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SHORT-RANGE CORRECTIONS FOR MIGRANT BIRD TRACKS ON SEARCH RADARS

BY BRUCE COHEN AND TIMOTHY C. WILLIAMS

INTRODUCTION

In recent years high resolution, short-range search and air traffic control radars have been used for studies of bird migration (Schaefer, 1969; Williams et al., 1972, 1974; Flock, 1974; Gauthreaux, 1974; Beason, pers. comm.). These instruments provide detailed information on the movements of birds within a few kilometers of the radar. Problems occur in following migrants with maximum angles of elevation $\geq 30°$ above the radar, but they have not been discussed previously in the literature. Tracks of birds in straight and level flight appear curved on the Plan Position Indicator display (PPI) of the radar. Such distortions are caused by the way target positions are mapped on the PPI, but can be corrected with graphical or nonlinear regression techniques after recording the migrant's track. In addition to correcting track curvature, these techniques provide a means of estimating the bird's altitude, information normally unavailable from surveillance radar data. This paper describes the cause of such track distortions and a means of correcting them.

MATHEMATICAL ANALYSIS

The lower portion of Figure 1 shows a bird flying in a straight line at a constant altitude (a) above the earth's surface, which is represented here by the xy plane. The radar is located at the origin of the coordinate system, and the bird's position at any given time in the system is given by three spherical (r, ϕ, θ) or rectangular (x, y, z) coordinates. The following simultaneous equations describe the bird's flight path in Figure 1 in rectangular coordinates:

$$y = \mathrm{m}x + \mathrm{b} \tag{1a}$$

$$z = \mathrm{a}. \tag{1b}$$

Equation 1a describes the projection of the path on the xy plane, a line with slope m and y-intercept b. Equation 2b gives the altitude of the bird, a. Rectangular and spherical coordinates are related by the equations below:

$$x = r \sin \theta \cos \phi$$

$$y = r \sin \theta \sin \phi$$

$$z = r \cos \theta.$$

Substituting spherical for rectangular coordinates in eq. 1a and 1b, we have

$$r \sin \theta \sin \phi = \mathrm{m}r \sin \theta \cos \phi + \mathrm{b} \tag{2a}$$

$$r \cos \theta = \mathrm{a}. \tag{2b}$$

The spherical coordinates r and ϕ, referred to respectively as the slant range and azimuth of the target, determine the position of the bird's echo on the PPI (see upper portion of Fig. 1). In order to see how the bird's flight path will appear on the PPI, eq. 2a and 2b must be solved for a single equation giving r as a function of ϕ. This equation will describe the path's image on the PPI. Using a trigonometric identity, eq. 2b can be rewritten

$$r\sqrt{1 - \sin^2\theta} = a,$$

and by rearranging terms as

$$r \sin \theta = \sqrt{r^2 - a^2}.$$

Finally, substituting $\sqrt{r^2 - a^2}$ for $r \sin \theta$ in eq. 2a and solving for r, one finds that

$$r = \sqrt{[b/(\sin \phi - m \cos \phi)]^2 + a^2}. \tag{3}$$

This last equation gives r as a function of ϕ and therefore describes the bird's track seen on the PPI. If eq. 3 is graphed using (r, ϕ) as the polar variables and assigning actual values to the constants m, b, and a, the results are a series of curves like those shown in Figure 2.

APPLICATIONS

Track curvature increases with a bird's maximum angle of elevation above the radar ($[90° - \theta]$ at the point of the bird's closest approach to the radar). The curves in Figure 2 represent PPI images of a set of flight paths with the same projections on the ground but different values for this angle. For values below 15°, the curve is indistinguishable from a straight line given the resolution of the PPI display. Thus, track curvature is not a problem with long-range search radars because they detect birds at very low angles of elevation. The short-range radar that we use (Williams et al., 1974) detects some birds at angles $\geq$30°, and as a result 5–35% of the tracks recorded per night are noticeably curved.

The small crosses in Figure 2 represent data from a bird track taken from our PPI display. In theory a variety of nonlinear flight paths could produce a curved track exactly like this one, but a large body of data gathered with tracking radars indicates that over 90% of all migrant flights are actually straight and level over distances of 1 to 3 km (Bruderer and Steidinger, 1972; Williams et al., 1972; Griffin, 1973; Able, 1974). Therefore, if a track looks similar to one of the curves in Figure 2, it is reasonable to assume that the original flight path was linear.

Our procedure for reconstructing a migrant's flight path from a curved PPI track combines both graphical and nonlinear regression techniques. As described in Williams et al. (1974), we record data from the PPI display with a time lapse camera, project the film onto large sheets of paper and mark down the position of each bird in each radar revolution. The results are tracks composed of discrete points about 2.2

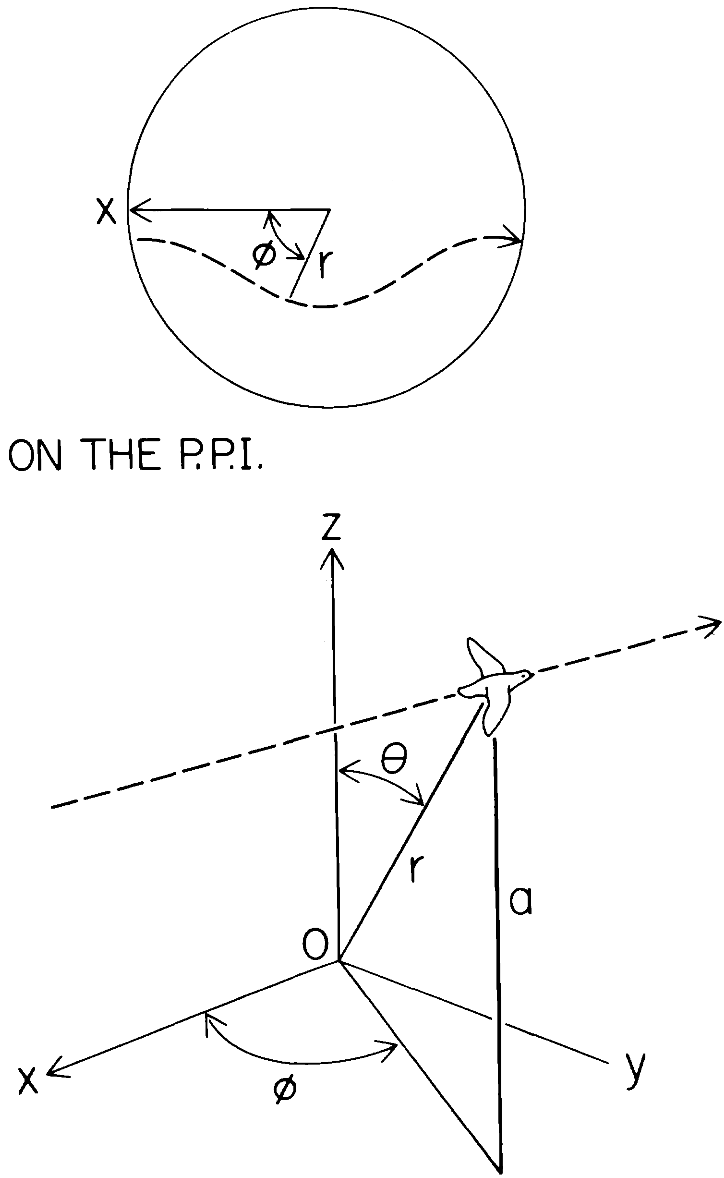

FIGURE 1. (lower) Schematic of a bird in straight and level flight above the earth's surface (xy plane) at an altitude a. Radar is located at the origin. r = bird's slant range to the radar, ϕ = its azimuth and $(90° - \theta)$ = its angle of elevation. (upper) Dotted line shows how its track appears on the PPI display of the radar.

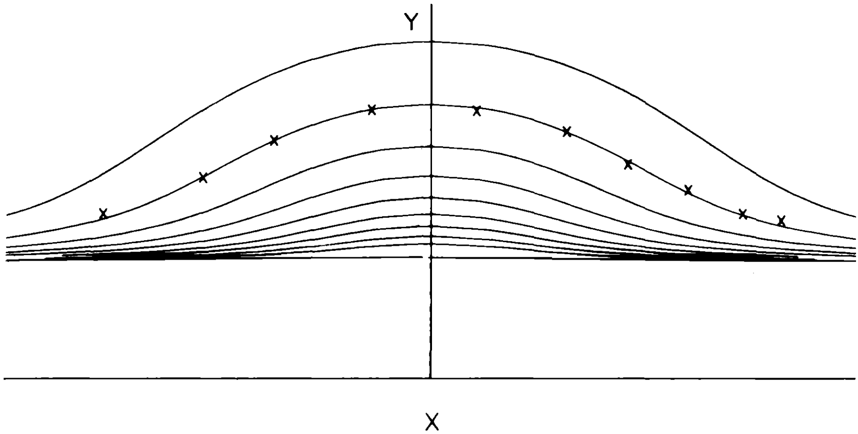

FIGURE 2. Computer generated curves showing the PPI images of straight and level flight paths with different maximum angles of elevation ($90° - \theta$) above the radar (see text). The maximum angle for the lowest curve is 15°, the next 30° and each succeeding curve is incremented by 5°. The x-axis is parallel to the projection of the birds' tracks on the ground. Small x's illustrate sample track of a migrant bird.

sec apart in time. The rectangular coordinates of these points are recorded directly on computer cards with a Bendix Datagrid Digitizer. Curved tracks are visually compared to graphs such as Figure 2 drawn on clear plastic overlays. These graphs are generated by a computer plotter using the following version of eq. 3 in rectangular coordinates (x, y) where $x = r \cos \phi$, $y = r \sin \phi$, and $m = 0$:

$$x = \sqrt{\frac{y^4 - y^2(a^2 - b^2)}{b^2 - y^2}}\,.$$

The curves in a graph have the same value for b but different values of a, and are matched to a track by rotating the overlay around the center of the PPI display. If a track conforms to one of these curves, a computer program estimates the bird's altitude (a) and uses this estimate to correct track curvature. First, the program fits a straight line to the rectangular coordinates of the data by the method of "finding the major axis" (Pearson, 1901). This method assumes equal error in the x and y coordinates and assures residuals unbiased by m. The altitude (a) is estimated by fitting eq. 3 to the polar coordinates of the track with nonlinear least squares regression (subroutine adapted from Sampson, 1974). Using this estimate of a, the slant range of the points (r) is transformed by $\sqrt{r^2 - a^2}$ to obtain the orthogonal projection of the bird's position on the ground and eliminate track curvature. Finally, the rectangular coordinates of the transformed data are recomputed and a new line is fit to them. If the transformation improves fit of the data to a straight line, the estimate of a and the new values for m and b are retained; otherwise, an altitude of 0 is assigned to the track and the original m and b are used. The compass heading of the track is computed from the arc tangent of m. This rather elaborate procedure insures that estimates of m, b, and the mean square residual from curved and straight tracks will be compatible, and inclusion of an additional parameter in the track model is warranted. If tracks are being analyzed without the benefit of a computer, m, b, and a can be directly estimated from the overlays.

Reliable estimates of (a) depend on obtaining uninterrupted tracks of birds passing the radar. The portion of the track closest to the radar is particularly important because it shows the greatest curvature. The use of MTI circuits (Eastwood, 1967) to reduce ground return cancels this portion of the track; thus, our methods require operation of the radar in the normal rather than the MTI mode.

DISCUSSION

The techniques described above could be used in the analysis of any search radar data where the altitude of birds could exceed one half their range from the radar. Because birds are not infrequently detected at 6 km altitude (Richardson, 1972; Hilditch et al., 1973), data obtained at ranges as great as 12 km with broad beam radars such as the ASR series (Gauthreaux, 1974) should be examined for curved tracks similar to those in Figure 2. Inspection of data taken with an ASR 4 airport traffic control radar operated at 18 km maximum range at Otis AFB, MA in 1969 revealed large numbers of such tracks. The large variance in the direction of tracks on some of these nights (Williams, 1972) is an error due to failure to correct for track curvature.

At least two important reasons exist for using the techniques described above in migration studies with short-range surveillance radars. First, they allow one to estimate the altitude of birds in straight and level flight with a sufficient number of observed PPI positions and a large enough maximum angle of elevation. Second, they enable one to distinguish true departures from straight and level flight from artifactually curving tracks. This discrimination can be essential for studies examining the reaction of birds to environmental factors such as geographic features and magnetic anomalies.

SUMMARY

Tracks of birds in straight and level flight with maximum angles of elevation $\geqslant 30°$ above a surveillance radar appear curved on the Plan Position Indicator display. The reason for this distortion and methods for correcting it, which allow one to estimate the bird's altitude, are described.

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Department of Biological Sciences, SUNY at Albany, Albany, NY 12222, and Department of Biology, Swarthmore College, Swarthmore, PA 19081. Received 28 September 1979, accepted 11 March 1980.