

Quantification of bird migration by radar – a detection probability problem

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Besides the scientific interest in the quantification of bird migration, there is an increasing need to quantify bird movements for the assessment of bird collision risk with artificial structures. In many environmental impact studies, the radar method is used in an inappropriate manner. The processing of echoes consists often of counting blips within defined screen fields, and the surveyed volume is estimated without reference to the detection probabilities of different 'target sizes' (radar cross-sections). The aim of this paper is to present a procedure to quantify bird migration reliably using radar by stating the theoretical requirements of every single step of this procedure and presenting methodological solutions using our own radar data from extensive field studies. Our methodological solutions can be applied to various radar systems, including widely used ship radar. The procedure presented involves discriminating the echoes of birds and insects and estimating the different detection probabilities of differently 'sized' birds (radar cross-sections). By ignoring the different detection probabilities, density estimations may be wrong by as much as 400%. We fear that quantification of bird migration and predicted bird numbers affected by collisions with artificial structures are in many cases based on unreliable estimates.

Keywords: collision risk, echo identification, flight speed, migration traffic rate, ship radar.

Quantification of bird migration deals with the spatial and temporal distribution of birds. As birds often migrate at too high an altitude for visual observation, and most often nocturnally (Bruderer & Liechti 1995, 1999), radar is regularly used to monitor bird migration (Eastwood 1967, Bruderer 1997a, 1997b). Scientific studies have usually paid considerable attention to appropriate recording and cautious interpretation of radar data (e.g. Sutter 1957, Gehring 1963, Schaefer 1968, Gauthreaux 1970, 1971, Bruderer 1971, Buurma 1987, 1995, Bruderer *et al.* 1995, Gauthreaux & Belser 1998, Gauthreaux *et al.* 1998). The need for quickly available environmental impact studies combined with the availability of relatively inexpensive ship

radars has led to a proliferation of radar studies. However, instrument capabilities and limitations with respect to detecting and quantifying birds and insects have not been considered sufficiently. The highest demand for environmental impact studies is currently connected to wind farms (e.g. Harmata *et al.* 1999, Hüppop *et al.* 2004, 2006, Desholm & Kahlert 2005, Desholm *et al.* 2006). To assess the significance of the potential threats to birds of such structures, bird movements have to be quantified.

The principle of quantification seems simple: the number of birds within the radar beam provides their spatial and temporal distribution. However, to achieve reliable results, echoes must be identified as birds and the surveyed volume must be known. The surveyed volume (i.e. the dimensions of the radar beam) changes with 'target size' (radar cross-section; for definitions see Table 1), which makes quantification of bird migration a rather difficult task (Eastwood 1967, Bruderer 1997a). Yet, in most applied radar studies and even in recent scientific studies,

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Table 1. Definitions of radar terminology.

Radar terminology	Definition
Target	Object detected in the radar beam.
Radar cross-section	A measure of the size of a target as seen by a particular radar; it has the dimension of an area (cm ²), and depends on the object's size, shape, aspect, reflecting properties, as well as on the length and polarization of the radio waves.
Echo size	The energy reflected by the target and detected by the radar (after passage through the receiver system). It depends on the target's radar cross-section, its position in the radar beam (mainly distance) and the technical properties of the radar system.
Echo signature	Temporal variation of energy reflected by the target.
Standardized echo size	Calibrated dB-value providing a logarithmic equivalent of the echo size (corrected for the effect of distance); see Equation 2.
Blip	Visualization of echo size on a radar screen.
MTR	Migration traffic rate: Number of birds crossing a virtual line of fixed length perpendicular to the flight direction within 1 h.

Table 2. Overview of echo parameters provided by five frequently used radar methods. Parentheses indicate that the radar cross-section can only be determined for targets flying through the centre of the beam, and that combining subsequent conical scans provides information on direction and speed. Methods used within this study are marked with an asterisk.

Radar measurement	Echo signature	Radar cross-section	Ground speed	Flight direction	Distance to radar	Representative sample
a) Fan-beam ship radar						
Horizontal scanning	no	(yes)	yes	yes	yes	yes
Vertical scanning	no	yes	no	no	yes	yes
b) Small pencil-beam						
Fixed beam*	yes	(yes)	no	no	yes	yes
Conical scanning	no	(yes)	(yes)	(yes)	yes	yes
Tracking*	yes	yes	yes	yes	yes	no

neither echo identification nor proper estimations of the surveyed volumes have been considered (e.g. Cooper *et al.* 1991, Harmata *et al.* 1999, Biebach *et al.* 2000, Hüppop *et al.* 2006). Considering the demand for fast but nevertheless reliable environmental impact studies, the importance of proper quantitative analysis cannot be overestimated. As these figures are the basis for nature conservation decisions, the shortcomings of analyses already published are worrying.

The aim of this paper is to depict for the first time a general procedure of how to estimate absolute bird densities by radar (Fig. 1). We discuss all crucial adjustments to radar data and necessary parameters for quantification. We stress the essential problems of echo detection (data sampling, calibration, sensitivity time control (STC)-filter and echo identification) and quantification (surveyed volume, as well as calculation of frequencies and densities). Each of these six features is first introduced by giving the theoretical background, presenting previous approaches (if any)

and discussing their shortcomings. We then state our solutions based on our own field data and thereby present a detailed general procedure of how to calculate bird densities based on radar data.

ECHO DETECTION

Data sampling

State of the art

Proper quantification of bird migration requires sampling of radar cross-section, echo signature, air speed, flight direction and position in the radar beam (mainly distance) of every single radar target (for definitions see Table 1). As no radar system as yet can provide all of these essential parameters with just one single sampling method (Table 2), at least two sampling methods must be combined to quantify bird migration successfully.

Bruderer (2003) gave an overview of radar systems used for ornithology, and assigned them to two basic

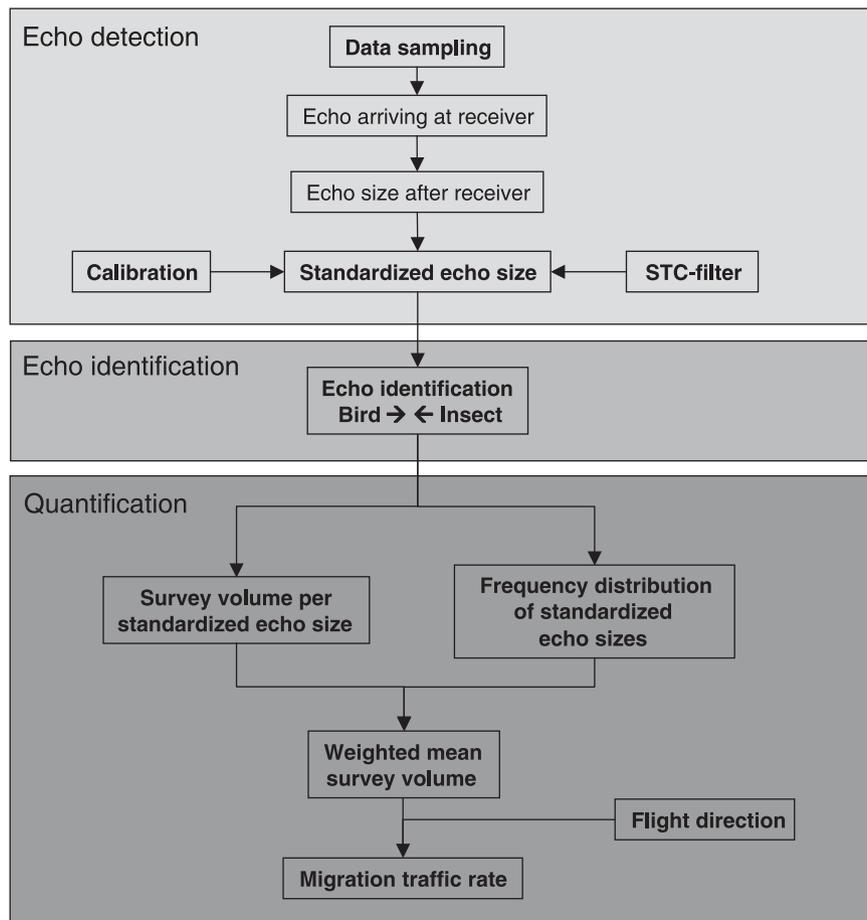


Figure 1. Quantification procedure. The three basic steps are given in separate boxes. Depending on the level of identification, the last step (quantification) may be applied separately for different bird classes (wader-, swift- and passerine-type). Emphasis in the text is on topics in bold.

types: (1) fan-beam radars (including fan-beam surveillance, ship navigation, nodding height finder and stacked beam radars); and (2) pencil-beam radars (weather and tracking radars, pencil beams adapted for ornithological use and wind-profilers). To simplify matters, we consider here only two fan-beam sampling methods usually applied for ship radars (horizontal and vertical scanning) and three pencil-beam applications (conical scanning, fixed beam and tracking). These five sampling methods are currently often used in ornithological radar surveys; their capabilities are given in Table 2.

A horizontally scanning fan-beam hits targets repeatedly over several revolutions, mainly providing information on bearing and distance. Echo size can be measured with appropriate equipment and indications of flight direction and ground speed are possible, although altitude information is generally very poor.

To obtain altitudinal distributions, fan-beam ship radars have been used in a vertical scanning mode (Gauthreaux 1984, Harmata *et al.* 1999), providing numbers of echoes with their distance and elevation angle, and possibly echo size. Conical scanning with a pencil beam at different elevations reveals echo size, distance and height (Bruderer *et al.* 1995). Fixed beam measurements provide echo size and its variation (= echo signature), distance and height, and radar cross-section can be calculated under particular conditions. These methods representatively sample targets in space and time, as long as the pulse volumes of the radar are small enough to contain single targets. The problem of multiple targets increases with the pulse volumes of the applied radar, because a large pulse volume may contain more than one target. During tracking, a single target is kept within the centre of the beam, providing all possible parameters mentioned above.

Quantification of migration is, however, not possible in this mode.

Many scientific (e.g. Biebach *et al.* 2000, Hilgerloh 2001) and most environmental impact studies (e.g. Harmata *et al.* 1999, Hüppop *et al.* 2004, 2006, Desholm & Kahlert 2005, Desholm *et al.* 2006) use ship radar to quantify bird migration. In these cases, the horizontal and vertical scanning methods are usually combined to obtain data on altitudinal distributions and flight directions. However, quantification and even relative comparisons with these methods are problematic (see below). Nevertheless, ship radar can be equipped with a parabolic dish antenna (Gauthreaux 1984) to allow fixed beam measurements – similar to those recorded with our system – to overcome the shortcomings of quantification by commercial versions of ship radar.

Application

To obtain all essential parameters of the echoes for quantification we used the fixed beam (quantitative) and tracking (qualitative) sampling method of our 'Superfledermaus' X-band radar (peak pulse power of 150 kW, Bruderer *et al.* 1995). The radar was operated in the western Sahara, Mauritania (20°56'N, 11°35'W) during three migration periods (6 March – 15 May 2003, 24 August–25 October 2003 and 15 March–10 May 2004; for further information see Schmaljohann *et al.* 2007a, 2007b).

The fixed beam measurements were carried out at a high (78.75°, $n = 3490$) and low (11.25°, $n = 2367$) elevation angle to cover comparable volumes at different altitudes every hour on the hour (Schmaljohann *et al.* 2007b). The beam was directed towards west (270°), perpendicular to the main flight direction of migration (Schmaljohann *et al.* 2007a). Each fixed beam measurement sampled targets flying through the beam for 246 s (in total about 90 000 targets). The echo-signatures of targets crossing the beam within a distance of 200–7500 m were recorded with a sampling rate of 130 Hz. The distance resolution was 30 m.

In the tracking method, flight directions, velocities and echo signatures of the tracks (about 70 000) were sampled between the fixed beam measurements to represent flight behaviour (Bruderer 1969). During daytime, targets were visually identified using a 12.4× telescope mounted parallel to the antenna ($n = 5226$). Based on wind profiles measured every 6 h, air speed and heading were calculated for each track (Bruderer *et al.* 1995). Statistics were calculated using the statistical software package R (R Development Core Team 2006).

Calibration

State of the art

Calibration is the first important step in quantifying bird migration. If the radar is not calibrated, the surveyed volume cannot be estimated and filters, to reduce detection of small targets at close range (STC; see below), cannot be applied properly.

Targets within a radar beam reflect some of the pulse energy to the radar antenna. This received energy at the antenna P_r is determined by the equation:

$$P_r = \frac{P_t \cdot G \cdot \sigma \cdot A}{(4\pi R^2)^2} \quad (1)$$

where P_t = transmitted power, G = antenna gain, σ = radar cross-section, A = surface of antenna and R = distance between antenna and target (Eastwood 1967). Radar can be calibrated empirically by recording the echoes of defined radar cross-sections at various distances. To our knowledge only Gauthreaux (1984) attempted a calibration of his ship radar by visual observations and indicated maximum detection ranges of different bird sizes. A more practical solution is to feed defined amounts of energy (dB-signal) to the antenna by using a signal generator. These dB-signals are transformed to raw video signals by the analog/digital converter of the receiver circuit. Based on this calibration, raw video signals can be assigned to certain dB-values (echo sizes) and these dB-values can be standardized, being then independent of distance.

Data from an uncalibrated radar are difficult to evaluate, because radar cross-sections are needed to control for the variation in detection probability for different targets. In addition, a defined distance-dependent detection threshold (STC; see below) cannot be applied, although this is highly important to reduce clutter at close ranges, and particularly insects in X-band radar.

Application

Our radar was calibrated regularly with a signal generator (Radar Test Set 75, Gigaset). Based on this calibration, it was possible to convert the relative values of the raw video signals into dB-values and finally to standardize all echo sizes to a distance of 3 km, as follows:

$$\text{standardized echo size} = \text{dB}_i + \log_{10}(R_i^4/3000^4)/\log_{10}(10) \times 10 \quad (2)$$

where dB_i = converted echo size_{*i*} (P_r) and R_i = distance [m] of target_{*i*}. The maximum of a standardized echo

size is equivalent to the target's radar cross-section, if the target crossed the centre of the beam.

STC-filter

State of the art

The amount of the pulse energy that is reflected by a target of a given radar cross-section increases dramatically with decreasing distance (roughly by R^4 according to Equation 1). To avoid the detection of numerous small radar cross-sections at close range (insect, sea wave or ground clutter), most radar systems reduce the sensitivity of the receiver with decreasing distance. This device is called sensitivity time control (STC), which applies a distance-dependent detection threshold (Bruderer *et al.* 1995). Standardized echo sizes allow exclusion of all radar cross-sections that would not be detectable at or beyond the defined threshold distance. Consequently, applying an STC on standardized echo sizes not only reduces the amount of small radar cross-sections detected but reduces the surveyed volume at a known rate.

In ship radar, the effect of the in-built STC is rarely documented; it can often be adjusted to incidental conditions, without any knowledge on the effect of such adjustment by the operator. Manipulating the STC to a degree where 'birds could still be detected', but actual clutter is reduced, is not a suitable method (Cooper *et al.* 1991). Any change of the STC

within an observation period must be avoided (Hüppop *et al.* 2004), because it always implies an unknown change in the surveyed volume. Some observers even switched off the STC, e.g. Biebach *et al.* (2000). In most radar studies, the STC-effect remains unknown to the reader. To solve this problem, there are two possibilities: (1) the radar manufacturer is prepared to provide a clearly defined STC-function; and (2) a calibration of the system provides defined dB-values for each echo size (see above), which allows application of a *post-hoc* STC-function. Without identifying the effect of the STC, insect contamination can be overwhelming (e.g. Biebach *et al.* 2000, Schmaljohann *et al.* 2007c) and the surveyed volume cannot be estimated.

Application

The working distance of our STC was defined empirically, with the aim of excluding the highest possible proportion of small echoes such as insects, but the least possible proportion of small birds. As the smallest European bird, Goldcrest *Regulus regulus*, can be tracked with our radar slightly beyond 3 km in tail-on view (our unpubl. data), we assumed that mainly clutter and insects, but not birds, are excluded with a threshold distance of 3 km. Figure 2 shows the difference between the raw radar picture (blips) and the same picture after applying a calibrated STC affecting echoes up to 3 km (in our case above the

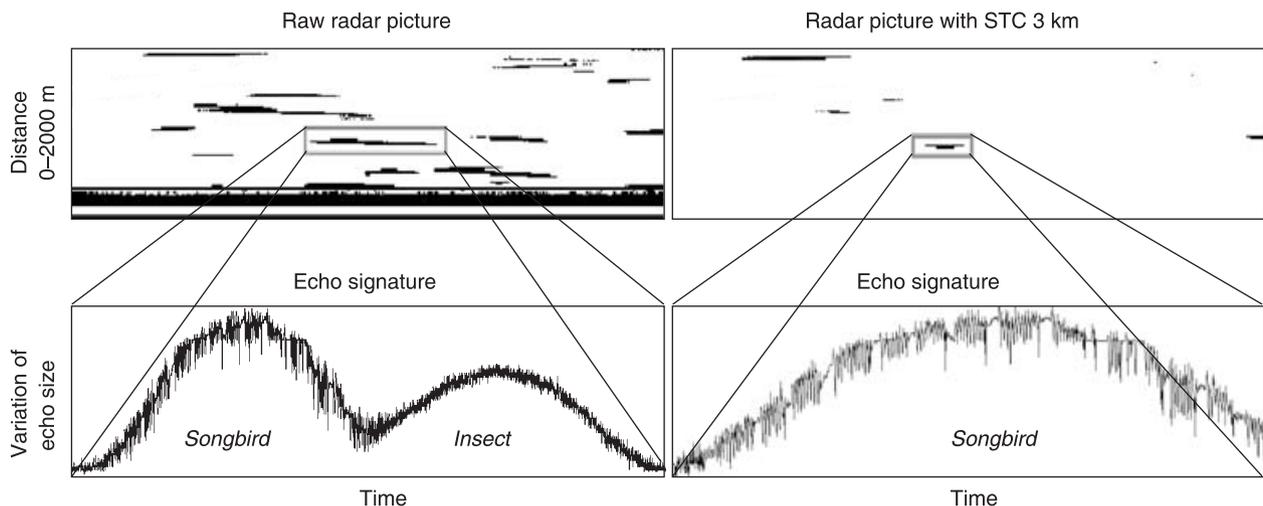


Figure 2. Effect of the sensitivity time control (STC). The raw radar picture of a fixed-beam measurement (top left) shows echo sizes after passage through the receiver circuit over time and distance (2 km). This includes birds, insects and clutter (mainly a band at close range). To the right, the same measurement is shown after applying the STC, comprising only echoes above the threshold chosen to exclude a maximum of insects, but a minimum of birds (see text). The bottom graphs show the temporal variation (echo signatures) of selected echoes. The echo to the left consists of two targets crossing the radar beam, a songbird and an insect. In the right picture the insect target did not pass the STC-filter and disappeared.

noise level threshold of -90 dB). Reducing the sensitivity in our radar system by increasing the STC from 3 to 4 km would reduce the surveyed volume by about 50%.

Echo identification

State of the art

Radar echoes must be identified as birds, if the aim is to quantify bird movements. Insects can make up an overwhelming proportion of targets depending on time, location (Riley & Reynolds 1979, 1983) and radar sensitivity (Eastwood 1967), and present the most significant interference with bird targets. Although radar for studying insect movements is widely accepted (Glover *et al.* 1966, Riley 1975, Smith *et al.* 1993, Chapman *et al.* 2003), insect presence was often ignored in bird radar studies, even when using X-band radars that are highly sensitive to insects (Harmata *et al.* 1999, Biebach *et al.* 2000, Hüppop *et al.* 2006). Butterflies, dragonflies and moths are known to migrate in large numbers between northern Europe and tropical Africa (Johnson 1969). Although numbers of large aerial insects possibly decrease towards the poles, Gudmundsson *et al.* (2002) report radar-detected mosquito swarms near the pack ice in the arctic up to heights of 800 m above ground level. Therefore, we have strong reservations that insects can be neglected in any study without specifically checking the facts.

Differentiation between bird and insect echoes should be carried out with radar cross-section, its variation over time (echo signature) or air speed. In general, the radar cross-section as well as its variation is much smaller in insect than in bird echoes (Gehring 1967, Bruderer 1969, Riley 1973). In birds, the echo signature mirrors the well-defined wingbeat pattern (Bruderer 1969, 1997a), whereas in insects the complicated structure of the echo signature probably consists of a mixture of wing and other body movements. Our own experiments suggest that the chitinous coat reflects the radar waves, because dry individuals provided as good radar targets as living insects (our unpubl. data).

Air speed is the other useful parameter for insect–bird discrimination, as most insects fly slower than 5 m/s (Larkin 1991) and most birds faster than 10 m/s (Bloch & Bruderer 1982, Bruderer & Boldt 2001). There are two problems: (1) some insects (e.g. large moths and locusts) can achieve high air speeds of up to 9 (Waloff 1972) or even 11 m/s (migratory locusts; our unpubl. data), while some birds fly with air speeds clearly below 10 m/s, e.g. Goldcrest (Stark 1996);

and (2) the precision of air speed, calculated from ground speed and wind vector, depends on the temporal and spatial vicinity of the two measurements. Our radar flight data of birds and insects show that even with very precise measurements (vertical distance to nearest wind measurement < 100 m and temporal < 1 h, respectively) an overlap between air speed of insects and birds exists (Fig. 3). As wind measurements cannot be carried out with ship radar, wind data must be derived from weather stations nearby or from modelled atmospheric datasets. However, these wind data are only rough estimates of local conditions, resulting in very inaccurate approximations of potential insect contamination. Because echo signature is independent of wind (Glover *et al.* 1966, Bruderer 1969, Bruderer *et al.* 1972, Riley 1973), we strongly suggest using the echo signature for the insect–bird discrimination.

Any attempt to identify tracks of flocks (several targets within a pulse volume) to species groups by means of echo signature and ground speed must be treated cautiously (Harmata *et al.* 1999, Desholm & Kahlert 2005). It remains unclear how echo signatures from flocks (hardly providing wingbeat patterns) and ground speed (highly dependent on wind conditions) can be used to discriminate between species. We are not aware of a method that allows identification of bird flocks at the species level, except by parallel visual observations.

Application

With our radar system, we could visually identify some tracked echoes, using the telescope, as insects or birds. These differed clearly in their air speed, standardized echo size and echo signature (Fig. 4). Based on these three parameters, one of the authors (H.S.) classified all tracks ($n = 71\,181$) as a bird ($n = 52\,195$) or an insect ($n = 16\,387$). However, some echoes with signatures between those of birds and insects remained unidentified ($n = 2599$, i.e. 3.6%). Echoes from fixed beam measurements ($n = 91\,164$) had to be identified by their echo signature only. H.S., who trained for echo signature identification of diurnal tracks with parallel visual observations during 7 months of fieldwork, carried out this classification ($n = 15\,433$ birds, 63 756 insects and 11 975 unidentified flying objects). For examples of insect and bird echo signatures see Glover *et al.* (1966), Schaefer (1968), Bruderer (1969), Bruderer and Steidinger (1972), Bruderer *et al.* (1972), Riley (1973), Demong and Emlen (1978) and Liechti and Bruderer (2002) and Figure 2.

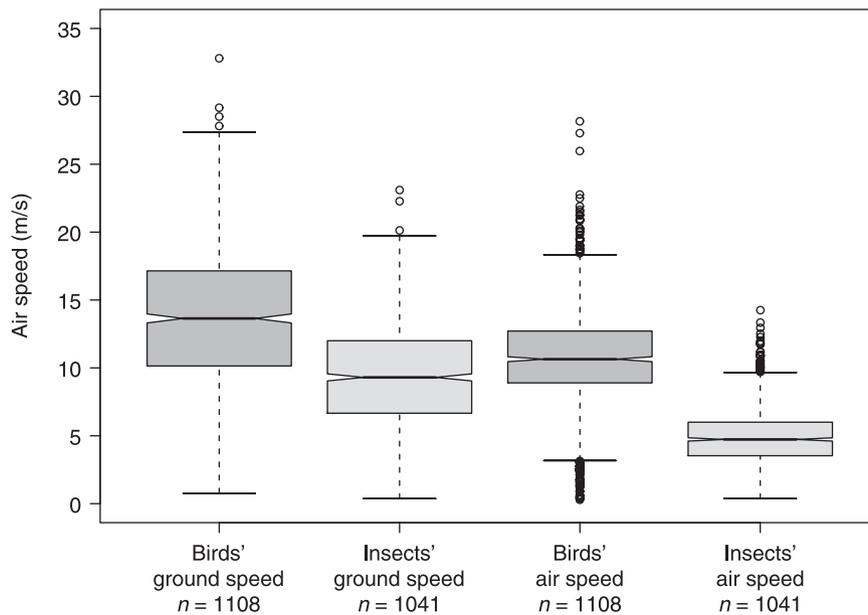


Figure 3. Ground and air speed of tracked birds (dark grey) and insects (light grey). One-sample Wilcoxon tests of bird ground-to-air speed and insect ground-to-air speed and Mann–Whitney *U*-tests of bird ground-to-insect-air speed and vice versa produced highly significant differences (all *P*-values < 0.0001). Altitude had to be higher than 100 m above ground level, difference to wind measurement < 100 m for mean vertical distance, < 1 km for horizontal distance and < 1 h for time.

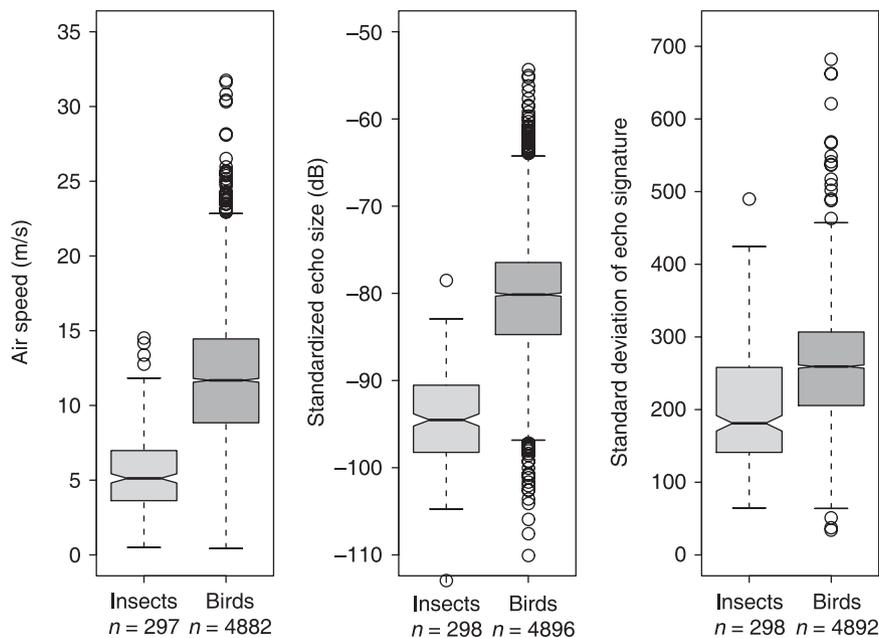


Figure 4. Boxplot of air speed, standardized echo size and standard deviation of echo signature of single tracked insects (light grey) and tracked birds (dark grey) identified visually using a telescope mounted parallel to the radar beam. Differences between insects and birds were all highly significant (Mann–Whitney *U*-tests: all *P*-values < 0.0001). Differences in sample size were due to missing values for some tracks.

As the echo signature of birds represents their wingbeat pattern, echoes from tracking and fixed beam methods – identified as birds – can be further assigned to different flight types (bird classes) using their wingbeat pattern (Bruderer 1969, 1997a): (1) continuously flapping (e.g. waders, waterbirds, rails, quails = wader-type); (2) intermittently flapping (passerines without swallows and corvids = passerine-type); (3) intermittently flapping birds with irregularly long flapping and pause phases (swifts and bee-eaters = swift-type); (4) raptors, storks, etc. (large single birds); (5) bird flocks (only visually determined); and (6) unidentified birds characterized by larger radar cross-section than insects, but no clear wingbeat pattern (unidentified birds; for further information see Bruderer *et al.* 1972, Bruderer 1997a). However, bird echoes can only be assigned to these different bird classes when flying singly in a pulse volume, a condition that was usually fulfilled for nocturnal migrants observed with our radar (Bruderer 1971). In flocks, usually prevailing in daytime, the mixture of various interfering echo fluctuations does not provide easily analysable wingbeat patterns. Identification of passerine-type single birds is straightforward because of the alternation of wingbeat phases and pause phase. Differentiation of wader- and swift-types is dependent on the duration of recording (short tracks of swifts in flapping flight may be taken as waders, if no pause phase is recorded; for examples see Schaefer 1968, Bruderer 1969, Bruderer & Weitnauer 1972). For the quantification of nocturnal bird migration (see below) we consider only wader-, passerine- and swift-type echoes ($n_{\text{wader-type}} = 4066$, $n_{\text{passerine-type}} = 7601$, $n_{\text{swift-type}} = 1468$) from the fixed beam method.

QUANTIFICATION

Surveyed volume

State of the art

For reliable quantification, not only do the echoes have to be identified, but the surveyed volume must also be estimated. In radar, the beam shape, which is geometrically similar for all radar cross-sections, describes the form of the surveyed volume but its absolute size varies with radar cross-section. Its absolute size can be calculated with the maximum detection range per radar cross-section and the antenna diagram (which should be available from the manufacturer). Finally, the mean surveyed volume depends on the composition of the radar cross-sections (target sizes) of the sampled echoes.

A reliable estimation for this mean surveyed volume is consequently the weighted mean of the surveyed volumes (radar cross-sections) involved.

Most studies used only the nominal beam width given by the manufacturer to consider the surveyed volume (e.g. Biebach *et al.* 2000), and assumed a maximum detection range either empirically due to blips on the screen or based on theoretical reflections. As far as we are aware, only Liechti *et al.* (1995) determined the operational radar beam for birds empirically by parallel passive infrared observations. Their results suggested that the operational radar beam was 2.5 times wider than given by the manufacturer. However, radar cross-sections vary considerably between birds, and with that their corresponding surveyed volume. To quantify bird migration precisely, radar cross-section-specific surveyed volumes should be estimated. In birds, this can be approximated by estimating the surveyed volume separately for the different bird classes (see above).

Application

As our standardized echo sizes (Equation 2) were based on calibrated dB-values, the maximum detection range can be estimated empirically by selecting the most distant target for a given standardized echo size-class. As we need to determine maximum detection range only for one standardized echo size-class (surveyed volume changes only absolutely but not relatively with standardized echo size), we chose the standardized echo size-class with the largest number of echoes, because the chance to record an echo at the maximum range increases with sample size (−78 dB → 5970 m, Fig. 5). The maximum detection range for all other standardized echo size-classes can be calculated proportionally. By inserting the maximum detection range in the equation of the antenna diagram (given by the manufacturer Contraves; see also Bruderer 1971) the surveyed volume can be calculated for each standardized echo size-class.

To estimate the overall surveyed volume for bird echoes, we first determined the frequency distribution of the radar cross-sections involved and secondly calculated a weighted mean surveyed volume based on this frequency distribution. In the fixed beam, targets fly across the beam at any (unknown) distance from its central axis (Table 2). Large targets grazing the beam edge produce smaller echo sizes than small targets crossing its centre. Therefore, only targets flying close to the beam centre should be considered to achieve an adequate distribution of the radar cross-sections. By considering the average ground speed

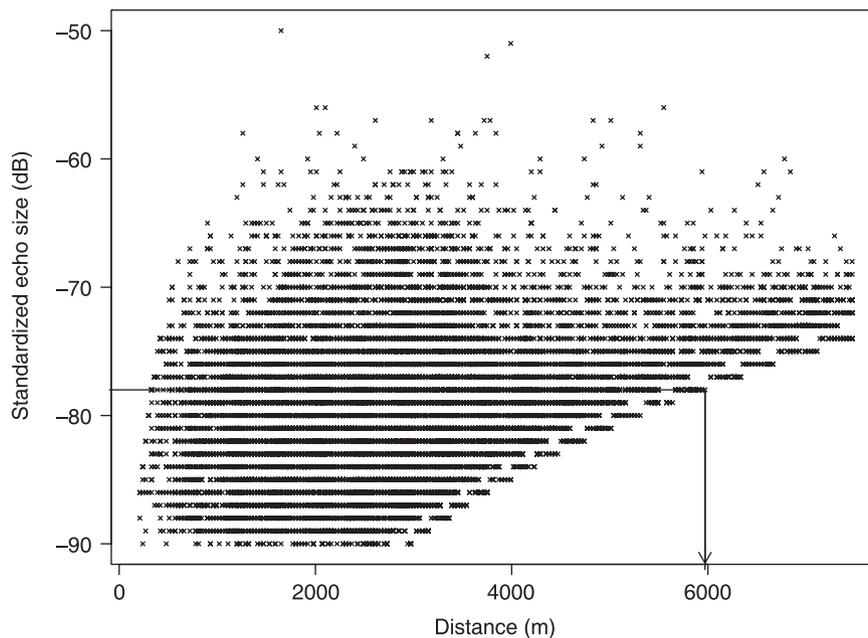


Figure 5. Determination of maximum detection range for bird targets of fixed beam measurements: standardized echo sizes were plotted over distance; standardized echo size class of -78 dB contained the most echoes ($n = 1154$). Its furthest echo was taken as a reference value for its maximum detection range (5970 m).

(from the tracking data) and time spent in the beam, we selected only targets flying close to the centre of the beam. Furthermore, echo distance must be restricted to the maximum detection range (or less) of the smallest radar cross-section assigned to a bird (in our case 3 km for a Goldcrest). Otherwise, small targets would be under-represented.

As the aspect at which a target is seen by the radar has a strong influence on the radar cross-section, standardized echo size distributions were calculated separately for high- (ventral view) and low-elevation measurements (mainly lateral view; Bruderer & Joss 1969, Houghton 1969). As we can also distinguish different bird classes with our radar method, we determined the standardized echo size distributions separately for wader-, passerine- and swift-type birds for the two elevations. Within the same bird class, the frequency distribution differed significantly between the two elevations with considerably higher standardized echo sizes at high elevation (ventral view, Fig. 6).

Based on standardized echo size distributions of these six subsamples, six weighted mean surveyed volumes were computed. Surveyed volume was 0.052, 0.046 and 0.056 km³ at low elevation and 0.192, 0.088 and 0.216 km³ at high elevation for wader-, passerine- and swift-type birds, respectively (Fig. 7). It was therefore 3.7 \times , 1.9 \times and 3.9 \times larger at high

than at low elevation and volumes differed distinctly between the subsamples (Fig. 7). If different bird classes as well as the aspect at which birds are detected are not considered, estimation of surveyed volume might be wrong by up to 400% (0.216/0.046). With this quantification procedure, we present for the first time a method to estimate echo size-specific surveyed volumes (considering bird class and aspect).

Calculation of frequencies and densities

State of the art

Having identified the echoes as birds and estimated the bird-specific (or as in our case the wader-, passerine-, and swift-type-specific) and aspect-specific surveyed volume (Fig. 7), migration frequencies and densities can be calculated. Migratory frequency can be measured as migration traffic rate (MTR). This is defined as the number of birds crossing a virtual line of fixed length (typically 1 km) perpendicular to the flight direction within 1 h (Lowery 1951, Bruderer 1971). MTR is calculated by counting birds within a known surveyed area over a given time period. Bird density per km³ can then be obtained by dividing MTR by ground speed.

The appropriate surveyed area, which is the vertical intersection plane along the beam centre, can be

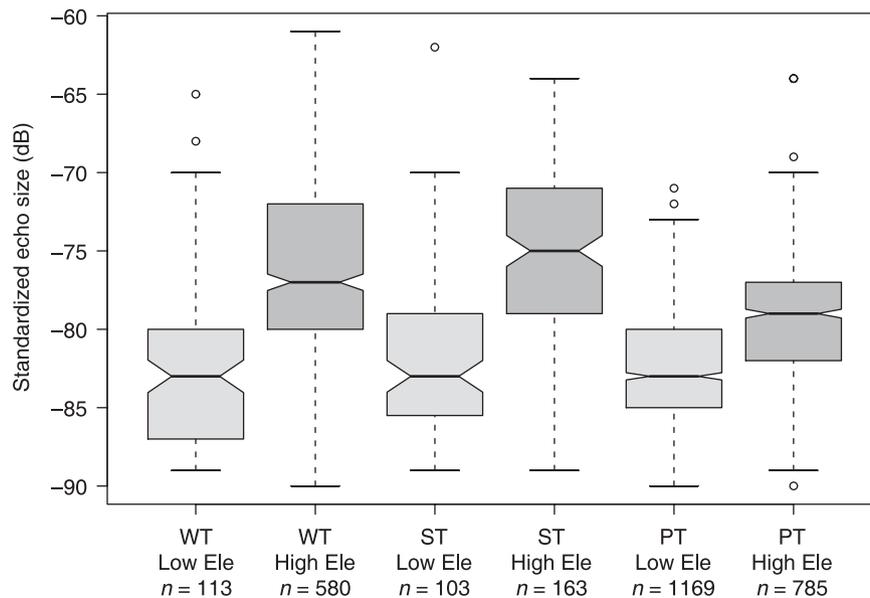


Figure 6. Distribution of standardized echo sizes of three different bird classes in relation to aspect of fixed beam measurements. Only targets flying through the beam centre were included, and this only within the range interval of 0.2–3 km, where the detection probability is kept constant by the STC-filter. Standardized echo size is a logarithmic equivalent of the radar cross-section. Light grey boxes indicate low- and dark grey boxes high-elevation measurements, respectively. Mann–Whitney *U*-tests for a comparison of low- and high-elevation standardized echo sizes for wader- (WT), swift- (ST) and passerine-types (PT) were significant (all *P*-values < 0.0001). A comparison between the different bird classes revealed only significant differences for PT vs. the two other groups at high elevation (*P*-values < 0.0001).

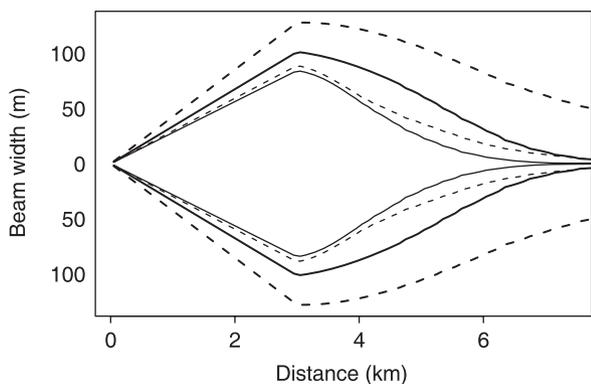


Figure 7. Radar beam-width over distance for passerine- (solid line) and wader-types (dashed lines) of low (thin lines) and high elevation (bold lines). Calculated radar beam widths for passerine-, wader- and swift-types resulted in opening angles of 3.2°, 3.4° and 3.6° for low elevation and 3.9°, 4.9° and 5.0° for high elevation, respectively. Radar beam width for swift-types was not included in this figure to simplify the presentation. Maximum detection range was restricted to 7.5 km. According to the manufacturer, the opening angle is supposed to be 2.2°.

calculated from the surveyed volume. However, flight directions of migrants have an important effect on the surveyed area and with that on frequency and density measurements. With a change in the flight

direction, the surveyed area decreases according to the cosine function; for example, at a flight direction of 30° to the beam, the surveyed area will be halved, and at 0° it is minimal. Hence, the surveyed area must be calculated with respect to the migrants' flight direction. In general, flight directions can be obtained by tracking or with a horizontal scanning method. If horizontal scanning is restricted to low altitudes, extrapolation to higher altitudes is inappropriate, because wind and flight direction may change with altitude.

Harmata *et al.* (1999) and Hüppop *et al.* (2004) accounted for the decreasing detection probability with distance of their vertical scanning ship radar by calculating distance-dependent correction factors based on the distance sampling method (Buckland *et al.* 2004). For this calibration only 'radar birds' (echoes were not identified as birds in these studies) within one height interval (100–200 m) were selected, assuming that the horizontal distribution of migrants is homogeneous. Applying this correction to all elevation angles of vertical scanning measurements leads to problems. First, the increase in the detection probability between lateral and ventral aspects was ignored (Fig. 6), resulting in an overestimation of the densities at high elevations. Secondly, the assumption

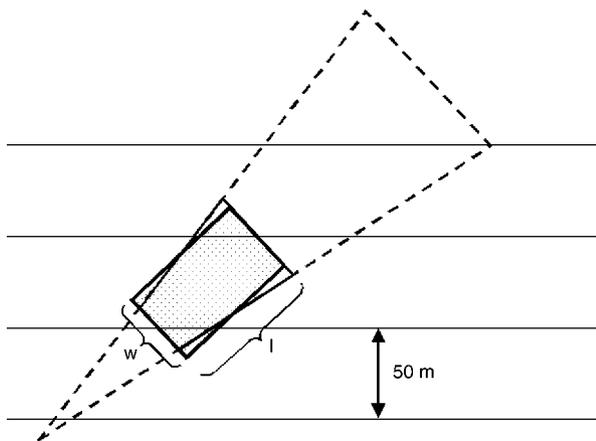


Figure 8. Determining the sampling units of different height intervals for fixed beam measurements. The dashed line indicates a simplified radar beam (with constant opening angle). The fine solid line describes the trapezium defined by the opening angle of the beam. We defined the sampling unit (bold solid rectangle) per height interval by multiplying l , the length of the sampling unit along the radar beam, by w , the corresponding width of the radar beam. The actual sampling unit used for analysis is the projection of the initial sampling unit perpendicular to the birds' flight direction (see text for further information).

of the distance sampling method that the detection probability should vary only with distance and not between echoes (radar cross-sections) is violated (e.g. a heron or a duck has a considerably larger radar cross-section than an average songbird). Although this seems to be the most advanced method used with ship radar, even relative comparisons between different altitudes have to be treated cautiously, especially if the radar was not calibrated and echoes were not identified.

Application

To estimate MTR for different height intervals, the surveyed area of these intervals has to be determined. Because we know from an echo only its distance to the radar, but not its position within the beam, we can assign echoes only to planes of equal distance within the radar beam. These planes of equal distance are perpendicular to the main axis of the radar beam. If the radar beam is held vertically, the surveyed area of any height interval can be easily calculated. Otherwise the surveyed area is a more complicated figure (Fig. 8), because planes of equal distance are sloping. With decreasing elevation there is an increase in the overlap of planes of equal distance with adjacent height intervals. We approximated the surveyed area per height interval by multiplying the length of

the sampling unit along the radar beam (l) by the mean beam width (w) in the corresponding height interval (Fig. 8).

This surveyed area is only representative of birds flying perpendicular to the radar beam, otherwise the decrease in the surveyed area must be compensated for. We therefore calculated mean flight direction per night and 1000 m altitude classes from the tracking data. We corrected the surveyed area by the cosine of the average flight angle of the birds with respect to the radar beam. Finally, to calculate the MTR, the number of birds within each height interval (50 m) was multiplied by the ratio of the surveyed area to the reference area of 1 km times 50 m (height interval), and divided by the cosine-corrected surveyed area and the recording time. As an example of migration traffic rates, we present the altitudinal distribution of nocturnal (between 19:00 and 06:00 h) spring migration of songbirds at our study site in 2004 (Fig. 9).

DISCUSSION

Only if the radar is calibrated, echoes are identified as birds and the surveyed volume is estimated (Fig. 1) can bird migration be reliably quantified by radar. Even with calibrated radar, where small echoes, such as most insects, are excluded by a defined STC, the remaining echoes are not 'automatically' birds. At our study site in the western Sahara, insect contamination was extremely high up to 2 km above ground level during spring (Fig. 9) and also during autumn migration (our unpubl. data). Even counting only songbird echoes, but neglecting the change in the surveyed volume with distance and radar cross-section (Fig. 7), results in a significant underestimation of songbird migration at altitudes between 1 and 2 km in our example (Fig. 9). This is due to the fact that the overall surveyed volume (from low- and high-elevation fixed-beam measurements) is relatively small in this altitudinal range.

We estimated not only bird class-specific surveyed volumes, but for the first time the effective beam width as a function of the frequency distribution of radar cross-sections. This is important, as the detection range varies greatly between birds, and is highly influenced by the bird's aspect (Fig. 7). Ignoring these differences and applying a surveyed volume derived from lateral detection to high-elevation measurements may lead to an overestimation of bird densities in the vertical beam by 200–400% (Fig. 7). Differentiating between different types of birds

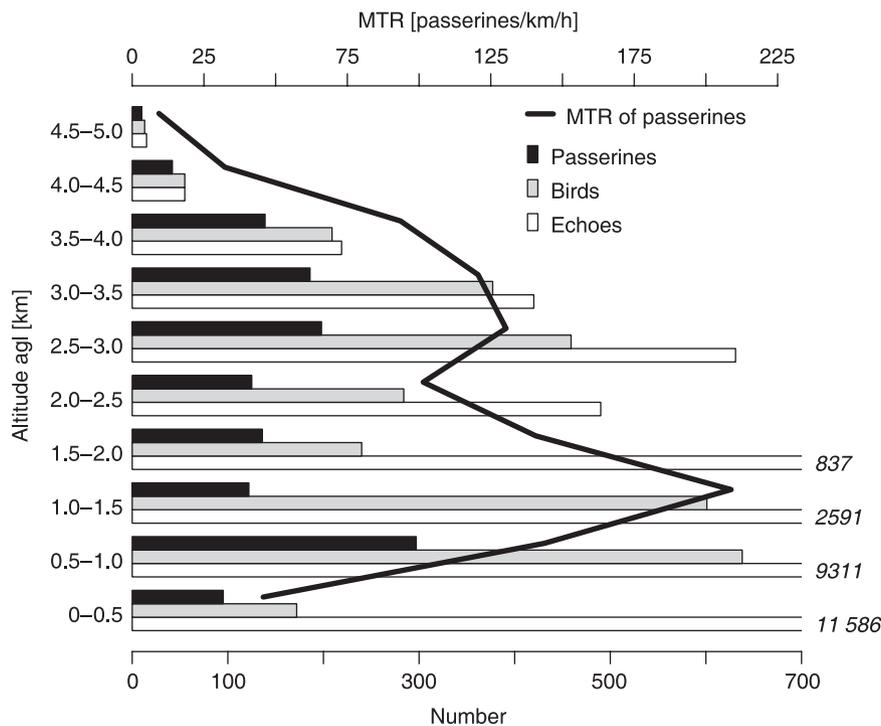


Figure 9. Altitudinal distribution of all detected echoes, echoes identified as birds and echoes identified as passerines (by their wingbeat pattern, see text for further information), and migration traffic rate (MTR) of passerines above ground level (agl). Echoes were recorded by the fixed beam sampling method and comprise birds, insects and unidentified echoes. We present here graphically only data from spring migration in 2004 to demonstrate the relationship between echoes' altitudinal distribution and actual migration traffic rates of passerines. For the sake of clarity, the lower x-axis was limited to 700 and numbers of echoes are given to the right of the truncated bars.

(passerine, wader, swift) provides not only more accurate migration intensities, but also allows investigation of differences in the temporal and spatial pattern of these groups.

The aim was to present a new and reliable procedure of how bird migration can be quantified by means of radar data. This is essential as many radar ornithologists neither considered a proper distinction between bird and insect echoes, nor correctly estimated the surveyed volume, although these two are the most critical factors for quantifying bird migration. The procedure presented here to quantify bird migration can be applied to many other radar systems, provided they are calibrated. Ship radar equipped with a parabolic dish antenna can be operated in a fixed-beam mode, which provides the ability to gather echo signatures, and thus to distinguish between birds and insects. We hope that our method will improve future radar studies in scientific and applied research.

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