Maximizing the Effectiveness of Search Effort in Land Search and Rescue: a Bayesian Priority Rating Approach

W. H. Finlay, PhD
Edmonton Regional Search and Rescue Association
Edmonton, Alberta, Canada
Email: warren.finlay@ualberta.ca

https://doi.org/10.61618/PEXK9532

Abstract

Land search and rescue (LSAR) operations often require decisions to be made between competing search strategies. Basing such decisions solely on the probability of success does not allow consideration of differences in search effort (i.e. searcher hours expended) between competing strategies. In the present work, we rely on existing optimal sequential Bayesian theory to reemphasize the utility of using a measure that considers both probability of success and effort, which we refer to as a priority rating (PR). When choosing between two competing search strategies, the more optimal strategy has a higher PR. For a search strategy employing searchers with given sweep width and travel speed in a search segment with probability density pden, PR is known to be given by PR=pden*sweep width*speed. PR values are compared for competing search strategies in a variety of scenarios, demonstrating the utility of this approach when it is used with recent developments in the literature. For example, it is found that searching by sound for a lost person in further out areas is more optimal than visual searching closer in, but this is only true out to a certain radius from the initial planning point; and dense vegetation areas have dramatically lower priority ratings, effectively concentrating search effort in them unless countermeasures are taken. The present demonstration of the use of the Bayesian priority rating approach may be helpful for search managers wanting to prioritize search efforts more effectively, including choosing the sequence to search different search segments and which search tactics are more optimal in each of these areas.

KEY WORDS: search theory, optimal, Bayesian, sequential, strategy

Introduction

Land search and rescue (LSAR) involves the use of teams of trained search and rescue (SAR) personnel, who are often volunteers, tasked either with finding a lost person, or finding evidence to support a forensic or criminal investigation on land. The large variability that is present in lost person behavior and the search environment, along with variability in the number and skills of SAR teams responding to a callout, combined with unknown values for some of the factors that determine the probability of success in a search, mean that it is not possible *a priori* to devise a single optimal strategy to conduct a given LSAR operation in the real world.

Despite this, concepts from search theory originating from operations research applied to marine searches have been adapted to develop more effective LSAR strategies (Cooper et al. 2003). Much of this work focuses on maximizing the probability of success (POS) by concentrating search efforts in areas with a higher estimated probability of containing the subject. These probabilities are typically based on statistical analyses of past searches (Koester 2008), expert judgment, or a combination of both (Stoffel 2017; Mansfield et al. 2020).

Because LSAR operations are often carried out by volunteers using personal equipment, ways to minimize labor and operating costs in LSAR are often given less importance than in marine or aerial SAR, where such expenses are considerable. This may partly explain the relatively low uptake of objective methods in LSAR for jointly maximizing POS and minimizing costs. In practice, LSAR teams that apply modern search theory tend to focus primarily on maximizing POS, without explicitly minimizing search effort in a quantitative way.

The present work highlights a simple method, based on optimal sequential Bayesian search theory, to help LSAR managers balance both objectives—maximizing POS while minimizing search effort. Here we use the term Bayesian to refer to the reliance on Bayes' theorem to derive optimal sequencing order, and to revise segmental POS values if the segment has already been searched. The essentials of this approach have long been known in the search literature (see e.g. Cooper et al. 2003), but its use is often neglected in LSAR operations. In addition, recent developments in the literature allow us here to consider its application to new comparisons, such as sound versus visual sweeps. Here, the basic search theory underpinning the approach is reiterated. We then apply it to a number of examples. that include recent developments in sound sweep methods, to choose the more optimal search strategy among competing strategies. Specific examples will be considered to illustrate how to use this approach to answer the following search strategy questions (note that the resulting recommendations in each example are not generally applicable, but are specific to the values used in each example):

- How far out from the initial planning point should sound sweeps be prioritized over visual sweeps?
- Should densely and sparsely vegetated areas be searched with equal coverage, despite the slow coverage rates in dense vegetation?
- Should off trail sound sweeps parallel to but further from trails be prioritized over visual sweeps close to trails?
- Where should drones versus visual ground search teams be sent?

Background

When conducting a land search, a number of operational search areas (called 'segments' or 'sectors' or 'regions') are usually defined. SAR personnel are then divided into strike teams, and each strike team is assigned to search a given segment. Since there are typically more segments than strike teams, a central aspect of search management involves deciding the order in which segments should be searched as time proceeds. For this purpose, the probability that the item or lost person is in a given area, commonly abbreviated as POA, is often used to assign strike teams to segments with higher POA. Values of POA are typically best defined using areas, called probability areas, that are chosen specifically for this purpose and are often different from the operational segment areas that strike teams are assigned to search (Cooper et al. 2003).

A common approach to estimating POA for an operational segment area is to multiply the segment area by the probability density, commonly abbreviated as pden, at that location. For lost persons, the value of pden can be estimated using historical data for a given subject category. For example, 25% of 568 hikers lost in temperate mountainous terrain were found within r_{25}=1100 meters of the initial planning point (IPP) (Koester 2008). Thus, an approximate estimate for pden for any operational segment area lying within a radius of r_{25} of the IPP can be estimated by dividing 25% by the area of this circle i.e.

$$pden_{25} = \frac{0.25}{\pi r_{25}^2} \quad (1)$$

Similarly, pden for the annulus lying between radii r_{25} and r_{50} where 25% and 50% of lost persons of a particular subject category have historically been found, respectively, is given by

$$pden_{25-50} = \frac{0.25}{\pi\left(r_{50}^2 - r_{25}^2\right)} \quad (2)$$

A similar approach to eqn. (2) can be used to find pden for the annulus between the 50th and 75th percentile, or the 75th and 95th percentile distances from the IPP.

As noted earlier, for an operational segment area that has area A lying entirely within one of these probability areas, the value of POA for this segment can be estimated as

$$POA = \ pden \times A \qquad (3)$$

For operational segment areas that overlap multiple probability areas, a weighted POA can be estimated by having the portion of a segment area lying withing a given probability area inherit pden from that probability area. The reader is referred to e.g. Mansfield et al. (2020) for further explanation of estimating segmental POA values[1].

With POA values in hand for each operational segment area i, the probability of success (POS) of finding the subject in segment area i is then

$$POS_i = POA_i \times POD_i \qquad (4)$$

where POD_i is the probability of detection i.e. the probability that the strike team assigned to search operational segment i would find the subject if the subject was in that segment. POD_i is determined by the coverage c_i achieved by the assigned strike team when they search segment i of area A_i, and is given by

$$c_i = \frac{sweep\ width \times total\ track\ length}{A_i} \qquad (5)$$

In eqn. (5), sweep width is proportional to the strike team individual member's average detection range (Koester et al. 2014) and total track length is the total linear distance travelled by the strike team while actively searching that segment, obtained by adding up the distance travelled by each strike team member. For simplicity, let us assume each strike team member operates as an identical idealized definite range detector, in which case

$$POD_i = c_i (6)$$

In reality, POD_i is a monotonically increasing nonlinear function of c_i (Cooper et al. 2003), but eqn. (6) suffices for our purposes here.

Using the above information, when search segments outnumber strike teams, a typical approach to assigning segments to strike teams would be to proceed in order of decreasing probability of success, POS_i. In other words, allocate strike teams first to those segments with the highest POS_i. When a strike team completes a given search segment, using Bayesian analysis arguments (Cooper et al. 2003), then POS_i should be multiplied by $(1-POD_i)$ to give a revised cumulative nonnormalized POS_i for that segment.

---

[1] Probability density when including two effects requires careful handling e.g. consider a wedge-shaped 25th percentile sector, labelled area 1, associated with dispersion angle, so $POA_1=0.25$; and the 50th – 75th percentile annulus associated with 25th – 50th percentile distance from the IPP, labeled area 2, also with $POA_2=0.25$; pden for the intersection of these two areas is then $\frac{POA_1 POA_2}{A_{12}}$ where A_{12} is the area of the partial annulus that is the intersection of the two areas. Thus, we see here that POA for the overlapping area is multiplicative not additive.

That strike team should then be assigned to search the segment with the highest cumulative nonnormalized POS_i.

As an aid to the reader, the table below presents a brief summary of the above notations and abbreviations as applied in the present manuscript. The reader is referred to Koester et al. (2004) for further explanation of these terms.

Symbol, abbreviation or notation	**Meaning**	**Definition**
POA	Probability of area	The probability that the lost person is within the given area
POD	Probability of detection	The probability that the lost person would be detected assuming they are in the search segment
pden	Probability density	The ratio of probability of area to its physical area
Sweep width	Effective sweep width	The width of the swath centered on the searcher's path such that the probability of failing to detect the subject within that width equals the probability of detecting the subject if it lies outside that width
c	coverage	The ratio of the area effectively swept to the area searched
i	Index whose value indicates different search segments or search strategies	i=1, 2, 3, …
j	Index whose value indicates different search segments of search strategies	j=1, 2, 3, …
PR	Priority rating	The ratio of probability of success (POS) of a given search task to the cost of that task (measured in searcher hours expended to complete the given task). Also referred to as probable success rate (PSR).

The above approach to search management is optimal in the sense that it is aimed at maximizing the overall probability of success of the search. However, it does not account for differences in search effort required to search the different search areas. For example, consider a search segment i with POA_i that has the same value of POA as segment j, but whose area A_i is twice that of segment j. Assuming searchers cover the two segments at the same rate (i.e. their search speed and sweep width is the same), it will then take a strike team twice as long to search segment i compared to segment j. Searching either segment has the same effect on the overall probability of success, so most search managers would probably intuitively assign a strike team to the smaller area first. However, more generally, it would be useful to have a quantitatively logical approach that prioritizes which segments are assigned sequentially during a search. This is the topic to which we now turn.

Prioritizing Segments

The problem of choosing the sequence in which search tasks should sequentially be assigned in order to maximize the probability of success with the least effort has been examined previously in the context of operations research (Assaf and Zamir 1985). Using a Bayesian analysis, these authors show that the optimal search strategy involves choosing tasks sequentially in order of decreasing values of $POS_i/cost_i$ where $cost_i$ is the cost of the ith task. In the context of land search and rescue, a logical measure of $cost_i$ is the number of person hours t_i required to complete that task. Although POS alone is often used in search management, the use of POS/cost (sometimes termed the probable success rate, PSR) to optimize land search has previously presented in the land search and rescue literature (Cooper et al. 2003). Let us define a priority rating PR as

$$PR_i = \frac{POS_i}{t_i} \qquad (7)$$

Here the time t_i includes transit time for searchers to deploy from a staging area to a segment, although in many cases this time is small compared to the time required to search that segment, so that we can approximate t_i simply as the number of person hours required to search that segment. In that case, t_i is related to total track length and average travel speed of the strike team by

$$t_i = \frac{total\ track\ length}{speed} \qquad (8)$$

Combining eqns. (3)-(8), it can be shown that the priority rating of the ith operational segment is given by:

$$PR_i = pden_i \times sweep\ width_i \times speed_i \qquad (9)$$

We can alternatively write eqn. (9) as

$$PR_i = pden_i \times \dot{c}_i \qquad (10)$$

where $\dot{c}$ is coverage rate, i.e. area swept per unit time. When transit time is not small compared to the time required to search a segment, we instead must use eqn. (7) directly, rather than eqn. (9) or (10). A demonstration of the inclusion of transit time is given later in the final example (see the section entitled *Where to send drones versus ground search visual teams*).

Eqn. (9), or equivalently eqn. (10), allows a priority rating PR to be calculated for each search segment, which can be used to prioritize the sequence that the segments should be searched in order to achieve the highest probability of success in the least expected amount of total active searcher time. Barring other available information, the optimal strategy to follow when sequentially choosing segments to search should therefore adhere to the following principle:

Given two search strategies with different total PR values, choose the strategy with higher PR value (11)

Alternatively, when deciding between two search strategies it may be easier to instead examine the ratio PR_1/PR_2, in which case strategy (11) can equivalently be written

Given two search strategies with total PR values PR_1 and PR_2, choose strategy 1 if $PR_1/PR_2>1$, otherwise choose strategy 2 (12)

The value of the ratio PR_1/PR_2 tells us how many times more probable strategy 1 would be in achieving success compared to strategy 2 for a given search effort e.g. $PR_1/PR_2=5$ indicates that strategy 1 is five times more likely to find the lost person than strategy 2 if the same amount of time were to be spent searching with each strategy.

Note that when a task consists of multiple subtasks, the PR value cannot be obtained by adding up the PR values for each subtask. Instead, in such cases it is necessary to use eqn. (7) directly. Thus, for a strategy i that involves searching multiple segments j (e.g. perhaps by assigning different teams to each segment), the priority rating for the strategy is given by

$$PR_i = \frac{\sum_j POS_j}{\sum_j t_j} \qquad (13)$$

This is because unless t_j is the same for each subtask, $\sum_j \frac{POS_j}{t_j} \neq \frac{\sum_j POS_j}{\sum_j t_j}$, so that we cannot use eqn. (9) or (10) to sum up individual segment PR_j values.

Various optimal operational search strategies that follow directly by applying strategy (11), or equivalently (12), are given in the Results section.

Estimating Searcher Speed

In order to use eqn. (9) to determine a priority rating for a given search segment, it is necessary to estimate searcher speed in that segment. For this purpose, the study of Campbell et al. (2024) is useful. These authors relied on a vast database of lidar based terrain data to develop an equation for walking speed as a function of slope angle, vegetation density, and terrain roughness. They give the following equation for estimating searcher speed in meters/second that we use here for speed in eqn. (9):

$$speed = \frac{1.78251}{(1 + 15.265 \times density + 16.505 \times roughness)\left(1 + \left(\frac{slope + 2.32}{26.315}\right)^2\right)} \qquad (14)$$

The variables in the denominator account for reductions in travel speed as follows:

- density captures obstruction by vegetation, with 0 meaning no vegetative obstruction; the maximum value observed in their field validation studies was 0.064
- roughness accounts for ground surface roughness , with zero being smooth ground and 0.054 being the roughest ground traversed in their field studies
- slope is the angle in degrees of the slope in the direction of travel; typical values of slope are as follows: slope=0° for flat ground, a moderately steep slope in LSAR operations would be perhaps 5°, and a slope of 15° would likely be considered quite steep terrain in LSAR operations that do not involve high angle rope teams

If traversing a side slope of angle j in degrees, based on Wood et al. (2023) we can estimate speed in a direct contouring traverse of a side slope (i.e. zero elevation change travel on a slope) by setting slope=0 in eqn. (14) and multiplying the resulting speed by $e^{-0.00731j}$.

Campbell et al. (2024) used lidar data to estimate density and roughness at 1 million random points placed within 100 random natural areas across the contiguous United States. The mode of the distribution of density values at these locations was 0.004, and the 90th percentile density value was 0.06. The mode of the distribution for the roughness values was 0.014. Finally, the approximate mode, 50th percentile and 75th percentile values of slope were 0°, 5° and 15°. We will use some of these values in the following Results section to provide estimates for searcher travel speed over a range of terrain conditions when estimating PR values from eqn. (9).

Results

Reflex tasking

A typical strategy at the start of a search is to immediately send searchers to areas with high probability density that can be searched quickly. This makes obvious use of the statement (11), since it prioritizes segments with highest PR because of high values of both $pden_i$ and coverage rate $\dot{c}_i$ in eqn. (10). Although we obtain no new understanding here, this does provide a trivial example of the use of statement (11).

Sound sweeps further out versus visual searching closer in

Consider a search for a responsive lost hiker, in a temperate mountainous ecoregion. Let us say that the inner 25th percentile circular region (Koester 2008) has been searched using the parallel sound sweep procedure given in Finlay (2024). Suppose the question now is whether to send two 2-person strike teams to search by sound within a segment in the 25th - 50th percentile annular region, or to instead combine the two teams into a single four person team that then starts visual searching in a segment within the inner 25th percentile region. We assume the two sound searchers on a single team stay together to avoid the increased risk of solo searching, since employing critical separation during sound sweeps would put separate sound sweep units beyond visual and audibility range of each other.

To answer this question in an actual situation we would need to know the ambient dB values in the field at the time the question is being asked, since sound sweep width depends on ambient dB (Finlay 2024). We would also need to know the sweep width for the proposed visual search segment. For the sake of demonstration, let us assume the detection range for the sound sweeps is the average intelligibility distance for the lodgepole pine forest measurements given in Finlay (2024) i.e. 98 m. Let us also assume the visual range of detection is the same as the value measured in the same forest for a standing human subject by Finlay (2025) i.e. 18.2 m. In addition, let us also assume that both range of detections are related to sweep width by the same multiplicative factor. Now define strategy 1 to be the case where we task the strike teams to continue sound sweeps but now in a segment in the 25th – 50th percentile zone. In strategy 2 we instead task the strike team members with parallel visual searching of a segment in the 25th percentile zone. Figure 1 depicts the two strategies schematically.

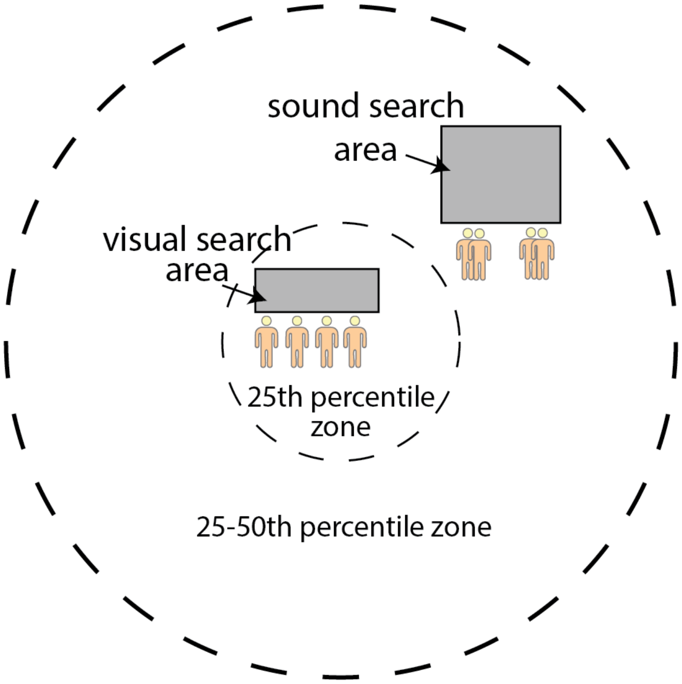

Figure 1. Schematic showing the two strategies to be chosen between. Strategy 1 involves two 2-person strike teams searching a segment by sound that lies within the 25th – 50th percentile radial zone from the IPP. Strategy 2 involves a four person strike team instead doing a visual search of a segment within the inner 25th percentile zone, where a sound search has already been done.

Finally, let us assume that the searcher travel speed would be the same in both strategies. With these assumptions, we can obtain the priority rating ratio PR_1/PR_2 as follows.

First, we find the probability density $pden_1$ for the 25th – 50th percentile zone using eqn. (2). For the present case of a lost hiker in the given ecoregion, r_{25}=1100 m and r_{50}=3100 m. Next we obtain the probability density $pden_2$ for the inner 25th percentile region using eqn. (1). But since this region has already been searched, we need to recalculate the probability density using Bayes theorem as noted earlier in the *Background* section when discussing POA, i.e. we need to multiply $pden_2$ by (1-POD) to give a revised cumulative nonnormalized probability density

$$pden_2' = (1-POD)pden_2 \qquad (15)$$

A method to determine POD from intelligibility distance is not yet available to the author’s knowledge, but in the interim Finlay (2024) suggests using POD=0.8 for properly executed sound sweeps, so let us use this POD value.

With all of the above in place, we can use eqn. (9) to evaluate PR_1 and PR_2. Note that since the two people on a sound strike team walk together, their coverage rate is half that of a single person, effectively halving their coverage rate compared to the visual search team where each individual sweeps a separate path, so we divide the strategy 1 PR value by 2, and we find

$$PR_1/PR_2 = pden_1\, rd_1/(2\, pden_2'\, rd_2) \qquad (16)$$

where rd_1=98 m is the above noted sound sweep detection range and rd_2=18.2 m is the above noted visual detection range. Putting in the numbers, eqn. (16) gives PR_1/PR_2=1.94. This is larger than one, so statement (12) indicates that strategy 1 is the preferred strategy i.e. in this particular example we should send the strike teams into the 25th – 50th percentile zone to search using a parallel line sound sweep protocol, rather than having them start a parallel line visual (‘grid’) search inside the 25th percentile zone. Doing so would have a 1.94 times higher probability of success with strategy 1 than for strategy 2 for a given search effort. Note that this is not a general recommendation, but is specific to the values used in this example.

Note that if we had used a single four person strike team for the sound searching, all walking together as a group (instead of splitting into two pairs) during the sound searching, we would need to halve the PR for strategy 1 again, and would obtain a PR ratio of 0.97. In that case, strategy 2 is marginally preferred and we see the importance of splitting up sound searchers into teams of two to avoid reducing coverage rates.

Using the same approach, we can also consider the same question but now applied to the 50th -75th percentile zone away from the IPP i.e. if the 25th – 50th percentile zone has already been searched using sound sweeps, should we send the sound strike teams to do sound sweeps in the 50th-75th percentile zone, or should we instead have them join up to have a four person strike team start a visual search in the inner 25th percentile zone? Using the above procedure, we obtain a PR ratio of 0.7. By statement (12) then, we should have the four person strike team begin visual searching in the inner 25th percentile zone. Thus, there is a limit to how far out from the IPP that sound sweeps should be completed before visual searching begins. This distance can be extended with the use of parabolic microphones and loud signaling devices (Finlay 2025). Also note that the decision to search the inner 25th percentile zone visually, rather than re-searching it acoustically, implicitly assumes a low probability that the subject remains responsive, since otherwise the vastly larger sweep width of sound searching would give a higher PR value to re-searching this segment acoustically rather than visually.

These strategy decisions are specific to this example. In other searches, decisions may differ because PR values depend on the detection ranges for that particular search and on the radii of the 25th, 50th, 75th and 95th percentile zones (which differ with different subject categories, see Koester 2008). Thus, it is necessary to carry out the above calculations for each search in order to decide which strategy is optimal for that search.

One may also question how robust the conclusions of the above example are because of the uncertainty in values of some quantities. In particular, the factor that relates detection range to sweep width, particularly the validity of the assumption that this factor is the same for sound versus visual detection, is unknown. Also, the value of POD for sound sweeps (assumed equal to 0.8 in this example) is unknown, as noted earlier. However, the assumptions made here regarding these uncertain values were chosen conservatively i.e. favoring visual sweeps . For example, the factor that relates sweep width to detection range for sound sweeps is likely double or more the value of this same factor for visual detection, given that Finlay (2025) finds audibility detection range is typically at least double the intelligibility distance we are using here for sound detection range, whereas a value of unity has been assumed. In addition, assuming POD=0.8 for sound sweeps done with a spacing of twice the intelligibility distance is probably an underestimate, again because audibility detection range is greater the intelligibility distance. For these reasons, the ratio of PR_1/PR_2 given by eqn. (16) may be several times higher than estimated above, so that strategy 1 may be the preferable strategy for further distances than noted above.

Avoiding the trap of dense vegetation

Vegetation can impede searcher speed during off trail travel, since it can significantly obstruct a searcher's path. In addition, sweep width is typically reduced in densely vegetated areas. Thus, if pden is constant, then eqn. (9) shows that PR values in areas with heavy obstruction due to vegetation will be lower than in lightly obstructed areas. The question is, how much higher does the probability density need to be before it is cost effective to search an area of dense vegetation, as opposed to instead choosing to search an area of sparser vegetation?

To address this, we can use eqn. (14) to estimate searcher speed in areas of varying vegetation density. However, to evaluate PR values we also need to know how sweep width varies with the vegetation density variable. Unfortunately, to the author's knowledge such data does not exist. Instead, as an approximate approach we can examine the data on sweep width obtained by Koester et al. (2014) in 10 different locations in the United States, where we see sweep width varies by a factor of approximately seven from its lowest to highest measured values for a fixed type of visibility (either high or low). Presuming that this variability is due to variations in vegetation density, then assuming a simple linear relation between sweep width and density, with the lowest sweep widths associated with a 90th percentile density value of 0.06 noted earlier when presenting eqn. (14), and a density of 0 for the highest sweep widths, we find the following relation between sweep width and vegetation density:

$$\text{sweep width} = \text{unobstructed sweep width} \times (1 - 14.286\ \text{density}) \qquad (17)$$

Now consider the following two strategies: 1) search off trail in an area that is heavily obstructed by vegetation, versus 2) search off trail in an area that is lightly obstructed by vegetation.

For simplicity, let us assume also that the areas being considered are flat i.e. slope = 0°. From eqn. (14), using slope=0, density=0.004 for light obstruction, density=0.06 for heavy obstruction, and the distribution mode value of roughness=0.014 noted earlier, we find searcher speed in the lightly obstructed area is 1.66 times that in the heavily obstructed area. Using eqn. (17), we find the sweep width in the lightly obstructed area is 6.6 times that in the heavily obstructed area. Multiplying these values, we find sweep width x speed is 11 times higher in the light versus heavy obstruction areas. Based on eqn. (9) and statement (12) then, the probability density, pden, in the dense vegetation area would need to be more than 11 times higher than its value in the light vegetation area in order for searching the dense area to be as cost effective as searching the lightly obstructed area. To put this in perspective, from eqn. (1) and (2) we find the probability density for a lost hiker in temperate mountainous terrain is 6.9 times higher inside the 25th percentile zone compared to the 25th – 50th percentile zone.

If the probability density is no different between the heavy and light obstruction areas, a strike team that chooses to search a region where the vegetation heavily obstructs a searcher's path, as opposed to instead searching an area where the vegetation only lightly obstructs their path, ends up focusing many times more search effort on the heavy obstruction area without commensurately boosting POS. In the example above, giving equal coverage to densely obstructed areas is equivalent to having the team re-search a segment that was previously searched at a POD of 91%, instead of sweeping a segment that has not yet been searched. It is also an even less optimal use of search effort than having the strike team search for a lost hiker in a segment in the 50th – 75th percentile zone before searching the inner 25th percentile zone.

Given the above perspective, search managers may wish to give instruction to strike teams regarding whether densely vegetated areas should be given the same coverage as lighter vegetation areas. In some types of searches it could be that densely obstructed areas do indeed have a considerably higher pden e.g. in a search for a deceased victim of criminal activity where the body has been intentionally placed in dense bush to reduce the likelihood of its detection. However, in searches where pden is not expected to be considerably higher in dense bush, the above example suggests that some thought should be given as to whether it is worthwhile to inadvertently misplace search effort by having teams search dense and light bush with equal coverage. To provide guidance in this regard, the ratio of priority rating normalized to PR with a vegetation density value of 0.004, with ground roughness 0.014 is shown in Figure 2. It can be seen that searching dense and light bush with equal POD, as is commonly done in SAR operations, dramatically focuses search priority on the most densely vegetated areas.

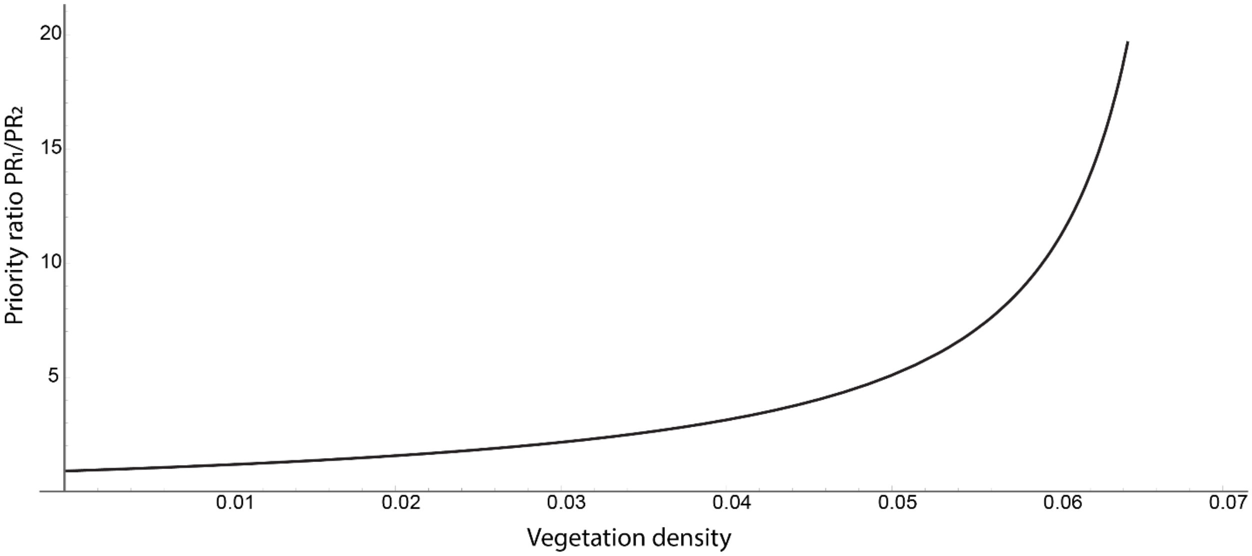

Figure 2. The priority rating ratio for searching lightly obstructed (PR_1) versus obstructed (PR_2) segments is shown as a function of vegetation obstruction density i.e. density in equation (13). Note this ratio is independent of slope angle, since slope cancels out in the priority ratio.

Given the above noted effect of heavy obstruction on PR values, three obvious approaches for searchers encountering dense vegetation are apparent, as follows:

1) reduce searcher spacing to yield the same POD that occurs in lightly obstructed regions e.g. by using the approach described in Chiacchia et al. (2025)

2) use the searcher spacing appropriate to lightly obstructed areas throughout, marking dense locations for later searching with revised (closer) spacing

3) skip the densely vegetated area, marking its location for later searching

If option 1 is chosen, densely vegetated areas will have more searcher effort allocated to them, which may not be warranted. Modern mapping and tracking tools, such as CalTopo, allow locations to be readily marked electronically and made visible to all team members at all times, improving the practicality of options 2 and 3 compared to older methods such as flagging. If option 2 or 3 is chosen, a PR value should be calculated for the marked areas so that they can put in the queue to be searched when their PR value becomes higher than other segments.

Effectiveness of sound sweeps adjacent to paths in dense forests

Costigan (2024) has already pointed out the generally higher effectiveness of sound versus visual sweeps when searching for responsive lost persons. But it is worth revisiting this in the context of the Bayesian priority rating approach presented above. In particular, consider a two person strike team that is trained on how to use the sound sweep protocol of Finlay (2024). They have measured ambient sound dB (due to wind in the forest trees) to be dB_{amb} =40 dB in a mature dense aspen forest, which is typical for this environment when treetop wind speeds are perhaps about 20 km/hr (Finlay 2024). The intelligibility distance equation from Finlay (2024), $d_i = 5619e^{-0.0978dB_{amb}}$, predicts a sound detection range of d_i=112 m for a person shouting at 88 dB at 1 m (which is a very loud shout). For lost hikers, 50% are found within a track offset of 100 m. The strike team has searched out to the 50th percentile track offset (since the intelligibility distance is > 100 m). Now define the following two strategies:

1) the strike team moves off trail and starts sound searching the 50th - 75th percentile track offset
2) The strike team instead searches visually in the 25th percentile track offset zone

For visual range of detection in a dense mature aspen forest, let us use the value measured by Finlay (2025) i.e. 8.6 m.

We can now use statement (12) to make a decision as to which is the more optimal strategy. Since that statement relies only on the ratio of priority ratings, we only need to know the ratio $pden_1/pden_2$, rather than absolute values of these. Here $pden_1$ is the probability density in the 50th – 75th percentile track offset zone i.e. in the region between distances o_{75} and o_{50} off path, where o_{50} and o_{75} are the track offset to the edge of the zones where 50% and 75% of hikers are found off path. Similarly, o_{25} is the track offset for the inner 25th percentile track offset zone. Koester (2008) gives o_{25}=50 m, o_{50}=100 m, o_{75}=238 m and o_{95}=424 m for a lost hiker. From equation (3), and realizing we need to use eqn. (15) (where we assume POD=0.8 for the sound sweep as before) to account for the fact that we have already searched the 25th percentile track offset (by sound), we find (using ’ to indicate the use of eqn. 15)

$$pden_1/pden'_2=0.25\ o_{25}/(0.25*\ (1-0.8)*\ (o_{75} - o_{50})) \qquad (18)$$

which has the value 1.8 in the present case. The ratio of coverage rates for strategy 1 versus strategy 2 can be approximately estimated as the ratio of detection ranges for the two strategies i.e. ½ (112 m/ 8.6 m) = 6.5 where the factor of ½ accounts for the fact that the two people on the sound team travel the same path when searching by sound, but not when searching visually, as noted earlier. As before, we assume the same conversion factor from detection range to sweep width for both strategies. The speed of travel is approximately the same for both strategies, since in either strategy the strike team will be moving off trail through dense bush. Now, using eqn. (10) we have

$$\frac{PR_1}{PR_2} = \frac{pden_1}{pden'_2}\frac{\dot{c}_1}{\dot{c}_2} \qquad (19)$$

and we find PR_1/PR_2 = 1.8*6.5= 11.7. This is > 1, so we find strategy 1 is the more optimal strategy i.e. the strike team should search by sound in the track offset zone 238-424 m off trail. Note that this is not a general recommendation, but is specific to the values used in this example.

Where to send drones versus ground search visual teams

As noted earlier, in cases where the strategies being compared involve multiple subtasks, we must work directly with eqn. (13) when comparing PR values. For example, consider two teams awaiting assignment during a search for a lost person. Let us assume the lost person is no longer thought to be responsive, so sound sweeps are not being considered. Of the two teams available, one team operates a drone and consists of a pilot and a spotter. The other is a four person visual search ground team. Two segments are to be searched, which have equal area but one lies in the inner 25th percentile zone from the IPP, and the other lies in the 50th-75th percentile zone. The inner area is dense bush with expected PODs of POD_{v1}=60% for the visual team, and POD_{d1} =15% expected by the drone team. The outer area is open i.e. sparse vegetation obstruction, with POD expected to be 80% for both drone and visual searches. The ground team estimates it would take 2.5 hours to search the inner area, but only 45 minutes to search the outer area, plus an hour to walk out to the outer area. The drone team estimates 30 minutes to complete a search of either area. Strategy 1 sends the ground team to the inner area and the drone team to the outer area. Strategy 2 is the opposite i.e. the visual team searches the outer area, while the drone searches the inner area. Which is the more optimal strategy?

To make this decision, we use eqn. (13) along with eqn. (3) and eqn. (4). Denoting t_{v1} as the person hours to visually search the inner area, and t_{d1} as the person hours for the drone team to search the outer area, with the above information we have t_{v1}=4*2.5=10 hours and t_{d1}=2*0.5=1 hour. Similarly, for strategy 2 we have t_{v2}=4*0.75 + 1 = 4 hours, and t_{d2}=1 hour. Adding POS values to obtain a total POS for each strategy, and similarly adding up the total person hours for each strategy, then the priority ratios are obtained using eqn. (13) and the priority rating ratio is given by

$$\frac{PR_1}{PR_2} = \frac{\frac{pden_{25}\,POD_{v1}+pden_{50-75}\,POD_{d1}}{t_{v1}+t_{d1}}}{\frac{pden_{50-75}\,POD_{v2}+pden_{25}\,POD_{d2}}{t_{v2}+t_{d2}}} \qquad (20)$$

Note the area A has canceled out since it is the same for the two segments. Using eqns. (1) and (2) to calculate probability densities, and putting in the numbers, we find a priority ratio of 1.5. This is greater than 1, so by statement (12) strategy 1 is the more optimal one. Note that this is not a general recommendation, but is specific to the values used in this example.

Discussion

The above examples highlight the ability of the Bayesian priority rating (PR) embodied by eqn. (9), or equivalently eqn. (10), to inform search management when a choice needs to be made between different search strategies.

For responsive lost persons, the increased sweep width when searching by sound (Finlay 2024) gives higher PR values than visual searching in the same segment, supporting Costigan's (2024) analysis that when searching for responsive lost persons, segments should be swept using sound before switching to visual detection. However, the rapid decrease of probability density with distance from the IPP means there is a limit to how far out sound sweeps should be completed before visual searching is begun closer in to the IPP. This distance will depend on the ratio of sound versus visual sweep width, as well as the subject category (since the rate of decrease of pden with distance from the IPP is subject category dependent), and speed of travel if it is different in the different segments under consideration. Redoing our earlier example but now using Koester's (2008) data on two different subject categories (lost hikers and lost hunters) in both temperate and dry ecological regions, as well as flat and mountainous terrain, we find that using two person sound strike teams to do sound searching in the inner 25th – 50th percentile zone (after already searching the inner 25th percentile by sound) always has a higher priority rating than visually searching the inner 25th percentile zone under the assumed conditions. For the case of a lost hiker or hunter in dry mountainous domains or a lost hunter in a dry flat domain, higher priority rating also occurs for two person strike teams sound searching the 50th -75th percentile versus visual searching of the inner 25th percentile zone. On the other hand, if sound sweep width is less than twice the visual search sweep width, as may occur on a windy day with considerable ambient environmental noise, doing two person sound sweeps (where two searchers travel the same path together) has a lower priority rating than visual searching with team members spaced at or beyond critical separation. Thus, while in many cases the optimal strategy would be to prioritize sound sweeps in the inner 50th percentile zone followed by visually sweeping the inner 25th percentile zone, this conclusion is not universal, so that PR values should be calculated during each search.

When assigning segments to strike teams, search managers may not know how fast the team will be able to travel in the assigned segment. For example, they may not know to what extent vegetation will obstruct the searchers' paths. Searcher speeds could be estimated with the use of lidar data to discern vegetation density (see Campbell et al. 2024), but many locations do not have publicly available lidar datasets for this purpose. In the author's experience, when vegetation density varies rapidly along the searcher's path, search volunteers naturally tend to cover dense and lightly obstructed regions with nearly equal searcher spacing, since it adds complexity for a team of searchers walking abreast to adapt to varying searcher spacing. However, this effectively prioritizes search effort in heavily obstructed vegetated areas versus lightly obstructed areas. If this is not desirable, e.g. if probability density is not expected to be significantly higher in densely vegetated areas, search managers may wish to advise strike teams to skip areas where vegetation cover dramatically obstructs their path, marking these areas and calculating a revised PR for such areas, queuing them for later searching once other areas with higher PR have already been searched.

One advantage of using PR values is the elimination of the need to consider segment areas explicitly. However, it does require knowing pden, which requires calculating areas of simple geometric figures (e.g. rings, circles, wedges, rectangles and their overlaps) if one starts with probabilities from the lost person behavior zones of Koester (2008). Including multiple effects, such as both track offset and radial distance from the IPP, requires multiplying probabilities and calculating overlapping areas, as illustrated earlier in footnote 1. Including non-searching person hours e.g. transit times between segments, also adds complexity to the analysis. As a result, a priority rating analysis can become somewhat tedious and prone to error if done by hand. Development of software that incorporates the present Bayesian priority rating approach while also calculating pden using intersecting zone probabilities from historical lost person behavior databases would be a powerful tool to aid land search and rescue management.

Limitations of this study

The priority rating given by eqn. (9) relies on an assumption that POD varies linearly with coverage, as given by eqn. (6). If one instead assumes an exponential 'random search' dependence (Cooper et al. 2003) where $POD=1-e^{-c}$, PR values obtained with an assumption of linear dependence on c would overestimate PR at most by a factor in the range 1.28-1.59 for c varying from 1 to 0.5, which would affect decisions only when PR ratios are not much different from 1 i.e. the two competing strategies being chosen are nearly equally optimal anyway. Our use of eqn. (6) to derive eqn. (9) simplifies the calculation of PR values, and in the author's view is worth any error introduced by the linear dependence assumption embodied by eqn. (6), particularly given that such errors are likely smaller than uncertainty in pden values in actual searches anyway. Finally, this error is only present when the two strategies being compared have different values of coverage c, since if c is the same then both PR values must be corrected by the same factor, which then cancels out in the PR ratio. In this author's experience, most strike teams aim for similar coverage values in different segments, negating concerns about linear versus exponential dependence on c.

Data that relates sound intelligibility distance to sound sweep width has not yet been obtained, to the author's knowledge. For this reason, in the above examples we have assumed the conversion factor between detection range and sweep width is the same for sound searching as it is for visual searching. This introduces an error whose extent is unknown. The conversion factor from detection range to sweep width varies from 1.1 – 1.8 for low to high visibility objects (Koester et al. 2014) for visual searching, whereas it is probably in the range of 2-5 for sound sweeps when using intelligibility distance for detection range (Finlay 2024). Thus, in the cases here where sound versus visual searching was considered, removing this error would increase the PR ratio for sound versus visual searching by a factor of perhaps 5/1.1 – 2/1.8 i.e. by a factor of 1.1-4.5. This correction would prioritize sound sweeps over visual sweeps somewhat more.

Conclusions

It has long been known that incorporating optimal sequential Bayesian decision-making into search theory makes it possible to determine the more optimal search strategy among competing strategies, accounting for both probability of success and search effort (measured as search-person hours). Here we apply this approach to various examples of search decision scenarios that include recent developments in the search literature, reemphasizing the utility of this approach, including what sequence to task search segments, which search tactics to use in different segments (e.g. remotely piloted aircraft versus visual searching versus sound sweeps), and quantifying the effect of densely obstructing vegetation on search cost effectiveness. The present restatement of the priority rating approach may be useful for searchers and search management interested in achieving more optimally effective searches.

About the Author

Warren Finlay is a Search Manager with Edmonton Regional Search and Rescue Association. He holds a PhD in Mechanical Engineering, and has published more than two hundred refereed archival journal papers in aerosol mechanics and fluid dynamics during his tenure as a Professor at the University of Alberta. He is a Fellow of the Royal Society of Canada, the Engineering Institute of Canada and the American Association for Aerosol Research.

References

Assaf, D. and Zamir, S. (1985) “Optimal Sequential Search: A Bayesian Approach”, Ann. Stat. 13(3):1213-1221.

Campbell, M. J., Cutler, S. L. and Dennison, P. E. (2024) “A singular, broadly-applicable model for estimating on- and off-path walking travel rates using airborne lidar data”, Scientific Reports 14:21838.

Chiacchia, K.B. , Billings, H. J., and Houlahan, H. E. (2025) “Head, Belt, Boots: Obtaining Consistent Probability of Detection in Human Visual Search”, J. Search and Rescue 8(1):1-27.

Costigan, R. (2024) “The Value of Searching by Voice in LandSAR”, J. Search and Rescue 7(1):1-29.

Cooper, D. C., Frost, J. R. and Robe, Q. R. “Compatibility of Land SAR Procedures with Search Theory”, Alexandria VA: Potomac Management Group, 2003.

Finlay, W. H. “Voice Calling Detection Range in Land Search and Rescue”, J. Search and Rescue 7(2):124-140, 2024.

Finlay, W. H. “Voice Calling Detection Distance with a Parabolic Microphone in Land Search and Rescue”, Wilderness and Environmental Medicine, accepted and in press, 2025.

Koester, R. J., Cooper, D. C., Frost, J. R., Robe, R. Q. “Sweep Width Estimation for Ground Search and Rescue”, Alexandria VA: Potomac Management Group, 2004.

Koester, R. J. (2008) Lost Person Behavior, dbS Productions LLC, Charlottesville, Virginia.

Koester, R. J., Chiacchia, K. B., Twardy, C. R., Cooper, D. C., Frost, J. R., Robe, R. Q. (2014) “Use of Visual Range of Detection to Estimate Effective Sweep Width for Land Search and Rescue Based on 10 Detection Experiments in North America”, Wild. Env. Med. 25:132-142.

Stoffel, B. C. (2017) Managing the Inland Search Function, National Association for Search and Rescue Centreville, Virginia.

Mansfield, G., Carlson, J., Merrifield, D., Rosenberg, E., Swanson, E., Templin, P. (2020) “A Pragmatic Approach to Applied Search Theory”, J. Search and Rescue 4(1):84-107.