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QUANTIFICATION OF NOCTURNAL BIRD MIGRATION BY MOONWATCHING: COMPARISON WITH RADAR AND INFRARED OBSERVATIONS

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Abstract.—Simultaneous observations by telescope, radar and passive infrared (IR) of birds crossing the disk of the moon enabled quantification of the proportion of birds seen by moonwatching. Distances of birds recorded by moonwatching or infrared were measured by the pencil-beam of a tracking radar aimed parallel to the optical observation systems. About ⅔ of the birds crossing the disk of the moon within 3 km of the observer were seen by the moonwatchers, whereas close to 100% were detected by infrared. The proportion of birds seen by moonwatching decreased steadily with distance. The sizes of the birds observed were classified by the moonwatcher and on the IR-screen according to the size of the silhouette. The size classes obtained by both methods were well correlated with the measured distances (the smaller the size the larger the distance). Calculating migration traffic rates (MTR) based on radar measured distances, according to uniform distribution, or according to mean distances per size class, showed that inclusion of size classes can improve the accuracy of MTR estimates considerably. Height distributions calculated from moonwatch data improved by (1) measured radar distances and (2) mean distances per size classes, showed good correlations. Moonwatching proved to be a useful method for the observation of bird migration below about 1 km height (<2 km distance). The use of size classes improves the results; rough indications of preferred height zones are possible; at least can nights with migration at low levels (and therefore good accuracy of the method) be distinguished from nights with high migration (poor accuracy).

CUANTIFICACIÓN DE LA MIGRACIÓN NOCTURNA DE AVES OBSERVANDO LA LUNA: COMPARACIÓN CON OBSERVACIONES DE RADAR E INTRARROJAS

Sinopsis.—Observaciones simultáneas de aves cruzando el disco de la luna utilizando telescopios, radar e infrarrojo pasivo permitió cuantificar la proporción de las aves vistas al observar la luna. Se registró las distancias de las aves detectadas por observaciones de luna o infrarrojas por el rayo-lápiz de un radar de trazo diriaido paralelamente a los sistemas de observación óptica. Cerca de ⅔ de las aves cruzando el disco de la luna más cercanos de 3 km del observador fueron detectados, mientras que cerca del 100% fue detectada por infrarroja. La proporción de aves notadas al observar la luna decreció consistentemente con aumentos en distancia. Los tamaños de las aves se clasificaron por el observador de la luna y en la pantalla de infrarrojo de acuerdo al tamaño de la silueta. Las clases de tamaños obtenidas por ambos métodos correlacionaron bien con las distancias medidas (menor tamaño a mayor distancia). El cálculo de tasas de tráfico migratorio (TTM) basadas en distancias medidas con radar, de acuerdo a una distribución uniforme o a distancias pormedios por clase, demostró que incluir clases de tamaño pueden mejorar considerablemente a la exactitud de los estimados de TTM. La distribución de alturas calculadas con datos de observación lunar mejoró al utilizar (1) distancias medidas con radar, y (2) distancias promedios por clases de tamaño, las cuales evidenciaron buenas correlaciones. Observar la luna resultó ser un método útil para observar la migración de aves a menos de km de altura (<2 km distancia). El uso de clases de tamaño mejoran los resultados: se pueden hacer indicaciones generales de zonas de alturas preferidas; en noches de migración de poca intensidad (y por tanto buena exactitud del método) se pueden distinguir de noches con alta intensidad de migración (exactitud baja).

Counting birds in front of the moon was the first approach used to analyze the direction and intensity of nocturnal migration. This easily applied method was used by several scientists before radar observations were widely established (e.g., Kiepenheuer and Linsenmair 1965; Lowery 1951; Lowery and Newman 1966; Nisbet 1959, 1963a; Nisbet and Drury 1969) and more recently in areas where radars were not available (Biebach et al. 1991, Bolshakov 1985, Dolnik 1990). The great potential of this method, particularly for surveys in large areas without appropriate radar coverage, is, however, hampered by the problems of estimating migratory intensity and flight directions from the observed numbers and directions. As a result of the lack of range information, most studies assumed a uniform distribution of birds from 0 to 1500 m above ground level (agl) for the calculations of migratory intensity (Lowery 1951). In the last decade, a group of Russian scientists tried to improve the calculation by classifying the sizes of the observed bird silhouettes and so estimating the distances and height distributions (Dolnik 1990). Yet, little is known about the range up to which birds can be observed by telescope when crossing the disk of the moon (Nisbet 1963a), and only theoretical considerations were applied to relate silhouette sizes and distances.

Our study uses three methods (moonwatching, radar and passive infrared) simultaneously, in order to validate them against each other and to show the potential and limitations of the moonwatch method. The main advantage of the radar is its capability to measure distances, its disadvantage is that the opening angle of the beam is not optically defined, but differs according to the size of the observed targets and distance, depending on the detection probability given by the radar equation (Bruderer et al. 1995b). Therefore distinguishing between birds and insect targets is sometimes difficult especially at short distances (<1 km). The IR-system is an optical system with an exactly defined opening angle; its disadvantages are the lack of range measurements and the lack of information on the detection range. In most instruments, unlike that used in this study, an additional limitation is given by a narrowly limited depth of focus. Moonwatching provides either no range information or only non-calibrated estimates based on silhouette sizes; the limits of detectability are unknown and only vague estimates exist on the proportion of birds missed at the edge of the moon (Nisbet 1963b). Focusing on the improvement of the moonwatch method, the following questions are analyzed. (1) How far can birds be seen by telescope in front of the moon? (2) How many birds are missed by moonwatchers? (3) What is the variation between different observers? (4) Do distances estimated by size classes correspond to measured distances; is it therefore possible to improve the accuracy of estimated migratory intensity? (5) What is the variation in the estimated migratory intensity when using the following basis for the analysis of moonwatch data: (a) uniform height distribution up to a fixed ceiling (calculations using a fixed distance), (b) three fixed distances corresponding to the three size classes of bird silhouettes, (c) distances measured by radar. (6) To what extent can size classes be used to calculate height distributions?

METHODS

Observations took place in southern Israel during spring and autumn 1992. Birds crossing the disk of the full moon were observed by a 40× telescope on 15–21 March, 13–18 April, 10–15 August and 10–13 September. In autumn, 216 birds were counted within 16 h, in spring 159 birds during 26.5 h. Distances were read from the calibrated A-scope of a pencil-beam radar with a nominal beam width of 2.2° (Bruderer et al. 1995b). Single small birds (e.g., Chaffinch, *Fringilla coelebs*) can be detected by this radar in tail-on view at ranges of at least 4 km distance (Bruderer 1971). The thermal imaging equipment (passive infrared) used was a Long-Range-IR System (LORIS, IRTV-445L, Inframetrics, Massachusetts, U.S.A.) with an opening angle of 1.4–1.87°. The passage of birds could be observed on a TV-screen, on which birds were counted within a circle corresponding to an opening angle of 1.1°. The telescope and the IR-system were attached parallel to the radar antenna within 1 m of the center of the radar beam (Fig. 1). For all birds reported by the moonwatcher or recorded by the IR-System, the distances were recorded immediately by the radar operator. The size of each bird was estimated independently by the moonwatcher and on the IR-screen. The birds were classified subjectively by the observers into three classes (large, medium, small) according to the sizes of their silhouettes. Operators changed position every 10 min to avoid eye fatigue. No radar distance could be allocated to 17 birds observed by the moonwatcher, because of several echoes in the radar beam. Four birds out of 143 were seen by the moonwatcher but not on the IR-screen.

To calibrate the detection range of the IR-system and the opening angle of the radar, additional observations vertically upwards, comparing the IR-system with the radar only, were performed during nights when no moonwatching was possible.

The number of birds crossing a front of 1 km perpendicular to the principal direction of migration in 1 h (Migration Traffic Rate = MTR) is used as a measure of the intensity of migration. In southern Israel the

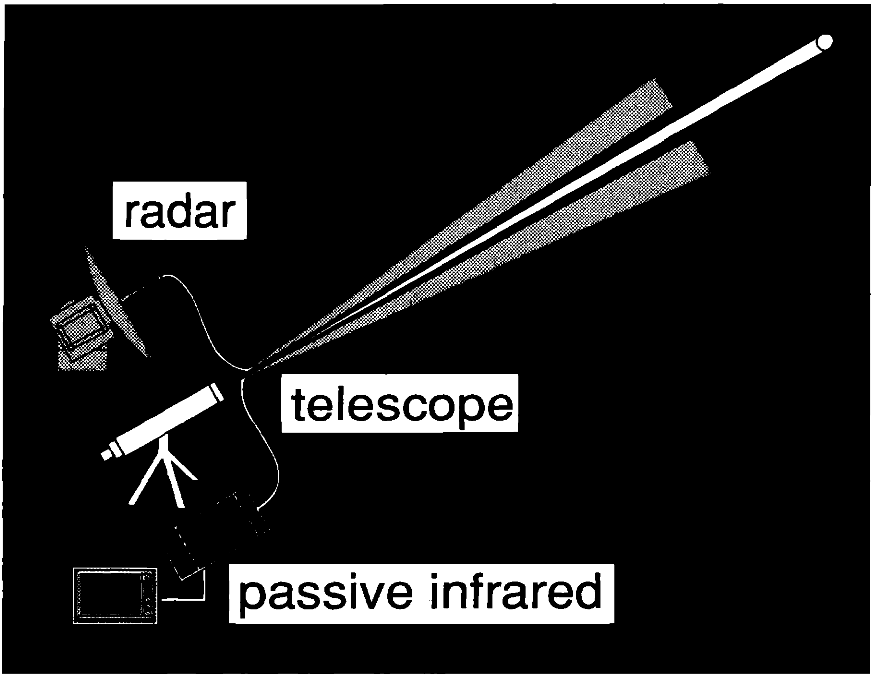

FIGURE 1. The three techniques used to count birds passing the disk of the moon. The opening angles of the three beams of observation are enlarged but true proportions maintained.

flight directions are concentrated within a sector of 30° (Liechti and Bruderer 1995). Therefore, calculations were somewhat simplified. The density of nocturnal migration was measured up to 5 km agl every 2 h with a second tracking radar of the same type, scanning the sky conically at several elevations (Bruderer 1994, Bruderer et al. 1995a). These routine measurements were compared with contemporary moonwatching and fixed radar-beam results. The routine radar measurements are corrected for the fact that the operational radar beam for birds is wider than the nominal beam of 2.2° (see below), and insect contamination was eliminated to a high degree by electronic means (STC = Sensitivity Time Control; Bruderer et al. 1995b). In the fixed-beam measurements used for comparison with moonwatching and IR a calibrated curve was applied to the A-scope as an "optical STC" (Bruderer 1971) to exclude insects by the observer. Due to the much lower heat radiation, insects would have been detected on the IR-screen only at very short distances (<50 m), where they were out of focus. Therefore, no insects were registered with the IR method. According to Figure 2, it seems that the elimination of insect radar-echoes by the observers with the optical method included also some birds, thus biasing the proportion of IR/radar targets in favor

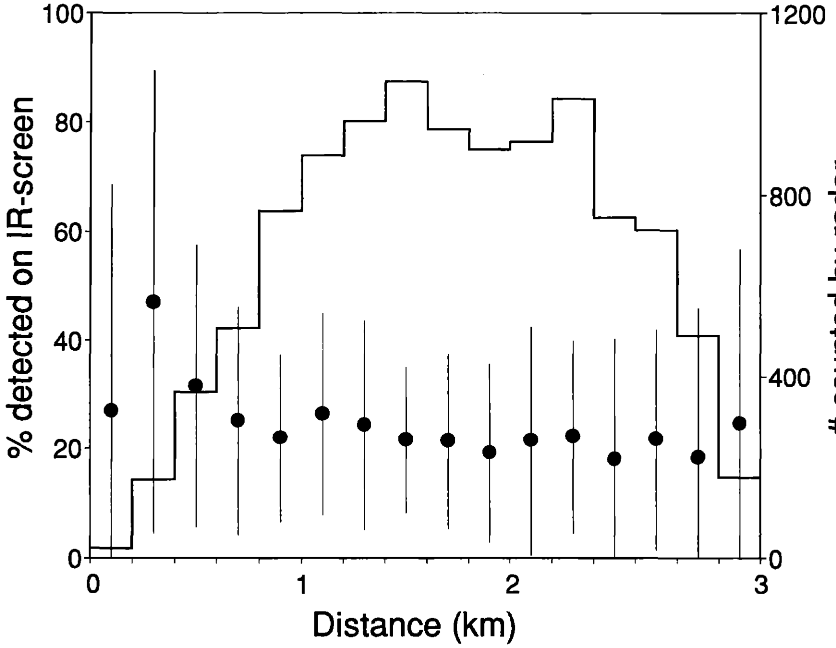

FIGURE 2. Proportion of birds seen with the infrared (dots) compared to radar counts and absolute number of birds seen by radar (line) in relation to distance. The total observation time includes 24 h in spring and 23 h in autumn (outside the period of moonwatching). For the proportions, means and standard deviations (vertical lines) are given.

of IR in the range of 200–400 m and still slightly in the range of 400–600 m. No insects were observed by moonwatching.

RESULTS

Radar versus IR-system.—Most flying objects detected in the IR-beam could be identified as birds; in many cases wing beats could be seen. No identification of species was possible, however, because the tail and the primaries radiate almost no heat. The proportion of IR to radar counts is (besides the biased range of 200–400 m; see above) at a constant level of 20–25% (Fig. 2). According to the nominal beam-width of the radar (2.2°) and the well defined cone of the IR (1.1°) one would expect a proportion of 50% to be detected by the IR, because frequencies and not densities are compared (the reference is the diameter of the observed cone perpendicular to the flight direction and not the surveyed volume, which theoretically would be one fourth). As the IR beam is optically defined, we conclude that the operational radar beam for the bird samples in Israel was about 4–5° instead of the 2.2° beam suggested by the 3 dB lines of the nominal antenna diagram. The proportion of birds seen by radar and IR did not change with distance between 0.5 and 3 km (Fig.

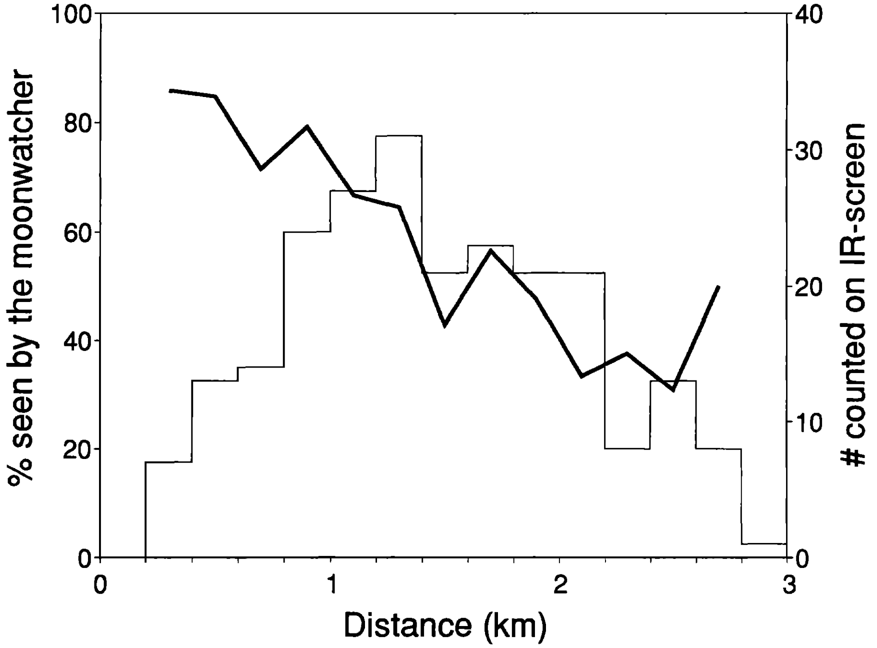

FIGURE 3. Proportion of birds seen by the moonwatcher (thick line) and absolute numbers seen on the IR-screen crossing the disk of the moon (fine line) in relation to distance as observed from the radar. Only observations from experienced moonwatchers are included from three nights (11–13 Sep. 1992) with a total observation time of 4 h.

2; analysis of variance $P > 0.05$). Therefore, we assume that up to 3 km all birds crossing the IR cone are detected.

IR-system versus moonwatching.—Direct comparisons between IR observations and moonwatching by experienced observers were available for three nights in September. Birds crossing the disk of the moon were easily detected on the IR-screen where the full moon was clearly visible, covering almost half the diameter of the screen (opening angle 0.5° for the moon and 1.1° for the IR-system). Distances of these birds were measured by radar. About one third of the birds crossing the moon within 3 km of the observer were missed by the moonwatchers (Fig. 3). Most of these birds flew either at large distances or across the edge of the moon. At a distance of 1.5 km almost half of the birds were missed by the moonwatchers. Remarkable differences occurred between experienced and inexperienced moonwatchers (Fig. 4). In their first night, none of the three inexperienced observers saw more than 50% of the birds that crossed the disk of the moon. Although similar proportions of the birds closer than 1 km were seen by all three experienced moonwatchers, differences between them increased with distance. At distances beyond 2 km more than one third were missed by all of them.

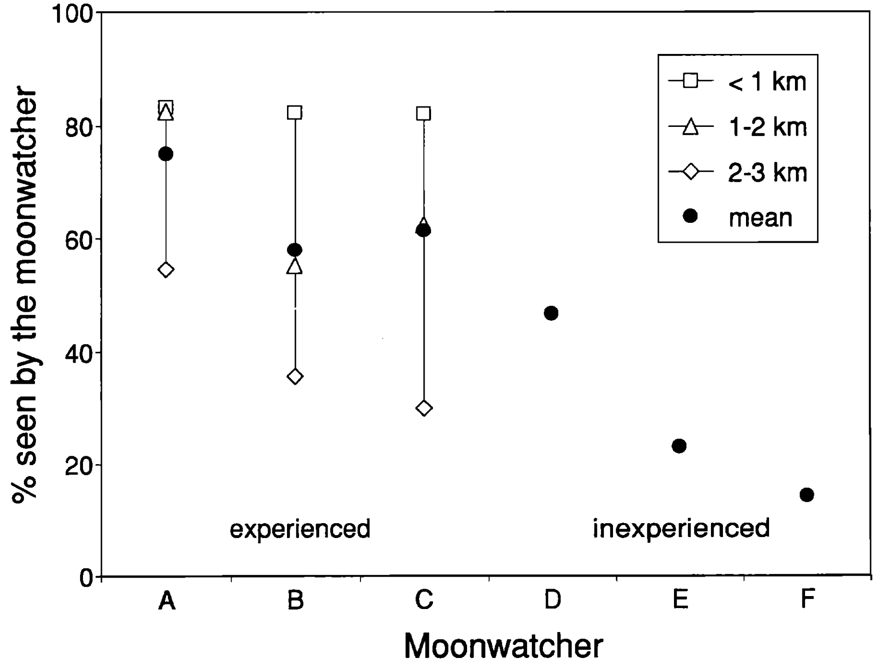

FIGURE 4. Proportion of birds seen by different moonwatchers (A to F) in relation to IR-counts. Only the first night observations of inexperienced moonwatchers are included. Numbers for these data sets are too small to calculate proportions for different distances.

Estimation of size classes.—The very rough grouping of birds into three size classes by moonwatchers and IR-operators is closely related to the distances measured by the radar (Fig. 5). Average distances for the three classes are very similar for moonwatching and IR. Within 0.5 km distance most birds were classified as large, whereas beyond 2 km almost 80% were classified as small. Generally the overlap between the classes is smaller in the IR-data than in the moonwatch-data, which might be due to the fact that birds could be observed longer on the IR-screen than in the telescope, and a simultaneous control of the classification was possible at the IR-screen, but not for moonwatching.

Estimation of Migration Traffic Rates (MTR) by moonwatching.—MTR was first calculated on the basis of the distance measured by radar, including the contribution of each bird to the MTR. For comparison two simplified methods were applied: (1) assuming that birds were distributed uniformly from 0 to 1500 m agl. A mean distance of 1000 m was used for cases where, according to the elevation of the moon, the height reached by the cone of observation at a distance of 2 km was below 1500 m agl. For higher elevations of the moon, the mean between 0 and the distance at the height of 1500 m agl was used. In a second simplification (2) the measured distance was replaced by the mean distance for the size class

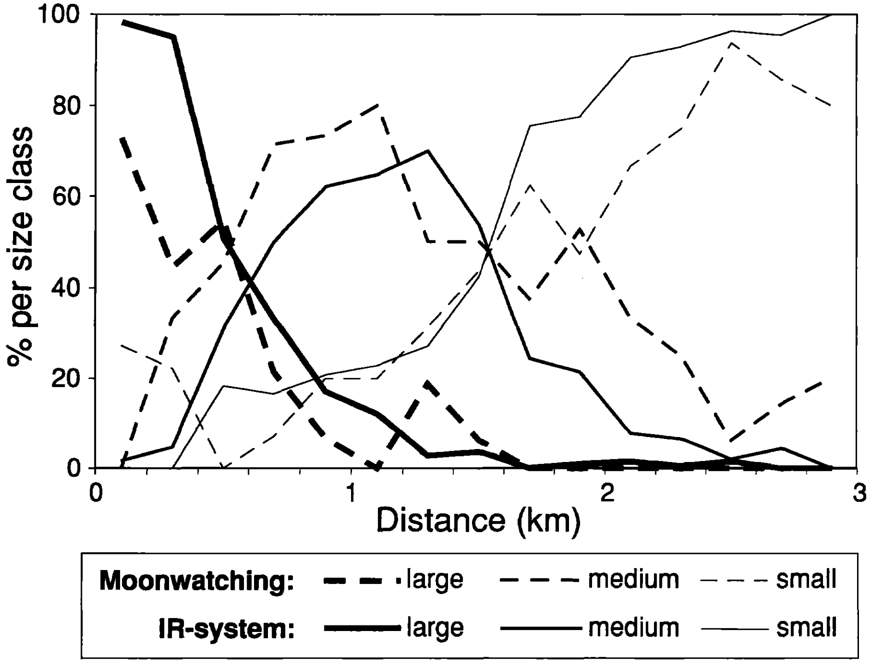

FIGURE 5. Distribution of size classes in relation to distance for moon and IR observations. Mean distances for large birds in front of the moon = 0.50 km, on IR-screen = 0.55 km; medium size 1.34/1.29 km; small size 1.95/2.13 km. (Sample sizes moonwatch: small $n = 99$, medium $n = 91$, large $n = 27$; IR: 973, 420, 182.)

estimated by the moonwatcher. Mean distances per size class were taken from Figure 5. MTRs based on measured distances correlated well with those based on the two simplified methods (Fig. 6), assuming (1) uniform distribution and (2) a mean distance per size class. If the single high value (MTR > 1000) was ignored, the regression with method (1) was at the limit of significance ($r = 0.45$, $P = 0.05$), whereas for method (2) there was a good correlation ($r = 0.65$, $P < 0.01$). Nevertheless, in both cases estimates can easily differ by a factor of two.

Height distribution and estimated MTR.—As a result of the relatively small sample sizes, height distributions were summarized for spring and autumn. The height distributions for nocturnal migration calculated according to measured distances (radar) and estimated distances (size class), respectively, corresponded well for both periods (Fig. 7). Only in the lowest height class in spring was there a remarkable difference between the two methods. Comparing these moonwatching results with simultaneous density measurements performed by conical scanning of the radar beam (routine measurements, see methods and Bruderer 1992), showed that above 1 km agl, a large proportion of the migration was missed by the moonwatchers. According to the elevation of the moon,

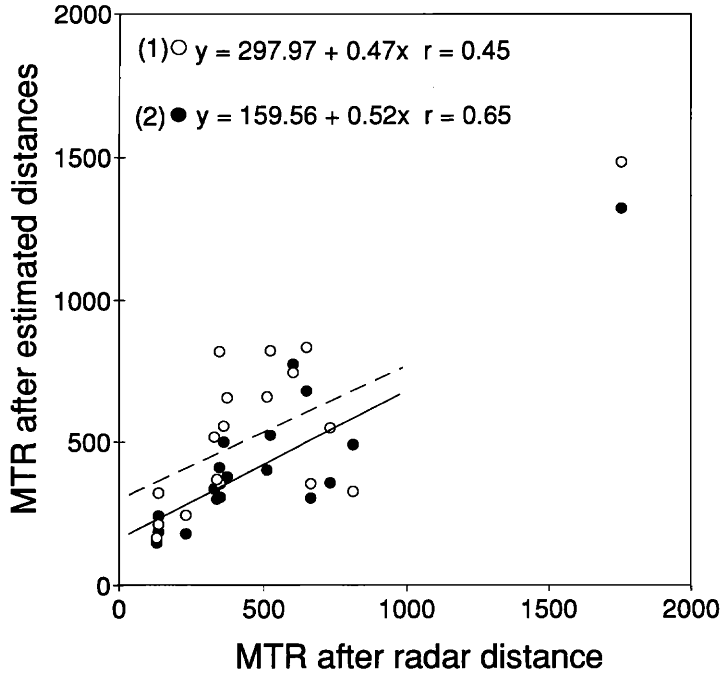

FIGURE 6. (1) Estimated MTRs with respect to a uniform height distribution (open circles) in relation to MTRs calculated after real distances measured by radar; (2) Estimated MTRs with respect to mean distances according to the size class (filled circles) in relation to MTRs calculated after real distances measured by radar. Only birds are included which were detected by both radar and moonwatching.

the mean distance at 1 km agl was about 1.5 km; according to Figure 3 about 50% of the birds were missed by moonwatchers at this distance, 60% between 2 and 3 km; practically no birds were seen beyond 3 km. In the trade-wind zones, autumn migration is mainly below 1500 m agl (Bruderer et al. 1995a), thus providing fairly good conditions for moonwatchers. In spring, a considerable proportion of migration takes advantage of the southerly anti-trades above the wind shear (about 1500 m agl) and thus, is mainly missed by moonwatchers.

DISCUSSION

Our study shows for the first time that a good passive IR-system can detect even small nocturnal migrants up to at least 3 km. Many birds were detected even beyond 3 km, but no systematic observations were made at these large distances. Some observations showed that cloud cover reduces visibility; this reduction can be explained by the reduced temperature difference when the cold clear sky is shaded by clouds. Comparing IR observations with radar data revealed that the nominal beam width of a radar is not necessarily the same as the operational beam width for a

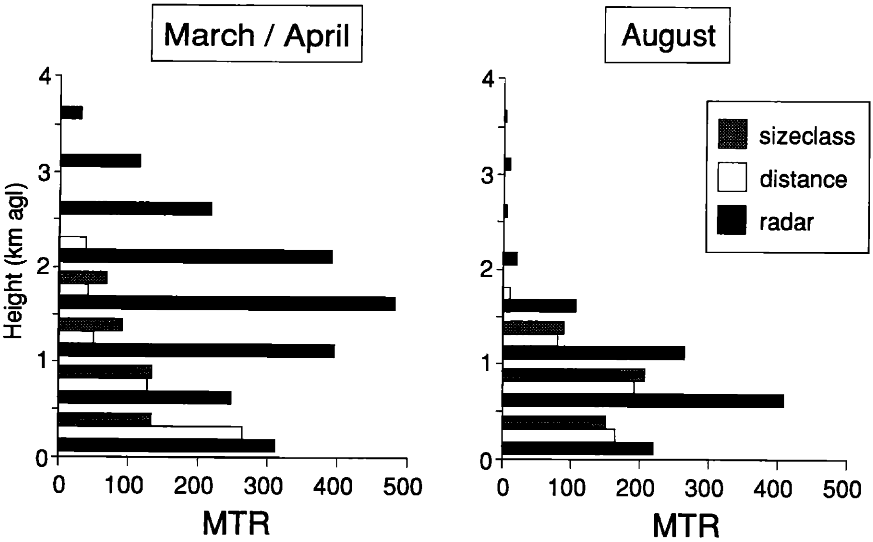

FIGURE 7. Height distributions of nocturnal migrants according to moonwatching with radar distances (white bars) and estimated distances according to size classes (hatched bars) compared with results from radar measurements with conical scanning (black bars).

certain mixture of bird targets. This problem needs to be studied in more detail. When we compared two different IR-systems, important differences in the depth of focus and thus in the detectability of birds were found.

Our findings, that within a distance of 2 km 20–40% of the birds crossing the disk of the moon were missed, confirm observations by Nisbet (1963b), who showed that birds crossing the edge of the moon are often missed. Although visibility during our study seemed to be mostly very good, only a few birds could be seen farther than 3 km distance. Extrapolating the proportion of birds missed, according to a linear regression (Fig. 3), no birds would be recognized beyond 3.7 km. In practice it is realistic to assume that the proportion of birds seen drops from about 50% at 1.5. km to zero at about 3.5 km (except very large birds). Experiments performed by Nisbet (1963b) with 20× telescopes, in which "warblers" could be seen regularly up to 2.6 km, were not in agreement with our results, even less so the Russian results, which provide detailed height distributions up to 6 km agl (Dolnik 1990). It is unclear to what extent the power of the telescope influences the proportion of birds seen. On the one hand maximum distances at which birds can be seen increases with the power of the lens, but on the other hand the proportion of birds missed at the edge of the moon would probably increase. The maximum distance at which we could observe a bird with a 40× telescope was 3.5 km, although the radar showed many birds beyond this distance (Fig. 7).

Obviously the visibility range of moonwatching was overestimated considerably in the past.

Improvement of distance estimates by classifying birds in relation to a crater on the moon were introduced by the Russians (Bolshakov 1985, Dolnik 1990). It may help to reduce the individual differences between observers and to increase the number of size classes. If these size classes can be calibrated by radar, the calculation of height distributions within a restricted range (~2 km distance) is a realistic option. On the other hand the height distribution of the birds has a paramount influence on the number of birds seen by moonwatching, thus imposing severe limitations to refinements of the method. MTRs based on moonwatch data are biased by the proportion of birds missed at the edge of the moon, by the decreasing detectability with distance, and by the restrictions imposed to the observable height because of the elevation of the moon. Thus, the reliability of moonwatching data increases when the elevation of the moon is high and altitude of migration is low. Taking 2 km as a reasonable observation range for moonwatching, the elevation of the moon should be above 30° to make a reliable estimate of the migratory activity up to 1000 m agl.

Moonwatchers need to be trained for some nights before their data can be used. The silhouette size of a bird when crossing the disk of the moon is related to the distance rather than to its size, because the length of the most frequent species differs by factors of 2–3, whereas the distances differ by a factor of 10. In addition, the visibility of a silhouette may often be determined by its surface rather than by its length (in spite of the fact that length should be estimated), thus, the visibility would decrease with the square of the distance. On the other hand, height distribution depends mostly on winds aloft (Bruderer et al. 1995a) and is not distorted by birds of different size classes, as these classes show no pronounced preference for different height zones (unpubl. data). Size classes are thus useful indicators of distances and are a valuable tool to improve the calculation of MTRs based on uniform distribution of birds. MTRs calculated by means of size classes may, however, still deviate by factors in the order of 2–5 from real MTRs, according to the actual height distribution of migrating birds.

A detailed identification of birds is very difficult, in spite of the fact that experienced bird watchers may sometimes be able to identify some of the targets. In our observations most of the birds were passerines, in 17 cases the observers provided additional information such as swift, heron, duck or wader.

We believe that our findings improve the application of the moonwatch technique, which is still the cheapest and easiest available tool to observe nocturnal bird migration. It has proven to be a useful method to observe bird migration up to about 1000 m above ground. Thanks to the knowledge of the quantitative restrictions, the interpretations of future results will be more appropriate. General guiding lines for the method would help to make moonwatching results comparable all over the world.

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