Optical-Electronic Matrix System for the monitoring of nocturnal migration of birds

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Abstract

This paper is dedicated to a new technique for advances in the study of the main parameters of flight and monitoring of nocturnal migration of birds. The Optical-Electronic Matrix System allows us to detect and record aerial targets in the night sky of a size greater than 5 cm and at an altitude of 100 to 1000 meters a.g.l. The principal design features are: (1) An optical device for receiving images of flying targets on three high-sensitivity CCD matrices when illuminated by infrared light from searchlight beams; and (2) Instantaneous parallactic computation enabling the distance from the device to target to be accurately measured, and sequential images of each target to be recorded to a computer. The device has been tested on songbirds during seasonal nocturnal migration and provides accurate image details of important target flight parameters including altitude, linear size (wingspan and body length), the direction of flight – track, the orientation of the body axis – heading, groundspeed, airspeed, wing-beat frequency, number of beats in each series of wing-beats, duration of the pause between series of wing-beats, and type of flight trajectory (straight or curved). Special attention was given to one of the major difficulties in research of bird migration – the potential for the identification of individual species of birds flying in the night sky by the combination of the recorded flight parameters. There are also potential practical applications for aviation bird-strike at night as well as the remote monitoring of insects, bats, and other targets of natural and artificial origin.

Keywords: optical-electronic device, monitoring, nocturnal migration, birds

1. INTRODUCTION

Ecological monitoring of bird migration involves both diurnal and nocturnal field observations. More than half of the species nesting in North America and Europe migrate nocturnally [1] and are difficult to record in the dark. They form from 63 to 85% of the total (day plus night) stream of passage [2]. Migration at night is typical for many waterfowl, waders, and especially passerine birds with a size range of 10 - 50 cm [3]. They fly at altitudes of 1-3 km and airspeeds of 5-20m/s [4,5]. The task is to solve the problem of detection and identification of the small size targets moving in darkness at a considerable distance from the observer and to capture their visual images. Monitoring of migration is not only a quantitative estimation of the stream of birds but also their identification and collective flight parameters. Because the flow of migrants usually consists of dozens of species that may exhibit different migratory directions, altitudes, flight abilities, and migratory strategies it is an advantage to be able to distinguish particular species or groups of species that are similar in their taxonomy and ecology. The study of the nocturnal migration of birds under natural conditions is limited by the possibilities of the methods used for observation and identification of targets in the sky at different altitudes. There are numerous current techniques for the detection of birds flying at night and observing their flight characteristics. Ornithologists have traditionally used the following methods: moon-watching, i.e. observing by telescope birds crossing the moon disc [6], the infrared thermal camera which generates an image of the warm part of the body of a warm-blooded animal flying at considerably low altitude [7], weather surveillance radars which are excellent for broad front bird survey and migration forecasts in real-time [8] and tracking pencil-beam radars [5]. These methods are applied to gather information on the numbers, flight directions, speeds, and altitudes of birds aloft. But they do not provide real images of the flying object and solve the main problem of nocturnal migration research - species identification. Visualization of the target, the shape of its silhouette, and measurements are important for bird species identification and discrimination between birds, large insects, and bats, all of which may be numerous in some regions [7]. Presented here are the results of five years of joint experimental research work of ornithologists and engineers, culminating in the design and testing of a new Optical-Electronic Matrix System (OEMS) for the detection and recording of nocturnal aerial targets. The images and the significant parameters obtainable using this equipment we believe will contribute a significant step forward in bird migration research.

2. REQUIREMENTS FOR THE DEVICE

The following requirements for further advances in this field of biological research have influenced our design during the development of this device:

I. To create a clear image of a flying target to ensure adequate accuracy of measurement of its linear size.

II. To collect and store statistically representative data.

III. To monitor continuously the migratory activity through a series of complete nights at frequent sample dates throughout the migration seasons.

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IV. To catalog the following main flight parameters for each recorded bird: a) altitude; b) linear size (body length and wingspan); c) direction of flight (track); d) orientation of the body axis (heading); e) ground speed and airspeed; f) wing-beat frequency and its variation; g) the number of beats in each series of wing-beats; h) duration of the pause between each series of wing-beats; and i) type of flight trajectory.

The principal system design used to meet these requirements is a parallactic computation of the distance from the device to the target. This enables subsequent calculation of the target linear size from a known distance and its angular dimensions; the ground speed from the angular displacement for a known time interval; and the dynamic characteristics of the target and its orientation in space from the pattern of trajectory with a sequence of the instantaneous images. The main concern was to overcome the contradiction between the need for a high angular resolution to ensure the required accuracy of measurements on the one hand and the need for a wide field of vision on the other to achieve a statistically representative sample of targets and to consider trajectory type.

3. DESIGN SOLUTIONS FOR THE DEVICE

The device consists of two main components: the recording unit (electronic-optical system) and the illumination system, separated from each other at the locating distance of 5 m.

3.1 The Recording Unit.

The image of an object, under the artificial illumination of infrared light, is received on three high-sensitivity CCD matrices. The optical system consists of three channels with parallel optical axes; the twined channels are separated from the third one at the locating distance by 1 meter (see Figure 1). Each channel includes a high-quality objective lens, a heating anti-condensation system, an image precise focusing unit, and a CCD matrix camera. The objective lenses have different focal distances. In this project we used three lenses with the following parameters: F (focal length)=50 mm (6°FoV), S (focal length/aperture)=1.7; F=86 mm (3.5°), S=1.5; F=120 mm (2.5°), S=1.8. Their different combinations determine the angular resolution and field of vision of the channels. The scales of the fields of vision differ by a factor of 1.5–2.5. Their centers are accurately superimposed by the laser beam. During the exposure time (0.3–1.5 seconds) a target usually passes an angular distance of 0.25–5 degrees depending on its altitude. One channel is equipped with an obturator (rotating) shutter which breaks the track of an object into 10–50 instantaneous and sequential images within one frame. The obturator shutter is servo-controlled by an independent computer which allows the setting of an accurate speed of rotation and required time interval between separate images with a duration of exposure of 18–25milliseconds. The speed of rotation is optimized and governed on the assumption that the most probable speed of a bird at the moment of observation varies between 5 and 20 m/sec, with an average of about 10 m/s [5]. Modern CCD matrix cameras allow us to use an electronic shutter and program a high frame rate (75-100 f/s) and set a short exposure (we used 5 milliseconds). The electronic shutter has several advantages. It is convenient to operate and makes it possible to generate up to 50 silhouettes of the bird on one saved image with an exposure of 1sec. Program subtraction of noise and background flare provides high contrast of a series of sequential silhouettes generated on one image. The channel with a wide field of vision works without a shutter and forms the image as a target track of variable width and brightness. Besides the frame, each file saves information on the moment of time of exposure on the matrix, exposure sequence, and other parameters of the obturator, which are required for subsequent processing. Average volume per night is about 50,000 files with a total volume of 25 Gb. To provide uninterrupted monitoring, the system works continuously throughout the night. Further data analyses are performed after the raw data collection.

3.2 The Illumination System.

The flying targets were illuminated from the ground by a narrow faint beam from searchlights. Nocturnal migrants can be attracted by white light which changes their natural behavior [9]. Our previous investigation showed that such attraction is typical of nights with rain, drizzle, high air humidity, and lower cloud cover [10]. We rejected the use of a white searchlight beam and switched to infrared (IR) light panels instead, composed of IR light-emitting diodes (in total 600 x 3W LEDs, with 5° FoV) with a wavelength of 805 nm. This wavelength is invisible to birds [11]. Adjustment to the searchlights is a critical technique that requires preliminary computer simulation depending on the current weather conditions. To improve this procedure an additional adjusting searchlight was used which formed a reference grid in the night sky using three needle-shaped beams. After adjusting this grid, white lights were switched off in order not to attract birds.

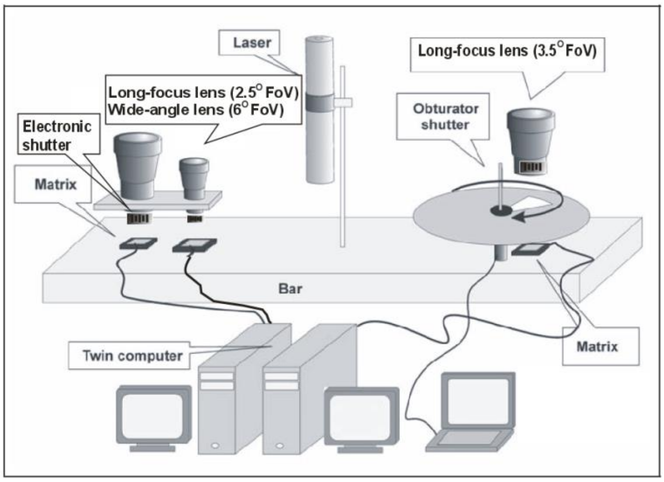

Figure 1. The Recording Unit. The objective lenses of 3.5°/ 6° and 2.5° are separated from each other at the locating distance by 1 m.

4. COMPUTATION OF FLIGHT PARAMETERS

4.1 Altitude of flight

The altitude of flight was calculated by a parallactic computation of the distance from the OEMS to the target simultaneous observed from two points separated from each other at a fixed distance. A locating distance of 1 m provides an error of altitude measurement of about ±50 m. The results of our observations have shown that small objects (birds of wingspan up to 20 cm) are recorded regularly at the range of 650 m and relatively large objects (birds with a wingspan of 30 cm and more) – at 800-1000 m. The illumination system of the OEMS allows the recording of targets within an altitudinal range of 100–1000 m. Birds flying higher have low-quality silhouettes and maximum error of estimation of their size is over 30%–40%. In the lowlands of Europe and North America, passerine birds may fly at altitudes up to 2000–3000 m a.g.l. during their seasonal migrations. Nevertheless, the bulk of passerines (70%–80%) fly below 1000 m [4,7].

4.2 Linear size of birds

No technical system is currently available which allows measurement of the real size of birds flying at night. The linear size, i.e. wingspan and body length, is measured on the basis of angular size and distance to the bird (see Figure 2). The margin of error in the measurements obtained from high-quality silhouettes (about 80% of received images) is 3%–10% depending on the altitude of the bird.

4.3 Flight direction (track) and Heading (axis of body)

Tracks and headings often may not coincide especially when the bird is subjected to wind displacement and tries to compensate for lateral drift. The clear image of the silhouette for the first time made it possible to measure an angle between the track direction and the heading. The accuracy of measurement was about 3°. We were surprised to find that in most of the birds (75%) the headings and track directions deviated by more than 5°. Long tracks (>30 m) were recorded in 37% of birds. A straight shape trajectory over the whole visible length of track was recorded in 80% of tracks.

4.4 Ground speed and air speed

Ground speed can be calculated by two methods: 1. From the duration of the exposure of one frame via any channel. In each frame during exposure time a bird passes a certain path. The exposure duration is known. The path is calculated relative to the altitude of the bird. The ground speed of a bird is calculated on basis of the length of its path and duration of exposure. 2. In some cases the beginning or the end of track are cut off by the edge of the screen. This is typical for the tracks of low flying birds. In these cases we can calculate the ground speed by the frame rate of an electronic shutter or frequency of rotation of an obturator shutter on the channels with fragmented tracks. The frame rate (or frequency of rotation of an obturator shutter) is known and the time interval between the sequential silhouettes of a bird can be calculated. Like in previous case knowing the altitude of the bird we easily can calculate the average ground speed for the fragmented track.

The vector of ground speed of a bird (direction of this vector is the track direction; its length is the ground speed value) is a sum of the vector of airspeed (direction of this vector is heading; its length is the airspeed) and the vector of wind (wind direction; wind velocity). Using wind profiling data at the altitude of a bird's flight there is no problem in calculating its airspeed.

4.5 Wing beat pattern (WBP) and its characteristics

WBP assumes the following characteristics: 1 Actual wing beat frequency within each cycle of beats (beats/sec) (in passerine birds the cycles are usually separated by pauses); 2 Effective wing beat frequency [12] – an average frequency during the whole track, including cycles of beats and pauses; 3 Pause duration between the cycles of beats (sec); 4 Proportion of pauses (%) during the whole track; 5. A number of beats in each cycle. Most of these characteristics can be calculated only for long tracks (at least 20 m) with several wing beat cycles and pauses present. The proportion of such tracks in our monitoring was about 60%.

The OEMS was tested and applied for data collecting at the Curonian Spit of the Baltic Sea at the Rybachy Biological Station (55°05´ N, 20°44´ E) during 2013 - 2019. Species identification was possible only in a few species by the silhouette, linear size, wing-beat pattern, and phenology. But accurate classification of the bird order was possible for 95% of images. In total, over 4000 birds were recorded and 477 of them were identified as the Song Thrushes (*Turdus philomelos*), the common nocturnal migrants in the Baltic region [13].

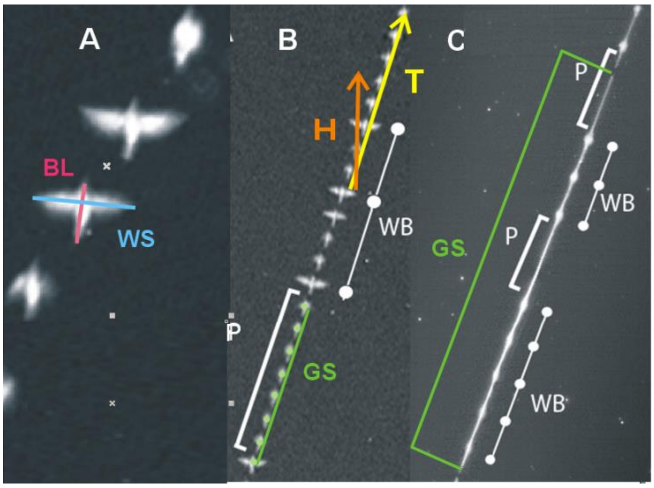

Figure 3. The images of the same bird identified as a Song Thrushes captured on three channels simultaneously. A) objective lens with the field of vision 2.5°; B) objective lens with the field of vision 3.5°;and C) objective lens with the field of vision 6°. Parameters: altitude-270m agl, track direction (T)-29°, heading direction (H)-11°, wingspan (WS)-37cm, body length(BL)-23cm, ground speed(GS)-14.9m/s, pause duration (P)-0.23s, wing beat frequency (WB)-9.9beats/s, 3-4 flaps in one cycle of beats.

5. ACKNOWLEDGMENTS

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