NATUR
WISSENSCHAFTEN AUFSÄTZE

# The Study of Bird Migration by Radar

## Part 1: The Technical Basis*

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Since the 1960s radar has been an established research tool in bird migration studies. Radar informs us about the actual course of migration under various environmental conditions: it covers wide distances, is independent of light and reasonably independent of weather, provides data on migratory intensity, flight paths and with special equipment the wing-beat pattern of birds. It thus fills an important gap left by other methods such as visual and auditory observations, laboratory research, trapping, and ringing studies. For an appropriate use of the sophisticated tool, however, it is important to know its capabilities and limitations.

Billions of birds migrate each year between breeding and nonbreeding areas, leaving seasonally inhospitable areas. Most of them, particularly small long-distance migrants, fly at night and are seldom noticed. Many methods have been used to monitor seasonal movements. Field observers note the changing composition of bird populations in the different habitats or count the diurnal migrants when they fly along coast lines or mountain ridges or wherever they tend to be funnelled by weather and/or topography. Visual observation of migrating birds is, however, limited in distance and depends strongly on light and weather conditions.

The possibilities to record the actual passage of nocturnal migrants are even more restricted. The permanent light beams of light houses erected prior to World War II were famous for attracting birds in foggy nights and were thereby able to show at least part of the nocturnal activity [1]. Vertical light beams have been suggested for the study of low-level nocturnal migration [2]. Catching birds during migratory flights on Alpine passes is a valuable means to obtain data on the diurnal and seasonal pattern of passerine migration per species [3] and even on differential migration at the intraspecific level [4]. However, the catches comprise only birds flying at the lowest levels and are highly dependent on weather [5]. Observing nocturnal migration in front of the disc of the full moon was introduced as a scientific method and compared to flight-call counting by Lowery [6]. This comparison indicated an inverse relationship between the numbers provided by the two methods, suggesting that the auditory method is restricted to birds close to the ground while the visual method improves with the distance-dependent increase in the observation cone, up to the individually varyable visibility limits [7]. In addition, many birds call only under disturbed conditions or not at all. The advantage of the moonwatch method is that a network of

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**Electronic Supplementary Material** Digitized radar screen showing a single conical scan of a pencil-beam at an elevation angle of 400 mills (=22.5°) and a range of 200 to 6000 m. The bright points are bird echoes (see our homepage at: http://science.springer.de/nawi/nawi.htm) observers may provide a continentwide view of relative densities and directions of migration [6, 8]. Disadvantages include the small surveyed space per observer, restriction to nights around full moon with clear sky, problematic assumptions about the distribution of birds, and until recently the lack of calibration [7, 9].

The invention of radar opened a wealth of new possibilities, which were, however, often overestimated. There was a boom in radar ornithology in the 1960s, but interest in methodology faded away after the very careful review of all aspects of radar ornithology by Eastwood [10] and a thorough description of the features of bird echoes by Schaefer [11]. In contrast to radar meteorology, where significant funds were invested, and commercial interests encouraged scientific development and application (e.g., [12]), only few ornithological research groups continued to analyze the limitations and possible improvements in the fascinating new tool [13, 25, 34].

This paper summarizes (in a nonmathematical and broadly understandable manner) the principles of radar, it emphasizes the problems connected with the interpretation of variable targets such as birds, and it highlights the advantages and disadvantages of different radar types for bird detection. A brief history of radar ornithology emphasizes the most important stages in the technical development, particularly in the period after Eastwood's book [10].

## Some Basic Features of Radar

### *Exploiting Reflected Radio Waves for Target Detection*

Radar stands for radio detection and ranging, i.e., radio location. Electromagnetic waves are radiated, in most cases in the form of pulses. Parts of these pulses are scattered when the waves meet an interface with a medium having a dielectric constant different from that previously encountered. A very small amount of the scattered energy is reflected back to the radar. In the case of pulse radars the antenna used for transmission usually also receives the reflected energy. An alternating switch opens the antenna to the receiver after transmission of a short high-power pulse. Pulses in the order of 1 µs duration (corresponding to a distance traveled of 300 m and a resolution of 150 m in space, due to the two-way distance covered by the radio waves) are transmitted at a rate of about 1000/s (the pulse repetition frequency, PRF, which is lower for long range radars and higher for short range radars). For a comprehensive introduction to radar systems see [19].

### *Locating the Targets*

The distance to a target is calculated using the delay in the echo and the speed of light ($c = 3 \times 10^8$ m/s). Different antennas concentrate the microwave pulses into beams of different shapes according to the purpose of the radar. According to a rule of thumb, the beam-width in degrees (where the density of energy has declined to half of that in the center of the beam) can be estimated by dividing the wave length (cm) by 1.5 times the width of the antenna (m) in the corresponding plane. The position of the antenna provides the angular coordinates of the target, the accuracy of this information depends on the beam-width in the corresponding plane. Combined with the distance, we obtain the polar coordinates of the target.

Pulse volumes are defined by the length of the pulses (e.g., in case of a pulse duration of 1 µs the simultaneously illuminated volume has a length of 150 m) and by the opening angles of the beam in the vertical and horizontal plane. The smaller the pulse volume, the higher is the resolution of the radar. Shorter pulses and narrower beams provide better information on the target's position and reduce the probability of including several bird targets in one echo. Scanning the air space provides two- or three dimensional pictures of the distribution of reflecting objects in the volume covered by the radar.

### *The Radar Cross-Section*

The radar cross-section ($\sigma$) is a measure of the size of a target as seen by the radar and has the dimensions of an area ($cm^2$). It depends on five parameters: the dielectric constants of the target, its size, shape, aspect, and the polarization of the radar waves. Circular polarization is often used to reduce reflections from small spherical targets such as rain drops; the following considerations apply to linear polarization, which is frequently used in ornithological studies.

The propagation of radio waves within a homogeneous medium depends on only two parameters, the refractive index and the absorption constant or, alternatively, on the complex dielectric constant (for details see [11]). Scattering occurs when the wave meets a boundary between two media having different dielectric properties. The amount of scattering in-

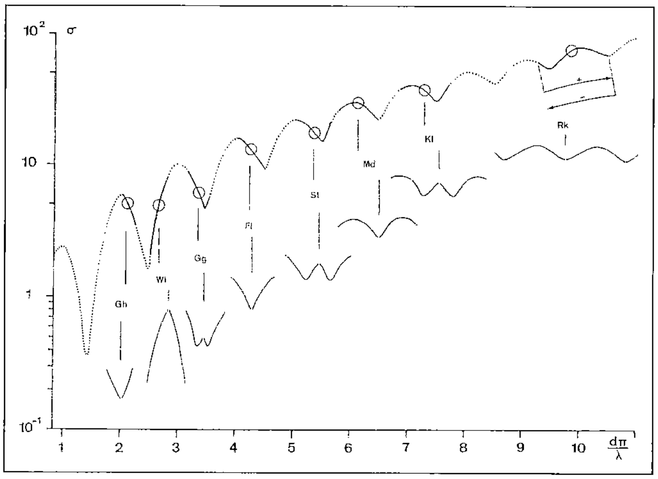


Fig. 1. Fluctuation of the radar signal in the Mie region, where the circumference of a virtually spherical target is in the order of one to ten times the wavelength. *Circles*, average radar cross-section of selected bird species for an X-band radar. *Gh, Regulus* sp.; *Wl, Phylloscopus sibilatrix*; *Gg, Silvia borin*; *Fl, Alauda arvensis*; *St, Sturnus vulgaris*; *Md, Turdus viscivorus*; *Ki, Vanellus vanellus*; *Rk, Corvus corone*. *Lines following the theoretical variation of* σ, the variation caused by the wing beats of the bird. *Graphs below each bird*, that one wing beat may cause more than one fluctuation in the signal; the probability of additional fluctuations increasing with the size of the birds. (Adapted from [14])

creases with the difference. Under special conditions even two different air masses (e.g., in an inversion layer or when hot air rises in a thermal) may lead to detectable scattering. Metals are nearly perfect reflectors because of their high conductivity, but water is also a good reflector because of its high dielectric constant. The radar cross-section of a large metal sphere corresponds to the geometrical cross-section ($\pi r^2$) while the radar cross-section of a water sphere with equal volume is 56% of it. Meteorologists dealing with small water drops are accustomed to the “Rayleigh” approximation, where the radar cross-section corresponds to 93% of that of a metal sphere of the same size. The equivalent water spheres of birds are of the size of the wavelength, i.e., in the so-called Mie region. Thus the reflectivity may be assumed to be somewhere between 56% and 90%. This uncertainty is, however, small compared to other variations of the radar cross-section (see below).

If a spherical target is large compared to the wavelength, the reflected energy is more or less proportional to its shadowing area, according to the principles of optical wave propagation (“optical region”). If, however, the target size is in the same order of magnitude as the wavelength, the relationship between echo strength and target size is less simple. If the circumference of the target is between one and ten times the wavelength (Mie, fluctuation or interference region) it is not only the specular reflection which returns to the radar but also an additional “creeping wave” which is diffracted around the target. The two waves traveling different distances interfere, increasing the radar cross-section by a factor of up to 4 when the two waves are exactly in phase and decreasing it when the two waves are phase shifted by half a wavelength due to a longer or shorter way of the creeping wave around the target. The amount of interference declines with increasing circumference of the target, fading out when specular reflection is reached at circumferences of more than ten times the wavelength. If the circumference of the target is smaller than the wavelength, the radar cross-section decreases with about the 6th power of the target dimensions (Rayleigh region, where σ is proportional $D^6$). For more information see [10, 11, 14].

The equivalent water spheres for most nocturnal migrants (passerines, waders, ducks of 10–500 g) fall into the Mie region for wavelengths of 3 cm. For wavelengths of 10 cm even very large birds of more than 1000 g are in the Mie region (Fig. 1). If the wavelength is more than 20 cm, birds below 100 g are in the Rayleigh region.

## *Wavelength*

For practical reasons, radar wavelengths λ are confined to the range between 2 m and a few millimeters. Long waves (lower frequencies) have the advantage of being less disturbed by rain; on the other hand, the dimensions of the antenna must be increased linearly with the wavelength to maintain a constant beamwidth. Decreasing wavelength (increasing frequency) implies more sophisticated technology, increasing noise level, increasing disturbance by small point targets, and decreasing range, but short waves can be directed into sharper beams by smaller antennas. Shorter waves are thus useful for mobile units, for exact location, and for detecting rain. The dependence of radar cross-sections on wavelength has important consequences for the detection of birds: if the dimensions of a point target are smaller than one-third of the wavelength, the radar cross-section decreases with the 6th power of the target circumference. The upper part of the C band (3.8–7.5 cm) and the lower part of the S band (7.5–15 cm) are optimal for small birds, while a larger wavelengths such as the L band (15–30 cm) suppress the echoes of small passerines, and longer waves may even eliminate echoes of larger birds. Wavelengths below the C band (X band = 2.4–3.8 cm), on the other hand, become increasingly contaminated by small objects such as water droplets and insects. Recent research on insects is described in [15].

## Point Targets, Volume Targets, and Clear Air Turbulence

Radar ornithologists usually deal with point targets, i.e., with discrete objects which occupy only small parts of a pulse volume, even if there are several birds or flocks of birds in the pulse. These targets usually produce well-defined echoes with steep flanks and an obvious peak. Large flocks may cover several pulse volumes and produce patches of echoes. Meteorologists usually deal with volume targets, i.e., with numerous targets distributed more or less homogeneously throughout a given pulse volume and in neighboring pulse volumes. Usually these echoes appear more cloudlike, larger, and less clearly delimited than bird targets on the radar screen.

The reflectivity of boundary layers of air masses with slightly different refractive index (e.g., clear air turbulence caused by rising air in thermals) is still the subject of controversy. Ultrasensitive radars are able to detect such small differences in the refractive index; the reflectivity of clear air turbulence is, however, several orders of magnitude smaller than the reflectivity produced by small particles drifting in these turbulences [12]. Real clear air turbulence is visible better by long waves, their reflectivity being proportional to $\lambda^{-1/3}$, while the radar cross-section of point targets increases with shorter waves according to $1/\lambda^4$ [12]. In the case of the radars normally available for ornithological research real clear air turbulence is seldom visible, while echoes of small particles in turbulent air may produce some echoes; these can, however, usually be distinguished from bird echoes by their dustlike appearance and by their movements which do not differ from wind.

## Birds as Radar Targets

The water in blood and muscles is mainly responsible for the echo produced by a bird; the reflectivity of feathers seems to be negligible [16]. For simple comparison of target size and wavelength, birds may be seen as near-to-spherical targets. In reality a bird's body is closer to a prolate spheroid, head and neck additionally complicating the shape. Edwards and Houghton [16] published scattering polar diagrams of pigeon, starling, and sparrow, showing that birds exposed to an X-band radar from different sides produce the largest echo in side view and the smallest in tail-on and head-on view, differing on average by factors in the order of 10–20 (10–13 dB), the extremes reaching 20 dB. Similar tests with other species and using two wavelengths provided general confirmation of the previous results but indicated less pronounced or even missing S band maxima at side view and more fine structured lobes in the X-band diagram [17]. Bruderer and Joss [18] measured the aspect changes in the $\sigma$ of free flying chaffinch and buzzard. Field tests confirmed the laboratory measurement of Houghton [17] with respect to the differences between the tail-/head-on view and the side view but revealed more pronounced minima at angles around 45° and 125°. The variation remained similar when small flocks were tracked.

Radar echoes of insects seem to depend rather on the size of the chitinous coat than on water contents. Even completely dry insects can be tracked up to considerable distances (e.g., a large beatle up to 1.8 km; our own unpublished data) and the broad side echo may be 10–1000 times larger than when viewed end-on [19]. This and the fact that the echo amplitude increases with diminishing range according to the 4th power law (i.e., half the distance leads to a 16 times larger echo) are reasons why insects may become quite disturbing in X-band radars, at least at short distances. Sensitivity time control (STC) may be used to reduce clutter of small targets at short ranges. For ornithologists it is important to know the effect of actual STC because it can considerably affect the detection of birds.

## Wing-Beat Pattern

The amplitude of a single bird echo usually shows rhythmic fluctuations which are correlated with the wing beats of this bird. At least in small birds the feathers and the wing stubs contribute little to the signal strength [16]. Thus it is likely that the changes in the circumference of the birds' body, caused by the extension and contraction of the pectoral muscles, the associated flexing and bending of the rib cage, and the relative movements of head and body are the major sources of these fluctuations. If observed at a wavelength in the order of bird dimensions, the changes in body shape are amplified in the echo signature by the continuous phase shift between specular reflection and creeping wave. The actual modulation may cover a range of up to ±40%, caused by a change in the diameter of the bird of only 5–10%. The relative variation in the signal decreases when its absolute amplitude increases (e.g., when a bird is first seen in head-on view and then in side view). Larger birds should produce smaller fluctuations, but it seems that the decrease in interference is compensated by increased influence of the wing stubs or by the relative movements of head and body. Thus, at least in wavelengths of 3–10 cm, the wing beats of all birds produce characteristic fluctuations and can be used to a certain extent for identification [11, 14].

The wing-beat frequency is the most distinctive feature of the echo signature [11], while the variation of flapping and resting phases is not a species-specific feature but is used by birds with intermittent beating flight (bouncing flight) to vary the vertical speed [20, 21]. Large passerines, such as thrushes, need important variation in flapping and resting phases for climbing and descending; in medium-sized passerines, such as the larger warblers, there is moderate variation in flapping and small variation in pausing phases; small passerines vary mainly the resting phases. Continuously beating crows show a clear correlation of wing-beat frequency and vertical speed [22], while no such correlation was found in waders and waterfowl, suggesting that the latter species use other means such as changes in wing-beat amplitude or wing position to modify vertical speed [21].

Bloch et al. [20] and the subsequent studies of the Swiss Bird Radar team [23] separated, in a first step, birds with continuous flapping (mainly waders and waterfowl) from those with intermittent flapping (mainly passerines). Within these main groups differently size categories were separated according to the wing-beat frequency, which is negatively correlated with wing length and size of the birds.

### Estimating Numbers of Birds per Volume of Space

The probability of detecting a target depends on the radar equation:

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

where $P_r$ is the received power and $R$ the distance between the antenna and the target. The transmitted power $P_t$ is concentrated into the radar beam with the antenna gain $G$. The density of the power decreases on its way to the target by $4\pi R^2$. The reflected energy, depending on the target's radar cross-section $\sigma$, is again reduced by $4\pi R^2$ on its way back. This two-way reduction in energy density leads to the so-called 4th power law, which says that the received power decreases with the 4th power of the distance between the radar and the target. The received energy is proportional to the surface of the receiving antenna $A$. The quality of the receiver determines the maximum range at which a certain radar cross-section can be detected. The antenna diagram (i.e., the shape of the transmitted beam) allows calculation of the distance, and the angle from the axis of the beam up to which a given cross-section provides an echo above the receiver noise level. The minimum range is given in most radars by the time needed to switch between transmission and reception.

In addition to the limits given by the radar equation, the detection probability is affected by the effects mentioned in the previous paragraphs, such as the aspect and wavelength-dependent radar cross-section, and variation in echo size caused by wing beats. The calculation of bird numbers is further complicated by different bird sizes and flocking of birds. Particular caution is needed when using special circuits such as STC (reducing echoes at short range), moving target indicator (MTI; reducing targets with low radial speed) and due to the varying detectability of differently sized birds according to distance and deviation from the center of the radar beam [13, 19]. The effect of MTI is particularly important because it eliminates mainly birds in side view (moving tangetially) while only the small echoes of birds in tail-on or head-on view pass the Doppler filter [13, 25].

## Different Radars in Ornithological Research

### Pulse Radar, Doppler Radar, and Continuous Wave Radar

Pulsed radars use the delay between transmission and reception of the pulsed radio energy to measure the distance to a target. Doppler radars measure the Doppler shift caused by the radial speed of targets relative to the radar; this enables the radar to separate moving targets from stationary objects (MTI). Doppler radar allows detection of birds even when flying over ground clutter. Its disadvantage is that an unknown proportion of bird targets is eliminated due to the fact that the echo strength is reduced by low radial speed, which is especially low when birds are flying against the wind. It is zero when birds fly tangentially to the radar. If the speed limit of the MTI is adjusted to a higher value than the speed of the birds, bird echoes are eliminated.

The Doppler effect is also used in continuous wave (CW) radars. Instead of rapidly switching between transmitting and receiving, CW radars transmit continuously and receive simultaneously. In the simplest form they measure the speed of all targets detected in the pointing direction of the antenna. When a frequency modulated (FM) signal is used, it is also possible to measure distances. These radars are used for special (rather short-range) applications, and only rarely in ornithological studies such as for some speed measurements of birds [24].

## *Different Radar Beams for Different Purposes*

Fan-beam surveillance radars (airtraffic control radars, ATC; airport surveillance radars, ASR; ship navigation radars) have beams wide in the vertical (e.g., 10°–30°) and narrow (2° or less) in the horizontal plane. Usually scanning the sky by rotating around a vertical axis, they offer high resolution in a horizontal plane but little or no altitude information. The echoes are shown on plan position indicators (PPI). Such radars provide good information on the horizontal distribution of targets. When the raw video picture is recorded by time exposure (several rotations of the antenna on one frame), time-lapse film (one rotation per frame), or electronically, ornithologists may obtain a summary of directions and intensities of bird movements. The disadvantages of such arrays are (a) the lack of height information, (b) the fact that the density of migration represented on the radar screen is strongly affected by the altitude of migration (because the density of the transmitted energy varies considerably in the vertical plane), and (c) the increasing ability of modern ATC and ASR radars to exclude unwanted targets, such as birds. The range of surveillance radars increases from the low-powered ship radars via ASR to the high-powered ATC and military radars. Modern military surveillance radars overcome many problems of the fan beam radars by combining several narrow beams in the vertical plane (stacked beam radars) and by using raw video [25]. In long-range radar displays, low-flying birds increasingly disappear behind the radar horizon at longer distances, due to the curvature of the earth.

Nodding height finders or precision approach radars (at airports) use beams which are wide in the horizontal and narrow in the vertical plain, thus providing information about altitudes by range height indicators (RHI). However, they provide less or no data on directions and horizontal distribution of echoes. Vertically and horizontally scanning radars may be combined to obtain three-dimensional distributions of echoes.

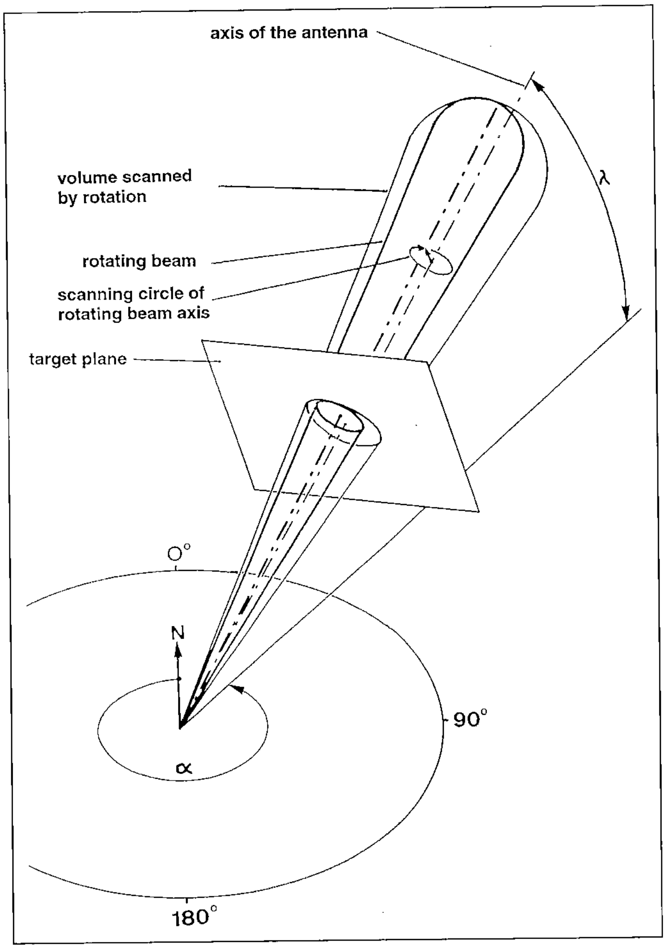


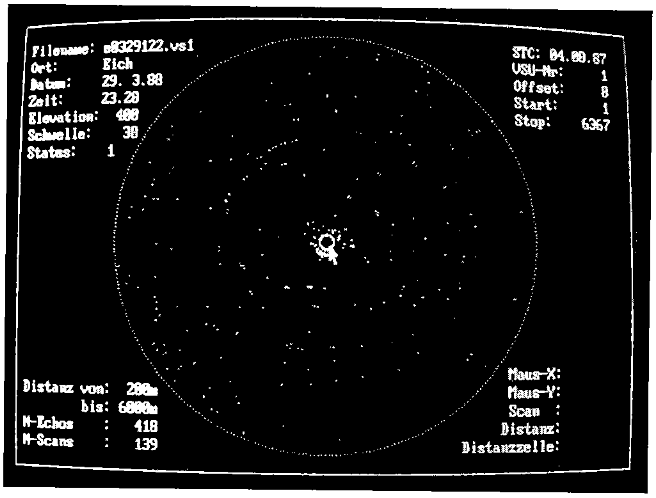
Fig. 2. Principle of a tracking radar using a pencil beam with a slight offset from the optical axis of the antenna, the beam scanning conically around the antenna axis. *α*, Azimuth, *λ*, elevation angle, and the target plane define the polar coordinates of the target. Changes in the target's azimuth and elevation angle are detected by the conically scanning beam and corrected for by movements of the antenna. The distance to the target is controlled by a moving range window. (Adapted from [20])

Single pencil beams provide three-dimensional information by subsequent scans (Fig. 2). Meteorologists use such radar beams to measure the extension and intensity of rain by weather surveillance radars (WSR) [12]. Pencil beams of tracking and other types of radar are produced by parabolic dish antennas [26]. Such pencil beams may be used as fixed beams, either pointing vertically upwards or at different elevation angles [27]. If the antenna is moveable, the beam may be used for vertical scanning perpendicularly to the principal direction of migration or for conical scanning at different elevation angles, thus providing information on the spatial distribution of birds in a half-sphere above the radar [13, 28, 29]. These radars, however, are often limited to short ranges. Another problem is that many ornithologists erroneously assume that counting echoes in such a simple beam provides direct information on the number and distribution of birds [13], thus neglecting the difficulties discussed above ("Estimating Numbers of Birds per Volume of Space").

Tracking radars are designed to track selected targets in three dimensions. Tracking may be achieved by one beam, scanning conically with a slight offset around the optical axis of the antenna or by four slightly diverging beams (monopulse radar). In each case the radar notes when a selected target moves off the overlapping central parts of the narrow beams and corrects the position of the antenna accordingly. The distance is measured by an electronic gate, moving along the beam following the target. Therefore a tracking radar provides data on the flight path in space of a tracked bird or of a pilot balloon, which informs about winds aloft [13, 27, 37]. Recording the fluctuations of the echo (discussed above) offers the possibility to obtain information on a target's echosignature, which in the case of a single bird reflects its wing-beat pattern.

## Development of Radar Ornithology

The development of radar ornithology before 1967 was comprehensively reviewed by Eastwood [10]. He showed that the first radar echoes associated with birds were flights of geese observed by a Royal Air Force station at Norfolk in 1940, using a wavelength of 1.5 m. The first evidence that bird echoes was received by centimetric radar in the United Kingdom is reported for 1941 [30]. After the introduction of high-power S-band surveillance radars in 1943, "angels" became a normal feature on the radar screen. Pioneering studies in Switzerland [31, 32] and the United Kingdom [33] opened the way for broad application of surveillance radars in ornithological research in the 1960s. During the following decade surveillance radar have been used for ornithological studies all over the world, but usually with low emphasis on methodological improvements. The usual methods have been time-lapse filming and time-exposure photography [34]. An innovation was announced by Clausen [35], who suggested electronic counting of bird echoes. This was pursued consistantly by the Royal Dutch Air Force in favor of bird



Filename: e8329122.vs1
Ort: Eich
Datum: 29. 3.88
Zeit: 23.28
Elevation: 400
Schwelle: 30
Status: 1

STC: 04.00.87
VSU-Nr: 1
Offset: 8
Start: 1
Stop: 6367

Distanz von: 200m
bis: 6000m
N-Echos : 418
N-Scans : 139

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Fig. 3. Digitized radar screen showing a single conical scan of a pencil-beam at an elevation angle of 400 mills (= 22.5°) and a range of 200–6000 m. The bright points are bird echoes

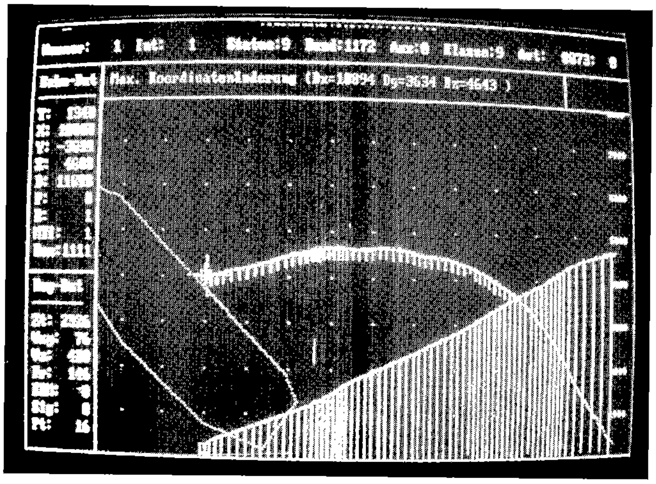

Fig. 4. Computer screen showing the horizontal and vertical projection of the flight path of a wind-measuring balloon. *Vertical marks*, intervals of 20 s, visualizing the speed of the target, which in another case may be a bird. The grid of points indicates squares of 1 km sidelength

strike reduction and materialized in the Radar Observation of Bird Intensity (ROBIN) system [25].

A different line was initiated by the use of narrow beams tilted vertically upwards or scanning the sky conically or vertically [28, 29, 37]. The vertical beam method (complemented by a beam at low elevation angle to cover the lowest 100 m over ground which is not shown by the vertical beam due to minimal range limitation [27]) and the conical scanning method [13] have been used extensively by the Swiss Bird Radar Team (Fig. 3).

An unpublished presentation by Schaefer at the 14th International Ornithological Congress marks the start of tracking radar studies [10, 11]. This has been taken up mainly in Switzerland, where the tracking radar Superfledermaus was combined with specially adapted recording equipment, continuously improved to provide data on the temporal and spatial variation in the numbers and distribution of birds and on their flight behavior. Important steps in this development are target identification [14, 18, 38, 39] and digital recording of echo signatures and flight paths [13, 20] (Fig. 4).

A new system of weather radars, termed the Next Generation Weather Radar (NEXRAD) was designed to identify dangerous and economically significant weather phenomena automatically over large parts of the United States. Possibilities for using this high-powered S-band Doppler radar with 1° pencil beam for monitoring bird migration were investigated in view of automatical warnings to pilots of potentially hazardous bird movements [36]. Conical scanning from 1° to 15° at steps of 1° provides information on horizontal and vertical distributions of targets, and Doppler shifts provide information on radial speeds. The large number of radars to be installed in the 1990s may provide a continentwide view of migratory activity. The low-resolution capacity, circular polarization, and other specifications leading to a notable reduction in bird targets will, however, impose limitations on the ornithological use of this system.

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