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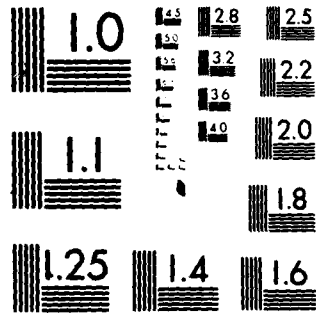
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Walter R. Nunn

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Operations Evaluation Group

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A RESULT IN THE THEORY OF SPIRAL SEARCH

INTRODUCTION

This note presents a result in the theory of spiral search which does not seem to be available in the literature in spite of its straightforward derivation and obvious applicability in certain types of "real life" search problems.

The result gives the probability of detection as a function of time for a class of prior distributions of search-object, i.e. target, position centered at the origin of the x,y plane. We restrict attention to a spiral-type search in which the searcher covers the AOU(area of uncertainty) in concentric rings, moving out from the center. In the common case that the prior density is circular normal, the time to detection is seen to be approximately exponentially distributed. This is a somewhat counter-intuitive result in that the detection rate is constant, since it would appear that detection rate must decrease with time as the searcher moves from high probability areas to low probability areas.

The literature devoted to the theory of search is extensive, expanding rapidly since the fundamental work of Koopman and colleagues during World War II, reference (1). Surveys of search theory literature are available, references (2), (3), and a text, reference (4). Reference (5) contains a very readable, brief summary of search theory development and recent applications.



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The Setup

A searcher, e.g. an ASW aircraft, commences search for a target at time $t = 0$. The searcher's knowledge of target position is in the form of a prior distribution of target position in the x, y plane with center at the origin. This prior distribution is assumed to be time-invariant, at least during the search time. The searcher has a sensor with "cookie-cutter" lateral range curve and sweep width W , i.e., targets at distance less than $W/2$ from the searcher are detected with certainty, those at distance greater than $W/2$ are not detected at all. The searcher searches the AOU by flying in concentric circles, moving out from the origin in such a way that there is no overlap of area searched. Figure 1 displays the flight path. The dashed lines are the concentric circles flown by the searcher. The circles are numbered (1), (2), (3) and

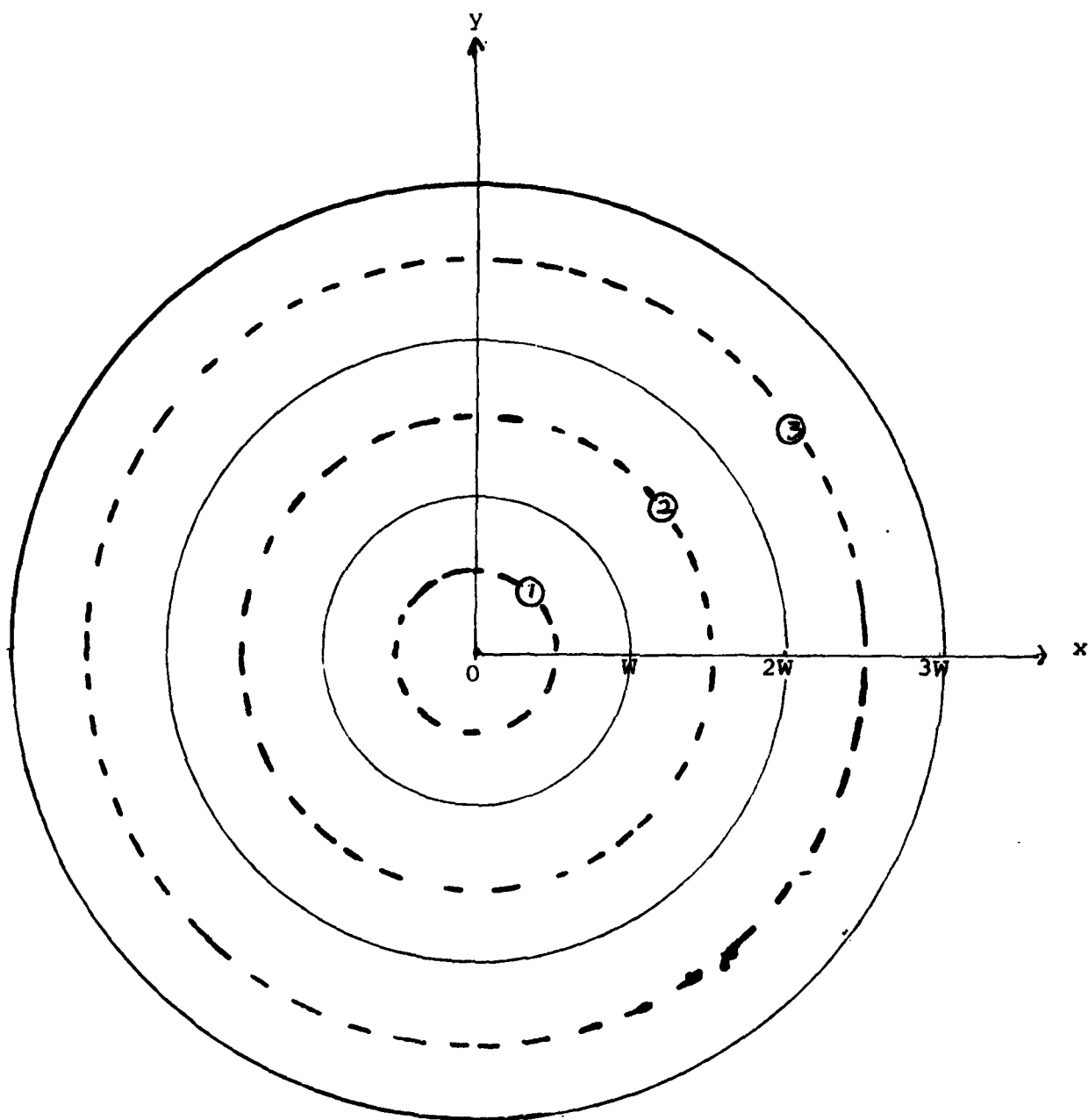


Fig. 1: Flight path of the searcher

are flown in that order. We ignore "end effects" and assume that the searcher can transition instantly from the end of one circle to the beginning of the next.

We require the additional assumption of circular symmetry of the prior distribution, i.e., we require that the contours of constant probability be circles centered at the origin. This is not a terribly restrictive assumption, including for example the circular normal distribution and the expanding "doughnut" (Rice Nakagami distribution). It results anytime that the target flees the origin by choosing a course at random (uniform distribution on $[0, 2\pi]$) and independently chooses a speed from some arbitrary distribution.

DERIVATIONS AND RESULTS

Because of the symmetry assumption on the prior distribution, the polar coordinate variables R, θ , which describe the position of the target with respect to the origin, are independent. We let $F_R(r)$ denote the cumulative distribution function of R , and let $f_R(r)$ denote the corresponding density function. The probability that the target is detected during transit of the first circle is the probability that the target is within distance W of the origin and is hence $F_R(W)$. The probability that the target is detected during the transit of the first two circles is $F_R(2W)$, and in general, the probability that the target is detected during transit of the first I circles is $F_R(IW)$, $I = 1, 2, \dots$

We can also calculate the cumulative time to complete the first I circles. The diameter of the first circle flown is W , so that the time to fly the first circle is $\pi W/v$ where v is the aircraft speed. The diameter of the second circle is $3W$, so that the flying time for that circle is $3\pi W/v$ and the cumulative time for the first two circles is $4\pi W/v$. In general, the cumulative time to complete I circles is $I^2 \pi W/v$. If we think of I as being a continuous variable rather than discrete, figure 2 shows how time varies with respect to I . The graph consists of straight line segments since for any given circle time accumulates linearly as the circle is flown. We let " t " denote the cumulative time and say that approximately $t = I^2 \pi W/v$, i.e., we are approximating the graph by the smooth quadratic function of I .

The probability of target detection during the first I circles was calculated to be $F_R(IW)$, but now we can relate t to I and obtain the probability of detection as a function of time. We have $IW = (vWt/\pi)^{1/2}$, so that the probability of target detection in time less than or equal to t is approximately $F_R(\sqrt{vWt/\pi})$. We may differentiate this with respect to t to obtain an approximate density function for the time to detection.

Example - Circular Normal Distribution

Suppose that the prior density is circular normal, i.e., proportional to $\exp[-\frac{1}{2}(x^2 + y^2)/2\sigma^2]$. The polar coordinate R

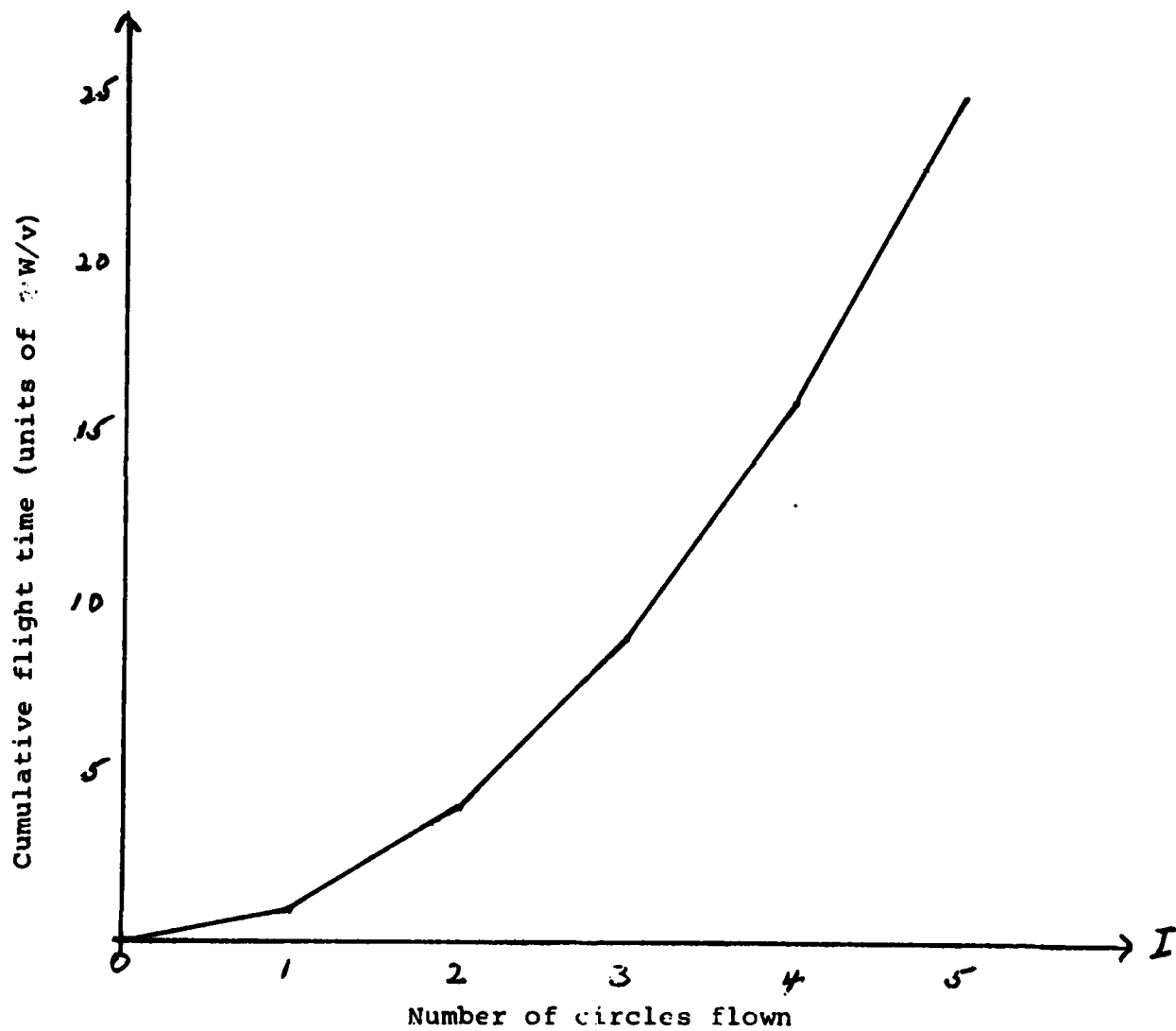


Fig. 2: Cumulative time vs number of circles flown

is Rayleigh distributed, i.e.,

$$F_R(r) = 1 - \exp[-\frac{1}{2}r^2/\sigma^2]$$

Hence the time to detection has distribution

$$1 - \exp[-\frac{1}{2}vWt/\pi\sigma^2]$$

i.e., time to detection is exponentially distributed with parameter $vW/2\pi\sigma^2$. This is ^{somewhat} counter-intuitive since it says that the instantaneous probability density of detection given no prior detection (detection rate) is constant, with value $vW/2\pi\sigma^2$. Superficially, it would appear that the detection rate must decrease with time since the searcher is moving from high probability areas to low probability areas. However, this is offset by the information that the target is not in the already-searched area, so that the overall detection rate remains constant.

Example - Fleeing Target

Suppose that the target flees the datum point by selecting a heading at random (uniform distribution on $[0, 2\pi]$), and independently choosing a speed S at random from an arbitrary, known distribution $F_S(s)$. The distance R covered by the fleeing target after time T is equal to ST , so that R has distribution $F_R(r) = F_S(r/T)$. At time T the searcher commences his search, and we let t denote search duration, measured from time T . We assume also that searcher speed v

is large enough that the distribution of target position does not change significantly during the search period. The probability distribution of time to detection is therefore given by

$$F_S(\sqrt{vWt/\pi T^2})$$

Differentiating this with respect to t , we obtain the density function

$$\sqrt{vW/4\pi T^2} (t)^{-1/2} f_S(\sqrt{vWt/\pi T^2}) .$$

Hence if either $F_S(s)$ or $f_S(s)$ is known in closed form, we have the corresponding closed form for the detection time distribution.

COMMENTS

The results depend heavily on three major assumptions:

- (1) circular symmetry of the target position distribution,
- (2) the cookie cutter lateral range curve, and
- (3) the time-invariance of the target position distribution

during the search. It is not clear that any of these assumptions

can be lifted without destroying the simple character of the results. It is perhaps worth commenting that the derivation generalizes easily to permit cookie cutter-type detection with fixed probability $p < 1$.

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