Quantitative bird migration information from operational weather radars

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ABSTRACT

A fully automated method for the detection and quantification of bird migration was developed for operational C-band weather radar, measuring bird density, speed and direction as a function of altitude. These weather radar bird observations have been validated with data from a high accuracy dedicated bird radar, which was stationed in the measurement volume of weather radar sites in the Netherlands, Belgium and France for a full migration season during autumn 2007 and spring 2008 (see Fig. 2). We find that Doppler weather radar is highly successful in determining quantitative bird densities as a function of altitude. Weather radar can extract near real-time bird density altitude profiles that closely correspond to the density profiles measured by dedicated bird radar. With the established continent-wide networks of weather radars (e.g. OPERA, consisting of over 180 radars (http://www.knmi.nl/opera) and NEXRAD (http://radar.weather.gov), consisting of over 150 radars) almost all bird flyways across Europe and the United States could be monitored simultaneously all year round. Apart from highly improved bird strike warnings, such a network would yield invaluable information for scientific research on bird migration.

1. INTRODUCTION

Migration of birds can strongly bias wind measurements by windprofilers and weather radars, and detailed quality control is necessary to suppress contaminations related to the active flight of birds. While suppression of bird signatures in operational profiling sensors is becoming common practice, little effort has been made to obtain real-time information on bird migration itself. As part of an international project by the European Space agency (ESA) aimed at reducing collisions between aircrafts and birds, we have explored the potential of operational C-band Doppler weather radar as a bird migration sensor.

Spatiotemporal information on bird migration is of invaluable use to scientists and society alike, but so far no sensor networks have been established that can monitor bird movement continuously over large areas. In aviation bird migration information is important for improving flight safety. Especially military low level flying has a high risk of on-route bird strikes [1] and spatial bird migration information is essential for generating reliable flight warnings to pilots. Operational bird density forecasts are badly needed, which could be made in combination with spatially explicit bird migration models. Analogous to numerical weather predication, such models depend assimilation of data with a large spatial coverage. Comprehensive monitoring of bird migration at continental scales can also provide insight into migration patterns and the impact on migratory flight of synoptic scale factors like weather and orography.

Figure 1. Doppler weather radar in de Bilt, The Netherlands

2. IDENTIFYING BIRD MIGRATION BY DOPPLER WEATHER RADAR

At the heart of a bird migration quantification algorithm lies the ability to automatically distinguish bird-scattered signals from all other echoes detected by weather radar. Many types of non-bird echoes are observed by radar, including most types of precipitation, dense clouds, insects and echoes related to anomalous beam propagation.

Radar meteorologists have been aware for long that

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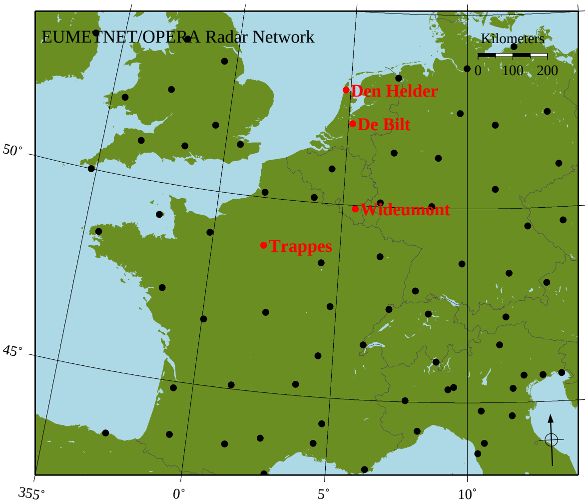


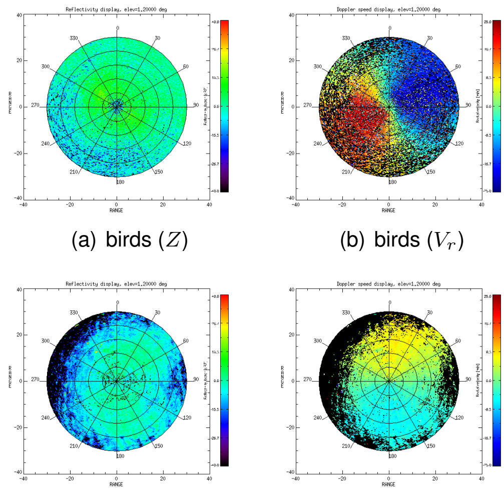
Figure 2. Operational weather radars for part of western Europe. The weather radars used in this study are labeled and colored red. A bird radar was stationed within a few kilometers of the De Bilt, Wideumont and Trappes radar sites during the migration season of autumn 2007 and spring 2008

echoes related to non-meteorological phenomena can 'contaminate' radar images. Such echoes show up most strikingly under stable atmospheric conditions when precipitation echoes are absent, and are therefore commonly referred to as clear-air echoes. While the exact origin of clear-air echoes has been debated for a long time, it is now well established that in C and S-band weather radar these echoes are caused nearly exclusively by flying birds and air-borne insects.

Bird echoes and other clear-air signals tend to be considerably weaker than meteorologically relevant signals from hydrometeors. Most radar meteorologist therefore use a reflectivity factor threshold (typically 7 dBZ) to filter out most non-meteorological reflections. At C-band bird-scattered signals are typically found below this reflectivity factor threshold in the low-reflectivity regime of -30 to 10 dBZ. At S-band bird reflectivity factors related to birds are much higher, easily reaching 50 dBZ

At C-band a reflectivity factor threshold usually successfully selects meteorologically relevant precipitation, but bird scattered signals cannot be selected on the basis of a reflectivity level alone. While most relevant precipitation has a reflectivity factor above 7 dBZ, there are numerous instances where precipitation has a lower reflectivity. Besides precipitation also flying insects give rise to significant scattering. Birds, insects and meteorological scatterers give rise to signals in an overlapping reflectivity regime, and more sources of information need to be considered to distinguish them.

Such additional information is available in Doppler weather radars from the radial velocity of scatterers. Figures 3 shows radar images during intense bird migration and during daytime in the absence of birds



(a) birds (Z) (b) birds (V_r)

(c) non birds (Z) (d) non birds (V_r)

Figure 3. Reflectivity factor (left) and radial velocity (right) Plan Position Indicators (PPIs) for the Wideumont radar (scan at 1.1 degree elevation) for a case of intense bird migration (a-b: 05 October 2007, 22:32 UTC) and a case showing non bird echoes (as verified by the reference bird radar) observed during daytime (c-d: 23 September 2007, 12:02 UTC). These non bird echoes are caused by insects.

(when mostly flying insects are present).

Areas of precipitation show a radial velocity that is spatially continuous and locally homogeneous. The same holds for clear air echoes observed during summer daytime (Fig. 3(d)), when convection has uplifted insects and possibly other scatterers into the air. The speed of hydrometeors is fully determined by the wind field and their terminal fall velocity, which are usually spatially smooth variables. Therefore the detected radial velocity field by Doppler radar is spatially smooth as well. The same holds for clear air echoes by insects, which have an active flight speed that is either negligible or non-directional. This causes the average velocity of insect scatterers per range-gate to be equal to the wind field velocity. Directed insect migration has been reported, but again the active flight speeds tend to be low and directed by the wind field.

Bird migration gives rise to a very different spatial structure of the radial velocity scan data, as illustrated in Fig. 3(b). A much higher degree of (local) spatial variation in the radial velocities is detected. Unlike precipitation a bird performs active flight, which may vary in speed and direction per individual. Bird migration therefore shows a higher variability in the Doppler velocity than precipitation.

Figure 4. Wingbeat pattern of a passerine with regular phases of wingbeats and pauses as recorded by the "Superfledermaus" bird radar. The single wingbeats are clearly visible. The increasing and decreasing amplitude (vertical axis) of the signal along the time axis (horizontal axis) reflects the bird's flight entering the radar beam at one edge, flying through the center and leaving at the other edge.

3. BIRD MIGRATION PROFILING ALGORITHM

We developed a bird detection algorithm based on existing wind-profiling algorithms for Doppler weather radars, using the Volume Velocity Profiling (VVP) technique [2, 5]. A target identification scheme was developed to filter out non-bird echoes from the radar volume data, based on an analysis of the local variance in radial velocity. As discussed in the previous section, this variance is high for cases of bird migration, while low for cases of precipitation or air-borne insects. Areas containing insects or hydrometeors are removed from the radar scan. The remaining reflectivity is averaged over all azimuths and ranges between 5 and 25 kilometer at different 200 m height intervals. This averaged reflectivity profile is used to construct a bird density altitude profile. Reflectivity η, reflectivity factor Z, and bird density ρ_{bird} are related according to

$$\eta = \frac{10^3\pi^5}{\lambda^4}|K_m|^2 Z = \overline{\rho_{\text{bird}}\sigma_{\text{bird}}} \quad (1)$$

with η in cm^2/km^3, Z in mm^6/m^3, $K_m = (m^2-1)/(m^2+2)$ with m the complex refractive index of the scatterer, λ in cm the radar wavelength, ρ_{bird} in birds/km^3 and σ_{bird} the bird radar cross section in cm^2.

4. BIRD RADAR FIELD CAMPAIGNS FOR WEATHER RADAR VALIDATION

We use a dedicated bird radar of the type "Superfledermaus" (see Fig. 5) to validate the weather radar bird migration quantification method. The radar is capable of detecting the wingbeat pattern of individual radar targets (see Fig. 4). Based on these echo signatures insects, birds and hydrometeors can be distinguished with a high selectivity. The mobile tracking radar is therefore a state of the art reference for validating the weather radar observations.

Three field campaigns were organized to validate the weather radar bird observations. The bird radar has been stationed within the measurement volume of the weather radar in De Bilt, the Netherlands from 19 Aug 2007 – 16 Sep 2007, in Wideumont, Belgium from 18 Sep 2007 – 22 Oct 2007 and in Trappes, France from 10 Mar 2008 – 9 May 2008. Hourly migration traffic rates were determined at the airfield of Soesterberg (52.13N/5.28E, 10m MSL), the airfield of St. Hubert, (50.03N/5.44E, 577m MSL) and at Flins sur Seine (48.58N/1.52E, 59m MSL) at 6, 12 and 24 km distance from the respective weather radar sites.

Figure 5. The bird radar "Superfledermaus" equipped with a camera mounted parallel to the radar antenna

The bird radar carried out fixed beam measurements [4] at three elevation angles (5.6°, 22.5°, 79°), which allowed a good coverage of all flight altitudes up to 6 km. The beam was directed towards WNW (293°), thus perpendicular to the main migratory direction. During the three elevations were scanned every half hour between 17 and 05 UTC, and for the rest of the day every hour. Echoes showing wing beat patterns corresponding to birds were automatically selected by a "vector support machine" [6] which was trained based on a large sample of visually classified targets by an expert. Between fixed beam measurements tracks of single targets were recorded for at least 20 seconds to determine flight paths. During the night this was performed by an automatic search algorithm selecting targets from all relevant heights. During daytime tracking was performed manually with an operator selecting targets on the radar screen and an observer watching through a telescope mounted parallel to the radar antenna. Bird densities are calculated from the number of recorded echoes, the average bird ground speed vector and the calibrated bird- and aspect specific surveyed volume [4].

5. WEATHER RADAR VALIDATION

In Fig. 6 the bird densities altitude profiles detected by bird radar and weather radar are displayed for the period of 11-16 October 2007. We find a remarkable correspondence in the detected bird densities by the two sensors. The altitude distributions and absolute number of detected birds match quantitatively. To convert weather radar reflectivity to bird density we use Eq. 1 assuming a constant bird radar cross section of 10 cm^2.

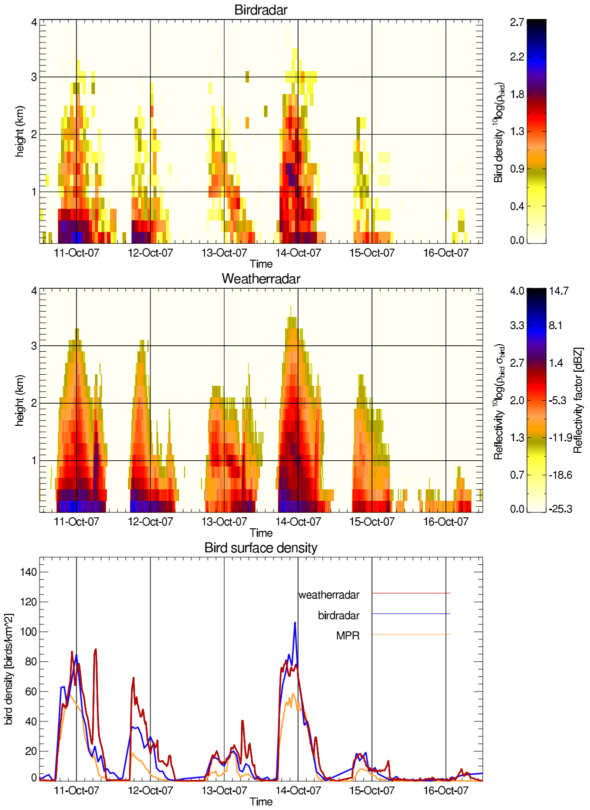


Figure 6. Comparison bird densities determined by bird radar and weather radar. Weather radar reflectivities were converted to bird density by assuming a constant bird radar cross section of σ_{bird}=10 cm^2. In the lower panel height-integrated bird densities are displayed for both weather radar (red) and bird radar (blue).

In the bottom panel we the height integrated bird densities are displayed for both bird radar and weather radar (also the bird densities detected by the military ROBIN system using the Medium Power Radar (MPR) in Glons, Belgium, is shown for comparison).

The detection probability of the bird detection algorithm is very high (up to 99%) and the fraction of false alarms is low (down to 2%). Most false positive detections are caused by precipitation contaminations. The quality of the bird density quantification depends mainly on the quality of the algorithms masking areas of precipitation.

At bird densities higher than 10/km^3 ($Z_{\rm bird} > -5$ dBZ), 66% of the weather radar bird densities are correct within a factor of 2 and 81% within a factor of 3. The current bird detection algorithm meets the requirements for operational implementation. At the Royal Dutch Airforce (RNLAF), the subsequent levels of Bird Strike Warnings (so-called BIRDTAMs) differ in bird density by factors of 2, which is on the order of accuracy that is obtained by weather radar.

6. CONCLUSIONS

We find that Doppler weather radar is highly successful in determining quantitative bird densities as a function of altitude. We find that weather radar reflectivity can be quantitatively correlated to the bird-densities determined independently by bird radar. The current bird detection algorithm meets the requirements for operational implementation. The developed methods for bird detection and quantification can be easily extended to full operational weather radar networks. With the establishment of the OPERA data center for radar data within the coming two years [3] the establishment of a continent wide bird migration sensor network in Europe is within reach. Such a network can enable important applications both in flight safety, health (avian disease spread) and environmental impact assessments (assessing the collision risk for birds by windfarms and other man-made structures).

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