Final Scientific Report

Project Title: Are flying wildlife attracted to (or do they avoid) wind turbines?

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Executive summary

Statement of findings:

> A DOE-sponsored research project found strong evidence that flying wildlife avoid or are attracted to commercial-scale wind turbines from a distance. Some nocturnally-migrating birds avoid flying near turbines and few or none change flight paths to approach them. High-flying bats less often avoid flying near turbines and some are attracted to them from a distance, although bats' flight paths were often complex and convoluted. The findings are being prepared for submission to a peer-reviewed scientific journal (Larkin, in prep 2013).

Migratory bats are seriously affected by wind turbines in widespread terrestrial locations, night-migrating birds also affected but probably to a lesser degree. "Risk" (impact/exposure) is the appropriate measure of such effects. To estimate risk one must know not only the number of animals killed but what mortality means in the context of the conservation of the species involved. The central problem is that we cannot currently estimate exposure of night-flying wildlife to wind turbines and thus cannot evaluate risk either nearby to turbines or at the population level. This project sought to begin to find a scientific basis for risk applied to flying wildlife approaching wind turbines at night.

The work concentrated on objective, quantitative identification of reactions of flying animals to turbines. Reactions are deviations from a previous steady-state of flight. The issue is complex: animals can fly straight or not when approaching turbines and can react to turbines by turning horizontally, climbing above or dropping toward turbine blades (we have not seen evidence of dropping below turbine blades), or a combination of these behaviors.

The research was conducted in three early fall migration periods with a tracking radar, currently the only instrument of its kind in active use for civilian research. Unlike other available techniques, radar can detect and follow single flying animals at night at great distance without disturbing their behavior. The tracking radar provided objective data because it followed animals essentially without operator intervention as they drew closer to wind turbines and recorded their location and height within a few meters. The radar was used at three field sites, generating 1,829 tracks of which 215 could be used for analysis of reactions. Researchers conservatively identified tracked "targets" using wing beat patterns of each animal. Information from night-vision equipment and thermal imaging, and supplementary field work on Brazilian free-tailed bats and flying birds feeding aloft at dusk confirmed this approach to separating birds from bats.

Turns and climbing/descending were analyzed separately, although flight paths of reactions sometimes included both horizontal and vertical deviations. A manual "eyeball" assessment gave clear but qualitative results on avoidance of and approach to turbines. To provide objective evidence and to generate estimates on values such as the distance at which animals react to turbines, a completely automated assessment was conducted independently. This avoided the popular but weaker case-study approach. Descriptive statistics for four-dimensional (X, Y, height and time) radar tracks provided input for five estimators of reactions in horizontal flight and two in height for animals coming within 344 m of a turbine. A skilled observer also manually classified plots of the tracks to compare with the automated assessment.

Using conservative criteria for reactions, 91 bats and 116 birds out of 1,829 radar tracks of flying animals were admitted to quantitative and manual assessment: “attracted”, “avoided”, no-reaction, or not classifiable. Bats’ paths were often nonlinear and even undirected by several measures. Simple 1-way parametric statistical tests were used on those tracks that could be successfully classified by both manual and automated assessment:

hypothesis		
Birds and bats react the same to turbines.	manual inspection	$p < 0.0035$
	automated algorithm	$p = 7.015^{-06}$
Subjective manual and objective automated methods disagree		$p < 0.0006$

The methods were in strong overall agreement with each other, showing that subjectivity was unimportant. Separately, each showed birds avoid more than are attracted, bats the opposite. The overall result that some proportion birds and bats react in opposite ways to wind turbines, significant at one part in seven million, explains or at least helps explain the larger, often much larger, numbers of dead bats than birds that are found near wind turbines in the morning during migration season. Moreover, the results for bats suggest that alterations to make wind turbines more easily detected by bats could increase rather than decrease fatalities of flying bats at wind power installations.

Background

Concern about fatalities of flying vertebrate animals (birds and bats) has had direct consequences for siting commercial-scale wind energy facilities and is an ongoing issue. Although there are important particular local issues when high concentrations of vulnerable species encounter wind turbines, the wider focus has been primarily on bats and birds, the latter especially (in the eastern two-thirds of the USA) passerines (songbirds) that migrate at night. These animals are killed by turbine blades as they fly at rotor-swept height (RSH), defined as about 40-140 meters above ground level (AGL) or at a slightly lower height (Kunz et al 2007a, b). Migratory bats are seriously affected by wind turbines in widespread terrestrial locations (Arnett et al 2007). Bats are thought at higher risk than birds because bat carcasses are found beneath wind turbines in greater numbers than those of birds even though it is thought that substantially fewer bats than birds migrate past wind turbines. The bats that are documented to be most at risk in temperate North America are migratory tree bats. These bat species do not live in caves and, unlike most bats that do, they annually migrate distances comparable to many birds. Although little is known about the details of their flight and stopover behavior during migration, there is no reason to suppose that the forces of natural selection that have given birds their migratory abilities have not produced equivalent and perhaps convergent adaptations in these tree bats (Larkin 2006).

In addressing known and potential effects it is critical to know not only the number of animals killed but what mortality means in the context of the conservation of the species involved. In the case of flying wildlife we cannot currently estimate exposure and thus cannot evaluate risk locally or at the population level. This proposal seeks to move toward a scientific basis for the term "risk"as applied to flying wildlife approaching wind turbines.

The research community believes that bats are at particular risk from wind turbines but does not know how that happens or why fewer birds than bats are found at wind turbine installations at certain times of year. If bats or birds are attracted to turbines (Cryan and Barclay 2009), the number of bats exposed is much higher than if they would simply encounter turbines in the course of straight migratory flight. Conversely, migrants avoiding turbines by turning away from them at night is an equally important possibility. If they avoid turbines, the risk is lower for those species that avoid. The project began in the context of a nearly-complete absence of data with which to estimate attraction vs. lack of attraction. These ideas have critical implications for siting turbines.

In this report "migratory bats" refers especially to three species of migratory tree bats presently common, or at least not uncommon, in migration in the eastern USA: *Lasiurus borealis*, *Lasiurus cinereus*, and *Leptonycteris noctavigans*. These bats are obligate migrants, some spanning much of the continent of North America annually. At the field sites, though, one or two of the species may also be resident bats and all migrant bats may or may not remain in an area for stopover at some times during long-distance migration. Almost all birds observed during this project were almost certainly engaged in goal-directed long-distance migration but bats could also have been engaged in local flights during interruptions in migration or local flights of some other kind. Thus the migratory bats were not necessarily migrating when their data were recorded, although a substantial fraction of the bats were indeed making progress when observed with the radar, flying in a seasonally-appropriate migratory direction. (A type of target called "steady flapper" is probably composed predominately of bats engaged in migration, but the radar classification of target types is less certain for these animals, see below.)

Flying wildlife and arthropods (insects and perhaps ballooning spiders) were studied with tracking radar, a special instrument uniquely suited to the task (Methods). Radar has previously shown reactions of aquatic birds to an offshore wind facility in Europe (Desholm and Kahlert 2005) and tracking radar in particular has discovered reactions of small birds to low-frequency electric fields (Larkin and Sutherland 1977), sounds of thunder (Larkin 1978), and a tall tower (Larkin and Frase, 1988). Importantly, the tracking radar and all or almost all other radars currently used in research on wildlife cannot follow small animals flying close to large metal-containing structures such as turbines. For this reason the project studied reactions of flying wildlife to turbines at distances up to a kilometer or more but not among or near the turbine blades. This is a report on an analysis of reactions to the presence of a turbine, not of the details of reactions to the blades, nacelle, etc. that are in any case not observable by the radar equipment.

The special cases and complexities of the geometry of radar, turbines, topography, wind, and flying animals proved difficult. Obviously, animals can avoid turbines by turning horizontally, climbing above turbine blades (we have not seen evidence of dropping below turbine blades), or both. Less obviously, based on our extensive computer analysis of paths, flying wildlife can and sometimes do:

- climb steadily while approaching a turbine, passing over it but not inflecting in height;
- never come close to a turbine in height, horizontally, or both;
- fly so irregularly that their path is not classifiable;
- fly neatly between two turbines while flying nearly straight without turning;
- pause in forward progress toward a turbine without changing direction;
- fly near radar clutter or behind another turbine (in its "radar shadow"), making the radar track difficult to interpret;
- fly almost tangentially to all turbines, passing them without coming close to any;
- while approaching turbines, turn so as to suggest possible attraction at a distance, then turn again indicating possible avoidance closer to the turbine(s), or vice versa;

and

- waver back and forth or up and down in flight path while drawing near a turbine, exhibiting no baseline direction for estimating a turn right or left (or ascent/descent).

Discrete echoes on radar are often called "targets" (Methods). This project required discriminating small flying birds from small flying bats and small flying arthropods (insects and perhaps spiders), a level of taxonomic distinction that required new techniques and new kinds of radar data. At this point the science supports that distinction to a great degree but there has been no replication of the taxonomic results by any other researchers and no comprehensive, direct "ground truth" to completely verify the taxonomic classification. Therefore this report uses the terms "birds" and "bats" with no reservation but the reader should realize that those terms are based on radar data concerning "bat-like targets" and "bird-like targets" rather than animals that were clearly seen somehow or held in the hand.

Two additional and inherent problems result from the observational paradigm (see Methods): Radar operators nearly by necessity tracked targets flying toward turbines (i.e. already approaching one or more turbines) to observe a reaction. The first problem is that, because of the resulting geometry, a binary yes/no (react/not) classification of possible reactions will be biased. That is because even random left/right turns will appear to be avoidance against a background high level of approaches. That is to say, because of the biased sample of already-approaching targets, most turns in the plane of the earth below (in XY) will most likely be away. The second inherent problem concerns the angular magnitude of a reaction (how much the animal turned away or toward). If that value is used to provide a better unit of analysis, a different problem develops because a target flying in the general direction of a turbine can make much wider turns away from the turbine than toward it. Clearly, because of the geometry, an objective, algorithmic approach requires finesse (see Discussion).

In addition to challenges resulting directly from the nature of paths of flying animals, quantifying animals' behavior aloft around wind turbines requires a series of underlying assumptions and definitions, some obvious, some subtle. Assumptions were developed with care when preparing the proposal and later during the course of the project. Those assumptions are fundamental (Appendix 6). Some of the assumptions are explained or clarified in Methods, below.

The question of whether bats and birds avoid or are attracted to turbines is important for policy and the answers to it deserve the strongest basis in science. Subjectivity (see previous Quarterly Report) is helpful but an objective (operational) definition of avoidance/attraction is better. Therefore, project staff put time into developing and writing an algorithm to classify tracks of flying wildlife on radar by logic and descriptive statistics and independent of the kind of creature being tracked.

In eastern and interior North America, most fatalities of flying wildlife at turbines occur at night. The work in this project was therefore at night. As seen in the unretouched photo at right, taken at the Casselman site with the moon behind thin cloud, turbines are visible to flying animals with even moderately good scotopic acuity. Turbines 17 and 21 at Casselman have red lights for aviation safety but studies have shown that such lighted turbines do not show casualty rates different from unlighted ones. The distant bright lights at lower right are a parking lot and maintenance building at the Iberdrola facility.

Two additional and inherent issues resulted from the observational paradigm: Radar operators must track targets flying toward turbines to observe a reaction. The first problem is that, because of the resulting geometry, a binary yes/no (react/not) classification of possible reactions will be biased. That is because sometimes even random left/right turns will appear to be avoidance against a background high level of radar-operator-selected approaches. That is to say, because of the biased sample of already-approaching targets, most turns will be away. The second inherent issue concerns the angular magnitude of a reaction (how much the animal turned away or toward). If that value is used to provide a better unit of analysis, an animal flying in the general direction of a turbine can make much wider turns away from the turbine than toward it. Clearly, because of the geometry, an objective, algorithmic approach requires finesse.

Regarding our classification of reactions into: can’t tell, none, attract, avoid (Methods): "none" is not easy to determine definitively because a small change in climb or slope in height(time) or direction of travel in XY may cause the animal to clear a turbine by a little more than it otherwise would have. What reaction is "small"; what reaction is "none"?

The standard aeronautical terms for directions and speeds are:

Relative to the earth,	speed is ground speed,	track is direction of flight path.
Relative to the air,	speed is air speed,	heading is direction the body is pointing.

These terms are used except for the semantic issue that “track” in the context of tracking radar refers to the collection of time/position points collected during autotracking a certain “target”. Therefore “flight path” or “direction of flight” are used instead of “track” to describe the direction of flight over the earth relative to True North.

In the course of this and another related project we discovered that North American bats often fly in strange ways high aloft at night and that consequently the behavior of the bats being tracked with radar is far more complex and difficult to analyze than anyone expected. Some bats sometimes fly fairly straight and level as one would expect from bats engaged in long-distance migration. Some turn or change height or speed, sometimes in apparent response to turbines. Other bats exhibit behavior that cannot be thus classified and may or may not relate to wind turbines. For example, two tracks from a single night in 2010 exceeded 12 minutes in duration and involved multiple related changes in speed, direction, height, and wing beat characteristics. Complex bat tracks are quite common in the data and occurred in both over agricultural fields in Illinois and over a shallow ridge in the Alleghenies in Pennsylvania.

These long tracks of bat-like targets represent a challenge in several respects. First, statistical analysis of reactions to turbines by bats depends on being able to discriminate reactions to turbines from spontaneous (if these behaviors are self-directed) bat flight behavior. Achieving such discrimination, in turn, depends on some degree of biological understanding of the behavior. Second, radar artifacts need to be ruled out. This is because, whereas straight level flight with regular wing beats is strong confirmation that the tracking radar is working properly, kinks, pauses, and bumps in tracks may indicate some artifact. Artifacts must be eliminated from the data. Less obviously, field workers using the equipment in a field at night cannot always rule out artifacts and therefore the real biological nature of these nonlinear tracks sometimes only becomes apparent on close inspection during analysis. Third, personnel needed to repeatedly upgrade the special and unique software used to take and analyze these data to handle tracks and wing beat records that are 10x or so longer than ordinary tracks of migrating animals and exhibit important details within them. Fourth, sample size of flying bats was greatly reduced not only because long tracks reduce tracks/hour but also because many of the convoluted, rising and dipping bat track could not be related to wind turbines in the vicinity at all. Grappling with this unexpected behavior by small temperate bats necessarily delayed analysis by diverting the project from its goals.

Methods

Radar methods

The research was conducted with a special, effectively unique, kind of radar called tracking radar. The Illinois Natural History Survey tracking radar is an X-band instrument for following individual flying animals and tight flocks. Its large antenna permits remotely observing flying animals at a great distance. It is currently the only tracking radar of which we are aware available for biological work in North America.

Specifications of the Enterprise Electronics Corporation model WF-100 tracking radar are given in Appendix 1. The basics of using radar for research on flying wildlife are covered in a book chapter (Larkin, 2005), an updated version of which is available at ftp://ftpext.usgs.gov/pub/cr/mt/bozeman/Diehl/ . A more recent revision of the chapter published in hard copy by The Wildlife Society contains only monochrome illustrations and is therefore inferior to the 2005 and web-based editions.

The WF-100 tracker was obtained in 2006 from Dr. John Westbrook at the Department of Agriculture. Designed as a balloon-tracking radar and later modified to track insects, it has required considerable repair-and-rebuild but has been reliable and accurate overall. Technical work included correcting design errors and replacing radar parts that were worn out during work for this contract, including incandescent panel lamps that, it seems, were not designed to last as long as we asked them to last during long nights of field work; the radar's On switch; and a high-voltage transformer apparently damaged because of working in August heat. A small wobble in the radar's large antenna was greatly reduced by the project engineering staff over the course of the project, decreasing error in height estimates for flying animals.

Because the invention of radar was initially motivated by desire to detect approaching military aircraft and ships, distinct areas returning radar echoes are classically referred to as "targets". In this project, the "targets" were flying vertebrates and insects that we not affected at all by the radar observing them and, in fact, were engaged in natural flight except that wind turbines were present at varying distances.

The project assembled a comprehensive flat-ASCII database of surface weather observations and turbine states (rotating/not and direction) to use in interpreting the behaviors.

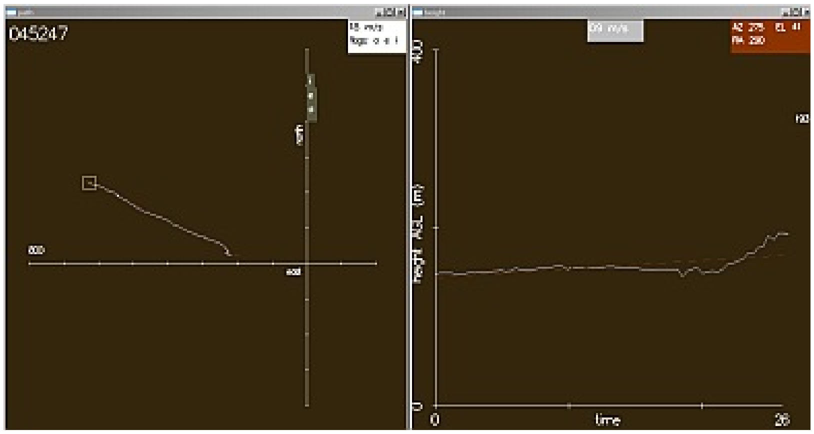
Radar operation and selecting "targets" to track

Except for a few brief periods, one field worker operated the tracking radar and examined an analog oscilloscope ("A-scope", Larkin 2005) to make sure the radar continued to track the same flying animal, thereby avoiding "switches" to a different flying animal. A second field worker took hand notes on every track, noted possible anomalies and artifacts in the radar tracks, made surface wind and weather observations, and observed wing beat patterns. During tracking both workers agreed on the type of target based on the A-scope and real-time digital wing beat displays. The target type was written down and also noted in the computer records. Except during the evening observations of flying insect-eating birds in 2011, neither field worker attempted to see or hear migrating animals and both remained inside the radar enclosure except for brief breaks. The exterior of the radar and its environs were in darkness, illuminated only with faint red light that reached the exterior through a small window or when doors were open. The radar was sited >200 m from any turbine except at the 2012 site in Pike County, IL.

Migrating birds normally fly above RSH. This work and other observations with the tracking radar indicate that bats of at least some species also often fly above RSH. But animals well above RSH are not at risk from turbines unless they descend a substantial distance toward a turbine. In this pioneering project there was no reason to look for improbable behavior first. Therefore operators searched for track-able targets at or near RSH; this was done by selecting a low elevation angle (angle up from the horizon, Larkin 2005) and slowly scanning the antenna manually back and forth, stopping to "lock on" to a suspected bird or bat. "Suspected" included echoes that fluctuated on the A-scope like wing beats of flying vertebrates, as opposed to the steady signal or shallow, high-frequency wing beats from most insects. Secondarily, small echo size was often a clue that a target was an insect, not a vertebrate. Many insects were tracked because operators were not entirely sure of their target identity at first or for other reasons.

Operators usually scanned places from which migrating animals were approaching the area of wind turbines, usually upwind in general. Sometimes, particularly when few migrating birds or bats were present and only seemingly-local bats were available to track or when wind at the surface was quite low, the operator scanned 360 degrees. Targets near serious ground clutter and therefore difficult for the radar to track accurately or targets too close to turbines and therefore with no previous path history with which to observe a reaction of lack of reaction were rejected.

After operating a switch that put the radar into autotrack mode, the radar operator examined the A-scope (see above) and glanced occasionally at a real-time display of the radar track (below) to determine if the flying animal might react to a turbine in some way. Animals approaching a turbine were tracked. Tracking of some animals at a distance was stopped by the radar operator before a reaction to a turbine could be observed, namely tracks that were steadily receding from all turbines or flying tangentially to them at a distance as opposed to approaching.



In the above screenshot taken while collecting data in Pike County, IL, the XY plot at left and the 26-second height(time) plot at right show basic information available to a radar operator during a radar track. In this Pike county, Illinois location, the single wind turbine was within a few meters of (0,0), which is the radar location in XY. Arriving from the northwest well below RSH, the bird stopped its XY flight upon coming within about 200 m of the wind turbine at about 20 seconds into the track and flew straight up, the ascent represented by the tiny blob of white at the end of the XY plot. Some but not most reactions were this dramatic but many could be watched in real time by field personnel.

Radar tracks were stopped manually for several reasons. Low-flying animals were often lost because of radar ground clutter–trees, buildings, cell towers, or other objects giving radar echoes much greater than a flying animal. Sometimes a different flying bat, bird, or arthropod passed near the target being tracked and the autotrack mechanism switched to the second target. Sometimes small tracked animals flew away so far that their echo became too weak to track, although the large antenna of the WF-100 could usually track animals well beyond any area of interest with respect to wind turbines. Low creatures sometimes descended and were lost to autotrack before they reached the ground or canopy. A common reason for end-of-track was animals that flew into the "radar shadow" of a turbine or because the turbine itself overwhelmed the echo from the animal. This bird in Tazewell County, IL was lost as it flew close to and behind a turbine (brown cartoon "turbine" at bottom). The radar quickly left the bird and jumped to the turbine location, giving a false "track". Skilled radar operators on some occasions were able to manually re-acquire the

same flying animal again when it left the vicinity of the turbine, but turbine clutter was one of the most common reasons a radar track was stopped.

Field sites and dates

We selected field sites year-by-year as the needs of the project evolved. The sites were commercial wind turbine installations on a shallow ridge in the Alleghenies in Pennsylvania and in agricultural fields in two locations in Illinois.

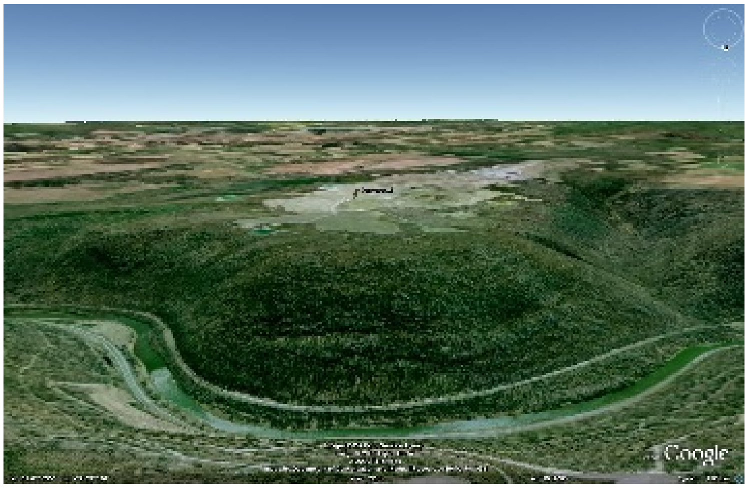
Criteria for field sites were (1) where migrant bats and birds are at risk, (2) with a good field of view and an acceptably low amount of radar-clutter-producing features on the landscape, (3) with access for a heavy trailer in mid-summer, (4) without prominent topographic or other features (aside from turbines) that may cause reactions from flying animals to be confused with possible reactions to turbines and (5) with only one (preferable) or two (less preferable) northernmost turbines such that the causative agent of a response on the part of animals flying roughly southward in fall would be as clear as possible. With respect to (5), a bird or bat encountering a diffuse array of turbines or a line of turbines running east-west might react, but it would have been difficult to tell which turbine or turbines were being reacted to and whether the flying animal was reacting to the turbines as a group.

We selected a Pennsylvania 2009 field site rapidly because of the date of start of funding. We worked under the auspices of Bat Conservation International (BCI) at the Casselman, Pennsylvania facility operated by Iberdrola Renewables, Inc. The radar unit at the Casselman site in August 2009 is shown at right.

Ongoing 2009 post-construction research by BCI proved that migrating bats are at risk at this facility, which is typical in that respect for similar wind energy facilities in most of the eastern and central USA. The site has two distinct lines of turbines; we chose to work at the one on open strip-mined land rather than the forested one because the trees on the latter would obstruct the radar beam. The turbines are located along a nearly-bare, open ridge surrounded by partly-wooded farmland at lower altitude. Aside from the ridge, no topographic features higher than turbines, lighted tall structures, or other human-built features were present to which flying animals might be expected to react. Access via the Company's access roadway was convenient, which proved to be important for driving to the field site in fog in darkness. The radar unit was about 240 m north of the northernmost turbine (Turbine 16), probably the optimal arrangement.

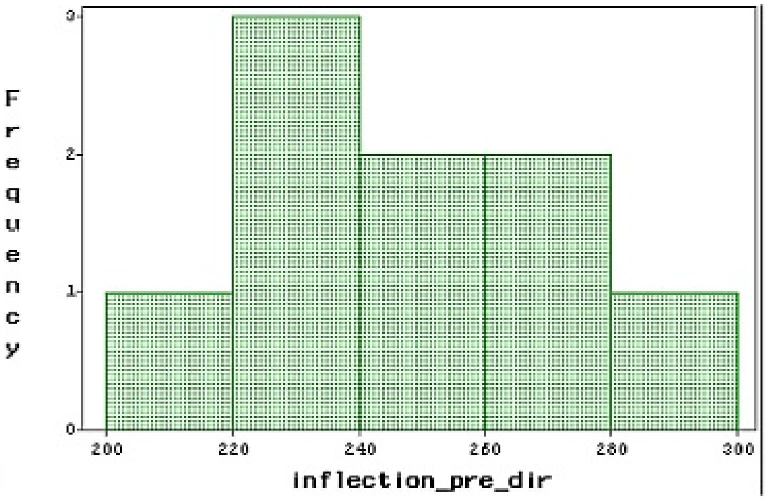
The assistance of BCI was critical to selecting this field site and obtaining permission to conduct research there. We greatly appreciate the help and cooperation of BCI in making our 2009 work at the Iberdrola Renewables, Inc. facility possible.

The 2009 Casselman PA site was productive but proved to have some disadvantages, prompting a search for a site with different characteristics. First, the turbines at Casselman are on a ridge, with considerable topographic relief in some directions. In the Google Earth image at right, topographic relief has been exaggerated for effect. Small birds and bats may pay attention to the topography (see Appendix 7) or may not but topography creates orographic winds that likely cause flying creatures to change height and exhibit horizontal movements passively. Jogs, changes in direction, and upward and downward movements near wind turbines were the subjects of the research and the possibility that they may be caused by orographic wind was a disadvantage.

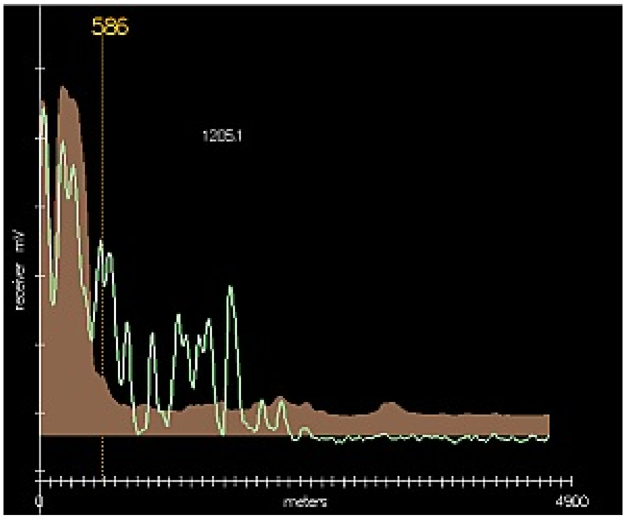


Second, turbines at Casselman are in a linear arrangement. The approximately 250-m distance between turbines is only about twice the height of the turbines. Animals flying at or below RSH from most directions except approximately parallel with the turbines (i.e. about 225°) must either climb above RSH or fly between turbines. These behaviors were observed but are difficult to interpret considering the topography of the ridge itself.

At right is a histogram of flight directions of birds approaching the turbines before they reacted (or not). The modal value of 220-240 degrees is parallel to the line of turbines at Casselman

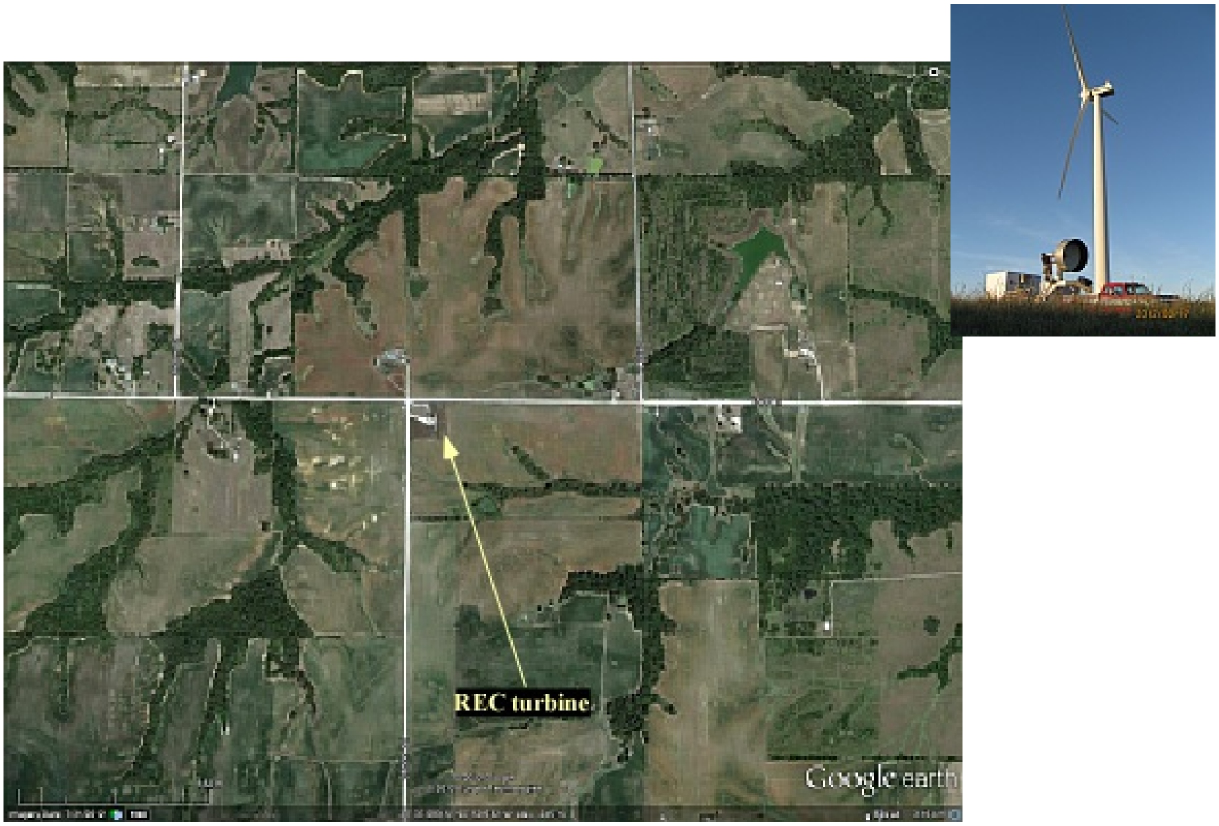


Third, "turbine clutter" at the Casselman facility was a problem for tracking 12-g animals near 125-m moving steel structures. At right is the digital A-scope at the end of a radar track, the green line of radar echo showing Turbines 16-21 looking down the line of turbines. The tracked animal was lost in the radar clutter."Normal" clutter at the site is shown as a brown background.



With these issues in mind, the P.I. selected flat agricultural land with turbines arranged in a two-dimensional array for the second field season. 2010 Illinois work with the tracking radar in Tazewell County, IL took place 23 July - 17 August, recording over 1,100 radar tracks. Rain and mud unusual even for summer in the midwestern USA prevented field work prior to 23 July: "... PRIMARILY THE SAME AREAS AGAIN TONIGHT THROUGH WEDNESDAY MORNING... DUMPING ANOTHER 1 TO 3 INCHES" (quote from a National Weather Service forecast). Few birds appeared until the latter part of that field work but bats appeared every night. Ground clutter proved to be a problem at this site, chosen especially for its flatness and favorable arrangement of turbines. Warm-front showers during early August prevented effective radar work for about a week because of an extended period with a combination of rain and winds unfavorable for migration (out of the south). Unlike the other two sites used here, the Tazewell County, IL site had few trees nearby, which may be relevant considering the reported tendency of tree bats to avoid migrating in areas without trees (Baerwald and Barclay 2009)–but plenty of bats were aloft at the Tazewell County, IL site.

Our central Illinois location was a highly appropriate site. A study at a nearby large turbine installation (Johnson et al 2010) had found many carcasses of bats. Hoary bat, eastern red bat, and silver haired bat (the three species of eastern migratory tree bats) comprised 98.7% of the carcasses. The authors estimated a total of 4,720 bats/year were killed at the turbines. (That 2010 study used vertically-aligned night-vision equipment 40 m from the base of a wind turbine. That is too close to a 125-m turbine to compare meaningfully with the radar work reported here even though the sites are so close to each other geographically.)



In 2012 we were offered an opportunity to study flying animals near a single isolated turbine in fairly flat farmland in Pike County, western Illinois (above). No other turbines exist nearby–for instance in all of Pike County or adjacent Adams County. The Google Earth image is about 2.5 km across. The turbine, a full-scale 1.65-MW Vesta model, has been operated since 2005 by the Illinois Rural Electric Cooperative (REC), which gave us excellent cooperation and some support for the research.

In Pike County we used the tracking radar at two sites very close to the turbine, one 70 m from the turbine tower base and one 22 m from it. Although siting a radar with respect to undesirable clutter is widely regarded as somewhat of an art rather than predicable from theory or first principles, personnel were pleasantly surprised that locations so close to the huge, spinning, metal-containing turbine blades would produce good results. The radar was used from 17 August through 11 September 2012 on almost all nights without interfering insect clutter, continuous bad weather, or radar problems. The area had experienced a serious drought during the summer, a condition that relented only during our August-September field work. On two nights insect targets were so dense in the air that we could not use the radar to detect flying bats and birds. Hurricane Isaac moved north as a tropical storm with 3-4 days of rain and strong winds from the south. A serious, difficult-to-diagnose failed connector affected the quality of data for the first part of the work and then took 10 days to find and repair, reducing the amount of tracking data we could obtain. A second connector failed but was replaced in about an hour.

We normally operated through the night. Most birds, aside from diurnal raptors, which have not yet been shown to be a problem at wind turbines in the eastern USA, migrate at night and accepted mammalogy dogma holds that bats also migrate at night. We took data beginning shortly before dusk until we stopped because weather became persistently unsuitable, flying vertebrates became so scarce in the sky as to make it unproductive to try to find them with the radars, or dawn. All-out sampling of the migrants normally took place on any night favorable for migration seven nights a week.

Auxilliary field work in an urban setting in Illinois in 2011 established that Common Nighthawks and Chimney Swifts disappeared after dark and had wing beat patterns on radar that were distinguishable from those of the bat-like targets used in this work.

Site in USA	Time period	latitude / longitude	purpose
Cassselman, PA	30 July - 13 August 2009	39° 52.171' 79° 5.859'	reactions to turbines
Tazewell County, IL	26 July - 22 August 2010	40° 22.7803' 89° 25.6945'	reactions to turbines
Champaign, IL	21 August - 1 Sept. 2011	40° 5.527' 88° 14.510'	wing beats of insect-eating birds
Pike County, IL	8 Sept. - 10 Sept. 2012	39° 37.099' 39° 37.099'	reactions to turbines

Turbines at the three sites used for studying reactions. Only a small number of the turbines at Casselman and Tazewell County were within useful range of the tracking radar for this work.

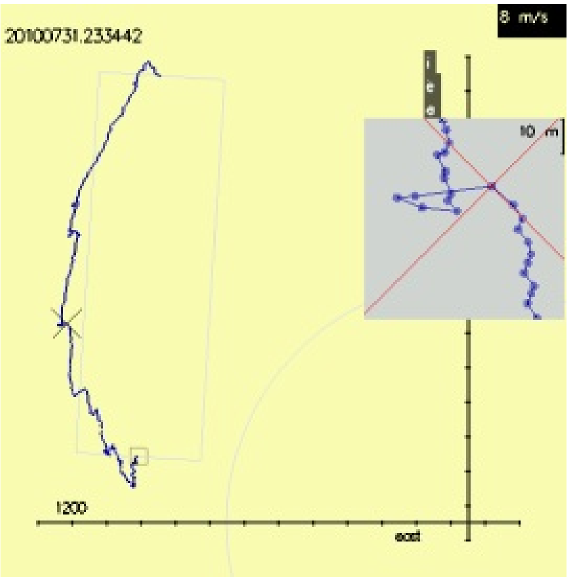
location	turbines	rated output, MW	blade length, m	tower height, m
Casselman PA	67	1.5	38.5	80
Tazewell County IL	38	1.5	38.7	81
Pike County IL	1	1.65	39.6	71

Preparation, track segmentation, and selection of radar data for analysis

All radar tracks used in the analysis of reactions to turbines were nocturnal. They started at night, defined as neither diurnal nor crepuscular, that is, between the end of civil twilight and the beginning of civil dawn.

Flying animals were studied with a tracking radar taking four-dimensional data (position north and east, height, and time) at night. Because the sampling rate was high enough to show "tracking noise" (1 or sometimes >1 point/second), the data were smoothed by a running average. Because the radar data sometimes contained certain artifacts, the data required initial graphical editing to remove single-point tracking artifacts, separate tracks when the radar switched from one target to another, and remove points affected by certain operations by the radar operator during difficult tracking.

The track-editing software was upgraded substantially for this project, for example to show on a moving inset the details of a long track (figure). One complex track took 2 days to edit, a slow process but necessary.



The bat target at left was flying south in central Illinois at rotor-swept height when acquired (the south end of track is the beginning) but soon reversed course and climbed to 650 meters over a meandering slow curve, never near a turbine. The inset shows a kink in the track at the X on the full plot. Such a target consumes time to track and later edit but results in no opportunity to study its reaction to wind turbines.

Tracking artifacts due to radar issues occur in the radar's space, which is in spherical coordinates, whereas animals fly in Cartesian coordinates, at least over the scale we studied. During editing of tracks, workers looked at both spherical and Cartesian coordinate plots. It was usually easy to tell if one of the spherical coordinates dominated a purported maneuver, in which case the data points were highly suspect. The decision matters especially the often-difficult case of points near end-of-track where radar operation may be compromised by e.g. turbine "clutter" and a track seems to veer in a different direction at the end. One can see if the Cartesian plots are easy to interpret while the spherical plot is not. Also it is nearly definitive when, clear wing beats and low scanner noise maintain during such a part of a track, showing that the radar was almost certainly pointed at one point target, the flying animal. One cannot easily confuse messy ground clutter "wing beats" or 4/second "wing beats" of 50-m turbine blades with a 15-g bird or bat.

The following table illustrates automated selection of flying "targets" during midstage development of the algorithm for automated assessment of reactions. Animals like the bat above are excluded from assessment by these criteria. Conservative later criteria for using/not using targets further restricted target identity to bat-like and flap-coast wing beat types.

Radar targets (flying animals) used and not used in partial quantitative analysis of reactions for extensive parts of 2009 and 2010, algorithm version 3.1		
targets used in midstage analysis		916
targets not used		1432
reasons not used (Appendix 8 gives details for various estimators)		
reason	**technical criterion**	
target type not clearly bat or bird *	e.g. arthropod or unclassifiable	826
not close enough to expect any reaction	target was never < 724 m from any turbine, the maximum distance a *possible* reaction was noted subjectively by a trained observer	522
totally straight	no join points	3
already curving when acquired for autotrack	first join point < 4 s after beginning of track	22
flying away from turbine	target already at its closest point to turbine by 4 s after beginning of track	45
never flew straight before passing turbine	no joinpoints earlier than closest approach to turbine	6
turn angle too great to classify a reaction, if any	|yaw| > 90°	8
* Possible bird target types were: flap-coast and intermittent flap-coast. Possible bat target types were: vertebrate-like, steady-flapping and/or "fluttery".		

An animal that *never* flies straight or level provides no baseline against which to assess avoidance or attraction and an objective evaluation is difficult or impossible. Therefore straight and level paths and, more importantly, straight or steadily-climbing or steadily-descending portions of crooked or climbing/dropping paths are the basis for evaluating reactions. Segments are within a minimum distance from a turbine. Careful statistical description and classification of such steady-state portions of radar tracks ("segments") is important for this analysis. Delineation of segments initially sought to place joinpoints , a technique from mathematical curve-fitting, in radar tracks between segments (XY and height separately). The design has since developed from simply lengthening segments through fitting segments backward in time and fitting segments to the straightest part of a track first and progressing to less straight parts, finally to using the index of curvature to stop the growth of segments and later rejoining adjacent segments whose direction of travel are not much different. This work on segmenting in the XY plane is now successful enough to support the spatial-progress-based measures. A backwards-moving segmentation scheme was developed but rejected as inferior to the original forward-moving one.

Assessment of reactions

Objective assessment of reactions or lack of reactions was a goal easy to adopt but difficult to implement with complete success. The automated assessment effort gave results that were clearly meaningful but less than definitive in achieving a clean result such as "avoided" versus "attracted" versus "ignored turbines". Two "eyeball" subjective assessments, here called "manual", were carried out, the first preliminary, partial, and carried out by a research assistant, the second more rigorous, comprehensive, and carried out by the P.I. The second subjective assessment is here called "manual" for brevity. The automated and manual assessments agreed with one another overall (Results, below) and the automated assessment took on the roles of quantifying reactions to turbines and supplying reassurance that subjectivity was not responsible for the project's conclusions. Manual assessment was applied to the same 215 radar tracks that had previously met selection criteria for automated analysis.

The manual assessments were carried out without direct knowledge of wing beat information or of the kind of target being tracked aside from knowledge that it was not an insect, balloon, or ground target. Of course the often-convoluted tracks of bats sometimes gave some indirect indication of the kind of animal.

At one site reactions were not in reality apparent even during the field work. In much of the 2009 work at the Casselman site the radar display was rotated 68 degrees unbeknownst to the the radar operator, real-time note taker, and graduate students editing the radar tracks, who were the same personnel. This had no effect on the radar's functioning or on data as analyzed but did create an effective double-blind situation in taking data: the personnel in the field and editing tracks to remove artifacts never could correctly interpret radar tracks as reactions or not; only later during analysis (and in perparing this report) was the actual layout of the turbines correct with respect to the flight paths of the animals. Needless to say, protocols were added to avoid this kind of stupid mistake in later field work.

Automated assessment of reactions

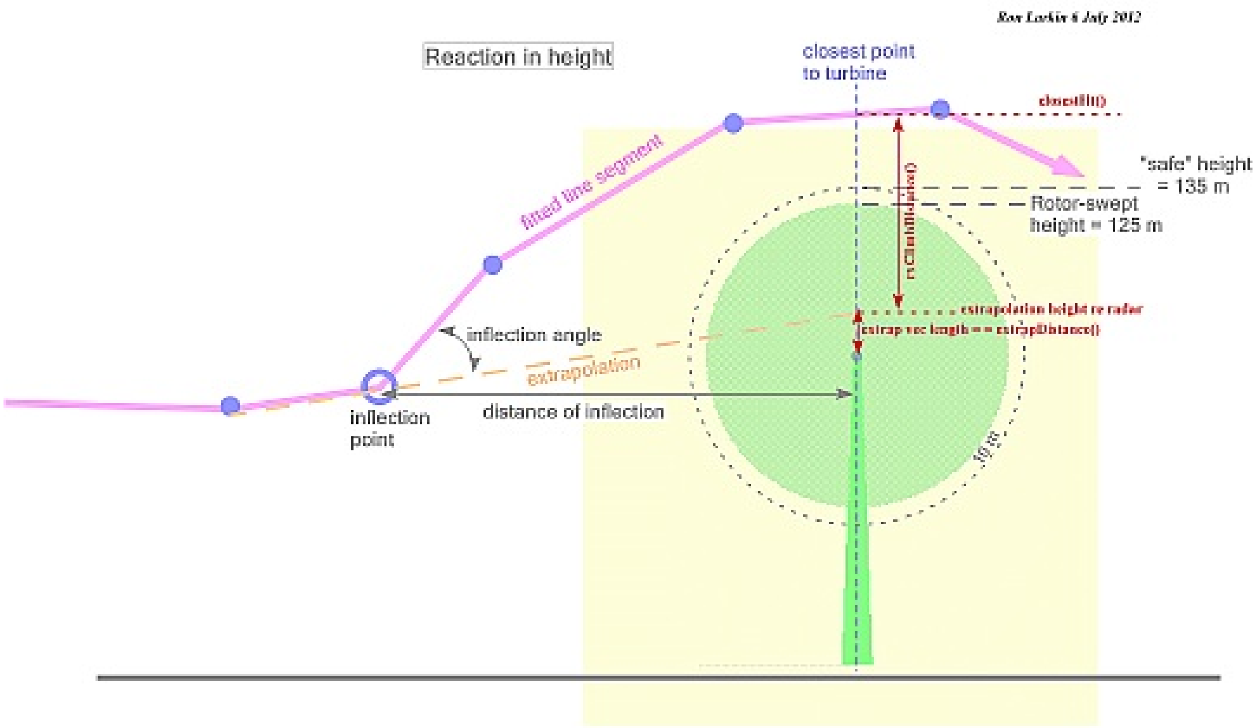
Following track segmentation, which was performed separately in the XY and height(time) planes, several quantitative procedures here called estimators were applied to each track, resulting in a score for attraction or avoidance. Scores with a positive sign were attraction because the animal had a positive speed toward the turbine and vice versa and the magnitude and sign of the result were converted into categories of reaction. The design focuses on the progress of the animal over the earth; most of the estimators concentrate on measures of actual progress over the earth (including vertical progress for reactions such as climbing over a turbine) rather than on directions of travel. Seven XY estimators and two height estimators were developed. Some XY estimators were discarded because they showed little variation or contributed nothing to the overall assessment.

XY and height were treated separately mainly because animals take a direction of flight and change height differently, the former by laterally-asymmetrical horizontal turns, the latter by laterally-symmetrical changes in body pitch and wing beat motions, although both can take place simultaneously. Each flying animal's path was scanned to find the track point that came closest to any wind turbine in XY. That point was never the first point of a track because such a flight would have been departing from all turbines and thus not part of the analysis but could be the last point of a track, especially for animals approaching a turbine and not traveling past it.

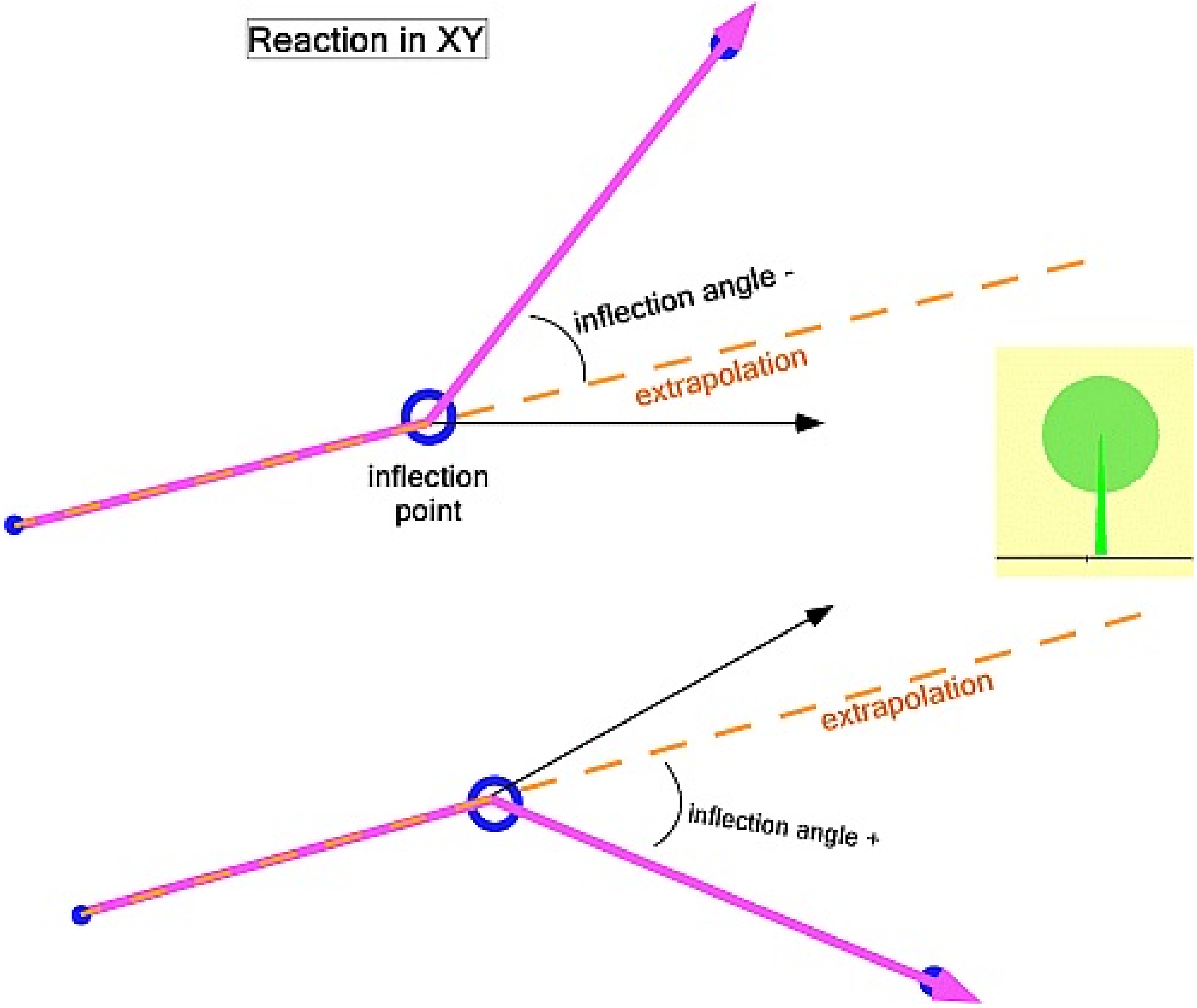
Changes in height are simpler conceptually. Climbs and descents can be measured as rate of climb (△ height / △ time)△ or as slope (rise/run, △ height /△ XY distance traveled from the turbine). Both were tried and each proved partially useful. Slope was selected because animals could (and a few animals did) pause in their XY progress and fly nearly vertically upward near a turbine or back away to some extent from the turbine. In the latter case the negative sign of the distance gives an appropriate negative avoidance value for slope. The automated assessment used heights above the ground below rather than heights relative to the radar unit; this was of importance only at Casselman, PA because the other sites were so flat. Use of heights above the ground meant that a flying animal climbing over the ridge at Casselman, staying parallel to the ground below was flying level for the purposes of automated assessment.

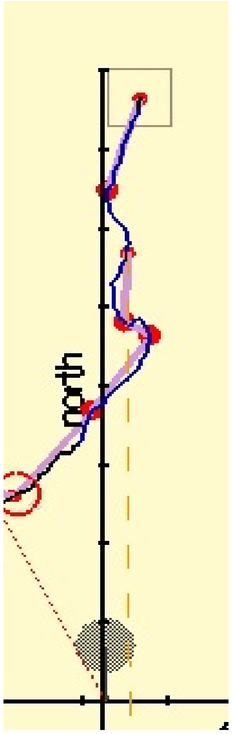
The conceptual diagrams to follow omit many details such as non-segment curved portions of tracks between segments; they are meant to explain the general geometry rather than the details of evaluators.

The diagram below shows the geometry of the algorithm with respect to reactions (avoidance in this case) that are changes in height. Line segments (pink lines) are fitted to the radar-produced height profile of the flying animal along with join points (blue dots and blue circle). A fitted extrapolation of the inflection segment is an orange dashed line. Positive scores here are in fact negative slopes (downward toward the turbine) because animals flying upward from lower than a turbine upward toward it were not likely with this radar and in fact were not observed.



The diagram below shows the geometry of the algorithm with respect to XY reactions (avoidance by left and right turns, respectively, in this case) that are changes direction of flight. The cartoon turbine is in the XY direction from the inflection point shown by the black arrows. Changes in speed do occur but are not considered because we concluded they affect when proximity to a turbine occurs rather than whether it occurs. Color conventions same as the diagram for height, above.



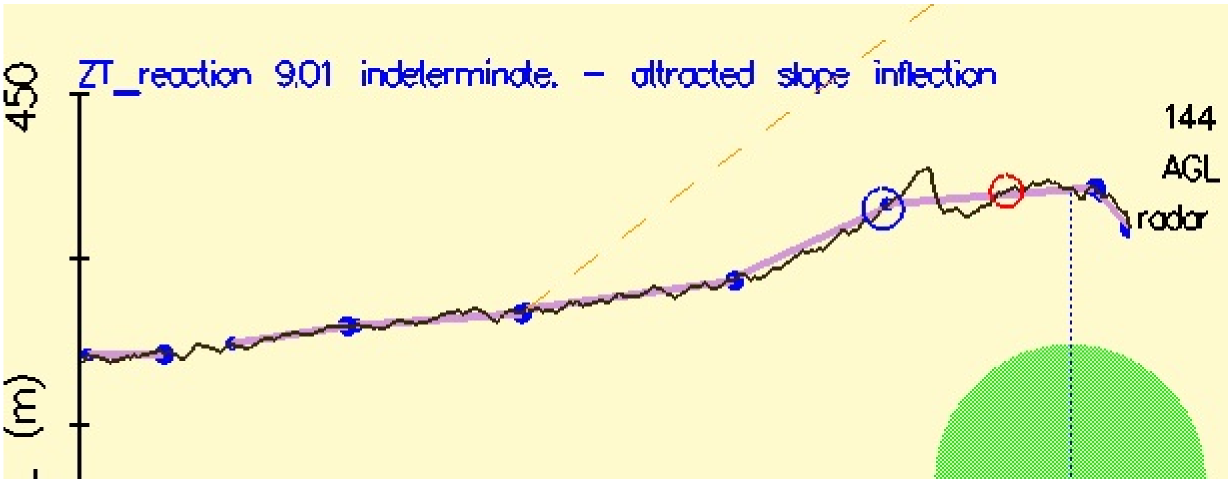


Tracks approaching a turbine can and do turn not only toward a turbine but farther so that a turbine that was to a target's right is now to its left, or vice versa. The track at left shows a flying animal approaching a turbine (lollypop-shaped gray object at bottom) from the north. The remainder of the track is off the figure to the left and is not shown.

This animal turned at least four times as if to fly to the west of the turbine, then as if to fly to the east of the turbine, and so forth. The algorithm treats such portions of tracks "right-left ambiguous" and now omits them from analysis by the algorithm, giving a shorter track but one that is much clearer to analyze. In this case, the right-left analyzer removed nearly the entire part of the track approaching the turbine, but neither computerized nor eyeball assessment of such a track would work anyway.

Height changes as animals begin to approach a turbine have been an ongoing problem for some tracks. A failure in the radar elevation control electronics (elevation tachometer) caused some of these and that artifact is handled as well as possible we think. In addition, and more importantly, some bat targets engage in short, swift climbs and descents and the behavior does not seem to be predicable on the basis of their other activity or proximity to wind turbines. (Such "fluttery" flight behavior and apparent insect-catching or social behavior aloft is quite plausible for bats and was no surprise.) The height changes result in poor segmentation. At this point, we have not succeeded in finding a way to reduce the resulting short, non-informative track segments in Z(t) that does not involve treating bats and bird differently, which would be a mistake in terms of the tracking protocols and design of the analysis.

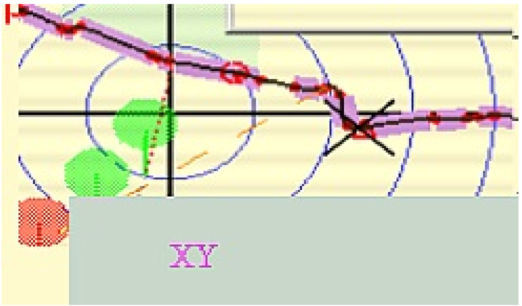
Asssessing changes in height is geometrically simpler that assessing XY (time) reactions, but subtleties intrude. The height(time) plot of track 20120908.212136 below illustrates near-optimal segmentation of the height profile of the animal (purple underlays and blue joinpoints) with the animal flying near the turbine and past it, slightly above the turbine--about 20 m > RSH. It shows a gentle, steady, climb while flying toward a turbine (XY not shown), an increase in slope approaching the turbine, then a leveling-off near and above it. The blue inflection point (blue circle) pertains to the height. That track segment levels off, decreasing climb rate as the animal comes to its closest location near the turbine in XY. The automated Z(t) assessmen was an approach, not the clear avoidance a human observer would score, a clear error. The automated assessment algorithm was not taken to a level needed to accurately score some such radar tracks.

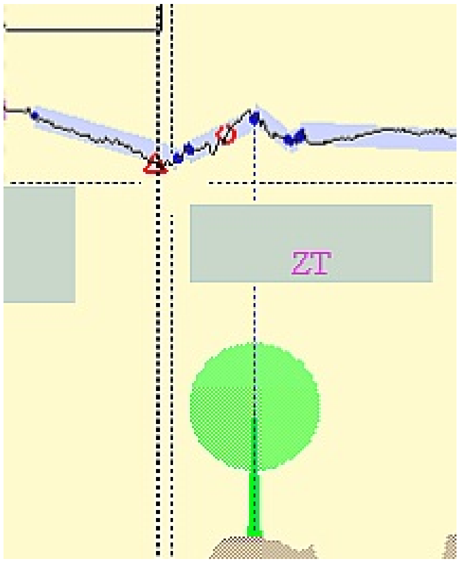


To assess animals that react by climbing above or descending toward turbines, one must ask what is "above" or "toward" a 100-m-wide set of blades rotating in a circle. Animals may also climb higher than a turbine or descend to near the turbine's height when not flying directly toward it. Humans near a helicopter may duck their heads at some distance from the blades and not only when walking directly toward it; birds and bats may be expected to similarly change height at some distance lateral to a turbine. What distance should be parameterized in this study?

The answer adopted here comes from animals that reacted in both planes, XY and height. If an animal reacts in XY, it perceives the turbine and changes its flight accordingly. One may expect that the same distance, perhaps related to "flight distance" in the field of ethology, might apply in height as well. A flying animal (track 20090806.235000) flew nearly exactly midway between two turbines, 253 m in XY from each, at the Casselman, PA site and climbed. Therefore the distance is at least 253 m, a conclusion supported by several other radar tracks. The maximum such distance was given by Track 20090730.224148, shown below, a bat that started to avoid the turbine in both planes when its XY distance to Turbine 16 was 573 m. In XY (left panel) the red dotted line shows the closest-to-turbine 286-m distance as the animal passed north of the turbine while flying WNW after reacting in XY. The distance X-to-Turbine 16 is 573 m. In height (time) (right panel) the XY reaction and obviously the height(time) reaction is marked by the bold blue dotted line and red triangle and the closest-to-turbine point by the lesser dotted line passing through the turbine graphic.

Therefore the maximum XY distance for a reaction that was a change in height was set at 580 m to accommodate this observed both-planes maximum reaction distance.





The algorithm was written as high-level computer code especially for this project. It was parameterized and improved based on judgements of its effectiveness on a small subset of the 1,829 radar tracks used in the study. The first tracks and last tracks in the study were selected as the test set: late July and very early August in Casselman, PA and tracks in mid-September in Pike County, IL. The test tracks thus included tracks of all kinds of targets with a linear array of turbines and considerable topographic relief and tracks at a single turbine in flat farmland. Using the software developed for this project, automated assessment of reactions in the 215-track subset took a couple of minutes on an ordinary desktop computer.

Manual assessment of reactions

The P.I. examined plots of the 215 eligible tracks resulting from the preliminary step of the automated assessment without knowledge of the type of target. Tracks were marked separately in each plane (XY and height) with one of four characterizations:

None	no reaction
Avoid	avoidance of a turbine
Attract	attraction to a turbine
Can’t tell	no characterization was possible

Avoid may involve turns or height changes that did not appear to be related to the presence of a turbine.

None bats and birds were sometimes climbing when acquired for tracking and continued to climb at the same rate while passing over or near a turbine at great height. Many None bat tracks consisted of complex nonlinear tracks that never approached a turbine or flew apparently haphazardly high above RSH.

Can’t tell, the most common category, was given for tracks that could not be clearly assigned to the other categories. In many cases one of the other categories appeared likely but not certain; the classification was conservative in that respect.

Results from informal carcass searches at the Pike County site are given in Appendix 4.

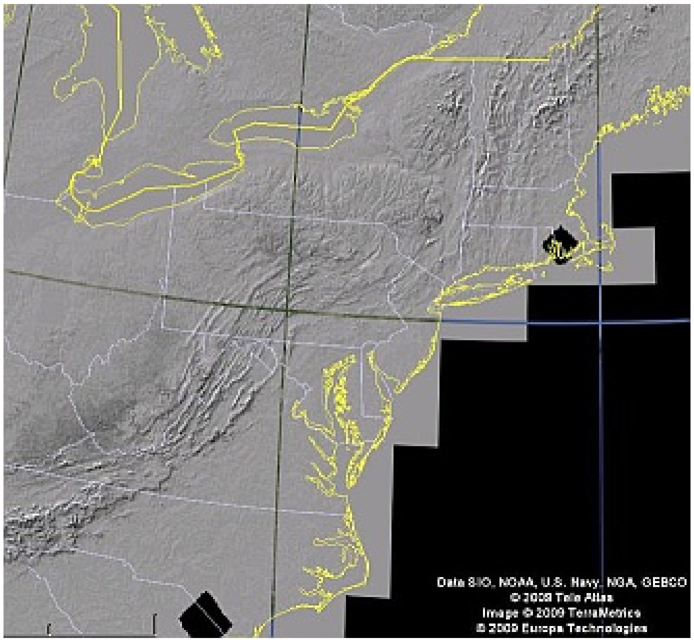
Results

Target types

Target types at wind turbine sites (see Appendix 2)	number of tracks	as used in reactions assessment	less-conservative categorization
flap-coast	401	bird	bird
helium-filled balloon (to measure wind aloft)	35	--	--
intermittent flap-coast	40	--	bird
multiple target (flock?)	11	--	bird(s) or bat(s)
non-vertebrate-like (arthropod)	661	--	arthropod
pauser	10	--	bird
steady-flapping	105	--	bat, usually
vertebrate-like	422	bat	bat
unknown (type not identifiable or ambiguous)	144	--	--
total	1829		

Flight directions and flight patterns

Many radar tracks at the Casselman PA site were parallel with the ridge and with the line of turbines on the ridge. On a larger scale, the Alleghenies are oriented in that direction, perhaps accounting for the flight directions of many birds and bats.



Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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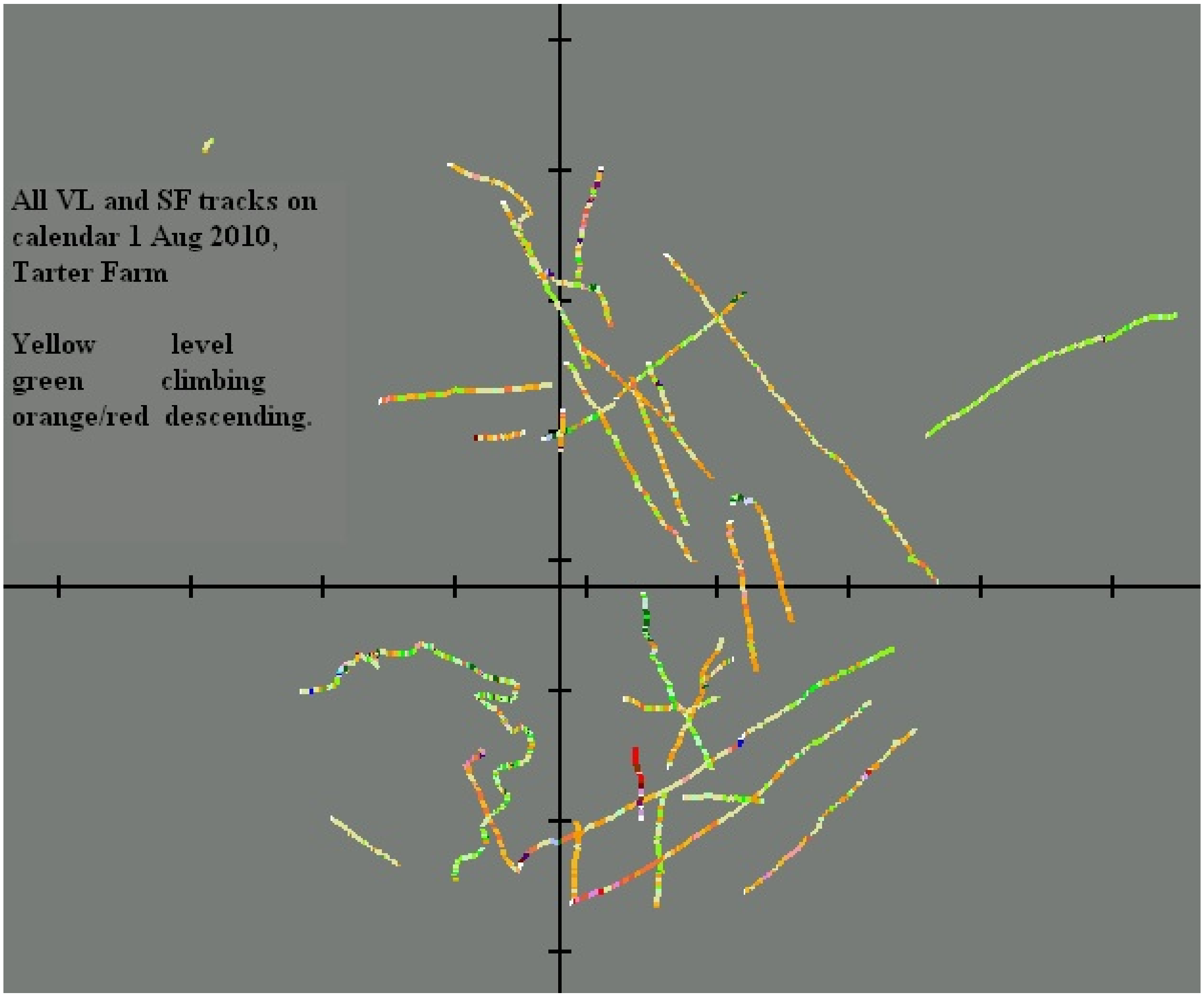


Bats were difficult study subjects (above). Shown are all bat tracks on a typical night when bats were common–indeed more common than birds aloft on this night at the beginning of August. The bat targets here are more broadly defined according to wing beat characteristic than in the analysis for this report, including both “vertebrate-like” and steady-flapping (Appendix 2). The radar is located at the origin and scale marks are at 500-m intervals. All turbines were south of the radar at this site. Color codes rate of climb, which is variable and shows most bats changing height while tracked.

Straight and nearly-straight tracks are common, taking two predominate directions but also several other quite different directions. However some tracks have quite nonlinear portions and one has no straight sections. Only one of these tracks is a possible XY reaction to turbines. A track to the south of the radar first ascended (green) then started to desend (orange) and turned right 90° to fly directly toward a turbine but turned right almost 90° again and veered away from the turbine for a few seconds just before being lost because it was low and at the same range as side-lobe clutter from the turbine.

While a flying animal was being tracked, field personnel could almost always watch the animal's path displayed in real time on a high-resolution computer monitor and observe reactions or lack thereof second-by-second. The fundamental reality of reactions to turbines was already apparent during collection of the radar data and was remarked upon in the written Radar Notes.

Flying birds and bats reacted to turbines, or failed to do so, at similar rates and in similar ways at each of the three study sites, so the data from all sites were analyzed together. The tracking data showed clear avoidance of the isolated Pike County IL turbine by migrating birds, justifying our desire to study a turbine isolated from other turbines.

Summary of the tracking data applied to the automated algorithm

		bird-like	bat-like
tracked targets		401	422
tracked targets available to algorithm (manually scored)		91	116
closest approach to a turbine in XY for targets where a manual score was given	mean	220 m	394 m
	maximum	475 m	711 m
mean radius of Hough arc		1,323 m	1,042 m
extrapolated clearance, animal-to-turbine, for direct approaches (applies to nelson estimator) (1)	N	25	14
	median	180 m	30 m
number of XY right-left ambiguities	total	91	116
	mean per target	0.3	0.51
median approach height (2)	all available targets	109 m	157 m
	manual score "react"	132 m	128 m
mean height at closest XY to a turbine		133 m	171 m
mean whole-track linearity (r-statistic) (3)		0.95	0.87
tracks with algorithm-found curved tails		2	3

(1) Tracks of bat-like animals approached turbines closely much more often than those of bird-like animals, sometimes assuming an path that, when extrapolated, would take them well within the rotor-swept area were they not lost to radar tracking because of interference from the immense steel turbine structure.

(2) We did not expect animals flying high above turbines to react to them and the manually-selected tracks confirmed that expectation. Importantly, when a manual score was given, median approach height was quite near RSH, nominally 125 m in this study but in reality varying by a few meters with model of wind turbine. Many bats were ascending when acquired near RSH so that, they were subsequently higher, as explained below in Discussion, except when reacting to a turbine, in which case the attraction of bats to turbines appeared to draw them lower. This means the data are realistic: animals were usually reacting to turbines at heights when interaction with and possible collision with turbine blades would be an issue. "Height" is height above the base of nearby turbines.

(3) Tracks of bat-like animals were less straight as seen in right-left ambiguities, linearity, and curved tails. Most bird-like (F-C) tracks, by contrast, were highly linear. Only eleven of 91 bird-like tracks had either whole-track linearity or linearity start-of-track-to-closest point $r < 0.90$.

Only 10% of Hough arc radii were < 150 m and the mean radius was over 1 km. This estimator was not directly applicable in assessing reactions because such a shallow circular arc as reported by the Hough estimator seldom changed a flight path enough to matter. The Hough estimator was, however, used to decide if an animal was flying tangential to the radar without turning in XY. A Hough-computed circular arc whose:

$$\frac{\text{distance from chord to arc}}{\text{arc radius}}$$

exceeded 2.5% excluded tracks from being considered as tangential by the algorithm because it was not flying straight enough.

The main reasons targets were not available for automated assessment of reactions (see also Appendix 8):

target type unsuitable (e.g. insect or poorly-known wing beat pattern):	861 targets
target never came close to a turbine (> 724 m):	627 targets
track was straight without deviations (only 1 XY segment):	191 targets

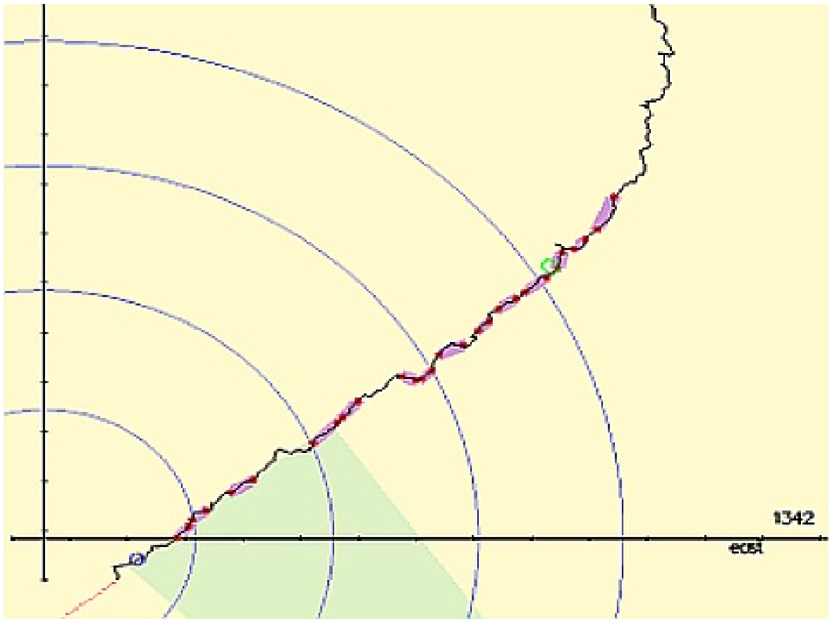
One IFC target (Appendix 2) was removed from the data at a late stage because at a critical point in the track a radar side lobe artifact proved to be responsible for a curve in the XY track. Because the target (20100806.033456) was an IFC, its data would not have been used anyway. It was also judged to be “not classifiable” in both XY and height. Side lobes of turbines sometimes appeared at the same range as bats and birds on the radar and the tracking mechanism switched to the larger echo of the turbine or wavered between it and the animal’s echo. The software optionally painted range rings for all nearby turbines and cell towers (see the next image) to permit such an artifact to be corrected.

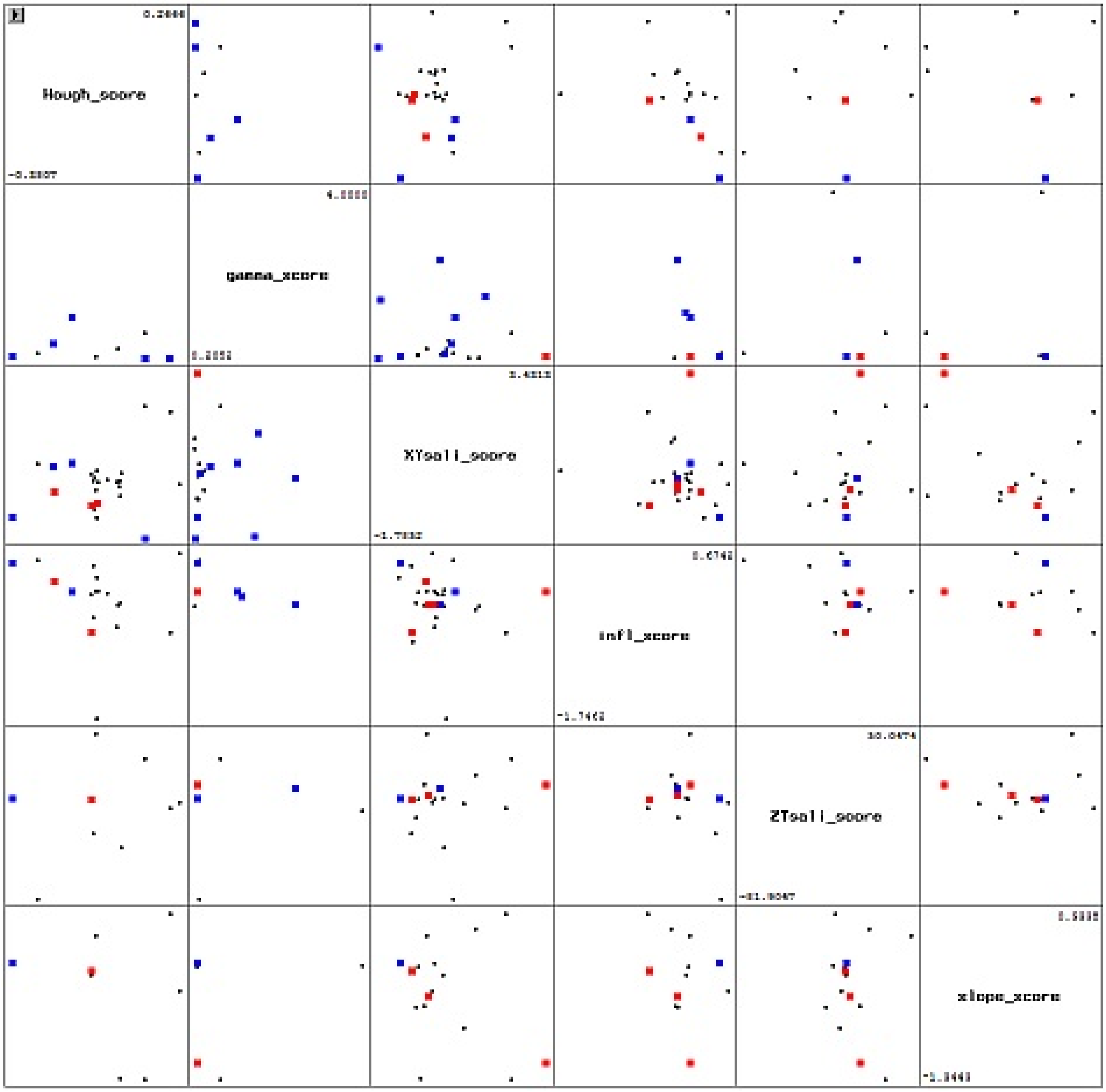
Below is the track of a bat moving southward and apparently responding to a turbine (or line of turbines) from about 1,350 m distance. The start of track 20090806.213138 is farther north, off the top of the plot. The closest wind turbine, Turbine 16 at Casselman PA, is in the direction of the dotted red line at end-of-track. Zigzagging slowly southward at height 295 m AGL, the bat clearly approached Turbine 16 and was scored "attract" by the algorithm. It was lost to autotracking because it came closer than the minimum range the radar could track, at 204 m from the turbine base and 332 m AGL.

Segmentation of the track was not performed by the algorithm prior to the first segment shown (purple underlays, red joinpoints). The last 16 points of the track were not part of a segment due to their nonlinearity. The accuracy of the last two or three track points is uncertain because the radar was beginning to lose the target, but wing beats persisted until the end of the left-jog seen here.

The green underlay at the bottom is an attempt by the Hough estimator to find a circular arc describing a reaction to Turbine 16. The radius of the arc is 1325 m and the chord, shown, 424 m. The Hough estimator correctly failed to provide a score for this bat because the depth of the arc, 17 m, indicated only a tiny contribution of this "arc" to the animal's behavior.

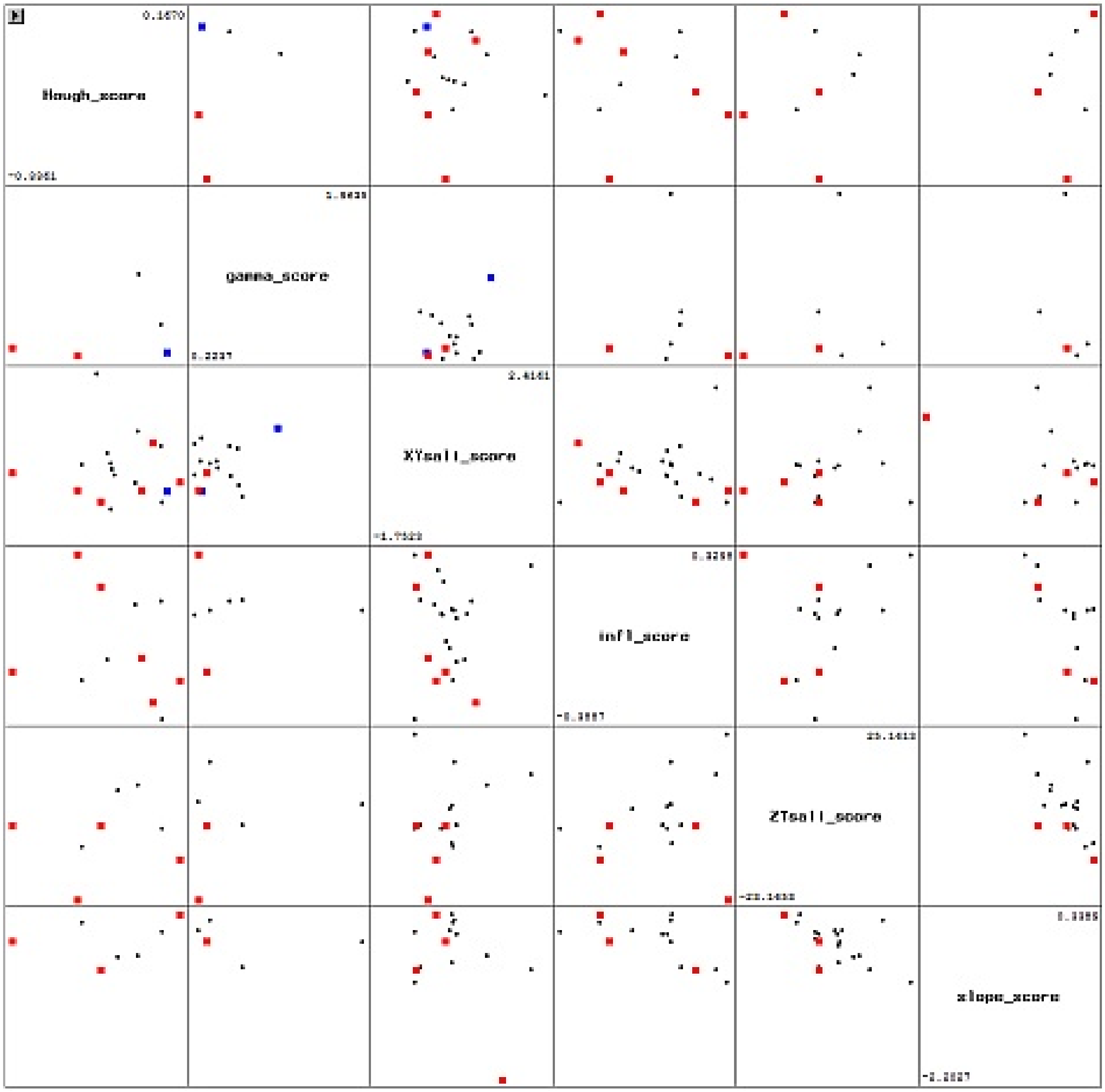
Tracks such as this raise the question of where to draw the line between reactions at a long distance and behavior at a long distance that results in interaction with a turbine (or distancing the animal from a turbine) by chance (see Discussion). In this case it is also possible that the bat was a local resident and had visited the turbine before, perhaps even regularly.





A scatterplot matrix of automated scores from individual estimators for bat-like targets only from an early version of the algorithm, to illustrate how estimators were chosen. Bold points are tracks that scored AVOID or ATTRACT manually. Red is AVOID, blue is ATTRACT. The two lower-right estimators are height estimators, the rest are XY estimators.

With the exception of Hough and inflection (left column center), the XY estimators are uncorrelated with each other and therefore independently useful (or not). Height estimators are uncorrelated and also uncorrelated with XY estimators for bats. The predominance of blue indicates bats are attracted to turbines more than they avoid turbines according to the manual assessment.



A scatterplot matrix of automated scores from individual estimators for bird-like targets. Conventions are as for the bat matrix above.

XY estimators are almost entirely uncorrelated with each other, as in the bat scattergram on the previous page. Height estimators, which are similar to each other in operation, are negatively correlated with each other, meaning that they may have opposite strengths or opposite weaknesses. For these birds, inflection (XY) and slope (height) are negatively correlated for some reason. The preponderance of red indicates birds avoid turbines more than they are attracted to them according to the manual assessment.

Resuslts of the manual assessments are given in the following table.

	Reactions in the XY plane			Reactions in the height(time) plane		
	bat-like	flap-coast	total	bat-like	flap-coast	total
attract	14	1	15	6	2	8
avoid	5	11	16	4	8	12
can’t tell	40	24	64	69	1	120
none	42	46	88	22	21	43
total	101	82	183	101	82	183

The XY result is significant at p=0.00074; the height(time) result is not significant, p=0.26 (Fisher Exact Test). Chi-square and likelihood chi-square probabilities were quite similar. Most of the data were manually scored “Can’t tell”, primarily because of multiple gentle XY turns, corresponding multiple gentle height changes, and possibly-meaningful turns and changes in height that occurred at moderate or great distances out to the 724-m maximum.

The 31 animals that scored attract or avoid in this manual assessment were used in the final assessment by the automated algorithm.

Statistical tests

Manual scoring clearly showed that birds mostly avoid and bats mostly were attracted to wind turbines but those scores had a subjective component. The objective, automated algorithm was implemented to confirm or fail to confirm the manual scoring. Algorithm results were restricted to the 31 animals for which manual scoring was Attract or Avoid in XY but the automated results included the CAN'T TELL and NONE categories of response. Therefore, manual scores "None" or "Can't tell" were removed from the samples supplied to the algorithm. All tracks with manual XY Attract or Avoid came within 344 m from the turbine in XY.

The automated algorithm strongly confirmed the manual scoring. In the table below agreeing tracks are **black** and disagreeing ones **red**. The automated algorithm decided ATTRACT or AVOID on 22 of the 31 tracks and agreed with the manual score on 19 of those 22, a ratio which has a 2-tailed probability < 0.0006 using the binomial test.

	manual score				
automated decision	Attract		Avoid		total
	bats	birds	bats	birds	
ATTRACT	**10**	**0**	**1**	**0**	11
AVOID	**1**	**1**	**1**	**8**	11
CAN'T TELL	**1**	0	0	**2**	3
NONE	**2**	0	**3**	**1**	6
total	14	1	5	11	31

	automated decision				
target type	ATTRACT	AVOID	CAN'T TELL	NONE	total
bat-like	**11**	**2**	1	5	19
flap-coast	0	**9**	2	1	12
total	11	11	3	6	31

The probability in this 2 x 4 table that birds and bats react the same to wind turbines is 7.015 E^{-06} using Fisher's Exact Test.

Discussion

Algorithm for describing reactions to turbines

The question of whether bats and birds avoid or are attracted to turbines is important for policy and the answers to it deserve the strongest basis in science. Subjectivity is helpful but an objective (operational) definition of avoidance/attraction is better. Therefore, project staff put time into developing an algorithm to classify bird tracks on radar by logic and descriptive statistics. The result of writing such an algorithm and running it on all targets from all field sites was objective results agreeing with a manual "eyeball" analysis and providing data on birds and bats avoiding and being attracted to commercial-scale wind turbines.

Initially the design followed the intuitive idea that animals fly along, sense (probably see or hear) a turbine and change flight direction, turning toward it (attraction) or away from it (avoidance). This idea is probably not incorrect but testing a computer algorithm designed to implement the idea directly, measuring angles themselves, was successful only sometimes. The main reason is that the radar-generated tracks of flying animals often display brief pauses, lateral "jogs", vertical "bumps" or, in the case of bats, vertical "swoops", that reflect changes in the direction of travel but in the context of the overall flight path do not cause any easily-interpretable and direct progress toward or away from the turbine blades. An analogy would be a person on a sidewalk turning to stop at a mailbox, then continuing. The transient change in direction has little effect on what the person encounters at a later time. Therefore the algorithm concentrates on changes in the flying animal's distance to the closest turbine or extrapolations thereof.

"No reaction" (NONE) is an interesting category that could include animals that fly near a turbine without changing course at all and animals that fly straight into the danger area . Many tracks are "CAN'T TELL"--the small proportion of the large dataset of tracks that could be included in the analysis is the result of being conservative with reference to such values as how far away from a turbine a deviation can be and still call it a reaction. That number is important for estimation of risk, of course, as well as questions that we need to deal with such as what percentage of animals react in a given way. Evaluating reactions conservatively reduced the N in this study to a small value.

There was a question of possible bias introduced by radar operators favoring selection of animals already flying toward the radar. That question is largely laid to rest by the automated algorithm's clearly relating attraction vs. avoidance to the kind of animal tracked. Either class of reaction was readily observed using this radar equipment.

Long, convoluted tracks of high-flying bats

Frequently-observed, long tracks of bat-like targets represented a challenge in several respects. First, statistical analysis of reactions to turbines by bats depends on being able to discriminate reactions to turbines from "spontaneous" (if these behaviors are self-directed) bat flight behavior, which, in turn, depends on some degree of biological understanding of the behavior. Second, radar artifacts need to be ruled out. This is because, whereas straight level flight with regular wing beats is strong confirmation that the tracking radar is working properly, kinks, pauses, and bumps in tracks may indicate some artifact. Artifacts must be eliminated from the data. Less obviously, field workers using the equipment in a field at night cannot always rule out artifacts and therefore the real biological nature of these nonlinear tracks only becomes apparent on close inspection during analysis. Third, the special and unique software used to analyze these data has needed to be upgraded repeatedly to handle tracks and wing beat records that are 10x or more longer than ordinary tracks of migrating animals and exhibit important details within them. Fourth, many bats were tracked ascending for long periods, descending for long periods, or both. Because radar operators looked for possibly-reacting targets near the ground, more useful-length bats ascended than descended and some ascended far above RSH and thereby ascended right out of the analysis. For these reasons results for flying bats were not as clear as would be expected from the effort exerted to track them and analyze the data.

Reaction to turbines at a distance

The distance at which wildlife reacts to wind turbines cannot be assumed to be the same for birds and bats or, indeed, even similar. In addition, distance is probably going to be a function of spatial arrangement, e.g. a turbine dead-ahead of a flying animal may produce a reaction at a different distance than one off to the side of the animal's path.

A certain logical conundrum impedes objectivity in identifying reactions that occur at a great distance from a turbine. The reason is that such a reaction involves an animal previously at a greater distance and then later near-enough to a turbine to be the subject of research on the subject. No such flying animal flies perfectly straight over the earth--and even if a path is perfectly straight along a rhumb line, that path will not be perfectly straight on a great circle route. (What kind of global-scale path is used by certain migrating animals is a research topic, not a certainty.) Therefore any animal that in its flight has drawn near enough to a point on the earth such as a wind turbine to be followed, even by the sophisticated radar equipment used in this research, must be assumed to have previously turned in some fashion at least to some extent, and the previous turn(s) necessarily resulted in its position and flight path when first detected in the vicinity of a turbine. Thus at the present level of knowledge of long-distance flight, one cannot rule out the possibilities that an individual animal flying near a turbine was there because it was attracted to the turbine from a great distance and that an animal avoiding a turbine from a great distance was never detected because it was out of range of the radar and thus removed from the study population.

It is not impossible that statistical analysis of data from long-range techniques such as Doppler "weather" radar or radio tracking will someday succeed in providing evidence on reactions at a great distance, but such an effort would need to be able to identify animals taxonomically to accurately separate birds, bats, and insects; find turbines located in level terrain free of potential leading lines and other land-cover features; and, even then, find a way to rule out or diminish the likelihood of magnetic, wind, or other subtle influences on flight paths. (See also

Appendix 6.) Clearly, the most feasible approach today is to confine study of reactions to turbines to a certain maximum radius from the turbine. That distance was set at 724 m in the XY plane, the maximum distance possible reactions were noted (track 20120908.204601 in western Illinois) in a preliminary visual analysis of plots of all tracks performed by a research assistant.

Hypothesis of long-distance avoidance of turbines

If low-flying birds detected the northernmost turbines at a distance and turned to avoid them, the birds may have already shifted laterally before reaching the range at which the tracking radar normally operated. This predicts a paucity of birds on paths directly approaching these turbines compared to birds right of turbines, left of turbines, or both, depending on response to wind.

The figure above from 28 July 2010 presents the hypothesis that a kind of long-distance avoidance may occur on some nights in a situation where two groups of wind turbines lie along the direction of travel of flying birds or bats. The radar is the red teardrop symbol and turbines near it are blue circles in this map figure. A similar group of turbines lies several km to the northwest, the direction from which birds are expected to appear at the radar site.

Radar operators found that birds flying in a mostly-downwind direction could be readily tracked northeast and southwest of the radar but almost no birds to the northwest. That pattern was verified on one or two nights at the Tazewell County, IL site by systematically acquiring low-flying animals at each direction around the compass. Birds were acquired in seconds to the northeast and southwest but only in minutes to the northwest, the direction opposite the track direction of the birds.

Birds may show such a pattern because they avoid a group of turbines by flying around it and leave a paucity of birds “downstream” of the turbines because they subsequently fly in the same direction without bothering to return to their original path on the far side of the turbines. Hypothetical paths of migrating birds are yellow arrows. Bats may show the same pattern for a different reason, namely they may be attracted to the turbines and dally there, failing to continue on to the next group of turbines “downstream”.

Proportion of night-flying birds and bats that avoid turbines

One wants to know whether a few, some, or perhaps most of different kinds of flying animals react in a given situation. This report firmly addresses the question of how bird-like radar targets and bat-like radar targets react when the reactions are distinct and visible in the tracking radar data, and the results are in good agreement with what we know from carcass searches and other research. However, even leaving the difficult question of reactions-at-a-distance (above) aside, this work cannot estimate what proportion of night-flying birds or bats avoid or are attracted to wind turbines.

Generality of the results

Whatever the robustness of these results, they should be used appropriately. The animals in this study were classified into bats (thought to be primarily migratory tree bats) and birds (thought with strong reason to be many species of small migratory songbirds, passerines). Although it is easy to say “birds avoid turbines” or perhaps “bats avoid turbines”, it is wrong at this stage. With 50-100 species of birds migrating on a suitable fall night and at least three species of bats, it is certainly a mistake to make generalizations at this stage about broad categories such as “birds”, “night-migrating passerines”, “bats”, “migrating bats”, and “tree bats”. It is valid to say and important to know that night-flying birds and bats behave differently around wind turbines, *some* birds avoid wind turbines, and *some* bats are attracted to wind turbines. We do not know whether only a few, many, or all species of bats and birds behave in certain ways. In statistical terms, unexplained variance dominates the behavior at this stage and one of the most important ways is taxonomically. Further taxonomic progress may come from work examining carcasses of animals found dead beneath turbines, deeper radar-based recognition of wing beats and other radar data, and studies using different techniques synergistically.

Acknowledgments

The research was funded by the Department of Energy and we wish to express our gratitude for its understanding in launching the project in a timely fashion to permit field work when animals were flying, granting freedom to alter the data-taking schedule as demanded by the work, and permitting completion of the quantitative automated assessment by extending the deadline for project completion.

The radar was transferred to the Illinois Natural History Survey by of the USDA Agricultural Research Service, after having been used at ARS by Dr. John Westbrook, His help and that of his staff in obtaining the radar made the research possible.

Field work could not have proceeded without field assistance from many dedicated people: Justin Gumbel, Peter Hughes, John Keating, Tess Larkin, Martin Miller, James Planey, Michael Schirmacher, Brian Steidinger, Heather Stewart, and John Weissman. The work demanded technical skill, stamina, and resourcefulness on the part of the field workers.

Benjamin Kamen and John Weissman provided essential skill upgrading, fixing, and maintaining the tracking radar and associated instrumentation.

We are grateful to the people who allowed us to park a large trailer on their property and observe flying wildlife at unusual hours. Access to and use of the Casselman PA site was granted by Iberdrola Renewables and could not have happened without help from Bat Conservation International and especially Edward Arnett. Access to and use of the Tazewell County, IL site was with the gracious cooperation of the landowner, Greg Tarter. Access to and use of the Rural Electric Cooperative site in Pike County IL was due to the enthusiastic cooperation of Bruce Giffen and Sean Middleton.

The project could not have been carried out without assistance with infrastructure and other support. The Illinois Natural History Survey shop (Larry Gross, Jamie Hopper, and Jim McNamara) and the University of Illinois garage contributed to trailer and other mechanical work. Staff at the Illinois Natural History survey handled the financial and other necessary paperwork for the proposal and its support. Help from Laura Clower at the University of Illinois allowed the project to gain road access to the site in Tazewell County, Illinois. The University of Illinois Department of Electrical and Computer Engineering permitted use of one of its field sites in Illinois for field tests of the equipment. Profit-free software by OpenGL, Google Earth, and freeglut supported the analysis and display of data.

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Appendix 1. Radar Specifications (mostly from WF-100 Theory of Operation)

Model

Enterprise Electronics Corp (EEC) model WF-100 4/82, serial number 85-2 (on trailer, 1 July 1985). Spare modules have s/n 83-3 (6 Jan 1983).

Transmitter (thyratron)

Frequency 9375 plus or minus 20 MHz (9355 to 9395)

Peak power output 60 kW

nominal PRF 800/second, measured about 798/s

Pulse length 0.25 or 1.0 microsec, range-dependent or selected manually

Tracking

minimum range resolution 2 m

angular tracking by nutating scan at 30 Hz

Elevation -2 to 89 degrees. (this spec varies among different manuals)

Antenna angular velocity operated manually is >15 degrees/sec, tracking mininimum 20 deg/sec.

Oct 1982 Theory:

Tracking ranges:

25 cm “reflector” (is that a corner reflector?)	50 km
50 cm	80 km
120 cm	120 km
maximum/maximum range	50 m / 185 km

Accuracy when signal/noise is >10 dB:

angle: 0.07 degree (1 milliradian) RMS

range: 10 m RMS

Azimuth acceleration 10 degrees/sec**2

Receiver

linear, non-coherent

dynamic range 70 dB minimum

AGC is apparently used, perhaps just in tracking mode

intermediate frequency (IF) 30 MHz

Antenna

1.8 m diameter, 41 dB gain

circular waveguide horn with subreflector

vertical polarization (the waveguide in the feed is circular though)

beam width 1.25 degrees nominal, with 1.8-m paraboloid, without cuff

side lobes nominal 18 dB maximum (presumably, -18 dB) without cuff

feed cover is 50 cm from surface of paraboloid to *bottom* of larger cylinder housing the end of the feed.

(Cover for spare feed seems to be longer than that.)

cuff is 61 cm (2') deep, lined with radar-absorbing material.

R.A.M. is square pattern of what appears to be Gaussian waves, λ = 3.4 cm. Depth of top of wave is 4.5 cm; depth of bottom of wave is 2.3 cm; therefore, waves are 2.2 cm high.

Appendix 2. Target classification using wing beats

Frequencie of wing beats were quantified by an algorithm that extracted peaks (i.e. inverse frequencies) from autocorrelograms of 1-s epochs of wing beat records. The records could be as long as tens of minutes for tracked targets. Peaks were extracted with minimum values of Pearson’s r of 0.5 (in somc cases, 0.2). Because many of the wing beat time series contain harmonic and sub-harmonic frequencies, bats generate some higher-frequency peaks in the range of birds and vice versa. Frequency of wing beats was important but the patten of the radar records was more decisive in differentiating birds from bats in this work.

Radar operators and technicians during later analysis characterized wing beats of flying “targets” in a manner designed to minimize bias and minimize the number of assumptions involved. Single keystrokes were:

0	>9 flying animals seen visually when optical means supplemented radar
1-9	this many flying animal(s) were seen visually
f	flap-coaster (F-C)
h	helium-filled balloon
i	intermittent F-C
m	multiple target
n	non-vertebrate-like (NVL: arthropod, ground target,...)
p	pauser
s	steady flapper (SF)
u	unknown or unclassifiable type
v	vertebrate-like (VL)

“helium-filled balloon” is a radar target launched specifically to check winds aloft. It has no horizontal velocity except that imparted by the wind at altitude as it rises.

Ornithologists and chripoterologists agree that “flap-coaster” applies to small birds but not to bats engaged in cruising flight; it is probably synonymous with “bursting flight” in others’ terminology. “intermittent flap-coaster” indicates irregular rather than periodic bouts of wing beats interspersed with pauses. “pauser” indicates pauses are quite brief, one or two wing beats. For unknown reasons some tracked F-C targets showed almost no wing beats initially. Regular cessation of wing beats and defined single strokes within a flap-period prove that these are single flying animals.

“steady flapper” targets’ wing beats continue uninterruptedly for long periods. When SF targets’ wing beats are rapid, their classification blurs with NVL (below). Some tracked targets are SF initially then later show VL characteristics, whereas SF targets never subsequently show F-C or IFC characteristics. This indicates a relationship, probably a causal one, between SF and VL.

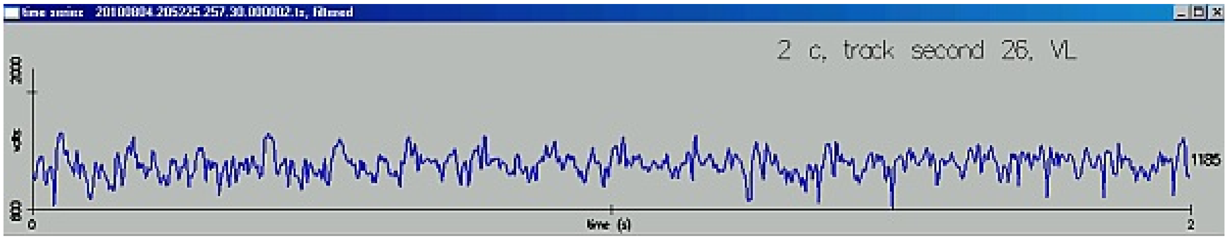
“non-vertebrate-like” targets include arthropods (Greenstone 1990) aloft and ground targets such as trees and structures picked up in radar side lobes. They are characterized by one or more of: very low amplitude fluctuations, often not visible or barely visible; very slow (< 3/s) fluctuations with some irregularity; or on the tracking radar, just the scanner frequency or a multiple or demultiple of the scanner frequency, often showing a slow beat-frequency. When wing beats are observed, they are >25 to 200/s, above the wing beat frequencies of night-migrating vertebrates. Except for descending (gliding or falling) vertebrates that do not seem to flap their wings. Flying arthropods often but certainly not always show smaller RCS than flying vertebrates. NVL targets are of no interest with respect to interactions of flying vertebrates with wind turbines.

“multiple target” was used infrequently based on a complicated echo pattern with occasional single or pairs of wing beats observable, as if occasionally all animals but one ceased flapping or the flaps of individual flock members came into synchrony. Multiple targets tracked with this radar are tightly-spaced pairs or flocks, not loose aggregations of nocturnal migrants (Larkin and Szafoni 2008).

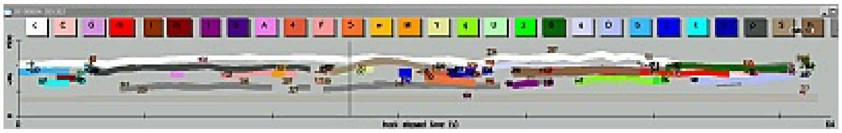
“unknown” indicates the operator could not classify the target on the basis of wing beats. Many unknown targets later proved to be VL targets after the investigators learned the nature of time variations in VL targets. Other unknown targets were often descending, presumably using gliding flight or partly gliding flight without wing beats.

“vertebrate-like” targets have been characterized as “non-NVL flying animals”, which is less redundant than it seems. They show more moderate-frequency fluctuations than NVLs but do not show periodic bouts of flapping. Their wing beat time always series show stretches of multiple wing beats in succession, which can be brief but which upon closer analysis prove to be in the range 6 to 12/s and usually 7 to 10/s. However wing beats are not continuous being interspersed with periods of sometimes-high-amplitude and usually quite irregular fluctuations in radar cross-section. Note that none of these criteria is definitive in itself. Overall, the most definitive trait of a VL target is that the variability of the variations in wing beats changes on a second to second basis–the bouts of wing beats show no readily-detectable periodicity or characteristic length. Although VL targets usually fly singly as shown by non-overlapping strokes in their wing beat records, multiple VL targets flying together probably sometimes defy attempts to separate their wing beats in the radar time series or to show that more than one target is being observed. The records look “fluttery”, as if they are produced by flying bats.

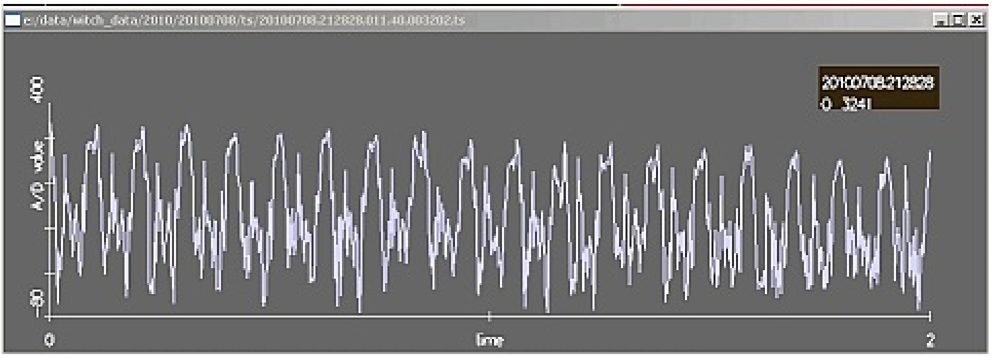
The VL category was originally invented as an unspecific umbrella category to express that a target is neither an arthropod nor ground target and that its Class, Aves vs. Mammalia, is unclear, but in the course of this and related research we have come to realize that all or almost all nocturnal VL targets are bats.



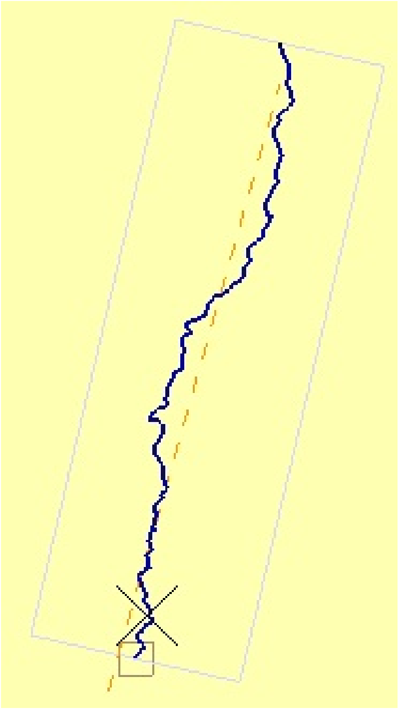
Above is a 2-second time series of radar received power (wing beat record) of a single flying bat with a wing beat frequency 8.42/s. The indistinct wing beats, lack of any flap-coast cycle, and frequency between about 6 an 12/s are characteristic of bats. In the time series of that bat and all targets within 300 m of it in range, below, the bat's echo is the white line extending until just before the bat was lost to autotrack. The expanded 2-s record occurs at the vertical line about second 30 on the full time series. All the colored lines are arthropod targets at various other ranges along the radar beam. It is tempting to speculate that the insects themselves were targets for a foraging bat ascending through the layer of insects from about 50 m to about 160 m AGL.



Below is an echo strength record of a single *Tadarida brasiliensis* (Mexican free-tailed bat) taken at a 40º elevation angle. It shows a 10/s wing beat rate characteristic of level flight as the animal disperses from the Marble Falls cave at a height of 1,876 m AGL. The legend indicates this bat was "target" number 3,241 of that data-gathering session and flew through the stationary radar beam shortly after dusk, flying swiftly from its day roost in a cave. This species of bat is nearly identical in size to two of the three migratory bats that are commonly found dead beneath and near wind turbines in more northern locations in the USA, and the species is also at risk from turbines in its own right.



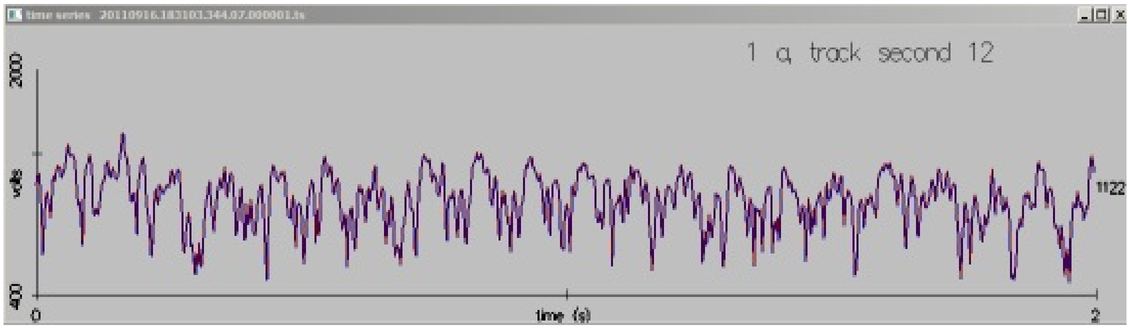
Appendix 3. Supplementary data on crepuscular-feeding birds



A tracking radar record of a single Chimney Swift on a northward flight returning to its night roost at 1831 local time, about 30 minutes before sunset.

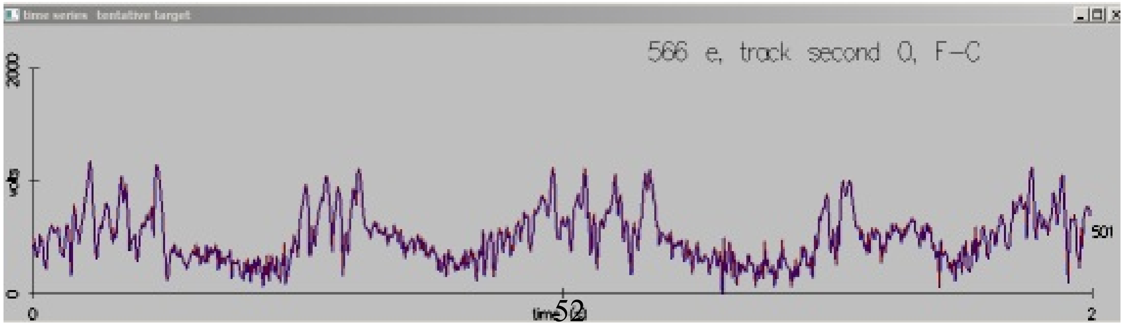
The XY plot at right (scale mark, 100 m) shows a typical, somewhat wandering flight path at 350-450 m AGL. The 2-second wing beat record below steady wing beats at 10.12/second (below). This small Apodid often has a highly irregular wing beat pattern like bats and its flight pattern when hunting for insects aloft is not readily distinguishable from nocturnal bat targets but the birds reliably enter their night roosts prior to darkness. The species was verified by direct observation at 35x in a high-quality spotting scope.

The tracking radar provided the first data showing the heights at which these birds feed, sometimes singly, sometimes in loose groups of four or more. The “X” indicates the time of the wing beat record.



Similar results for Common Nighthawk established that the wing beat frequency of this species is lower than that of tree bats. These results rule out the two bird species that might be aloft when tree bats are migrating or engaged in other high-altitude activity and further increase our confidence that these radar methods can distinguish North American birds from bats.

Wing beats of a small songbird show a regular flap-coast pattern not known for flying bats.



Appendix 4. Carcasses discovered at the Pike County, IL site

The Pike County, Illinois site had a single wind turbine on low-relief topography and isolated from other wind turbines of any size. To our knowledge, no systematic or controlled carcass searches had been done at this site. However the Illinois Department of Natural Resources sent personnel to look for carcasses in late spring/early summer 2012 and found an unusually large number of bat carcasses in a short time period compared even to the late summer/early fall period when most sites report highest numbers of killed bats (anectodal data).

We have requested data or information from IDNR on this work but have not received any response. In September we literally stumbled upon a carcass of a hoary bat, then found more bats and one bird carcass over subsequent days, adding to the reported IDNR findings. The most likely explanation of the high number of carcasses, along with other factors, is that this turbine is responsible for a large number of bat fatalities, more than would be expected at a turbine in a conventional midwestern USA facility with many turbines spaced around the landscape. The anecdotal carcass data from the REC turbine suggest the hypothesis that single isolated turbines are a greater threat specifically to bats than turbines that are part of a larger group of turbines.

If that hypothesis fails to be disproved at REC and at other sites, its validation would have several effects:

- Most directly for this DOE project, the probable reason that an isolated turbine would attract more bats would agree with the hypothesis that bats are attracted to wind turbines. That is because a single, isolated, commercial-scale turbine, without other turbines nearby to attract bats, can attract bats from a wider area and thus would be expected to cause more fatalities.
- It would be a red flag for issuing permits for isolated turbines.
- For bats, it would cast substantial doubt on the most common measure for wildlife mortality at wind tubine installations, which is fatalities/MW.
- Finally, because most isolated turbines are currently smaller than the approximately 1.5 MW commercial ones, it would demand more and better research on effects on wildlife of such smaller turbines. Single large turbines are not common in the USA but smaller turbines are beginning to be erected more as demonstrations of "green energy" and so forth.

Appendix 5. Estimators used in evaluating reactions to turbines in the XY plane.

XY is the challenging plane of analysis; changes in height are simpler and are treated separately.

Estimator	Brief description
Estimators used in assessing reactions	
Hough transform	A tool used in computer graphics and adapted to the special case of part of a track of a flying animal. Fit an arc (portion of a circle) to the track by identifying all arcs that touch the closest point to a turbine and all track points linked to that point. The arc that touches the longest such series of track points models the animal's path past the turbine. Paths that are convex away from the turbine (bowing out as the animal passes the turbine) represent avoidance and vice versa. The depth of the arc chord measures the spatial magnitude of approach or avoidance. The Hough transform omits arcs centers created by track points that span in time two successive track points with curvature away from the turbine. This feature provides Hough centers more closely focused on the flying animal's path near the turbine instead of including irrelevant sections that are nearly straight. It also omits arcs that include turns whose angle of turning intersects the closest turbine; i.e. when the extrapolated flight path of the animal crosses the turbine such that attraction and avoidance are confounded. For an animal approaching or flying past a turbine the flatness (lack of arc) of the portion of the track approaching was used to strengthen the tangential estimator (below).
inflection	Change in direction from the segment prior to the closest point to the turbine to the segment including that point. The last turn before nearing the turbine is assumed to have the most immediate effect on the animal's flight past (or toward) the turbine. Inflections toward the turbine are scored "approach".
nelson	An animal sometimes approached a turbine directly, head-on. This was measured by the distance an extrapolation of the last segment came from a turbine's tower (not its RSZ). The estimator perhaps could have been better adjusted to assist in the automated assessment as shown by the distribution of the extrapolated distances: 75% quartile 299 m. However the low end of these extrapolations was highly successful in revealing animals closing directly upon turbines. See below for further discussion of the nelson estimator.

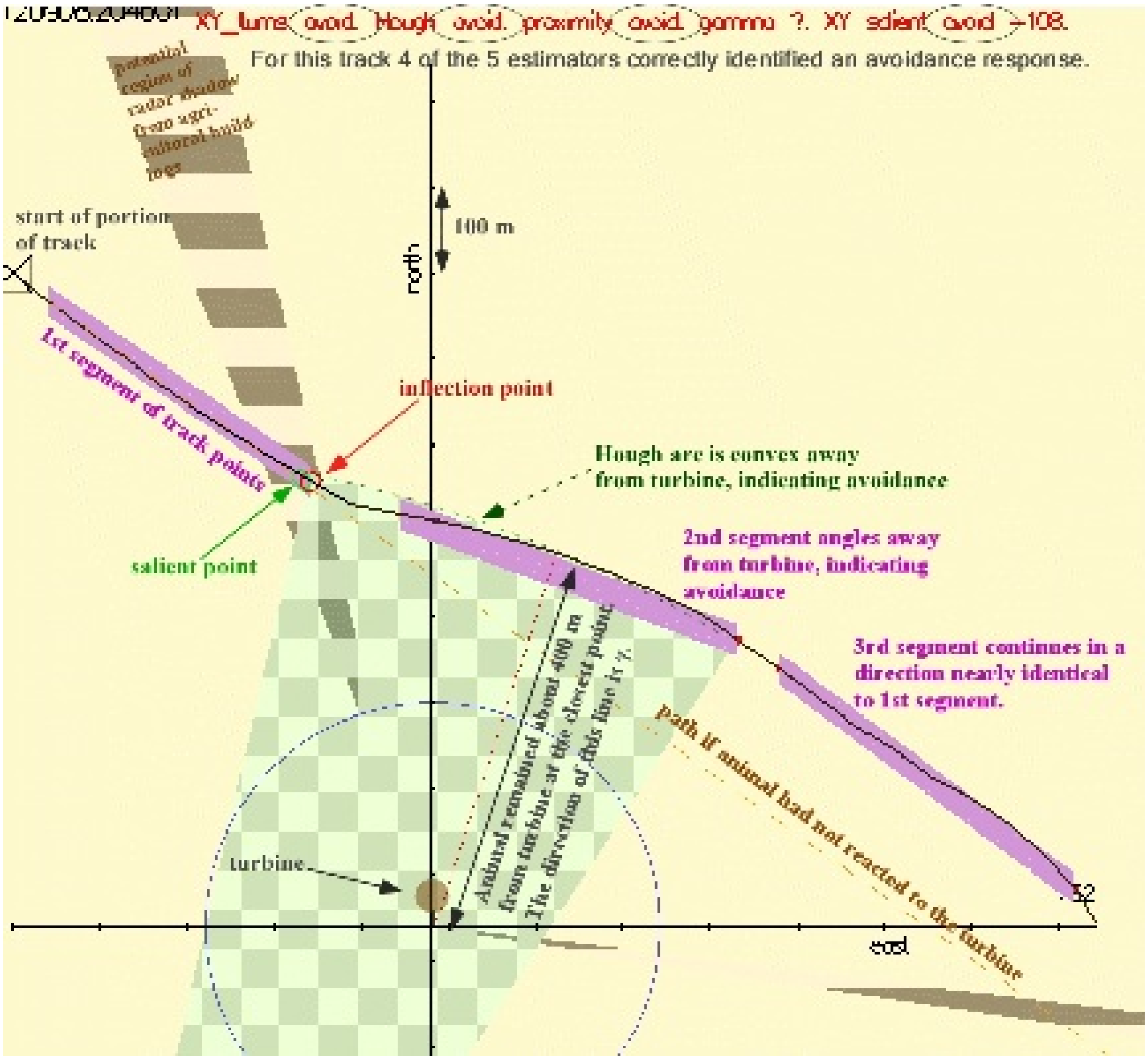
salient	Angle between two adjacent segments that, if the later segment were extended past the turbine, would have the greatest effect on distance from turbine; angles toward the turbine are approach. Salient differs from γ, below, in that it assumes that the animal does not turn again after assuming the direction of the later segment. Like γ, the salient estimator measures a distance in a certain direction, not the angular direction itself. The salient estimator extrapolates from the end of its segment.
tail	A small number of tracks approach or pass a turbine but have no straight or even approximately straight portions as they come close to the turbine or pass it. These short “tails” were recognized as a special sixth estimator when they occurred and the curvature, whether toward or away from the turbine, or neither, used as a basis for an approach/avoidance assessment.
tangential	Tracks whose segment closest to a turbine passed by the turbine without deviating toward or away from it were scored “no reaction”. This was done by comparing the direction of that segment to the direction of the preceding track points such that the more similar were these two portions of the track, the higher the tangential score. Tangential tracks were never scored “avoid” or “attract”, mainly because the nelson estimator identified tracks whose path took them directly toward a turbine. The tangential estimator was augmented using a Hough transform-generated circular arc of track points near the turbine in question to disqualify those tracks that had excessive curvature there.
Estimators developed for the project but not used because they had little or no value.	
γ, gamma	Angle from the point in XY space where the animal is closest to the turbine to the turbine. It is the direction the flying animal would look if it wanted to see the turbine from the closest point while being tracked. γ-based reactions are excursions in the direction γ or γ-180°. γ , similar to salient, was originally designed as a jog-detector to counter inflections (below) that are actually the second turn of a brief jog: _____|¯¯¯¯¯¯ . γ failed to detect jogs.
proximity	Speed of the radial component of a segment from the turbine, resulting in a value in m/s toward (approach) or away from (avoidance) of the turbine. This is the only estimator that took speed into account as well as direction of travel.

Because the tail estimator acted on track points following the last track segment, which was sensitive to point-to-point track curvature, the presence and length of a tail was determined in part by the criteria for straightness in XY used for track segmentation. An estimator that reported the curvature of a tail arrived at an estimation in only 5 cases; all 3 of the bats curved toward the closest turbine (attracted) and both of the birds curved away (avoided). No attempt was made to make the tail estimator more generally useful.

The Hough transform omits arc centers created by track points that lie beyond (in time, earlier or later) two successive track points with curvature away from the turbine. This specialization of the Hough Transform provides arc centers more closely focused on the flying animal's path near the turbine instead of including irrelevant sections that are nearly straight.

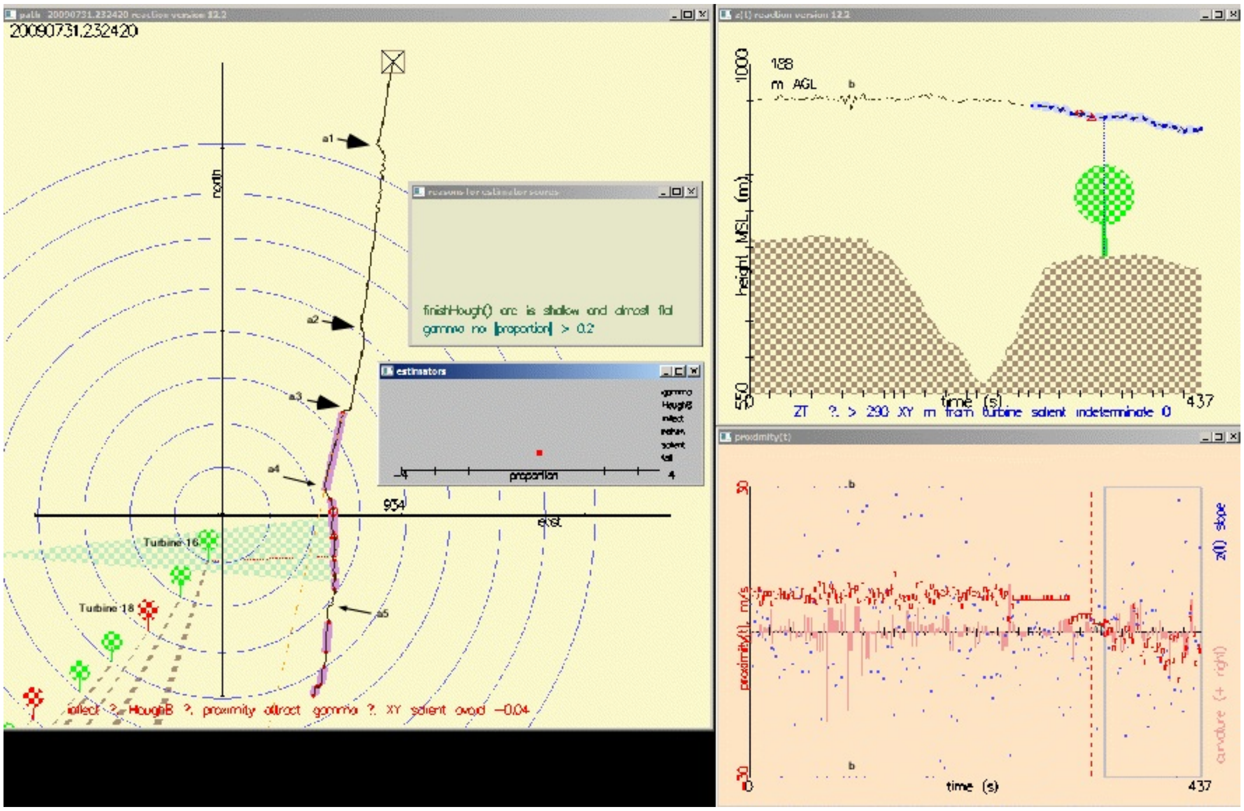
Although the Hough transform was not used directly in the final analysis (deciding animals' reactions to turbines), preliminary tests of the Hough estimator gave a result contrary to the final statistical result: bats showed more AVOID in Hough ($p<0.02$, Wilcoxon Test). This odd result was because curvy tracks of bats are more amenable to fitting a circle: the radius of a Hough arc was significantly longer for birds (vs. bats) because birds' tracks were much straighter overall and tracks that curve are geometrically more likely to curve in the many directions away from a turbine than in the smaller number of directions toward it.

Height changes as animals begin to approach a turbine have been an ongoing problem for some tracks. A failure in the radar elevation control electronics (elevation tachometer) caused some of these and that artifact is handled as well as possible we think. In addition, and more importantly, some bat targets engage in short, swift climbs and descents and the behavior does not seem to be predicable on the basis of their other activity or proximity to wind turbines. (Such "fluttery" flight behavior and apparent insect-catching or social behavior aloft is quite plausible for bats and was no surprise.) The height changes can result in poor segmentation. The problem is now solved to the point of being tractable.



XY plot of a track of a nocturnal flying animal in Pike County, IL in fall traveling roughly southeast past the REC turbine. The plot illustrates computerized implementation of the estimators and the performance of an earlier version of the algorithm on one radar track. Except for the colored arrows and associated text identifying features on the illustration, the algorithm generated all the shading and symbols.

The turbine here is a few meters from the origin. The animal would have flown 108 m closer to the turbine if it had not gently deviated north-northeastward when still over 500 m away from it. During this track the animal's height was slightly greater than rotor-swept-height.



finishHough() arc is shallow and almost flat
gamma no |proportion| > 0.2

inflect ?. HoughB ?. proximity attract gamma ?. XY salient avoid −0.04

ZT ?. > 290 XY m from turbine salient indeterminate 0

An example of algorithm estimators as used and a radar artifact. The migrating animal's path is shown in the XY (left) and height/time (upper right) plots. Time-ordered annotations "a1", "b" and so on were added by hand, the rest of the figure is generated by the reactions algorithm developed for this project. Inserts are overlaid on the XY plot to save space. This steadily-flapping vertebrate target was flying slightly west of south, tracked as it overflew the valley northeast of the Casselman, PA turbines and drew near them.

The XY plot shows turbine symbols with their tower bases at their location on the earth. Blue range rings representing ranges of possible side-lobe echoes from the large turbines. A green wash shows the best-fit Hough circular arc. Purple segments are marked in the vicinity of the turbines. Red marks indicate algorithm-generated inflections. The outcome of this version of the estimators is given in red text along the bottom. In the text, "?" indicates no-decision, which can be a numerically-small result not useful to an assessment or inability of an estimator to function because of the nature of the track. As usual, the radar is at the origin. Axis tics are at 1 km intervals. Range rings help find side lobe artifacts, as explained above.

a1-a5 show jogs in XY. These occur in some otherwise-straight tracks. Their cause is usually uncertain although wind gusts can be responsible, as can two or more bird targets flying together but at a distance (Larkin and Szafoni 2008). Only the turn or jog at a4 respresents an enduring change in direction. a4 occurred when the target way flying over 700 m from Turbine 16 and not on a course to come near any turbine.

a5, which happens as the target begins to draw away from the line of turbines, occurs at the range of Turbine 18 and is probably an artifact caused by the temporary effect of the radar echo of the turbine on that of the flying animal. Such artifacts were removed from the radar track if they occurred at a point in the track where they could be confused with a reaction. In this case, by definition, no reaction is taking place because the animal is departing the turbines.

The height(time) plot shows a cross-section of the underlying topography. The animal was flew level, then gradually descended, with a few transient vertical deflections ("b", jitter) caused by a weak element in the elevation tracking circuit during this part of the Casselman work. Computed track segments for this track were short mainly because of high variability resulting from the atifactual height jitter. The turbine symbol is to scale at the location of Turbine 16. Height above the ground (AGL) was measured at 188 m at the end of the track and it was considerably above rotor-swept-height of the turbines (125 m AGL) at its closest point to Turbine 16, marked with a dotted line. The animal's track over the steep river valley roughly 400 m below it was completely unaffected by the topography, which is common in many wind situations in this location.

Again, text along the bottom of the height(time) plot indicates the outcome of the height(time) estimators. In this case, because the animal never approached closer than 290 m from a turbine, the estimators did not function.

The rest of the panels show operation of the assessment algorithm.

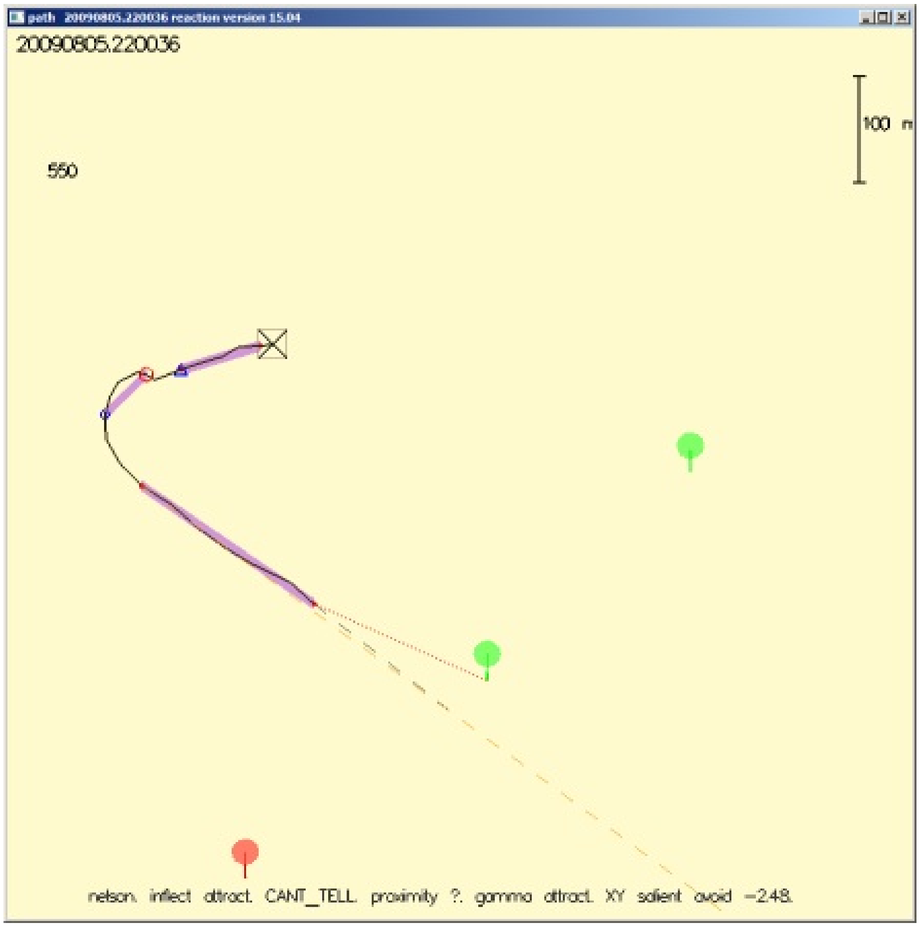
The small gray panel indicates that the salient estimator functioned; as indicated at the bottom of the XY plot, its magnitude was only -0.04 on a scale of -1 to +1 for that estimator, a negligible value. Therefore, "no reaction" was the outcome for this track.

The panel above it shows reasons for some of the estimator scores in English, indicating why two of them did not return a decision. In this case, the Hough arc was nearly a straight line and the γ value was smaller than would be useful to the algorithm if γ were actively used.

Finally, the larger panel at lower right overlays several kinds of complex, internal data useful for evaluating the functioning of the estimators, scaled to fit on a common vertical axis. Each track point is represented over the track's 437-second duration. The vertical dashed line is the point in time when the target was closest to Turbine 16 and the faint gray rectangle is that portion of the track distinctly after the closest track segment to Turbine 16, a portion of the track ignored by the algorithm. Dull pink bars show curvature (the ordinary mathematical definition); the jogs a1 through a5 on the XY plot can be related to the curvature values. Red rectangles are changes in distance from Turbine 16 used by the subsequently-discarded proximity estimator; the indications are shown for individual points, then for segments as a whole as the target approaches closer to Turbine 16. Finally, the blue specks are point-by-point values for instantaneous slope, XY distance(time). "b" marks excessive positive and negative height excursions caused by the elevation data jitter (above); such high values are constrained to the extent of the vertical axis.

The nelson estimator was able to assess reactions close to turbines irrespective of irrelevant previous sharp turns. Note the 100-m scale mark at upper right of the detailed XY plot below. This short (41-second) track of a bat turns sharply, with the bat lost to the larger radar echo from the turbine when traveling 17 m/s at a distance of 147 m (red dotted line) from the turbine. The bat was flying level at the height of the top of the arc of the rotor blades. Its last segment is extrapolated (dark dashed line) to pass 44 m from the tower of Turbine 17 at the Casselman, PA site. That distance is only about 5 m from the tips of the turbine's blades. The salient estimator gave a highly negative (i.e. avoidance) score of -2.48, which is incorrect, but the nelson estimator correctly assessed ATTRACT.

Turbines 16 and 17 are shaded green in plots. Turbine 18, at the lower left here, is shaded red to indicate that it has a red aviation warning lamp on it.



nelson. inflect attract. CANT_TELL. proximity ?. gamma attract. XY salient avoid −2.48.

The plot of 20090805.220036 above also illustrates a subtle feature of the nelson estimator. If a flying animal's path takes it between two turbines equidistant or nearly equidistant from each of them, the nelson estimator assesses AVOID. At least one bird thus threaded its way between two of the turbines at Casselman.

The table below lists details of reasons that estimators were not applied to a track.“ZT” refers to height(time) estimators and “symbol” is synonymous with “turbine”. The list of reasons is not comprehensive because, for example, tracks were skipped that never came within 724_m of a turbine. Reasons are not unique because different estimators can fail to be applied for the same reason. Most of the reasons that estimators were not used by the algorithm are obvious such as the track was so straight that it had only one segment without a tail. An animal flying so straight as that cannot be said to be attracted to or avoid a turbine. And a track with several curved, non-segment points at the end is never a nelson because of the curvature at the end of the track.

number of tracks	reason estimator(s) not applied to track
1	ZT linear fit not possible for pre-inflection segment
1	XY stitchSegments only 1 input segment
1	XY salientTurns highly contorted
1	XY fitSegments only 1 segment
2	ZT inflect only 0 segments
2	ZT salient only 0 segments
3	XY all segments traveled away from turbine
3	ZT salient only 1 segment
3	ZT inflection only 1 segment
3	ZT inflections call to setAllInflections failed
3	ZT salient only 1 segment
3	XY proximity: animal always flew away from symbol
4	ZT inflections last segment extrapolates into the ground
6	ZT inflect highly contorted
6	ZT salient highly contorted
6	XY anomaly: |yaw| >90 degrees
7	ZT salient too few segments < segEND
7	ZT inflection closest segment is 1st segment
8	XY nelson last segment between two turbine
8	ZT linear fit not possible for post-inflection segment
10	XY nelson last segment not clearly toward a turbine
11	ZT setClosestExtrapolation failed to find a best extrapolation

11 XY stitchSegments track has only 1 segment

12 XY Inflection segBEGIN is closest segment or later

12 XY proximity: track segment closest to symbol is the only segment

13 ZT salient right-left ambiguities

15 XY finishHough arc is shallow

19 XY Hough end of track travels almost directly at a turbine

23 ZT inflect reaction unlikely > 580 XY m from turbine

23 ZT salient reaction unlikely > 580 XY m from turbine

24 XY salient right-left ambiguities

37 XY rx_tangential |nelson clearance| >0.4 precludes tangential

41 XY rx_tangential last segment shows symbol still ahead

45 XY finishHough arc is almost flat

49 ZT cannot set closest segment

49 ZT salient No closest element to turbine

49 ZT salient no closest segment

63 XY rx_tangential Hough arc is pretty definite

64 XY nelson last-.k() beyond closestElement

66 XY finishHough arc is shallow and almost flat

76 XY nelson 2 or more points beyond last segment

141 XY gamma no |proportion| > 0.2

Appendix 6. Assumptions behind quantifying reactions to wind turbines

General assumptions

The observations pertain to commercial-scale terrestrial turbines, which are presently about 1.5 to 2 MW and 125 m tall (rotor-swept height) or greater. These turbines are usually deployed in arrays across the landscape.

Insects being killed or injured by wind turbines are not presently a concern. "Flying animals" and "flying wildlife" are used synonymously, referring to vertebrates on the wing high enough to possibly come near to the blades of wind turbines.

Flying wildlife may encounter one or many turbines aloft and may respond to turbines singly or to an array of turbines as an aggregate. However flying wildlife are not known to suffer cumulative damage from several turbines in an array and therefore conservation interest centers on encounters, sometimes fatal, with a single turbine. That is not to say that the animals do not respond to arrays of turbines from a greater distance than a single turbine, do not respond to cues generated by multiple turbines, or do not take flight paths in response to more than one nearby turbine.

If flying animals are attracted to turbines or avoid them, the behaviors are reactions to the turbines themselves or to an effect closely associated with turbines such as the altered airflow or sound levels in their immediate vicinity. Attraction is defined verbally as flying animals taking flight paths that place them at greater risk from turbine blades than if they did not react; avoidance as less risk. The behavior that ultimately determines greater versus less risk and the time of that behavior are of interest; additional prior behavior that may have temporarily increased or decreased risk may also be of interest but is not apt to be important for the ultimate outcome. Therefore, attraction and avoidance determine the outcome of an encounter with a wind turbine and are mutually exclusive. Although the wildlife may have been attracted to a turbine from the ground, the subjects of this study were already aloft and above the canopy when first tracked by radar.

“Attraction” and “avoidance” may be simplistic categories of response to turbines by flying animals and these categories will need to be modified as we begin to understand responses to wind turbines. Animals may deviate their flight to inspect a turbine then fly away without coming close to it. Animals downwind of turbines may show deviations in their flight paths as a result of being passively affected by air currents (including “turbulence”) produced by the turbines.

The cues to which animals may react may include air motion, visual, auditory, and infrasonic. If ultrasonic, reactions would have to be at very close distance, considerably less than the height of a turbine. They cannot include odor unless an animal approaches a turbine from downwind. Magnetic cues are open to speculation but positing perceiving turbines by magnetic stimuli necessarily involves some kind of directionality in the cue, or at least perception of change in cue strength with distance.

Carcass searches show that on the order of ten times as many bats as birds are killed and fall to the ground near turbines during times of the year when most bats are found. Therefore during that time of the year birds and bats must be analyzed separately and with the assumption that the biological mechanism behind fatalities at turbines is different for bats and birds. There are also probably taxonomic differences within "bats" and "birds" but that is to be determined.

If flying animals react to turbines, differences in carcass-search results are correlated with differences in animals' reactions, in time of year, taxonomically, or both.

Based on extensive work on migrating birds, which adopt an altitude at which to fly based on wind, topography, and other factors and direction of flight based on geography, flying animals react left-right and up-down independently. Therefore reactions in height(time) may be analyzed separately from reactions in direction(time).

Reactions may include changes in horizontal speed unaccompanied by noticeable changes in direction. Because is difficult to imagine changes in speed alone having an appreciable effect on mortality at turbines, we may ignore changes in horizontal speed in initial analysis, concentrating on changes in direction. However, vertical responses may include actively climbing or descending, which are changes from level flight (zero vertical speed).

Curved portions of tracks are difficult by their nature. Therefore, in a preliminary analysis step, straight sections of tracks were fit linearly (Larkin and Thompson 1980), but not curves between straight sections. (Mathematically, track points between adjacent straight sections are joinpoints.)

Assumptions with reference to reaction to turbines

Animals that appeared to react to turbines did not react to the radar, may have reacted to topography, if any, and other structures or features on the ground as well as or instead of turbine(s), reacted at some indeterminate distance either before or after the start of a radar track, were at some time close enough to a turbine to perceive it and tell its rough direction and/or relative height, and may show ambiguous reactions such as approach (moving closer) to investigate followed by avoidance (moving away), with one or more hovers or other maneuvers along the way while using sensory systems.

Flying animals are widely assumed to engage in cruising flight in a certain direction over the earth toward a goal, actual or perceived. They are separately assumed to assume a given height and to change height for efficient flight and/or accurate navigation. Therefore, horizontal direction of flight and ascending/descending are treated separately in analysis–although alteration of flight paths may occur in both planes of travel together. In real life, the horizontal (XY) and height planes interact because animals flying high above turbines may not react at all and animals probably do not change height to avoid turbines if no turbine is in their path.

Either attraction or avoidance may occur in response to a part of a turbine (nacelle, tower, moving blades, stationary blades), to a combination, or to the entire large structure.

Flying animals are not at risk from turbines whose rotors are not rotating (BCI citation); therefore any animal at risk while making a possible decision to approach or avoid a wind turbine is flying in wind. Migrating birds seek to fly in favorable winds, that is, approximately downwind rather than into a headwind. Therefore many or perhaps most flying animals encounter turbines ahead of them in the general direction of downwind. A turbine is designed to face into the wind. Because the three-dimensional wind field near a large turbine is difficult to know in detail on a second-by-second basis, the animals' position over the earth was used in the analysis (see Background). Ground speed and direction of flight are the appropriate measures of the animals' vectors, rather than relative to the air.

More specifically, a reaction consisting of a turn toward or away from a turbine or a change in rate of climb or vertical slope is recognized because the path departs from its previous direction. And a "previous direction" is almost necessarily a straight or somewhat-straight portion of a path. This logic suggests that reactions are best approached by identifying straight or somewhat-straight segments of a path through space and looking closely at the departures from such steady progress in a certain direction. Segmenting a path should be the next step after being satisfied that the data describing the path are valid and free of artifact.

In the XY plane (parallel to the earth), animals may turn right then left or vice versa and do so repeatedly. If a straight portion of a track traveling to the left of a turbine and the next straight portion after a turn travels to the right of a turbine, it is usually not possible to determine which, if either, of the segments represents a reaction. Therefore segments characterized by such "right-left ambiguities" and all preceding track segments are omitted from analysis; only segments with the turbine consistently to the right or to the left of the flying animal's path are used for analysis in the XY plane. This constraint most strongly affects tracks of targets approaching a turbine nearly straight and directly, but losing early portions of such tracks is not harmful because possible reactions by such targets are impossible to assess until they finally draw close to a turbine and turn (or not).

Animals are not "sucked into" a turbine. Because rotors extract energy from the wind, the net wind speed is slower not only at and behind a rotor but also some distance (albeit not a large distance) upwind of the turbine. An air parcel or a passive drifting object such as a balloon should decelerate slightly as it nears a turbine from upwind rather than experiencing any acceleration toward the turbine. This also implies that a flying animal seeking to avoid a turbine and experiencing a slowing of its progress (albeit perhaps slight) near the turbine is able to avoid the blades somewhat more easily even without increasing its cruising speed, by flyiing to the side, climbing/dropping, or a combination of horizontal and vertical motion. And an animal may, in fact, devote all its energy to flying upward (or downward) while its flight path still approaches a turbine at the speed of the wind. These generalizations do not apply in or near the actual blade wash; ordinary radar is not very useful very close to moving rotor blades anyway.

Animals that appear to react to turbines:

- Did not react to the radar. The best evidence indicates birds do not perceive radar (or, if they do so, they ignore it) (Bruderer et al 1999). The great majority of hundreds of birds and bats flying past the 65-kW radar used in this study flew straight and without changes in rate of climb unless they reacted to nearby turbines. Recent publications purporting to show bats reacting to radar are not peer-reviewed, are disputed, and are based on suspect methodology that does not pertain to the radar used in this study or to tracking radar.

- May have reacted to topography, if any, and other structures or features on the ground as well as or instead of turbine(s).

- Reacted at some indeterminate distance either before or after the start of a radar track. Only reactions within about 1-2 km of a turbine could be observed in this study. No known technique can rule out unobserved reactions of animals (whose taxonomic classification is to some extent known) to turbines at an arbitrary huge distance.

- Were at some time close enough to a turbine to perceive it and tell its rough direction and/or relative height. Animals cannot react without a cue.

- May show ambiguous reactions such as approach (moving closer) to investigate followed by avoidance (moving away), with one or more hovers or other maneuvers along the way. Additionally, some reactions in the present study seemed to show animals “inspecting” a turbine by deviating transiently as they flew past on generally-straight paths.

Assumptions with reference specifically to approach or attraction to turbines

An animal that approached a turbine: may or may not have been flying toward a turbine before reacting; if flying toward a turbine before perceiving it may have merely continued on that course; and if not flying toward a turbine, changed direction at some point on a course to intersect or nearly intersect the RSZ

Assumptions with reference specifically to avoidance of turbines

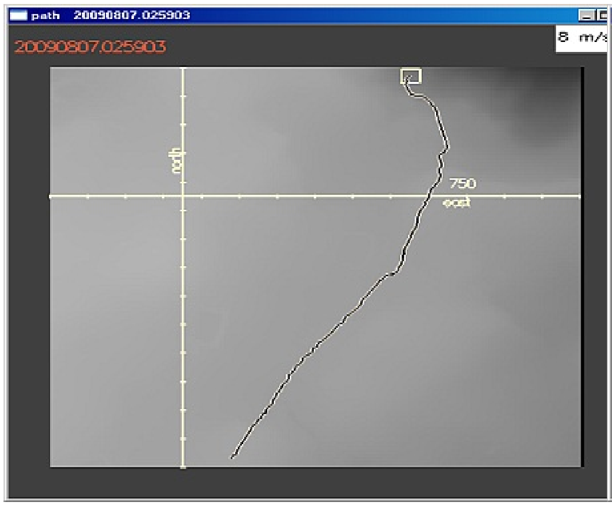
Animals that avoided turbines: had been on a course at some time before the reaction that would have placed them in or near RSZ, subsequently altered course so that they did not fly in or near the RSZ, or alighted on the ground, and may or may not have hovered or excecuted some other maneuver to decrease closing speed with the turbine.

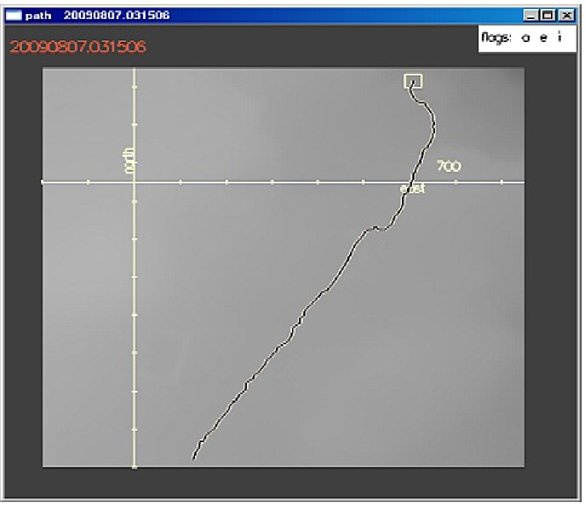
Inside the RSZ of a turbine is dangerous but near the RSZ may also be dangerous or be perceived by a flying animal as dangerous. For example in height(t), commercial turbines used in our 2009-2010 work have RSH minimum 55 m and maximum 125 m but flying animals probably cannot judge the height of tips of rotating blades accurately, so the perceived area of danger around a turbine probably exceeds the actual dimensions of the RSZ. (Avoidance is more likely by birds than by bats because fewer birds are killed, although this supposition shall not affect the analysis.)

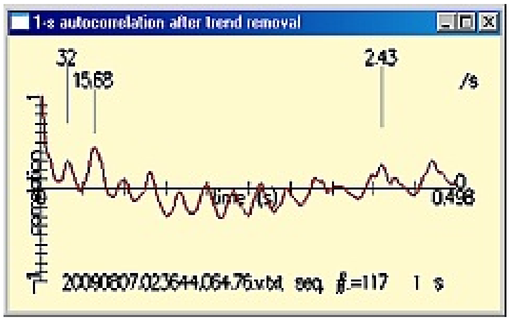
Appendix 7. Closely similar tracks at Casselman, PA

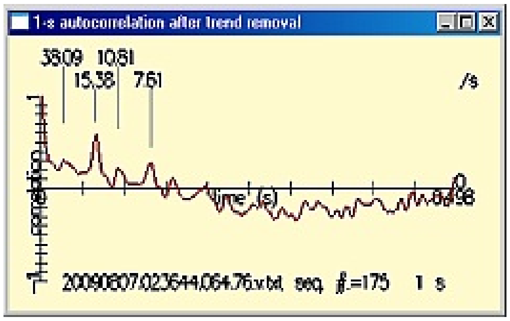
Two tracks, 16 minutes 3 seconds apart, passed the radar on the night of 7 August 2009, showing nearly identical flight behavior . The tracks are to the knowledge of the P.I. unprecedented and raise questions not only about the statistical independence of study subjects but more generally about the sensory abilities and orientation flight behavior of flying birds. (It is doubtful if it is appropriate at this point even to label these "migrating" birds.)

025903	031506	
figure below left	figure below right	XY path
F-C	F-C	target type
151	121	duration, s
698	653	m East of radar where track crosses latitude of radar
825 to 940	820 to 860	approx altitude MSL, track start to end
1253	2558	Hough radius
629	543	closest approach to Turbine 16
0.88	0.87	r-statistic to inflection
15.68 to 16.32	15.09 to 15.38	wing beat frequency (see figures below)
1660	1751	approx. maximum received radar signal, mV









Appendix 8: Decision logic for assessing reactions

In the following logic, expressed as SAS® code, the default reaction is “cannot tell”, which was likewise the most common category of manual (eyeball) assessment. Estimator scores of 0 indicate “cannot tell” or rarely “no reaction”.

First, XY and height(time) salient and inflection scores are combined if they agree completely. (`slope_score` is an inflection assessment in the height(time) plane). The forced agreement eliminates XY turns and height(time) changes in rate of climb that otherwise would be ambiguous and acts to compensate for the intrinsic difficulties in characterizing track segments and changes in path by using salient and inflection estimators conservatively. Then a decision on reaction to the turbine is made based on the strongest estimators and proceeding through less-strong ones. In the syntax, the `else` keyword means that the `decision =` that follows it takes place only if none of the `decision =` statements have executed; XY turns determine the decision only if none of the other conditions holds.

```
turn_vote = "CANT_TELL" ; * in XY ;

if      XYsali_score lt 0 and  XYinfl_score lt 0 then turn_vote = "AVOID" ;

else if XYsali_score gt 0 and  XYinfl_score gt 0 then turn_vote = "ATTRACT" ;

else if XYsali_score eq 0 and  XYinfl_score eq 0 then turn_vote = "NONE" ;

slope_vote = "CANT_TELL" ;  * in height(time) ;

if      slope_score lt 0 and ZTsali_score lt 0 then slope_vote = "AVOID";

else if slope_score gt 0 and ZTsali_score gt 0 then slope_vote = "ATTRACT";

else if slope_score eq 0 and ZTsali_score eq 0 then slope_vote = "NONE";

decision = "CANT_TELL" ;

if (nelson_vote eq "ATTRACT") and not (zt_climbed_gt_RSH eq "true")

                                    then decision = "ATTRACT" ;

else if tangential_vote eq "NONE"   then decision = "NONE" ;

else if tail_vote eq "AVOID"        then decision = "AVOID" ;

else if tail_vote eq "ATTRACT"      then decision = "ATTRACT" ;

else if zt_climbed_gt_RSH eq "true" then decision = "AVOID" ;

else if turn_vote eq "CANT_TELL"    then decision = slope_vote ;

else decision = turn_vote ;
```

The logic proceeds from more- to less-deterministic conditions. The first step involves the nelson estimator (`nelson_vote`) and the condition `zt_climbed_gt_RSH`, which is TRUE if the animal’s track started in or below RSH and during its approach toward a turbine it ascended to a height safely above RSH. Estimates of nelson ATTRACT were not straighter than those that yielded “NONE” for the same target type (Wilcoxon 2-sample test $p<0.41$); they often turned in XY as they approached a turbine from a distance but their final trajectory was unswervingly toward it in XY. Hence, if an animal also approaches in the other plane with an at-risk height and does not climb above it, the decision must be ATTRACT.

Similarly, if a path does not approach the turbine unswervingly but its last few tracked points (tail) turn unambiguously toward or away from the turbine, the decision is decided by the tail estimator. Remaining tracks that climbed above a turbine while approaching it in XY are AVOID. Finally, conservatively-estimated turns occurring at XY joinpoints classify a reaction as ATTRACT or AVOID providing the animal’s height when closest to the turbine is not greatly above it, exceeding (RSH + 200 m). All other tracks are CAN’T_TELL because, aside from tracks that passed a turbine on a tangential path in XY, the manual (eyeball) scoring could seldom distinguish CAN’T_TELL from no-reaction and because a reaction at a great distance could never be ruled out using a radar with a useful range for such work of only a few kilometers.

Appendix 9: Constant parameters used by the assessment algorithm

Parametrization of the algorithm was done using a subset of the data, namely tracks from the few first nights at the Casselman site (early August 2009) and the last few nights at the Pike County, IL site (September 2012). These tracks were selected to provide a subsample spanning the data collection with majority bats and topographic relief (Casselman) versus majority birds and flat terrain (Pike County, IL). Units are degrees, meters, and seconds.

<u>general constants for reaction algorithm</u>:

version=15.04
blade clearance far above turbine=185
height AGL far abve turbine (m)=200
maximum distance away (m)=724
minimum seconds prev. to inflection pt=4
minimum track seconds=8
minimum clearance past a turbine (m)=45
turbine blade length (m)=35
turbine nacelle height (m)=90

<u>constants for XY reactions algorithm</u>

fastest ground speed=35
gammaThreshold=0.2
Hough minimum proportion (arc depth/radius)=0.025
Hough negligible curvature=0.01
Hough % of centers seed=4
maximum curvature between segments=0.3
minPositiveNahen=0.05
minimum segment duration=3
minimum + closing speed=0.05
minimum degrees turning=4
steadyXY::proportion of variation=0.995
nelson rightAtEmFactor=3
r-statistic epsilon, degrees=3.55663
tangential negligibleMagnitude=0.15
tangential aheadLimitDeg=80

tangential shortVector=0.6

tail negligibleMagnitude=0.03

tail maxTotalTailCurvature=0.7

tail minDistanceRatio=0.05

tail minLRTotal=2

tail minTailN=3

salient negligibleMagnitude=0.01

nelson negligibleMagnitude=0.4

inflect negligibleMagnitude=0.01

HoughB negligibleMagnitude=0.01

Hough proportion=0.025

gamma negligibleMagnitude=0.01

Hough Transform constants

accumulator cells=180

middle accumulator cell=90

cell size, m=20

<u>constants for Z(t) reaction algorithm</u>

maximum closest XY distance from turbine=580

maximum relevant target z[]=425

minimum turbine RSH (m)=45

minimum meaningful delta rise/run @ inflection=0.1

minimum linearity of whole radar track=0.4

minimum linearity for salient assessment=0.4

minimum segment duration (s)=3

z(t) proportion of variation=1.41

inflect negligibleMagnitude=0.01

salient negligibleMagnitude=0.01

z baseline for slope calculations=AGL