The Radar Window to Bird Migration

Bruno Bruderer[1]

1 Introduction

The history and methodology of radar ornithology was comprehensively reviewed by Eastwood (1967) and updated by Bruderer (1997a). The present chapter gives an outline of the possibilities and limitations of the method, summarizes the main fields of research, and indicates recent achievements as well as chances for the future.

Radar and satellite tracking are the tools to fill the gap between ringing recoveries and visual observations. Satellite tracking deals with small samples of large birds on a continent-wide scale, while radar inlcudes large samples of any size of birds over ranges of 0.1-100 km. Radar resembles visual means, such as light amplification, infrared, moon-watching or ceilometers, but is independent of light, less dependent on weather, and normally less restricted in distance covered. Its capability to show the distribution of targets in space, to measure distances, altitudes, directions, speeds, and in some cases also to detect wing-beat patterns made it a key instrument to study the flight behaviour of free-flying migrants and thus an essential counterpart for research dealing with birds on the ground and in laboratory experiments.

Disadvantages compared to the visual systems are due to the relatively long electromagnetic waves used, which make it difficult to concentrate the radiated energy into well-defined beams. Therefore, backscatter from the ground produces disturbing echoes (ground clutter), and the vague definition of the surveyed space poses problems to quantitatively estimating densities of migration.

2 Types of Radar - Capabilities and Limitations

Two basic types of radar beams have been adapted for specific - usually non-ornithological - tasks. Their suitablity for migration studies is briefly summarized; for further details and references see Eastwood (1967) and Bruderer (1997a).

[1] Swiss Ornithological Institute, 6204 Sempach, Switzerland, e-mail: bruno.bruderer@vogelwarte.ch.

P. Berthold, E. Gwinner, E. Sonnenschein (Eds.)
Avian Migration

2.1 Fan-Beam Radars

Fan-beam surveillance radars (airport surveillance radars and air traffic control radars) have beams wide in the vertical (e.g. 10-30°) and narrow (2° or less) in the horizontal plane and cover the medium to large radar distances. Scanning the sky by rotating around a vertical axis and presenting the result on plan position indicators (PPI), they offer high horizontal resolution, but little or no altitude information. The density of migration appearing on the PPI varies with flight altitude due to varying sensitivity within the fan beam. Recording several consecutive scans provides flight directions and speeds. Due to increasing use of electronic niters to exclude unwanted targets, the suitability of such radars for ornithology is declining. The problem of ground clutter is severe. Moving targets indicators (based on Doppler effects) help to reduce ground echoes, but they also reduce moving targets with low radial speed.

Ship navigation radars are usually short-range (0.1-5 km) surveillance radars; for small birds the range is usually below 1 km. These radars, produced in large numbers, came mainly into discussion because of their low costs. The beam rotates around a vertical axis. Currently, ideas are being developed to let it rotate additionally around a horizontal axis in order to obtain vertical scans. Calibration and ground clutter are persisting problems.

Nodding height finders use beams which are narrow in the vertical plain and wider in the horizontal plain; swinging up and down, they provide altitude information on range height indicators (RHI).

Stacked beam radars: modern military surveillance radars combine the advantages of fan-beam and pencil-beam radars by several pencil-beams arranged in the vertical plane; and they use raw video. The Royal Dutch Air Force has developed an electronic recording system providing a large scale view of directions and speeds in two altitudinal zones (Buurma 1995, 1999).

2.2 Pencil-Beam Radars

Pencil-beam radars in general have better-defined antenna diagrams than fan-beams and are therefore easier to calibrate and less exposed to ground clutter. Pencil-beams provide three-dimensional data, the accuracy of the information depending on the pulse volumes used, which, in turn, depend on the pulse length, working distance and beam-width.

Weather radars are designed for long-range conical scanning at various elevation angles, using narrow beams and long pulses. Within the limits of the resulting low resolution they inform on horizontal and vertical distribution of reflecting material. Directions and speeds (of multitarget echoes in most cases) can be derived from consecutive scans or from radial speeds based on Doppler shifts. Quantification of migration is difficult.

Pencil-beam radars/or ornithology: in the 1960s, it became clear that radars with short pulses and narrow beams would provide the best data on bird movements, in spite of restrictions to relatively short ranges. Used as fixed beams or scanning vertically, they show the altitudinal distribution; applied over time they reflect the spatial distribution of migrants. Conical scanning at various elevation angles provides echo densities from a half-sphere. Cross-calibration with visual methods such as infrared recording parallel to the radar beam is possible (the radar providing the distances, infrared a clearly defined beam). Pencil-beams are particularly apt to study singly flying nocturnal migrants, while the mixture of various flock sizes and singly flying birds during daytime poses quantification problems (Bruderer 1999; Bruderer et al. 2000). Recent developments allow recording of echo signatures from fixed beams. The cheap marine radars mentioned above have also been modified into pencil-beam radars by mounting parabolic dish antennas. Biebach et al. (2000) improved such a system by increasing power output and mounting a dish antenna of 1.2 m diameter. As most of these radars use X-band (3 cm wavelength), they are affected by rain and contaminated by insects. In the Swiss system, most insect targets are excluded by sensitivity time control (STC).

Tracking radars are pencil-beam radars designed to track selected targets and to provide their flight path data. Recording the target's echo signature allows multi-target echos from single birds to be distinguished, and in the latter case to detect the birds' wing-beat pattern.

Wind-profilers: a new type of highly sensitive radars is currently being introduced to measure continuously the vertical profile of winds up to heights of more than 5 km (Kretzschmar 1998). Unfortunately, the initial intention of rapidly equipping many airports and meteorological stations with these radars has been slowed down, due to problems among others with bird echoes obscuring the wind data. Eliminated bird echoes might, however, be diverted to bird-sampling units and used for ornithological research. Installed over large areas and made available for coordinated analysis, the system could result in a quantitative tool for a continent-wide surveillance of bird migration.

3 Radar Information on Bird Migration

Eastwood (1967) provided a comprehensive review and Bruderer (1997b) an up-date of radar achievements in ornithology. To keep the present chapter within the limits, I resume the thread of the latter publication, draw the main conclusions, show new developments, and provide recent examples.

3.1 Geographical Patterns of Migration

3.*1.1 Flapping and Soaring Migrants, Diurnal and Nocturnal Migration*

Large birds using the soaring and gliding strategy tend to aggregate where rising air provides lift or where off-shore flights would deprive them of thermal updrafts. Surveillance radar photos from Israel (Leshem and Yom-Tov 1998;

Leshem 1999) show lines (sometimes up to 90 km long) of thousands of soaring migrants progressing SSW parallel to the coast, the lines moving inland with the sea-breeze front during the diurnal cycle.

Large birds capable of sustained powered flight enjoy more freedom in the choice of time and route at the cost of higher energy consumption. Nocturnal flights become possible, and flights across the sea less risky (recent examples in Spaar et al. 1998 and Meyer et al. 2000). Water birds migrate day and night; flight altitudes differ according to the time of day and between flights over land and over water. Adjustments of the general flight directions to coastal areas have been observed in waders and water birds. Medium-sized diurnal flapping fliers like woodpigeons usually fly high and, on surveillance radars, provide good examples of diurnal broad-front migration concentrating at coastlines.

Small diurnal flapping fliers pose problems to radar observations, as large proportions fly low. As surveillance radars show mainly high broad-front migration favoured by following winds, while low-level visual migration appears most intense in opposing winds and when drifted towards leading-lines, pencil-beam radar and visual means should be used in parallel. A striking example of simultaneaous broad-front migration in three directions combined with narrow-front migration across the narrows and island along the Dutch coast is shown by Buurma (1995).

3.1.2 Large-Scale View of Directions and Densities

A network of surveillance radars is a powerful tool to show differences in directions over large areas, e.g. according to winds behind and ahead of frontal systems (Richardson 1971). Richardson's early suggestion to use such possibilities on a wider geographical scale was not followed until the installation of the weather surveillance radars WSR-88 all over North America. Gauthreaux and Belser (1998) demonstrated the potential of the system, and presented (Gauthreaux and Belser 1999) first ideas for its application to the question of trans-Gulf migration. In Europe, for want of anything better, intensive use was made of subsequently or independently acquired data from many sites, often using small radars at strategic points and combining heterogeneous information from various sources such as surveillance radars, infrared, and moon-watching. This mosaic of data resulted in a reasonably good general view of migratory directions and rough density estimates (Bruderer and Liechti 1999; Bruderer 2002).

3.7.3 *Migration Across Large Ecological Barriers*

The most impressive examples of barrier crossing are the transocean flights of waders and some water birds (Williams and Williams 1999). Regular and widespread ENE migration, mainly of waders, from NE Siberia seem to follow orthodrome-like routes based on sun-compass orientation, reaching North American stopover sites after 1000-2500 km flights (Alerstam and Gudmundsson 1999a). After continuing to the Atlantic coast of North America they will, supported by favourable winds, fly over 3000 to 4000 km to the Caribbean and South America. Such long-distance flights over water or large ice caps are part of the normal migratory behaviour of waders, and occur also in waterfowl and some passerines. Yet, the quantitative importance of transoceanic flights in relation to land-bound migraton still needs to be clarified.

Great challenges for radar research are the barriers across the main fly-ways between or within continents on the N-S axis, such as the Gulf of Mexico and Caribbean, the Mediterranean-Sahara complex, the Himalayas and the SW-Pacific route between SE Asia and Australia. All of them require specific strategies for crossing which are far from being understood. One of the basic tasks is to define the difference in the intensity of migratory streams prefering shortest routes across vs. detours in favour of more safety. Another important subject is the proportion of intermittent vs. non-stop flights across barriers with resting possibilities. Recent radar studies allowed calculation of the recruiting areas of birds arriving on the Balearic Islands and the Andalu-sian coast, based on their arrival time, measured groundspeed and arrival directions (Bruderer 2002). These data show that birds arrive in equal numbers from the North African coasts and from areas further inland, particularly from the Highlands of the Chotts and from large wadis in the Atlas Mountains.

3.1.4 Broad-Front Migration and Concentrations

Radar has confirmed that most migration occurs on broad fronts as long as there are no important advantages of concentrating. The directions within such fronts may be astonishingly homogeneous as long as atmospheric and topographic disturbances are negligible. An impressive example of two homogeneous fronts merging in The Netherlands shows one cohort arriving across the North Sea with SSW directions, while the other moves SW above Holland (Buurma 1999). Similarly, in Israel, the main stream of nocturnal migration is parallel to the coast, while high-density broad-front migration across the sea arrives after midnight from Cyprus and Turkey, shifting southward after crossing the coastal strip (Alflya 1995).

Many radar documents are available on directional shifts and concentrations when birds approach a coast or a mountain ridge, deviations often increasing with opposing winds, cloud cover, and particularly with decreasing flight levels (see Williams et al. 2001 for a recent example). Bruderer and Liechti (1998) observed a temporal shift in directions at a coast, based on increasing reluctance to fly off-shore with the progress of the night, leading to birds adjusting their directions along the coast. This was confirmed by infrared observations at various coasts with differing directions (Fortin et al. 1999).

3.2 Density and Timing

Radar is the best tool to study the temporal variation of migration, as long as the limitations of the tool are taken into account. For high-quality studies high-resolution pencil-beam radars are needed.

3.2.1 Diurnal Variation

Takeoff from islands with a restricted population of resting birds allows the duration of takeoff to be studied. On Mallorca, the start of nocturnal migration was on average already 13 min before sunset due to important nearby resting sites of waders. The main rush of passerines followed about half an hour, the peak about 50 min after sunset and ceased on average 200 min after sunset (Bruderer 1999). The question of some further takeoffs later at night - as suggested by other methods - remains still to be solved, because on Mallorca the few birds involved may easily have been overlooked within the normal background noise of other targets, such as roosting swifts, other local birds, bats and large insects. In areas with continuous influx of migrants, intensity declines during the second half of the night and fades out towards sunrise, while diurnal migration in temperate areas starts around dawn. In the deserts of Israel a pronounced gap between nocturnal and diurnal migration proved the lack of non-stop passerine migration in this area (Bruderer 1999). Non-stop migration is suggested for birds flying at dawn over habitats unsuitable for resting, e.g. for land birds over water. For birds flying over land, different strategies are possible and behaviour may vary according to species and environment. Continuation of migration into the day was observed in wading birds above the deserts of Israel, particularly with favourable winds (Bruderer 1999). Biebach et al. (2000) identified three types of migrants in the western deserts of Egypt: (1) a (relatively small) day group arriving across the sea, continuing non-stop into the desert, (2) a night group, landing in the coastal strip and taking off for a night flight next evening, (3) an evening group resulting from birds having rested in the desert. It remains a challenge for further studies to define the proportion of migrants using non-stop vs. intermittent migration strategies under varying environmental conditions in the Sahara.

3.2.2 *Day-to-Day Variation*

Recent studies confirm that maximum numbers of passerines are migrating with fair weather and weak or following winds. Such conditions occur in the Northern Hemisphere when a low-pressure area is to the left and/or a high-pressure area to the right of the main vector of migration. Erni et al. (2002) were able to explain 70% of the day-to-day variation of nocturnal migration by a log-linear regression model including variables for actual wind, rain, previous precipitation (to account for bird accumulation) and the general seasonal trend. In the western Mediterranean, weather influence on migratory intensity is reduced, in the trade-wind zone (in southern Israel) it is nearly lacking due to relatively weak variation in weather and favourable winds nearly always available at some height (Bruderer 1999).

3.2.3 *Variation Between and Within Seasons*

Data on full seasons and particularly on spring and autumn migration at the same site are rare. Quantitative data are available for Israel, the western Mediterranean and some places in central Europe. In Switzerland and in Israel migratory passage is reduced in spring compared to autumn. In Israel the question is open whether the 40% reduction is due to mortality during winter or to part of the birds taking different routes in spring. In Switzerland it is obvious that migration is concentrated along the Alps in autumn, while in spring the narrow entrance between the Alps and the Jura mountains deviates the main stream of migrants around Switzerland (Bruderer 1999).

3.2.4 *Long-Term Variation*

Long-term monitoring is possible if the same radars can be used with the same performance over long times. This is difficult because development in electronic equipment is fast. We would need a dedicated bird radar for which maintaining standard conditions has priority over development.

3.3 Altitude of Migration

Radar is the tool of choice to study the altitudinal distribution of bird migration. The height zone in which most migrants fly comprises levels up to 4000 m a.s.L, the distribution being skewed towards the lower levels and modified by winds and topography. New measurements from the Arctic confirm these general features, but show higher average flight levels (1.3 km) than in central Europe, and scatter up to heights of 4.8 km. Long-distance nights across high mountain ranges or where favourable winds prevail at high altitudes may take place at the upper end of this zone (e.g. autumn migration across the western Atlantic, and spring migration over the deserts of Israel). Spring migrants reached heights of 5000 to almost 9000 m a.s.l. and ground speeds of up to 50 ms^{-1} in low-level jet streams above southern Israel (Liechti and Schaller 1999). Spaar et al. (2000) used radar data from Israel to test a model, forecasting the thermal conditions and thus the ceiling of raptor migration according to the altitudinal profile of atmospheric conditions of the previous night. Liechti et al. (2000) used radar data on nocturnal migration from Israel to test the efficiency of various models, including physiological models, in predicting nigh altitudes.

3.4 Orientation

Radar studies on orientation are handicapped by the fact that species identification is normally lacking. In spite of this drawback, radar studies have shown the normal directions and their scatter in various regions and the modifications induced by wind, reduced visibility and topography. The wide variation in the recorded effects of the three factors and their probable interference is, however, still far from being explained. New data from the Arctic fall in the category of full compensation for wind drift (Alerstam and Gud-mundsson 1999b), but any intermediate behaviour between this and full drift has been reported.

Alerstam and Gudmundsson (1999a) and Alerstam et al. (2001) were able to demonstrate the use of orthodrome-like sun compass routes of mainly waders when flying across the Arctic Ocean between Siberia and North America. Nievergelt et al. (1999) found that the species mixture of free-flying birds shows much less scatter and is less impaired by overcast skies than birds simultaneously tested in orientation cages. The directions of caged birds were more southward in the late night hours compared to early at night (due to increased ambiguity between SW and SE activity). The directions of free-flying birds were close to the mean vectors of caged birds early at night, but shifted westward along the Andalusian cost towards morning, demonstrating that free-flying nocturnal migrants may react differentially to a coast according to their readiness for further flight.

Reverse and reoriented movements became wellknown due to radar observations, and data showing these particular features are accumulating, but only partially understood. Reverse migration occurs often in connection with unfavourable weather or with a barrier ahead. A certain percentage of reverse directions is, however, nearly always present even under generally favourable weather conditions and with no barrier ahead, as in spring migration in Israel. It seems that this omnipresent part of reverse movements might be part of the normal scatter of individual directions (Komenda-Zehnder et al. 2002).

Dawn reorientation at nearly right angles was observed among others over the North Sea and over the Atlantic Ocean near Nova Scotia. These SE and NW movements, respectively, bring the off-shore flying birds back to the coast at the time when their land-bound conspecifics tend to descend for diurnal rest. Birds having crossed an island late at night may return to the island (Bruderer and Liechti 1998). Less dramatic, but with a similar effect, birds flying over the sea within sight of land tend to shift directions closer to the coast in the course of the night (Fortin et al. 1999).

3.5 Flight Behaviour

Tracking radar studies opened a new world of insights into the flight behaviour of migrants and offer important possibilities to test flight theory predictions. Liechti and Bruderer (1998) used tracking radar data from central

Europe, Israel and the western Mediterranean to demonstrate the relevance of wind with respect to optimal migration theory.

3.5.*1 Airspeeds*

Detailed information on and explanation of airspeeds of various bird types at various sites is provided in (Bruderer 1997b). The speeds of 139 western Palearctic species demonstrate intraspecific variation and allow interspecific comparisons (Bruderer and Boldt 2001): while larger birds seem to be increasingly limited to speeds close to minimum power speed V_{mp}, small birds seem to be capable of selecting between various speeds, approaching predicted V_{mp} when just tending to remain airborne at low cost, but flying at much higher speeds when optimizing energy and distance covered. Predictions of maximum range speed V_{mr}, proved to be too low for small passerines, probably because the models do not account for the gain in speed which is achieved by reducing profile drag during bounding flight. Predictions are too high for large birds because the power output available for flight seems to decline much more with size than previously assumed. The airspeeds of arctic birds reported by Alerstam and Gudmundsson (1999b) are intermediate between predicted V_{mp} and V_{mr}; they correlate with altitude and wind, thus corroborating some earlier reports. Recording stoops of *Faico peregrinus* and *pelegrinoides* with tracking radar yielded a maximum of 51 ms^{-1} (184 kmh^{-1}) (Peter and Kestenholz 1998).

3.5.2 *Flight Mechanics and Wing-Beat Pattern*

The flight of passerine birds is characterized by alternating flapping and pausing phases, wing-beat frequency decreasing with increasing size of the birds. Flap-bounding implies completely closed wings during pauses and is observed mainly in small birds, while flap-gliding occurs mainly in medium-sized passerines and in aerial hunters. Vertical speed is in most species controlled by the duration of flapping over time, achieved by varying primarily the length of flapping phases, secundarily the pauses. Small flap-bounders seem to increase horizontal speed by increased wing-beat frequency and longer pauses. Flap-gliding hirundines showed an increase in the number of wingbeats over time when increasing vertical speed, and a reduction when increasing horizontal speed. The latter effect could be explained by additional wind tunnel experiments revealing that the high speed is achieved by longer glides with flexed wings; the number of wingbeats over time are in a U-shaped relationship with airspeed (L. Bruderer et al. 2001).

Continuous flapping is used by a large variety of taxonomic groups and size classes. Variation of vertical speed by varying wing-beat frequency was observed only in special cases. Normally, these birds seem to use means which are not measured by radar (such as angle of attack or amplitude of wingbeats) for flight manoeuvres.

Hedenstrom and Liechti (2001) used dives of landing passerines to estimate the body drag coefficient $C_{D,par}$. Their calculations support the notion that 0.4 is a realistic value of $C_{D,par}$ in passerines and should not be replaced by a lower value, as suggested recently.

There is still a great potential in the analysis of tracking radar data with respect to flight mechanics and comparison with flight-theory predictions. Progress can be improved by better identification of the radar targets.

3.5.3 *Birds of Prey and Other Thermal and Dynamic Soarers*

Striking optimization of migratory flight behaviour of thermal soarers and data on the soaring performance of Antarctic and Atlantic seabirds have been summarized in Bruderer (1997b). Meanwhile, Spaar (1997) produced a comparative study on flight strategies of migrating raptors and Spaar et al. (1998) showed that Levant sparrowhawks *(Accipiter brevipes)* minimized time per distance in soaring-gliding flight similar to other raptors; additionally, they used flapping-gliding flight in poor thermal conditions and at night; adjusting airspeed to wind in order to fly at maximum range speed, they seem to minimize energy consumption per distance.

4 Chances and Perspectives

The future of radar ornithology is, on the one hand, in the field of large-scale and long-term surveillance. Combined with computer simulations of migration (Erni et al., in press), this will help to understand present adaptations of migration to weather and topography on continent-wide scales and will provide the basis to monitor expected global changes. On the other hand, studies at specific sites have to be designed to test particular predictions generated by the simulations. The combination of on-ground and in-flight studies will open new horizons. The refinement of identification of radar targets is an urgent goal and will allow more specific answers to open questions about flight behaviour in relation to environment, especially in regions where extreme conditions induce the birds to approach the limits of their performance.

Acknowledgements. The main supporters of our own radar studies are the Swiss Army (providing the radars) and the Swiss National Science Foundation (last grant no. 31-432 42.95).

References

Alerstam T, Gudmundsson GA (1999a) Bird orientation at high latitudes: flight routes between Siberia and North America across the Arctic Ocean. Proc R Soc Lond B 266:2499-2505

Alerstam T, Gudmundsson GA (1999b) Migration patterns of tundra birds: tracking radar observations along the Northeast Passage. Arctic 52:346-371

Alerstam T, Gudmundsson GA, Green M, Hedenstrom A (2001) Migration along orthodromic sun compass routes by Arctic birds. Science 291:300-303

Alfiya H (1995) Surveillance radar data on nocturnal bird migration over Israel, 1989-1993, Isr J Zool 41:517-522

Biebach H, Biebach I, Friedrich W, Heine G, Partecke J, Schmidi D (2000) Strategies of passerine migration across the Mediterranenan Sea and the Sahara desert: a radar study. Ibis 142: 623-634

Bruderer B (1997a) The study of bird migration by radar. Part 1: The technical basis. Naturwissenschaften 84:1-8

Bruderer B (1997b) The study of bird migration by radar. Part 2: Major achievements. Naturwissenschaften 84:45-54

Bruderer B (1999) Three decades of tracking radar studies on bird migration in Europe and the Middle East. In: Leshem Y, Mandelik Y, Shamoun-Baranes J (eds) Proc Int Semin on Birds and Flight Safety in the Middle East. Tel Aviv University, Tel Aviv, pp 107-141

Bruderer B (2002) Recent studies modifying current views of nocturnal bird migration in the Mediterranean. Avian Ecol and Behav 7:11-25

Bruderer B, Boldt A (2001) Flight characteristics of birds: I. radar measurements of speeds. Ibis 143:178-204

Bruderer B, Liechti F (1998) Flight behaviour of nocturnally migrating birds in coastal areas - crossing or coasting. J Avian Biol 29:499-507

Bruderer B, Liechti F (1999) Bird migration across the Mediterranean. In: Adams NJ, Slotow RH (eds) Proc 22nd Int Ornithol Congr, Durban. Johannesburg, pp 1983-1999

Bruderer B, Liechti F, Kestenholz M, Peter D, Spaar R, Stark H, Steuri T (2000) Vogelzugstudien mit Zielfolgeradar im Siiden Israels. Ornithol Beob 97:21-44

Bruderer L, Liechti F, Bilo D (2001) Flexibility in flight-behaviour of barn swallows *(Hirundo rustica)* and house martins *(Delichon urbica)* tested in a wind tunnel, J Exp Biol 204: 1473-1484

Buurma LS (1995) Long-range surveillance radars as indicators of bird numbers aloft. Isr J Zool 41:221-236

Buurma LS (1999) The Royal Netherlands Air Force: two decades of bird strike prevention "en route". In: Leshem Y, Mendelik Y, Shamoun-Baranes J (eds) Proc Int Semin on Birds and Flight Safety in the Middle East. Tel Aviv University, Tel Aviv, pp 71-83

Eastwood E (1967) Radar Ornithology. Methuen, London

Erni B, Liechti F, Underhill LG, Bruderer B (2002) Wind and rain govern the intensity of nocturnal bird migration in central Europe - a log-linear regression analysis. Ardea 90 (in press)

Erni B, Liechti F, Bruderer B (2003) The performance of stopover strategies in a simulation of bird migration. J Theor Biol (in press)

Fortin D, Liechti F, Bruderer B (1999) Variation in the nocturnal flight behaviour of migratory birds along the northwest coast of the Mediterranean Sea. Ibis 141:480-488

Gauthreaux SA, Belser CG (1998) Displays of bird movements on the WSR-88D: Patterns and quantification. Weather Forecast 13:453-464

Gauthreaux SA, Belser CG (1999) Bird migration in the region of the Gulf of Mexico. In: Adams N), Slotow RH (eds) Proc 22nd Int Ornithol Congr, Durban, Johannesburg, pp 1931-1947

Hedenstrom A, Liechti F (2001) Field estimate of body drag coeffiecient on the basis of dives in passerine birds. J Exp Biol 204:1167-1175

Komenda-Zehnder S, Liechti F, Bruderer B (2003) Is reverse migration a common feature of nocturnal bird migration? - An analysis of radar data from Israel. Ardea 90:325-334

Kretzschmar R (1998) Quantum neurofuzzy bird removal algorithm (NEURO-BRA) for 1290-MHz wind profiler data. Institute for Atmospheric Science (LAPETH), Zurich, pp 1-77

Leshem Y (1999) Developing a real time warning system in the Middle East; from vision to reality. In: Leshem Y, Mandelik Y, Shamoun-Baranes J (eds) Proc Int Semin on Birds and Flight Safety in the Middle East. Tel Aviv University, Tel Aviv, pp 45-69

Leshem Y, Yom-Tov Y (1998) Routes of migrating soaring birds. Ibis 140:41-52

Liechti F, Bruderer B (1998) The relevance of wind for optimal migration theory, J Avian Biol 29:561-568

Liechti F, Schaller E (1999) The use of low-level jets by migrating birds. Naturwissenschaften 86:549-551

Liechti F, Klaassen M, Bruderer B (2000) Predicting migratory flight altitudes by physiological migration models. Auk 117:205-214

Meyer SK, Spaar R, Bruderer B (2000) To cross the sea or to follow the coast? Flight directions and behaviour of migrating raptors approaching the Mediterranean Sea in autumn. Behaviour 137:379-399

Nievergelt F, Liechti F, Bruderer B (1999) Migratory directions of free-flying birds versus orientation in registration cages. J Exp Biol 202:2225-2231

Peter D, Kestenholz M (1998) Sturzfluge von Wanderfalken, *Faico peregrinus*, und Wiistenfaike, *F. pelegrinoides.* Ornithol Beob 95:107-112

Richardson WJ (1971) Spring migration and weather in eastern Canada: a radar study. Am Birds 25:684-690

Spaar R (1997) Flight strategies of migrating raptors; a comparative study of interspecific variation in flight characteristics. Ibis 139:523-535

Spaar R, Stark H, Liechti F (1998) Migratory flight strategies of Levant sparrowhawks: time or energy minimization? Anim Behav 56:1185-1197

Spaar R, Liechti 0, Bruderer B (2000) Forecasting flight altitudes and soaring performance of migrating raptors by the altitudinal profile of atmospheric conditions. Techn Soar 24:49-55

Williams TC, Williams JM (1999); The migration of land birds over the Pacific Ocean. In: Adams NJ, Slotow RH (eds) Proc 22nd Int Omithol Congr, Durban. Johannesburg, pp 1948-1957