Adapting a military tracking radar for ornithological research – The case of the “Superfledermaus”

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This is an extended summary of a presentation given at a USGS-USFWS sponsored workshop on “Applying Radar Technology to Migratory Bird Conservation and Management”. It reviews the main steps of the historical development of dedicated bird radar, starting with military tracking radar. Thus, it provides the historical background for the “Swiss Bird Radar”. It aims at providing access to the cited original publications, which can be ordered from the Swiss Ornithological Institute (www.vogelwarte.ch/publikationen.html) or from the author (bruno.bruderer@vogelwarte.ch).

The “Superfledermaus” and its use in ornithology

Over the last 38 years the German word „Superfledermaus“ has become a well-known term in radar ornithology. This terms stands for a military tracking radar that is housed in a 5 t trailer with attachable tent (or container), and is characterized by 3.3 cm wavelength, 150 kW peak pulse power, 0.3 µs pulse length, and a pencil-beam with a nominal width of 2.2°. Automatic tracking is achieved by the beam conically scanning at a rate of about 30 Hz and with an offset of 1° around the optical axis of a parabolic dish antenna, and a distance gate locked on the target. The nominal tracking accuracy is 0.06° in azimuth and elevation, and ± 10 m in distance. Minimum distance for detection is about 100 m, maximum range for tracking a single Chaffinch *Fringilla coelebs* in tail-on view (i.e. with minimal radar cross-section) is 4 to 4.5 km. Used in a fixed beam mode (and with improvements on the receiver side, see below), the maximum range increases to 7 km for small passerines seen from below or from the side.

Produced by the company Oerlikon Contraves AG, the “Superfledermaus” became the standard radar for tactical air defense in the Swiss Army from 1963 onwards. For military surveillance, the radar could either cover a chosen sector by rapid vertical scanning, or it could use the so-called “helical searching”, the beam rotating like in airport radars, but scanning different elevation angles in a sequence of rotations, thus providing additional height information. It was equipped with MTI (Moving Target Indicator for electronic clutter reduction) from 1969 onwards, and was gradually replaced by the „Skyguard“ radar after 1975. In ornithological research the radar was used without MTI whenever possible. This in order to avoid reduction of targets with low radial speed, and thus implicitly restricting detection to targets exposing reduced radar cross-sections to the radar (when flying towards the radar or away from it). To screen the radar off against ground clutter, a natural or artificial hollow with ideally 30 to 40 m radius and an altitude of the surrounding dam of about 2.5 m was required. The radar remained the same over the years; only a few modifications were implemented to improve performance for ornithological research. The main modification (in the mid 90-ies) was the replacement of the IF-Preamplifier and the additional installation of a Log-Amplifier for precise measurement of radar cross sections. Both amplifiers had improved stability compared to the original ones. The main development occurred with the improvement of the recording system.

From the beginning of ornithological work in 1968, the radar was used for the acquisition of three types of data: (1) Data on the quantity and spatial distribution of migrating birds over time, (2) data on the flight paths of tracked birds and wind-measuring balloons; the latter providing information on winds at the altitude of bird flight and allowing calculation of headings and airspeeds of tracked birds, (3) echo-signatures of tracked targets providing information of the amplitude variation of the echoes, and thus allowing target identification, including wing-beat pattern of birds.

The present paper uses the historical development of the “Superfledermaus” to demonstrate the most important steps of methodological improvements over time, referring to available publications for technical details, and avoiding reference to ornithological results. A methodological overview including other radars is available in Bruderer (1997a), a summary of major achievements of radar ornithology since the book of Eastwood (1967) in Bruderer (1997b). For reviews of our research in the area of the Alps see Bruderer (1996), for the studies in the Middle East consult Bruderer (1999) and Bruderer et al. (2000), data on migration in the western Mediterranean are summarized in Bruderer and Liechti (1999)) and Bruderer (2001). Note that the studies with tracking radar were combined with other methods throughout. These methods comprised airport surveillance radar, moon-watching, infrared observations, orientation studies with caged birds, banding, taking physiological data of caught birds, and studies on flight mechanics (e.g. using wind-tunnel experiments). The basic methodological outline of the ornithological use of the “Superfledermaus” is given in Bruderer (1971). Major technical progress is included in Bloch et al. (1981)), Bruderer et al. (1995), Liechti et al. (1995), (Schmaljohann et al. in press).

Major steps of methodological development

1968 - 1970:
Quantification of passage was done with a vertical beam and an additional low-elevation beam (perpendicular to the principal direction of migration), this to cover the dead zone in the first 100 to 150 m of the vertical beam. In a first approach, the echoes appearing above an STC-threshold (adjusted approximately to the fourth power law) were counted by eye on the R-scope and recorded orally on tape. In a second approach, we used a continuously moving film to record the Z-modulated R-scope. Thus, we obtained filmstrips showing 4 km range on the y-axis, and time on the x-axis (Bruderer 1971; summary in Bruderer and Steidinger 1972). – Our first method to obtain *flight paths* was to take photographs of the radar instruments showing the three polar coordinates of a tracked target every 30 seconds, with the date, a running number for each object, and the time as additional information on each photo. Data analysis occurred by punching the data on punch cards and calculating the flight path (of birds and wind-measuring balloons) with one of the big computers used at that time (Bruderer & Steidinger 1972). – For the *recording of wing-beat pattern* we modulated a carrier frequency of 400 Hz with the amplitude of the automatic gain control. Thus, we were able to record the fluctuations of the echoes while tracking a target, and could actually hear the wing flapping of the birds. This allowed us not only to separate insects and birds, but also to distinguish singly flying birds, two birds, and groups of more than two birds, thus providing information on changes in flocking behavior in the course of the day. We could also show that passerines are characterized by intermittent flapping, while echoes with continuous fluctuations mainly represent waterfowl and waders (Bruderer 1969, 1971, Bruderer & Steidinger 1972). In similarly shaped birds the wing-beat frequency decrease with increasing size. A special study was dedicated to calibrate the radar by tracking metal spheres of various diameters and to show the variation of birds’ echo sizes with changing aspect (Bruderer and Joss 1969).

1971 – 1980:
In order to increase the space under surveillance for the *quantification of migratory passage,* we started an experiment, using photo recording of the range-height indicator, the radar beam vertical scanning in a plane perpendicular to the principal direction of migration. A rough analysis of the data showed, however, too many limitations of the new method (Bruderer 1980). We never proceeded to a serious scientific analysis of data and didn’t use this method later on. But note that many of the new ship radar studies are based on this method (with additional problems imported by using fan beams). – Improvement of *flight path record-*

ing was achieved by a multiplex-pulse-length modulation of the Cartesian coordinates provided by the computer of the radar. This allowed recording of the flight paths on the second track of the audiotape containing the echo signatures on the first track. For the analysis, track data and echo signatures had to be decoded, thus being transformed into to simple electric signals proportional to the echo amplitude and coordinates, respectively. These signals were on the one hand visualized on one- or three-dimensional plotters, on the other hand transferred to an analogue-digital-interface and analyzed in an IBM 3033 computer. For details see Bloch et al. (1981). – The *interpretation of echo signatures* was improved by recording tracked birds and their echo signatures simultaneously on the video and audio track of a video camera, and by using Fourier transformation to determine wing-beat frequencies (Bloch et al. 1981). In order to increase the number of known wing-beat patterns, birds were released in front of the radar, then tracked visually by the operator sitting next to the antenna, and handed over to the radar operator for automatic tracking before they disappeared from sight (Bruderer et al. 1972). At night the released birds were made visible for optical tracking by the luminescent substance "Cyalume" (Bruderer and Neusser 1982), first by smearing the substance to the tip of the tail feathers, later by fixing a Cyalume-filled gelatin capsule to a thread and gluing the other end of thread to the base of the tail. – A radar study at an Alpine pass in 1974/75 marks the starting point of a long-term scientific program on the influence of ecological barriers on bird migration. At this site we released not only birds for identification but also some bats; an analysis of the data was, however, only envisaged after a request from outside (Bruderer and Popa-Lisseanu 2005).

1981 – 1990:
This was the main period of *radar studies in and around the Alps* (Bruderer 1996), characterized by the combination of various methods on the same subject (Bruderer and Jenni 1990). This decade was also the main development phase of mini- and microcomputers. In 1982 synchro-digital converters were connected with the instruments of the radar to digitize directly the polar coordinates given by the position of the antenna and the distance gate. These were first recorded on tape and later analyzed in our first PC. In the following year on-line transmission to the PC was possible. For the studies in the approach area to the Alps in autumn 1987 we had at our disposal *a fully computerized recording system* based on an interface sampling the data provided by the radar, and transmitting them to a PC. Flight path data as well as conical scans of the radar beam could be presented on the computer screen. One year later, on-line presentation of echo signatures on the computer screen became possible. The tracks and echo signatures were also visualized on the traditional plotters as back-up (Bruderer et al. 1995). – Conical scanning at several elevation angles was chosen as the new standard method to measure the *number and distribution of birds* in a half-sphere of 6 km radius around the radar. Migration traffic rate MTR to be calculated by multiplying the density (birds/km^3) by the average ground speed. The paper by Bruderer et al. (1995) explains the procedure of data recording and analysis. In particular it shows quantitatively the effects and the compensation of variations in detection probability with distance, elevation angle, and aspect. Considering this paper when intending quantification of bird migration will help to reduce negligent interpretation of radar data, which unfortunately became too frequent with the off-the-shelf availability of cheap ship radars in recent years.

1991 – 2000:
This decade was devoted to *radar studies in the eastern and western Mediterranean*. It comprised also the first applied project, an environmental impact study for a planned antenna array of Voice of America and Radio Free Europe in the Arava Valley (Israel), leading eventually to a remarkable scientific output (Bruderer 1999, Bruderer et al. 2000). Progress with respect to the *quantification of bird migration* comprised the use of a mathematically exact STC to compensate for the R^4-law up to 3 km range. Two radar stations, one on the Negev Highlands, the other in the Arava Valley, showed that an ideally constructed dam around the radar could efficiently eliminate ground clutter (photos in Bruderer 1999, Bruderer et al. 2000). An important step forward consisted in the use of an efficient long-range infrared system (LORIS IRTV-445L, Inframetrics Massachusetts), allowing to cross-calibrate the three

counting systems radar / passive infrared / and moon-watching (Liechti et al. 1995). Directing all three against the moon allowed us to determine the detection range of the two optical systems by radar (roughly 2 km for the moon, 3 km for the infrared, good visibility). On the other hand we could show that the operational opening angle of the radar beam within these distances was about twice the theoretical beam width. Mounting the passive infrared parallel to the radar antenna and tracking birds temporally with this device allowed to switch off the radar transmitter during short periods and thus to show that switching on and off the transmitter did not alter the flight paths of tracked bird, while a strong spotlight had a considerable influence on the flight behavior of the tracked birds ((Bruderer et al. 1999)). A new presentation of *flight paths and wing-beat pattern* (figure in Bruderer 1999) was another step forward. – Towards the end of the decade we compared the passage of migrants across the Balearic Islands and the Iberian Peninsula (Bruderer and Liechti 1999). The main progress on the technical side was the development of a control program for the radar, allowing automatic searching, target selection, and tracking by the radar (thus avoiding personal bias by the operators). – The interpretation and application of *tracking data and echo signatures* continued with a comparison of the flight behavior of swallows in a wind tunnel and in free flight (Liechti and Bruderer 2002). A first publication on the flight characteristics of birds (Bruderer and Boldt 2001) dealt with radar- measured speeds. A second publication following in 2007 will deal with wing-beat frequencies.

2001 – 2006:
After having dealt with the barriers of the Alps and the Mediterranean Sea, it was nothing but consequent to continue with the *Sahara*. The design of the project on bird migration in the western Sahara (Mauritania) comprised two fixed and one mobile radar stations, one of the fixed stations at the coast, another one 500 km inland, the mobile radar moving from the coast about 800 km inland. *The mobile radar* consisted of a transmitter-receiver system of the “Superbat” and the antenna moving in the vertical plain only. At the cost of loosing the tracking capability, the weight of the array was reduced to less than one ton, and the power consumption to about 1 kW, the whole array together with the recording system mounted on a 7t truck. This mobile radar was one reason to revive the old fixed beam method. Another reason was that the operational range for birds increases from about 5 km in the scanning mode to about 7km with the fixed beam due to more hits per target and improved data recording and processing techniques. For the *quantification of bird migration* in the Sahara we continued on the one hand with our established conical scanning method at the fixed radar stations. In parallel we applied the fixed-beam method, but now with fully computerized recording, at the fixed stations as well as on the mobile radar. The fantastic thing compared to the earlier photo recording is, that each target passing through the beam provides its wing-beat pattern. The scanning rate along the beam is 130 Hz, sufficient to detect even high wing-beat frequencies. For each chosen target, the wing-beat frequency is automatically extracted by fast Fourier transformation, and provided on the computer screen (Zaugg et al. 2007). – Note that even in the desert the radars as well as the recording systems were regularly calibrated.
The calculation of MTR runs automatically: STC compensation for the R^4-law is done mathematically in the computer, in the standard case up to 3 km (but adjustable if needed). A subsequent computer program detects all remaining targets and extracts a number of variables for each target. These variables are fed to program that runs a discriminant function analysis and differentiates between birds, insects and “other signals”. The bird targets will be extracted for further use and afterwards corrected for distance, elevation and aspect as shown (above) for the conical scanning method (Schmaljohann et al. 2008).

Quantification of bird migration by fixed pencil-beam radar

1) We need calibrated radar. We need to know what the radar detects.

2) Energy reflected from various objects is detected by the radar according to the critical signal-to-noise ratio of the system and the equally critical filtering systems of the radar (e.g. STC, clutter reduction by MTI or other means).
3) A threshold defines which echo amplitudes enter our sample and are transferred as blips to the radar screen or as pixels to a digital unit.
4) An STC (compensation for the R^4-law) is applied to this sample. In the computer the amplitudes per recording cell are transformed into dB-values. The result is standardized echo sizes.
5) At this stage we exclude permanent clutter by some sort of clutter mask, and eliminate variable clutter (e.g. rain clouds) interactively.
6) The next step is echo identification, discriminating birds and insects, assigning bird echoes to bird classes, and measuring the size of each echo.
7) Quantification then starts with defining the recording area per echo size, based on the known antenna diagram and the empirically established detection range per echo size and elevation of the beam. This includes implicitly the earlier distance correction. Estimating the frequency distribution of different echo sizes provides the possibility to define a mean detection range across the size classes (if not, one defines a mean detection range over all echoes).
8) The next step considers aspect variation with flight directions.
9) Dividing the echo numbers recorded per unit time and distance-interval by the width of the recording area in the interval considered, provides us with birds passing in one hour a recording surface of one km^2 (i.e. a migration traffic rate per height interval in each beam-elevation). Combination of the results from all elevations results in migration traffic rates per height zone.
10) Dividing the MTR (given in bird passage per hour and recording area of 1 km^2) by the ground speed provides densities (i.e. birds per km cube).
11) In case of conical scanning, the outcome of the measurements is bird density (birds/km^3), which has to be multiplied by average ground speed to obtain MTR for height zones of 1 km. Summing up all height bands results in total MTR.

Possible applications

After successful application of our radar and recording system to estimate the potential impact of a huge antenna system of Voice of America and Radio Free Europe in Israel (Bruderer et al. 2000), the system was recently used to study the potential effects of a planned off-shore wind turbine park in the Baltic Sea on Crane (*Grus grus*) migration. Other wind turbine projects are envisaged. In this context it is important to note that our system can provide the flight paths and spatial distribution of bird migration in the area of a planned turbine project, as long as the observations are not too severely impeded by surrounding obstacles (e.g. by mountains along a narrow valley). It can, however, not provide flight paths of birds flying through a wind park or passing a single turbine at distances of less than 100 m. It is therefore not a valid tool to see the reactions of single birds in the immediate vicinity of turbines. The same is true with respect to other obstacles. A recent study to estimate the potential impact of a large bridge on bird migration provided the percentage of birds theoretically colliding with a structure of the bridge. After construction of the bridge it would, however, not be possible to document flight paths within the immediate neighborhood of the bridge.

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Suggested citation:

Bruderer, B. (2007): Adapting a Military Tracking Radar for Ornithological Research – The case of the “Superfledermaus”. In: Ruth, J.M. (ed.) Applying radar technology to migratory bird conservation and management: strengthening and expanding a collaborative: Fort Collins, Colo., U.S. Geological Survey, Biological Resource Discipline, Open-File Report 2007 – 1361: pp. 32-37.