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RADAR MONITORING OF SEASONAL BIRD MIGRATION OVER CENTRAL ISRAEL

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ABSTRACT

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A radar ornithological station has been created based on the meteorological radar MRL-5 and a specially designed algorithm. The system enables to plot radar charts within the radius of 60 km combining meteorological data with vectors of bird field flying at different heights and pass these charts online over to air traffic control operators. The data accumulated in the study made it possible to obtain certain characteristics of seasonal bird migration over central Israel. The system and the results of the study have become an integral part of ensuring air safety for Israeli military aircraft. The paper is an overview and summary of a development of the system, which was described in a few earlier publications.

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Key words: radar ornithology, radar meteorology, radar echo, bird migration, air traffic safety

INTRODUCTION

The number of collisions between aircraft and birds directly depends on flight velocities, flight intensity and the concentration of both aircraft and birds in the air (Yakobi 1974, Leshem and Gauthreaux 1996). These collisions lead to loss of human life, highly expensive equipment and death of birds (Bahat and Ovadia 2005, Richardson and West 2005, Thorpe 2005).

The problem is especially acute for military aviation. Striving towards high speeds and high manoeuvrability within significant height range, as well as towards optimum ratio between the net load capacity and the dead weight makes it difficult to protect military planes from at least partial destruction caused by their collisions with birds. In Israel, during the period and within the air layers of intensive seasonal bird migration the number of birds can reach over 500 individuals per square kilome-

tre of air (Bruderer 1992). At the same time, a relatively small territory and Israel's special situation in the region requires extremely high concentration of military aircraft in the air.

In order to develop a concept of coexistence of birds and aircraft within the common air space, one needs, first and foremost, to get a detailed picture of how birds use the air space, namely, to obtain data on maximum bird concentrations, diurnal bird activity, as well as dominant directions, speeds and heights of large and small bird flocks engaged in intercontinental migration. These data can be successfully obtained with the help of radars, which enable not only to reveal bird presence in the air, but also to measure online the abovementioned characteristics of bird flights in the radius available within the radar's range of coverage. A computerized ornithological radar system of this type was created in Israel for bird monitoring and has been used both for research and operational purposes (Dinevich *et al*. 2000, Dinevich *et al*. 2004, Dinevich and Leshem 2007).

The aim of this paper is to give a brief description of the system and to overview some results of the research into the parameters of seasonal bird migration over central Israel.

THE PRINCIPLES UNDERLYING THE COMPUTERIZED BIRD MIGRATION MONITORING SYSTEM BASED ON MRL-5 METEOROLOGICAL RADAR

Glossary and symbols

1. Radar reflectance (Z or η) characterizes the dispersive properties of a target within the ranges of the waves used. Its value depends on the target's dimensions, concentration of targets within the surveillance area, as well as on the dielectric properties of targets and wave length – for details see Stepanenko (1973).
2. Effective scattering area (ESA or σ) characterizes a target's square in cm^2 or m^2, but depends on the of targets and wave length – for details see Skolnik (1970).
3. Differential reflectance (dP) characterizes the ellipticity of a target and its orientation in the space. For globular targets (*e.g.* small drops) it approaches zero dB, while for non-globular targets horizontally oriented in the space (*e.g.* birds) its value is significantly greater than unity – for details see Shupyatsky (1959), Zrnic and Ryzhkov (1998).
4. The polarization device attached to MRL-5 enables to alter the polarization of the radiated signal pulse-by-pulse, from the horizontal to the vertical one and *vice versa*, as well as to measure the polarization parameters of the echo and their correlations.
5. The device for measuring signal fluctuation is a peak detector that enables to isolate and to store in a digital form all the maximum signal values per pulse within any 200 m long strobe selected on the radar during a certain time segment (usually 10-15 s). On the basis of samples thus obtained the software plots their spectrograms with exact binding to the measurement time and target coordinates. The spectrogram is the function of changeability of the target's reflectance in time.

6. Average flight altitudes, maximum flight altitudes, average level of maximum birds' concentration (for entire period) are calculated using formulas:

$$\overline{H_{\max}} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{k}\sum_{j=1}^{k}h_{mij}$$

$$H_{\max} := \max\{\max(h_{mij})\}$$

$$\overline{H_{\max.con}} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{k}\sum_{j=1}^{k}h_{m.con.ij}$$

where:
$\overline{H_{\max}}$ – the mean maximum bird flight altitude over a prescribed period (observation series during a single day or night),
$\overline{H_{\max.con}}$ – the analogous mean maximum bird density value,
$H_{\max}$ – the maximum of all maximum bird flight altitudes over a prescribed period,
j (from 1 to m) – the number of night (daytime) observations,
i (from 1 to k) – the number of 1 h long observations conducted during a given night (day),
h_{mij}; $h_{mcon.ij}$ – the maximum altitude and the maximum bird density over each single observation, respectively.

Theoretical essentials of using radars for bird monitoring

Schaefer (1966, 1968) and Shestakov (1971) measured the dielectric properties and calculated the electromagnetic constants typical of different parts of a bird's body. According to the calculations, 83% of a bird's mass is tissues with high water content and the mean complex conductivity of 52-17·i and 17% of a bird's mass is adipose tissues, bones, *etc*. with the mean of 3-1·i. If we average over these values taking into account the percentage of different body parts, we will obtain the mean value of the dielectric constant to be 44-15·i. The radar echo from birds depends mostly on the reflection from the globe-shaped body (71%) and less on the muscular stem of a wing (11%), the head (6%) and the neck (5%). The plumage has the least contribution to the reflected wave (<2%), just as the reflection from wings and legs (2 and 3%, respectively). The complex conductivity of cloud drops at the temperature of 20°C ranges between 78.5-12.3·i for λ = 10 cm and 34.2-35.9·i for λ = 1.24 cm (Stepanenko 1973). Thus, the reflectance of a large bulk of a bird's body is close to that of cloud drops and is sufficient, therefore, for radar monitoring of birds, just as for monitoring clouds, with meteorological radars being suitable for this purpose.

A review by Eastwood (1967) compares capabilities of various pulse radars for bird monitoring. In a number of works (Shupyatsky 1959, Atlas 1964, Houghton 1964, Bruderer and Joss 1969, Stepanenko 1973, Chernikov 1979, Ganja *et al*. 1991, Gauthreaux *et al*. 1998, Zrnic and Ryzhkov 1998, Buurma 1999, Larkin *et al*. 2002, Gauthreaux and Belser 2003) different echo properties are presented that make it possible to recognize bird echoes against the background of other echoes and evaluations are made regarding application of various wave widths and radar types for bird monitoring.

In Israel, a two wave high-grade meteorological radar MRL-5 has been used for bird monitoring. The radar is mainly intended for measuring the structure as well as the dynamic and microphysical parameters of cloud formations. The radar enables to

scan the surrounding on two wave lengths (3.3 and 10 cm) simultaneously, using a narrow beam (0.5 and 1.5°, respectively), with the scanning being performed both by the azimuth (0-360°) and by the elevation within the upper hemisphere (-2 ÷ +90°). The main parameters of the radar station are presented in Abshaev *et al.* (1980).

Operating MRL-5 on both wave lengths simultaneously allows to reach equality of radar scan ranges and of both transmitter-receivers. Using this mode of operations, the echo ratio at the two wave lengths is determined entirely by the properties of the target.

The MRL-5 used in Israel for ornithological purposed is computerized and equipped with a supplementary device for measuring fluctuations of radar targets echoes and with an auxiliary polarization device.

The accuracy and the resolution of MRL-5 in bird monitoring, as well as the limitation of surveillance range due the Earth's curvature are described in Dinevich and Kaplan (2000). Briefly, these limitations are the following. Within short distances, the main factor that determines the possibility of locating low-flying birds is the value by which the antenna elevation exceeds a certain criterial value that is equal to $r \times \theta / 2$ (where r is the distance from the radar to the target and θ is the magnitude of the beam). At longer distances, the elevation can be decreased, but then the curvature of the Earth will have an impact. Both factors can be taken into account in the formula stating the dependency between the minimum height (in m) at which a target is detectable and the distance (m), being the root of the sum of squares

$$h_{\min} > \sqrt{(r \times \theta / 2)^2 + 3.25 \times 10^{-15} \times r^4}$$

where the first item under the root depends on the beam width while the second one does not. As the width of the beam decreases, the radar's ability for detecting low-flying birds increase, however, the smallest extreme can not reach zero being dependent on the Earth's curvature. At regular refraction level, the radar being located at the sea level and the beam width of 0.5° (at 3.2 cm wave length) the minimum height at which birds are detectable is: 100 m at the distance of 25 km, 350 m at the distance of 50 km and 1000 m at the distance of 100 km. If the radar is located above the sea level, these values decrease correspondingly. For example, the MRL-5 in Israel is located in Latrun at 270 m above the sea level. At the regular refraction level, at the distance of 25 km the radar detects all the birds flying at the level of the skyline ($\theta = 0°$) and even at a certain negatively oriented angle. At the distances of 50 and 100 km the radar detects birds flying at the heights of 100 and 700 m, respectively.

In view of these considerations and based on the calculation of the effective scattering area – ESA or σ (cm^2), we see that at low heights the main factor that limits the distance for radar location of birds is not the station's potential but rather the Earth's curvature and the beam width. According to experimental results, the ESA of a single stork enables the MRL-5 in Latrun to locate it at the distance of 100 m if the bird is flying at the height not below 700 m above the radar level.

Selecting MRL-5 wave length for bird monitoring

ESA measured at both used radar wave lengths are differentiated for birds and insects (Fig. 1). For the sake of comparison, some results obtained to this effect by other researches who used radars of different types are presented as well (Chernikov 1979). We calculated the value of σ by the following formulas (Stepanenko 1973):

$$\text{for } \lambda = 3.2 \text{ cm}, \sigma\ (\text{cm}^2) = 0.6 \times 10^{-24} \times 10^{0.1n} \times R^{4,}$$

$$\text{for } \lambda = 10 \text{ cm}, \sigma\ (\text{cm}^2) = 0.28 \times 10^{-25} \times 10^{0.1n} \times R^{4,}$$

where:
n – the radar reflectance of the target (dB),
R – the distance to the target (m).

The coefficients in the formulas are calculated based on values of the corresponding parameters of the antenna, the transmitters and the receivers. The principle used in the study for isolation of bird echoes is described in Dinevich *et al.* (2001).

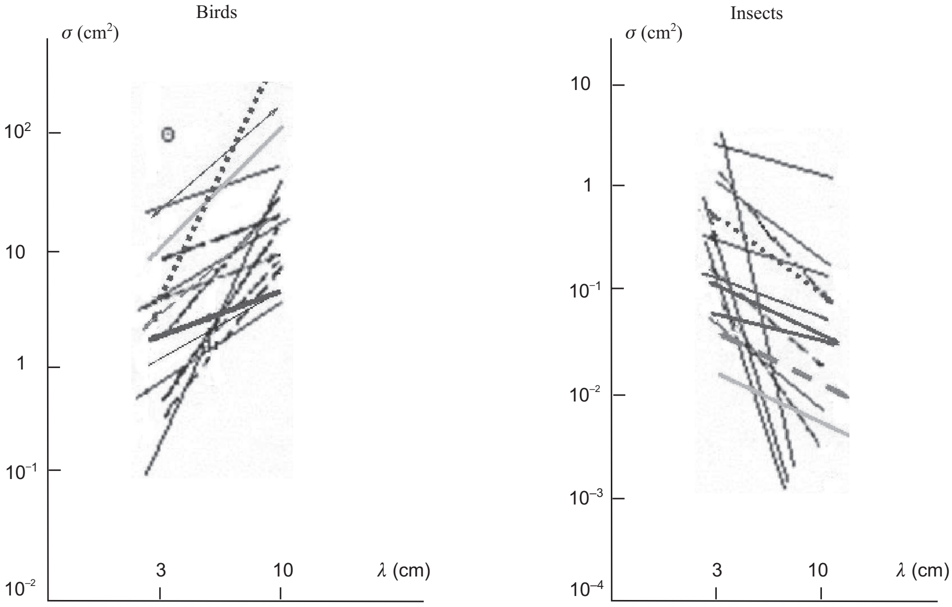

Fig. 1. Effective scattering area – ESA (σ) for different birds and insects on two wave lengths (3 and 10 cm) – examples.

Figure 1 shows that the bird ESA value on the second channel is greater than on the first one and our results are similar to findings obtained by other authors (Chernikov 1979). In some cases, we attributed ESA with certain values to echoes from insects. These ESA values are greater on the 3 cm wave length than on the 10 cm one. Visual observations made within air near ground (at the night time) detected a signifi-

cant increase in the number of insects (midges, moths, mosquitoes, *etc*.). The insects were clearly seen in the light of street lamps, car headlights and observed immediately at a close distance. According to radiosonde data, higher humidity and light NW/W breeze took place in the surface air at the rime of such observations.

For example, on 25 October 2002 at 9.30 *p.m.* the first inversion level was at the height of 800-1200 m. The moon was seen through ambient light and on both MRL-5 channels, a weak but spacious echo was detected, reflected from an invisible atmospheric formation about 500 m thick. One can assume the presence of vertical air flows in the bottom sub-inversion air layer, which led to build up formation of different admixtures, among them insects. A characteristic feature of this echo was the difference between the values of differential reflectance measured at its top and bottom levels. Differential reflectance was measured by the dependency

$$dP = P_{||} \,/\, P_{\perp}$$

where:
dP – the differential reflectance (a dimensionless quantity),
$P_{||}$ – is the power of the reflected signal in mW – a wave of horizontal polarization was transmitted and received,
$P_{\perp}$ – the power of the reflected signal in mW – a wave of vertical polarization was transmitted and received.

The wave's polarization was altered pulse-by-pulse. At the rate of 500 pulses per second the frequency of polarization alteration is 1500 s. Within such a short time segment, positions of the targets relevant for our tasks (clouds, atmospheric inhomogeneities or birds) cannot change.

The value of differential reflectance in the top part of the echo was close to unity (or 0 dB), which is typical of reflections either from globular cloud particles or the boundaries of atmospheric layers with a high temperature-humidity gradient (Chernikov and Shupyatsky 1967, Dinevich *et al*. 1990, Zrnic and Ryzhkov 1998). This phenomenon can be accounted for by the isotropic reflection properties of atmospheric inhomogeneities (invisible thermics or mesofronts), small global cloud drops or small crystals with chaotic spatial orientation (however, there could not have been any crystals in the case considered above).

Differential reflectance of the lower part of the echo was >1, which is typical of non-spherical reflectors horizontally oriented in the space (Dinevich *et al*. 1990, 1994). It suggests that the lower part of the echo was formed not only due to the temperature-humidity gradient, but also due to the horizontally-oriented doublets that are present in the sub-inversion level and that can be caused only by insects or oblong plant seeds. In addition, it should be noted that, according to the radiosonde readings that were closest in time, all these echoes shifted under the direction of and at the velocity of wind. Thus, one can conclude that the echoes we observed within the sub-inversion level on both radar channels were echoes from insects. In all cases, the ESA on the 3 cm wave length was greater than that on the 10 cm band, which well agrees with findings of other authors (Glover and Hardy 1966, Chernikov 1979).

The results of the observations showed that the 10 cm band is more efficient for bird monitoring, *i.e.* both the number of birds located and the distance of location are higher. This can be attributed to the higher potential of the band and a wider beam

that is able to cover birds from a larger space, as well as to the general laws of dispersion for different ratios of a target dimensions and the wave lengths. In view of all these considerations, the second channel, namely, the 10 cm band was chosen for bird monitoring (λ = 10 cm).

Taking into account the diversity of radar targets in the atmosphere (clouds, precipitation, invisible atmospheric inhomogeneities, aircraft, *etc*.), the main goal of the study is to find the properties that are typical of bird radar echo.

The ESA value of the same bird can alter by factor of 10 depending on the bird's body position relative to a radar (Houghton 1964, Eastwood 1967, Bruderer and Joss 1969). According to the data obtained in bird ESA measurements in an anechoic room at different angles relative to the radar beam, Zavirukha *et al*. (1977) found the echo maximum to be between 65 and 115 degrees relative to the radiation beam, which corresponds to the side-ward exposure (beam directed onto a bird's beak is assumed to be 0°). Besides, variations in ESA values can be caused by wing flapping, when the value can increase by factor of 10 or drop down to almost zero. The frequency of these fluctuation can reach 2-24 Hz (Chernikov 1979). Therefore, the ESA of a bird depends on its dimensions, its body projection relative to the radar and the instant configuration of the flapping wings. Hence alterations in the amplitude of an echo reflected from a single bird flying at the same body angle relative to the radar will depend entirely on the wing flapping frequency. The research we conducted into fluctuation characteristics of different types of reflectors enabled to find a fluctuation pattern specific only for birds. On the basis of this pattern and a vast statistics obtained concerning different types of reflectors, a special low-frequency filter was developed for isolating bird echoes (Dinevich *et al*. 2004). The filter enables, at radar antenna haltered, to isolate averaged 1-15 s echo samples reflected from a bird flock at the accuracy of over 80%, and echoes from a single bird at the accuracy up to 95%.

Several researchers (Shupyatsky 1959, Houghton 1964, Chernikov and Shupyatsky 1967, Lofgren and Battan 1969) point to a distinct dependence of bird ESA on the polarization of the signal both transmitted and received, as well as on bird's body position relative to the radar. According to Chernikov and Shupyatsky (1967), the depolarization degree for bird echoes is about -12 ... -13 dB. For a polarimeter with a linear depolarization of transmission and reception, depolarization is defined as the ratio between the values of the main component of the reflected signal and its orthogonal component. If the waves have horizontal polarization, the depolarization expression can be written as:

$$\Delta \mathrm{P}_x = P_{xy} / P_{xx} \text{ or } \Delta P_x \text{ (dB)} = \lg P_{xy} / P_{xx}$$

In the case of vertical wave polarization, the expression is written as:

$$\Delta P_y = P_{yx} / P_{yy}.$$

Here, P_{xx}, P_{yy}, P_{xy}, P_{yx} stand for the components of the received signal power, where the first index is the transmitance polarization type and the second index is the reception polarization type, while x and y stand for the horizontal and vertical polarization, respectively.

In the case of pulse-by-pulse alteration of polarization while transmitting and receiving the same signals, differential polarization can be calculated as:

$$dP = P_{xx} / P_{yy} \text{ or } dP = 10 \times \lg P_{xx} / P_{yy}$$

In a number of studies (Shupyatsky 1959; Dinevich *et al.* 1990, 1994) it was shown that values of depolarization and of differential polarization are functionally related only to the shape of the target and its orientation in space, while being independent from other parameters such as permitivity, signal attenuation, *etc*. Using the two polarization components ΔPx and dP, one can calculate birds' orientation in space and their shape, *i.e.* the ration between the length and the width.

According to Shupyatsky (1959) the formula for calculating the angle of a bird's spatial orientation (θ) is:

$$\mathrm{tg}2\theta = 2 \times dP^{1/2} \times \Delta P^{1/2} \times [dP^{1/2} - 1]$$

The opportunity of isolating bird echo by polarization properties is also mentioned by Zrnic and Ryzhkov (1998). It should be noted that identifying bird echo, either by polarization properties or fluctuation pattern, requires that a sufficient number of echoes is obtained enabling their averaging. According to experimental data, at the rate of 500 pulses per second it takes not less than 10 s to obtain the required number of echoes on the basis of the fluctuation pattern, and not less than half a second at each azimuth on the basis of polarization properties. This fact makes it difficult to use these properties for identifying echoes from large numbers of reflectors in real time within the radar scan range (*e.g.* 60 km in radius) with a rapidly rotating antenna.

As we see both from Table 1 and 2, as well as from the above considerations, signals from all the mentioned reflectors not only have distinct features typical of a certain type of reflectors, but also vary within a wide dynamic changeability range. Due to this fact, all the properties described above, including fluctuation and polarization properties, cannot be sufficient for online monitoring of the ornithological situation within radar scan range. It was necessary to find more distinctive properties that could characterize bird radar echo.

Table 1
Reflectors typically present within bird monitoring area

Reflectors	Characteristic echo properties	Researchers*
Ground clutter (hills, buildings, trees)	Occupy large space, high power, wide fluctuation spectrum both by amplitude and by frequency, relative immobility.	Atlas 1964, Hajovsky *et al.* 1966, Chernikov 1979
Clouds of different types, including convective and stratus clouds	Occupy large space, shift along the direction of the dominant wind flow. Unlike bird echo, the echo from atomized clouds and precipitation is larger at the 3 cm wave length than on the 10 cm one. Echo from globular clouds, at both wave lengths, are significantly larger than bird echo.	Shupyatsky 1959; Atlas 1964; Stepanenko 1973; Chernikov 1979; Doviak and Zrnic 1984; Dinevich *et a1.* 1990, 1994; Zrnic and Ryzhkov 1998

	Polarization parameters of signals in atomized clouds are typical of spherical targets. Differential reflectivity, being the ratio between horizontally oriented reflected signal (when the radiated signal is horizontally polarized) to vertically oriented signal (when the radiated signal is vertically polarized). Is close to unity for small drops. Although clouds evolve in time and space, echo from them remains for a long time located in the same coordinate points, unlike echo from birds.	
Invisible atmospheric inhomogeneities	Low power, chaotic shift patterns in space. Polarization echo parameters are close to similar parameters of spherical hydrometeors.	Shupyatsky 1959, Salman and Brilev 1961, Khardy 1969, Lofgren and Battan 1969, Kropfli 1970, Chernikov 1979, Doviak and Zrnic 1984, Zrnic and Ryzhkov 1998, Venema *et al.* 2000
Aircraft	Significant powers. High shift velocities.	Skolnik 1970
Active noise caused by outside radiators (nearby radars)	Radial orientation, random pattern of signals in time and space.	Skolnik 1970, Dinevich *et al.* 2001
Insects	Low power, the direction and velocity of shift coincide with wind direction. ESA at the 3 cm wave length is larger than that on the 10 cm wave length.	Glover and Hardy 1966, Hajovsky *et al.* 1966, Skolnik 1970
Birds	Relatively low power O Z < 30 dBZ, forward and relatively straightforward movements, maximum amplitude fluctuations within the low-frequency range (up to 10 dB within the frequency range of 2-50 Hz). Echo is larger on the 10 cm wave length that on the 3 cm one. Polarization parameters of signal are characteristic of horizontally oriented targets. Differential reflectivity is significantly higher than unity. The mean ESA values of different bird species at the value of radar wave length less than 10 cm from 15 cm^2 (sparrow) to 400 cm^2 (albatross).	

* only a few of the scholars who studied echo properties from various reflectors are mentioned in the Table.

These newly determined properties, as well as the algorithm of their application and the principles of the radar ornithological system based on MRL-5 radar are fully described in Dinevich and Leshem (2007). Here, we will present the main principles of the solution and some examples of its practical implementation in monitoring bird migration.

Table 2
The ESA (σ) values for different bird species with wings folded measured at different body positions, orientation relative to the radar at the 10 cm wave length (data obtained by Zavirukha *et al.* 1977)

Bird species	σ (m^2) value of birds exposed to radiation in different projections		
	Side	Head	Tail
Rook	2.5×10^{-2}	-	-
Pigeon	1.0×10^{-2}	1.1×10^{-4}	1.0×10^{-4}
Starling	2.5×10^{-3}	1.8×10^{-4}	1.3×10^{-4}
House sparrow	7.0×10^{-4}	2.5×10^{-5}	1.8×10^{-5}

THE ALGORITHM SCHEME

Digitalized signals are entered into the computer and undergo limitation and filtration procedures. In order to increase the “signal/noise” ratio, signals obtained over several pulses are summated (usually 16 pulses). Periodically, signals undergo calibration using the design values of the radar constant and the receivers noise level. For greater efficiency, data are collected more often than it is required due to the radar resolution by distance (Abshaev *et al.* 1984). Each bird is presented in the coordinates “distance-angle” in the form of a spot rather than a dot. Resolution parameters of the radar and the registration system are: for azimuth – 0.5° (radar) and 0.176° (registration), while for distance – 150 m (radar) and 60 m (registration).

In the study described here we obtained a number of additional properties characteristics of a bird’s echo. They are related to the time and space patterns of birds’ behaviour in the course of flying (Fig. 2).The figure shows the total echo field over 18 scans after digital processing. One can clearly see the dot structure of echo streaks obtained from flying birds. Thus, an essential property of bird echo is the character of its motion resulting in transformation of a set of dots into streaks. As can be seen from the enlarged fragments (1, 2, 3, 4) the streaks are relatively straightforward. The increment in the streak length is due to the straightforward motion of echo in time. It is noteworthy that, at the same coordinate point, echoes from ground clutter, clouds and other spacious targets remain unchanged from scan to scan. Only bird echo changes, being characterized by small dimensions and mobility. If we remove all echoes that at the same coordinate point remain unchanged more than a set number of times (1-2) from a summated echo obtained over several scans, we can say with high certainty that the remaining signals are entirely bird echoes. In order to analyse echoes obtained from a hemisphere, the radar must scan the space within a preset range several times, each time at a different tilt. The duration of a single scan is 10 s, the number of scans at the same tilt was experimentally determined to be 8, and the number of tilts, usually not exceeding 6, depends on the beam dimensions and bird flight heights. Further analysis of signals thus selected enables to perform an additional filtration of bird echoes and to plot corresponding vectors representing their flight direction, velocity and height.

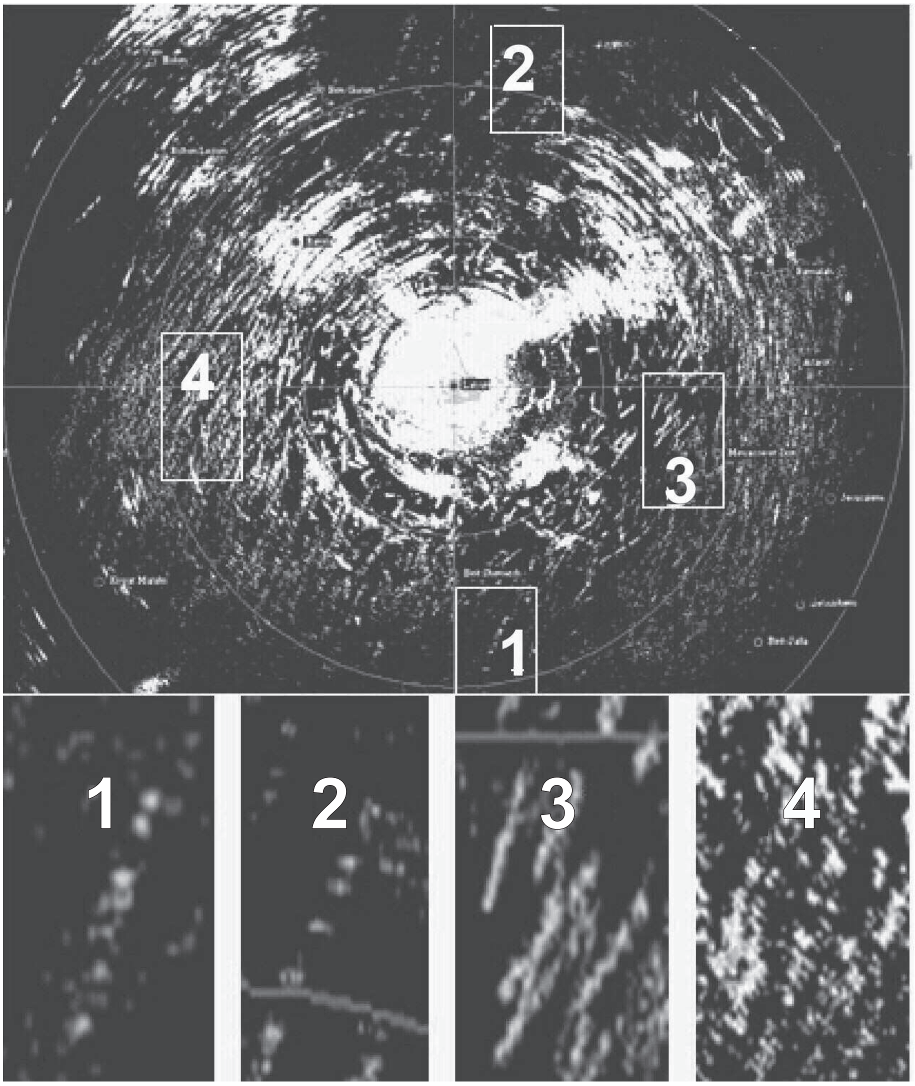

Fig. 2. The echo field after digital processing. Lines formed by sequential dot-like echoes represent bird flight routes. Areal shapeless echoes are reflections from hills. The isolated fragments show how bird flight route lines are being formed by dot-like bird echoes: 1 – a single bird of a single bird group, 2 – two birds or two bird groups, 3 – several birds or several bird groups, 4 – many birds or many bird groups within a zone of high bird density.

The flow chart of the algorithm used for bird identification and measuring bird flight velocities was published by Dinevich and Leshem (2007). The algorithm includes several steps of echo field processing with the main stages being:

1. Analysing echo power.
2. Excluding echoes whose power is below the noise level and above theoretical maximum of a bird echo.

3. Summation of all remaining echoes over a preset number of scans (in this study, 8 scans were chosen as a result of experiments).
4. Isolation of a single bird (bird group) from other reflectors by selecting bird echoes on the basis of motion and the motion pattern.
5. Calculating velocity vector for each bird (bird group).
6. Excluding false vectors using a special method of analysing vector fields based on additional properties (values of radar reflectance, velocities and the degree of chaotic state in flight directions).
7. Plotting ornithological charts of several kinds.

For each bird echo thus isolated, the location of the echo's centre of gravity is calculated taking into account the echo's power:

$$\overline{X}(j) = \sum_i S_{ij}\ X_i \ / \sum_i S_{ij} \qquad \overline{Y}(j) = \sum_i S_{ij}\ Y_i \ / \sum_i S_{ij}$$

where:
S_{ij} – the signal power value,
i – the number of a point within each scan,
j – the number of a scan.

On the basis of values $\overline{X}(j)$, $\overline{Y}(j)$, $t(j)$ (time) root mean square linear regression dependencies $X(t)$, $Y(t)$, $Y(X)$ are formulated. Tangents of slope angles for dependencies $X(t)$ and $Y(t)$ serve as evaluations of bird's velocity components V_x and V_y. Correlation coefficients R_{xt}, R_{yt}, R_{xy} obtained as a result of the regression dependencies are modulus of precision in evaluating velocity components.

Performing the selection of reflected signals based on the properties described above (Dinevich and Leshem 2007) we get a corpus of data obtained over a preset scan range, including separate data on echoes from different targets, such as ground clutter, clouds, precipitation, local and migrating birds, *etc*.

GRAPHIC REPRESENTATION OF THE BIRD MONITORING DATA

A chart of bird vectors within the radar scan range is presented in Figure 3. As an example, two vectors are shown enlarged together with the echo spots used for plotting these vectors. The presence and the pattern of motion are the main characteristics underlying isolation of bird echoes against the background of other reflectors. The actual application of the selection procedure is described in detail in Dinevich and Leshem (2007). After we project bird echoes extracted from the summated data file onto a horizontal plane, we obtain vectors representing the birds within the radar scan range. If we map on this horizontal projection cursors, roads, cities, the coastline, *etc*. and orient the map along the cardinal directions, we will obtain a radar ornithological chart (analogous to a weather chart). The summated data file contains, besides the bird monitoring data, also some data on ground clutter, clouds, precipitation, *etc*. Using colours or other symbols, we can present this information in ornithological charts.

As an example, the processing steps are illustrated in Figures 4-7 basing on data from 21 October 2002, 8.20 *a.m.* Figure 4 presents the total echo chart with bird echoes

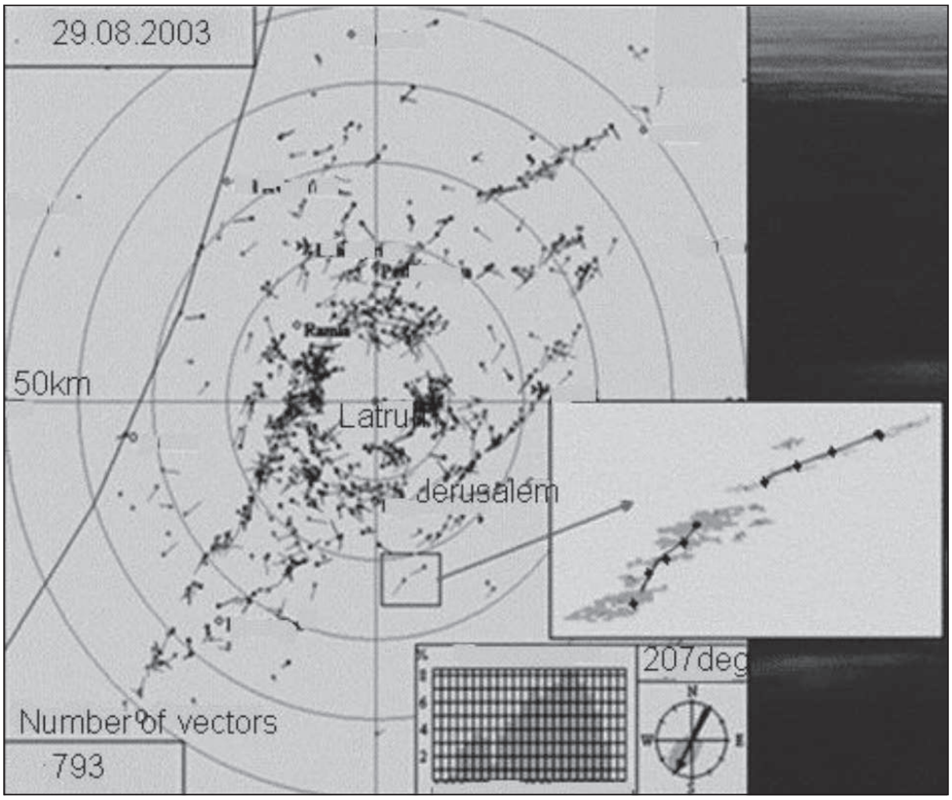

Fig. 3. Example of the ornithological chart - for 29 August 2003. Thin solid line in the west – the border between the land and the sea. Streaks formed by vectors represent birds. An enlarged fragment showing two vectors enables to understand the principle of plotting two vectors formed by the centers of echoes gradually shifting from scan to scan. Distributions of speeds and directions of vectors are given.

not isolated, Figure 5 shows the bird vector field against the background of ground clutter and clouds while Figure 6 is a final picture of the birds movements.

Using the original charts, we can see the type and volume of information it contains:

a) The total number of birds within the 30 km distance from the radar is 2770 (usually charts of this type are plotted in scales of 1 : 30, 1 : 40 and 1 : 60).
b) The number of echoes from birds flying in a certain direction (number of vectors) is 1670. Different colours mark birds with different flight patterns: red – straightforward uniform motion, blue – straightforward non-uniform motion, brown – non-straightforward and non-uniform motion.
c) Maximum bird echo movement velocity relative to the radar is about 68 km/h.
d) Minimum bird echo shift velocity relative to the radar is about 13 km/h.
e) Most bird echoes move at the speed of 45-50 km/h.
f) The dominant flight direction is 177°.

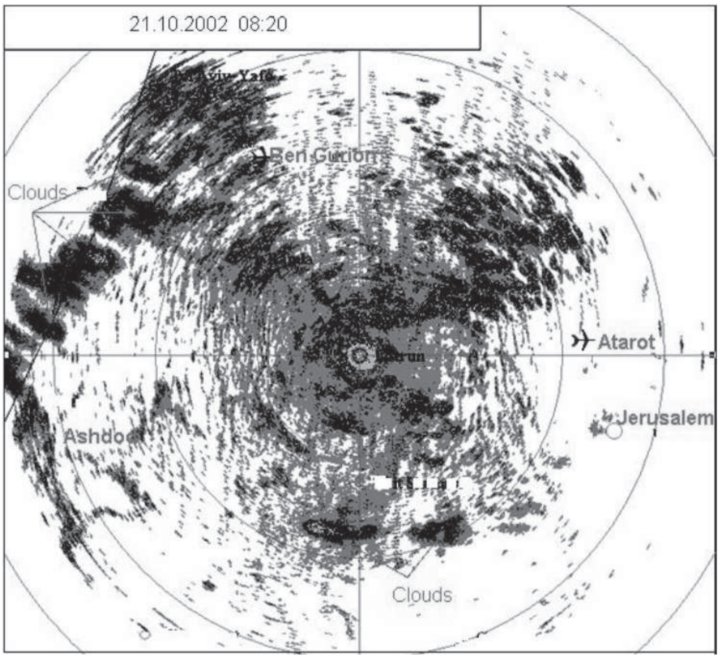

Fig. 4. Chart of the total echo (before the algorithmic echo processing)

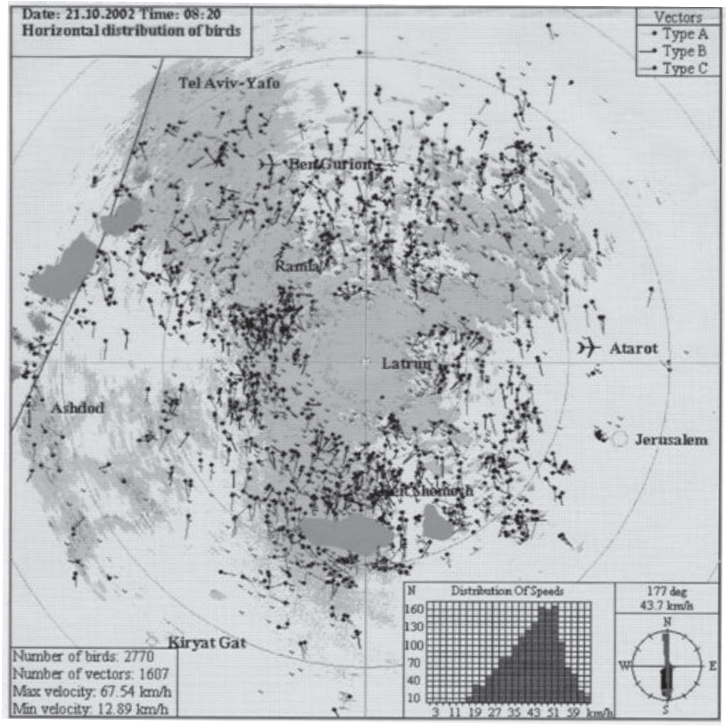

Fig. 5. Ornithological chart with the background of ground clutter and clouds

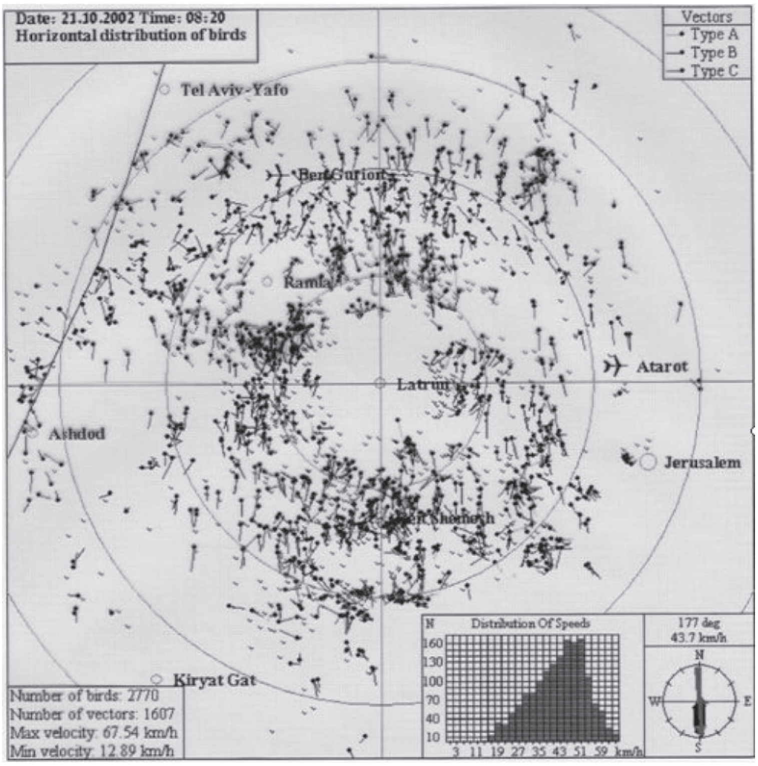

Fig. 6. Ornithological chart in the vector form

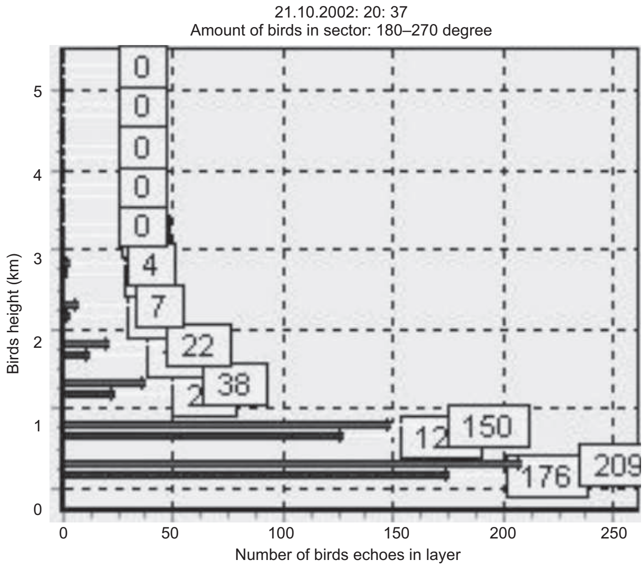

Fig. 7. Distribution of birds in different layers of migration. The maximum concentration of birds is observed within the layer up to 500 m from the ground surface (209 bird groups).

g) The majority of birds fly at a variable speed and deviate from a linear direction, however, there are many birds that, while deviating form a linear direction, fly at a uniform speed.
h) Within the scan range against the ground clutter (hills), one can isolate several groups that differ in bird density.
i) Within the cloud layer, birds tend to fly around clouds over their perimeter or to squeeze through separate cloud cells (to the south of the radar, a bird flock is trying to fly between cloud cells).
j) Within the 180-270° sector (Fig. 7) the maximum concentration of birds is observed within the layer up to 500 m from the ground surface (209 bird groups), a significant number of birds are flying within the 500-1000 m layer (150 bird groups), while a small number of birds are found even in the layer of 1000-3000 m. A complete analysis of the ornithological situation enables to get all this information for the entire hemisphere (360° sector). On the original graph the red stripe shows the total number of birds within a layer (migrating birds flying along certain directions as well as local species flying about chaotically), while the blue stripe represents only echoes of migrating birds, which can be used for plotting vectors.

The system enables to obtain this total data set within the radius of 60 km from the radar every 10-15 minutes online and to forward this information to any user *via* the Internet. In addition, there are several issues to mention.

Atmospheric formations in the charts described above enable only to get some data about their locations and shifts. More detailed information about atmospheric formations (clouds, precipitation, atmospheric inhomogeneities) can be found in other radar meteorological charts, which are plotted simultaneously with the ornithological ones, but are based on data collected through different procedures. For example, one of the requirements for collecting such data is antenna elevation up to 85°. A sample of the meteorological charts is presented in Dinevich *et al.* (2000).

The bird migration pattern changes in the course of a day. Figure 8 presents such changes over time on 29 August 2003, when the migration of storks was intensive. In the left panels one can see how total radar pictures changed with time (including echoes of hills, planes, atmospheric inhomogeneities, birds), while the right panels present the corresponding changes in vectors representing bird flights.

These examples are typical of two types of bird migration, namely, night flights (including few hours of the morning when there are no ascending air flows) and daytime flights (when there are convective flows in the troposphere). In the first case, the birds fly in large flocks occupying large squares and within various heights. In the second case, the bird flocks form long streaks (Leshem and Yom-Tov 1996, 1998; Alpert and Tannhauser 2000).

Experimental data obtained with the help of the developed algorithm enable to collect statistics to evaluate some parameters of inter-seasonal bird migration over central Israel.

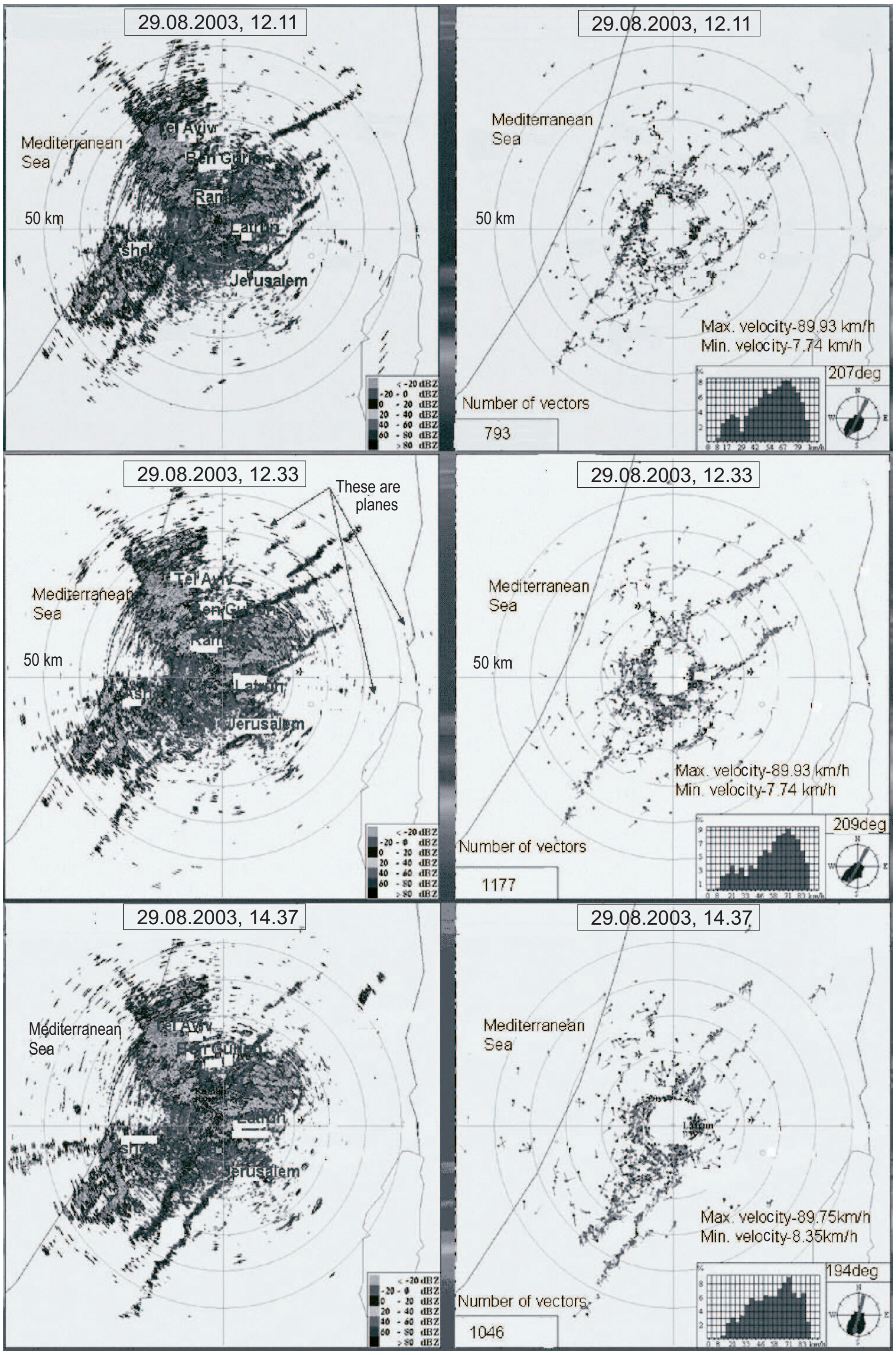

Fig. 8. Progress in stork migration on 29 August 2003, between 12.11-2.37 *p.m.* (on the left - echo from all the reflectors, on the right – bird vector field)

ANALYSIS OF THE EXPERIMENTAL DATA

Techniques used for collecting and processing experimental data are described in Dinevich *et al.* (2001). Basic analytical parameters were defined earlier (Dinevich and Kaplan 2000, also in Dinevich *et al.* 2004) – average flight altitudes, maximum flight altitudes, extreme maximum (for entire observation period), average level of maximum birds' concentration (for entire period). The example patterns for spring and autumn 2003 are given in Figure 9.

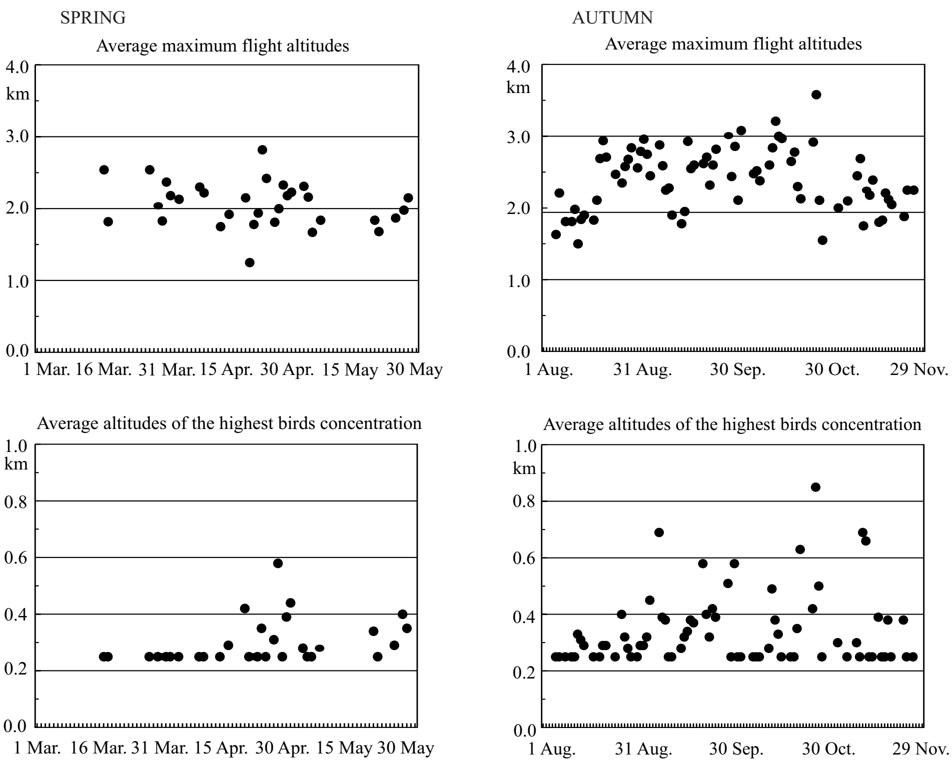

Fig. 9. Some altitude parameters of spring and autumn migration in 2003 for the diurnal/nocturnal migrants

Mean altitude values calculated from the experimental data for the night-time were found to be within the range of 1900-2600 m in autumn (September-November) and 1500-3000 m in spring. These values were much lower in August (600-1700 m). In the daytime, mean altitude values were found to be within the range 1000-2700 m in autumn (September-November) and 1200-3500 m in spring.

BIRD FLIGHT VELOCITIES AND THEIR RELATIONSHIP WITH THE CORRESPONDING WIND PARAMETERS

Bird flight velocities are to some extent differentiated in spring and autumn, both during the day and night (Table 3).

Table 3
Bird flight and wind speeds (m/s) in autumn and in spring

Velocities (m/s)		Spring	Autumn
Mean velocity	daytime night	14 14	15 13
Maximum velocity	daytime night	18 16	16 16
Mean wind speed at the ground surface	11h	5.5	5.0
Mean wind speed at the height of 600 m	11h	3-6	4-7

The mean velocity of nocturnal movements was found to be:

– about 14 m/s in spring – 24% of the total number of birds have flight velocities within the range of 10-12 m/s, over 35% within the range of 12-14 m/s and almost 27% within the range of 14-16 m/s, the remaining 14% have a wide range of velocities,
– about 13 m/s in autumn – about 7% of the total number of birds have flight velocities within the range of 10-12 m/s, 70% within the range of 12-16 m/s and almost, 11% within the range of 16-18 m/s, the remaining 12% have a wide range of velocities.

The mean velocity of diurnal flights was found to be:

– about 14 m/s in spring – over 24% of the total number of birds have flight velocities within the range of 10-12 m/s, over 35% within the range of 12-14 m/s and almost 27% within the range of 14-16 m/s, the remaining 14% have a wide range of velocities,
– about 15 m/s in autumn – over 7% of the total number of birds have flight velocities within the range of 13-14 m/s, over 70% within the range of 14-16 m/s and the remaining 12% have a wide range of velocities.

The mean wind speed at the altitude of 600 m (the values close to that where the maximum migrant bird concentration was found) was within the range 3-6 m/s in spring and 4-7 m/s in autumn. As can be seen from the table, both mean and maximum values of bird flights are significantly higher than the wind speed values both at the ground surface and at the altitude of 600 m.

BIRD FLIGHT DIRECTIONS

The typical bird direction patterns are shown in Figure 10. The radius of the wedges corresponds to the observation frequency. The most common direction of night migration for 90% birds is 183° in autumn and 6° in spring. We observed bird flocks migration at the night-time and early morning towards the Mediterranean Sea in spring and from the Mediterranean Sea in autumn. The sector of these directions is

different from the general sector of seasonal migrations being on average 135° in autumn and 315° in spring. This deviation from the dominant direction of migration in the lower altitudes can be accounted for by the fact that the birds migrating over the Mediterranean Sea are the waterfowls. The most common direction of daytime migration for 90% birds is 190-220° in autumn and 10-50° in spring. The spring direction spectrum is much wider than that in autumn.

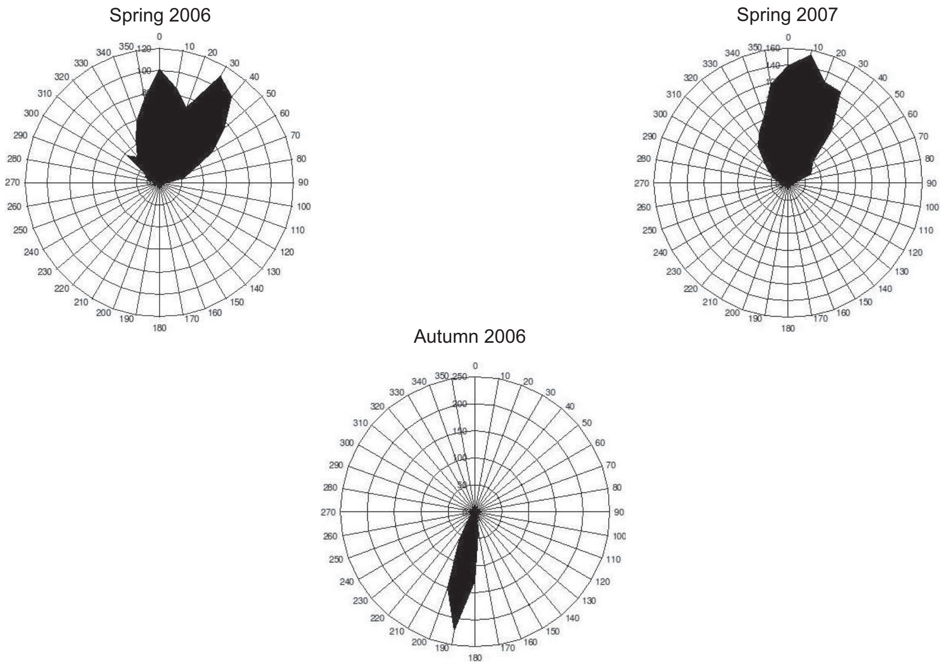

Fig. 10. Distributions of migration directions in spring 2006-2007 and autumn 2006 for the diurnal/nocturnal migrants

The problem of relations between wind pattern and the bird migration pattern is extremely complicated and it will be not discussed here in detail. Both in autumn and in spring the areas of dominant migration directions coincide with the areas of the most infrequent wind directions. Winds over central Israel most often blow from one side relative to the daytime bird flight migration direction, having no significant impact on the distribution of flight altitudes.

RELATIVE CHANGES IN MIGRATING BIRDS DENSITY AT DAY/NIGHT TIME IN AUTUMN AND SPRING

The accuracy of radar estimation of bird quantities depends on several parameters of the radar ornithological system, among them the surveillance span, receiver sensitivity and errors in the bird identification algorithm. In addition, within the ra-

dius of radar surveillance some low-flying birds are screened by high hills or even fly at the altitude that is below the radar beam zero level. For example, a part of the bird migration flow over Israel routes along the Jordan Valley and the Dead Sea. The Dead Sea is located 500 m below sea level. Since the radar is located 270 m above sea level, birds flying at the altitude of 500 m are significantly lower than the beam zero level and these birds cannot be seen by the radar. Taking this into consideration, further research and special techniques are required, in order to determine the error in radar estimation of the absolute number of birds currently in the air.

Nevertheless, using the same technique for collecting data set over several years enables to estimate relative bird density within a unit of air volume in autumn and spring, in the day and at the night-time. According to our data, both during the day- and nigh-time maximum bird quantities cross central Israel in September-October and in late March-April. At night the number of flying birds is by tens greater than in the daytime. For example, during a day within a cubic kilometre of air the maximum number of migrating birds can reach 170 (up to 200 in some cases), while at night this figure approaches 5000 in spring and 10 000 in autumn. The number of birds migrating in autumn significantly exceeds that in spring.

GENERAL CONCLUSIONS

1. Radar ornithological charts plotted on the basis of the algorithms developed in the study contain the following information collected within the radius of 60 km from the radar:
   – the general number of birds currently in the air, among them the number of migrating birds,
   – maximum and minimum bird flight altitudes and velocities,
   – quantitative distribution of birds over altitudes,
   – spectra of flight directions and velocities, including the vector of total direction,
   – vector fields of birds' movement against the background of current meteorological situation and ground clutter,
   – distribution of birds by their flight patterns (degrees of straightforwardness and uniformity).
2. The method proposed for bird identification can be applied to other types of high-grade radars, both coherent and non-coherent ones, whose antennas form sharply targeted symmetric beams.
3. The research enabled to evaluate the main parameters of bird migration over central Israel based on a vast corpus of experimental data. These parameters can be used for plotting optimum routes for aircraft.
4. The radar ornithological system developed in the study has been efficiently used in Israel for the air traffic control.

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