution view of activity out to distances of at least 5 km. This makes avian radars well-suited to monitoring temporal and spatial patterns of local activity, such as habitat use and various management needs. Automatic track recording by digital avian radars provides the geographic coordinates for each track in a database, which can be imported into a GIS-based program for analysis and visualization.

Monitoring habitat use is important for many conservation efforts. Many avian species of concern, including threatened or endangered species, are restricted in their geographic distribution and habitat. A strategically located radar could allow observers to monitor the movements of individuals of those species and determine the specific locations that they frequent. Follow-up visual observations would determine why the birds are using specific locations. Because of radar's ability to detect birds in darkness without relying on their vocalizations, radar has been used to estimate population sizes for species, such as marbled murrelets (*Brachyramphus marmoratus*). Like many alcids, this species flies between nests and foraging locations in pre-dawn and dusk darkness (Burger et al. 1997, Burger 2004). Radar monitoring resulted in approximately a 50% increase in numbers of birds detected as compared to audio-visual monitoring (Paton et al. 1990, Hamer et al. 1995). Using digital avian radars would provide a greater increase in detected birds because clutter mapping and tracking algorithms render tracks that are not visible on a PPI display.

Large weather radars (e.g., WSR-88D) have been used to deduce the general locations of migratory stopover habitat (e.g., see Figure 3 in Gauthreaux and Bellser 2003). Because of the characteristics of their signals, weather radars provide only a coarse-grained picture of habitat use, such as riparian habitats along major rivers or, when migrants exit, as they begin a night's migration. The characteristics of avian radar signals provide a higher resolution picture of habitat use in both time and space and can be used to enhance the overview provided by large radars.

On a larger scale, avian radars can be used to establish temporal and spatial patterns as birds move among feeding, loafing, and watering sites. These patterns are especially important for managing target species in sensitive locations, such as contaminated detention ponds, airfields, high-value agriculture crops, etc. (Klope et al. 2009). Knowledge of such patterns can be used by refuge and park managers when planning habitat modifications or when analyzing the responses of target species to habitat manipulations.

The altitudinal distribution of birds in the airspace is of major interest in siting wind-turbine farms (Harmata et al. 1999). The blades of large wind turbines extend into the airspace used by migrating or aerial foraging birds. Avian radars with either vertical array antennas, dish antennas with dual-axis scanning, or multi-beam dishes easily provide precise altitude distributions.

Migration studies

Traditionally, the migration traffic rate is defined as the number of birds crossing through a plane 1.6-km wide that is oriented perpendicular to the direction of travel in 1 hour (Lowery 1951). Using a standard definition allows researchers to compare migration densities and fluxes among sites. Historically, this value has been based on viewing birds pass across the face of the moon (Lowery 1951) or through a bright, vertically pointed light (Gauthreaux 1969). Using avian radar, the density of migrants can be estimated based on the volume of the radar coverage and the number of targets detected in a revolution of the antenna. However, the researcher must keep in mind that that farther a bird is from the antenna, the lower the probability that it will be detected and the greater is the uncertainty in the altitude of the bird. Further, birds that are moving perpendicular to the radar beam exhibit the largest radar cross-section (and detection probability), while birds oriented toward or away from the antenna have the smallest (Nohara et al. 2011). These differences in detectability necessitate correction factors in order to increase the accuracy of estimates of the numbers of birds in the radar's coverage (Schmaljohann et al. 2008).

During spring and autumn in northern latitudes, individual birds and species elect to migrate during a restricted period that is optimal for them. Radar allows researchers to monitor nocturnal, as well as diurnal, migratory movements and approximate the migration passage interval of various identified guilds or species-groups. Thus, the night-to-night fluctuations in density and composition of migration and the influences of weather and other variables can be assessed.

In addition to determining the altitude of migrants, the direction of the path (i.e., track) taken by individual migrants can be determined. For example, Figure 14 shows tracks of tundra swans (*Cygnus columbianus*) in coastal North Carolina passing overhead toward the Chesapeake Bay. Tracks can be categorized based on their speeds, which are representative of taxonomic groups, and a mean vector computed for each group (Mardia 1972, Batschelet 1981). Such information can reveal interesting behavior by migrants. For example, Gauthreaux (1991) reported that birds migrating ahead of a cold front differed in their altitudinal distribution from those behind the same front. The high resolution of avian radars allows researchers to study the effects of weather on the paths followed by individual birds in addition to the effect on the population of birds aloft.

Summary

Avian radars provide a high-resolution picture of bird movements through space and time. They are capable of detecting birds in situations (e.g., at night, at far distances) that wildlife managers would not be able to monitor otherwise. Many characteristics, including speed, altitude, flight direction, and size of avian radar echoes allow users to distinguish birds from other echoes and to discriminate among categories of birds. The data from avian radars can be used to evaluate day-to-day patterns of movement on a local scale and migration on a regional scale.

Digital avian radar systems can operate continuously and record processed data to a computer hard drive or other data storage device. These data can be viewed in real-time or analyzed later. The 3D volume of coverage is determined by the antenna pattern and limited by clutter and shadowing. The maximum range at which birds can be detected is determined by the physical size of individual birds and the number of birds moving together as a flock, combined with the sensitivity of the radar. Small, single songbirds can be detected 1 to 2 km away and larger birds, including ducks, geese, and hawks, farther away, with flocks tracked to beyond 20 km.

Analog and digital avian radars are powerful tools but are limited by the physics upon which they are based. By itself, radar information can rarely be used to identify the species being tracked or the exact number of individuals within a flock. Neither can it discriminate intra-flock dynamics of individual birds. Thus, wildlife scientists and managers can exploit a wealth of information provided by avian radars, but should do so carefully, and "Beware the Boojum."

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Appendices

Appendix 1. Comparison of X-band and S-band radars.

Attribute	X-band	S-band
Frequency	9 GHz	3 GHz
Wavelength	3 cm	10 cm
Horizontal beam width of 2-m antenna	1.2°	3.6°
Antenna length needed for 1.2° beam width	2 m	6 m
Weight of antenna scanning unit	40 Kg	130 Kg
Resolution cell width at 1 km with 2-m antenna	21 m	63 m

Appendix 2. Explanation of the radar equation

The intensity (i.e., loudness) of the transmitted or outgoing signal is noted as P_t and is usually constant for any given radar. Typical marine radars used in avian applications have transmitted power P_t = 25 kW (marine radars are available from 4 to 50 kW). However, the intensity of the received signal (P_r) is influenced by several factors given by the radar equation (Equation 1). Larger values of received intensity result in brighter dots or colors on the radar display. Signals that are too weak cannot be distinguished from electronic noise in the receiver (discussed below).

$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi)^2 R^4} \quad (1)$$

The transmitted power P_t is focused along the beam axis by a factor called the antenna gain (G_t), which is usually stated in decibels (dB). A typical antenna (array or dish) used with an avian radar can produce a gain of at least 30 dB (an amplification of 10^3 or 1,000 times) along the center of its beam. The gain of a microwave antenna used in marine radars is proportional to its frontal area (A_r). The power density at a target at distance R from the radar is P_tG_t divided by $4\pi R^2$ (i.e., the surface area of a sphere of radius R). The factor $4\pi R^2$ appears because the energy travels away from the radar and spreads spherically. The target's RCS (σ) represents the effective target area reflecting power back toward the radar. Spherical spreading on the return trip results in a second $4\pi R^2$ factor decrease in power density at the receiver, which is captured by the receive antenna (with area A_r) resulting in the received power from the target P_r. Thus the received signal is proportional to the inverse fourth power of distance (R). The maximum distance that an animal of a certain size can be detected is R_{max}, where

$$R_{max}^4 = \frac{P_t G_t A_r \sigma}{(4\pi)^2 S_{min}} \quad (2)$$

S_{min} is the radar's minimum detectable signal, which is limited by electronic noise in the receiver. As might be expected, larger birds (with greater σ) can be detected farther from the radar antenna than smaller birds (Figure 6).

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Tim J. Nohara is the founding president and CEO of Accipiter Radar Technologies, Inc. Beginning in 1994, he assembled

a world-class team of radar engineers and scientists focused on the development of avian radar for use at military airports, civil airports, and in natural resource management applications. Prior to this, he was with Raytheon Canada Limited working on advancing space-based, airborne, and ground-based radar systems. He received his B.Eng. degree in 1985 and his M.Eng. and Ph.D. degrees in 1987 and 1991, respectively, in electrical and computer engineering from McMaster University. His graduate work was in radar. He is a licensed professional engineer and a member of the IEEE. His current research interests are in intelligent, wide-area surveillance and information systems for avian and security applications.

Peter Weber is a principal radar engineer at Accipiter Radar Technologies Inc. Since 1996, he

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