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An Evaluation of Some Inland Search POD Experiments

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Table of Contents

Chapter 1
Introduction.....1

Chapter 2
Background.....3

Chapter 3
Basic Definitions.....7

Chapter 4
Analysis of *New Concepts for Grid-Searching* 11

Chapter 5
Applying Search Theory to Ground Search.....45

Chapter 6
Optimal Effort Allocation.....79

Chapter 7
Conclusions and Recommendations 95

References.....99

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Chapter 1
Introduction

1.1. Introduction

As described in the Forward to *Search Is An Emergency* [1], the ground search and rescue (SAR) community has been engaged in developing and improving upon techniques of search management for the last 25 years or so. Out of these efforts, mostly from uncompensated volunteers, has come a wealth of practical advice, techniques, and guidance, gleaned in large part from operational experience. As this work progressed, it became clear to many that the school of field experience wasn't necessarily providing all the needed answers. As a result, several authors tried to take a more scientific approach to certain aspects of search management.

1.2 Ground SAR Research

In the previous paragraph, the term "ground SAR community" was used with the implication that the work being done was undertaken by that community as a whole. This has not actually been the case. The very nature of ground SAR makes it seem more a matter of local, rather than global, or even national, concern. Ground SAR efforts, for example, are generally managed by local authorities. Therefore, most of the work done to advance the state of the art has been done by individuals working independently of one another to solve local problems. The authors of *Search Is An Emergency* [1] have done a great service in consolidating ground search management techniques from a variety of sources into a single volume. However, when two or more techniques that address the same problem are included, little or no guidance is provided for making decisions on which is best or most appropriately applied in any given circumstance. It also isn't clear whether the techniques presented have been carefully reviewed to determine whether they are appropriate to any situation or are even based on correct premises. The content of *Search Is An Emergency* [1] appears to be synopses of various methodologies independently developed, and in some cases independently published, by various individuals working from different viewpoints. There does not appear to have been a scientifically rigorous review process in place and no scientifically accepted general methodology is presented.

1.3 Maritime SAR Research

In the maritime SAR arena, circumstances have been much different. In the United States, a single federal agency, the U. S. Coast Guard, has been made responsible for coordinating and performing maritime SAR operations, and advancing the state of the art of maritime SAR activities. This has allowed a more focused approach to SAR research, and, due to the Coast Guard's close association with the U. S. Navy, Coast Guard researchers have been able to take advantage of the extensive amount of Navy-funded research in the area of search theory and its application to problems of naval interest. The Navy's interest in search theory began during the Second World War when the techniques of operations research were first applied to the problems of locating enemy ships

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and submarines. The Navy has continued research in this area as sensor technology and knowledge of the oceanic environment, both above and beneath the waves, has advanced. Using much of the Navy's research as a springboard, the Coast Guard has performed a considerable amount of additional research specifically directed at advancing the state of the art in maritime SAR.

1.4 Search Theory Awareness

In general, it does not appear that the formal scientific discipline of search theory, initiated in the 1940's in response to naval wartime needs but nevertheless applicable to search problems in general, has been applied to developing a comprehensive ground search management methodology. This should not be surprising since, even though maritime search planning techniques are based on this work, most of the maritime SAR operations community today is itself unaware of the formal scientific underpinnings of the methods it uses on a daily basis. In the past, this lack of awareness in the maritime community has proven to be somewhat problematic. From time to time persons who are expert in the area of field operations, but ignorant through no fault of their own of the scientific principles that form the basis of the methods they use, take it upon themselves to try and "improve" search planning and management techniques. These "improvements" typically address only a single, specific aspect of the search problem, thus taking it outside the context of the theory from which the search methodology as a whole is derived. As a result, such "improvements," when viewed from a "big picture" perspective, often either add complexity for no statistically significant benefit or actually make matters worse. For ground SAR, it appears this problem has been exacerbated because, apparently, no comprehensive methodology has ever been developed from scientific foundations in the first place. Thus ground SAR researchers have, in effect, been faced with reinventing search theory from scratch — an extremely challenging task for which they are neither trained, equipped, organized nor funded.

1.5 Purpose

The purpose of this paper is to examine some of the ground search management research and conclusions published to date in light of the general theory of search, point out a number of serious misconceptions and errors in that work, and establish a direction for the correct application of search theory to ground SAR.

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Chapter 2
Background

2.1 History of Search Theory

The seminal work establishing the basic scientific principles and theorems of search theory was Report Number 56, *Search and Screening*, by B. O. Koopman [2] of the U. S. Navy's Operations Evaluation Group, published in 1946 as a classified document but declassified circa 1958. Koopman [3] later developed a somewhat expanded version of this work that was published in 1980 as a text on search theory and its practical application to naval problems. Although the applications and examples in Koopman's work are clearly aimed at situations and operating environments of interest to the Navy, the general theory of search he established is applicable to virtually any type of search problem, including that of ground SAR.

2.1.1 Historically, search theory has its roots in World War II. In fact, the larger discipline of which search theory is only a part, *operations research*, finds its origins in World War II as well. The major impetus behind the effort to develop and apply search theory was the war at sea, antisubmarine warfare in particular. The work done during this period was the first formal scientific research ever done on the general search problem. So, before it could be applied to real-world problems, the general theory of search had to be developed. It is the general principles developed in Koopman's and subsequent research that find useful application in such a wide variety of search problems well beyond those of naval interest.

2.1.2 In the years since the Second World War, research into search theory has continued for a number of reasons. The number of search problems, both military and civilian, to which search theory was applied continued to grow. Research was needed to determine how to apply search theory principles to each of these various problems. Many advances and changes were made, and continue to be made, in systems of detection (sensors) and the platforms that carry them. The types of objects, signals, etc. being sought have also changed a great deal in both the military and civilian communities. Finally, there have been advances in both the mathematical theory bearing on search, and the ability to implement search theory-based algorithms on modern, fast, inexpensive computers for practical use in the field. This has led to an enormous increase in the volume of literature on search theory and its applications. One of the most notable additions to the search theory literature is L. D. Stone's *Theory of Optimal Search* [4] that, as the title implies, addresses the problem of making the best use of the available search resources in a variety of situations.

2.1.3 Searching consists of four elements. These are the *sensor(s)* employed, the *properties of the search object* that make it detectable by the sensor(s), the *environmental conditions* prevailing during the search that affect detection, and finally, the *tactics* employed when applying the available search resources to the problem at hand. In the past, there has been a regrettable, but natural, tendency on the part of engineers and field researchers to put the first three elements (sensors, search objects and environment) at center stage and

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to ignore, or forget, that (paraphrasing Koopman [3]), *the operation of search must be viewed as a complete system, having a structure of its own making it more than just the sum of its parts.* This is nowhere more evident than in most engineers' descriptions of new sensor systems. While the sensor's ability to detect small objects at long ranges is always emphasized (usually by citing test results for ideal conditions), the best methods for employing the sensor to find objects in actual operational search situations are rarely addressed. Similarly, sensor manufacturers always have maximum detection ranges readily available but rarely can they respond to questions about expected probability of detection (POD) over an area.

2.1.4 In his preface to [3], Koopman notes two other dangers any treatment of search theory, or research into search planning/management methods for that matter, must seek to avoid or ameliorate. One of these is an "...overemphasis on immediate practical answers to all kinds of questions of how to plan searches — rules without scientific explanation. There are manuals for this purpose, but they must be based on knowledge and reasoning (often mathematical)..." Where such manuals do in fact exist (e.g. the maritime search planning chapters of the U. S. and Canadian National Search and Rescue Manuals), they have proven both a boon and a bane to practical search planning over the long term. Clearly there is a need for such manuals to make the knowledge gained in the study of search theory and its application available for practical, and often rapid-response, use by field personnel. However, these manuals in the past have provided no inkling to their users that the methods they contain are based on a wealth of scientific research and are constructed of pieces that have been carefully designed to work together as a complete search planning and management system. As noted in the first chapter, this has led well-meaning, but not necessarily scientifically qualified, operations personnel to propose (usually invalid) modifications because they had no way of knowing about the scientific research on which the methods in their manuals were based. Some invalid proposals were actually adopted and later had to be removed at the cost of considerable sums and chagrin.

2.1.5 The other danger Koopman pointed out is the "...inappropriate handling of the mathematics. At one extreme, there is often an impulse to leave it out as such. But, since in most cases the essential reasoning concerns the structural and quantitative aspects of the question — viz., concerns essentially mathematical factors — to leave out the mathematics is to leave out the essential reasoning." Regrettably, and despite the best intentions, high levels of effort and even personal sacrifice on the part of operations personnel not familiar with search theory, there is another aspect to the "...inappropriate handling of the mathematics." It is relatively easy for almost anyone with a marginal knowledge of a subject to unintentionally develop fundamentally false formulas and "theories" that seem altogether plausible, not only to themselves, but also to other non-scientists or even scientists working outside their fields of expertise. If these are not subjected to rigorous scientific review but are nevertheless published in manuals for operational use, serious consequences, even loss of life, could result.

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2.2 Ground SAR Research

Search Is An Emergency [1] contains contributions from researchers working over the past 25 years or so to improve the management of ground searches. To their credit, the authors cite their references in both the text and an extensive bibliography. However, as anyone acquainted with the field of formal search theory initiated by Koopman will quickly discern, there is not a single entry from the wealth of scientifically established search theory literature. It is somewhat less surprising that *A Survey of the Search Theory Literature* [5] contains no references from the bibliography of [1]. Much of the research cited in [1] appears to come from individuals involved in ground SAR *operations* who have little or no background in either search theory or operations research. This is not to say that all research related to ground SAR lacks the necessary scientific rigor. For example, recent research into lost person behavior by qualified psychologists not only seems to have scientific rigor, it has already shown and will likely continue to show significant improvements in determining the most likely places to find lost persons. However, in those areas of ground search management on which basic search theory clearly bears, the approaches have been less thorough.

2.2.1 In 1973, J. Wartes performed some experiments in Washington state and published the results in *An Experimental Analysis of Grid Sweep Searching* [6] in 1974. From POD vs. Spacing estimates tabulated in this work, a table was created and published in [1] listing spacing, number of hours, number of searchers and number of searcher-hours needed to search a mile square at that spacing, and the corresponding POD from [6] for spacings of 20, 60, and 100 feet. That table is reproduced below as Table 2-1.

Spacing (ft)	Hours	Searchers	Searcher-Hours	POD
100	3.5	53	185.5	50%
60	3.5	88	308.0	70%
20	3.5	264	924.0	90%

Table 2-1

A formula based on this table that related POD to searcher spacing was also derived and published in [1]. That formula appears here as Equation [2-1] below.

[2-1] $$POD\% = 100 - (0.5 \times Spacing)$$

The original POD estimates in [6] were based on searching for human subjects (conscious and “unconscious”) in daylight under conditions of thick ground cover. Also in [6], Wartes introduced and tried to quantify the concepts of “thoroughness” and “efficiency” that almost, but don’t quite, echo some proven search theory concepts. We shall look at [6] more carefully in Chapter 5.

2.2.2 In 1992 M. Colwell published results of his own POD experiments along with a number of conclusions in *New Concepts in Gridsearching* [7]. Among these was the rather startling conclusion that, for some initially large spacings, doubling the spacing between

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searchers did not have an adverse impact on POD. Colwell proposed a method for determining "POD Calibration Curves" and gave a number of examples from his own experimental data. Again, POD was related to searcher spacing. However, in Colwell's analysis, the normal relationship between number of searchers and searcher spacing for a given baseline length is not maintained but allowed to vary in a rather one-sided fashion. Colwell's work will be revisited and carefully analyzed in Chapter 4.

2.2.3 At some point D. Cooper observed that the amount of time expended by searchers in an area was an important variable affecting POD that had been largely overlooked. He proposed some ways of correcting this situation. However, he was building on Wartes' and Colwell's concepts of "thoroughness" and "efficiency."

2.2.4 In 1996, R. Goodman and R. Cowan [7] developed the concept of "Probability of Coverage" to address situations where it is known that not all of the area of a segment has actually been searched or where the search management team cannot precisely reconstruct exactly how much of the segment actually had a search team travel through it. As things turn out, Goodman and Cowan came very close to the formal search theory concept of *coverage*, a concept explained in Chapter 5.

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Chapter 3
Basic Definitions

3.1 Introduction

The purpose of this chapter is to define a number of terms that will be used in the analyses of the next chapter. Where appropriate, terms from ground SAR that have synonyms in maritime SAR will be noted, and vice versa. Any terms used strictly for the purpose of analyses in this paper will be so noted. As part of the analysis in Chapter 5 describing some aspects of how search theory should be applied to ground searches, a number of additional terms will be introduced and defined at that point.

3.2 Baseline

For ground searches, the **baseline** is the line defining one edge of a segment (search sub-area) where search teams form a line abreast at the spacing directed by the search manager. The corresponding dimension for maritime search sub-areas is the width of a rectangular search sub-area covered by a parallel sweep (PS) search pattern.

3.3 Effort (z)

For ground searches, **effort (z)** is usually defined as the number of searcher hours spent searching a segment (search sub-area). Thus, effort would be defined as

[3-1] $$Effort = (Number\ of\ Searchers) \times (Number\ of\ Hours\ Spent\ Searching).$$

For aircraft, **effort** may be defined as the number of flight hours expended while actually searching in the segment (search sub-area). An alternative definition in both cases would be the distance traversed in the segment (search sub-area) during the search. (*Note: This term is not to be confused with* **search effort (Z)** *as defined in Chapter 5.)*

3.4 Maximum Detection Range

The **maximum detection range** is the maximum distance at which the sensor in use can detect and recognize, under the environmental conditions prevailing at the time of the search, the search object as the object being sought. For the purposes of the analyses in this paper, **maximum detection range** and **visibility distance** will be considered synonyms unless otherwise stated.

3.5 Probability of Containment (POC)/Probability of Area (POA)

Probability of Containment (POC) is the probability that the object being sought is contained in a defined area. **POC** values are usually assigned to segments (search sub-areas). In the recently published *International Aeronautical and Maritime Search and Rescue Manual (IAMSAR Manual)*, the term **Probability of Containment (POC)** is the accepted international standard term in the aeronautical and maritime SAR communities. It is an exact synonym for **POA**. For the moment, however, **POA** will continue to be

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used in this paper because there are enough concepts new to inland search without replacing an old term with a precisely synonymous new one.

3.6 Probability of Detection (POD)

Probability of Detection (POD) is the probability that the search of a segment (search sub-area) will detect the search object **if** the search object is contained in the segment (search sub-area). This means **POD** is a *conditional probability*; it is conditioned on the assumption that the search object is in the segment (search sub-area) at the time the search is conducted.

3.7 Probability of Success (POS)

The **Probability of Success (POS)** is the probability that the search object will be, or should have been, found during a particular search (operational period). **POS** is a function of both **POA** and **POD**. It is computed by

[3-2] $$POS = POA \times POD .$$

3.8 Search Sub-Area/Segment

The search sub-area is a defined geographic region that is believed to contain the search object. In maritime SAR terminology, a search sub-area is an area, usually rectangular in shape, that a specific search facility (vessel or aircraft) is assigned to search at the assigned **track spacing**. Maritime **search sub-areas** correspond to inland ground search **segments** and inland air search grids. The terms **search sub-area** and **segment** will be used interchangeably in this paper.

3.9 Search Corridor/Lane

This is a term adopted for the special needs of this paper to make discussion of certain points in Chapters 4 and 5 a little easier. It is not a standard term in any search planning/management system nor should it become one. For this paper, a **search corridor** or **search lane** is defined as a rectangular strip centered on the searcher's track whose width extends to the **maximum detection range** either side of the searcher's track and whose length equals that of the **searcher's track** (ground) or **search sub-area** (maritime).

3.10 Search Leg

In situations where a single facility, such as a vessel or aircraft, performs a **search pattern** as a series of parallel sweeps one **track spacing** apart, the **search legs** are the long legs where most searching is done while the cross legs are the short legs connecting the ends of the search legs where the search facility moves from one leg to the next as it proceeds through the **search pattern**.

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3.11 Search Pattern

A variety of **search patterns** are available to cover assigned **search sub-areas**. The **search pattern** is usually specified in the search action plan as well as the **search sub-area** and **track spacing**. By far the most common **search pattern** for single facilities is the parallel sweep (PS) pattern. It is generally used to cover rectangular **search sub-areas**. The **search legs** are parallel to the long sides of the rectangle and the direction of creep is parallel to the short sides. The width of the **search sub-area**, the **track spacing** and the commence search point are all adjusted so the first and last **search legs** are positioned one-half of the **track spacing** inside the nearest search sub-area boundary and the legs are equally spaced one **track spacing** apart.

3.12 Searcher Spacing

Searcher spacing is the distance between adjacent **searcher tracks** in a ground search. It is synonymous with **track spacing** for **search patterns** and the two terms may usually be used interchangeably.

3.13 Searcher's Track

The **searcher's track** is the path the searcher follows while searching in a **segment (search sub-area)**. For most purposes of this discussion, **searcher tracks** and **search legs** are treated as synonyms and both are considered to be perfectly straight, parallel lines separated by one **track spacing**.

3.14 Track Spacing

For **search patterns**, **track spacing** is the distance between adjacent **search legs**. It is equivalent to **searcher spacing** in ground searches using line abreast formations and may be used in place of that term.

3.15 Visibility Distance

Visibility distance is generally intended to be synonymous with **maximum detection range** and will be so treated in this discussion.

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Chapter 4
Analysis of *New Concepts in Gridsearching* [7]

4.1 POD, Searcher (Track) Spacing, and Effort Relationships

The relationship between POD and track spacing seems to form the corner stone of ground search management, with many calculations, formulas, and decisions dependent upon it.

4.1.1 Let us begin our analysis by stating some relationships among POD, Spacing and Effort that seem to be intuitively obvious for searches employing visual search along equally spaced parallel tracks in a given area for a given search object under a given set of environmental conditions.

a) Smaller searcher (track) spacings produce higher PODs than larger spacings.

b) Larger efforts produce higher PODs than smaller efforts.

c) Smaller spacings require greater efforts than larger spacings.

These observations immediately beg the question, "Is POD more dependent on spacing or effort, or does a certain effort imply a certain spacing and vice versa so that effort and spacing are just different ways of measuring the same quantity?" In *New Concepts in Gridsearching* [7], POD is invariably expressed as a function of spacing. Only when attempting to compute a value for "efficiency" is POD related to effort.

4.1.2 Perceiving a need to more accurately quantify the relationship between POD and spacing, and develop techniques for making the most efficient use of the available resources, Colwell [7] performed some relatively extensive experiments circa 1992 in a mature, coniferous forest typical of the Pacific Coast of northern North America. Rather than review the actual experiments, we will construct a "table-top exercise" and conduct a similar set of "experiments" using the techniques and lines of reasoning described in [7]. After presenting the basic approach given in [7], we will examine it more closely in paragraph 4.2.

4.1.3 To set the stage, consider a square area measuring 300 meters on a side. For convenience, we will assume that the sides are oriented along north-south and east-west lines. The south side of the square will be considered the baseline and the searchers will move from south to north along parallel tracks. We will assume further that the maximum detection range is 10 meters and that all objects passed by a searcher within 10 meters to the right or left will be detected, and none will be detected at greater ranges. This is called a "definite range law of detection" and we are choosing it for its simplicity and illustrative value, not because any real-world sensor performs in this fashion. Other more realistic detection functions will be considered at a later time in this inquiry. Finally, we will assume that our 300m x 300m square is approximately uniformly populated with 900 search objects. The segment with its population of search objects is illustrated in Figure 4-1. The search object positions were determined using a random number generator that

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produces an approximately uniform distribution of values. The non-uniformity of the object distribution is due solely to the "noise" present in the random number generator.

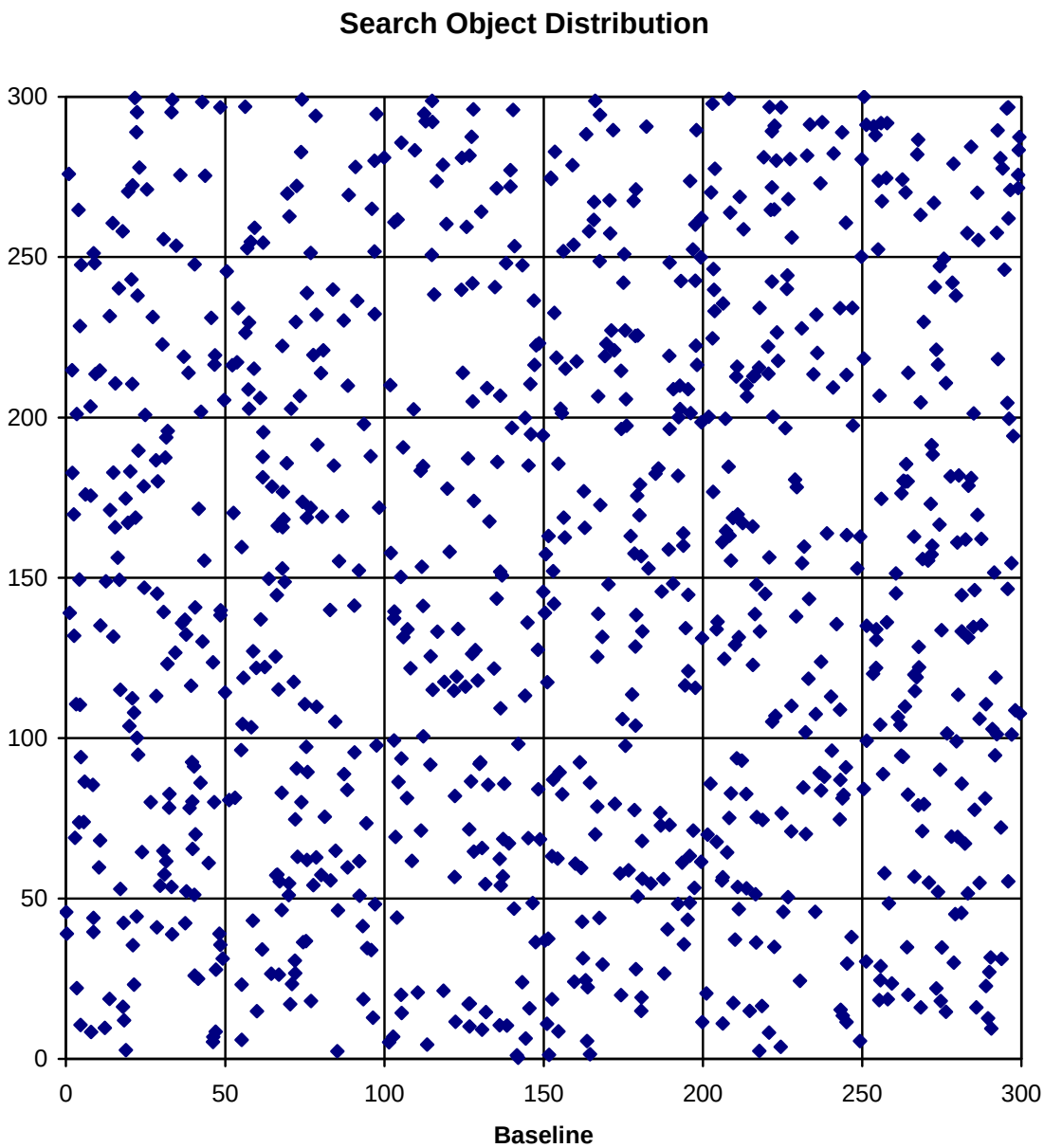

Figure 4-1

4.1.4 Since each searcher detects every object within 10 meters either side of his track, 15 searchers will be able to cover the area completely with a POD of 100%. Therefore, we will divide the segment into 15 north-south search corridors, each 20 meters wide. This will place our 15 searchers at 20 meter intervals, beginning at 10 meters from the west end of the baseline and going to 290 meters; i.e. searchers are at 10m, 30m, 50m, ..., 250m, 270m, 290m from the west end of the baseline. The search corridors are shown in Figure 4-2.

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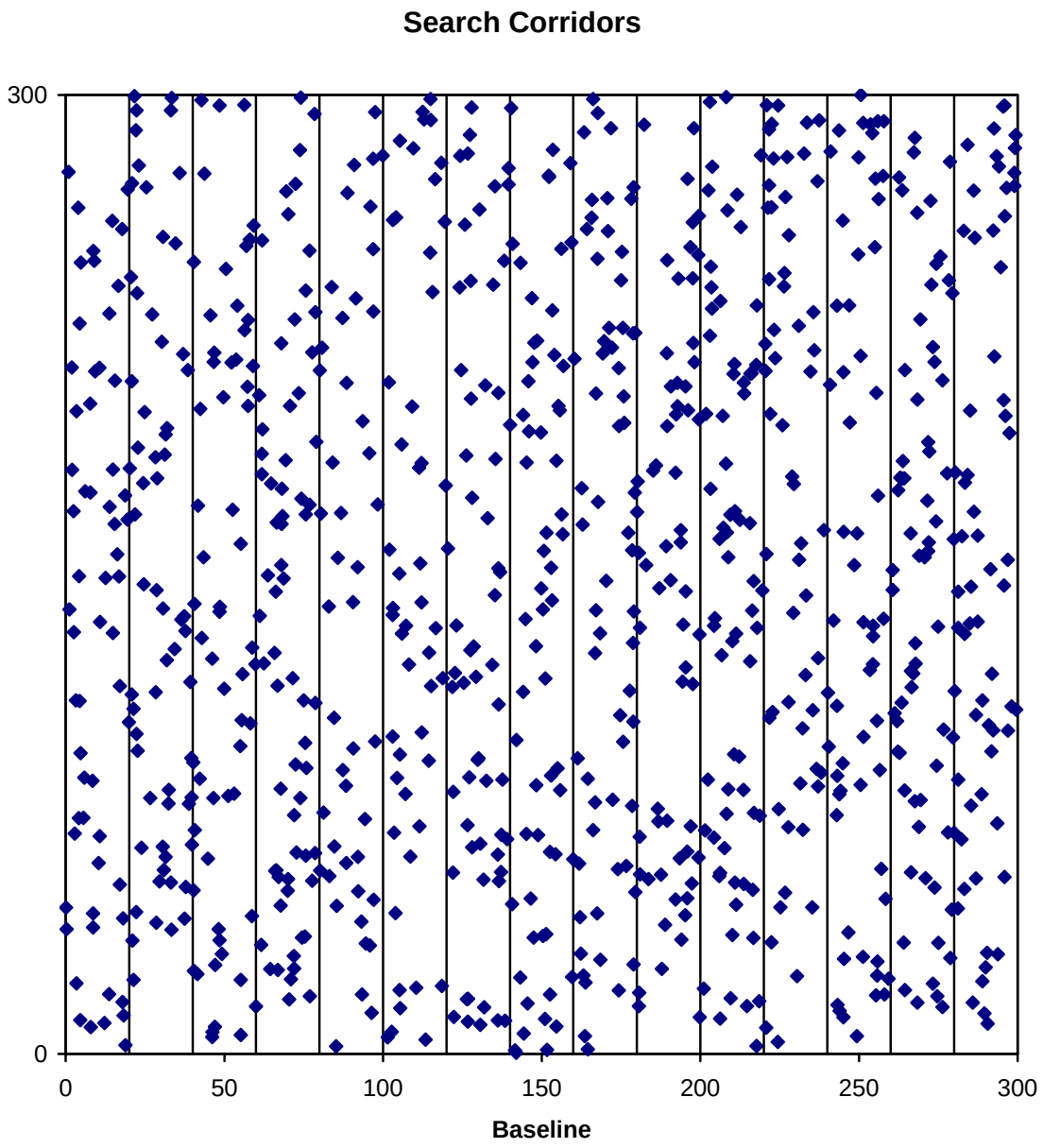

Figure 4-2

Table 4-1 lists the number of objects in each search corridor and also lists the corresponding POA for each search corridor. Note that if the random number generator was "perfect," then each search corridor would have contained exactly 60 search objects for a POA of 6.67%. The "(POD)" in the column heading indicates that if the corridor is searched with our definite range detection function, the amount of POD contributed to the total POD for searching the entire segment will be the same as the corridor's POA.

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Center of Corridor (in meters)	Number of Objects	POA (POD)
10	60	6.67%
30	62	6.89%
50	59	6.56%
70	66	7.33%
90	45	5.00%
110	49	6.44%
130	58	6.44%
150	62	6.89%
170	63	7.00%
190	61	6.78%
210	68	7.56%
230	57	6.33%
250	59	6.56%
270	68	7.56%
290	63	7.00%

Table 4-1

4.1.5 Figure 4-3 shows the situation when all 15 searchers are used. The entire segment is covered and a POD of 100% is achieved. The method given in [7] treats this as the initial data point for plotting POD against searcher spacing.

4.1.6 Rather than repeat the experiments for different spacings, Colwell hit upon the apparently ingenious idea of creating subsets of his experimental data by simply removing the "finds" of some searchers so as to create the effect, for data analysis purposes, of a wider spacing. For example, when all 15 searchers' data are used, the searcher spacing is 20 meters. If every other searcher's data are removed from the data set, then the effect is that of having performed the experiment with a 40 meter spacing, as illustrated in Figure 4-4. This provides a second point for the POD vs. Searcher Spacing curve. Since we are assuming a definite range law of detection, each searcher finds every search object in his or her assigned search corridor. Adding the number of search objects in each searched corridor from Table 4-1 and dividing by the total number of objects in the segment (900) gives the average POD over the segment as a whole. Alternatively, adding the POA values for the searched corridors produces the same result since, for a definite range law of detection, the POD contribution for each searcher in relation to the total segment will equal the POA of that searcher's assigned corridor. This relationship exists because our assumed detection function is 100% effective across the width of the corridor and completely ineffective at greater distances. Thus, by adding the appropriate values from Table 4-1, the POD for a 40 meter spacing based on the situation depicted in Figure 4-4 is computed to be 52.78%.

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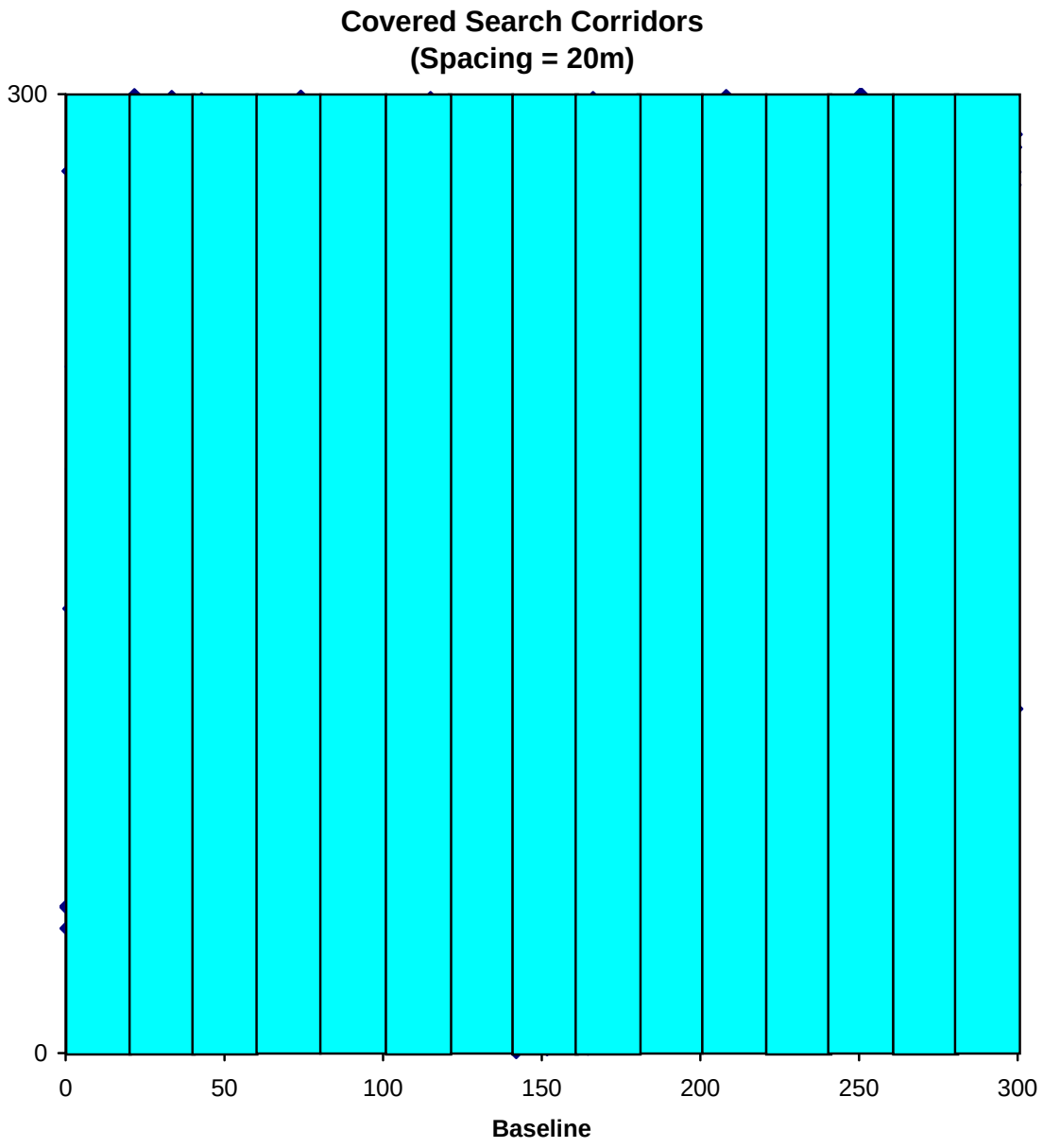

Figure 4-3

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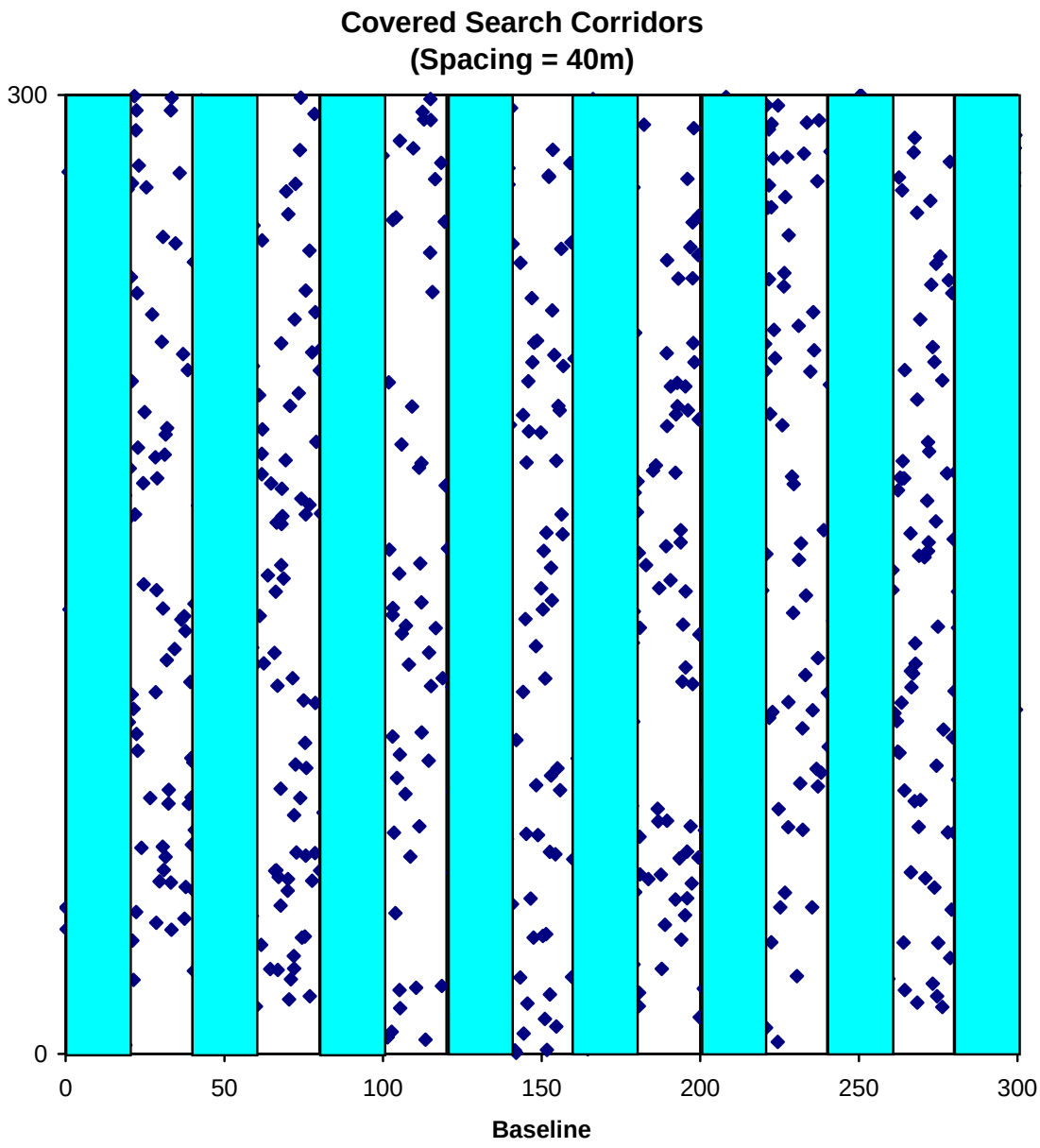

Figure 4-4

4.1.7 To get a data point for the next spacing, it is only necessary to remove searchers' data in pairs to create the effect of a 60 meter spacing. This would require removing the data for searchers at 30m, 50m, 90m, 110m, 150m, 170m, 210m, 230m, 270m and 290m. By continuing to use the first (10m) search corridor's data as an "anchor" and repeating this procedure, a data point for each of the possible spacings up to 300m may be obtained. This would provide a total of 15 data points for spacings of 20m, 40m, 60m, ..., 280m, 300m. This technique was labeled the "Single Pass" method. However, it was determined in [7] that multiple data points for each spacing greater than the minimum (20m in our example) could be extracted from the data. To get another data point for the 40 meter

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spacing, the technique of removing selected searchers' data was extended to include what was called the "Baseline Offset" procedure. Whereas in Figure 4-4, the data for searchers at 30m, 70m, 110m, 150m, ..., 270m were removed, the same 40m spacing could be achieved by removing the data for searchers at 10m, 50m, 90m, 130m,..., 290m and leaving the previously removed searchers' data in place, as shown in Figure 4-5. The POD computed for this configuration is 47.22%. Figures 4-4 and 4-5 show the only two possible configurations that produce a 40m spacing. Why the two POD values are not more nearly equal is a topic that will be explored in paragraph 4.2.

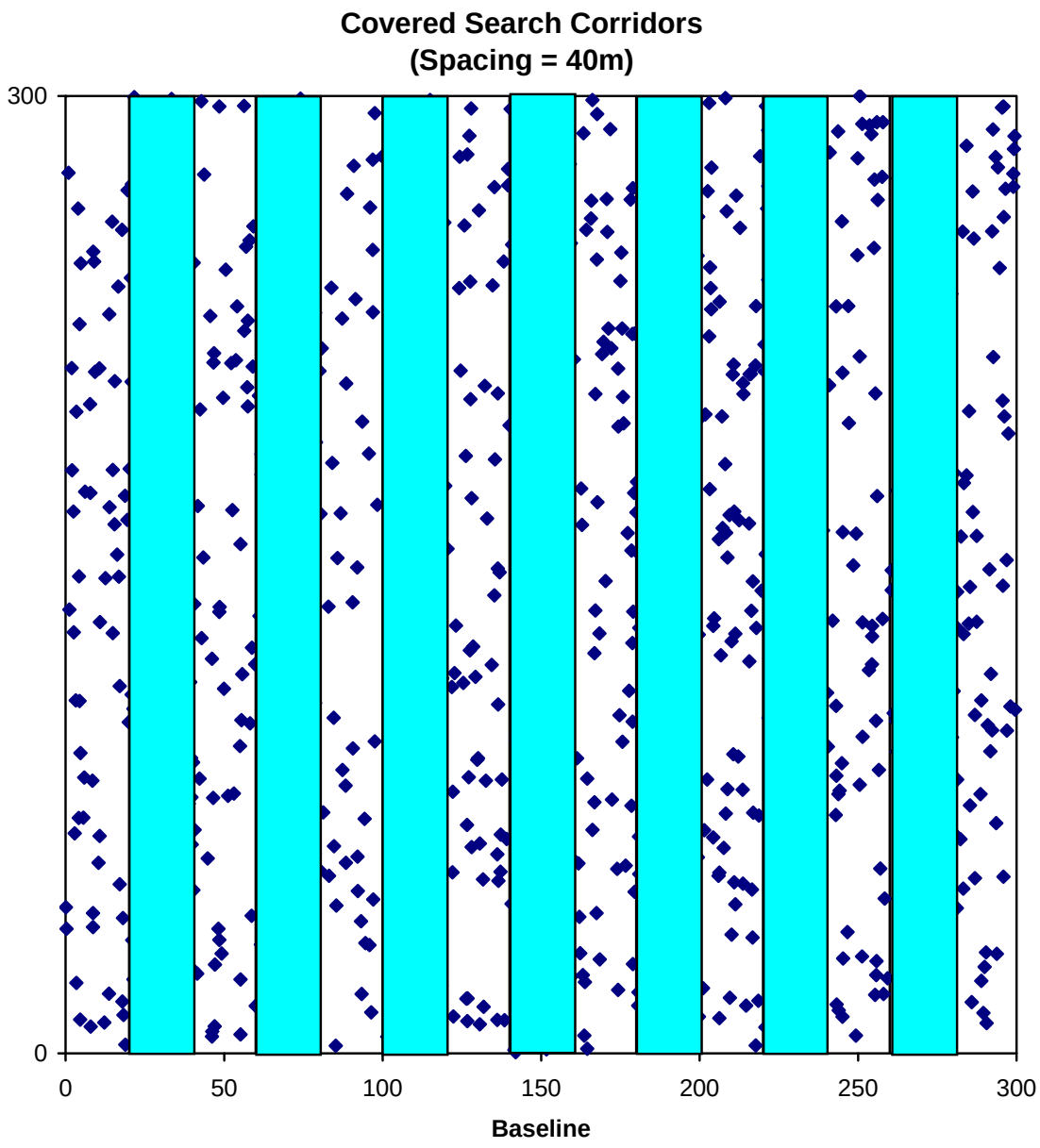

Figure 4-5

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4.1.8 As previously stated, to get data for a spacing of 60 meters, it is only necessary to remove search corridor data sets in pairs and evaluate the effect of the remaining searched corridors. Figure 4-6 shows how this may be accomplished using the "single sweep" procedure. Using the baseline offset procedure, two other configurations at this spacing are possible. These are shown in Figures 4-7 and 4-8. The POD values from all three are relatively close, falling between 32% and 34% in all cases. The number of corridors searched is the same in all cases.

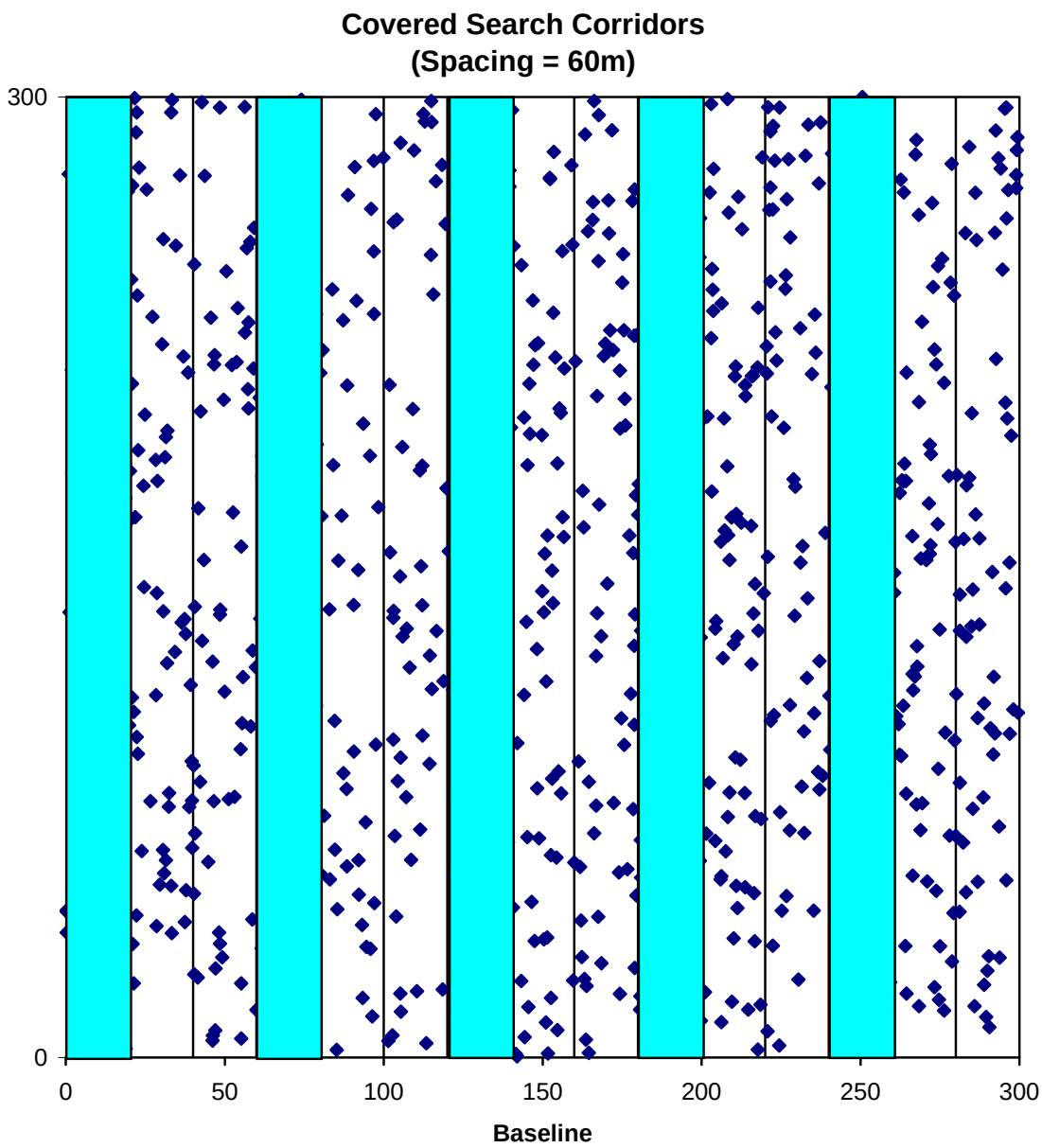

Figure 4-6

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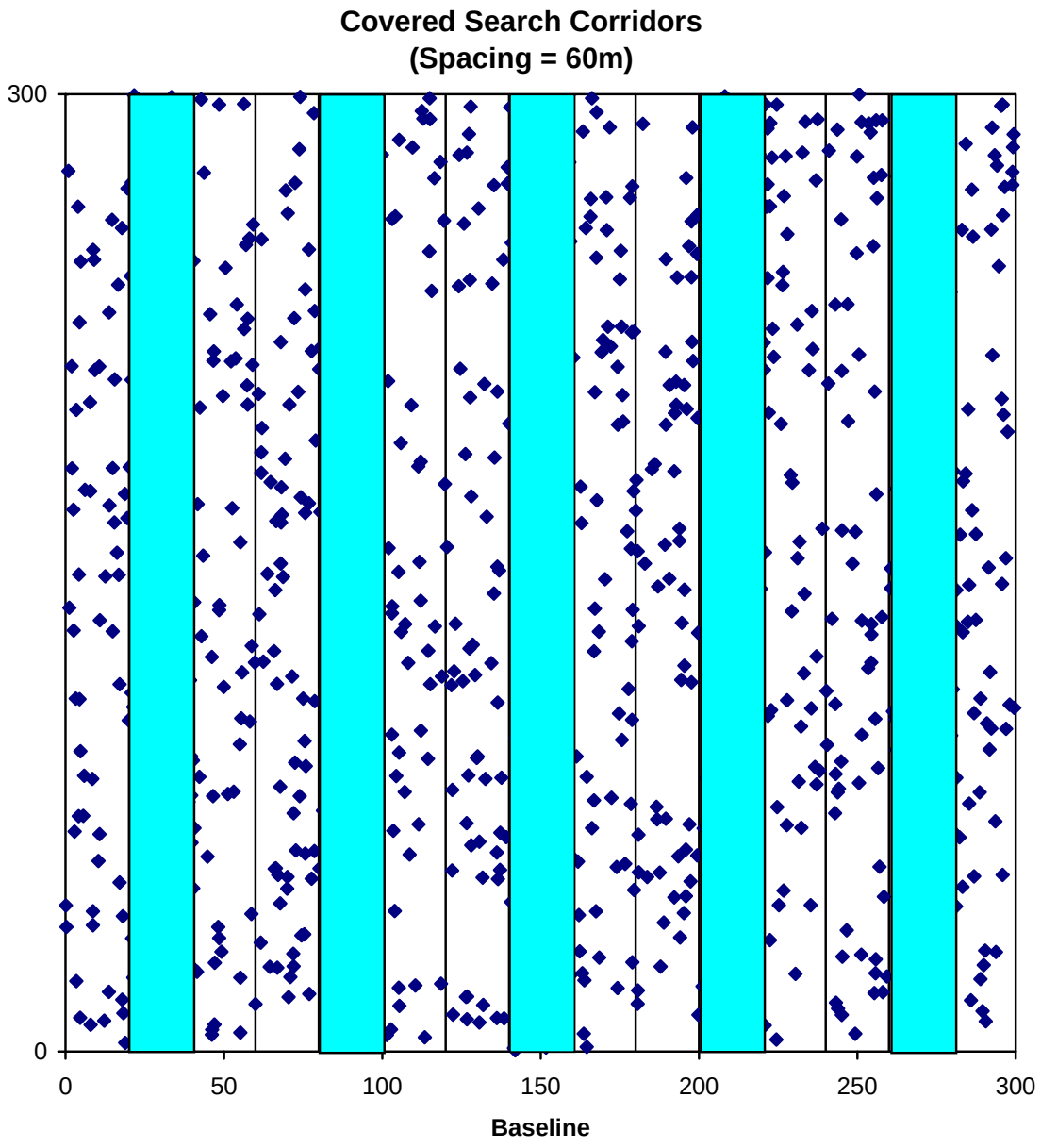

Figure 4-7

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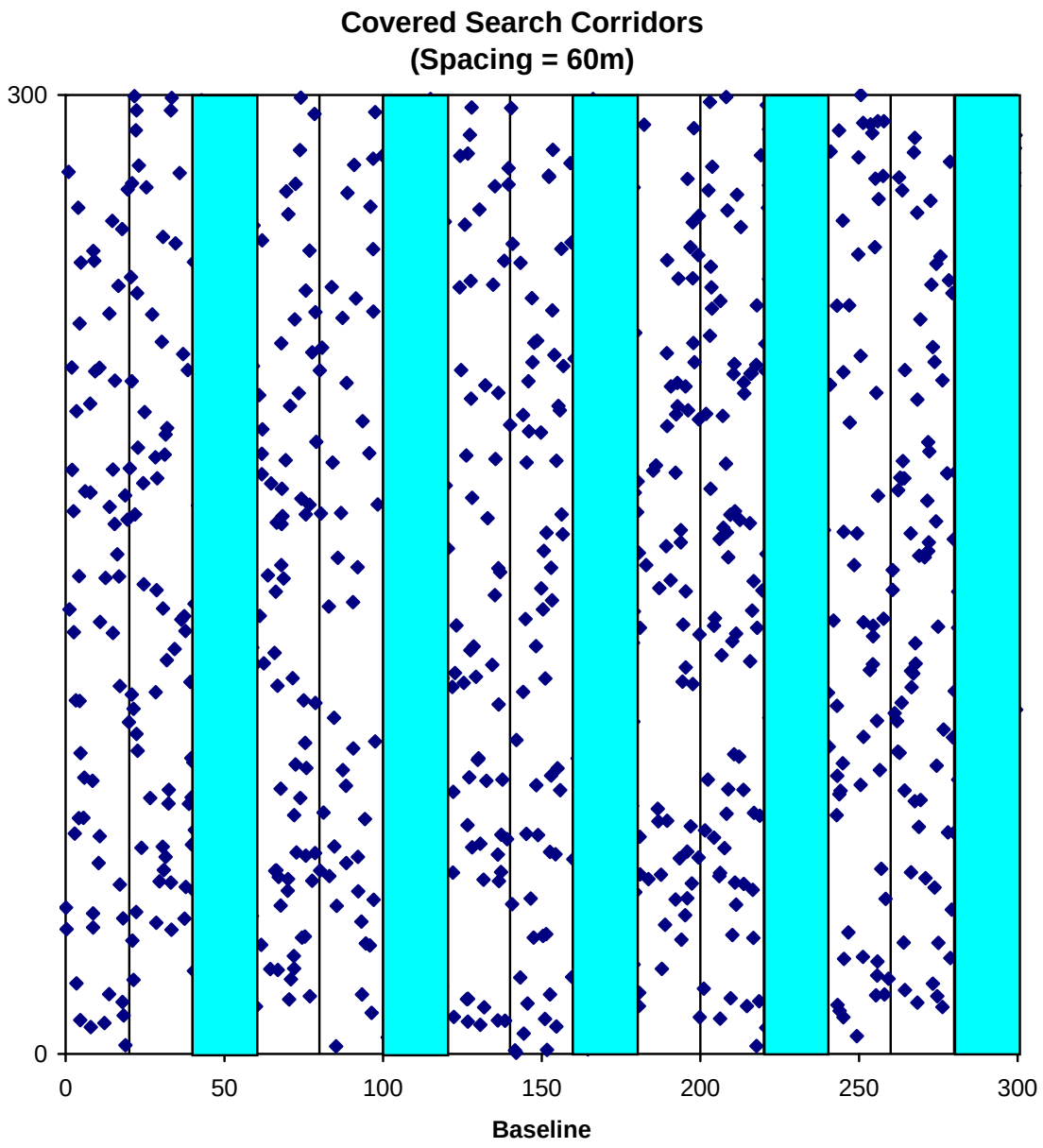

Figure 4-8

4.1.9 A sampling of the various configurations for each of the possible spacings from 20 meters to 300 meters can be similarly displayed. Of particular note are the configurations and POD data for the larger spacings. Figure 4-9 shows the POD vs. Searcher Spacing data points obtained using the Baseline Offset method plotted on a graph.

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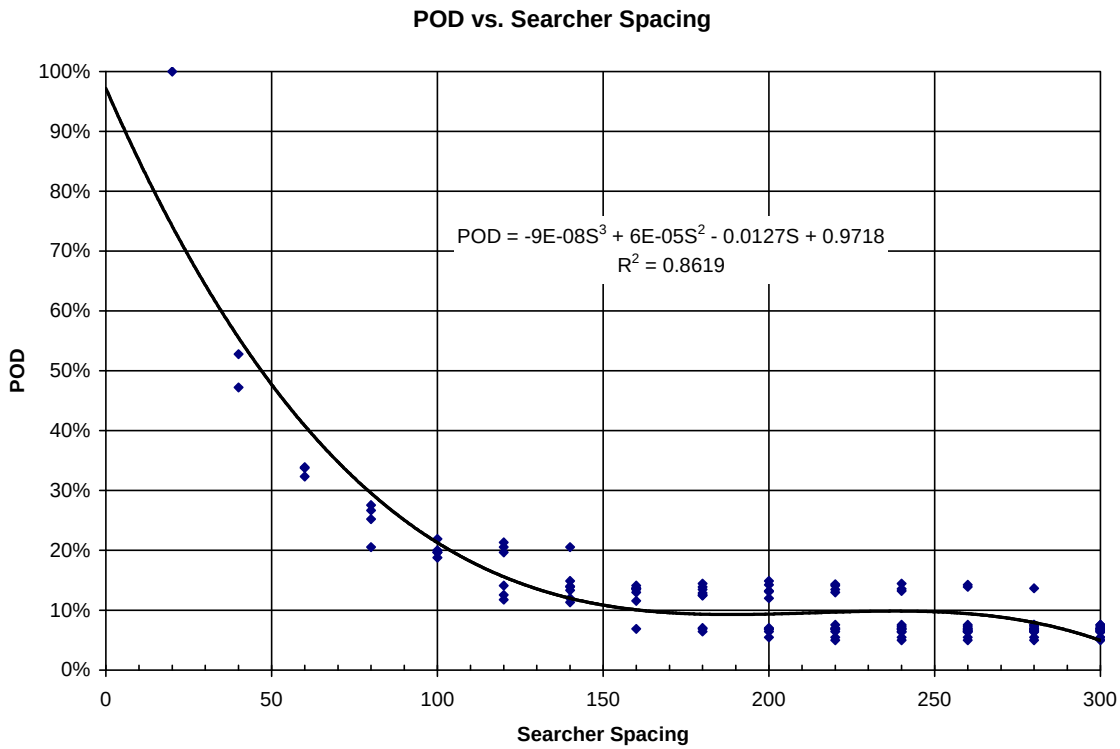

Figure 4-9

Since third degree polynomial functions of the form

[4-1] $$POD = aS^3 + bS^2 + cS + d$$

where the coefficients *a*, *b*, *c*, and *d* are chosen to provide the best "fit" using a standard least squares regression method, were used in [7], such a function has been fitted to the data points in Figure 4-9 and plotted as well. Such fitted curves were called "POD Calibration Curves" in [7] since it was intended that local SAR organizations conduct their own experiments using this technique to "calibrate" POD vs. Searcher Spacing data for their own regions. Following this "calibration" curve from left to right, the POD appears to drop off sharply as spacing increases, then level off at the larger spacings, and then resume its downward trend. In fact, it appears that as spacing increases from about 150 meters to about 270 meters, the POD remains roughly constant. The analysis given in [7] referred to this as a "POD plateau" and it was an important feature for later recommendations regarding effort allocation.

4.1.10 The data generated by the Baseline Offset method and the subsequent analysis of that data using the techniques described above led to a number of conclusions regarding the data and the resulting calibration curves. These are quoted below.

1. There is a great deal of scatter in the POD results obtained. This is probably due in large part to the random nature of the forest and undergrowth.

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2. The large degree of scatter in the results, especially at wider spacings, dictates that large numbers of data points should be obtained if a valid, i.e. reproducible, calibration curve is to be obtained.

3. The 'closeness' of the calibration curves indicated that valid, reproducible calibration curves can be obtained using the Single Pass and Baseline Offset procedures.

4. The shape of the curves, steep down to approximately 100m spacing and then leveling off at wider spacings, reinforces Perkins[9] hypothesis that 'visual overlap' is taking place between searchers at close spacings.

5. The horizontal 'plateau' region between approximately 100m and 200m spacing indicates that no benefit is obtained by placing the searchers at the closer 100m spacing. The 200m spacing permits a much larger area to be searched at approximately the same POD level.

6. The gradual drop towards 0% POD, between 200m and 300m, indicates the searchers' true limit of visibility.

Aside from the spacing values cited in conclusions 4, 5 and 6, the results of our "table top" experiment are consistent with the field experiments and data analyses described in [7]. In the actual experiments, a minimum spacing of 10 meters was used rather than the 20 meters used here and of course the "real-world" detection function, although no mathematical description is available, certainly wasn't of the idealized definite range type assumed here for simplicity. So, even though we have not repeated the results precisely in a quantitative sense (although with some adjustments we could have), it is clear that our table top experiment is an accurate representation of the methods described in [7].

4.1.11 A number of other conclusions were given in *New Concepts in Gridsearching* [7]. As we shall see, it will not be necessary to look at all of them in detail. However, the conclusions regarding how searchers should be employed to make the most efficient use of them do bear recording. *Search efficiency* was defined as the ratio of POD to number of searcher hours expended in the segment. That is,

[4-2] $$Efficiency = \frac{POD}{Searcher\ Hours}.$$

Based on this definition and the POD "plateau" cited above, [7] concluded that multiple sweeps of an area at large spacings would produce a higher *cumulative* POD for the total number of searcher hours expended than fewer sweeps at closer spacings. For example, suppose we have data indicating a searcher spacing of 100 meters produces a POD of 30% for a certain search object under certain conditions. Suppose that we also have data for the same conditions and search object indicating a spacing of 200 meters will produce a POD of 20%. If we then consider a "standard" square segment measuring one kilometer on a side and a standard search speed of 0.4 km/hr, we can compute the "search efficiency" as follows. For a 100-meter spacing, the number of searchers required for a 1 km baseline is 1000/100 or 10. At 0.4 km/hr, it will take each searcher 2.5 hours to traverse the segment. This computes to 10 x 2.5 or 25 searcher hours. Using equation 4-2, the "search efficiency" is computed to be 30/25 or 1.20% per searcher-hour. For a spacing of

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200 meters, the "search efficiency" is computed in a similar fashion to be 1.60% per searcher-hour. Furthermore, if the segment is searched **twice** at a 200 meter spacing, thus consuming 25 searcher-hours, and the cumulative POD after the two searches is computed using the standard cumulative POD formula, a cumulative POD of 36% is produced along with a corresponding "search efficiency" of 1.44. The inescapable conclusion from this line of reasoning is that if 25 searcher-hours of effort are available, it is better to apply it to two searches at a 200-meter spacing than one search at a 100 meter spacing. As we will see, this conclusion cannot be true for several reasons.

4.2 An Analysis of *New Concepts in Gridsearching* [7].

Before proceeding, credit needs to be given where credit is due. Only a handful of individuals in the entire world, almost all working as volunteers (in addition to working for a living) and usually without any funding assistance, have had the initiative, taken the time, and had the dedication, perseverance, and resourcefulness needed to develop and conduct actual experiments and research aimed at improving ground search management procedures. Martin Colwell is one of these rare individuals. He saw a need and did his best to fulfill that need. He also took a great deal of time to explain and illustrate, with complete candor, his techniques and lines of reasoning to this author. Therefore, it seems almost unfair and in bad taste to proceed with a critique of his work. But, however admirable the effort may have been, hard work and good intentions are not guarantors of scientifically valid results. Also, this critique (1998) is aimed at *New Concepts in Gridsearching* [7] because it is a convenient target in that it clearly documents certain misperceptions common throughout the ground, and even much of the maritime, SAR communities. So, even though Colwell appears to be the man on the spot, he is certainly not alone, and in that regard the critique below is indeed unfair for singling out his work for criticism. For that, I do owe Mr. Colwell an apology. Fortunately, we remain on good terms (2003) and he is moving toward more scientific methods in his continuing software development efforts.

In a nutshell, the basic problems with much of ground SAR research, especially research into the conduct of search operations, stem from a general lack of awareness that a significant body of formal scientific research into search theory and its operational application even exists. Neither Colwell nor anyone else in the ground SAR community can really be faulted for not knowing about the search theory library. As a topic, it can hardly be called popular reading. Books on the subject don't stay in print for very long and soon become quite hard to find even with all the publication data available. When they are located, they tend to contain so much mathematical jargon as to be unreadable to all but professional mathematicians. Although the U. S. Navy has funded much of the search theory research and the U. S. Coast Guard's search planning methods are based on the results, the number of SAR professionals in that world-leading maritime SAR organization who are even aware that search theory exists is minuscule. So, however unfortunate it may be that search theory principles are generally unknown to those who are so desperately trying to improve ground search planning/management, it is not at all surprising. Perhaps somewhere, sometime, somehow there will be an opportunity to build and

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fund a combined team of theorists and operators tasked with developing an improved, scientifically-based, but practical, ground search methodology.

Having made motions of apologies and excuses, it is time to get on with the unpleasant business of pointing out the flaws in *New Concepts in Gridsearching* [7]. Chief among these, as we shall see, is a false premise (see paragraph 4.2.7 below) that seems to have been taken for granted throughout the SAR community for many years.

4.2.1 The Method Provides no PODs for Spacings Corresponding to Numbers of Searchers between the Maximum and About One-half the Maximum Number. Removing selected searchers' data from the data sets to simulate searching at larger spacings has some serious limitations. The first time this procedure is invoked, the number of searchers is effectively reduced by about half. In our table top exercise where the maximum number of searchers was 15, getting to the next available spacing required removal of 7 or 8 searchers' data from consideration. That is, no data was available for searcher spacings or numbers of searchers between 20m and 40m or 15 and 8 respectively. Clearly, if a search manager had 10 searchers available for a 300m baseline, he might choose to use them on a 30 meter spacing. This is a relatively minor deficiency when plotting POD against searcher spacing, but it is a major problem when the situation is viewed from other vantage points.

4.2.2 The Normal Relationship Among Number of Searchers, Searcher Spacing and Baseline Length Is Not Maintained. As implied by the next to last sentence in 4.2.1 immediately above, there is normally a fixed relationship in practice among searcher spacing, the number of searchers employed and the baseline length. Specifically, the searcher spacing usually equals the baseline length divided by the number of searchers, i.e.

[4-3] $$Searcher\ Spacing = \frac{Baseline\ Length}{Number\ of\ Searchers}.$$

Alternatively, the number of searchers required to attain a given desired spacing is usually computed as

[4-4] $$Number\ of\ Searchers = \frac{Baseline\ Length}{Searcher\ Spacing}.$$

In other words, the number of searchers and the searcher spacing are normally in inverse proportion to one another, with the baseline length being the constant of proportionality. The analysis technique used in [7] does not maintain this relationship. For example, a spacing of 40 meters, using the Baseline Offset procedure, is obtained in one case by using 8 searchers and in the other case by using only 7. This produces two PODs for the same spacing with a difference much too large to be explained by the "noise" in the random number generator used to populate our simulated segment with simulated search objects. The problem is even more pronounced at the larger spacings. Spacings of 80, 100, 120, and 140 meters may all be produced using three searchers. However a spacing of 80m requires 4 searchers for the other three possible configurations while three of the six

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possible configurations that produce a spacing of 120m require only 2 searchers as do six of the seven possible 140m configurations. Only a spacing of 100 meters invariably requires three searchers. Spacings of 120, 140, 160, ..., 280 meters may all be produced by using only two searchers. These situations arise from the combined effects of the Baseline Offset procedure and the length of the specific baseline under consideration. One would expect that using different numbers of searchers, even at the same spacing, would produce different POD values since different numbers of searchers imply different amounts of searching are being done. Alternatively, when using the same number of searchers at different spacings, especially when those spacings are large enough to make any overlap in the scanned area insignificant, one would expect the POD to be roughly constant and spacing-independent. These effects are observable in our table top exercise results, and they create data analysis problems, as described below, when trying to relate POD to spacing.

4.2.3 The Method of Analysis Induced Much of the Apparent Scatter in the Data. Because the usual relationship among searcher spacing, number of searchers and baseline length is not maintained, situations arise where significantly different PODs are computed for the same spacings. The majority of the "scatter" in Figure 4-9 stems from this source and is not the result of random number generator "noise." Note that at most spacings, the data points in Figure 4-9 form two distinct groups whose vertical separation is generally greater than the "spread" within either group. This happens because two distinct levels of effort (numbers of searchers) are associated with the same spacing. This flaw is much more serious than it might appear because it obscures the true nature of the data and leads to some quite false conclusions about the general behavior of POD.

4.2.4 Polynomial Approximating Functions Are Inappropriate for the Type of Data being Modeled. It is clear that any POD vs. Searcher Spacing curve should behave as follows: At and near a searcher spacing of zero, the POD should approach 100%. The POD should decline rapidly as spacing increases and then gradually become more, but not completely, level at higher spacings, approaching the horizontal axis asymptotically from above. No polynomial function behaves in this fashion.

4.2.4.1 The third degree polynomial in Figure 4-9 has an initial rapid drop to be sure, but it then shows a "plateau" with a minor undulation, increasing very slightly from a local minimum at about 190m to a local maximum at about 240m, before continuing its downward trend. The slightly undulating "plateau" in this curve is an inherent feature of the polynomial function itself, not a reflection of either POD behavior or the nature of the data being approximated. For someone unaware of polynomial characteristics or unaware that the graphs shown in or taken from [7] are produced by polynomials, it is even possible to incorrectly interpret POD values taken from the graph in the vicinity of the "plateau" as evidence that at some searcher spacings, increasing the spacing somewhat further actually increases POD slightly.

4.2.4.2 Approximating functions attempt to maximize their *correlation* with the data. It is never correct to equate correlation with *cause and effect* without some other independent line of evidence to support the claim. The claim that increasing spacing in an operational situa-

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tion does not generally decrease POD, and may even increase it, is not supported by any such independent line of evidence. It is clear that such a claim cannot be true in the general case and it is difficult to conceive of any special set of circumstances where it might be true in a particular case. Since polynomial functions are inappropriate for the nature of the problem, any "efficiency" computations that used POD values from these functions to demonstrate that multiple searches at wide spacings are more efficient than fewer searchers at narrower spacings are likewise inappropriate and produce false results.

4.2.5 The POD "Plateau" Is Artificially Induced. The apparent POD "plateau" within a range of the larger spacings has three primary causes, all of which are artifacts of the data analysis method.

4.2.5.1 As observed at the end of paragraph 4.2.2 above, using the same number of searchers, especially when the number is small and the spacing is large, should produce the same POD. Plotting POD against different spacings while keeping the number of searchers constant will produce an apparent "plateau." However, the plateau has no significance because the POD is not related to the spacing between the searchers, only how many searchers are moving through the segment. This issue is discussed further in paragraph 4.2.7 below.

4.2.5.2 As observed in paragraph 4.2.3 above, the use of POD vs. Spacing data without regard to the number of searchers involved introduced considerable scatter into the data to be analyzed. This obscured the true nature of the data and once the POD reached a sufficiently low rate of decline, this artificially scattered data gave the appearance of a nearly constant POD over a considerable range of spacings.

4.2.5.3 Finally, the approximating function that was chosen, a third degree polynomial, cannot follow a slowly declining trajectory very well. It can approximate a small rate of change in only one way. It must place its one and only inflection point near the center of the region where the most data points are showing the smallest rate of change. Even by just visually inspecting Figure 4-9, it is possible to see that the data between 160m and 280m seems to change very little and the inflection point of the third degree polynomial, also by visual inspection, is near 220m – exactly halfway between those two values. This is why the approximating function is nearly flat with a slight undulation in this region. It is the only way a third degree polynomial can come close to approximating a slowly declining data set. A third degree polynomial also cannot maintain such a nearly flat trajectory for very long, and that is why it has such poor predictive performance for larger spacings as we will see in paragraph 4.2.7.4 below.

4.2.5.4 In summary, the apparent POD "plateau" is caused entirely by the manner in which the data was arranged for analysis and the choice of the approximating function. The POD "plateau" does not represent a real-world phenomenon.

4.2.6 Cumulative POD Computations are used Inappropriately.

4.2.6.1 Strictly speaking, cumulative POD computations apply only to those portions of segments that have actually been looked at by searchers more than once. If, for the first

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search, the searchers are sufficiently separated so that no ground is looked at by more than one searcher, and the searcher tracks of the second search are offset from those of the first search so that no ground is looked at a second time, then the cumulative POD formula does not apply and, if used, will tend to underestimate the cumulative POD of the two searches. In the scenario just described, the net effect of the two searches would be the same as having searched the area all at once by sending searchers down all the tracks used in the two searches.

4.2.6.2 This brings up an interesting anomaly with respect to the example given in paragraph 4.1.11. In that example, it appeared that two searches produced a higher cumulative POD than one search, even though the total amount of effort expended was the same. Suppose the first 5 searchers in that example were sent through the one kilometer square segment on tracks located at 50, 250, 450, 650, and 850 meters and the second 5 searchers were sent out on tracks located at 150, 350, 550, 750, and 950 meters. One must ask what mechanism is at work to create the increase in POD from 30%, which is what sending all ten searchers down all ten tracks at once is supposed to produce, to 36%, which is what sending the same ten searchers down the same ten tracks, but in two groups of five separated by some period of time, is supposed to produce.

4.2.6.3 The cause of this anomaly is not obvious, for it lies in the POD data used in the premise of the problem. The amount of "visual overlap" between searchers spaced at 100m must be insignificant and even less significant for searchers spaced at 200m. Therefore, 10 searchers on a 100m spacing will actually scan about twice as much "virgin" ground as 5 searchers on a 200m spacing. This in turn means, for a uniform distribution of search objects, the POD for 10 searchers should be about twice that of 5 searchers. Therefore, the POD values of 30% for 10 searchers (100m spacing) and 20% for 5 searchers (200m spacing) cannot both be correct. If the 30% value for ten searchers is correct, then the POD for five searchers must be around 15%. If the 20% value for five searchers is correct, then the POD for ten searchers must be about 40%. In the first case, even if the cumulative POD formula was appropriate, two searches at a POD of 15% would produce a cumulative POD of only 28%, which is less than the single search POD. Likewise, the cumulative POD of 36% from two 20% searches is less than the 40% POD for a single search.

4.2.6.4 While there may be some practical situations where multiple searches at wider spacings do produce higher PODs than fewer or single searches at smaller spacings, this is certainly not true in the general case. For example, using two search teams of equal size in succession, each starting their respective operational periods from a refreshed state, might produce a higher POD than leaving one team in the segment for two operational periods due to the toll fatigue would take on a single team's effectiveness over such a long span of time. (On the other hand, formal search theory tells us that putting both refreshed teams into the segment at the same time for one operational period would produce an equal or higher POD than using them in succession.) However, there are other ways to explain and properly account for such differences, using the concepts of *sweep width* and *coverage*, as we shall see in the next chapter. It is safe to say that in no case is increased POD "efficiency" an inherent quality of multiple searches at wide spacings

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when compared to applying to same amount of effort to a single search at a proportionately smaller spacing. In fact, the opposite is generally true from a search theory perspective. That is, applying a given level of effort to a single search generally produces better results than splitting the effort and applying it to multiple searches. Only if the effort is precisely optimally allocated will it be possible for multiple searches to just keep pace with single search results when the total amount of effort expended is the same.

4.2.7 POD "Calibration" Curves are based on a False Premise. By now, most readers have probably discerned from the figures depicting the searched corridors that the POD in our table top exercise depends on the number of corridors, i.e. the amount of *area effectively searched or swept*, not on the spacing between the searchers. That is, for a given baseline length, POD depends more on the number of searchers employed, i.e. the amount of effort expended, than it does on searcher spacing. In fact, as long as there is no overlap in the detection envelopes of adjacent searchers, POD is no more related to the spacing between the searchers than it is to the cost of the apples in their box lunches. For baselines of finite length, the "searcher data elimination" process used in the Baseline Offset analyses gives the *appearance* of POD dependency on searcher spacing simply because, at a given spacing and offset, only a certain number of searchers will "fit" between the ends of the baseline. But, as the data from our table top exercise shows, it isn't the spacing itself that modifies the POD, it's the number of corridors (or amount of *area*) actually searched that is the critical factor.

4.2.7.1 Consider the situation where enough effort is available to search only two corridors. It is easily verified from our table top exercise that searching **any two corridors,** out of the 105 possible unique combinations of 15 corridors taken two at a time, will produce about the same POD — 13.33% on average. This is true for our definite range detection function even if the corridors are adjacent to one another with the searchers only 20m apart. The same principle applies to the 6,435 possible combinations of 15 corridors taken 8 at a time — the POD for each combination of 8 corridors will be close to the average value of 53.33%. The spacing between the searchers isn't even a consideration. This means that the **premise** of POD being purely spacing dependent, on which the analyses in [7] (and most other ground search POD research methods) are based, is **false** and all conclusions based on this premise are likewise false.

4.2.7.2 Figure 4-10 shows the same POD data used in Figure 4-9 plotted against the number of searchers, or more accurately, the number of corridors actually searched. Note that the scatter in the data when viewed this way is virtually non-existent and what little there is can be easily explained by the noise in the random number generator originally used to populate our segment with points representing search objects. Also plotted on Figure 4-10 is a regression line that fits the data nearly perfectly. (An R^2 value of 1.0 would indicate a perfect fit with no error.) The conclusion one may reach for this data set is that POD is directly proportional to the number of searchers. As observed above, this conclusion is fully supportable as long as there is no overlap in the areas scanned by adjacent searchers.

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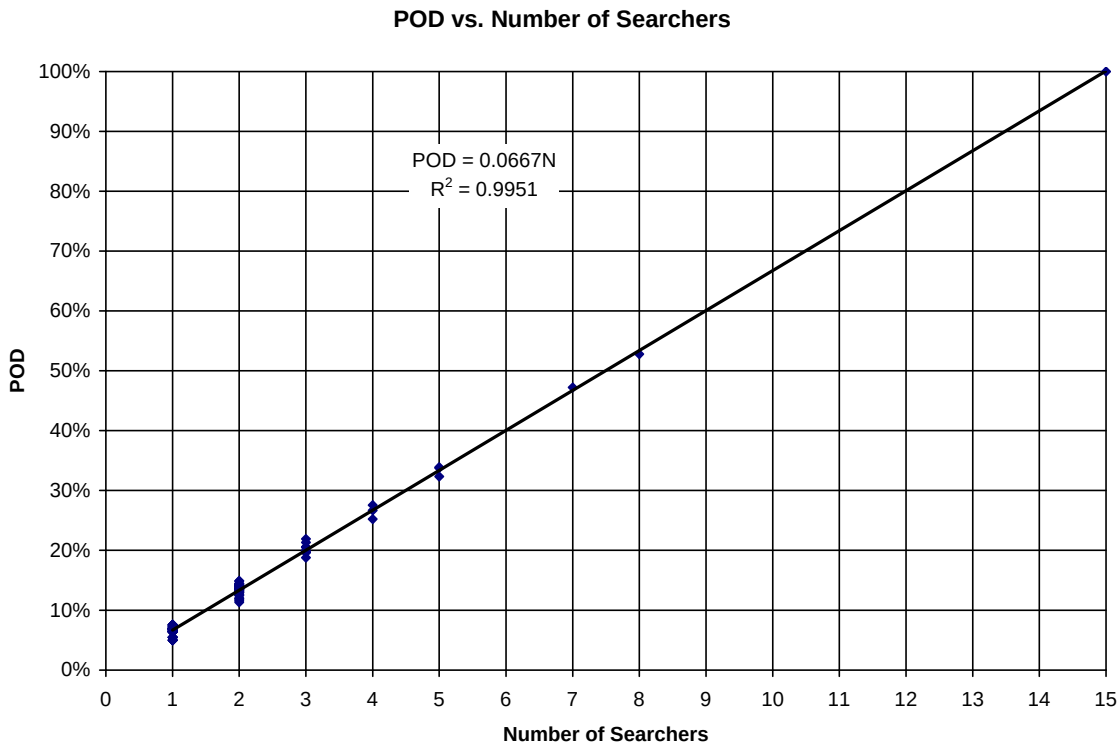

Figure 4-10

4.2.7.3 If POD is proportional to the number of searchers, and if we assume the normal relationship among numbers of searchers, searcher spacing and baseline length exists where the spacing is inversely proportional to the number of searchers, then the POD should likewise be inversely proportional to the spacing through this relationship. To test this hypothesis, we may try fitting the points in Figure 4-9 with a power function of the form

[4-5] $$POD = aS^b$$

where S is spacing and a and b are constants chosen to provide the best fit to the data. If the inverse proportion hypothesis is correct, then b should be equal to -1 and a would be the constant of proportionality. Figure 4-11 shows a power curve fit to the points of Figure 4-9. Note that the value of b is -1.0197 that is indeed very close to -1. This is in spite of the fact that the data points in Figure 4-11 do not strictly adhere to the normal inverse proportion relationship between searcher spacing and number of searchers. The value of a is also close to the width of the search corridors, a fact that will prove significant as our analysis progresses.

4.2.7.4 When comparing the third degree polynomial fit to that of the power function, it is seen that the R^2 value for the polynomial (Figure 4-10) is significantly closer to 1.0 than the R^2 value for the power function (Figure 4-11). It is tempting to conclude that the polynomial is a better representation of the data and reject our hypothesis regarding the inverse proportion relationship between spacing and POD.

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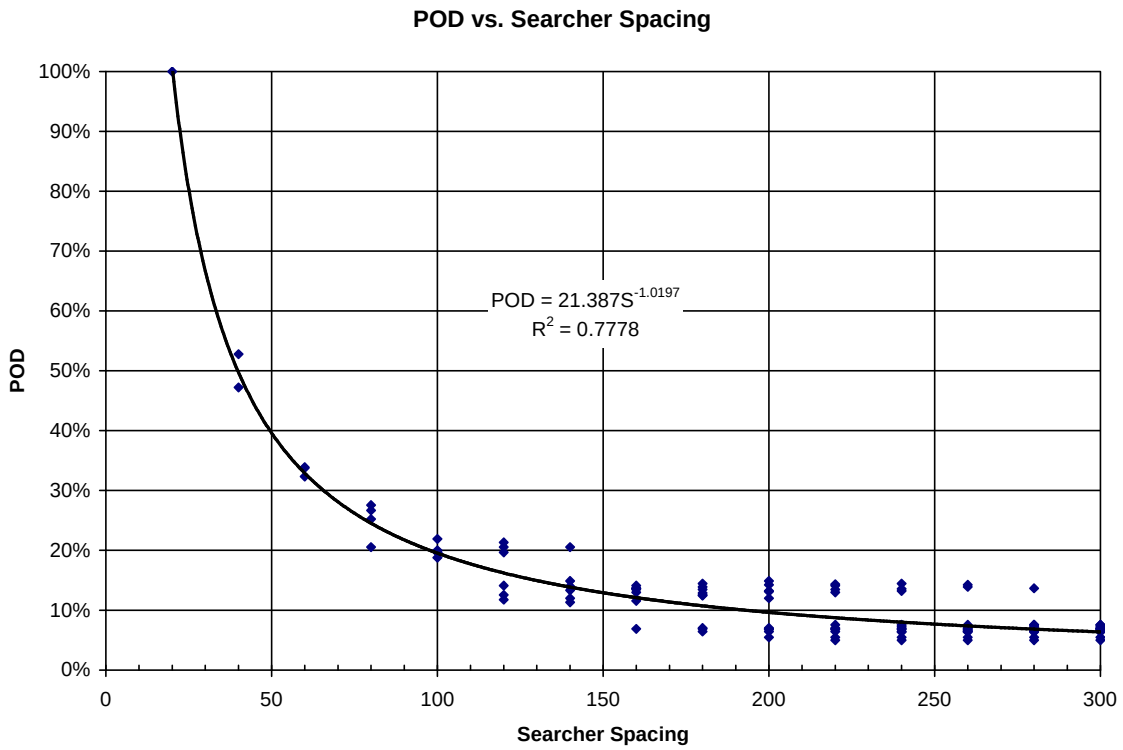

Figure 4-11

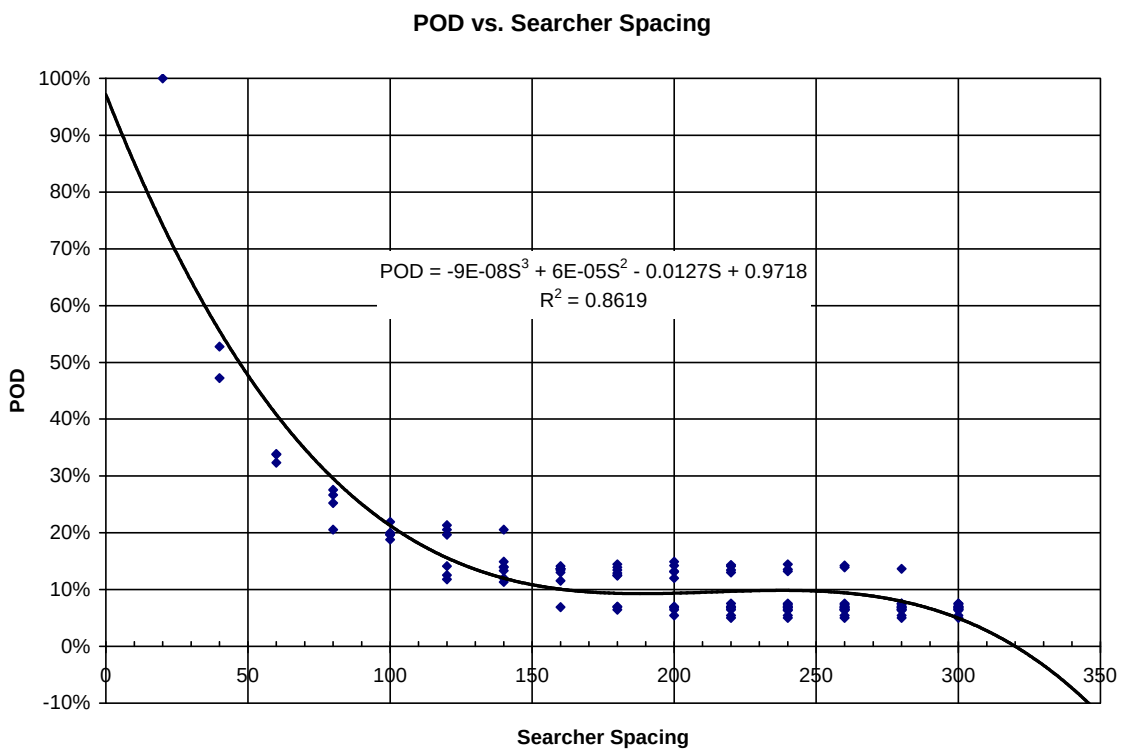

Figure 4-12

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However, if one tries to use each function to predict POD values for larger spacings, say up to 350 meters, a fundamental difference in the two functions immediately becomes apparent. Figure 4-12 shows the behavior of the polynomial when it is extended to 350 meters. Figure 4-13 shows the behavior of the power function when extended to the same range.

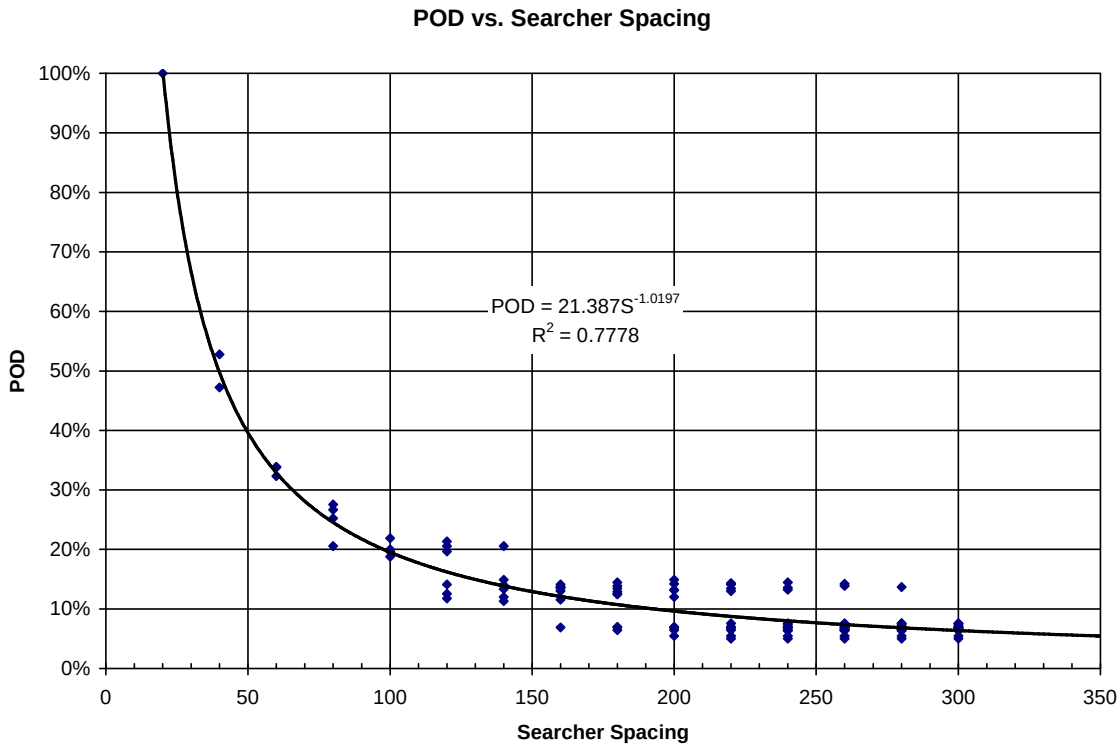

Figure 4-13

Recalling that POD should generally decrease toward zero without ever actually reaching it as spacing increases (because that implies the effort and the fraction of the segment's area effectively searched are decreasing), it is clear that the polynomial has no predictive value whatsoever beyond 320m since the POD becomes negative at about that point and remains so forever afterward. At the very best, it may be useful as an interpolating function between smaller spacings. The power function, on the other hand, does have predictive value and does approach the horizontal axis asymptotically as spacing increases without bound. Therefore, despite its lower R^2 value, the power function is far and away the better approximating function for this application.

4.2.7.5 When attempting to fit curves to data, polynomials must be used with extreme caution. They have a number of vices. Given a polynomial of degree *n*, it is always possible to fit *n*+1 data points exactly, thereby obtaining an R^2 value of 1.0. What may not be obvious until the curve is actually plotted are extreme departures from the vicinity of the data in the intervals between the data points. Polynomials never fit asymptotic data well except over short intervals. Polynomials, especially those of higher degree, have more "degrees of freedom" and thus may follow more complex paths through the data to maximize R^2

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than most other functions available in standard curve fitting software. In our examples, the third degree polynomial has four degrees of freedom whereas the power function has only two. This means polynomials often achieve higher R^2 values without being as good a representation of the data's true nature as some of the other functions might be. The additional scatter introduced by the Baseline Offset procedure exacerbates the fitting problem for the power function while actually making things easier for the polynomial as we shall see in some later comparisons of the two using less scattered data. In short, R^2 values alone are not reliable indicators of which function is truly a best fit for the data.

4.2.7.6 Even when a "correct" approximating function is in use, the way the data is represented may not be the most useful way to view it. To illustrate, note that as searcher spacing increases beyond about 150m in our table top exercise, the POD vs. Searcher Spacing curve in Figure 4-9 becomes more and more nearly flat (i.e. the slope of the curve approaches zero ever more closely). This gives the illusion that significant changes in searcher spacing above 150m do not produce significant changes in POD. In fact, halving the searcher spacing doubles the POD for our sample search situation. This is much more apparent from the POD vs. Number of Searchers graph in Figure 4-10. Here, it is quite clear that doubling the number of searchers (something you would need to do in order to halve the spacing over the same baseline length) doubles the POD, at least until "visual overlap" becomes a factor.

4.2.8 <u>The Method is Not Extensible to Larger Baseline Lengths</u>. The analysis of the data from the field experiments, using the methods given in [7], indicated no significant change in POD between spacings of about 100m and 200m. The actual cause of this phenomenon was almost certainly that, because the average baseline length was around 260m, the majority of data sets for spacings in this range, using the Baseline Offset procedure, contained data from the same number of searchers (two). That is, the POD's were approximately constant across this range of spacings because the number of searchers, and therefore the amount of searching being done, was approximately constant according to the data analysis technique being used.

4.2.8.1 The conclusion in [7] that a 200m spacing is just as *effective* as a 100m spacing in terms of POD doesn't hold up when applied to a longer baseline. Using this logic for a one kilometer baseline, one would conclude that five searchers on a 200m spacing would be just as effective as 10 searchers on a 100m spacing. This runs counter to plain common sense. Additionally, in our table top exercise it is clear that doubling the number of searchers will double the POD, especially at such wide spacings where "visual overlap" is not a significant factor.

4.2.8.2 Another comparison is worth noting. If we were to perform a second table top exercise like that described in paragraph 4.1 using a one kilometer baseline instead of 300m but keeping all other parameters and methods the same, we would not always obtain the same POD values for the same spacings. For example, an 80m spacing on a 300m baseline produces PODs of about 26.67% and 20%, depending on the number of searchers. For a one kilometer baseline, the same 80m spacing produces PODs of about 26% and 24%, again depending on the number of corridors searched. On the other hand, a spacing of

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100m produces PODs of about 20% for both baseline lengths. We will show in paragraph 4.4 below how to both remove the scatter induced into the data by the method of analysis and resolve this apparent discrepancy through an improved analysis technique.

4.2.9 The Logic Used to Reach Conclusions Concerning Efficiency is Fallacious. The POD Calibration curves in [7] are produced from data where very often a given spacing is produced by at least two, and possibly more, numbers of searchers, i.e. distinct levels of effort. That is, a given spacing does not imply a certain, unique, number of searchers for a given baseline length. Conversely, the same number of searchers (effort) often corresponds to many different spacings for the same baseline. That is, a given number of searchers does not imply a certain, unique, spacing for a given baseline. However, when "POD efficiency" computations are done, a given spacing and baseline length do imply a specific, unique number of searchers and conversely, a given number of searchers produces one, and only one spacing for a given baseline length. So, we have a situation where a POD value taken from data where spacing, level of effort (searcher-hours), and baseline length were not uniquely related is compared to a level of effort that depends exclusively and uniquely on both the spacing and the baseline length. This is the same as saying that when searching is done as an exercise for the purpose of gathering POD calibration data, spacing, effort and baseline length are not related, but when searching is done operationally, spacing, effort and baseline length are related via a specific mathematical formula. The error is then compounded by comparing a POD based on the first assumption to a level of effort based on the second, opposite, assumption. In formal logic theory, this is known as the fallacy of denying the antecedent. In layman's terms, it is known as trying to have one's cake and eat it, too.

4.3 Comparison with Aeronautical and Maritime Searching

Many of the situations that caused problems in the analyses given in [7] would never arise in those aeronautical or maritime search patterns where straight, parallel tracks are used, either experimentally or in actual SAR operations. In particular, the strict mathematical relationship among number of search legs, track spacing and search sub-area width (baseline length) is religiously maintained for such parallel track search patterns as a result of the search planning doctrine associated with them.

4.3.1 In maritime search planning, and also in aeronautical search planning over reasonably flat terrain, search legs in parallel track patterns are always arranged to provide the most uniform possible coverage of the search sub-area. If a rectangular search sub-area is 30 nautical miles wide and 60 nautical miles long, and the search aircraft flies at 120 knots and has a five hour endurance on scene (excluding transit times), then the aircraft will be able to complete 10 legs of a PS pattern (search legs parallel to the long sides of the rectangle). This corresponds to a track spacing of 3 NM. The first leg would be set at one-half track spacing (i.e. 1.5 NM) inside the search sub-area and subsequent legs would be spaced at 3 NM intervals from it. The tenth, and final, leg would end up exactly one-half of a track spacing inside the search sub-area on the opposite side from the first leg. Given 10 searchers and a 300m baseline, an aeronautical/maritime search planner would immediately decide upon a 30 meter spacing, place the first searcher at 15 meters (one-

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half of the track spacing) from one end of the baseline, and place the remaining searchers at 30m intervals (i.e. at 45, 75, 105, ..., 255, and 285m) which would leave the 10th searcher one-half track space inside the opposite end of the baseline. Neither the "Single Sweep" nor "Baseline Offset" procedures as described in [7] consistently provided the most uniform possible distribution of effort over the segment's area.

4.3.2 We could recompute POD values based on each of the 15 aeronautical/maritime-style parallel track configurations (one for each possible number of searchers from 1 to 15) that would apply to our table top exercise. However, to save time and effort, let us assume that our 900 simulated search objects are arranged in a perfectly uniform distribution so that **any** corridor 20 meters wide, perpendicular to the baseline, and spanning the full length of the segment contains exactly 60 search objects regardless of where it is placed along the base line. This would give each such corridor a POA (and POD contribution when searched with our definite range detection function) of 6.67%. Using this "idealized" distribution of search objects, Table 4-2 shows the spacings and corresponding PODs for numbers of searchers ranging from 1 to 15.

Number of Search Legs (# of Searchers)	Searcher Spacing (meters)	Sample POD Values
1	300.00	6.67%
2	150.00	13.33%
3	100.00	20.00%
4	75.00	26.67%
5	60.00	33.33%
6	50.00	40.00%
7	42.86	46.67%
8	37.50	53.33%
9	33.33	60.00%
10	30.00	66.67%
11	27.27	73.33%
12	25.00	80.00%
13	23.08	86.67%
14	21.43	93.33%
15	20.00	100.00%

Table 4-2

4.3.3 Plotting the POD vs. Number of Searchers (which is proportional to both effort expended and area effectively searched and inversely proportional to track spacing) from Table 4-2 produces the graph shown in Figure 4-14. Note that we have covered all possible numbers of searchers between 1 and 15 whereas the previous analysis did not produce POD values for 6 searchers or numbers of searchers between 9 and 14 inclusive. Also note that the regression line fits the data perfectly and has a slope equal to the average POD (6.67%) contribution per search corridor.

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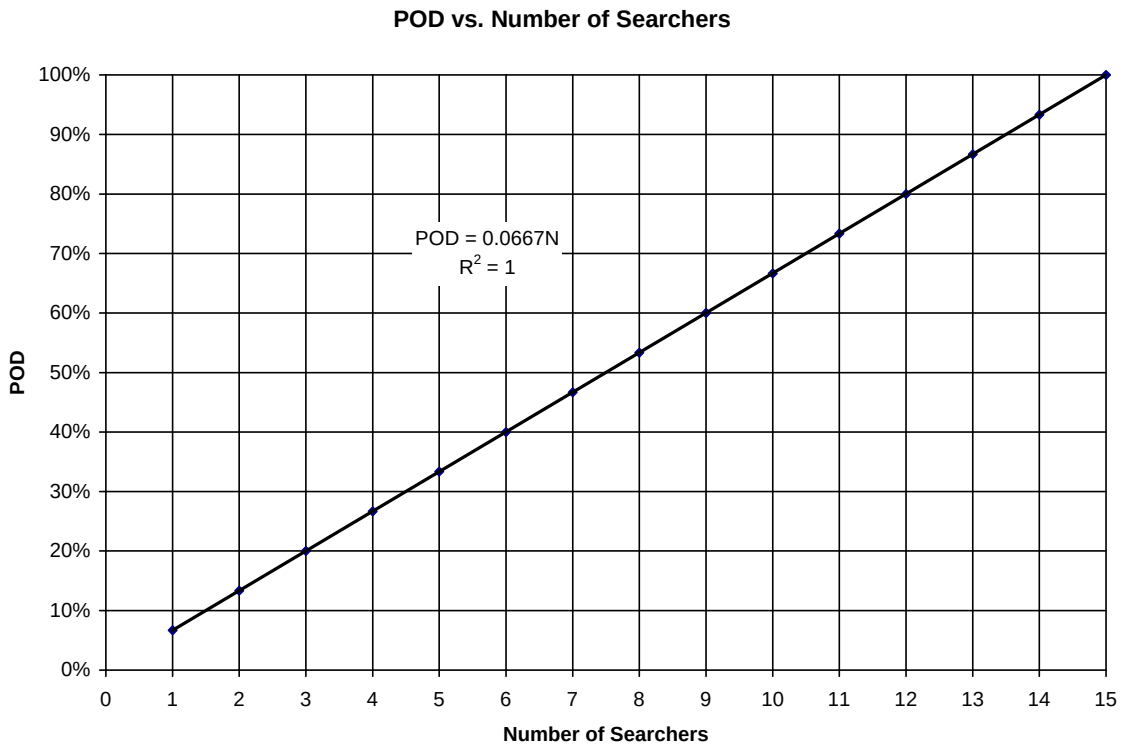

Figure 4-14

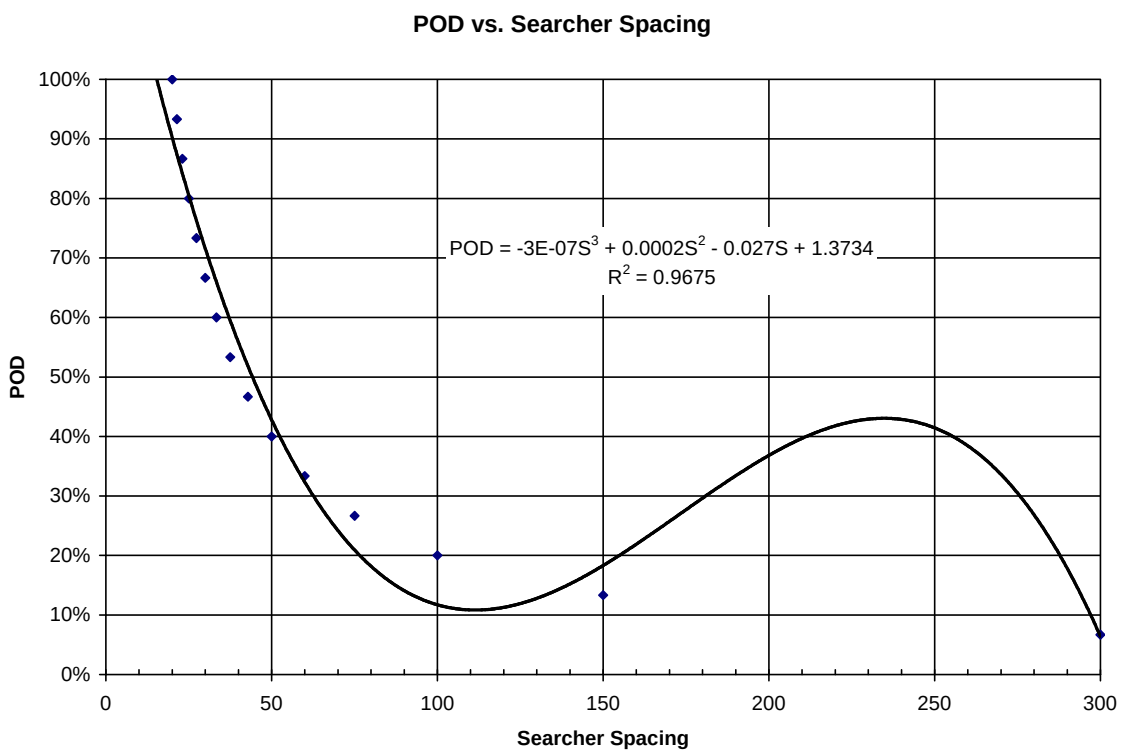

Figure 4-15

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4.3.4 Figure 4-15 shows a plot of the POD vs. Searcher Spacing data from Table 4-2 along with a third degree polynomial fitted curve. Note that the natural form of third degree polynomials is much more pronounced in this example. Although the R^2 value for our third degree polynomial is quite close to 1.0, the peak between 200m and 250m is clearly an anomaly and is not reflective of the true nature of the data. Plots of higher degree produce even more extreme values, well off the graph, in between the data points. The power function approximation of the data shown in Figure 4-16, on the other hand, is exact, with an exponent (*b*) of -1.0.

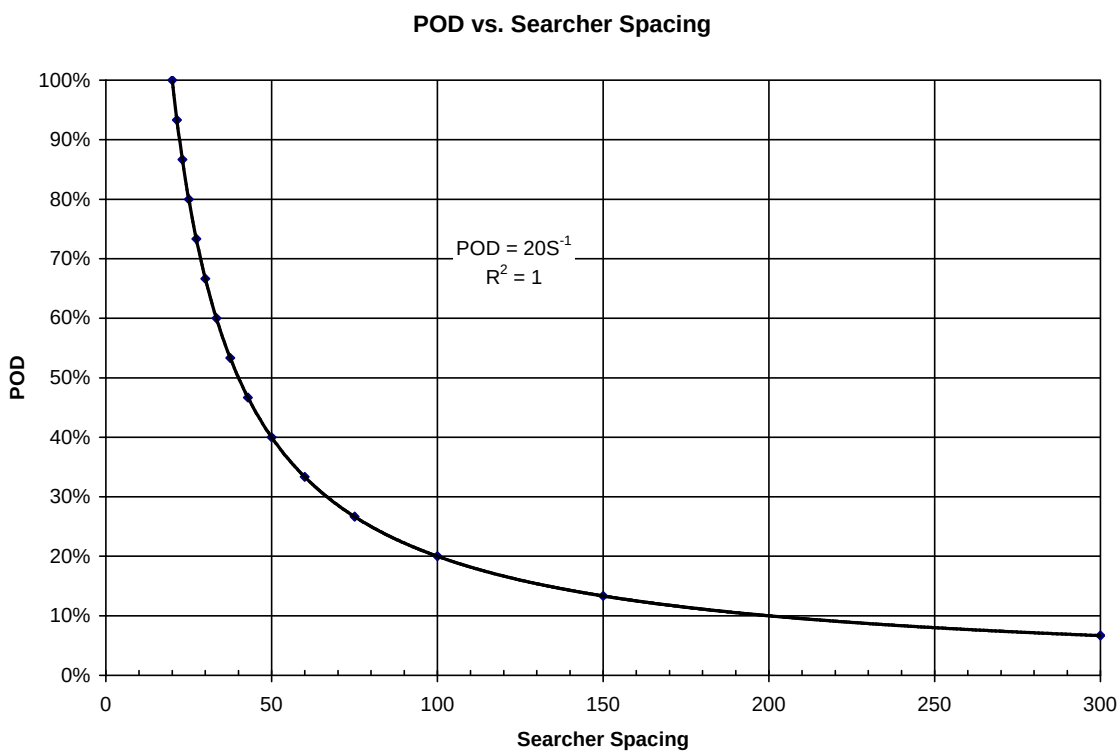

Figure 4-16

This supports our previous conclusion that it is the better approximating function for POD vs. Searcher Spacing data sets. Note also that the coefficient *a* is exactly equal to the width of the search corridors. If we let *W* represent the width of the definite range detection function (i.e. twice the definite range), then the equation of the power function fitted to the data in Figure 4-16 may be rewritten as

[4-6] $$POD = WS^{-1} = \frac{W}{S}, \text{ for } S \geq W.$$

This relationship will appear again in Chapter 5 where it will be viewed from the vantage point of formal search theory.

4.3.5 Perhaps an observation is in order at this point. If Equation [4-6] is taken out of context, it could be misinterpreted as implying that POD is generally inversely proportional to

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spacing, and that *W* is merely the constant of proportionality. It may be that such a misinterpretation is the root cause of the widespread misperception that POD is exclusively dependent on searcher spacing. As we will see in Chapter 5, Equation [4-6] is only valid for definite range detection functions where the searcher tracks are parallel, uniformly distributed over the segment's area and there is no "overlap" of detection envelopes from one track to another. We have already observed that no real-world detection function is of the definite range type, which means attempts to establish POD vs. Spacing relationships based on the application of Equation [4-6] to the general case are doomed before they begin. Finally, the true significance of *W* goes well beyond being a simple constant of proportionality, as we shall also see in Chapter 5.

4.4 Further "Table Top" Analysis

Several of the problems with the analyses described in [7] were related to "scatter" in the data. One of the surest ways to reduce or eliminate "scatter" is through simple averaging. Let us see what happens if, for each spacing, we average the PODs and numbers of searchers from our table top exercise and plot the results.

4.4.1 Table 4-3 below lists the average of the PODs for each spacing using the values from our table top exercise. The averages for both POD values and numbers of search legs were computed by simply averaging all the values for each spacing. However, note that the average number of searchers may also be computed by dividing the baseline length by the spacing. These values are plotted in Figure 4-17 along with a third degree polynomial approximation.

Searcher Spacing (meters)	Average of POD Values	Average Number of Search Legs (# of Searchers)
20	100.00%	15.00
40	50.00%	7.50
60	33.33%	5.00
80	25.00%	3.75
100	20.00%	3.00
120	16.67%	2.50
140	14.26%	2.14
160	12.50%	1.88
180	11.11%	1.67
200	10.00%	1.50
220	9.09%	1.36
240	8.33%	1.25
260	7.69%	1.15
280	7.14%	1.07
300	6.67%	1.00

Table 4-3

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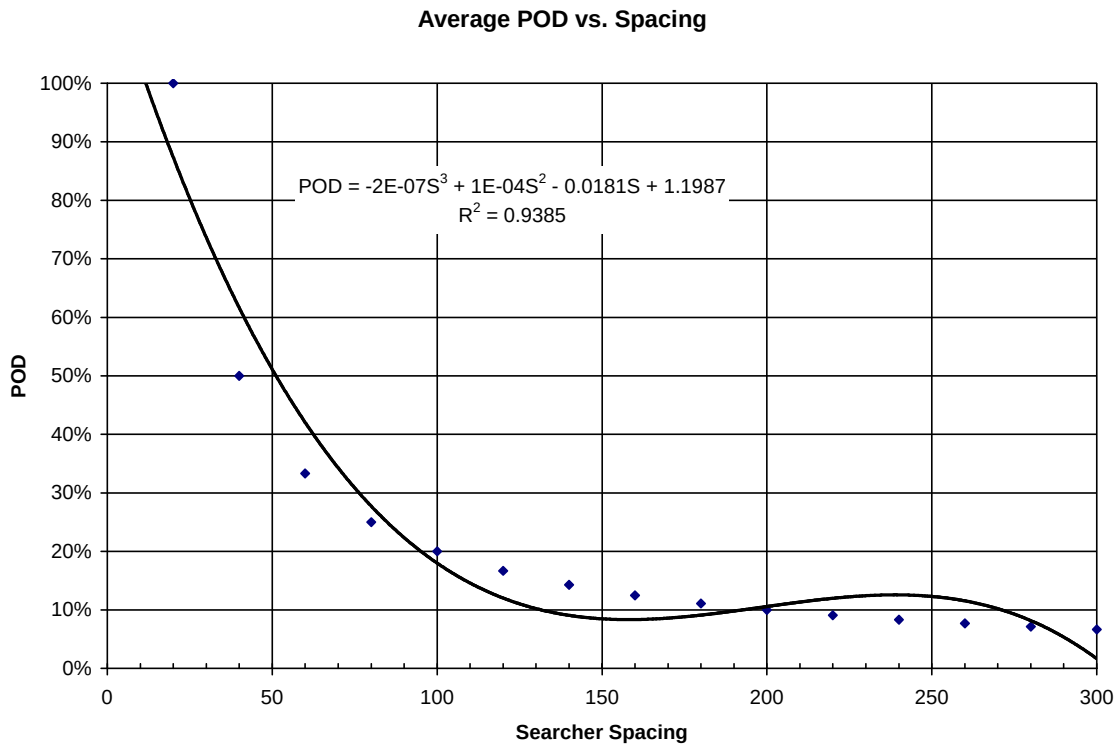

Figure 4-17

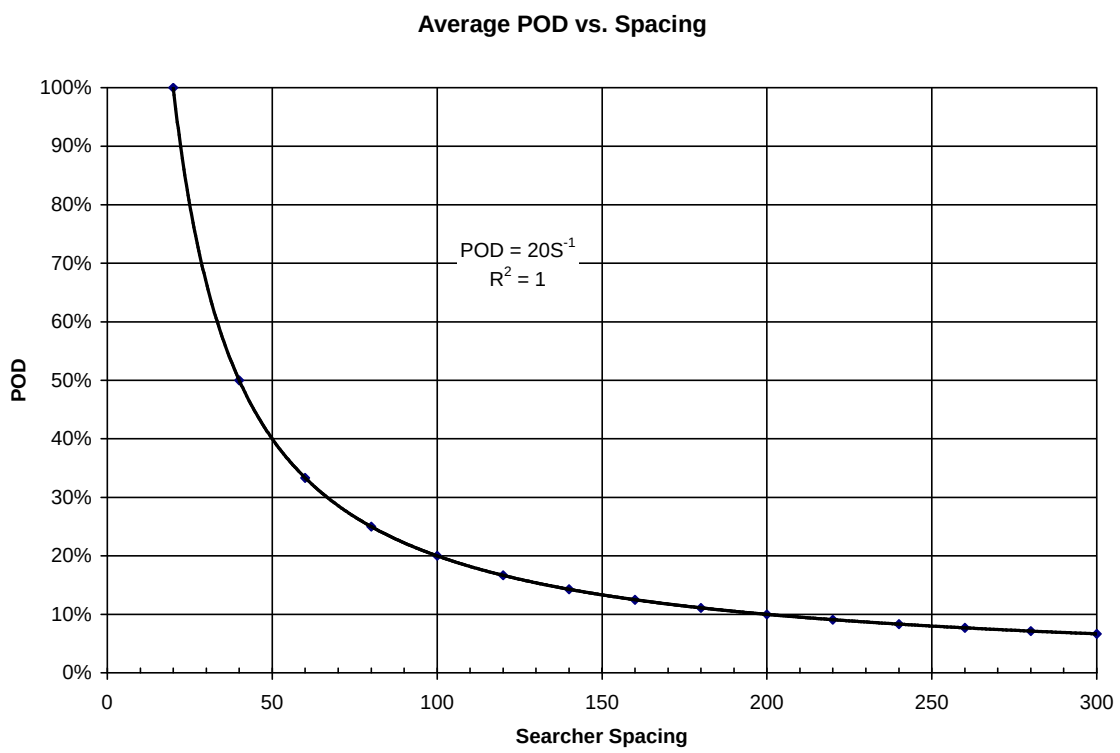

Figure 4-18

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Note that although the added data points for spacings between 100m and 300m improve the behavior of the curve considerably in this region as compared to Figure 4-15, it still does not fit the data well and in fact has a lower R^2 value. Figure 4-18 shows the same data points and a power function approximation. Note that this is exactly the same curve as the one in Figure 4-16 and that the data is fitted perfectly.

4.4.3 The technique of computing average PODs for average numbers of searchers also allows the data to be extended to other baseline lengths. For example, on a 300m baseline, an 80m spacing requires 3.75 searchers. If each searcher has an effective search width of 20m, then 20×3.75 or 75m of the 300m baseline are "covered." This amounts to 75/300 or 25% of the baseline and hence 25% of the segment's area being "covered" and, given our definite range detection function, this in turn produces a POD of 25%. Performing the same analysis on a one kilometer baseline, we see that an 80m spacing requires 12.5 searchers who can cover 250m or 25% of the baseline for a 25% POD. We have thus removed the unexplained inconsistency reported in paragraph 4.2.8 above.

4.4.4 By averaging the PODs and numbers of searchers for each spacing in our table top exercise, we have removed all of the previously induced artificial scatter in the data, restored the normal operational relationship among spacing, number of searchers and baseline length to our experimental data, made the POD vs. Spacing curve applicable to other baseline lengths, and produced results that are consistent with both formal search theory and our intuitive grasp of general POD behavior.

4.5 Assessment of Visual Sweep Calibration Curve Conclusions from [7]

The conclusions in [7] regarding visual sweep calibration curves are reevaluated below in light of the analyses given in paragraphs 4.2 - 4.4.

1. There is a great deal of scatter in the POD results obtained. This is probably due in large part to the random nature of the forest and undergrowth. Much, perhaps even most, of the scatter in the data was induced by the method of analysis after the fact. That is, scatter not due to either measurement error or the nature of the environment in which the experiments took place was artificially, and unintentionally, added by the Baseline Offset method used to generate the (POD, Spacing) data points from the original "raw" data.

2. The large degree of scatter in the results, especially at wider spacings, dictates that large numbers of data points should be obtained if a valid, i.e. reproducible, calibration curve is to be obtained. The advantage of obtaining larger data sets will be seriously compromised without a better methodology for data analysis that does not artificially induce scatter and anomalies.

3. The 'closeness' of the calibration curves indicated that valid, reproducible calibration curves can be obtained using the Single Pass and Baseline Offset procedures. The above analysis indicates that neither of these procedures produces valid "calibration" curves. Valid methods imply reproducibility. The converse, that reproducibility implies va-

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lidity, is not true. The contrapositive, that non-reproducibility implies invalid methods, is true, however.

4. The shape of the curves, steep down to approximately 100m spacing and then leveling off at wider spacings, reinforces Perkins[9] hypothesis that 'visual overlap' is taking place between searchers at close spacings. The apparent "leveling off" of the curve at wider spacings says nothing about "visual overlap." It can be shown that the point on a POD vs. Spacing curve where "visual overlap" begins to have an effect is the point at which the actual detection function's curve separates from the curve of the "equivalent" definite range detection function. The meaning of "equivalent" in this context will be explained in the next chapter.

5. The horizontal 'plateau' region between approximately 100m and 200m spacing indicates that no benefit is obtained by placing the searchers at the closer 100m spacing. The 200m spacing permits a much larger area to be searched at approximately the same POD level. These statements are completely false. The apparent "plateau" was induced by the combined effects of an inappropriate data analysis methodology and an inappropriate choice of approximating function. The "plateau" does not exist in the real world. Where the proper relationship among searcher spacing, baseline length and number of searchers is maintained, wider spacings will consistently produce lower PODs, all other things being equal.

6. The gradual drop towards 0% POD, between 200m and 300m, indicates the searchers' true limit of visibility. This statement is likewise false. The drop in POD towards 0% in this interval and below 0% shortly thereafter is the result of an inappropriate data analysis method and an inappropriate choice of approximating function. In reality, the POD approaches 0% asymptotically and there is no feature anywhere on a true POD vs. Spacing curve to indicate a maximum detection range. Only by comparing an actual detection function's POD vs. Spacing curve to the "equivalent" definite range detection function's POD vs. Spacing curve is it possible to infer a maximum detection range from POD vs. Spacing data.

4.6 Assessment of General Conclusions from [7]

1. The Single-Sweep field POD calibration method. This POD calibration method allows POD values to be obtained rapidly for a broad range of searcher spacings, while only performing a single calibration sweep. This procedure is recommended to all search groups wishing to perform POD calibrations for their search area. This method is not recommended unless the searcher tracks and segment boundaries bear the same relationship to one another as the search legs and sub-area boundaries do in aeronautical/maritime parallel track search patterns. This would require uniformly distributing search objects over a larger area than that actually "searched" so as to allow adjustments in the "segment" boundaries to preserve the proper relationship with the search legs.

2. The Baseline Offset Procedure. This mathematical tool allows a very large number of POD data points to be calculated from the POD values obtained curing the Single Sweep, and so greatly increases the reliability of the calibration data. This mathematical tool introduces additional scatter to the data along with a number of anomalies and greatly ***decreases***

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the reliability of the resulting POD vs. Spacing values. Although simple averaging did result in a valid POD vs. Spacing curve for our single-segment table top exercise that used the simplest and most nearly theoretically "perfect" detection function, it may not necessarily perform as well with real-world data from more complex exercise scenarios. A greatly improved method, based on formal search theory, for estimating POD is presented in the next chapter.

3. The concept of Search Efficiency. We have developed an understanding of what Search Efficiency is and how it is determined. By learning how to calculate and select efficient search procedures we may significantly increase the efficiency of our searches, and so greatly improve the probability of a successful search. Maximizing the total Probability of Success (POS) over the entire search area, which may contain segments with significantly different probability densities with respect to search object containment and significantly different levels of search object detection difficulty, is a valid goal. However, "search efficiency" as defined here does not directly address that goal. Furthermore, when the concept is combined with the erroneous POD calibration curves produced by the unaveraged Baseline Offset method, it will actually ***decrease POS***, not increase it. The most efficient use of the available effort is the one that produces the highest POS in the shortest time. Methods for determining how to deploy the available effort to achieve this are described in the mathematics of formal search theory, but have not yet been adapted for practical ground SAR field use.

4. The concept of an Audible Sweep. Data obtained from the field calibration exercise has shown that the new Audible Sweep search technique is a powerful, highly efficient means of searching for a missing person. It can cover a large search area far more efficiently, and with a much higher probability of detection, than the normal, visual, sweep. This portion of [7] was not specifically analyzed. It certainly seems reasonable that under some conditions, effective search widths for sounds above a certain level would be larger than those for visual search. However, this presumes that the subject is capable of making noise and will do so when searchers are in the vicinity. Continuously playing radios are probably not a valid simulator for audible sweeps since subjects would not be expected to be continuously noisy. Also, children afraid of strangers might actually go silent at a searcher's approach rather than make noise. Search tactics whose effectiveness depends on overt actions by the subject should be used with caution.

5. The Recommended Sweep Conditions table. This is the search manager's 'User Guide' for conducting a search. It contains carefully selected, scientifically evaluated search information, customized to provide the optimum search conditions for a variety of typical search scenarios. This table was not specifically evaluated. However, since it is obviously based on data from a methodology that has been found to have serious flaws and does not address the goal of maximizing POS, it probably should not be used in its present form.

6. A re-definition of Visibility Distance, as it is currently practised, as a High Probability Distance. We have demonstrated that visibility distance-based searching, as currently practised, is an unreliable, inefficient procedure that should only be used in an emergency, when no better POD information is available. First of all, nothing was demonstrated about visibility distance since the visibility distances "actually determined from the POD calibra-

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tion curves" were based on a completely artificial feature in those curves stemming from the inappropriate choice of a polynomial approximating function. Only by comparing the actual detection function's POD vs. Spacing curve to the "equivalent" definite range detection function's POD vs. Spacing curve, as shown in paragraph 5.5.2 of the next chapter, is it possible to infer a maximum detection range from POD vs. Spacing data. Second, the above analyses of the methodology used to produce the POD calibration curves has shown it to be inaccurate, unreliable and inconsistent. Therefore, it cannot be used as a basis for criticizing either visibility distance-based searching or the ability of searchers to accurately estimate visibility distances.

7. The concept of Over-counting and the Limitations of the Human Searcher. Data obtained during the field calibration exercise has demonstrated that searchers become increasingly less efficient at close searcher spacings and must repeatedly overcount, i.e. visually overlap, to obtain small additional increases in POD. Understanding this human limitation permits us to redeploy the searchers in configurations that minimize this limitation. The phenomenon of "diminishing returns" is not due to a specifically human limitation. Any detection function (e.g. radar, sonar) will experience a similar diminishing of returns once the detection envelopes of adjacent tracks begin to overlap. More important, however, is the dangerous conclusion implied by the definition of "efficiency" used here. Defining "efficiency" as the ratio of POD to searcher-hours expended inevitably leads to the conclusion that the most "efficient" searches are the ones in which there is no overlap. The only detection function for which any overlap at all is definitely inefficient is the (unrealistic) definite range detection function. It is a well-known fact that the probability of detecting an object visually does not have the form of a definite range type, but decreases more gradually as the object's distance from the searcher increases. Therefore, if any POD at all is to be achieved midway between searchers, some overlap must be allowed. Also recall that the goal is to attain the highest possible probability of success. If the probability density of one segment is much higher than the probability densities of its neighbors, and the area and detection function are about the same for all segments, then the high-density segment should be searched to a higher POD (i.e. should have more searcher-hours invested in it) than the others in order to maximize POS. This in turn could require considerable overlap and bring the "efficiency" definition given in [7] into direct opposition with the goal of maximizing POS.

4.7 Conclusions

- For a definite range detection function, average POD over the segment depends on how much area the searchers scan in relation to the size of the segment, not on the spacing between the searchers.

- When the proper relationship among number of searchers, baseline length, and spacing is maintained, spacing, together with the effective search width of the searchers, may be used to compute the fraction of the segment's area that was scanned. As we will see in the next chapter, this value is called *coverage*.

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- Putting the above two bullets together, POD is a function of *coverage*, and is not a function of spacing alone.

- The "POD plateau" is not a real phenomenon. The notion that fewer searchers deployed at wider spacings can achieve PODs equal to (or greater than) the PODs more searchers deployed at narrower spacings can achieve under the same conditions is false.

- Multiple searches at wide spacings do not produce higher cumulative PODs than single searches at proportionately narrower spacings when both tactics employ the same amount of effort (searcher-hours) under the same conditions.

- "Efficiency" as defined in [7] is not a valid criteria for allocating effort and, if used, will often lead to sub-optimal searches in terms of the POS values achieved.

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Chapter 5
Applying Search Theory to Ground Search

5.1 Introduction

The following discussion will be a very brief overview of how search theory, as developed by Koopman [2,3] during the Second World War and expanded upon by others since, may be applied to ground search. While a complete discussion of search theory and all of its possible applications to ground search will not be discussed here due to insufficient time and space, the concept of ***sweep width*** and its relationship to ***search effort***, ***coverage***, **POD**, and **POS** will be given special emphasis.

5.2 Three Types of POD

The definition of POD given in paragraph 3.6 above is the one usually used in search planning/management. It is the average POD over an area. However, it is actually a function of two other PODs — instantaneous and lateral range.

5.2.1 For the purposes of the present analysis, the searcher's track relative to the search object is always assumed to be a straight line. This means that either the search object is stationary and the searcher is moving along a straight line (or vice versa), or, if both searcher and search object are in motion, they are moving in straight lines at constant velocity. As a searcher approaches the search object from a distance greater than the maximum detection range, as soon as the object passes inside the searcher's detection envelope, the searcher will begin having brief, "one-glimpse" detection opportunities. The average probability of detecting the object with any one given glimpse in its direction is the instantaneous detection probability. This probability will normally be smaller at greater ranges than at closer ranges, but it will remain small in any case due to the brief duration of each glimpse.

5.2.2 The search object may fall directly on the searcher's track or, more likely, at some distance to the right or left. The perpendicular distance from the searcher's track to the search object is called the **lateral range**. As the searcher approaches the search object from some distance greater than the maximum detection range, passes the object to the right or left at some lateral range, and moves away from the object until it is again beyond the maximum detection range, the instantaneous "one-glimpse" PODs accumulate. When these accumulations are grouped according to the object's lateral range, a POD vs. lateral range curve may be plotted. Normally, objects close to the searcher's track will have higher lateral range PODs (perhaps realistically as high as 100% when right on the searcher's track) while those farther away but still within the maximum detection range will have lower lateral range PODs. So, in practice, we would expect the lateral range POD curve to be high in the middle for search objects right on the searcher's track, and decrease to the right and left as lateral range from the searcher's track increases. Figure 5-1 is the lateral range curve of the definite range detection function used in our table top exercise of Chapter 4. Some examples of other possible lateral range curves are graphed in Figures 5-2, 5-3 and 5-4.

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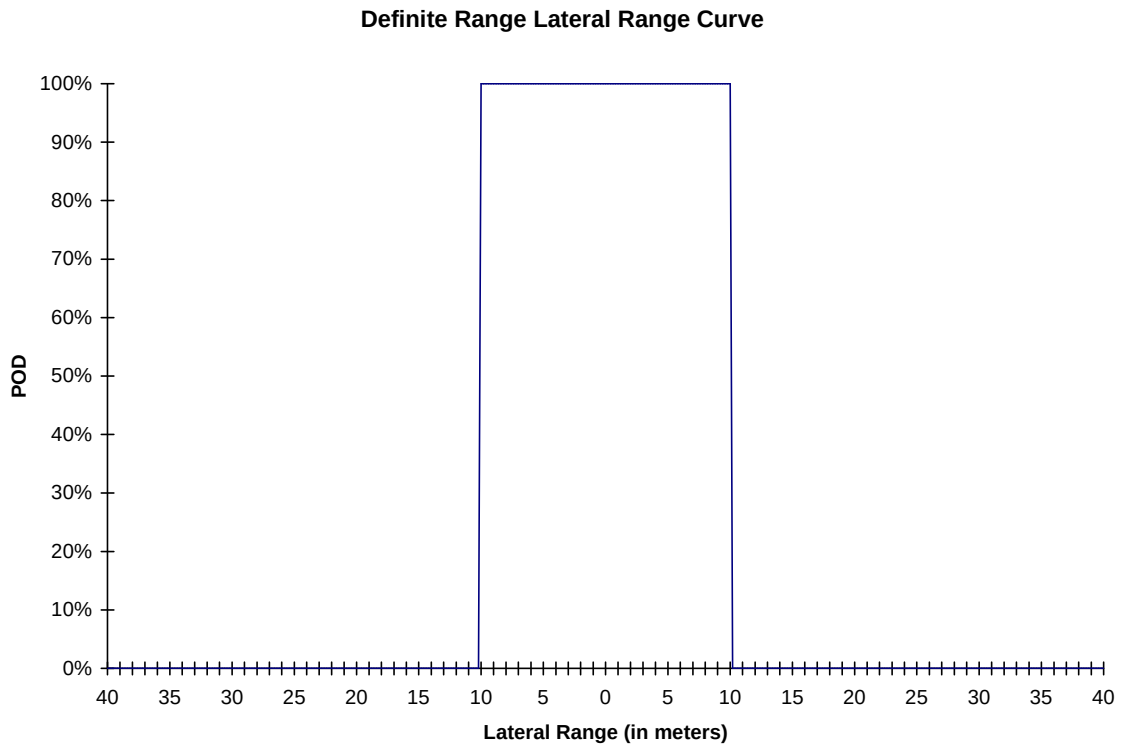

Figure 5-1

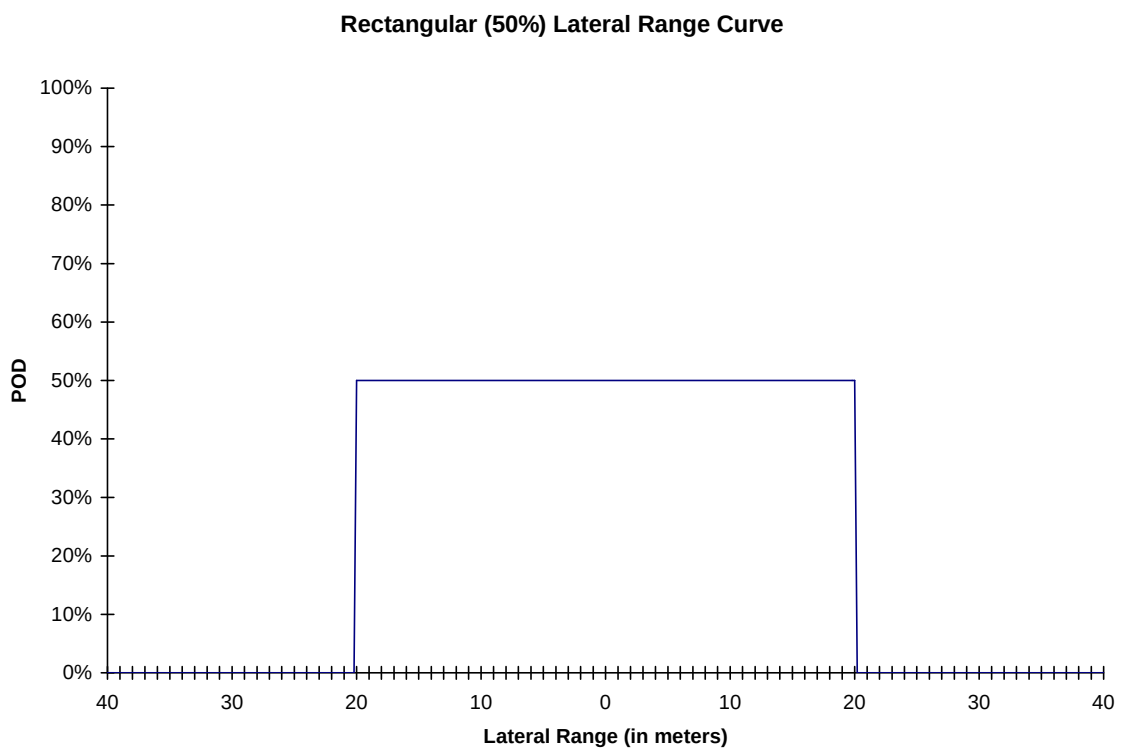

Figure 5-2

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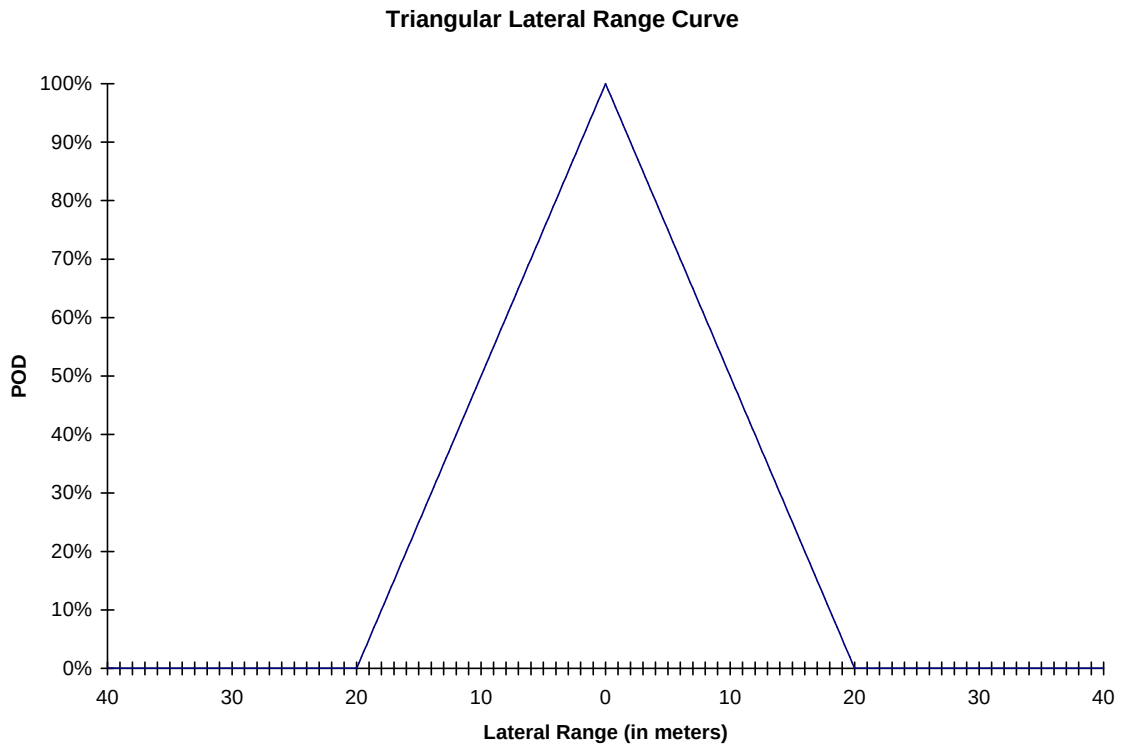

Figure 5-3

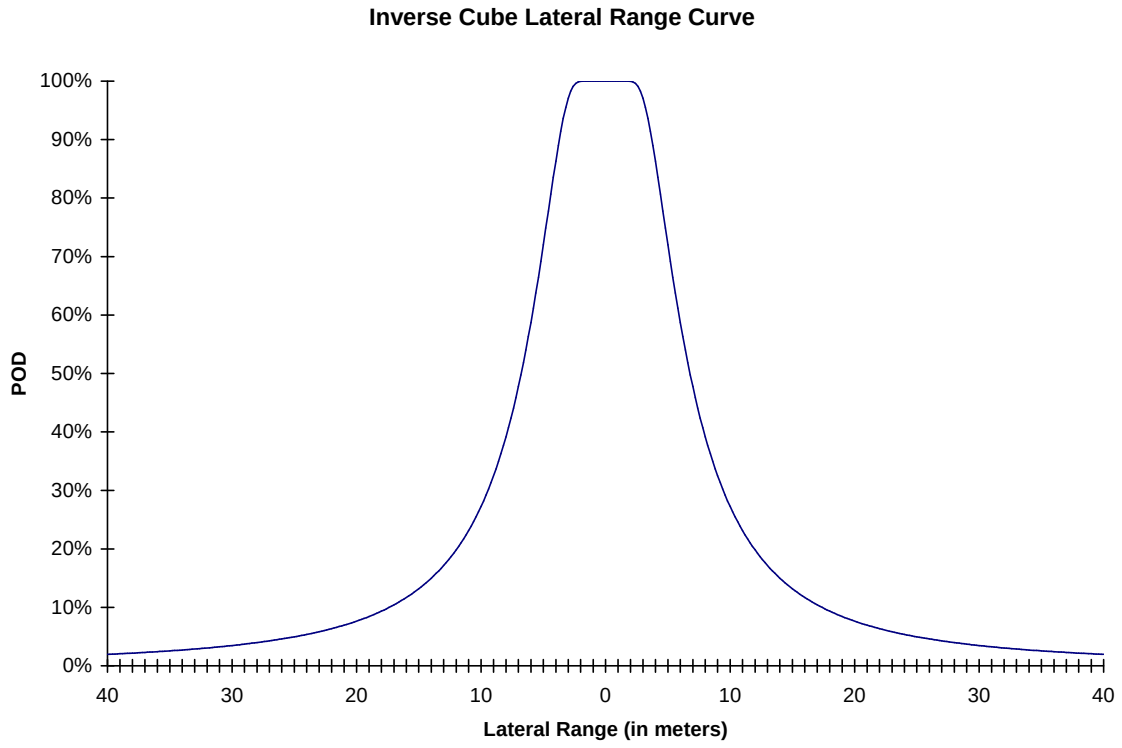

Figure 5-4

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5.2.3 If the lateral range curve for a given sensor, search object, and set of environmental conditions is known, it is possible through some straightforward, if tedious, computation to determine the **average POD over the area** containing the parallel, equally spaced, searcher tracks. (It is assumed that the area containing the searcher tracks extends no farther than one-half the searcher spacing beyond the left-most and right-most searcher tracks.) The primary concern, of course, is to account for the effects of overlapping search corridors. If the spacing is sufficient to assure no overlapping of search corridors, then searcher spacing becomes of no concern except as it may affect, or be affected by, the number of searchers, or more accurately, the amount of effort, expended in the segment. The average POD over an area is the value commonly used in search management.

5.3 Significant Factors Affecting POD

As stated earlier, there are four classes of variables that affect POD. These are the sensor, search object, environment, and method of searching (*tactics*). All of these have the potential of affecting one another so they cannot be regarded as entirely separable entities.

5.3.1 The most common sensor used in SAR, by a wide margin, is the unaided human eye. Variations include such aids as binoculars and night vision goggles. Other human senses, such as hearing, may be used if it is believed the survivor is capable of calling for help or has a whistle or other sound-making device. Dogs, with their keen sense of smell, may also be used in ground searches. The number and variety of electronic sensors are too numerous to list and are beyond the scope of this discussion in any case. We will restrict our attention to visual search, although extension to other types of sensing should be clear to the reader, at least at the conceptual level.

5.3.2 For visual search, a number of factors related to the searcher's role as a "sensor system" may be significant. Visual acuity is an obvious one. Raindrops or mist on a searcher's corrective lenses is a less obvious one but it illustrates one point of interdependence between the sensor and the environmental conditions in the segment. Searcher fatigue is another significant factor affecting POD and fatigue levels are also likely to be at least partially dependent on environmental conditions.

5.3.3 Characteristics of the search object that are likely to affect POD include the object's size, its contrast (brightness and/or color) with its surroundings (another point of interdependence with the operating environment), whether the survivors are able to signal searchers in any way such as waving their arms, making some sort of loud noise, using a visual signaling device (e.g. strobe light, mirror, dye in the water, smoke, fire, flares, etc.), making a sign or pattern visible from the air, etc. For uninjured, active survivors, the list of possibilities is a long one. For injured, immobile survivors, the list is much shorter and they are generally more difficult to find.

5.3.4 The list of environmental conditions that may affect POD is nearly endless. A few examples include: visibility, both in the meteorological sense and, when searching on or over the ground, in terms of obstructions to the searcher's view such as trees, underbrush, boulders, ridges, snow cover, etc.; weather conditions including temperature, wind speed,

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precipitation, thunder and lightening, etc.; lighting conditions (e.g. open area in bright sunshine vs. deep forest on an overcast day); and the list goes on.

5.3.5 Finally, there is the method of searching, and here we include the level of effort as part of the "method" or search tactics. The two primary methods of applying effort are random search, where searchers follow no organized pattern but simply wander about the segment at random, and parallel sweep searching. Parallel sweep searches may be conducted in one of two ways. In the first method, multiple searchers move through the segment along equally spaced parallel tracks, usually simultaneously in a line abreast. In the second method, a single search facility, such as an aircraft, follows a series of parallel tracks in sequence (sometimes called a "ladder search"), each connected with the next at one end or the other by a short "cross leg." In either case, the amount of effort required to "cover" the search sub-area depends on how closely the legs are spaced or vice versa, the spacing of the tracks depends on the amount of effort available. In general, the amount of effort required is inversely proportional to the track spacing, and vice versa, the smallest attainable track spacing is inversely proportional to the amount of effort available. For example, cutting the searcher spacing in half generally requires that twice as much effort be made available for searching. Both random and parallel track searching assume the entire segment is "covered" as nearly uniformly as possible with the available effort. That is, searchers don't search in only one half of the segment while leaving the other half completely unsearched. Instead, they attempt to disperse themselves more or less uniformly over the segment. When comparing random searching to organized searching with parallel tracks, the latter usually produces the higher POD for a given level of effort.

5.4 Koopman's [3] Analysis

We will now review Koopman's [3] analysis of the search problem as it relates to estimating POD over an area. The description will be necessarily brief. The reader desiring more details on this and other aspects of search theory and its practical application is referred to Koopman [2,3], Stone [4], Frost [10], and, for a less mathematical treatment that is more nearly in layman's terms, Frost [11,12,13,14].

5.4.1 <u>The Definite Range Detection Model</u>. Koopman began his analysis, much as we began ours, by examining the characteristics of the definite range detection function. Being a very simple model, it has only one significant variable. As its name implies, that variable is the definite range within which all objects are detected and outside of which no objects are detected. An equivalent variable to examine is twice the definite detection range or the *width of the area swept* by a searcher as he or she moves along his or her assigned search track. Figure 5-5 shows the definite range detection function's lateral range curve graphed as a function of *sweep width*. Graphing lateral range curves in this fashion makes them more general-purpose and allows the same graph to be used for any situation where the *sweep width* is known.

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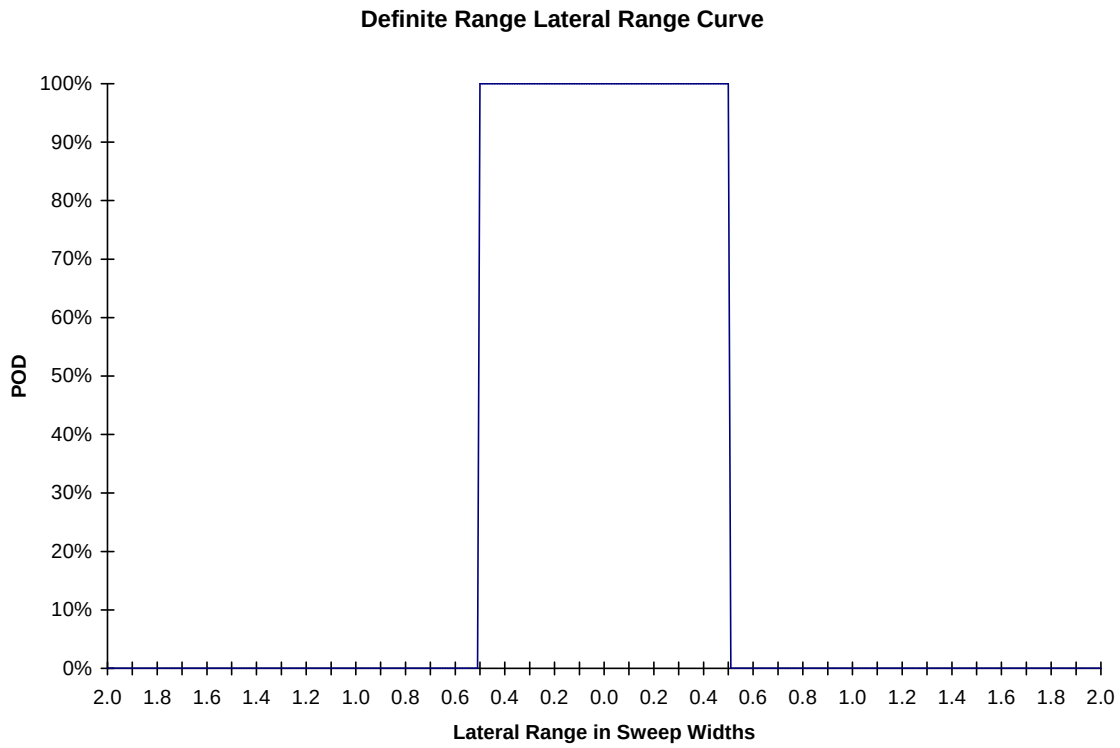

Figure 5-5

5.4.1.1 To use the definite range model operationally, it would be necessary to either measure or estimate the *sweep width, W*. Actually, the most practical approach would probably involve a mixture of both. Carefully designed and conducted experiments could identify the significant variables affecting *sweep width* and then further experiments could provide actual measurements under a variety of specific conditions to determine just how changes in each significant variable affected *sweep width*. That is, it would be necessary to first determine what the significant variables are, and then determine how they affect the *sweep width*.

5.4.1.2 Once such experiments were done, methods for estimating *sweep widths* from measurements of the significant variables could be developed. These would also allow interpolation, and limited extrapolation, for situations not covered by the experiments themselves. It is unlikely that direct measurement of *sweep width* would ever be possible, but it might be possible to establish a relatively simple link between certain types of limited but direct "experimental" field measurements at the scene of a search and *sweep width*. For example, techniques for directly measuring "visibility distance" or average maximum detection range are given for ground search team use. Since such measurements probably involve most, if not all, of the same factors that affect *sweep width*, it might be possible to establish, through carefully designed and conducted experiments, sweep width correction factors based on the ratio of the "visibility distance" for a sweep width experiment that at the scene of an actual search.

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5.4.2 <u>*Sweep width*</u>. For a definite range detection function, *sweep width* is clearly a measure of the ability to detect search objects. *Sweep width* also has an obvious geometric interpretation in that instance. However, Koopman knew that many different detection functions exist in the real world with characteristics quite different from those of the definite range law of detection. This raised the question of whether other, even possibly all, detection functions could be characterized by an equivalent "*sweep width*."

5.4.2.1 Koopman reasoned as follows (with terminology adjusted to be consistent with ground searching). If, under a certain set of environmental conditions, a searcher walks with constant velocity w through a swarm of identical search objects uniformly distributed over a large area (such as those in Figure 4-1) having a density of ρ (Greek letter rho) objects per unit area on average, and visually detects, on average, N objects per unit time, then the *effective search (or sweep) width* W for that particular combination of sensor, search object and environmental conditions is given by

[5-1] $$W = \frac{N}{\rho w}.$$

Koopman's definition embodied in Equation [5-1] means that W is a "catch-all" value that characterizes the average, or expected, performance of the detection function for a particular search situation. As such, it includes the effects of all the different factors affecting detection probabilities in that situation. This means that W is a function of all those factors noted in paragraph 5.3 above. The challenge is to learn how these factors affect the value of W so we may infer a value for W from measurements and estimates of those factors. Note also that W itself provides no information about the type of detection function in use, just information about how much detecting it would do along a single track through the uniform distribution of search objects under the given conditions. All of the objects detected could be very close to the searcher's track, as in the case of the definite range detection function, or a significant percentage could be substantially farther from the searcher's track, as with some other types of detection functions.

5.4.2.2 Two detection functions having the same *sweep width* are said to be "equivalent" in the sense that per unit of elapsed time, each will detect, on average, the same number of uniformly distributed search objects of the same type under the same conditions while moving along a single straight track through the objects. We may also say that the *sweep width* of any detection function is equal to the width of a definite range detection function that detects, on average, the same number of objects per unit time as the given detection function does under the same conditions. As we shall see, "equivalence" in this sense of "raw" detection performance along a single straight track does not lead to equivalent POD performance when it comes to searching areas with multiple parallel tracks. However, *sweep width* does provide the basis for developing methods to estimate POD for both random and parallel track searching as we shall see shortly.

5.4.2.3 *Sweep width* may be interpreted as a measure of an individual detection function's "raw" performance, or detection capability, along a single straight track as we have just seen. Alternatively, *sweep width* may be viewed as a measure of how easy or difficult it will be

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to detect the search object in a given situation. Objects with larger *sweep widths* are easier to find than objects with smaller *sweep widths*, and conversely, objects that are easy to find will have larger *sweep widths* than those that are hard to find. Of course, the ease or difficulty of detection often will be less a function of the object sought, especially if the search object is the same for several different situations, and more a function of the environmental conditions and sensor in use during the search. However, all three classes of factors will have some impact on the magnitude of the *sweep width* in any given situation.

5.4.3 Comparing *Sweep Width* Definitions. Before proceeding further, let us digress for a moment to verify whether the general definition given in Equation [5-1] above agrees with the definition given earlier in paragraph 5.4.1. To do this, we will return to our table top exercise scenario.

5.4.3.1 In our table top exercise we used a definite range detection function with a definite range of 10 meters. This meant that each searcher detected every object he passed within 10 meters to the right or left. This in turn meant the width of the area swept by each searcher was 20 meters, i.e. the *sweep width* was 20 meters.

5.4.3.2 Before using the *sweep width* definition given in Equation [5-1], we need to establish a speed for our searchers. For simplicity, let us assume that it takes each searcher exactly one hour to complete the assigned track. That is equivalent to searchers moving at a rate of 300 meters per hour. The search object density, ρ, is computed as 900 objects over an area of 300 x 300 or 90,000 square meters for a density of 0.01 objects per square meter. For 15 searchers, all 900 objects were detected, making the average detection rate 60 objects per hour for each searcher. Substituting these values into Equation [5-1] yields

$$W = \frac{60\frac{objects}{hour}}{0.01\frac{objects}{m^2} \times 300\frac{m}{hour}} = 20m.$$

Note that this alternative method for determining *sweep width* produces the same result as measuring the width of the swept area. Also note that **any detection function** that detects 60 objects per hour when passing through our table top segment at the rate of 300 meters per hour will have a *sweep width* of 20m, *regardless of where the detected objects actually are in relation to the searcher's track.* Therefore, it is in fact correct to say that the *sweep width* in any situation equals the width of a definite range detection function that detects the same number of objects per unit time as the actual detection function does in that same situation. Let us now examine a different detection function.

5.4.4 The Inverse Cube Detection Model. It was clear to Koopman from the outset that the definite range detection function was not a very good model of visual detection, at least not in the Navy's open ocean operating environment. Koopman was faced with developing, either by experiments, empirically from operational data, or a purely geometric and mathematical analysis, a suitable detection model. The war effort precluded extensive

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experimentation and no high-quality empirical data was available so the purely geometric and mathematical analysis route was the only one available.

5.4.4.1 Since there were no other models or even data to work with, Koopman postulated a mathematical model of visual detection based on the geometry of detecting objects from aircraft patrolling over the ocean. In this model, he postulated that the instantaneous POD was proportional to the solid angle subtended at the searcher's eye by the search object. After working through the resulting mathematics, he found that this is, to a close approximation, equivalent to saying the instantaneous POD is inversely proportional to the cube of the search object's distance from the searcher. As a result, Koopman's model became known as the *inverse cube model of visual detection*.

5.4.4.2 Koopman's next step was to determine the lateral range function for his inverse cube model of instantaneous visual detection. To do this, he derived the general formula for the inverse cube lateral range curve:

[5-2] $$p(x) = 1 - e^{-\frac{2kh}{wx^2}},$$

where the function *p(x)* (read "*p* of *x*") gives the POD as a function of lateral range *x* and is defined by the expression on the right, where *e* is the base of the natural logarithms, *h* is the aircraft's altitude over the ocean, *w* is the aircraft's velocity relative to the search object, and *k* is the constant of proportionality with respect to the solid angle subtended at the observer's eye. The value of the constant *k* depends on all those factors that affect detection, such as those discussed in paragraph 5.2 above, that are not otherwise explicitly included in our formulation.

5.4.4.3 A general method for computing the *sweep width* of any detection function from its lateral range curve is not too difficult to develop. Consider a searcher traversing the center track (150m) of our table top exercise. Suppose the searcher has an inverse cube detection function and takes one hour to traverse the length of the segment as before. Suppose we have done an experiment where searchers whose eyes are 2m above the ground (*h*) look for objects on the ground while moving at a speed of 300 m/hr (*w*) and have experimentally determined the value of *k* to be 2,387.3 m^2/hr. (Just how this value of *k* was determined is not important for this discussion.) This gives us all the values we need to compute the value of *p(x)* for any lateral range *x*. The curve graphed in Figure 5-4 was generated using these values.

5.4.4.4 Continuing with our line of reasoning, suppose further that we look at strips parallel to the searcher's track that are only one meter wide (the "tick marks" on the horizontal axis of Figure 5-4 are at one meter intervals) so we can capture the variation in POD with lateral range. At our search object density of 0.01 objects per square meter, the *linear density* along each one-meter strip is 0.01 objects per meter and we can expect each strip to contain, on average, three objects. For the two strips right next to the searcher's track (0 to 1 m left and 0 to 1m right of track), the lateral range POD is at or very near 100% so we would expect to find objects in each of those two strips at the rate of about 3 per hour

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on average. Further away, in the strips between 6 and 7 meters from the searcher's track for example, the lateral range POD is about 53%. This means that only about 1.6 objects per hour would be detected on average in each of those two strips. Computing the average number of objects detected per hour in all the one meter strips (which isn't physically practical since the "tails" of this bell-shaped curve are infinitely long), and then adding all those values together would give the total number of objects detected per hour by that particular detection function. Since the total works out to about 60 objects per hour, then by Equation [5-1] the *sweep width* is 20m. Those who recall their integral calculus course from college or high school will recognize that the exercise we have just gone through amounts to computing the area under the lateral range curve. Therefore, we may say that *the sweep width is equal to the area under the detection function's lateral range curve*. That is,

[5-3] $$W = \int_{-\infty}^{\infty} p(x)\, dx$$

where *p(x)* is the function that gives the POD at lateral range *x*. For those who recall their elementary physics, this application of the integral calculus is similar to computing the distance moved by an object traveling with varying velocity by computing the area under its velocity-time curve. Koopman carried out the necessary integration, and found that the *sweep width* for the inverse cube model's lateral range function (Equation [5-2]) is given by

[5-4] $$W = 2\sqrt{\frac{2\pi kh}{w}}$$

It is now possible to write the inverse cube model's general lateral range function in terms of *sweep width*, *W*, as follows

[5-5] $$p(x) = 1 - e^{-\frac{W^2}{4\pi x^2}}.$$

Figure 5-6 shows the inverse cube model's general lateral range function where the lateral range from the searcher's track is measured in *sweep widths* (i.e. multiples of *W*).

5.4.4.5 The U. S. Coast Guard Research and Development Center in Groton, CT, has conducted extensive controlled experiments to obtain data from which detection functions and their *sweep widths* may be inferred. Their results show that when searching visually for moderate to large drifting objects (sizes of multi-person life rafts up to large yachts, fishing vessels, etc.) under ideal search conditions (clear, calm weather), Koopman's inverse cube detection function does remarkably well, especially considering his original premise involved finding large warships underway by sighting their wakes. However, the experiments' results also show that for small objects (e.g. a person in the water) or poor search conditions (lowered visibility, rough weather, etc.), Koopman's inverse cube detection function is not a good representation of the actual detection function. In particu-

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lar, its high peak of 100% POD for objects right on the searcher's track is considerably optimistic.

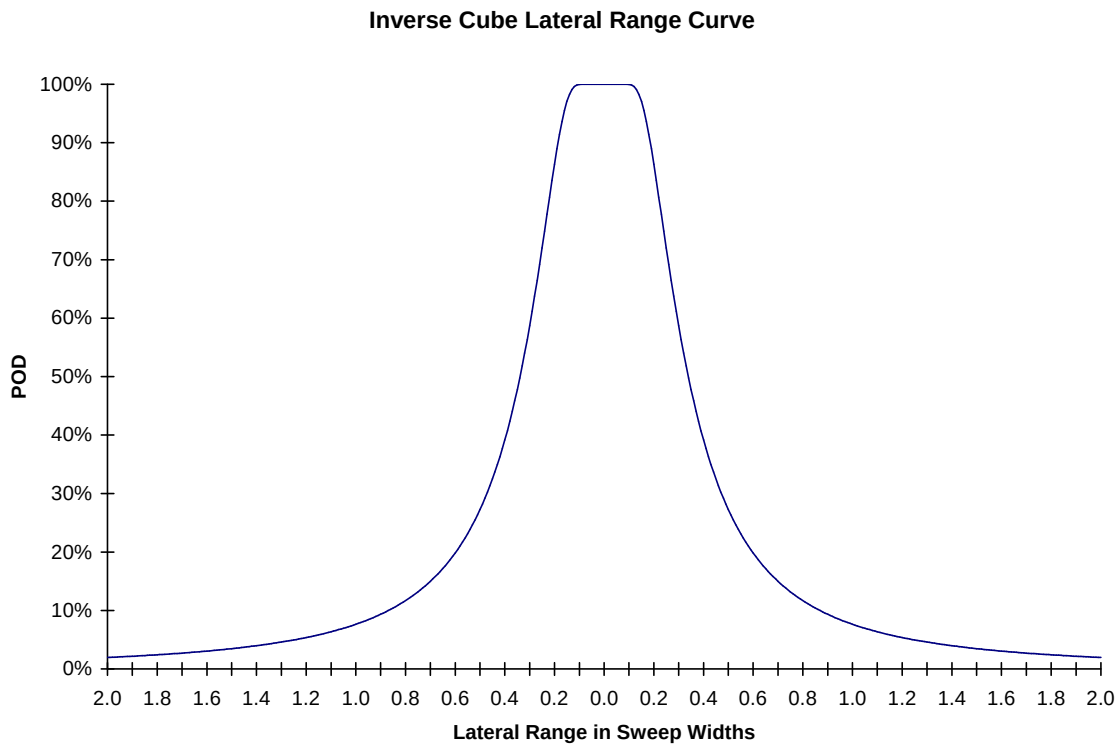

Figure 5-6

5.4.5 <u>*Sweep Widths* for Other Lateral Range POD Functions</u>. It is instructive to go back and examine the other lateral range curve examples given in paragraph 5.2.2 in terms of *sweep width*. For the definite range detection function in Figure 5-1, the area under the curve is easy to compute since it is a rectangle with a height of 1.0 (100%) and a width of 20 meters. The area is just 1×20 or 20 meters. In Figure 5-2, we also have a rectangle, only this time the height is 0.5 (50%) and the width is 40 meters. The area is 0.5×40 or 20 meters. In Figure 5-3, we have a triangle with a height of 1.0 (100%) and a base of 40 meters. Computing the area using the well-known formula for triangles (one-half the base times the height), we get (0.5×40)×1 or 20 meters. Finally, we have Figure 5-4 whose area must be computed using the integral calculus. The result is also 20m. (However, if one tries to approximate the area under this curve using Figure 5-4, it will be found that only about 92% of the curve's total area is captured on this graph due to truncating the "tails" at 40 meters.) The bottom line of this exercise is that all of the detection functions whose lateral range curves are shown in Figures 5-1 through 5-4 have the exact same *sweep width*, i.e. all of them have exactly the same amount of "raw" detecting power, even though that detecting power is distributed differently with respect to the searcher's track from one detection function to the next.

5.4.5.1 The relationship of *sweep width* to a definite range detection function's average POD for a parallel track search of an area is simple and clear enough since "visual overlap" be-

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tween adjacent searchers is never really a problem. Computing the average POD over an area for a series of parallel tracks all using an inverse cube detection function is considerably more complicated since the infinitely long "tails" from all tracks overlap one another. The computations used to determine the average POD over the searched segment will have to account for all this overlapping. However, we need to examine two other concepts, *search effort* and *coverage*, before attacking this problem.

5.4.5.2 For the moment, it is most important to realize that while two quite different detection functions, perhaps representing two quite different operating environments and two quite different search objects, for example, may have identical *sweep widths*, this does **not** mean they will produce identical PODs for identical levels of effort when used in parallel track search patterns. In order to determine average POD over an area for a particular type of detection function in a given situation we must first determine the detection function's *sweep width* for that situation. If a parallel track search pattern is used and the tracks are less than twice the maximum detection range apart, overlap will take place and its effect must then be properly accounted for as well when determining the average POD over the area. *Sweep width* represents only the number of objects detected by a single searcher moving along a single track. POD performance in parallel track search patterns depends, as we shall see, on the exact nature of the detection function, i.e. the shape of its lateral range curve, as well as the magnitude of its *sweep width*.

5.4.6 <u>*Search Effort*</u>. Up to now, the word "effort" has been used with pretty much the same connotation as everyday usage in the workplace. That is, effort, symbolized by a lower case *z*, has been defined in terms of available or required searcher-hours. It would be extremely useful if we could establish some measure to quantify how much searching or detecting can actually be accomplished with a given number of searcher-hours in a given search situation. Now that we have the *sweep width* concept at our disposal, it is possible to develop such a metric.

5.4.6.1 Recalling the table top exercise of the last chapter, it was seen that the number of objects detected depended on the amount of area "effectively" scanned. This in turn depended on the "effective" search (or sweep) width and the number (or total combined length) of the tracks that the searchers traversed. Although it wasn't emphasized at the time, the number (or total combined length) of the tracks traversed depended in turn on the total number of searcher-hours available and the searchers' average speed of advance. Thus the amount of area "effectively" searched will be a good measure of how much searching was done with the expended searcher-hours. We will call this quantity *search effort* and symbolize it with an upper case *Z*, as opposed to "plain" effort symbolized by a lower case *z*. From the above discussion, it is easy to see that *search effort* may be computed by

[5-6] $$Z = z \times w \times W$$

where *Z* is *search effort* and has units of area (e.g. square meters), *z* is "plain" effort in units of time (searcher-hours), *w* is searcher speed (e.g. meters per hour), and *W* is *sweep width* in units of distance (e.g. meters).

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5.4.6.2 Before going any further, we must stop and clarify the meaning of the word "effective" as used in the current context. When we speak of "effective search (or sweep) width" we are describing the width of the definite range detection function that has the same "effect" as the actual detection function under consideration *in terms of number of "finds" (detections) per unit time* when both are used under the same conditions. When we speak of "area effectively searched" we are describing the amount of area a definite range detection function having the same *sweep width* would have to cover in order to amass the same number of detections under the same conditions as the actual detection function did. Again, we are using the word "effective" to mean "has the same effect as" in terms of "raw" detection counts. We are not yet concerning ourselves with average POD over an area, or POS, and the reader is cautioned to avoid thinking in those terms until they are discussed later in this development. At this point, we are not even concerning ourselves with overlap or overcounting, just the "raw" number of detections. The issues of overlap, POD, POS, etc. will be dealt with in due course.

5.4.6.3 The concept of *search effort* is extremely important. Ordinary effort, in terms of searcher-hours, is simply a measure of resource availability or requirement. The number of available searcher-hours alone does not tell the search manager how much "effective" searching can be done with that level of effort. It can't, because it is independent of the search object, search conditions and even the "sensor" (are eyes or ears considered the primary detection device?). It is easy to see that in an experiment, the amount of detecting (i.e. the number of "finds") a given number of searcher-hours represents will vary considerably depending on the type of search object, the environmental conditions and the type of sensor used (e.g. eyes vs. ears), even if the search object density is kept constant. *Search effort*, on the other hand, does provide a measure of how much detecting can be done (i.e. the number of "finds") because, in addition to involving the number of searcher-hours and searcher speed, it also involves, through the *sweep width*, all those parameters directly affecting detection and the "raw" number of detections that can be expected. Just as *sweep width* may be interpreted as a measure of a detection function's "raw" detection capability along a single track, *search effort* may be interpreted as a measure of the "raw" detection capability a given number of searcher-hours represents for a particular search object in a given environment when using a particular sense (sensor) such as sight or hearing.

5.4.6.4 While it is intuitively obvious that expending more searcher-hours in a segment having a given uniform distribution of search object density will result in more finds, there is no way to actually quantify the effect without also knowing the *sweep width*. Without postulating a detection function, and with it a *sweep width*, there is no way we could have conducted our table top exercise that has taught us so much about what we should generally expect from both field experiments and actual operations. Remove one key piece of information, namely knowing that the *sweep width* is 20 meters, and all the other exercise information about numbers of searchers, searcher speed, search object density, spacing, baseline length, and even the type of detection function, becomes useless. In other words, we could not have built a working model of the searching process without the *sweep width* concept.

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5.4.6.5 Before moving on to *coverage*, we need to make one more observation about "effort." Although it may seem confusing to have two different terms involving "effort," both are necessary, and not just because *effort (z)* is used in the computation of *search effort (Z)*. We will see later that situations may arise where several adjoining segments have significantly different environments, and hence significantly different *sweep widths* for the same object and sensor. Thus the amount of *search effort* the available searcher-hours (*effort*) represent will depend on which segment(s) the searchers are sent into. These segments may also have significantly different probability densities (POA divided by segment area). The objective will be to use the available searcher-hours in a way that will maximize the POS. This is called optimal effort allocation, and methods for optimally allocating effort under the above circumstances have been developed and documented in the mathematics of formal search theory but these have not yet been adapted for practical use in the field. Optimal effort allocation in some simple situations will be discussed toward the end of this paper, but a comprehensive methodology for practical use will require a considerable amount of further development.

5.4.7 Examples of *Search Effort*. We will now see some examples of how *sweep width* may be used to compute a meaningful metric for quantifying the amount of searching a given amount of effort represents in various situations.

5.4.7.1 Let us suppose that the 20 meter *sweep width* used in our table top exercise represents searching in a wooded area with moderate amounts of undergrowth. We can ask how much *search effort (Z)* 15 searcher-hours represents under conditions where the *sweep width* is 20 meters. As discussed above, s*earch effort (Z)* is defined as the amount of area that can be "effectively" searched with the available searcher-hours of *effort (z)*. Using Equation 5-6 to compute *search effort* for this example,

$$Z = 15_{hours} \times 300 \frac{m}{hour} \times 20_m = 90{,}000_{m^2},$$

or 90,000 square meters of *search effort*. As we saw in our table top exercise, this yields a POD of 100% for our definite range detection function if the effort is uniformly distributed over the segment's area. Similarly, seven searcher-hours of effort would represent 42,000 square meters of *search effort* for a POD of 46.67% on average, again assuming a definite range detection function and uniformly distributed effort. We can also turn the question around and ask how much *effort* in searcher-hours would be required to completely "cover" the segment in our exercise. Solving equation [5-6] for *z (effort)*, we have

[5-7] $$z = \frac{Z}{w \times W}.$$

It is easily seen that "covering" every square meter of our 90,000 square meter segment would require 90,000 square meters of *search effort (Z)*

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$$z = \frac{90{,}000m^2}{300\frac{m}{hour} \times 20m}$$

or 15 searcher-hours of effort (z) using Equation [5-7].

5.4.7.2 Let us suppose that in a more open area of the same size where the search object density is also the same as in our exercise, we find that the same searchers, moving at the same speed, find twice as many objects per unit time. This would double our estimate of the *sweep width* from 20m to 40m. Now, seven searcher-hours represent twice as much detecting capability as before or 84,000 square meters of *search effort*. This time, the average POD over the same amount of area for seven searcher-hours would be about 93.33% on average as a result of being able to "cover" twice as much area as before with that level of effort. Again, our POD figure assumes a definite range detection function and uniform distribution of effort.

5.4.7.3 It is clear from the last two examples that even for a definite range detection function, the POD - effort relationship does not remain constant if conditions change. However, if we consider the *search effort* represented by 14 searcher-hours in the woods with moderate underbrush where the *sweep width* is 20m, we find that it also amounts to 84,000 square meters of *search effort* and also yields a POD, on average, of 93.33%. Therefore we may conclude that when the same amount of *search effort* is applied to the same amount of area while using the same type of detection function, the same POD is produced. This brings us to the concept of *coverage*.

5.4.8 <u>*Coverage*</u>. From time to time we have spoken of "covering" an area without stating exactly what that means in any quantitative terms. Now that we have a definition of *search effort* as an amount of area that can be "effectively" searched, we may define *coverage (C)* as the ratio of the *search effort* to the area searched. That is,

[5-8] $$C = \frac{Z}{A},$$

where C is the *coverage*, Z is the *search effort* and A is the *area of the searched segment*. The value of C is a measure of how well, or thoroughly, the segment has been covered.

5.4.8.1 Going back to the situation with 15 searcher-hours in a wooded area with moderate underbrush where the *sweep width* is 20m, we find that the *coverage* is 90,000 square meters of *search effort* divided by 90,000 square meters in the segment or 1.0.

5.4.8.2 Suppose we now double the segment's, width along the baseline. Suppose we again have 15-searcher hours of effort available and we maintain the same 20m *sweep width* by assuming all the other parameters of the problem remain unchanged. This means we still have 90,000 square meters of available *search effort*, but we now have 180,000 square meters to search. The best *coverage* we can attain is 0.5 (90,000/180,000). Clearly, this will have an impact on the POD. So we cannot say that POD is dependent only on

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search effort. It is dependent on the amount of *search effort* as compared to the amount of area searched. In this example, the POD for our definite range detection function will be 50%. In fact, it is easily shown that for a definite range detection function used with parallel track searching, the POD is equal to the *coverage* for all *coverage* values between 0.0 and 1.0, and that for higher *coverages*, the POD is always 100%. It can also be shown that for detection functions in general, the **POD is a function of *coverage***.

5.4.8.3 Relating POD to *coverage* is almost the final refinement in our efforts to relate POD to the significant variables of the search problem. *Sweep width* is a measure of searcher performance as a function of the method of sensing (e.g. visual, aural, etc.), the type of search object being sought (i.e. all of the object's characteristics affecting detection), and the environmental conditions (i.e. all of the environmental conditions that affect the searcher's ability to detect the object). *Search effort* is the product of searcher-hours, searcher speed, and *sweep width* and is a measure of how much detecting a given number of searcher-hours represents. *Coverage* is the ratio of *search effort* to *segment area* (assuming the effort was more or less uniformly deployed over the segment) and is a measure of how thoroughly the segment can be (or was) covered with the assigned effort.

5.4.9 <u>Random and Parallel Track Searching</u>. So far, the only detection function whose behavior has been examined in depth is the definite range detection function, and its behavior has been viewed only in the context of parallel track searching. We need to look at the behavior of detection functions under conditions of random searching and to look at the behavior of detection functions other than definite range in parallel track searches.

5.4.9.1 Koopman [3] develops the relationship between POD and *coverage* under conditions of random search in some detail using the definite range detection function. He found that this relationship is given by

[5-9] $$POD = 1 - e^{-C},$$

where C is *coverage* as defined above and e is the base of the natural logarithms. It turns out that this relationship holds regardless of the detection function in use. In other words, for random searching, POD is a function of *coverage* alone.

5.4.9.2 Koopman also developed the relationship between POD and *coverage* for parallel track searching. He showed that for a definite range detection function, the POD is equal to the *coverage* for all *coverage* values between 0.0 and 1.0, and is equal to 1.0 (100%) for all *coverage* values greater than 1.0. He also derived the relationship between POD and *coverage* for the inverse cube detection model. Whereas with the definite range model there is no overlap of the areas swept by searchers on uniformly distributed adjacent tracks until the *coverage* exceeds 1.0 (i.e. the spacing is decreased to some value less than the *sweep width*), and then it has no effect (other than wasting effort) because the POD is already 100%, the situation is quite different with the inverse cube model. The bell-shaped lateral range curve of the inverse cube detection model has, in theory, infinitely long "tails." That is, the lateral range POD approaches, but never actually reaches, zero as the lateral range increases without bound. This means that there is always an

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overlap situation present involving all of the tracks. Koopman, taking this effect into account, derived the POD vs. *Coverage* relationship for the inverse cube detection model and found it was given by

[5-10] $$POD = erf\left(\frac{\sqrt{\pi}}{2}C\right),$$

where C is the *coverage* and *erf* is the well-known error function. The POD vs. *Coverage* curves for all three situations (definite range detection with parallel track searching, inverse cube detection with parallel track searching, and random searching) are all plotted in Figure 5-7.

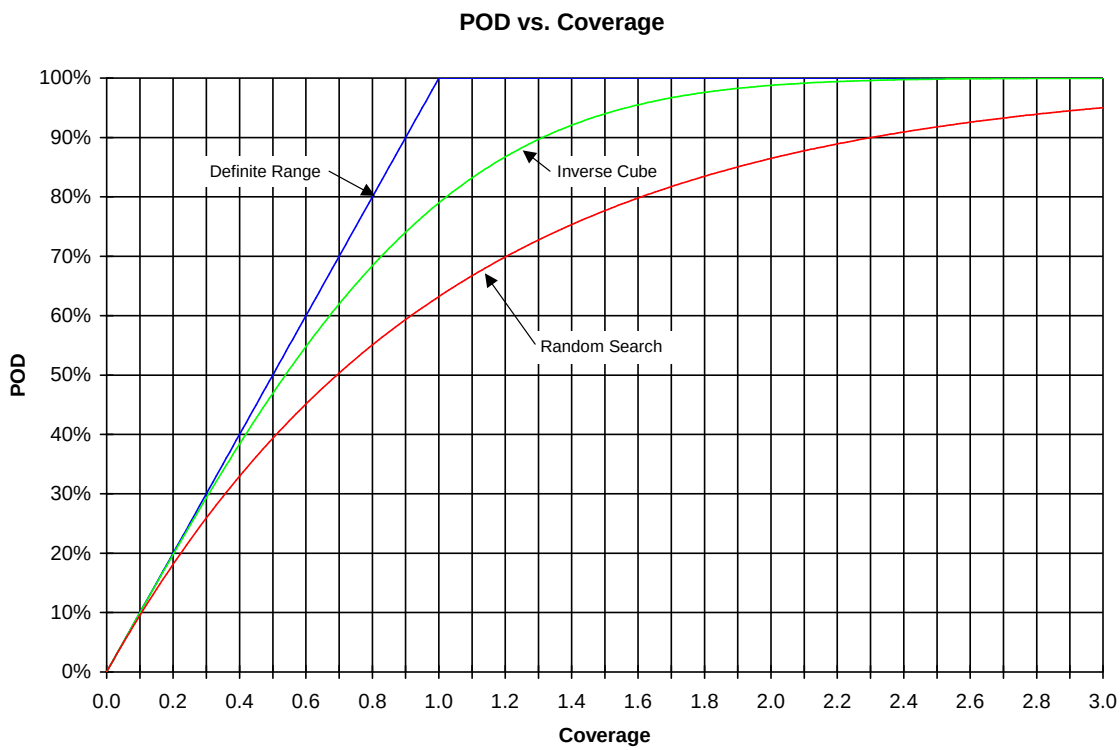

Figure 5-7

5.4.9.3 In general, all detection functions that have a finite maximum detection range behave the same as the definite range detection, as far as POD vs. *Coverage* is concerned, for parallel track spacings greater than or equal to twice the detection function's maximum detection range. The reason for this is that there is no overlap between the areas scanned by adjacent searchers and so the amount of area scanned once, and only once, is proportional to the effort expended. After the spacing between parallel tracks is decreased to the point where overlap between searchers becomes an issue, then the behavior of the POD vs. *Coverage* curve will depend on the exact nature of the detection function, i.e. the shape of its lateral range curve. Highly peaked lateral range curves will produce higher PODs than low, flat lateral range curves. In fact, the more highly peaked the lateral range

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curve, and the more its total area falls near the track, the more closely it will approximate the definite range detection function. On the other hand, the lower and flatter the lateral range curve, i.e. a uniformly low lateral range POD over a possibly quite large maximum detection range, the more closely it will approximate the random search curve, even if it is employed in parallel track patterns. This is because while accurate placement of highly peaked lateral range curves by using parallel tracks is essential to ensure some areas are not searched twice with very high PODs while others are searched with only very low PODs or not at all, accurate placement of low flat lateral range curves is not nearly so important or different in result as compared to random searching.

5.5 Relationship of *Coverage*, *Sweep width*, and Track Spacing for Parallel Track Searches

We will now explore the relationship among *coverage*, *sweep width*, and *track (searcher) spacing* in searches that employ equally spaced parallel tracks where the usual inverse proportion relationship between spacing and effort is preserved and where the tracks are uniformly distributed over the segment.

5.5.1 Recall that in the aeronautical/maritime arena, search sub-area boundaries are always considered to be exactly one-half track spacing outside the outermost limits of the search pattern. Under these conditions, it is easy to show that an equivalent method for computing *coverage* is to compute the ratio of the *sweep width* to the track spacing. That is, for searches using equally spaced parallel tracks,

[5-11] $$C = \frac{W}{S},$$

where C is *coverage*, W is *sweep width*, and S is track (searcher) spacing. This is really the only situation where it is valid to use the spacing between search legs more or less directly to compute POD.

5.5.2 It is worth recalling at this point Koopman's observation that, for parallel track searches with *coverages* less than or equal to 1.0, the POD for a definite range detection function was equal to the *coverage*. This means we may write

[5-12] $$POD = C = \frac{W}{S}, \text{ for } C \le 1.0.$$

Comparing this with Equation [4-6], we see that they are identical. However, in Figure 4-16, POD is plotted against searcher spacing whereas in Figure 5-7, POD is plotted against *coverage*. If a new *sweep width* value is inserted in Equation 4-6 to account for a different terrain, or a difference in some other parameter affecting detection, and the result is plotted against searcher spacing as in Figure 4-16, a new and different curve will result. On the other hand, when POD is plotted against *coverage*, a change in *sweep width* will require a new *coverage* value to be computed for each contemplated searcher spacing, but having done this, the same POD vs. *Coverage* graph may be used. Thus the

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sweep width concept, on which *coverage* is based, provides a much more general and useful way to view POD data.

5.5.3 It is possible to develop curves of the same basic shape as POD vs. Searcher Spacing curves that have the generality of the POD vs. *Coverage* curves by plotting POD data against *inverse coverage* or *normalized searcher spacing* where *sweep width* is the normalizing factor. That is, we could plot POD as a function of searcher spacing measured in *sweep widths*, i.e. in units of spacing divided by *sweep width*. Normalized spacing is computed by

[5-13] $$S_{normalized} = \frac{S}{W} = \frac{1}{C},$$

where $S_{normalized}$ is the normalized spacing (or inverse *coverage*, $1/C$), S is the spacing in the usual units of measure, and W is the *sweep width*. Thus we may rewrite the definite range POD equation as

[5-14] $$POD = \frac{1}{S_{normalized}},$$

the inverse cube POD equation as

[5-15] $$POD = erf\left(\frac{\sqrt{\pi}}{2S_{normalized}}\right),$$

and the random search POD equation as

[5-16] $$POD = 1 - e^{-\frac{1}{S_{normalized}}}.$$

The graphs of these three functions are shown in Figure 5-8. Note that the only thing actually done to get these curves was some minor algebraic maneuvering to change the independent variable against which the POD was graphed. Also note that without *sweep width*, *W*, the generality achieved in these graphs simply is not possible.

5.5.4 At this point, it is worth recording another of Koopman's observations. When comparing the definite range, inverse cube and random search detection functions, Koopman observed,

> At one extreme is the case of the definite range law, at the other the case of random search. All actual situations can be regarded as leading to intermediate curves, those lying in the shaded region [between the two curves]. The inverse cube law is close to a middle case, a circumstance which indicates its frequent empirical use, even in cases where the special assumptions upon which its derivation was based are largely rejected.

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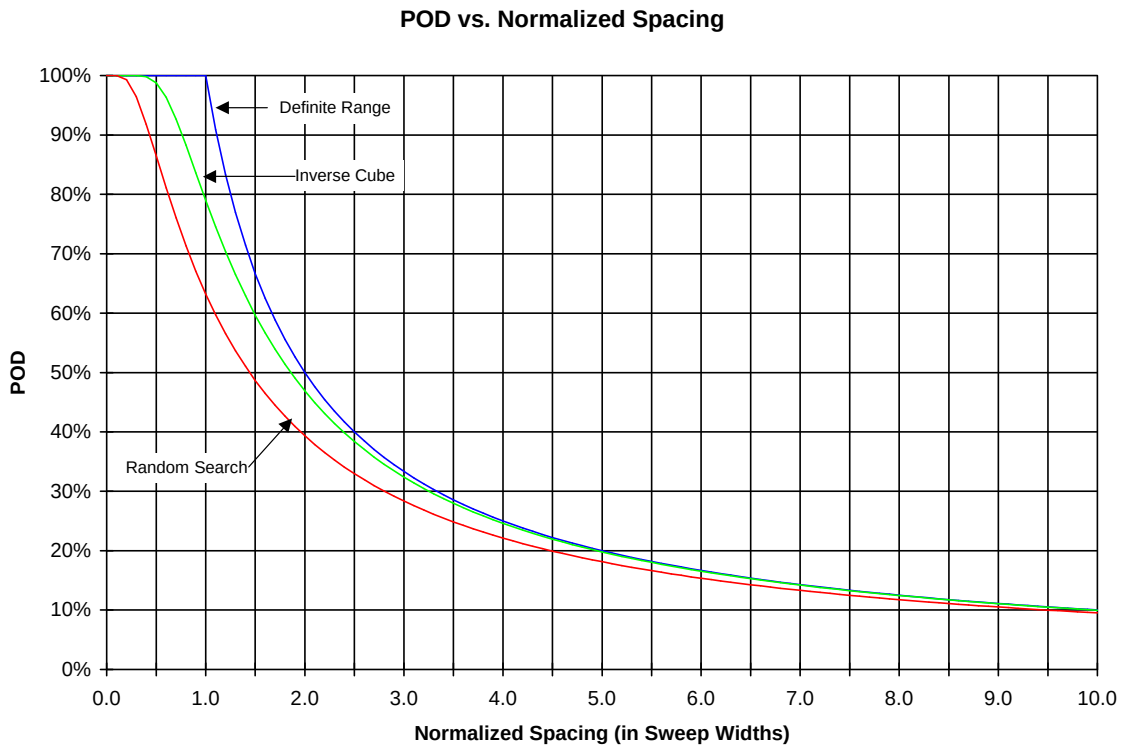

Figure 5-8

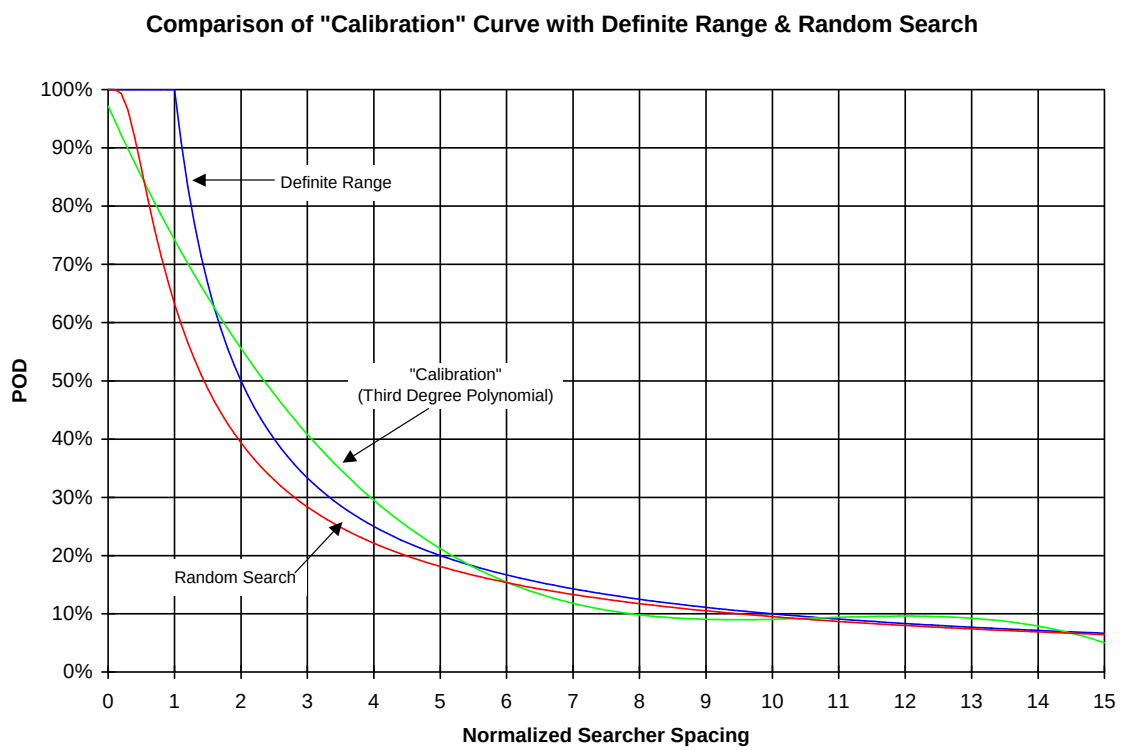

Figure 5-9

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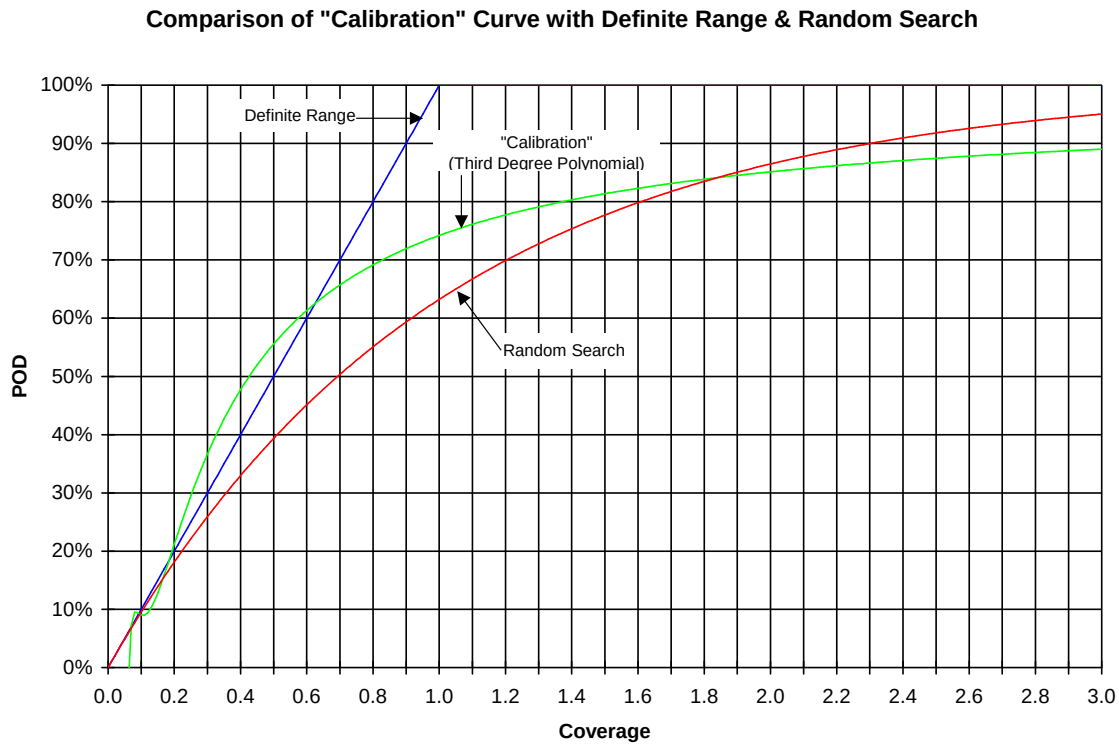

Figure 5-10

Figures 5-9 and 5-10 show the definite range, random search, and third degree polynomial "calibration" curve from Figure 4-9 plotted against both normalized searcher spacing and *coverage*. The *sweep width* of 20 meters was used to normalize the "calibration" curve so it could be plotted at a scale consistent with the other two. Note that the "calibration" curve does not fall between the other two but cuts back and forth across them, going into "impossible" areas on the graph. Note in particular that the "calibration" curve generally over estimates the POD at low *coverages* (wide spacings) and under estimates POD at high *coverages* (small spacings). It is little wonder that using such a curve would lead one to the incorrect conclusion that wide spacings are generally more "efficient" that narrow ones. Figures 5-9 and 5-10 provide yet another reason for rejecting the polynomial approximating functions used in [7] along with the conclusions based on them.

5.6 Some Other Issues Previously Raised

In the preceding chapters, a number of references were made to this chapter, with the implication that certain issues and terms would be explained here. We have already covered most of these. However, there are two that remain.

5.6.1 "Probability of Coverage". In 1997, R. Goodman and R. Cowan [8] published an article in *Response* describing a technique for estimating POD for "non-thorough" search techniques. "Non-thorough" Type II searches are those where small search teams are sent

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into a segment as opposed to forming a line abreast along the entire length of a segment boundary with a much larger number of searchers who then march through the segment.

5.6.1.1 Goodman and Cowan were concerned that in a Type II search, a significant fraction of a segment's area might actually be unsearched but the POD, based only on the spacing between search team members, would be applied to the segment as a whole. Their concern was certainly legitimate if POD was being computed and applied in this manner. Their idea was to compute how much area was actually "covered" by the search team and combine that value with the average POD over the "covered" area based on searcher spacing. If "critical separation" was used (which amounts to separating the searchers by twice the maximum detection range), the amount of area actually "covered" was computed as the number of team members times the "critical separation" to get the "covered" area's width. This width was then multiplied by an estimate of the distance traveled by the team in the segment. The ratio of this area to the total area of the segment was called the "probability of coverage." The interpretation was that if the "covered" area was one-half the segment's area, then there was a 50% chance that if the object was in the segment, the piece of ground it occupied was looked at. Note that this does not imply that the search object would have been detected, just that its location would have been "covered." If the average detection probability over the "covered" area was estimated to be 50%, then the "corrected" average POD for the segment as a whole was computed to be 25%.

5.6.1.2 It is interesting to note that, if Goodman and Cowan had known about *sweep width*, if actual *sweep width* values had been available, and if they had been used instead of "critical separation," then their definition of coverage would have matched that of formal search theory precisely. However, it wouldn't have done much good since the rest of the underlying structure of search theory is still missing from ground search procedures.

5.6.1.3 The "probability of coverage" technique actually produces valid results as long as certain conditions are met. First, the search object's location probability density has to be uniformly distributed over the segment's area. Second, there can be no overlapping of "covered" areas, either by multiple search teams working in the same segment or by one search team "covering" some area more than once. Third, the estimate of the average POD over the "covered" area must be accurate. Since the first assumption is quite common (often based on lack of information to the contrary), Type II searches are "non-thorough" making significant amounts of overlap unlikely, and, until accurate *sweep width* determinations can be made, the POD estimate is probably the best available, search managers aren't likely to get into too much trouble using it. However, it must be pointed out that the Goodman/Cowan definition of "coverage" is significantly different from that of formal search theory and lacks its general utility. Since procedures derived from formal search theory would address Goodman's and Cowan's concerns, and a great many other issues besides, as soon as such procedures are available they should be used in favor of "probability of coverage." In the meanwhile, care must be taken to minimize the potential confusion that could be generated by defining "coverage" one way for a while and then re-defining it another way later when more formally based techniques come on line. Likewise, steps need to be taken to avoid confusing the acronyms for "probability of coverage" and "probability of containment."

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5.6.2 Inferring "Visibility Distance" from POD data. In paragraph 4.6, the response to general conclusion number 6 from [7] noted that the proper way to infer maximum detection distance (i.e. "visibility distance") from POD vs. Spacing data was to compare the actual detection function's curve to that of the equivalent (i.e. same *sweep width*) definite range curve in order to identify the transition point from spacings where there is no overlap to spacings where overlap does take place. This comparison can also be made using POD vs. *Coverage* curves. Consider the rectangular (50%) detection function whose lateral range curve is depicted in Figure 5-2. Figure 5-11 shows this detection function's POD vs. *Coverage* curve along with the definite range and random search POD vs. *Coverage* curves.

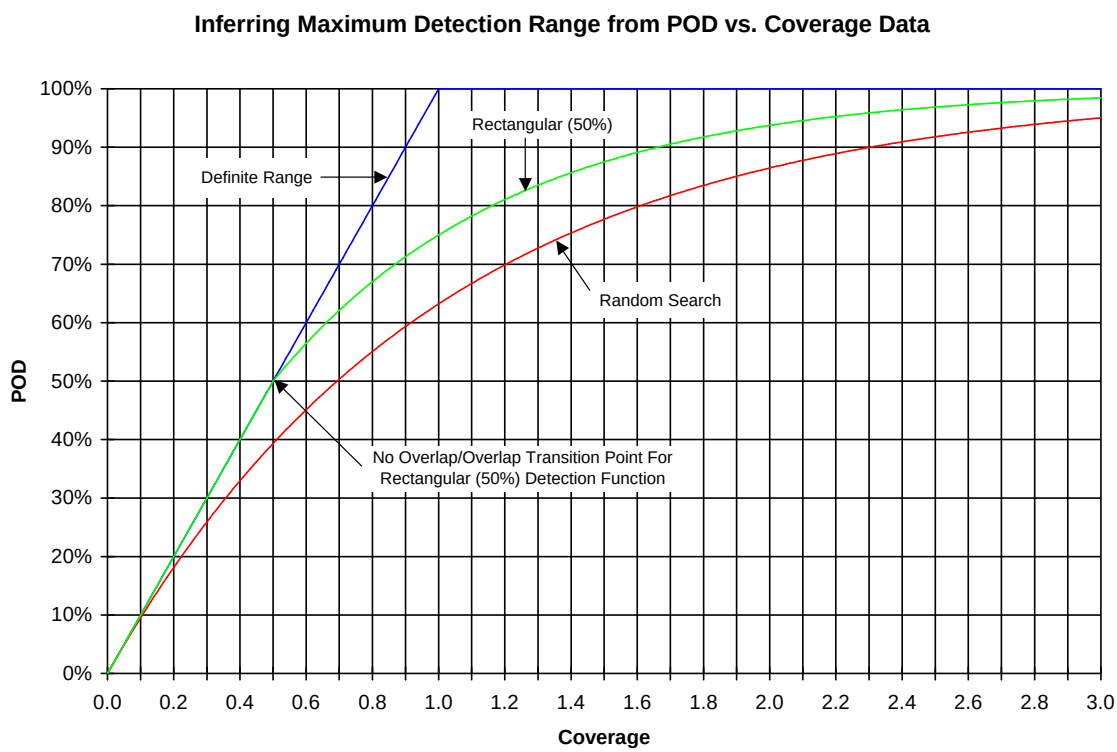

Figure 5-11

Note that at a *coverage* of 0.5, which, for a parallel track search corresponds to a spacing equal to twice the *sweep width*, the rectangular lateral range function's curve separates from the definite range function's curve. If the *sweep width* is 20m, this means that at spacings of less than 40m, overlap is taking place, causing the rectangular detection function to perform less well than the definite range detection function. Looking at Figure 5-2, it is easily confirmed that tracks that are closer than 40m will experience overlap. Assuming the detection function is symmetric, one half this distance, or 20m, will be the maximum detection range. We see the same phenomenon when the rectangular detection function's POD vs. Normalized Searcher Spacing curve is plotted on the same graph as that of the definite range detection function, as in Figure 5-12. At a normalized spacing

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of 2, which corresponds to a 40m spacing if the *sweep width* is 20m, the rectangular detection function's curve begins to fall away from the definite range function's curve. This again implies that a 40m spacing is the transition point between overlapping and non-overlapping detection envelopes, and again a maximum detection range of 20m may be inferred.

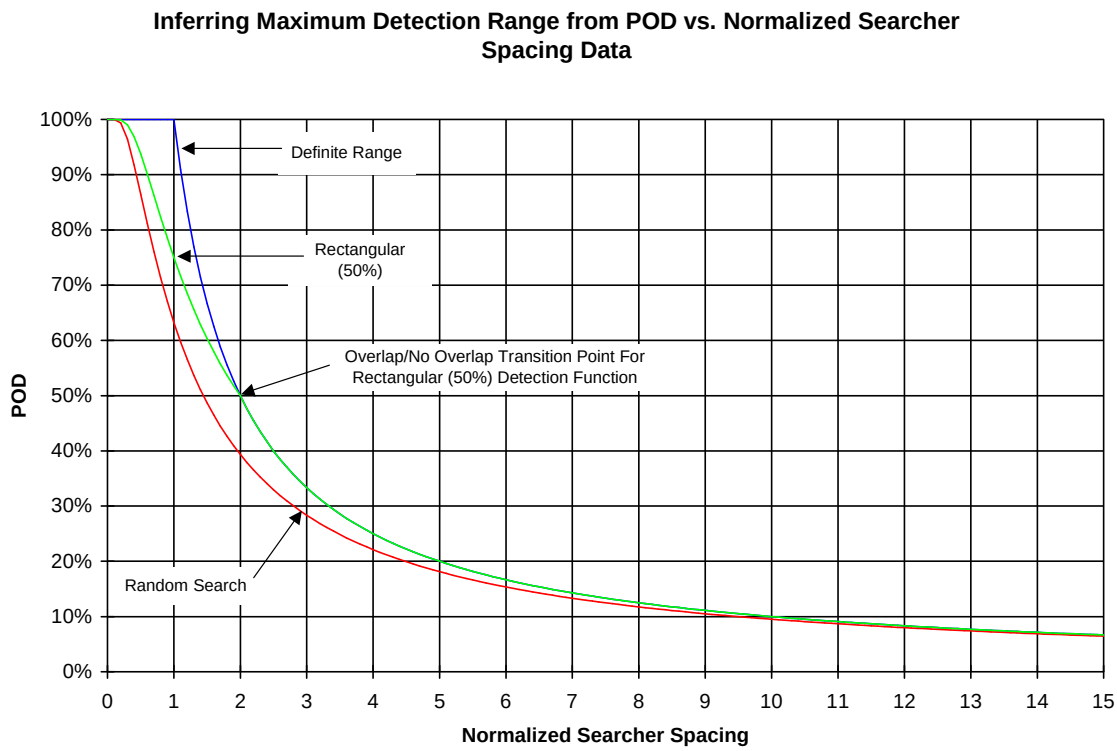

Figure 5-12

5.7 A Brief Review of *An Experimental Analysis of Grid Sweep Searching* [6]

In the summer of 1973, J. Wartes conducted a field experiment "to test the thoroughness and efficiency of three grid sweep spacings under conditions of thick ground cover." The results of this experiment were documented in [6] the following year. The experiment was conducted within a 600 x 2,000 foot test area located in the western portion of Washington state. The area was divided lengthwise into 5 marked lanes, each with a width of 120 feet. The area was also divided in half at the 1,000 foot mark. Three different searcher spacings were used (20', 60' and 100'). Forty-five adult and teenaged volunteers were used as search objects, with 23 being instructed to behave as immobile but conscious survivors while 22 were instructed to behave as though they were unconscious. Some 200 half-pint milk cartons were also distributed to simulate "clues." Both day and night searches were conducted. We will now take a brief look at Wartes' 1974 paper in light of what we have learned so far.

5.7.1 Background. Apparently one impetus for doing the experiment was that in a number of instances, friends or relatives found the subject in the search area before the search teams

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did. This was taken to mean that untrained searchers using unsystematic, non-thorough methods were doing a better job in less time than trained searchers using thorough, systematic techniques. Without doing a careful "case study" on each instance where this happened, it is impossible to determine the true causes. While several instances of relatives finding the subject before the search teams might be a valid signal that the search techniques in use could bear reexamination, one must be wary of reading too much into unanalyzed anecdotal "evidence." In any case, an effort was made to find a better measure of "search effectiveness." (It is easily shown that the only valid measure of search effectiveness is Probability of Success. The method that yields the highest POS is, by definition, the most effective, and also the most efficient.)

5.7.2 "Thoroughness". In the experiment, search teams consisted of 6 members each and three search tactics were used. In the first method, search team members were spaced 20' apart. In this case the team's "path width" was defined as 120' and they were sent down one of the five marked corridors. In the second method, the searchers were spaced 60' apart for a "path width" of 360' that corresponded to three of the 120' corridors. In the third method, the search team was split into two groups of three with members of the same group spaced 50' apart while the distance between the centers of the two groups was 300'. This produced an average spacing of 100' and a "path width" of 600'. Wartes then defined "thoroughness" as

[5-17] $$Thoroughness = \frac{A}{B} \times 100\%$$

where A was defined as the number of items found and B was defined as the number of items within the team's path. It was noted that the value of "thoroughness" could exceed 100%, as when a team finds 9 of 10 possible objects within its path width plus two more off to the side of its path (i.e. outside the team's "path width") for a "thoroughness" value of 110%.

5.7.2.1 Wartes' definition of "path width" is consistent with formal search theory in that it places the search sub-area boundaries one half the searcher spacing outside the two outboard searcher tracks. However, "thoroughness" as defined in Equation [5-17] is not a useful number since it is merely a corrupted POD. As Wartes observes, a true POD value for the region whose dimensions are the "path width" and track length would consider the ratio of detected to undetected objects only within that defined region and would disregard "finds" outside that region. A true POD could also be obtained for the larger region whose width is defined as the distance between the leftmost and rightmost detected objects if it was computed as the ratio of detected to undetected objects within that entire area. However, to add only "finds" outside the intended "path width" to the computation without also considering how many objects could have been found within that distance adds nothing but confusion. Likewise, his later method for estimating POD from experimental data is flawed. Here, he realized that an object detected "outside the team's path" would be within an adjacent team's path and therefore subject to another detection. His preference would have been to remove objects upon detection and thus eliminate this problem. However, that would have added time, expense and difficulty to the experi-

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ments. Instead, he just added the number of objects found outside the team's path to the denominator of his ratio for computing "thoroughness." This keeps the estimate below 100%, but it is still a corrupted value for the same reason as "thoroughness." Including "finds" without also including "detection opportunities" is an invalid procedure no matter how the figures are juggled.

5.7.2.2 Recalling our discussion of *sweep width*, and Equation [5-1] in particular, we see that Wartes was really grasping for *sweep width* without realizing it. If the total detection count, *A*, was kept on a per searcher basis, it would correspond exactly to *N* in Equation [5-1]. Instead of comparing this value to the "number of objects in the teams path," *B*, he should have compared it to the product of search object density and searcher speed. Had he done so, he would have produced *sweep width* data.

5.7.2.3 Wartes was also correct in observing that there should be some quantity that connotes "thoroughness" or how well a segment was searched. As we have already seen, that quantity is *coverage*.

5.7.3 <u>"Efficiency"</u>. Wartes went on to define "efficiency" as the proportion of items found within a unit of area per searcher-hour of effort expended. His formula was

[5-18] $$Efficiency = \frac{AD}{BC},$$

where *A* is the number of items found, *B* is the number of items in the team's path, *C* is the number of searcher-hours of effort, and *D* is the size of the area searched.

5.7.3.1 If we write the expression on the right of Equation [5-18] as the product of two fractions, we see that "efficiency" is the product of "thoroughness" and "search rate" or area searched per searcher-hour expended. Interestingly, about 30 years previously, Koopman had observed that the quantity *wW*, or searcher speed times *sweep width*, produced an *effective search or sweep rate* that also has units of area per unit time. Koopman's definition could conceivably be used as a measure of "efficiency" for comparing one detection function to another. However, Wartes (and later Colwell) were trying to compare *tactics*, not detection functions.

5.7.3.2 Here we must digress for a moment to discuss the usage of *time* in the various research efforts. *Time* can be used as a measure of effort, as in searcher-hours, or it can be used in the sense of elapsed time from search beginning to search end. Too often, a clear distinction in usage is not made, and confusion results. For example, Wartes defines "efficiency" using searcher-hours but then states, "If method R produces the same results as method T in half the time, it is twice as efficient." By "half the time" Wartes clearly means "half the searcher-hours" but the sentence could easily be misinterpreted, especially if taken out of context. In any case, it needs to be recognized that maximizing the probability of locating survivors in the minimum elapsed time (perhaps due to survivability considerations) and maximizing "efficiency" as defined above are two quite different things.

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5.7.3.3 If we invert area per searcher-hour we get searcher-hours (effort) per unit area, i.e. "effort density." This is strongly reminiscent of *coverage*. In fact, *coverage* is *search effort density* since it is the ratio of *search effort* to area searched. If we substitute POD for "thoroughness" and *search effort* for searcher-hours, we get "efficiency" as POD per unit of *coverage*. For a specific segment and set of search conditions (i.e. fixed segment area and fixed *sweep width*), this is proportional to POD per searcher-hour, just as in Colwell's definition. However, as we have already seen, this isn't a useful quantity, either.

5.7.3.4 It is easily seen from Figure 5-7 that the ratio of POD to *Coverage* is highest at low *coverages* for all detection functions (other than definite range for *coverages* less than 1.0 where the ratio is constant). Regardless of the definition used, if "efficiency" were the only consideration, search managers would never send more than one searcher at a time into a segment. That is the problem with all definitions of "efficiency" introduced up to this point. Although the goal was to help the search manager decide how to make the best use of the available resources, "efficiency" computations so far presented do not provide meaningful guidance on how to maximize the chances of finding the subject with the available assets.

5.7.3.5 Apparently the driving force behind attempts to define and use "efficiency" values was the realization that as more and more effort is put into a segment, the *increase* in POD per unit of added effort becomes less and less. Surely there had to be some criteria for deciding when enough is enough. It appears that an attempt was made to maximize the return on investment, where POD was the "return" and number of searcher-hours was the "investment." The problem with this approach is that maximizing POD (or any other POD-based "efficiency" value) on a per segment per searcher-hour basis is the wrong criteria and that is why all such "efficiency" methods fail. The correct criteria is maximizing the overall POS, as Koopman, Stone, and others in the academic community have long recognized and as Colwell also recognized in his paper *Search Priority* [15] which we will examine briefly in a moment.

5.7.4 <u>Evaluating the Experiment's Results</u>. Qualitatively, the experiment's results don't display anything unexpected. Quantitatively, however, the POD estimates given on page 30 of [6] contain some serious anomalies. The table of POD estimates given in [6] is reproduced below for convenience.

	Day			Night		
Searcher Spacing	20'	60'	100'	20'	60'	100'
½ pt. Milk Carton	43%	21%	15%	28%	18%	11%
Unconscious Subjects	94%	67%	51%	64%	37%	19%
Conscious Subjects	89%	86%	56%	94%	68%	50%
Unconscious and Conscious Subjects Combined	92%	71%	53%	81%	52%	35%

Table 5-1

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Consider the following. For parallel track search patterns, if the POD is known and a POD vs. *Coverage* curve is assumed, then an estimate of the *coverage* may be obtained. From the *coverage*, one may estimate the *sweep width* by solving Equation [5-11] for *W* to get

[5-19] $$W = C \times S$$

If a similar *sweep width* value is computed for all spacings using this technique, then the likelihood that the POD values are valid is enhanced. For example, the figures for unconscious subjects in daylight produce *sweep widths* of about 42', 48' and 51' for an average of 47' when using the "rectangular" (50%) lateral range function's POD curve from Figure 5-11. Using this average *sweep width* estimate to compute *coverage* and then POD values yields PODs of 96% for 20', 66% for 60' and 47% for 100'. Therefore, the original set of values at least seems to form a reasonable progression. On the other hand, if no curve falling between the random search curve and that of a definite range detection function could produce the listed PODs as a set, then the validity of those values must be seriously questioned. For example, there seems to be a serious problem with the values for the conscious subject data during daylight. Increasing the *coverage* (decreasing the spacing) by a factor of 3 in going from a 60' spacing down to a 20' spacing produces a paltry 3% increase in POD. No realistic detection function would produce such a modest increase except at very high *coverages* and PODs, e.g., from 2.5 to 7.5 and 96.9% to 99.9% respectively for the "rectangular" detection function. However, the PODs in Table 5-1 are not in this range and even if they were and the corresponding *coverages* for 60' and 20' spacings were that high, then the *coverage* for a 100' spacing would be 1.5 and the POD of 56% would be unbelievably low. Even the so-called random search curve has a POD of about 78% at a *coverage* of 1.5. Therefore, we must conclude there is a serious error somewhere.

5.7.5 Observations. Wartes made a number of interesting observations. One of these relates to the "randomness" imposed on the search process and the other related to the atypical behavior of "efficiency" curves as defined for searching.

5.7.5.1 Wartes observed that even when a searcher walks in a perfectly straight line, the boundary of the area where detection is possible is quite irregular and "random." Colwell in [7] cited the random nature of the environment. Perkins and Roberts have described a search technique called "purposeful wandering" where searchers leave their assigned tracks to look behind obstructions to their vision and in places that seem "likely" spots for a subject to go. Such actual searcher tracks would qualify for "random" searching from a search theory perspective, albeit at a higher *coverage*, however "purposeful" they might be from the searcher's perspective. In short, the random search curve may be the best all-around estimator for ground search POD once *sweep width* values are established.

5.7.5.2 Wartes also observed that "efficiency" as he defined it in terms of searcher spacing is atypical of most "efficiency" functions that rise to a maximum value and then decrease. Beyond a certain point, Wartes' "efficiency" value becomes constant and he states that, "There is no 'most efficient' spacing." As Wartes observes, the point where his measure

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of "efficiency" becomes a maximum, and constant, value occurs at the point where overlap ceases.

5.7.5.3 The problem with both Wartes' and Colwell's definitions of "efficiency" are that they are applied to single segments and try to address the essentially non-existent problem of maximizing POD in relation to searcher-hours expended in the segment. For any given situation where the probability density is uniformly distributed over the segment's area (an approximation that is almost always made), the most efficient thing to do, and the one that gives the highest POD, is to apply the available effort uniformly over the segment. Whatever spacing results is the most efficient, regardless of how the "efficiency" values defined by Wartes or Colwell come out. However, when trying to allocate the available effort among two or more segments, there is a division of effort that produces the highest POS. When looking at "POS efficiency," i.e., POS per searcher-hour expended in a multiple segment situation, the "efficiency curve" becomes more typical as we will see in Chapter 6 below. Furthermore, once the allocation of effort among the segments has been determined, then a spacing for each segment may be computed that provides the most uniform possible *coverage*. For example, for uniform distributions (same probability density in all segments) under uniform search conditions (same *sweep width* in all segments), the "peak" of the "POS efficiency" curve is always at the point where the effort is spread uniformly over the entire area without "spilling" any over the edges (same *coverage* in every segment), regardless of how low the *coverage* may go. For non-uniform distributions and/or non-uniform search conditions, the optimal effort allocation problem becomes considerably more complex and difficult to solve. However, there is still a "peak" to the "POS efficiency" curve, even if it is harder to find.

5.7.6 In 1975, Wartes [16] came very close to correctly formulating the true goal of search planning when he began looking for ways to maximize the rate of increase in POS as a function of elapsed time. Although he was working with experimental POD values that contained some error, he correctly apprehended a fundamental truth – for an object that is equally likely to be anywhere in the search area (uniform probability density distribution), the probability of success (POS) is increased most quickly by spreading the available resources over the area uniformly in both ***space*** and ***time***. That is, it is better to spread the available resources out to search the entire area simultaneously, or several times rapidly in succession, at a low coverage than to search it only once at a high coverage. High coverage searches that use a line-abreast formation of closely spaced searchers leave large portions of the search area completely unsearched for a considerable length of time. Even if both techniques produce the same POD and POS at the end of the day, the tactic of spreading the resources out uniformly over a uniform distribution makes finding the search object at an earlier point in time much more likely.

5.7.7 Unfortunately, Wartes also erroneously concluded that the final POD and POS, after all the resources were expended, were also higher for the repeated low coverage searches than for the single high coverage search. Although the apparent POD improvement was small and even if true was relatively unimportant, this erroneous conclusion was widely seized upon as justification for searching a segment once at a low coverage (i.e., low POD) and not searching it again until all other segments had been searched at least once.

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Wartes' far more important correct conclusion that ***simultaneous*** low coverage searching everywhere at once, or approximating this as closely as practicable by using ***rapidly repeated*** low coverage searches, increased POS at a faster rate in the early hours **for uniform distributions** was ignored. We will revisit Wartes' "discovery" in Chapter 6.

5.7.7 Conclusions. It appears that while Wartes came tantalizingly close to formulating some of the key concepts of formal search theory, he was unable to do so without having the *sweep width* concept at his disposal. Consequently, his results are of limited value. In particular, the concepts of "thoroughness" and "efficiency" as described have no mathematical validity and are more confusing than helpful.

5.8 A Brief Review of *Search Priority* [15]

In 1994, M. Colwell published a technique for optimally allocating effort called "search priority." In a nutshell, it presents two methods for "ranking" segments in terms of where resources should be placed. The first method simply ranks the segments by probability density, i.e. the ratio of POA to segment area. Colwell calls this "area-based search priority." The second method ranks the segments by ratio of POS to searcher-hours which include, significantly, transit time to and from the segment as well as the time required/available to actually search the segment. Colwell calls this "manpower-based search priority."

5.8.1 "Area-based Search Priority". The method of simply ranking segments by probability density has two weaknesses. First, ranking by probability density alone does not provide information on how the available effort should be divided among the segments, even if the *sweep width* ("raw" detection power) is the same everywhere. The search manager knows that he should put more effort into more dense segments than less dense segments, but he doesn't know just how much more effort to put into one segment as opposed to another to maximize POS. Second, if the *sweep width* is different from one segment to another as well, then even this simple "rule of thumb" may no longer be valid in terms of maximizing POS.

5.8.2 "Manpower-Based Search Priority". The method as presented uses the correct measure of search effectiveness, namely POS, and does relate POS to the effort required to attain it. However, the method doesn't explicitly address the issue of maximizing the overall POS for the total amount of available effort. Instead, it has the search manager establish a POA for each segment, set a POD "goal" for each segment, compute the effort required to meet each segment's POD goal, compute the POS that would result if the goal was met, and finally compute the ratio of POS to effort for each segment. Since the total amount of effort required to meet all the segment POD goals simultaneously is almost certain to be prohibitively high, the method does provide some rough guidance on which segments to search with the effort that is available. However, it doesn't guarantee that the POS achieved will be the most that could have been achieved. There are also several other weaknesses in this method. First, the setting of POD goals is an ill-defined process not related to maximizing POS in any explicit, clearly defined manner. Second, the method of relating POD to the effort required to attain it is likewise ill-defined and what data is used in the examples appears to be based on the techniques used in [7] which were

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reviewed in Chapter 4 above and found wanting. Third, by establishing the amount of effort for each segment up front as a result of having established a POD goal, the method puts the cart before the horse. The objective should be to decide how much of the available effort, if any, to put into each segment so the overall POS is maximized. The objective should not be a simple ranking of the segments after the effort levels have already been determined, even if the ranking is by "search priority," a.k.a. "POS efficiency."

5.8.3 Conclusions. Again, we have a situation where a researcher has come tantalizingly close to addressing the key question in search management, namely, "How to I apply the available resources to maximize the probability of finding the subject in the shortest time?" without actually accomplishing that goal. And again the missing link is ***sweep width***. The problem "search priority" seems to be trying to solve actually has a solution documented by Stone in [4], but it is couched in mathematical terms that are indecipherable to all but professional mathematicians — and it requires knowing or at least having estimates of all the *sweep widths*. However, it seems reasonably likely that it, or a reasonably valid approximation, can be translated into usable terms if an individual with the right mixture of mathematical ability and pragmatism can be found who has the time to do this work, and if *sweep width* values or methods for estimating them can be established. Chapter 6 provides an "appetizer" showing some examples of optimal effort allocation between two segments under a variety of conditions and outlines an optimal effort allocation methodology.

5.9 Some General Remarks Regarding "Efficiency"

Much energy has been expended trying to find a definition for "efficiency" with the goal, apparently, of providing a method for comparing one search tactic to another based on efficiency ratings. In [1], maximum "efficiency" is always defined as obtaining the maximum POD for the effort invested. "Search priority" [15] is used to rank segments in order of where effort should be placed based on picking segment POD goals. However, like both [6] and [7] which had a valid goal of improving POD estimates but missed the mark because the key concept of *sweep width* was missing, "search priority" almost sets the correct goal of obtaining the maximum POS with the available effort but likewise misses the mark when it comes to actually accomplishing the goal, again because the key concept of *sweep width* is missing.

5.9.1 It was stated earlier that the goal of search planning/management is to maximize the probability of success (POS) as quickly as possible using the available effort. This means that the only truly useful measure of "efficiency" is the POS per unit of effort expended as time passes. However, since searching is usually effort-constrained, that is, search managers can usually use more effort than they can get, there is no need to compute or use an "efficiency" figure in search management. Deploying the available effort so the POS is maximized at each point in time automatically ensures the effort is being utilized in the most efficient manner.

5.9.2 "Efficiency" figures as defined by Wartes and Colwell can also be quite misleading. On the POD vs. *Coverage* graphs of Figure 5-3, the slopes of all the curves are steepest at

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low *coverages* (wide spacings). This means the POD per unit of *search effort* expended (since *coverage* is proportional to *search effort* for a given set of search conditions) is higher there than it is at higher *coverages* (closer spacings). Some have speculated that because low *coverage* searches appear "more efficient" using this metric, effort should be divided and applied as successive low *coverage* searches rather than as a single higher *coverage* search. It is easy to show mathematically that multiple low *coverage* searches provide no advantage over single searches when the total amount of *search effort* expended in both cases is the same. For random searching, uniformly applied over the entire area, the results of the two tactics are identical in terms of POD. In all other cases, **multiple low *coverage* searches** produce **lower cumulative PODs** than single higher *coverage* searches using the same amount of *search effort*. This is not to say that practical, operational considerations don't exist for preferring multiple low *coverage* searches to single higher *coverage* searches in some circumstances. However, there are no mathematical reasons based on POD vs. *Coverage* (*search effort*) behavior that support such tactics.

5.9.3 Another aspect of trying to be "efficient" involves the avoidance of "visual overlap" between searchers because it is "inefficient." How much overlap, if any, constitutes an "efficient" use of resources depends on a number of factors. One factor is the shape of the lateral range curve. We saw that in the case of the inverse cube detection function, overlap is inevitable, at least in theory. In general, lateral range curves where the POD decreases with increasing lateral range must have some overlap if a reasonable POD in the region midway between searchers is to be achieved. Another factor is the distribution of probability density among the segments. The distribution of probability density might dictate searching one segment at a much higher *coverage* than the other segments in order to maximize POS. High *coverages* generally require at least some overlap between adjacent searchers. Optimal effort allocation based on maximizing POS is not a simple problem. But, simple or complex, it is **not** related to the POD-based efficiency concepts advanced in [1] and elsewhere for ground search use.

5.10 The Importance of *Sweep width*.

The importance of *sweep width* cannot be over-emphasized. It is the fundamental, quantitative measure of how much detecting a searcher does when moving along his/her track.

> ***Sweep Width*** is the essential link between effort and accurate estimates of the POD that can be obtained with that effort.

With *sweep width*, it is possible to relate the quantity of searching that can be done to the amount of effort available to do it. Therefore, it forms the very basis of POD estimation and optimal effort allocation (as described in Stone [4]). Attempts to bypass *sweep width* and go directly to estimates of POD from apparent POD vs. Searcher Spacing relationships do not provide a valid basis for optimal effort allocation because they do not describe the general behavior of POD in relation to amount of available effort vs. the amount of area to be covered. This in turn means there is no basis for determining how the effort should be applied so as to maximize the probability of success. In the worst

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case, as we have seen, viewing POD as a function of Searcher Spacing leads to serious misperceptions about POD behavior and erroneous conclusions about how effort should be allocated.

5.10.1 Measuring Detection Performance. *Sweep width* is a measure of individual searcher detection performance. Neither "thoroughness" nor "efficiency" as defined by either Wartes or Colwell, nor even POD itself, capture in such absolute terms the individual searcher's "raw" detection performance on a single leg. Knowledge of detection performance on individual search legs is needed before we may develop valid generalized methods for estimating PODs over areas. *Sweep width* is the summary of that knowledge for any situation where *sweep width* values are known. As such, it forms the basis for quantitatively defining *search effort* and *coverage* which allow us to compute the average POD over an area, even when it is covered by random searching with no definable searcher spacing, as long as the effort is contained within, and more or less uniformly applied, over the entire area. Together with the type of detection function in use, the *search effort* and *coverage* derived from *sweep width* also allow us to compute the average POD over an area covered by organized searching using parallel tracks. Finally, by providing a method for converting effort, as measured in searcher-hours, into *search effort*, i.e. the amount of area that can be effectively swept with that effort, *sweep width* allows us to optimally allocate the available effort so as to maximize the *probability of success (POS)*.

5.10.2 *Sweep width* Characteristics. We can make a number of general observations with respect to the correlation between *sweep widths* and factors affecting POD. The following list is by no means exhaustive. It is offered simply for purposes of illumination and to increase the "comfort level" for those heretofore unfamiliar with the *sweep width* concept.

- Larger objects will generally have larger visual *sweep widths* than smaller objects.
- Louder sounds will generally have larger aural *sweep widths* than softer sounds. The frequency (pitch) of the sound (in Hz) may also affect aural *sweep widths*. The frequency with which intermittent sounds are made could also have an impact on aural *sweep widths*.
- Objects with high color and/or brightness contrast with the background will generally have larger visual *sweep widths* than objects with low contrast.
- Trained search dogs may have significantly greater *sweep widths* than humans with respect to sound and especially scent.
- Trained searchers may have significantly larger *sweep widths* than untrained searchers in the same situation.
- *Sweep widths* will generally be larger in flat, open areas than in rough terrain heavily covered with vegetation.

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- "Purposeful wandering" will probably produce higher PODs than "beeline" searching, partly because the searchers that use it are generally trained for it, partly because it tends to reduce the degradation in *sweep width* due to visual obstructions, and partly because this technique requires more time and a longer actual track length. All of these factors increase the level of *search effort*, hence the *coverage* of the segment, and finally the POD.

- *Sweep widths* will generally be larger for fresh, rested searchers than for fatigued searchers.

- The smaller the *sweep width*, the larger the effort needed to achieve a given level of *coverage* or a given desired POD.

The above examples show that *sweep width* is indeed a good measure of "raw" detecting power or the ease or difficulty of detecting a particular search object with a particular sensor under a particular set of environmental conditions. As such, it is useful for comparing one search situation to another and, when used with *effort* to compute *search effort*, it may be used to determine the optimal way to allocate the available *effort*.

5.10.3 The Need to Obtain and Use *Sweep width* Values. Some search managers may well ask whether experiments to determine *sweep width* and computations to use it in determining *search effort*, then *coverage*, then POD, and finally the optimal way to deploy the available effort, are really necessary. They would like to have some way to go directly from searcher spacing, something they understand and often have under their control, to POD. They would like some really simple procedures for optimally allocating the available effort, i.e. determining which segments to search and which spacings to use. These are fair questions, and ones we have either tried to answer in this paper or at least indicate where answers exist if *sweep width* data is available. As we saw in Chapter 4, POD is **not** directly related to searcher spacing alone. As we have just seen, it is related to the *coverage*, the detection function (whose exact nature may or may not be known), and the manner of searcher employment, i.e. random searching vs. organized parallel track searching. Since, regardless of how it is computed, *coverage* depends on *sweep width*, there is simply no getting around it. Koopman's analysis was carefully and scientifically done, and has stood the test of time after more than 50 years of scientific scrutiny. Building on Koopman's work, a number of researchers have significantly improved upon methods for optimally allocating effort. All depend on *sweep width*. Many of these methods may be profitably adapted to improving ground search management, if only reasonably accurate estimates of *sweep widths* can be developed.

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Chapter 6
Optimal Effort Allocation

6.1 Introduction

6.1.1 We will now look at some very simple examples of how to optimally allocate the available effort between two segments. The first segment is assumed to have an area of one square kilometer and the second segment is assumed to have an area one-quarter as large or 0.25 square kilometers. The *sweep width* in the second segment will be kept constant at 50 meters. The searchers' speed is assumed to be 0.5 kilometers per hour in both segments. Three levels of available effort will be considered — 40 searcher-hours, 20 searcher-hours and 80 searcher-hours. For each level of effort, four combinations of POA values will be considered — 80% in Segment 1, 20% in Segment 2; 50% in each segment; 90% in Segment 1, 10% in Segment 2; and 20% in Segment 1, 80% in Segment 2. Finally, for each combination of POA values, three *sweep width* values for Segment 1 will be considered — 50 meters, 100 meters, and 25 meters. For each unique combination of these parameters, the overall POS will be computed and graphed based on the amount of effort expended in Segment 1, assuming the remainder is expended in Segment 2. The division of effort that produces the highest POS value will be considered "optimal" or "most efficient." *Search effort* is always computed using Equation [5-6], *coverage* is always computed using Equation [5-8] and POD is always computed using the random search formula, Equation [5-9]. POS is then computed using Equation [3-2].

6.1.2 The numerous graphs shown in the remainder of this chapter are of little or no practical use. The purpose for showing them is two-fold. First, we wish to show that Wartes' [6] assertion that, "Besides, at least in theory, there is no 'most efficient' method." is false. There are indeed most efficient methods for allocating effort provided one chooses the correct quantity to maximize (POS). In addition, the "efficiency curves" based on this parameter do have clear maximum values, or "peaks" and are not atypically flat beyond a certain point as Wartes also asserted. The second reason for so many examples is to show that simple rules about allocating effort in proportion to either POA or Pden are not always reliable.

6.2 Some Examples

6.2.1 The graphs in Figures 6-1, 6-2, 6-3, and 6-4 all show how 40 searcher-hours of effort should be divided between the two segments in various situations. To keep the problem simple, the POA, area (and hence Pden) and searcher speed for each segment are kept constant for each set of curves. The *sweep width* ("detectability") for Segment 2 is kept constant as well, but the *sweep width* for Segment 1 is allowed to take on three different values – half that of Segment 2, the same as Segment 2 and twice that of Segment 2. This approach shows what happens as the search conditions in Segment 1 vary from significantly worse to significantly better than those in Segment 2. The reason search conditions in one segment might be significantly different from those in the other segment include such things as differences in the environmental conditions (roughness of terrain, amount/density of vegetation, etc.) or differences in the sensing (detecting) capabilities of

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the assigned resources. Note that the "POS Efficiency Curves" in these and all the other graphs always converge in a point on the vertical axis at the left. This point represents the situation when no effort is put into Segment 1 and all of it is put into Segment 2. The *sweep width* and other parameters for Segment 1 are then inconsequential since no effort is being expended there. The different figures show what happens as the POAs and areas of the two segments change in relation to each other.

6.2.1.1 Figure 6-1 shows the POS efficiency curves when the POA values are 80% and 20% for Segments 1 and 2 respectively. Note that this makes the probability density (Pden) of the two segments equal. When the *sweep width* in Segment 1 is twice that in Segment 2 (100m vs. 50m), the best allocation of effort is to expend about 31 searcher hours in Segment 1 and about 9 in Segment 2. When the *sweep widths* in the two segments are equal (i.e. 50m), then exactly 32 searcher hours should be expended in Segment 1 and 8 in Segment 2. Finally, when the *sweep width* in Segment 1 is only one-half that in Segment 2 (25m vs. 50m), then about 29 searcher hours should be expended in Segment 1 and about 11 should be expended in Segment 2. In this situation, allocating effort in the same proportion as the POA values is always nearly optimal.

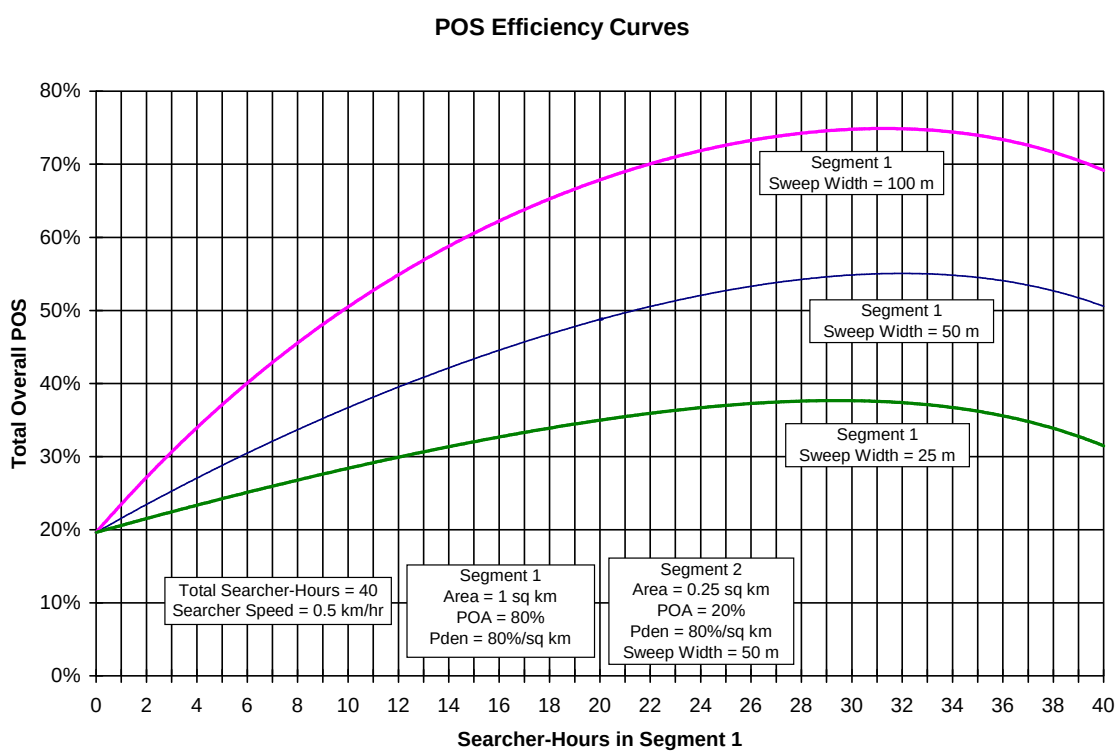

Figure 6-1

6.2.1.2 Figure 6-2 shows the POS efficiency curves when the POA values for each segment are both 50%. Note that this makes the probability density in Segment 2 four times that in Segment 1. So, Segment 2 is both smaller and more dense. When the *sweep width* in Segment 1 is twice that in Segment 2, about 22 searcher hours should be expended in Segment 1 and about 18 searcher hours should be expended in Segment 2 to maximize

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the overall POS. When the *sweep widths* in both segments are equal, then about 21 searcher hours should be expended in Segment 1 with about 19 searcher hours being expended in Segment 2. Finally when the *sweep width* in Segment 1 is only half that in Segment 2, only about 17 searcher hours should be expended in Segment 1 with about 23 searcher hours being expended in Segment 2. In this case, the distribution of effort is somewhat more sensitive to *sweep width* variations than in Figure 6-1 and there is a definite reversal in terms of where most of the effort should be placed. Even so, expending effort in proportion to POA, i.e. 20 hours in each segment, would still be nearly optimal.

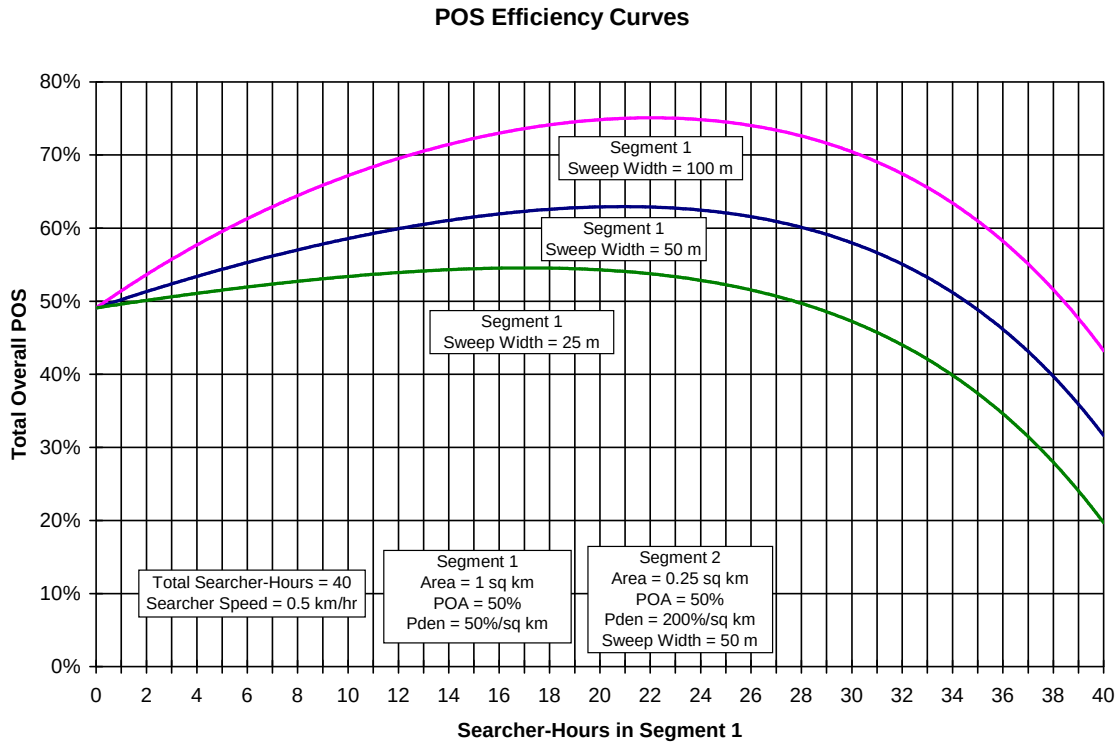

Figure 6-2

6.2.1.3 Figure 6-3 shows the POS efficiency curves when the POA values are 90% in Segment 1 and only 10% in Segment 2. Note that this makes the probability density in Segment 1 more than twice that in Segment 2. So, Segment 1 is both larger and more dense. When the *sweep width* in Segment 1 is twice that in Segment 2, about 37 searcher hours should be expended in Segment 1, with only 3 expended in Segment 2. When the *sweep widths* in the two segments are equal, then about 38.5 hours should be expended in Segment 1, about 1.5 hours in Segment 2. Finally, when the *sweep width* in Segment 1 is only one half that in Segment 2, we are back to expending about 37 hours in Segment 1 and about 3 hours in Segment 2. Again we see that expending effort in proportion to POA (36 hours in Segment 1 and 4 hours in Segment 2) would not be terribly sub-optimal. It will be interesting to see if this trend holds for other levels of total available effort.

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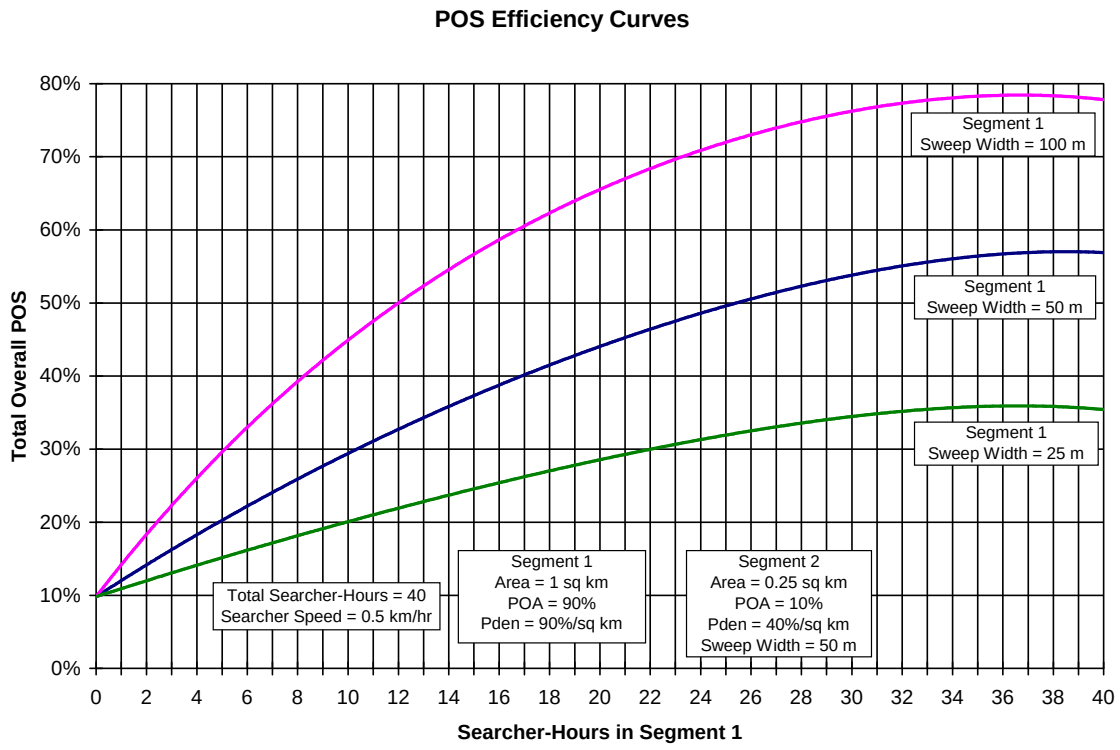

Figure 6-3

6.2.1.4 Figure 6-4 shows the POS efficiency curves when the POA values are 20% in Segment 1 and 80% in Segment 2. This means the probability density in Segment 2 is much, much higher than that in Segment 1. When the *sweep width* in Segment 1 is twice that in Segment 2, about 13 hours should be expended in Segment 1 and the remaining 27 hours expended in Segment 2. When the *sweep widths* of the two segments are equal, then about 10 hours should be expended in Segment 1 and about 30 hours expended in Segment 2. Finally, when the *sweep width* in Segment 1 is only half that in Segment 2, only about 5 hours should be expended in Segment 1 with the remaining 35 hours being expended in Segment 2. Expending effort in proportion to POA (8 hours in Segment 1, 32 hours in Segment 2) could be somewhat farther off the mark than before, but still in the optimal ball park. When substantially less effort is available, allocating effort in proportion to POA will no longer be nearly optimal, as we shall see momentarily.

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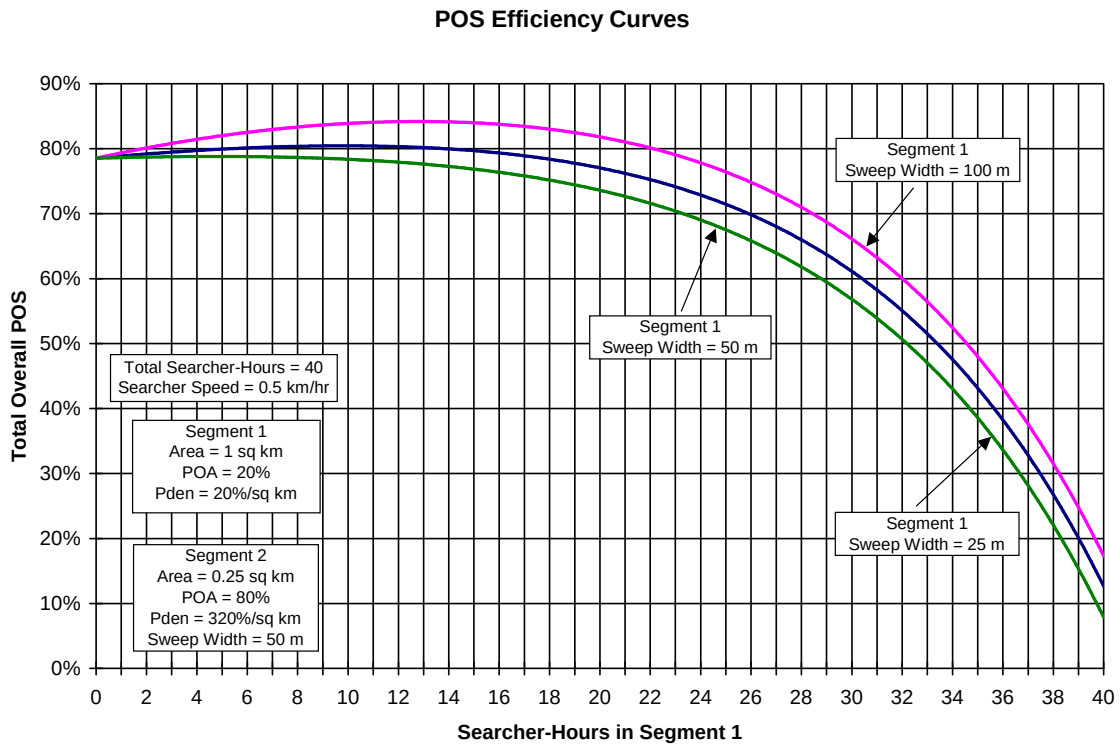

Figure 6-4

6.2.2 In Figures 6-5, 6-6, 6-7, and 6-8, the total effort available is only 20 searcher-hours. The other parameters used to compute total overall POS remain unchanged.

6.2.2.1 Figure 6-5 shows the POS efficiency curves when the POA values are 80% and 20% for Segments 1 and 2 respectively. Note that this makes the probability density of the two segments equal. When the *sweep width* in Segment 1 is twice that in Segment 2 (100m vs. 50m), the best allocation of effort is to expend about 18 searcher hours in Segment 1 and only about 2 hours in Segment 2. When the *sweep widths* in the two segments are equal (i.e. 50m), then exactly 16 searcher hours should be expended in Segment 1 and 4 hours in Segment 2. Finally, when the *sweep width* in Segment 1 is only one-half that in Segment 2 (25m vs. 50m), then about 11.5 searcher hours should be expended in Segment 1 and about 8.5 hours should be expended in Segment 2. In this situation, allocating effort in the same proportion as the POA values is optimal only when the *sweep widths* also happen to be equal.

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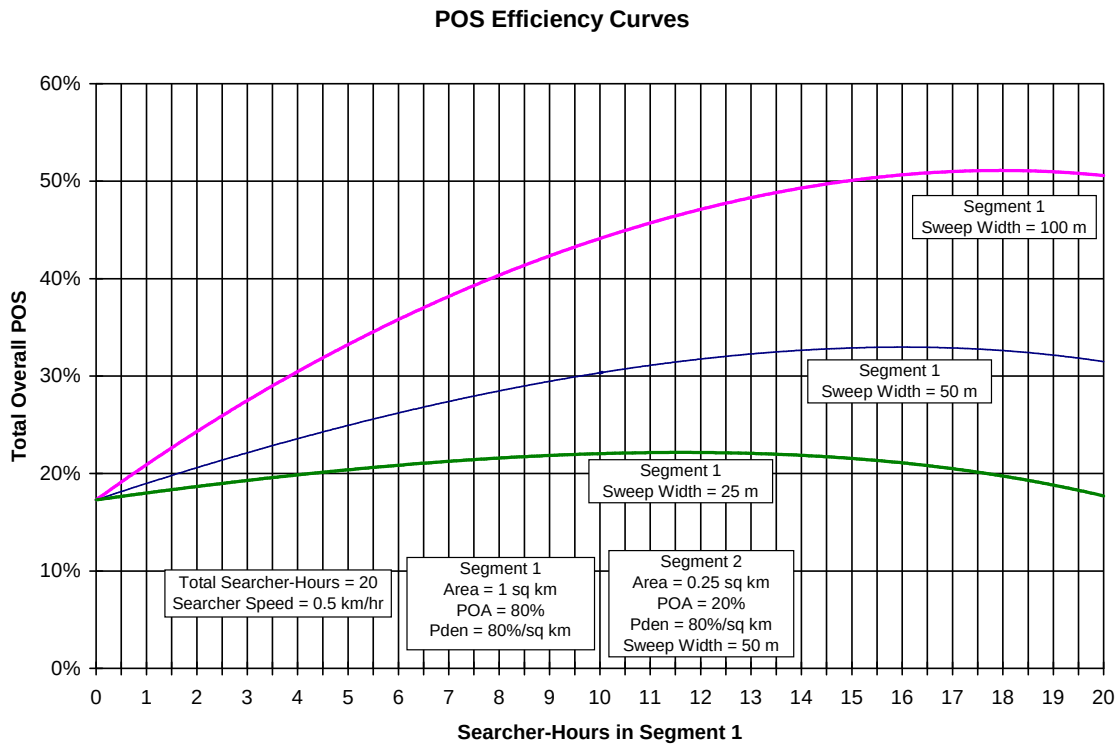

Figure 6-5

6.2.2.2 Figure 6-6 shows the POS efficiency curves when the POA values for each segment are both 50%. Note that this makes the probability density in Segment 2 four times that in Segment 1. So, Segment 2 is both smaller and more dense. When the *sweep width* in Segment 1 is twice that in Segment 2, about 8.7 hours should be expended in Segment 1 and about 11.3 hours expended in Segment 2 to maximize the overall POS. When the *sweep widths* in both segments are equal, then about 5 hours should be expended in Segment 1 with about 15 hours being expended in Segment 2. Finally when the *sweep width* in Segment 1 is only half that in Segment 2, no effort at all should be expended in Segment 1 and all of it should be expended in Segment 2. In this case, the distribution of effort is quite sensitive to *sweep width* variations. Expending effort in proportion to POA, i.e. 10 hours in each segment, would be close to optimal only when the *sweep width* in Segment 1 is large compared to that in Segment 2. Otherwise, expending effort in proportion to POA is definitely sub-optimal.

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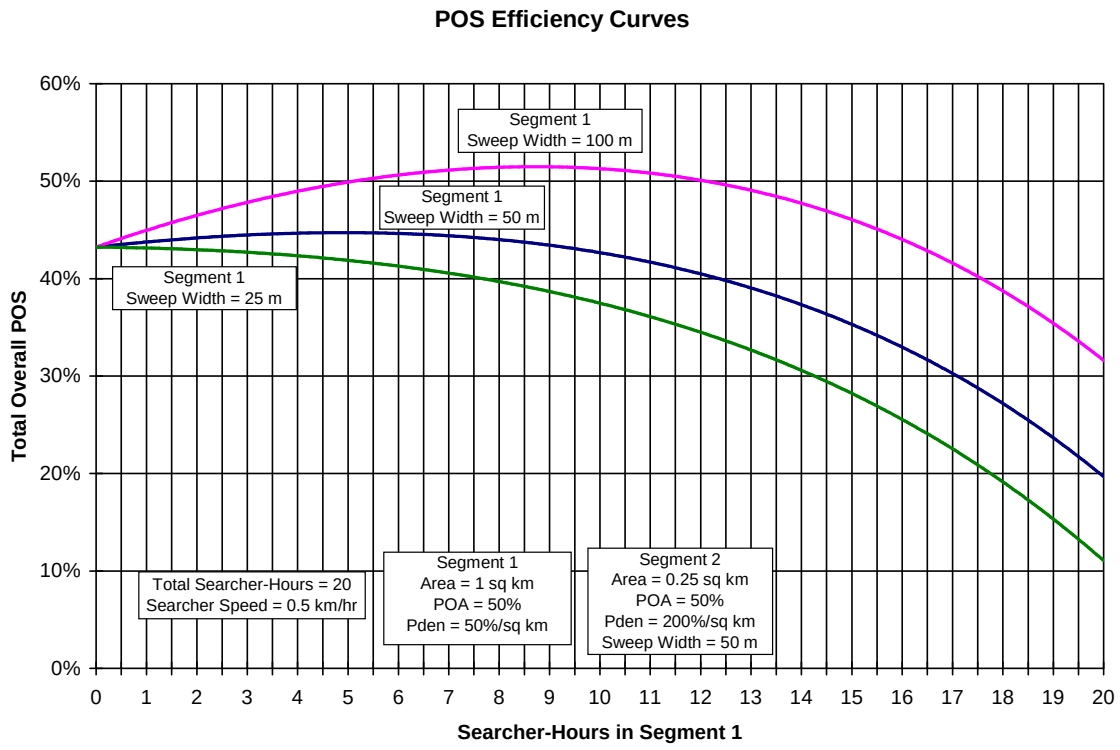

Figure 6-6

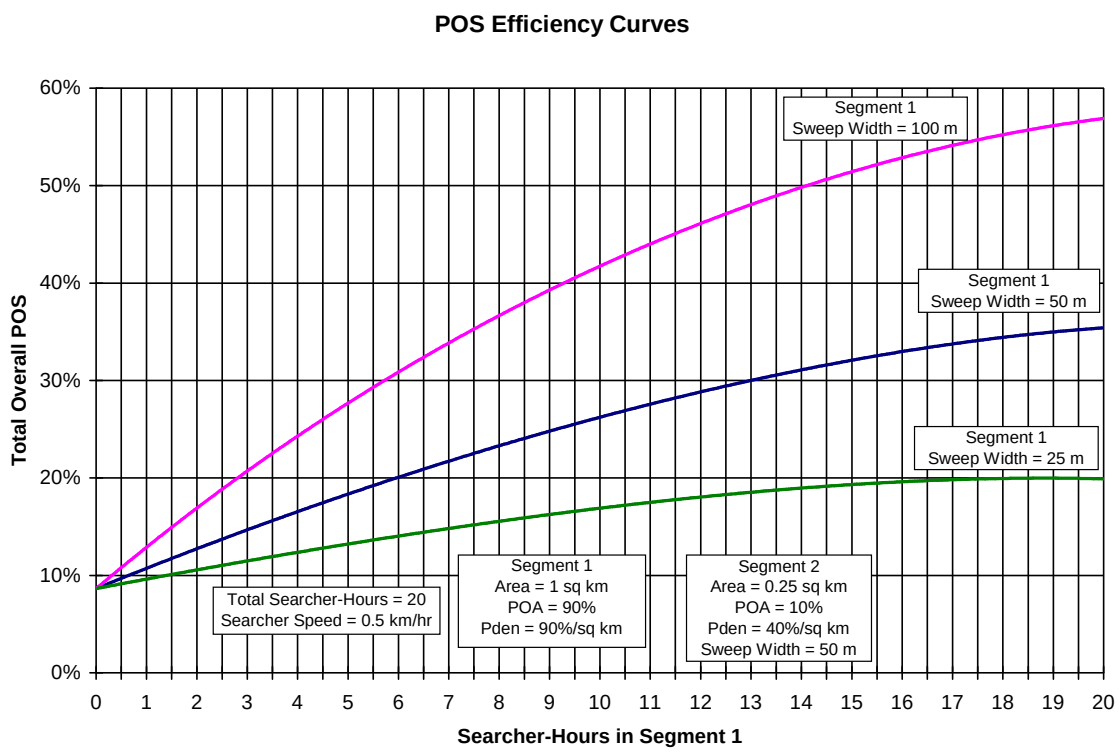

Figure 6-7

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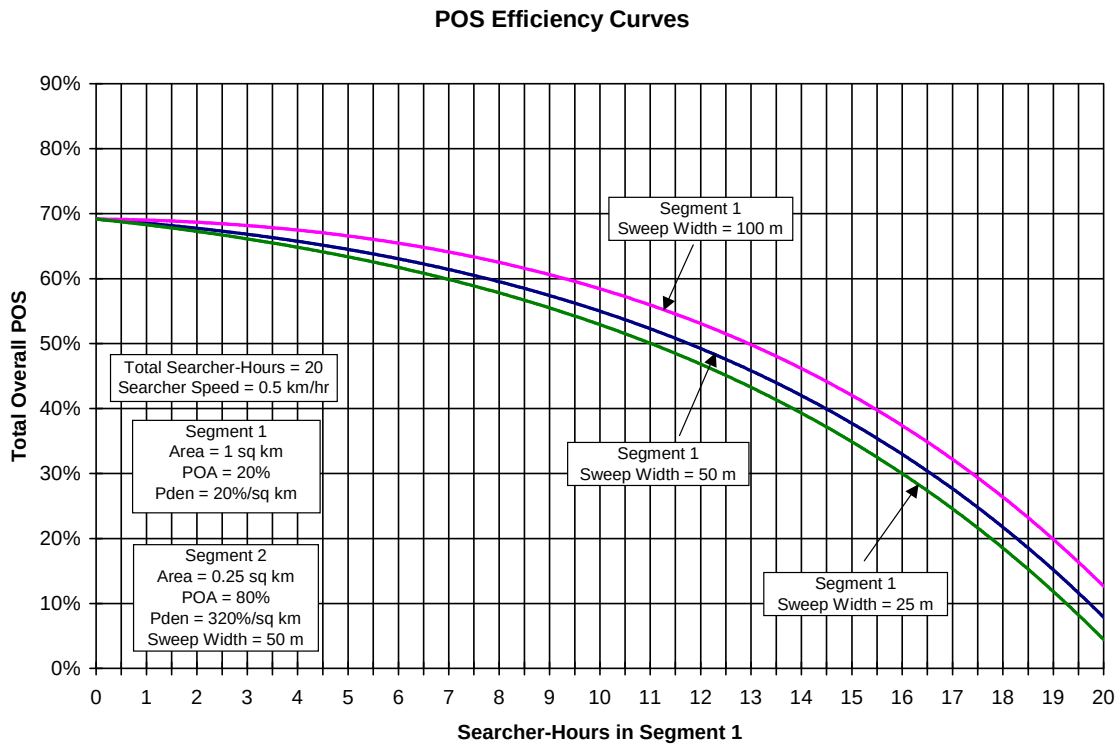

Figure 6-8

6.2.2.3 Figure 6-7 shows the POS efficiency curves when the POA values are 90% in Segment 1 and only 10% in Segment 2. Note that this makes the probability density in Segment 1 more than twice that in Segment 2. So, Segment 1 is both larger and more dense and in all three cases, all the effort should be expended in Segment 1 in order to maximize POS.

6.2.2.4 Figure 6-8 shows the POS efficiency curves when the POA values are 20% in Segment 1 and 80% in Segment 2. This means the probability density in Segment 2 is much, much (16 times) higher than that in Segment 1. Note that this time, none of the effort should be placed in Segment 1. All of it should be concentrated in Segment 2 in order to maximize POS, regardless of which of the three estimated *sweep width* values is assumed for Segment 1.

6.2.3 The graphs in Figures 6-9, 6-10, 6-11, and 6-12 all show how 80 searcher-hours of effort should be divided between the two segments in various situations. The other parameters used to compute total overall POS remain unchanged.

6.2.3.1 Figure 6-9 shows the POS efficiency curves when the POA values are 80% and 20% for Segments 1 and 2 respectively. Note that this makes the probability density of the two segments equal. When the *sweep width* in Segment 1 is twice that in Segment 2 (100m vs. 50m), the best allocation of effort is to expend about 58 searcher hours in Segment 1 and about 22 hours in Segment 2. When the *sweep widths* in the two segments are equal (i.e. 50m), then exactly 64 searcher hours should be expended in Segment 1 and 16 hours in Segment 2. Finally, when the *sweep width* in Segment 1 is only one-half that in Seg-

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ment 2 (25m vs. 50m), then about 65 searcher hours should be expended in Segment 1 and about 15 hours should be expended in Segment 2. In this situation, allocating effort in the same proportion as the POA values is always nearly optimal.

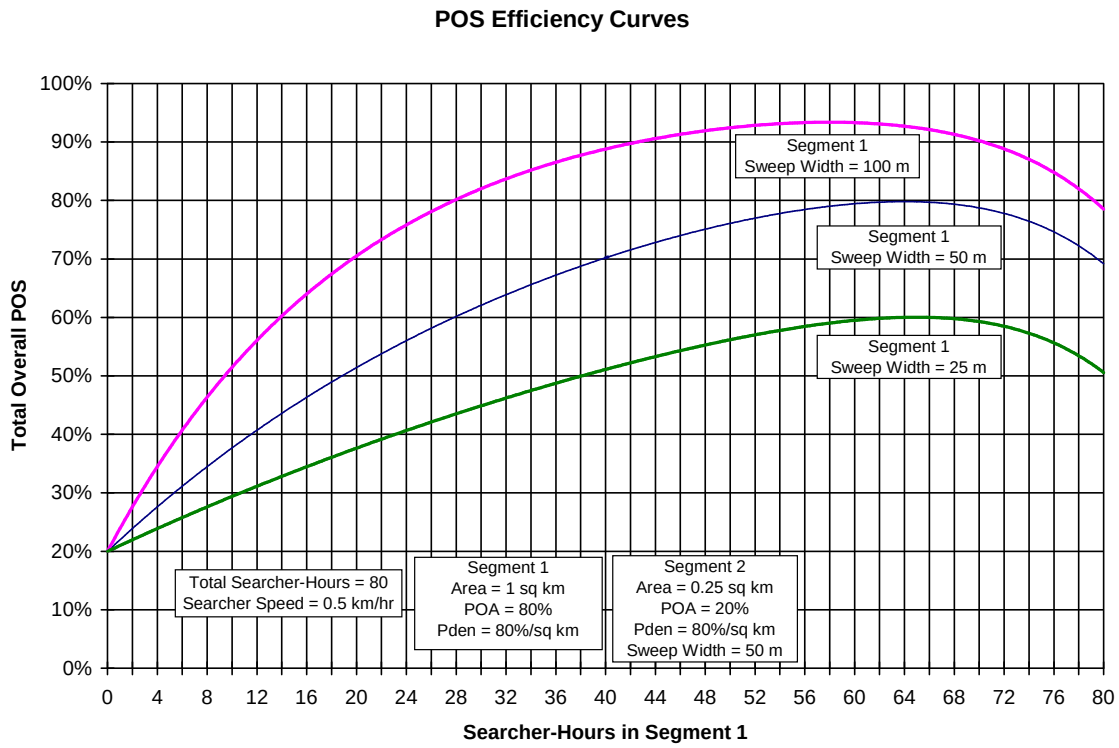

Figure 6-9

6.2.3.2 Figure 6-10 shows the POS efficiency curves when the POA values for each segment are both 50%. Note that this makes the probability density in Segment 2 four times that in Segment 1. So, Segment 2 is both smaller and more dense. When the *sweep width* in Segment 1 is twice that in Segment 2, about 49 searcher hours should be expended in Segment 1 and about 31 hours expended in Segment 2 to maximize the overall POS. When the *sweep widths* in both segments are equal, then about 53 searcher hours should be expended in Segment 1 with about 27 hours being expended in Segment 2. Finally when the *sweep width* in Segment 1 is only half that in Segment 2, about 52.5 searcher hours should be expended in Segment 1 with about 27.5 hours being expended in Segment 2. In this case, optimal the distribution of effort is not very sensitive to *sweep width* variations. However, it also is not proportional to the POA values. Expending effort in proportion to POA, i.e. 40 hours in each segment, is clearly sub-optimal.

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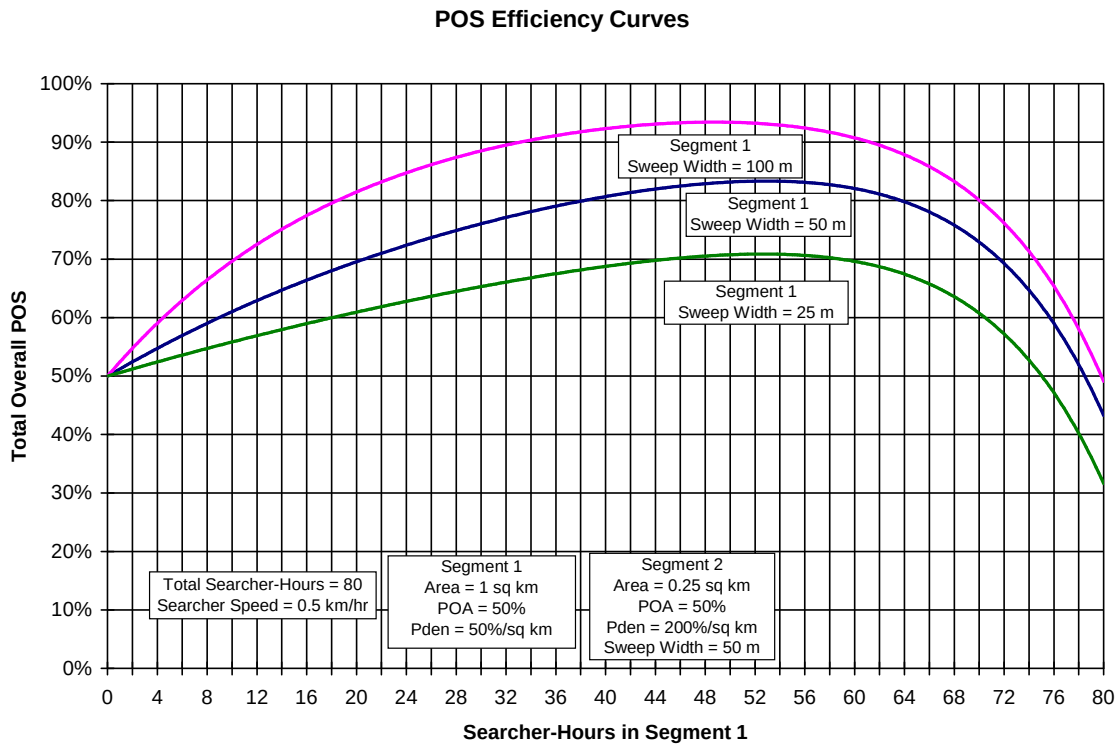

Figure 6-10

6.2.3.3 Figure 6-11 shows the POS efficiency curves when the POA values are 90% in Segment 1 and only 10% in Segment 2. Note that this makes the probability density in Segment 1 more than twice that in Segment 2. So, Segment 1 is both larger and more dense. When the *sweep width* in Segment 1 is twice that in Segment 2, about 63 searcher hours should be expended in Segment 1, only 17 hours in Segment 2. When the *sweep widths* in the two segments are equal, then about 70.5 searcher hours should be expended in Segment 1, only about 9.5 hours in Segment 2. Finally, when the *sweep width* in Segment 1 is only one half that in Segment 2, about 72 hours should be expended in Segment 1 and only about 8 hours in Segment 2. We see that expending effort in proportion to POA (72 hours in Segment 1 and 8 hours in Segment 2) would be nearly optimal in the latter two cases and not terribly sub-optimal in the first case.

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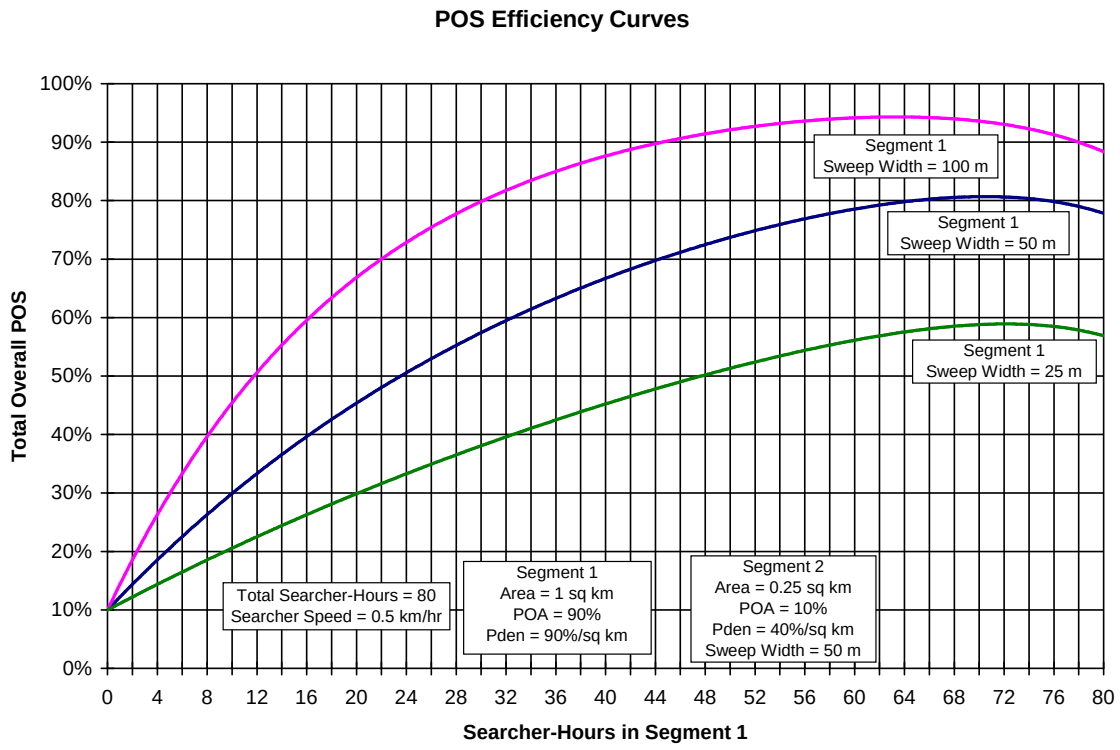

Figure 6-11

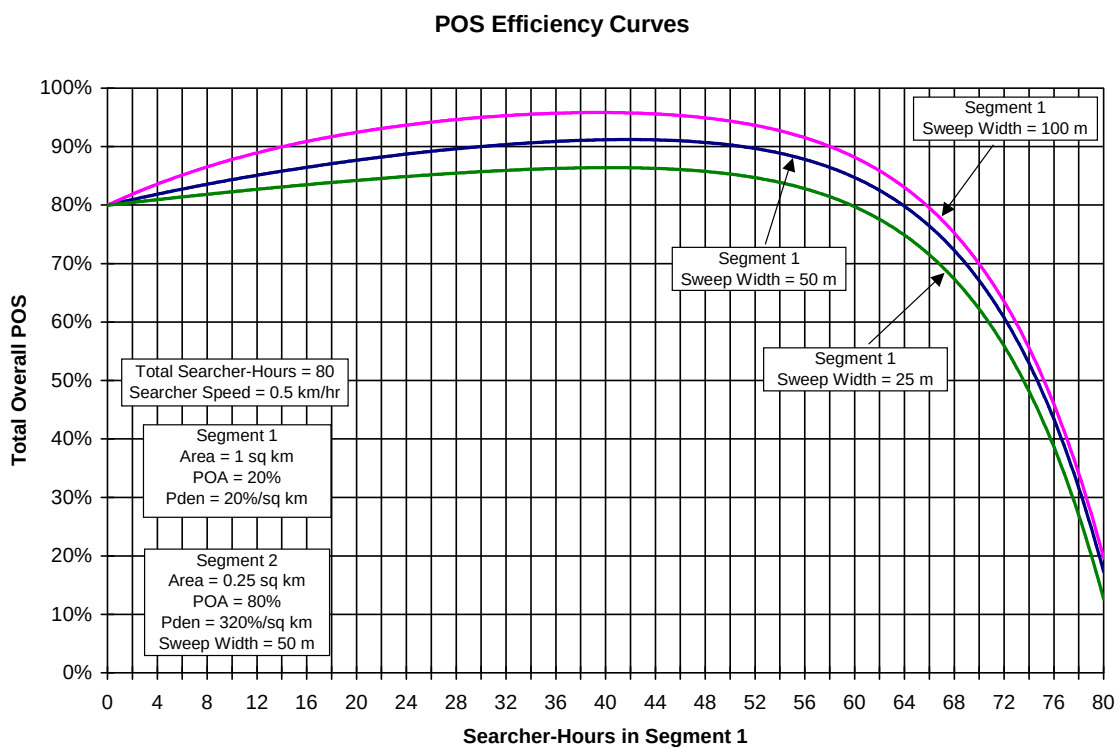

Figure 6-12

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6.2.3.4 Figure 6-12 shows the POS efficiency curves when the POA values are 20% in Segment 1 and 80% in Segment 2. This means the probability density in Segment 2 is much, much (16 times) higher than that in Segment 1. When the *sweep width* in Segment 1 is twice that in Segment 2, about 40 searcher hours should be expended in each segment. When the *sweep widths* of the two segments are equal, then about 42 searcher hours should be expended in Segment 1 and about 38 hours expended in Segment 2. Finally, when the *sweep width* in Segment 1 is only half that in Segment 2, we are back to expending about 40 hours in each segment. In this case, the effort should be about equally divided between the segments for all three *sweep width* situations. Expending effort in proportion to POA clearly does not work for these POA and *sweep width* values.

6.2.4 All of the above graphs and accompanying discussion show that valid "efficiency" curves do exist and do have typical forms – provided the "efficiency" variable is POS and not POD. Wartes and Colwell simply chose an inappropriate variable to use as a measure of "efficiency." As discussed in paragraph 5.7.6 above, Wartes did come very close to a correct statement of the optimal effort allocation problem (at least for uniform distributions) in [16]. In [16], Wartes posed the following problem: If there is sufficient manpower to search the entire area known to contain the search object one time in 30 hours at a spacing of 10 feet, and the search object is equally likely to be anywhere in the area (uniform probability density distribution), then how should the effort be allocated so as to maximize the chances of finding the object in the minimum amount of time? Wartes offered an assumed POD table based on experimental values from his experiments described in [6]. As we have already noted, these values are likely to contain significant experimental error.

6.2.4.1 Instead of using these questionable values, it was assumed that the *effective sweep width* for this hypothetical search was 30 feet and that the detection function was that of the so-called random search. A comparison of the PODs is shown in Table 6-1 below.

Spacing	Wartes' Experimental POD	Coverage	"Random Search" POD
10 feet	95%	3.00	95.02%
20 feet	92%	1.50	77.69%
30 feet	--	1.00	63.21%
60 feet	71%	0.50	39.35%
100 feet	53%	0.30	25.92%
120 feet	--	0.25	22.12%

Table 6-1

6.2.4.2 Using the POD values in the last column so as to avoid drawing any incorrect conclusions that might be solely based on experimental error in the data, Wartes' analysis was repeated as follows. The POS at the end of each 0.1 hours (6 minutes) of searching was computed for each of the following tactics:

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1. Search the entire area one time with a single line abreast formation of searchers spaced at 10-foot intervals (coverage = 3).

2. Divide the search area into two "segments" and search each one twice with searchers spaced 20 feet apart (coverage = 1.5 per search).

3. Divide the search area into three "segments" and search each one three times with searchers spaced 30 feet apart (coverage = 1.0 per search)

4. Divide the search area into six "segments" and search each one six times with searchers spaced 60 feet apart (coverage = 0.5 per search).

5. Divide the search area into twelve "segments" and search each one twelve times with searchers spaced 120 feet apart (coverage = 0.25 per search)

The results are graphed in Figure 6-13 below. Despite the differences in the POD values shown in Table 6-1 and the certain presence of significant experimental error in Wartes'[16] POD values, he nevertheless developed a graph strikingly similar to Figure 6-13.

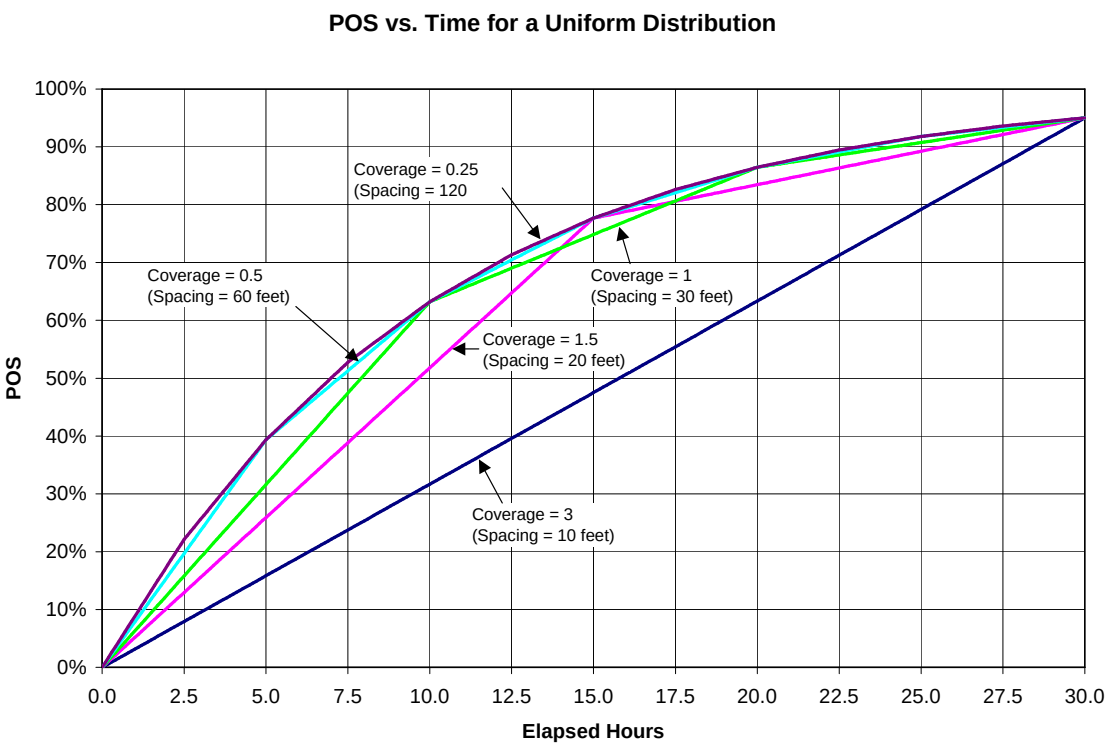

Figure 6-13

Figure 6-13 shows that formal search theory does support Wartes'[16] thesis that "non-thorough" search methods can be beneficial when the objective is to maximize the chances for finding the subject quickly. However, also note that it does **not** support his conclusion that after all the effort has been expended, the final cumulative POD of "non-

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thorough" methods will exceed that of "thorough" methods. Note that in all cases in Figure 6-13, at the end of 30 hours all produce a POS (and POD) of 95%. In fact, the very term "non-thorough" as used by Wartes in this context is called into question. One must ask whether searching the same area ("segment") six times at a coverage of 0.5 is really any less "thorough" than searching it once at a coverage of 3.0. Both methods are equally "thorough" in the end. What Wartes' example shows is that by spreading the effort more uniformly over the area initially, rather than concentrating it in one end, the chances of finding the subject sooner can be significantly enhanced.

Note: For detection functions above the so-called "random search" curve (e.g., the one based on Koopman's inverse cube model in Figure 5-7 or the one based on the rectangular detection model in Figure 5-11), it can be shown that repeated "non-thorough" (low coverage) searches produce ***lower*** cumulative POD values than a single "thorough" (high coverage) search using the same total amount of effort. This does not change the fact that initially distributing the search resources uniformly over a uniform distribution will result in a more rapid increase in POS in the early stages of a search. However, it does show that multiple "non-thorough" (low coverage) searches of an area can never produce cumulative POD values that are greater than the POD obtained from applying the same resources to the area in a single "thorough" (high coverage) search.

6.2.4.3 Although one of Wartes' conclusions was basically correct, there are some significant limitations to its applicability. From Figure 6-13 it is clear that decreasing coverage below about 0.5 produces little benefit. The curves for coverages of 0.5 and 0.25 are almost identical. There are also other practical limitations. An important hidden assumption is that the searchers "cover" their assigned areas uniformly on every search. This is unlikely since objects near the searchers' actual tracks are more likely to be detected than objects midway between the searchers' tracks – and the more widely separated the tracks the more true this becomes. This lack of uniformity can be partially overcome over the course of multiple searches by using accurate navigation techniques. By offsetting the assigned searcher tracks of successive searches to ensure searchers do not retrace their own steps or those of another searcher, the "peaks" and "valleys" of coverage (like furrows in a freshly plowed field) can be smoothed considerably. This will make the POD more nearly the same everywhere in the searched area. However, searching any area multiple times at a low coverage and achieving a truly uniform distribution of searching over the area can be a very difficult proposition in practice. Another limitation is the assumption of uniform probability density everywhere. This is an unlikely situation in practice. However, Wartes [16] does not attempt to show how the POS vs. Time curve can be made to rise as quickly as possible in situations where probability density, *sweep width*, and searcher speed all vary from place to place in the search area. This is just as well, because that complex problem had already been addressed in formal search theory some 17 years earlier.

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6.3 Outline of a Method for Optimally Allocating Effort

Stone [4] shows a method adapted from the Charnes-Cooper [17] algorithm developed in 1958 that may be used for optimally allocating effort among segments having different areas, POAs, *sweep widths* and searcher speeds. We will look at this method in a ground search context and find that we have seen something like it before.

6.3.1 As Stone [4] points out, and as the data used to construct the figures in this chapter confirm, the optimal allocation of effort is that which makes the product of *sweep width* and adjusted probability density (computed from the adjusted POAs) as nearly the same as possible in all segments when the search speed is the same in all segments. The correct criterion for allocating effort is to maximize the product of *sweep width* (*W*), *probability density* (*Pden*) and *search speed* (*V*). This product is called the *probable success rate* (*PSR*). *PSR* represents the rate of increase in POS per unit of elapsed time, i.e., it is the slope of the POS vs. Time curve. *PSR* is the correct criterion for maximizing the chances for finding the search object in the minimum amount of time with the available resources. This means that, on paper, the first order of business should be put enough effort into the segment with the highest estimated or predicted *PSR* so that by the end of a sortie its *PSR* will be reduced to the level of the segment having the next highest *PSR*. Next, the goal would be to place enough additional effort into each of those two segments (that now have equal *PSR* values) so that their *PSR* values are reduced to the level of the third highest *PSR*, etc. until all the available effort is used up. If one keeps track of how much total effort is assigned to each segment while performing this exercise on paper, then one will have the amount of effort that should be assigned to each segment in the actual operation in order to obtain the highest possible *POS* in the shortest possible elapsed time with the available resources.

6.3.2 It should be pointed out that when the *PSR* values are the same in two or more segments, those segments should be searched with the same *coverage*. Recall that *coverage* is a function of searcher-hours, search speed, *sweep width* (that together comprise *search effort* or *area effectively swept*) and the size of the segment. Therefore, the amount of effort in searcher-hours required for the same *coverage* in segments having equal *PSR* values will vary.

6.3.3 The process outlined in paragraph 6.1.1 above is strongly reminiscent of *Search Priority* [15]. The problem in [15] was the difficulty in establishing the correct criterion for ranking the segments. We now have the correct criterion – *probable success rate* (*PSR*). Segments should be ranked according to the values of their *PSR* values. Effort should then be allocated to the segments having the highest *PSR* values first, as described above, so that at the end of the first operational period all of the searched segments have the same adjusted *PSR* value, and one that is no less than the highest *PSR* value from the unsearched segments. At least that's the goal. In practice, operational exigencies may require slight departures from the ideal case.

6.3.4 Using *PSR* as a criterion for ranking segments also makes intuitive sense. *Sweep width* measures the ease or difficulty of detecting the object. *Probability density* measures the concentration or sparseness of the object's likelihood of being at one place or another.

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Search speed measures the rate at which searchers can move through an area and still be reasonably effective. (Note: The searcher's rate of movement over the ground can affect *sweep width*. Consider how detectable a search object in a wooded area with significant underbrush and deadfalls would be to a running searcher as compared to a walking searcher.) Where all three are at a maximum, we would say the object is easy to detect, there is a large likelihood that it is in a small area, and searchers can move through the area quickly and effectively. Certainly this is a good place to put effort and such a segment would, and should, be at or near the top of the priority list. Alternatively, if both *sweep width* and search speed are small (frequently these two parameters are correlated in this way for ground searchers), and the probability density is also small, then the object is difficult to detect, the likelihood of it being at one location or another is spread out over a wide area, and the searchers have to move at a slow pace. This would not be a good place to put effort until most other possibilities have been exhausted. So, the segment with minimum *sweep width*, search speed, and probability density values rightly belongs at the bottom of the priority list. All the various possibilities in between should likewise be ranked in relation to one another by the sizes of their respective *PSR* values.

6.4 Conclusions

6.4.1 Dividing the available effort among the segments in proportion to either their POA or Pden values alone is not a reliable way to allocate effort optimally or even nearly so.

6.4.2 The relative ease or difficulty of detecting the search object, as measured by *sweep widths* for the various combinations of segments and resources, the distribution of probability density among the segments, and the rates at which searchers can effectively move through the segments taken together (as *PSR*) provide reliable guidance for determining how the available resources should be allocated among the segments.

6.4.3 Although *PSR* provides reliable guidance, the method for employing it properly to allocate effort is computationally intensive and should be done by a computer programmed for the purpose. Nevertheless, search managers without a computer should at least give qualitative consideration to the *PSR* parameters (the combined effects of differences in "detectability," probability density, and searcher speed among the segments) when making effort allocation decisions.

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Chapter 7
Conclusions and Recommendations

7.1 The Need for Further Research

We have seen in the course of this investigation that a number of researchers in the ground SAR community have recognized that their methods of search management need to be improved. A great deal of effort has already been expended in attempts to develop such improvements. However, it is clear at this point that those efforts have not been nearly as successful as they could have been. Although the term "search theory" is used throughout much of the ground SAR literature, many of the methods and assertions made in the name of "search theory" do not agree with the formal scientific discipline of search theory that may be found in academic texts and articles published in established scientific journals. In fact, a number of the methods and assertions made in the ground SAR literature are provably incorrect. The primary reason for this state of affairs is that the academic search theory literature was effectively unavailable to the ground SAR community since its existence was not widely known. Even when its existence is known, finding the material is very difficult, and understanding the scientific and mathematical jargon in which the theory of search is described is even more difficult. The way out of this dilemma is to secure the best available talent mix of academia, practitioners, and at least one translator/facilitator to interface between the two groups, and engage them in a deliberate, well-organized applied research effort. The goal of this effort would be a practical, comprehensive search planning/management methodology for inland SAR.

7.2 Directions for Future Ground SAR Search Management Research

Given that a number of individuals have already invested a great deal of time and effort in researching ground search management without yet fully re-creating the careful analyses done by Koopman, Stone, et. al., and given that resources for research (time, people with the requisite skills and experience, and money) are in short supply, we would do well to give some careful thought as to where future research efforts in this area should be aimed.

7.2.1 Develop an Improved, Comprehensive, Inland Search Management Methodology. The U. S. Coast Guard, probably by the luck of being closely associated with the U. S. Navy and sharing its operating environment as well as being ***the*** single federal agency charged with maritime SAR, has a search planning/management methodology based on the fundamental scientific principles of search theory and has had the resources to develop practical methods from them to meet maritime SAR needs. Because its methods do have a recognized scientific foundation, and because for many years the Coast Guard was, and probably still is, regarded as the world's leading maritime SAR organization, its methods are used by virtually all maritime SAR organizations around the world.

7.2.1.1 The inland SAR community has not had the Coast Guard's good fortune. As we have seen, ground search management guidance seems nearly as fragmented as the ground search community is localized and contains a number of provably incorrect assertions

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and assumptions. So, the first order of business should be to develop an improved and comprehensive inland search management methodology based on the work of Koopman and more recent researchers such as Stone, and adapt their work to meet the special needs of the inland SAR community.

7.2.1.2 Inland search managers should not be forced to expend their very limited resources re-inventing the search theory wheel. As should be clear from this paper, inland SAR researchers will probably eventually re-create the conclusions of formal search theory if given enough time. However, it makes no sense to expend scarce resources or delay using known search theory principles while waiting for this to happen. The resources and time can be much more productively spent determining the best way to apply known search theory principles to inland search management needs. Even though the "behind the scenes" research still needed to turn theory into practice may be complex and highly mathematical, there is every reason to believe the end product of this research will be a reasonably simple, practical, comprehensive methodology that will greatly improve the inland search managers' ability to make the most effective, efficient possible use of the available resources for the search problem at hand.

7.2.2 Develop Inland *Sweep Widths*. Since the *sweep width* concept is apparently new to the inland SAR community, *sweep width* values, as such, don't appear to have ever been tabulated. Based on the Coast Guard's experience, developing and tabulating *sweep width* values should be at least a two-stage process.

7.2.2.1 The first order of business should be identification of those parameters that significantly affect detection in the inland environment. Some of these will almost certainly be the same or similar to some of those encountered in the maritime environment. However, it is likely that an equal or greater number will be unique to the inland situation. Identifying interdependencies among the various significant parameters is also an important part of this initial stage. In the maritime environment, for example, both sea state (wave height) and the number of whitecaps per unit of area affect the searcher's ability to detect small boats, rafts, etc. on the ocean's surface. Both also depend strongly on the surface wind speed at the scene. Therefore, it is possible to have a single *sweep width* correction factor based on wind speed that accounts for the effects both sea state and whitecaps have on visual detection. There may be similar opportunities in the inland environment for reducing the number of parameters search planners/managers need to consider.

7.2.2.2 The second stage of the *sweep width* experiment process should quantify and tabulate *sweep widths* for various combinations of values for the significant factors. Depending on the number of significant factors identified in the first stage, decisions will need to be made on the most operationally efficient way to represent and use these *sweep width* values. In the maritime environment, for example, *sweep width* values are tabulated directly for various combinations of search platform type (e.g. helicopter), altitude, type/size of search object (e.g. 8-person raft), and meteorological visibility. These are termed "uncorrected" *sweep widths*. Correction factors are provided for wind speeds, based on the approximate size of the search object, and another correction factor is provided for search crew fatigue. A third set of correction factors is provided for aircraft speeds, based on

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the approximate size of the search object and aircraft type (fixed wing or helicopter). (Search speed was not found to be a significant factor for surface vessels.) A similar approach would probably work for the inland environment as well, although researchers should be open to other possibilities that may suggest themselves during the course of the experiments.

7.2.2.3 A third stage of the inland *sweep width* experiment process should be to investigate the feasibility of on-scene *sweep width* estimation procedures. Unlike the maritime community, inland searchers, especially those on the ground, have an opportunity to directly measure the detectability of objects similar to the search object in the environment where the search is to take place. For example, procedures are already available for estimating average maximum detection ranges using a short field experiment conducted at the scene. Maritime searchers get this opportunity only when search objects similar to the one they are looking for happen to be in their assigned search sub-areas. However, average maximum detection range and *sweep width* are not the same thing. Although they are clearly related, that relationship is a complex one that varies with the sensor, search object and environment. *Sweep widths* must be inferred from measurements and estimates of the significant factors and interpolation or extrapolation using data tabulated from controlled experiments conducted under similar conditions for similar search objects. While it is unlikely anyone can invent a "*sweep width* meter," it seems reasonably likely that valid procedures for more accurately estimating *sweep widths* at the scene based on some direct detectability observations can be developed. If so, this could substantially reduce the number and extent of the *sweep width* experiments that might otherwise be needed.

7.2.2.4 An opportunity that should not be overlooked is the possibility of extracting *sweep width* estimates from experimental data already collected. In this regard, it may be possible to obtain some *sweep width* estimates from experiments already done, such as the work of Wartes and Colwell, even though those experiments were not designed to produce *sweep width* data. Obtaining *sweep widths* from the results of these already completed experiments would require re-analysis of both the conduct of the experiments and the raw data they collected.

7.2.3 <u>Some Lessons Learned</u>. The Coast Guard's many years of experience with *sweep width* experiments have produced a number of "lessons learned" in addition to providing *sweep width* values for their operating environment.

7.2.3.1 The first lesson is that *sweep width* experiments must be carefully designed, controlled, and conducted by persons with expertise in the design of experiments. There is a mighty temptation to try and save time and money by doing one or a very few grand experiments that involve every possible significant variable. These invariably fail under the weight of their own complexity, wasting time and money rather than saving it. Another mighty money-saving temptation is to use anecdotal data from either actual search operations or "situations of opportunity." The Coast Guard's earliest attempts to develop *sweep width* data used this technique. Later analysis and controlled experiments indicated the data gathered in this fashion tended to significantly overestimate *sweep width* values, more nearly resembling twice the maximum detection range rather than valid *sweep widths*.

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7.2.3.2 Data analysis likewise needs to be done carefully and by qualified individuals who are not only skilled in data analysis techniques, but who are also familiar to at least some minimum extent with the actual physical act of searching so they can recognize anomalies that may appear in either the raw or analyzed data.

7.2.3.3 Finally, the stated goal, or "deliverable" of the experimental process as a whole must be a set of operationally valid *sweep widths* with operationally usable methods for employing them correctly in search planning/management. Simply documenting the experimental results in scientific jargon should be considered insufficient and unacceptable. The whole purpose of these experiments should be to produce data and methods that search planners/managers in the field may productively employ to save more lives.

7.2.4 Obtain Federal Involvement and Commitment. It is abundantly clear that much of the inland search management community recognizes the need for improving its search management practices. Unfortunately, the inland SAR community is necessarily fragmented by the very nature of inland SAR. They are neither organized, trained, equipped, nor funded to take on the tasks outlined above. It is, however, a matter of national interest that the various local SAR organizations, whether paid or volunteer, be able to perform as well as possible to save the lives of our citizens who may find themselves in distress. Therefore, the federal government should be willing to provide the necessary focus and invest the comparatively modest sums required to substantially improve inland search management based on current technology, known scientific principles, recent developments, and the wealth of operational experience now available.

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