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Radar wind profilers and avian migration: a qualitative and quantitative assessment verified by thermal imaging and moon watching

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Summary

1. Radars of various types have been used in ornithological research for about 70 years. However, the potential of radar wind profiler (RWP) as a tool for biological purposes remains poorly understood. The aim of this study is to assess the suitability of RWP for ornithological research questions.
2. A 1290 MHz RWP at the south-eastern coast of the Bay of Biscay has been known to exhibit seasonally occurring nocturnal signals attributed to migrating birds. As a first step to verify the origin of these seasonal patterns, historical radar data from 2010 to 2012 were analysed, and both bird patterns and temporal occurrence were identified in RWP data at different levels of the signal processing. A thermal-imaging (TI) camera in conjunction with moon watching was used as verification systems at the radar site to confirm the ornithological origin of the radar echoes. The simultaneous data on spring migration served as a basis for the identification of biological signatures (qualitative parameters) on time-series level (raw data) and to derive quantitative migration parameters (flight altitude, migration traffic rates) thereof. Finally, the quantitative measurements of the TI camera and the radar were compared considering meteorological conditions.
3. The approach allowed identifying reproducible criteria based on time series to calculate migration traffic rates and altitudinal flight distribution. General flight directions were only available in the final wind data. In clear weather conditions, the calibration methods coincided well with the wind profiler data.
4. Findings show that wind profiler raw data offer reliable information on migration intensity, flight altitudes and flight directions in a variety of meteorological conditions. The method presented can be applied as a complement to present efforts to use weather radars for large-scale bird monitoring. Furthermore, it is also interesting for the meteorological community to refine signal-processing methods.

Key-words: calibration, infrared, ornithology, remote sensing, wind profiling

Introduction

Radars offer many advantages in ornithology in comparison to other investigational methods such as visual counts or ringing because of less expenditure of time and effort, superior visibility and detectability (e.g. at higher altitudes or in the dark), as well as better applicability for large-scale monitoring (Shamoun-Baranes *et al*. 2014).

Detailed bird radar studies have mainly used X-band tracking or marine radars (e.g. Bruderer 1999; Gauthreaux & Belser 2005; Karlsson *et al*. 2012). However, it has also been known from S- and C-band weather radar networks, such as NEXRAD or OPERA, that these remote-sensing systems register bird movements (Gauthreaux, Mizrahi & Belser 1998; Koistinen 2000; Holleman, Van Gasteren & Bouten 2008; Dokter *et al*. 2010). In connection with weather radars, the COST action ENRAM (European Network for the Radar surveillance of Animal Movement; www.enram.eu) is dedicated to 'establishing the basis for a coordinated network of monitoring radars for the provision of real-time spatio-temporal information on animal movement through the air on a continental scale', potentially benefitting both the environment and humankind (ENRAM Memorandum of Understanding 2013). In contrast, in radar wind profilers (RWPs) great efforts have been undertaken to remove the biological signals rather than to study them (e.g. Wilczak *et al*. 1995).

RWPs measure clear-air echoes, which are generally weaker than biological scatterers, and require very long dwell times to be detectable. Nocturnal migrants, consisting mostly of passerines having a typical length of 10–20 cm, are strong scatterers. If non-atmospheric signal components are present, the atmospheric signal component is likely to be masked and thus atmospheric data quality is deteriorated (Merritt 1995). So appropriate signal processing plays a decisive role. To remove

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so-called 'biological contamination', various methods were developed at the spectral (Merritt 1995; Pekour & Coulter 1999 and Kretzschmar, Karayiannis & Richner 2003) and the time-series level (Lehmann & Teschke 2008; Lehmann 2012; Bianco, Gottas & Wilczak 2013). All these studies regarded birds as contamination to be removed. However, the potential of RWP for actual ornithological purposes remains poorly understood. In particular, the continuous vertical profiles, covering the entire air column up to several kilometres, i.e. where bird migration takes place, paired with the widespread use of these radars in networks such as E-Profile in Europe (http://www.eumetnet.eu/radar-wind-profilers) or for air quality monitoring as the Cooperative Agency Profilers could potentially be an interesting complement to the horizontal scanning method of weather radars. Therefore, RWPs are of potential ornithological interest and worth undergoing a closer evaluation.

Each radar type exhibits specific patterns associated with different targets. Therefore, if the characteristics of bird signatures in a radar type are unknown, the source of the radar signals needs to be verified first independently, e.g. by visual observations, thermal imaging or dedicated bird radars. Target identification by radar alone is often insufficient (Schmaljohann *et al.* 2008). Otherwise, considering migration, the content of the sampled volume remains ambiguous given the fact that not only birds can migrate in large numbers but also insects and bats (Chapman, Drake & Reynolds 2011).

When using two or more systems simultaneously in calibration field studies, it is important to be aware of the potential limitations of each. For example, meteorological conditions can have a major impact on target detection in case of thermal imaging. Increased humidity (e.g. precipitation or fog) or cloud movement can be a limiting factor as it decreases detectability of targets (Zehnder *et al.* 2001). However, no bias is to be expected from atmospheric echoes in RWP because they are always greatly inferior to bird echoes (Merritt 1995).

To evaluate the potential of RWP for providing qualitative and quantitative information on bird migration, year-round data from a wind profiler on the Basque coast (Spain) were analysed in combination with thermal-imaging and moon-watching data. Since its installation in 1996, biological signatures were observed in the radar data particularly during bird migration season.

The aim of this study is to provide an in-depth characterization of bird signals vs. other biological and atmospheric signals to (i) explore the capacity to obtain quantitative and qualitative wind profiler data for ornithological purposes; (ii) to compare RWP data with thermal-imaging and moon-watching data and to discuss discrepancies and similarities considering technological and meteorological factors; (iii) to discuss advantages and disadvantages of 'raw data' (time series) vs. further processed (spectral, moment and wind data) RWP data. On the one hand, the results will help the ornithological community harness a new observation tool, both at a local and a broader scale to study migratory behaviour in an ecological context (e.g. close to a geographical barrier). On the other hand, they will also support future improvements in signal processing in meteorology.

Description of the system

RWP SPECIFICATIONS AND TERMINOLOGY

Radar data for this study were retrieved from the 1290-MHz (23-cm wavelength) LAP 3000 boundary layer wind profiler with integrated Radio Acoustic Sounding System (RASS) owned by Euskalmet (Basque Meteorology Agency). The radar site is situated at the north-eastern side of the estuary of Bilbao, Spain, on a cliff top (43.37°N, 3.04°W) (Fig. 1). The RWP is a Doppler radar with a phased-array antenna providing continuous, real-time vertical profiles of the three-dimensional wind vector and virtual temperature. The wind is measured using a five beam sampling configuration (see Fig. 2). The nominal beam width is 6 degrees. For a detailed description of the system, see Carter *et al.* (1995) and the Vaisala (2007).

RWP OPERATION: SAMPLING AND PROCESSING

The RWP operates in two modes, a low mode with a 60-m pulse length (corresponding to a 417-ns pulse) typically covering a vertical range of about 2 km and a high mode with 400-m pulse length (corresponding to a 2833-ns pulse) covering about 4–8 km in favourable conditions. The vertical resolution is defined by the pulse width, and the received signal is sampled by the radar electronics at discrete range gates (32 gates in low mode, 20 gates in high mode). The measurement is taken with a dwell time of typically 30 s per beam. The sequential switching between the five beam directions for both short and long pulses defines a full-scan cycle of 5 min. For wind measurements, data from several full scans are used.

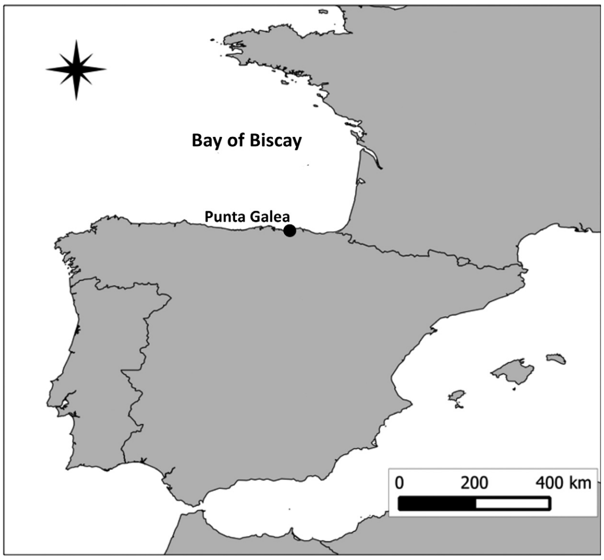

Fig. 1. Radar wind profiler site at Punta Galea, Bilbao, Spain.

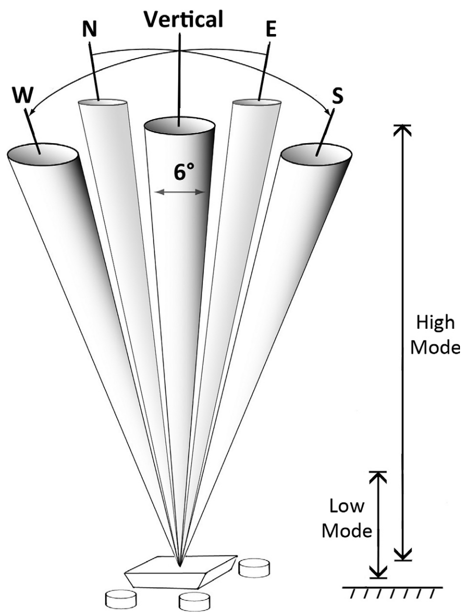

Fig. 2. Beam configuration of the boundary layer wind profiler radar at Punta Galea, Spain.

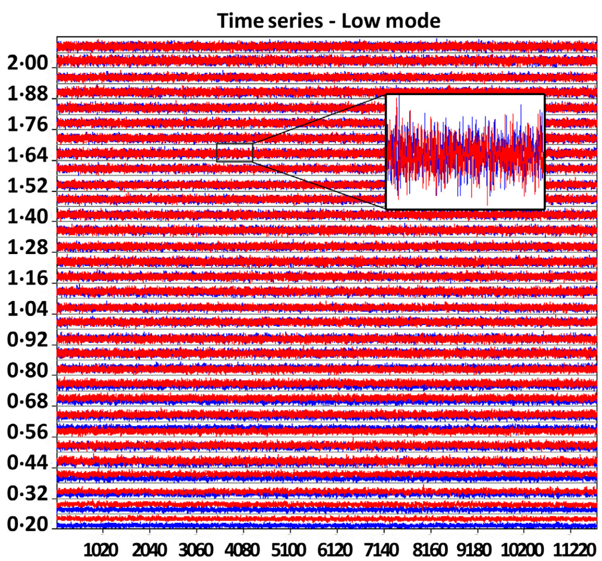

Fig. 3. Example of clear air in time series presented as normalized I/Q plots for each gate in low mode.

The resulting measurement along one beam direction is the receiver voltage, which is available for each range gate as the time series of the so-called in-phase and quadrature components (I/Q) (Fig. 3). It is the raw data of the radar and thus the starting point for all further processing, as schematically shown in Fig. 4.

Time-series data are typically visualized using normalization, i.e. the strongest echo determines the scale of a plot. (If strong and weak echoes are mixed, weaker ones could be indiscernible and visualization would require an analysis with a higher resolution.)

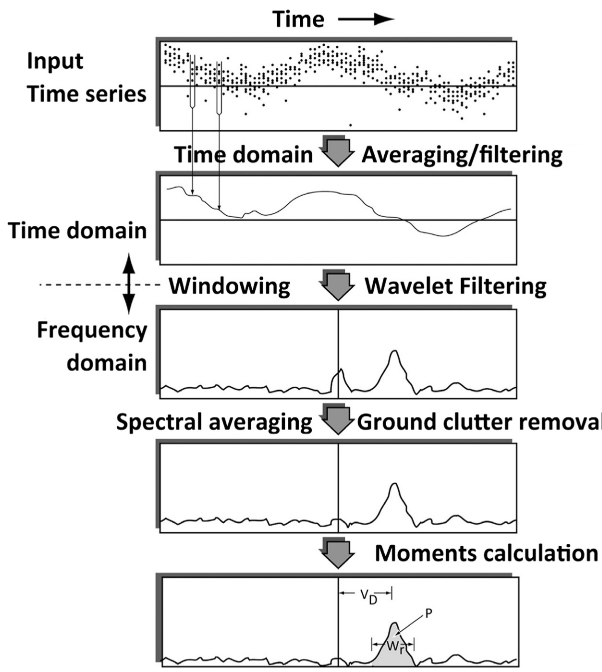

Fig. 4. Data processing: Moments estimation from I/Q time-series data (Vaisala 2007).

Based on these time series, power spectra (known as Doppler spectra, in short 'spectral data' hereafter) are estimated as the next step in the signal processing chain (Strauch *et al.* 1984). In general, this inevitably leads to a loss of (phase) information. While not relevant for the signals typically observed in RWP (refractive index fluctuations, precipitation or electronic noise), this loss of information does matter for bird echoes and other intermittent signals. In other words, it is not possible to recalculate a bird signal from the Doppler spectrum.

Spectral data can be visualized in plots either in normalized or non-normalized stacked and contour mode (Fig. S3, Supporting Information).

Based on the Doppler spectra, the moments data consisting of signal-to-noise ratio (SNR), radial velocity and spectral width are determined. This step can again lead to a loss of information. Only if the spectrum contains a single signal peak with a Gaussian shape, then the complete information is conserved.

Moments data are visualized using contour plots (e.g. Fig. S2).

Finally, consensus averaging by a consensus algorithm (Fischler & Bolles 1981; Vaisala 2007) is applied to radial velocity data. Based on this, the wind vectors for each gate are calculated every 30 min, resulting in the final wind data, which can be visualized using time–height plots with wind barbs (Fig. S4). All SNRs displayed in this article were range corrected.

For an efficient data analysis (e.g. to gain an overview over seasonal occurrence of bird presence), it is important to use data at all levels of processing, as the data volume is significantly decreased by the signal processing.

Methodology

The methodology is divided into three sections: (i) preparative approach and verification of biological targets (see supplement), (ii) qualification and (iii) quantification of biological targets (see scheme of Fig. 5). All steps consist of manual processing.

PREPARATIVE APPROACH

The Euskalmet wind profiler database ranges from 1996 to 2015. Throughout this time period, data quality was observed to severely deteriorate in spring, i.e. during bird migration season in line with available literature on bird contamination patterns (Maruri 2001).

Based on the findings from the preparative studies (see supplement), a shorter study interval of 10 nights was chosen for the actual calibration campaign in March 2015, which was previously identified as peak migration period (Weisshaupt, Maruri & Arizaga 2016a). No radar data were available for 18 March 2015 due to a system breakdown.

QUALITATIVE ANALYSIS OF TIME SERIES (TARGET IDENTIFICATION)

For reliable quantitative measurements it is very important to have a solid qualitative understanding of individual bird signatures in time series, and to consider the beam geometry (Schmaljohann *et al.* 2008).

Time-series data from the vertical beam only was selected to exclude as many potentially confounding factors potentially arising from beam geometry and asymmetrical positions of side lobes in the tilted beams (see Fig. S9 for beam geometry). Furthermore, flight activity of a front is best measured by a vertical measurement system (Lowery 1951). Of the two vertical beam options (low vs. high mode), the low mode was chosen, as its sampling height coverage is more similar to the thermal-imaging (TI) range and because of the higher resolution in comparison to the high mode. The high mode was consulted for a general overview over altitudinal migration activity only.

In a first qualitative step, the signals were classified as bird echoes, atmospheric echoes and echoes of unknown origin. For a better understanding of the joint time frequency structure of all possible signal components, Gabor spectrograms (essentially a windowed Fourier transform of the time series; not to be confused with spectral data!) were calculated. It is important to note that the spectrograms provide just another view on the time series, to highlight the variable frequency structure of the data. This so-called time frequency analysis method is particularly useful for the analysis of non-stationary data and often allows for a clear separation of the various signal components in RWP data (Muschinski *et al.* 2005; Lehmann & Teschke 2008).

Echoes from biological sources, i.e. birds, typically exhibit elliptical sinusoids (for a selection of bird echoes of different qualities see Fig. 6). In spectrograms, birds exhibit typically a regular 'zigzag pattern' associated with flapping flight, representing the only radial movement of birds in perpendicular position, which is perceived by the radar.

The following aspects are important when analysing time-series data. (i) Vertical multiplication of echoes: Signatures of birds (and other signals stronger than precipitation) can spread into two or more adjacent gates based on their very high reflectivity (Fig. 6a–d). This spreading is described by the range-weighting function for a single-range gate (Doviak & Zrnić 1993). The nearest gate where a target is located is the one with the highest I/Q values, i.e. the one with the 'nicest' echo signature of all gates in question, together with the spectrogram of the highest SNR scale value. (ii) Horizontal multiplication caused by the trajectory of a target across the radar beam: Targets passing both side lobes and main lobe exhibit weaker horizontal copies closely before and/or after the main echo in the same gate in time series and one or more steeply diagonally aligned copies in spectrograms (Fig. 6a), compared to echoes passing only through one lobe. Strong echoes of targets passing both main and side lobes can thus be duplicated horizontally and vertically. (iii) Shape of sinusoids: A target passing the main lobe typically exhibits a distinct dense sinusoidal curve interspersed with gaps in time series and transiently a frequency of 0 Hz in the spectrogram, i.e. it crosses the zero line (based on its perpendicular position relative to the beam). All other targets, passing beside the centre of the main lobe, i.e. the zero line in the spectrogram, present a continuously dense sinusoidal curve without gaps. In addition, the quality of these marginal signals is poorer and the I/Q and SNR scale values lower. (iv) Concurrently passing targets, be it bird–bird or bird–other target, cause a superposition of frequencies (beat frequencies, Fig. 7d).

This classification is crucial to clean data from duplicates, which would falsify any further analysis.

Once duplicates were excluded from the time-series dataset, all echo signatures were classified into four categories according to their quality and origin based on time series and spectrograms (Table 1). Only targets with a spectrogram intensity of >60 dB were included because of strongly deteriorating quality of echo signatures below 60 dB. All non-bird echoes [e.g. airplanes, strong atmospheric (e.g. lightning) and unknown signals] were classified as 'fail' and excluded from further analysis (for an overview see Fig. S5). The same procedure was applied to signals involving multiple overlapping birds if it was not possible to assign an individual qualitative class to the targets involved, e.g. in case of beat frequencies. Bird echoes were classified as 'poor' if the signal was clearly ragged and/or irregular, typically with I/Q maxima of <10 000 a.u. (i.e. arbitrary units) and maximum spectrogram intensity of <75 dB; as 'good' if the signal was clean and regular, but less ragged and stronger, with I/Q maxima of 10 000–20 000 a.u., and a maximum spectrogram intensity of 75–100 dB; and as 'very good' if the signal showed a very clean and regular sinusoidal shape, with I/Q maxima of >20 000 a.u. and a maximum spectrogram intensity of >100 dB (e.g. see Fig. 6a–e). Slight deviations of the thresholds were possible. 'Very good' was only assigned to targets passing through the centre of the main beam. 'Good' was

GOALS		REFERENCE SYSTEMS
WPR: **Preparative approach and verification** of the biological target (Supplement)	**RWP (1996-2015): Consensus level** Identification of the clutter signal in the historical database. **RWP (2010-2012): Qualification of the target** - CNS level. - Moments level. - Spectral level.	**TI (2014): Characterization of the nocturnal bird migration** - MTR levels.
	Field campaign 2015	
WPR: **Qualification** of Biological target	**RWP: At time series level (vertical beam)** **Classification based on:** - Signal power - Trajectory through radar beam - Signal shape - Overlapping echoes **Bird composition**	**TI+MOONWATCHING**
WPR: **Quantification** of Biological target	**RWP: At time series level (vertical beam)** - Migration traffic rates - Meteorology	**TI (2015): Characterization of the nocturnal bird migration.** - MTR levels.

	RESULTS	DISCUSSION
WPR: **Preparative approach and verification** of the biological target (Supplement)	**Historical database** - Seasonal occurrence - Temporal extension - Pattern description	- Limitations and advantages of data levels – raw vs. processed data
WPR: **Qualification** of Biological target	**Target qualification in time series** - Echo quality of an individual bird trajectory: main lobe and/or side lobes - Bird composition	**Main challenges** Elimination of the duplicates - Duplicates across gates - Duplicates from side lobes - Overlapping - Bird composition
	QUALITY FLAG OF THE TARGET	
WPR: **Quantification** of biological target	**Target quantification in time series** - Migration traffic rates - Flight altitude	**Main challenges** - Low vs. high MTR and impact on analysis - Flight altitudes
WPR: **RWP vs. thermal imaging**	**Migration parameters in RWP vs. thermal imaging** - Meteorological conditions - Migration traffic rates - Flight altitudes - Flight directions - Bird composition	**Main challenges** MTR: - Discrete vs. continuous data - Meteorological conditions - Determination of flight altitudes - Flight directions

Fig. 5. Work flow for data analysis of radar wind profiler (RWP) data.

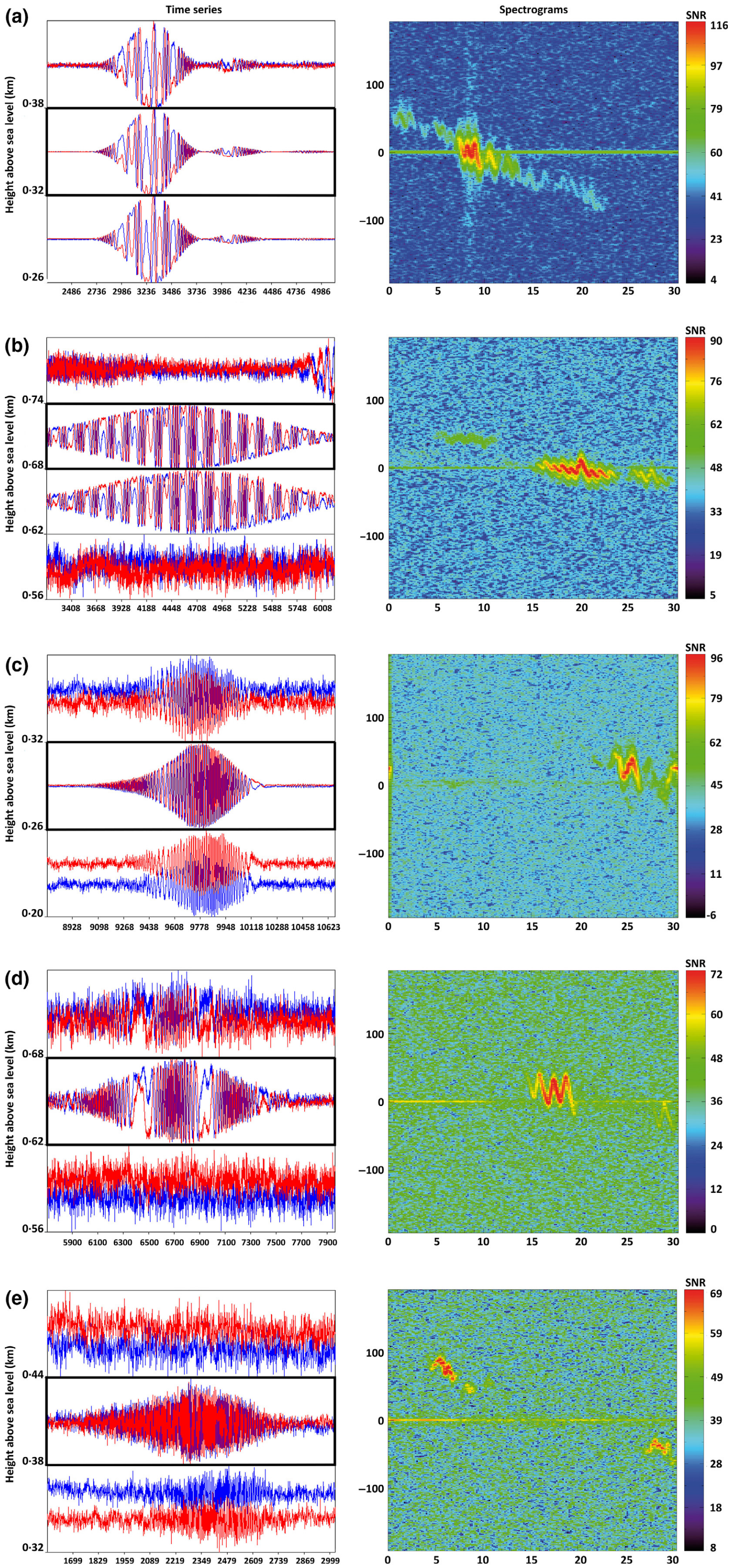

Fig. 6. Time-series (left) and spectrogram (right) plots for qualitative classification: (a) is 'very good' (15 March 2015, gate at 0·32 km), (b) is 'good through beam centre' (10 March 2015, gate at 0·68 km); (c) is 'good marginal' (17 March 2015, gate at 0·26 km); (d) is 'poor through beam centre' (17 March 2015, gate at 0·62 km) and (e) is 'poor marginal' (17 March 2015, gate at 0·38 km). The spectrograms show only the data from the single-range gate framed in the time-series plots.

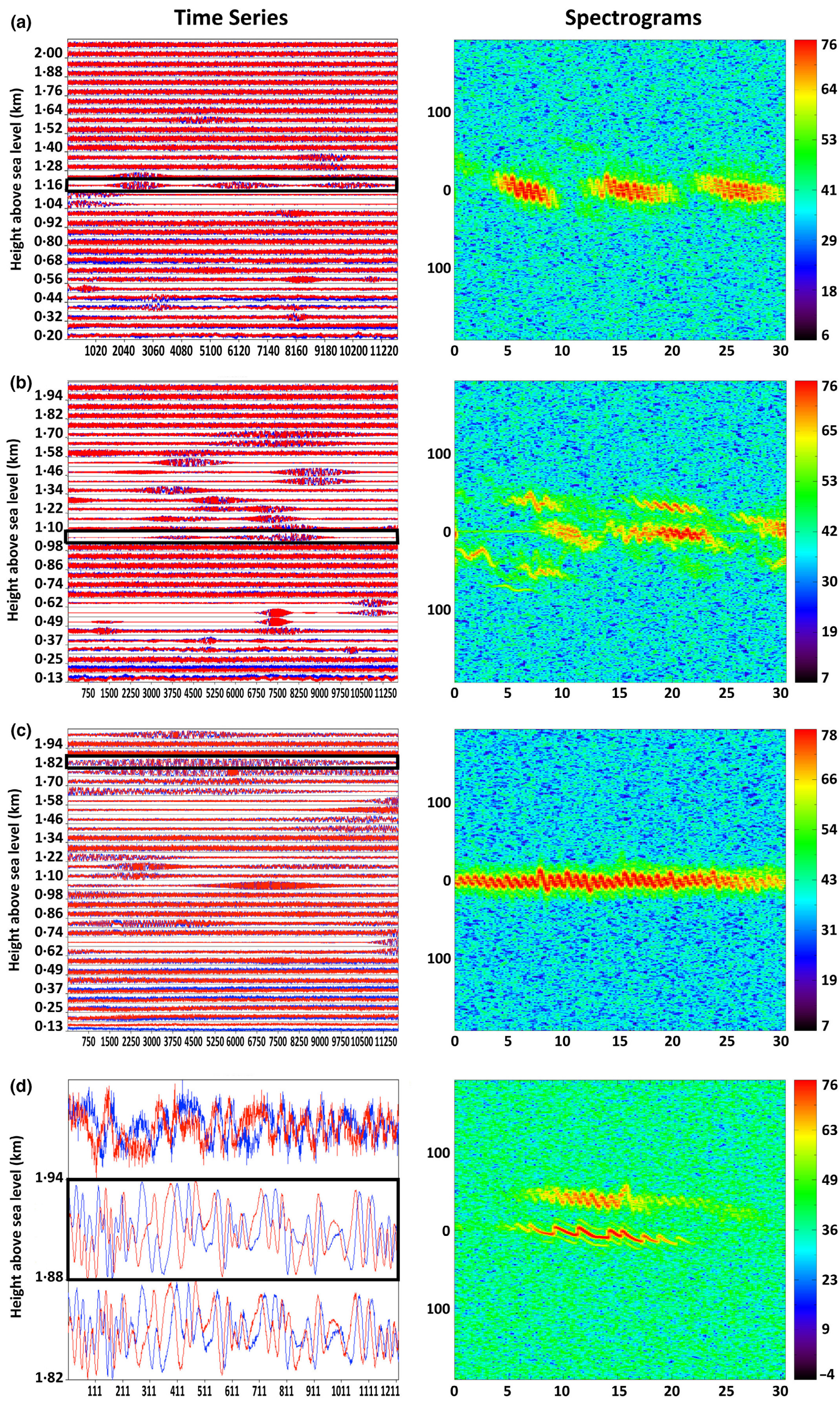

Fig. 7. Various examples of birds in time series and spectrograms on 30 March 2015. (a) Three different birds in the gate at 1·16 km; (b) high migration intensity, birds occurring simultaneously in the gate at 1·097 km; (c) long bird echo in the gate at 1·82 km and (d) overlapping echoes of two birds in the gate at 1·88 km. The spectrograms show only the data from the single-range gate framed in the time-series plots.

Table 1. Classification criteria for echo signature analysis based on signal-to-noise ratio (SNR) in time-series data

	Very good	Good	Poor	Fail
SNR in spectrograms (dB)	≥100	75–99	60–74	Any ≥60

assigned to targets both passing through and beside the centre of the main beam. Those not passing through the centre were excluded from the further analysis to rule out the presence of side lobe echoes. In cases of echoes of different quality in one gate, it was possible that a 'poor' echo (e.g. from target present in a side lobe only) was assigned a (correct) low I/Q value, but a '(very) good' spectrogram intensity which was actually based on the 'good' echo (from a target in the main lobe) coexistent in the same time interval and gate.

Bird composition

In thermal-imaging passerines vs. non-passerines can be roughly differentiated based on individual tracks vs. well-defined groups, as passerines typically travel singly or in loosely dispersed flocks at night (Bruderer 1971; Balcomb 1977). A similar pattern would be expected for bird echo arrangements in time-series data, i.e. various echoes at close time intervals or overlapping for flocks vs. temporally isolated single echoes for individual birds.

QUANTITATIVE ANALYSIS OF TIME SERIES

Migration traffic rates

MTRs were calculated from RWP time series to attain a comparable measure of migration intensity with TI data and to account for the conical sampling method of the system (nominal beam width of RWP: 6 degrees) (*sensu* Lowery 1951). Thereby, it is important to consider the different types of input data. While the thermal imaging offers continuous recordings of migration intensity, the RWP provides discrete (intermittent) measurements based on its scan cycles. The 'good' and 'very good' echoes crossing the main lobe in each 30 s of time series were therefore first extrapolated to a 5-min time period until the next scan cycle would start to achieve pseudo-continuous data per hour. Then based on these hourly values, mean nightly MTRs were calculated. Flight altitude distribution was similarly estimated from the 30 s MTRs per gate. Importantly, while the altitudes required for MTR calculations of the thermal-imaging camera were derived from target size classes (Weisshaupt, Maruri & Arizaga 2016a, b), altitudes in the RWP were predefined by the gates.

Meteorology

As meteorological conditions can affect both systems (and thus the results) as described previously, meteorological data were collected as follows. Cloud cover at the radar site was estimated in oktas at sunset of each sampled night. Complementary ground-level data on wind direction and force, visibility and temperature were obtained from the nearby meteorological stations at the airport of Bilbao and Santander [Euskalmet, the Department of Atmospheric Science of the University of Wyoming (http://weather.uwyo.edu), Metar (http://www.ogimet.com)]. The large-scale meteorological situation over Europe was assessed using synoptic surface charts (UK Metoffice) to account for a potential influence on migration activity.

Results

QUALITATIVE ANALYSIS OF TIME SERIES (TARGET IDENTIFICATION)

Differentiation between various types of targets proved to be most reliable in both time series and Gabor spectrograms compared to the processed spectral, moment and final wind data. Birds could be readily distinguished from precipitation, airplanes and non-bird echoes of potential biological origin (for comparison, see Fig. S5). Bird echoes typically appeared during up to 20 s (depending on the gate/altitude). In spectrograms each echo is slightly diagonally aligned from upper left to lower right, when a bird enters and exits the beam. Bird echoes at high altitudes, i.e. in gates 20–32, could extend considerably given the larger diameter of the beam. Temporally prolonged echoes could also result from head winds decelerating a bird's flight, as was verified by TI camera recordings. Airplane echoes affected several gates in time series and had a distinct short steep shape in the spectrograms (Fig. S5c). Precipitation depicted as weak homogenous pattern occurring uniformly in all gates in time series and as a horizontal line in the positive frequency area in spectrograms (Fig. S5a).

There were various types of frequency patterns for classified bird echoes in spectrograms (see Fig. 7a–e), it was, however, not possible to assign them to particular groups of birds (family or genera level).

As a product between the time-series and moment data, spectral data allowed obtaining a better understanding of signal processing. Comparisons with time series showed that signal processing could merge two signals from adjacent gates into one signal in an actually unoccupied gate (i.e. removing true echoes and keeping an unreal copy), so that neither number nor altitude of a target would be accurate. This fact is important to consider when handling processed RWP outputs. However, in case time-series data are not available, spectral data can help understand the moment data. No differentiation between birds and other potential biological targets is possible.

QUANTITATIVE ANALYSIS OF TIME SERIES

Migration traffic rates in RWP

Overall, 3612 echo signatures extracted from time series were included in the quantitative analysis. Fourteen per cent were classified as 'fail', 58% as 'poor', 26% as 'good' (22% through

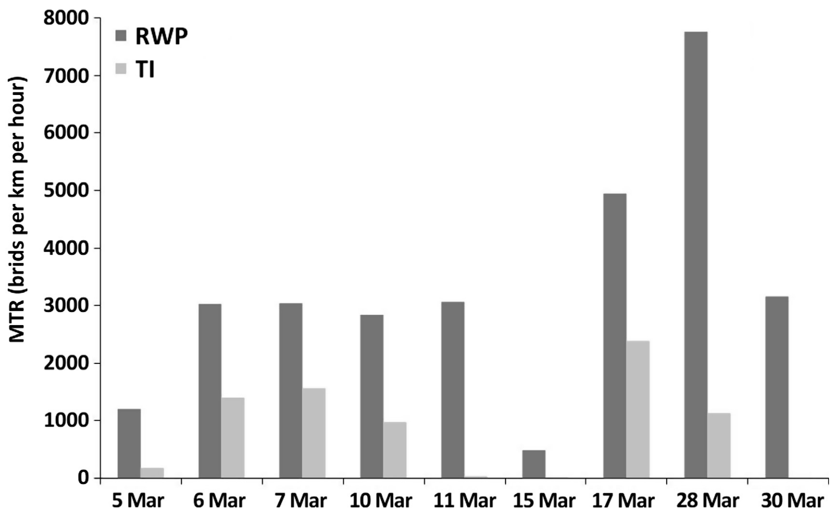

Fig. 8. Comparison of nightly mean migration traffic rates (MTR) measured by radar wind profiler (RWP, dark grey) and thermal imaging (TI, light grey).

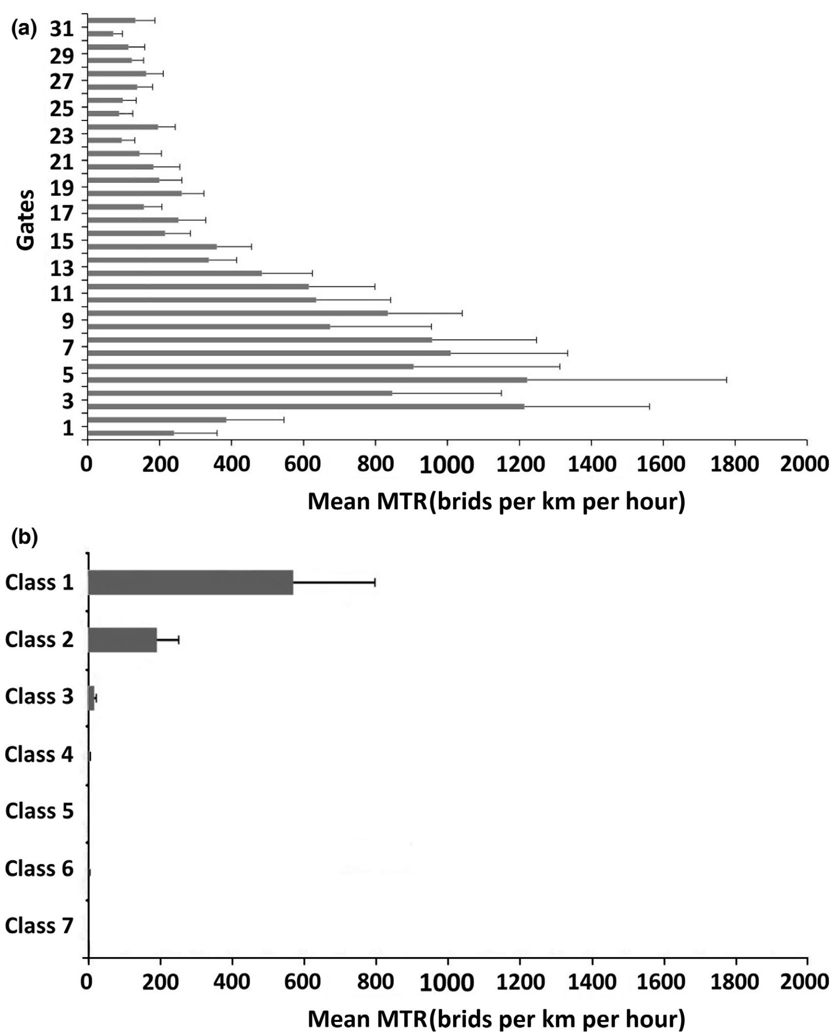

Fig. 9. Comparison of altitudinal distribution of migration intensity measured by wind profiler (a) and thermal imaging (b).

the beam centre) and 2·5% as 'very good'. So overall, 25% of the echo signatures (i.e. 'good' passing through the beam centre and 'very good') were incorporated into the MTR calculations. Nightly mean MTRs ranged from 482 to 7763 birds per km per hour (Fig. 8).

Flight altitudes in RWP

Altitudinal flight distribution concentrated in most nights in the gates 1–16, i.e. up to 1 km, without any noteworthy activity in the highest levels at about 2 km (Fig. 9). A comparison with the maximum migration height in the high mode showed migration beyond 2 km in 7 of 9 nights (Fig. S6), i.e. beyond the low-mode sampling range. In the two nights of maximum migration altitudes below 2 km, the two modes exhibited similar values.

MIGRATION PARAMETERS IN RWP VS. THERMAL IMAGING

Meteorological conditions

Overall, meteorological conditions (Table 2) were highly variable during the campaign and can be divided into four scenarios: (1) from 5 to 7 March with calm, dry and clear conditions with E/SE winds; (2) from 10 to 15 March warmer weather with increased humidity, fair visibility and E winds; (3) 17 (and 18) March with similar conditions as (1) and (4) 28–30 March with high humidity and W/NW winds.

Migration traffic rates

In general, nightly mean MTRs of the RWP were between 2 and 607 times higher than the TI MTR (Fig. 8). Although MTRs of both systems correlated well in some nights, there were large discrepancies in other nights.

During clear and dry conditions as on 5, 6, 7, 10 and 17 March, the four-hourly MTRs of the TI camera and the radar correlated well ($r = 0{\cdot}95$, $n = 5$; Fig. 8). The highest activity measured by the camera was on 17 March (rank 2 in radar). On 6, 7, 10 and 17 March, the radar showed 2 times and on 5 March 6 times higher MTRs than the camera. There was, however, a considerably weaker correlation during the nights of 11, 15 and 30 March with the radar showing migration intensities 41–607 times higher than the camera ($r = 0{\cdot}17$, $n = 3$). In addition, 28 March was the most intense night in the radar, whereas in the TI it was only the fifth most intense. These four nights were characterized by high humidity of around 80–95% and continuous cloud cover or haze. Particularly, striking is the practical absence of migration on 11, 15 and 30 March in the TI device (25, 12 and 5 birds per km per hour, respectively), whereas the RWP registered similar numbers as on 6 March which would correspond to about 1400 birds per km per hour in TI. The greatest discrepancy was recorded on 30 Mar (RWP MTR >600 times than TI MTR), followed by 15 Mar (RWP MTR >41 times than TI MTR).

Flight altitudes

The altitudinal distribution of the RWP diverged considerably from the patterns observed in the TI device (Fig. 9). While migration observed by TI evolved predominantly in the upper height classes corresponding to an approximate altitude of 2–3 km as estimated by Zehnder *et al.* (2001), the RWP profiles showed a concentration of migration at 1 km or lower.

Flight directions

Time series do not provide any directional information. Only in the final wind data involving measurements from several

Table 2. Meteorological conditions at the radar site of Punta Galea, Bilbao, Spain, during the 10 study days

	5 March	6 March	7 March	10 March	11 March	15 March	17 March	18 March	28 March	30 March
Large-scale situation	Anticyclone over W France and Britain	Anticyclone across entire W Europe. Inversion closer to surface level	Inversion is now almost on surface level	The anticyclone slowly moves southwards	Low-pressure area has moved further south, but anticyclone does not cede	Low-pressure area has largely replaced the anticyclone, which has moved southwards, occlusion zone at the Cantabrian coast	Low-pressure area over southern Iberia	Identical to 17 March	Low-pressure area disappeared from Iberia. Fronts approach despite anticyclone west of Portugal	Anticyclone over Atlantic Ocean influenced by fronts
Wind conditions	Very weak SE winds <1000 m a.s.l., inversion at 1000 m a.s.l., >1000 m slightly stronger E winds	Weak ESE surface winds and the winds in altitude are weaker.	Calm conditions, faint N wind only at about 3 km a.s.l.	Calm with weak eastern winds in altitude	Calm with slightly easterly winds below 900 m and westerly winds above 900 m	Calm	Weak E winds at surface level and SE winds >1000 m a.s.l.	Weak SE winds <3 km	W winds, increasing with altitude	Moderate SW/W winds <1000 m a.s.l., strong NW winds >1000 m
Visibility	Good	Good	Good	Fair	Fair to poor	Fair	Good	Good	Good	Good
Cloud cover at radar site	0/8	1/8	1/8	6/8	8/8	7/8	4/8	7–8/8 at sunset, clearing up after 1 h	4-6/8	8/8
Humidity	65–80%	60–81%	62–87%	80–93%	87–93%	81–93%	51–62%	54% (at sunset)–81% (hour 4)	82–93%	82%
Temperature	6–8 °C	8–11 °C	8–12 °C	10–11 °C	11–12 °C	5–7 °C	12–14 °C	11–14 °C	11–13 °C	14 °C

beams flight directions generally point towards NE in spring. Thermal imaging indicated a mean direction of 45·9° for the major part of the migrants (>90%; Weisshaupt, Maruri & Arizaga 2016a).

Bird composition

The camera registered a low fraction (1·8%) of dense bird flocks including 4–8 individuals, indicating presence of non-passerines. However, in the radar no suspicious patterns could be observed that would have been indicative of bird flocks of more than three individuals.

Discussion

QUALITATIVE ANALYSIS OF TIME SERIES (TARGET IDENTIFICATION)

Overall, the qualitative analysis enabled an objective identification of birds. The temporally and spatially limited distinct zig-zag pattern of the bird echoes contrasts clearly against the extensive, although weaker clear-air and precipitation pattern, or other non-bird echoes.

Target classification (bird vs. non-bird) was easiest if migration intensity was low or moderate, as on 5 or 15 March, as the probability for overlapping echoes was low. In case of high bird densities as on 17 and 28 March care is needed not to confuse migrants flying close to one another with copies from side lobes in time series and spectrograms. The diagonal allocation of the individual echoes together with the shape of the echo signature in spectrograms facilitates differentiation (see Figs 6 or 7). However, few ambiguous cases remain, which can either lead to over- (if copies are counted) or underestimation (if true birds are classified as copies). In such cases, a conservative approach which interprets such cases as one bird or alternatively remove them, as done in this study, will lead to a slight underestimation of birds.

As one of the few drawbacks, the present data analysis did not provide any insight into bird composition, for instance, based on flocking vs. individual birds. Theoretically, the dwell time of 30 s per beam should suffice to record flocks. Expected patterns would be multiple echo signatures at close intervals in the same gate in both time series and spectrograms (if birds flew behind each other) or also beat frequencies in time series. Or alternatively, if birds flew side by side, it could be expected to see similar echoes passing in close temporal intervals in both the main lobe and the side lobes, resulting in clustered echoes passing through and outside the zero line in spectrograms. However, the dataset did not present any such case. This could be theoretically explained by the RWP sampling method of recording 30 s vertically followed by a gap of 5 min – given the overall low proportion of bird flocks it could be concluded that they are not readily captured by the beam in this narrow time slot. Considering the TI and moon-watching findings (Weisshaupt, Maruri & Arizaga 2016a, b) and previous literature (e.g. for an overview see Alerstam 1990), it can be assumed that the majority of the targets represent passerines. However, more specific verification devices would be needed to relate any frequency pattern to a specific type of bird.

QUANTITATIVE ANALYSIS OF TIME SERIES

Migration traffic rates

The adaptation of the MTR designed for continuous data to the discrete RWP sampling provided an easily calculable pseudo-continuous estimation of migration intensities. Based on the conservative inclusion criteria for bird echoes, the MTR values can be considered a reasonable absolute and relative measure of migration activity. Given the fact that the migration flow is not uniform throughout the night, the extrapolation of the 30-s MTRs to 5 min seems appropriate. Measurements with high birds numbers are likely to be balanced by low bird numbers which would in the end prevent severe over- and underestimation. In case of high densities, bird echoes could overlap and would be removed based on the rigid inclusion criteria applied in this study. Therefore, peak events as, e.g. the 17 or 28 March, where many overlapping echoes can be expected may potentially represent a slight underestimation of bird numbers. The altitudinal resolution of 60 m in the low mode provides a very fine scale compared to other resolutions used in literature (e.g. 200 m in Zehnder *et al*. 2001 or Dokter *et al*. 2010). The probability of overlapping bird echoes would be expected to be higher in a coarser altitudinal resolution (e.g. 400 m as in the high mode) with a larger sampling volume. Further studies would be needed to assess the effect of the height resolution on quantification.

Flight altitudes

Flight altitudes are based on the radar-specific resolution of the gates. Certainly, a RWP with a high resolution provides a more detailed and more accurate account of height distributions. Therefore, the low mode with its 60-m resolution seems appropriate to provide a good approximation to the altitudinal flight patterns.

MIGRATION PARAMETERS IN RWP VS. THERMAL IMAGING

Migration traffic rates

Migration traffic rates differed considerably between the two sampling systems. There are three possible explanations, (i) the sampling intervals, (ii) sampling volumes and (iii) the (in)dependency on meteorological conditions. An effect from the discrete vs. continuous sampling does not seem very likely given the frequent sampling of the radar. An important point could be the different opening angles of the systems that may account for some leeway in measurements. Possibly the nominal RWP beam width of 6° deviates from the actual operational beam width, influencing thus the MTR calculations, as found for other bird radar systems (Liechti, Bruderer & Paproth 1995). As to meteorological conditions, there are clear indications that the RWP works spotlessly in a variety of weather situations, whereas for the camera clear skies and low humidity are a must, in particular in humid regions as the Basque Country.

Flight altitudes

The divergent patterns remain unclear. Given the nature of the thermal-imaging system based on temperature differences, it could be expected to find a negative bias towards higher flying and small targets as heat differences might not be registered equally well with increasing altitude and small targets might not emit enough heat to be registered (as it is the case with insects in higher altitudes). Also meteorological factors, such as clouds, would lead to the same effect of favouring low-flying targets. Another reason could be the detection range of the camera, which is not as clearly delimited as in the radar. So birds registered in the upper height classes were possibly beyond the detection range of the RWP low mode. In the high mode migration was visible up to about 4 km. However, this does not explain the practical absence of low-flying birds either. Also a bias resulting from the rigid selection criteria applied to RWP data can be excluded as the tentative inclusion of unqualified echoes did not change the altitudinal pattern. Another contributing factor could be that the camera looses sensitivity with increasing age of the system. The initial calibration by Zehnder *et al*. (2001) might not be accurate anymore because far-flying and/or small passerines might not be detected equally well anymore. So even though Weisshaupt, Maruri & Arizaga (2016a) did record the entire spectrum of size classes, it is theoretically possible that migration actually evolved on a somewhat reduced height scale.

Flight directions

Flight directions of targets can be readily analysed in TI data. Directional information of the RWP, in contrast, is only accessible in the final data. These wind (and flight) directions result from the subsequent measurements of the five beams, of which a consensus average is calculated. If birds are present in all beams flying in a narrow directional range, as is the case in high densities in spring (Weisshaupt, Maruri & Arizaga 2016a), their echoes are not removed because there is directional consensus. In case of low densities with potentially higher directional variability in autumn (Nilsson, Bäckman & Alerstam 2014, Weisshaupt, Maruri & Arizaga 2016a), there is the possibility of having no consensus between the beams, whereby the aberrant strong signals (birds) are removed. So both higher variability in track directions and low densities could explain the fact that wind barbs indicating presence of birds are hardly observed in autumn data. However, more research is needed involving analyses with the tilted beams.

Conclusions

The applied methodology combining time series and derived spectrograms allowed for the objective unequivocal distinction between bird targets from all other echo sources and to identify reliably duplicates resulting from strong reflectivities (vertical duplicates) or side lobes (horizontal duplicates), as well as overlapping echoes. Therefore, the quantification could be based on a clean high-quality dataset without any bias from any other (non-)atmospheric signals for the entire vertical profile of 2 km of the low mode. The unambiguousness of target classification as opposed to other meteorological radars (see, e.g. Martin and Shapiro 2007). The reduced storage volume of the RWP time series and the better height resolution make RWPs a valuable and overall user-friendly complement to weather radar data sources.

More work is required to fully assess possible bird composition patterns in spectrograms, e.g. by exploring different frequencies and reflectivities. It would be also interesting to develop an approach to obtain directional birds-only information independent of migration flow by including the tilted beams.

Finally, we would like to stress that this study applies to this boundary-layer RWP model only. Future work will focus on the applicability of the presented approach to RWPs with other specifications (e.g. height resolutions and frequencies) and of other manufacturers. It will help evaluate if the method can be broadly implemented on other wind profiler systems, and potentially develop an operational automated solution to extract bird parameters within wind profiler networks such as E-Profile.

Authors' contributions

N.W. and M.M. conceived the ideas and designed the methodology together with V.L.; N.W. and M.M. collected and analysed the data; N.W. led the writing of the manuscript with valuable inputs by M.M. and V.L.; J.A. provided the facilities for part of the analyses. All authors contributed critically to the drafts and gave final approval for publication.

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Data accessibility

Time-series data plots representing the core of the analysed 4-h intervals per night can be reviewed at the following link on Dryad: http://dx.doi.org/10.5061/dryad.dh62b (Weisshaupt *et al*. 2017). Furthermore, historical data and the original format of the radar wind profiler data can be requested from the Basque Meteorology Agency (Euskalmet) free of charge via infor2-meteo@euskadi.eus by using the following request form: http://www.interior.ejgv.euskadi.eus/contenidos/informacion/tramites_admisnistrativos/es_tramites/adjuntos/Impreso_solicitud_informacion_meteo.pdf.

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Supporting Information

Details of electronic Supporting Information are provided below.

Fig. S1. Mean number of migration nights per month.

Fig. S2. Examples of bird migration in moment data.

Fig. S3. Examples of spectral data.

Fig. S4. Bird migration in final wind data.

Fig. S5. Examples of non-bird echoes in time series and spectrograms.

Fig. S6. Bird migration in low vs. high mode.