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Application of MRL-5 radar in bird migration research

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Abstract. The computerized radar-tracking ornithological system developed for MRL-5 meteorological radar enables to carry out automatic tracing of bird migration at any time.

The algorithm of bird signals identification on the background of other signals is constructed due to the following principles:

– The radar signal reflected by a bird changes its location in time because of movement. If, even within a short period of time, the bird moves without changing its direction, the coordinates of the radar echo central point form a straight line of continuous tracing as reflected at one angular location of the antenna.

– This feature can be used for vector calculations (both direction and speed) reflecting movement of the bird flock or of a separate bird.

The peculiarity of MRL-5 is that it is equipped with a polarizing device enabling on the 3.2 cm wavelength to change polarization of pulse-to-pulse radiation and, correspondingly, to accept the signal of the same polarization as that of the radiated one, together with its depolarization components. The present report shows that the depolarization degree of the signal as reflected by birds is approximately that of 7 $div - 10$ dB. Calculated and experimental data indicate that the MRL-5 radar characteristics at the height of 270 m above the sea level provide identification of a single bird of the albatross size flying 700 m high at the distance of 100 km. Bird like sparrow could be detected at the flight height exceeding 100 m, 15 km (in flock – up to 30 km) away from the radar location. The narrow symmetrical diagram of the antenna direction is 0.5° for 3 cm and 1.5° for 10 cm. This enables to determine the flight height of a single bird or of a flock within the radar-tracking space with high precision.

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1 Statement of the problem

Development of the aircraft industry, dense concentration of aircraft vehicles on rather small territories, especially within the vicinity of large airports, aspiration for high speeds of light flying devices brought about inevitable conflicts between the technical progress and natural phenomena, among them the conflict between aircraft and other artificial flying devices and migrating birds. Quite often, such collisions not only lead to extermination of birds, but also result in heavy accidents and human victims. This phenomenon brings about the necessity of developing efficient operative means for control of the ornithological situation.

2 Standard tasks and peculiarities of MRL-5 Radar installed in Israel

The MRL-5 radar is a meteorological radio location appliance of high potential, developed and produced in Russia. The station (see Fig. 1) is intended mainly for measurement of internal structure and microphysical characteristics of various cloud formations at different stages of their development. Its basic practical application relates to investigation of clouds and seeding with the purpose of increasing or reducing precipitation, preventing growth of large hailstones, and measurement of the rain quantity.

Four years of experiments held in Israel (4, 5, 6), showed that MRL-5 can be successfully applied in ornithology to provide the aircraft with information on parameters of large bird flocks migration, such as flight height, speed and direction, both at daytime and at night.

The MRL-5 radar features are as follows:

1. Two separate channels with high potentials, 3 cm (the first channel) and 10 cm (the second channel). Sensitivity of the first channel (the minimal signal identified on the background on noises) is 10–14 W, and of the second one is 10–13 W. By the operator's choice, the channels can function both simultaneously and separately.

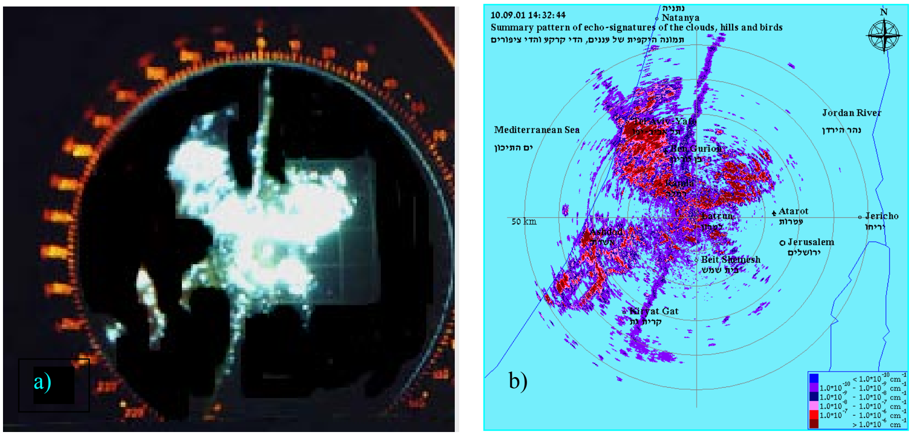

Fig. 1. (a) Photo of radar screen; **(b)** File print of radar echo computer processing for the same time interval presenting the flight of Honey Buzzards on 9 September 2001.

2. The antenna system proves identical width (1.5°) and coincidence of direction diagrams as reflected on both channels with high precision. Since coincidence of diagrams is not required in some cases, it is possible to use the parabolic antenna of the 10 cm channel with diameter of 4.5 m for the 3 cm channel, thus forming a direction diagram of 0.5°.

Such application of the parabolic antenna for the purpose of increasing the direction diagram precision was realized by means of the Israeli MRL-5 radar, its direction diagram for the first and the second channels being 0.5 and 1.5°, respectively.

The technical specifications of MRL-5, equipped with a polarizing appliance, are provided in (1) below. Concise characteristics of the polarizing appliance are summarized in (3) below. Here we shall only note the feature that enabled to obtain an additional advantage in detecting weak bird signals.

On the standard MRL-5 antenna, radiation and reception of electromagnetic energy of both wave bands are generated in orthogonal planes, while vertical polarization is chosen for the 3 cm channel. The small beam angle of the 3 cm channel (0.5°) makes it extremely convenient for measurement of changes in the bird flight heights. Precision of the measurement implemented on this channel, due to its small beam angle, is much higher than that on the 10 cm channel (which is 15°). For example, at the distance of 50 km, the measurement precision for the 0,50 beam is 200 m, while for the 1.5° beam it is 500 m. Taking into consideration that the initial position of birds in space is horizontal, and concurrence of the target orientation and the radiated signal results in increase of reflection (6), the horizontal polarization of the radar-tracking signal renders to reflect in our case the optimum value. Hence, for the first channel of the standard MRL-5 version, it is necessary to turn the polarization surface of the radiated signal and to make it horizontal. As obtained by experimental data (see Table 1), this provided an increase in the size of the signal reflected from birds on the 3.2 cm wavelength for about 5–10 dB.

Table 1. Reflection from night birds moving at different distances from the radar (at least 8 km) under horizontal and vertical radar signal polarization ($\lambda = 3.2$ cm)

No	Distance (km)	Horizontal polarization (dB)	Vertical polarization (dB)	Difference (±)
1	10	15	10	+5
2	12	24	16	+8
3	30	18	8	+10
4	21	16	6	+10
5	26	19	14	+5
6	17	22	13	+9
7	14	21	12	+9
8	19	16	8	+8
9	29	14	8	+6
10	32	12	6	+6
11	8	27	20	+7
12	26	18	8	+10
13	24	16	8	+8
14	31	14	6	+8
15	17	25	18	+7
16	18	16	10	+6
17	9	18	12	+6
18	25	18	9	+9
19	31	13	6	+7

In Table 1 below, reflection data are presented in dB since they are provided with the corresponding data of distances to the targets. Besides, the values of the signal polarization ratio do not depend on the distance and are usually measured in dB.

Table 1 provides the reflection data related to horizontal and vertical polarization on the 3.2 cm wavelength, as obtained from night birds detected at various distances by means of MRL-5.

Table 2. Calculations of the efficient scattering area (ESA) for several bird species

No.	Species	Body length (cm)	Body width (cm)	Cross section (cm^2)
1	Sparrow	5	3	15
2	Pigeon	8	4	30
3	Starling	6	3	15
4	Sea gull	15	8	120
5	Albatross	30	12	400
6	Lark	10	6	60

3 Efficient scattering area for several bird species

Table 2 provides calculations of the efficient scattering area (ESA) for several bird species. These calculations were performed by means of the principal radiolocation equation for a single isolated target detected on the radar wavelength $\lambda \leq 10$ cm. ESA of a single bird, which is big enough (i.e., comparable to the wave length), is approximately equal to its cross section without feathers (8). This ESA depends on its flight phase as related to the radar. These correlations can be used for identification of the bird species. The level of the signal which serves the basis for ESA calculation, renders to be one of the criteria for recognition of the bird radio echo.

4 Limitations of bird migration observation range due to the Earth curvature

As it is known, the maximum observation range $\boldsymbol{r}_{max}$ (km) caused by the Earth curvature depends on the height h_1 of the radar location and the height h_2 of the target:

$$\boldsymbol{r}_{max} = 4.18\left(\sqrt{h_1} + \sqrt{h_2}\right). \quad (1)$$

Actually, the height of the radar location is substantially insignificant as compared to that of the target, and thus it can be neglected in formula (1):

$$\boldsymbol{r}_{max} = 4.18\sqrt{h_2}. \quad (2)$$

In reverse representation, this formula defines the minimum height (m) at which the target is visible at the given range (m):

$$\boldsymbol{h}_{min} = 5.7 \times 10^{-8} r^2. \quad (3)$$

Upon defining the maximum observation range (1, 2, 3), the width of the direction diagram beam is accepted as negligibly small, and it is supposed that the angle of the radar beam towards the Earth surface renders to be zero. However, under extremely small angles of the antenna, the beam "clings" the Earth surface, thus causing changes in the amplitude of the received signal and, what is even more essential, appearance of reflections from ground objects (mountains, buildings, constructions etc). Since the bird signals are weak, the reflections from ground objects conceal them and make them indistinguishable. Even at high elevation angles of the target, the sought signal can be concealed by reflections from local ground objects at the expense of the flank lobes of the antenna direction diagram. Neglecting these flank lobes, let us accept that the whole radiation is concentrated in the major lobe. Then, under the elevation angle of the target exceeding half of direction diagram width $\gamma > \theta/2$, the whole antenna beam is located above the Earth surface, thus enabling to get rid of reflections from the local ground objects. It must be noted here that distant local ground objects cause no reflection, since radar-tracking beam avoids the Earth surface because of its curvature. At the lowest position of antenna $\gamma > \theta/2$ the minimum target height depends on its range:

$$\boldsymbol{h}_{min} > r\theta/2. \quad (4)$$

Thus, for small distances, the principal factor determining the possibility of low-flying birds radio location is exceeding of the elevation angle by the antenna above some crucial threshold value equaling $r\theta/2$. For large distances this elevation angle can be reduced, however in this case the surface curvature will effect the reflection. Both these factors can be taken into consideration in the formula providing the minimum height value depending on the distance, as a root of the sum of squares (3), (4).

$$\boldsymbol{h}_{min} > \sqrt{(r\theta/2)^2 + 3.25 \times 10^{-15} r^4} \quad (5)$$

Here the augend under root depends on the direction diagram width, while the addent does not. Upon reduction of the directional diagram width, the capacity of the radar to receive signals from low-flying birds increases, however the low height limit cannot be zero, since it depends on the Earth curvature. Under normal refraction, radar location at the sea level and direction diagram of 0.5°, the minimum height at which birds can be distinguished is 100 m for the distance of 25 km and 350 and 1000 m for 50 and 100 km respectively. In case of the radar location above the sea level, these parameters decrease accordingly. Thus, for example, the MRL-5 radar in Latroun (Israel) is located 270 m above sea level. Thus, under normal refraction, it will distinguish all the birds at the horizon level ($\theta = 0°$), and even under some negative angle, at the distance of 25 km. At distances of 50 and 100 km, the radar will distinguish birds flying at heights of about 100 m and 700 m accordingly.

Out of the calculations above, we can assume that at small heights the curvature of the terrestrial surface and the width of the direction diagram, and not the potential of the station, are the principal factors limiting the range of radar-tracking identification of birds.

Let us calculate the identification range of a single pigeon, an albatross (cross section approx. 100 cm^2), a lark (10 cm^2), and a sparrow (1 cm^2). For the 10 cm channel, the pigeon and the albatross will be distinguished at the distance of 110 km, the lark – at 62 km, and the sparrow – at 35 km.

For the 3.2 cm channel these parameters are 50, 26, and 15 km accordingly.

Observations of the MRL-5 radar functioning in Latroun showed that the maximum distances enabling reliable identification of a single bird on the 3.2 cm channel are as follows: For large birds such as storks, eagles etc., this distance is 100 km and, occasionally, more (in case the birds fly high, there is no positive refraction, etc.); for small birds such as larks, sparrows, this distance is 20–30 km. Such dispersion of the above findings is connected with different flight heights of these birds under different weather conditions. The higher the birds fly, the larger is the distance at which they can be identified. The calculated distance of identification for the common crane under the value of its ESA 1000 cm^2 at the 10 cm wavelength is 190 km. However, for the 1.5° direction diagram (the second channel of MRL-5), it must fly at a height of 3 km at least, and for that of 0.5° (the first channel) – 2 km at least.

5 Characteristic reflectors of the radio location signal and sources of false signals

The obtained findings of the observations identify the specific features characterizing the reflectors of the radio location signal and the sources of false signals (clutter) within the range of the experiment, as follows:

- Clutter caused by local ground objects (hills, structures, trees);
- clouds of various types (convective, stratum, warm precipitation typical for this region, caused by clouds without overcooled areas);
- invisible atmospheric formations (atmospheric temperature heterogeneities, such as bubbles, fields or lines of breeze and mountain-valley origin);
- flying objects (planes, helicopters);
- reflective effects appearing under conditions of positive refraction;
- fruit pulse of transmitters working on similar or close waves;
- insects and birds.

Signals from the objects above are characterized by a wide dynamic range of sizes, and possess specific features, which are characteristic of each kind of the reflected object or of any active interference. Due to preliminary experimental evaluations, the distinctive attributes of bird signals on a background of other targets can be identified on the basis of analysis of their static characteristics, by using the whole scope of possibilities provided by this non- coherent radar, as follows:

- ratio of signals on two wavelengths;
- values of signal polarization characteristics for various types of reflectors;
- peculiarities of signal fluctuation;
- specific reflection values for various targets;
- mobility of reflectors and the character of this mobility, etc.

6 The basic principle of algorithm selection for radio-echo processing of bird migration

The initial data for these measurements are the fields of radar-tracking reflection received by means of successive azimuth scanning implemented under the fixed antenna elevation angle. The regular number of scanning procedures is 7–9. The signal reflected by a bird changes its location because of its movement. Under successive scanning, the coordinates of the center of this signal form a direct line, if the bird flies without changing its direction. This feature enables to single out the moving signal on a background of motionless signals as reflected by other objects (spreading surfaces, clouds, precipitation, etc.). Besides, the information obtained from the moving signal can be used to evaluate the speed vector for a single bird. The algorithm includes three basic stages, as follows:

- analysis of the power of signals received, and their selection due to the power level;
- contouring of the area occupied by the signal from a single flying bird (or a group of birds) and separation of each single bird (or a group of birds) from other reflecting objects;
- speed vector calculation for each single bird (or a group of birds) and selection due to the correlation index criterion.

The program provides that at least 4–5 of the 7–9 possible points of the radio echo obtained will be within the area adjacent to the direct line. The last two stages are repeatedly recycled at various thresholds of the contour construction. This recurrence allows equally efficient identification of birds both in case of spaces with rarefied signals (few objects reflected) and in case of dense spaces (many objects reflected). On the basis of this concept, mathematical algorithms and methods of computer processing were developed to provide the digital presentation of the radio echo as an integrated image (all kinds of radio echo as observed on the radar screen) and as separate reflections from individual birds singled out from the summary radio echo, presented as vectors. A detailed analysis of the radio echo from birds is provided in (6).

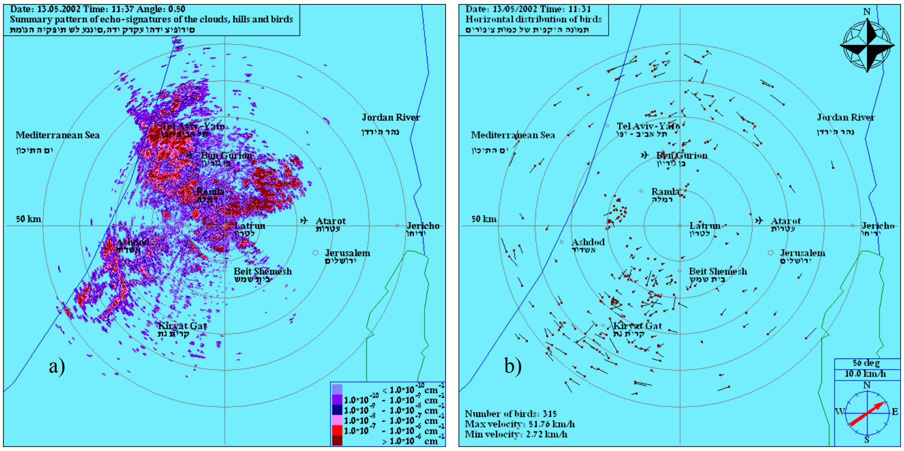

Fig. 2. File prints of the same ornithological situation presented as integrated radar echo from all targets **(a)** and vector radar echoes after allocation of signals only from the birds due to accepted algorithms **(b)**.

7 Findings of bird tracing by means of the computerized radar-tracking system and their discussion

On the basis of the said above, a radar-tracking computerized ornithological complex has been established in Israel, allowing to transform the analog signal of the radar echo into a digital one and to distinguish, on the background of various reflectors, a radar echo from birds. Figure 1a and b presents a photograph of the radar screen (a) and a file printout of the corresponding radar echo computer processing (b) for the same time interval, describing the flight of large flock of honey buzzards on 9 September 2001. The screen radius of the photographs and the radius of the big circle in the file printout is 50 km. The flock moved not far from the radar location, from the north to the south, at a height of about 150–200 m, which allowed its visual observation. The figure, both in (a) and in (b), presents a clearly distinguishable strip of birds 100 km long. The space radio echoes, both in (a) and in (b), constitute clutters as reflected from ground objects. If the photograph is accepted as an authentic model of the system, then the file printout presents correctly the actual radar echo from birds and from other reflectors.

In Fig. 2a presents the file printout of the integrated radar echo under elevation angle 0.5°, showing everything detected by the radar in the radius of 60 km: local ground objects, birds, planes, atmospheric formations. Long strips and points display the radar echo from birds. Section b in Fig. 2 is the file printout of the same situation after the bird signals are separated by means of the algorithms as described above. This figure presents only the radio echo from birds as vectors with lengths corresponding to the speed of the bird movement. The selection program discriminated 351 bird or bird groups located in one radar-tracking volume. Accepting that each point echo of the radar present 20 birds on average (7), the given field of vectors in the layer located under 0.5° above the horizon within the radius of 60 km, corresponds to seven thousand birds. The maximum bird speed is about 52 km/h, the average flight direction is 565°.

These vectors coincide well with the locations of strips and point echoes of the radar, as displayed on Fig. 2a. Comparison of the file printouts indicates that the chosen algorithm allows efficient selection of the signals from the birds with a high degree of reliability.

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