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Land Search and Rescue Probability of Detection: New sweep widths values, correction factors, models, and detection model validation.

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Abstract

Search theory allows for correction factors to account for conditions (such as night) that affect the sweep width value. Search theory also predicts that the coverage is proportional to the probability of detection by either the inverse cube curve or exponential function (random search). The objective is to determine the correction factors from night searching and validate the coverage curves.

An Effective Sweep Width experiment was conducted with the same medium visibility adult-sized targets during both the day and the night in a temperate forest. In addition, high and low visibility clue-sized objects were placed directly on the trail.

We found an effective sweep width of 64 meters during the daytime and 22 meters at night for a correction factor of 0.34 for the adult-sized targets. Both high (100% vs 94%) and low (83% vs 43%) visibility clues were more detectable during the day versus night (P<0.001). Searchers with dim flashlights (<200 lux at one meter) resulted in an additional correction factor of 0.5. The probability of detection versus coverage plots of both day and night experiments fell between the inverse cube and exponential curves.

This single experiment for only one visibility class of search target showed that visual searching is significantly degraded by searching at night. The daytime coverage suggests the inverse cube model while the night coverage suggests an interim result. The use of effective sweep width, correction factors, and validated coverage curves can lead to more accurate assessments of the probability of detection.

Keywords: decision support systems, search theory, search and rescue, model validation, correction factor.

Introduction

Formal search theory was established during World War II in response to the need to detect enemy submarines, but has been applied and adapted to aid aeronautical, maritime and land search and rescue (SAR) incident management (Koopman, 1980)(Kratzhe, Stone, & Frost, 2010)(Stone, 2007)(Cooper, Frost, & Robe, 2003). SAR operations rely on search theory to inform decisions about the search action plan. Search theory generalizes that whether or not something is detected depends on (1) searching in the right area, and (2) being able to detect the subject of the search. Mathematically these principles can be expressed as:

$$\text{OPOS} = \sum POS = \sum (POD * POC) \qquad (1)$$

In other words, the overall probability of success (OPOS) is the product of the Probability of Containment (POC) and the Probability of Detection (POD) (Charnes & Cooper, 1958). The ultimate aim of search theory is to provide an optimal allocation of resources that maximizes the probability of success for each additional increment of effort (Charnes & Cooper, 1958)(Stone, Royset, & Washburn, 2016). In land or wilderness SAR applications the Probability of Containment is often referred to as the Probability of Area (POA), the terms are synonymous (National Search and Rescue Committee, 2011). Thorough discussions on the determination of POC/POA are given in other resources (Cooper, Frost & robe, 2003)(Stone, 1989)(Koester, 2008)(Wysokinski, Marcjan & Dajda, 2014).

Probability of Detection

The Probability of Detection was first described by Koopman as part of his initial work (Koopman, 1946). The key to determining the POD is estimating the coverage of a search area, which relies on the size of the area, the amount of resources put into that area (effort), and the effective sweep width. Several books and papers have detailed how the coverage of a search task is determined (Stone, 2007)(Koester, Chiacchia, et al, 2014)(Koester, Cooper, Frost, Robe, 2004)(Abi-Zeid, Frost, 2005). Once the coverage is either determined or predicted then various detection models (discussed in 1.1.2) can be applied to determine the POD.

Effective Sweep Width (W) or (ESW)

Effective sweep width (W), which is also known as the detection index in land SAR, is determined by considering the searcher (sensor), the search object, and the environment. The W values are derived from field experiments which yield a lateral range curve (LRC) for each search sensor, search object or target, and environment combination. The effective sweep width is a single number measured in units of distance that integrates all of these factors. Theoretically, the sweep width is the area under the lateral range curve p(x) where P is the probability of detecting the object at a distance x. (Abi-Zeid, Frost, 2005).

$$W = \int_{-\infty}^{\infty} p(x)dx \quad (2)$$

Lateral range is the perpendicular distance to the left or right of a searcher at the closest point of approach to the search object. The LRC is a plot of the POD versus the lateral range as the searcher approaches the object (Koopman, 1980). In the land environment where the lateral range distance can be small and the curve can be noisy due to variations in the land the crossover technique described in Robe and Frost is recommended to determine W for each LRC when conducting land-based experiments (Robe and Frost, 2002).

Detection Models

Koopman was the first to describe three possible relationships between coverage and the POD. These are typically referred to as detection models. The Definite Range (parallel track search), Inverse Cube (parallel track search), and Exponential Detection (random search) curve are shown in **Fig. 4** in the results section. A more thorough discussion and derivation of these curves can be found in Koopman (Koopman, 1980)(Koopman, 1946), Stone et. al. (2016), or Washburn (2014). The Definite Range is considered an upper-bound and the Exponential Function a lower-bound with the Inverse Cube in the middle.

Definite Range

The definite range is based upon an ideal sensor that detects everything within a specific range (R) and misses everything outside of that range. Washburn calls this the cookie-cutter search (Washburn, 2014). The effective sweep width value would then be given by W=2R. The relationship between the POD and coverage is linear until the coverage equals 1 and then every part of the search area is covered and every search object detected. The model assumes parallel track searches with a spacing given by S and all effort occurring inside the search area.

$$POD = \mathrm{C} = \frac{\mathrm{W}}{\mathrm{S}} \quad (3)$$

In conditions of coverage less than 1 it is assumed the sensor has perfect parallel tracks with spacing greater than W. The definite range is considered the upper-bound because perfect parallel tracks are unlikely, and more importantly, actual sensors tend to make a certain number of misses even when well inside the operational range.

Inverse Cube

The inverse cube was derived by Koopman based upon the searcher being in an aircraft looking for the wake of a ship (Koopman, 1946). The wake of the ship approximates a rectangle, and the height and range of the aircraft creates a triangle for viewing the ship's wake. Ultimately two angles are formed at the sensor: one measures the length of the wake (β), the second measures the observed width of the wake (α). The shorter the range between the sensor and the search object the larger the αβ angles will become and the greater the instantaneous probability of detection (Koopman, 1946). From these physical factors it was possible to derive the inverse cube equation. It is shown in the format easiest to integrate into spreadsheets.

$$POD = erf\left(\frac{\sqrt{\pi}}{2} * C\right) \quad (4)$$

The inverse cube model is used by the U.S. Coast Guard as one of its standard models for visual search (IMO/ICOA, 2013). Furthermore, the model is integrated into SAROP (Kratzke, Stone, & Frost, 2010) and SARPlan (Abi-Zeid, Frost, 2005) (examples of computer software used in maritime (US Coast Guard) and aeronautical (Canadian forces) search). However, the inverse cube model's use may need to be limited under certain conditions since it is based upon ideal conditions. It assumes perfect parallel and equally spaced tracks. This is often possible from the air with modern navigation equipment, but may be difficult in a land environment. Other factors that may cause deterioration include random movements of search objects (survivors) and adverse environmental conditions (Abi-Zeid, Frost, 2005)(Washburn, 2014). Furthermore, Frost maintains "its validity as a model of visual detection has never been confirmed for any situation."(Frost, 1996).

Searching on land clearly does not involve looking for wakes or from a substantial height above the ocean. However, the actual physics of the two angles are much the same. A search object on the ground can still be characterized by two angles formed at the searchers eyeball. A human being lying on the ground can be represented by a flattened cylinder as shown in **fig.1 A**. The length of the object would be reflected by angle β (**fig. 1B**) and the combination of the height of the object and depth of the object would be viewed by the observer with dimensions represented by line c and reflected by angle α. Thus angle αβ still describes the search object. If the subject is standing instead of lying down the product of αβ remains the same. In the land environment, as the sensor moves, vegetation often hides the search object temporarily much like swells can cause smaller objects to appear and disappear in the ocean.

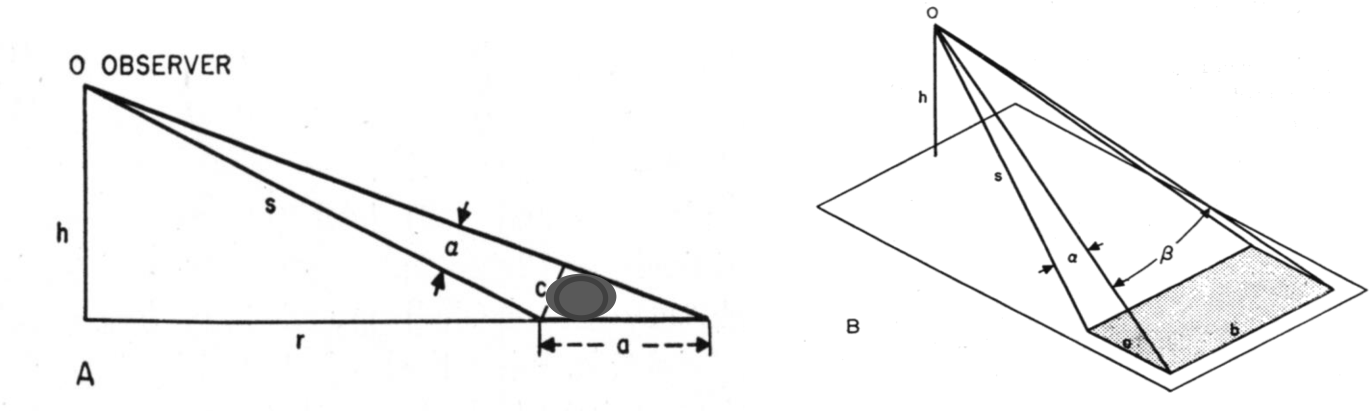


Fig 1 AB. Koopman (1946) originally created the model to describe the angles subtended by a wake of a ship (width a and length b). However, in a land environment, detection of a search object such as a human lying down is described by side c which is also the basis of angle α.

Exponential Model

The final detection model is the exponential model or random model which is considered the lower-bound model. It was also originally derived by Koopman (1946). The model makes two mathematical assumptions: First, each small increment of effort follows a uniform independent distribution over the search area; and second, no effort falls outside the search area. In the first case it is possible that the search sensor will pass over an area it has already searched and will miss an area that hasn't been searched. This is even possible when conducting parallel searching, due to error in navigation, search subject (survivor) motion or factors in a land environment that makes straight line travel impossible to difficult. The formula for the exponential detection model is given below:

$$POD = 1 - e^{-C} \qquad (5)$$

The exponential detection model has been suggested as the best model for land searching (Cooper, Frost, & robe, 2003)(Koester et al, 2014).. In fact, in most of the land SAR literature it is the only detection model shown (National SAR Committee, 2011)(Frost, 1996)(O'Connor, 2007)(Stoffel, 2006). However, this has not been validated with actual field testing.

Effective Sweep Width Correction Factors

Although W values and correction factors are available for various maritime and aeronautical search conditions, no standardized resource exists for the wide variety of land SAR variables (IMO/ICAO, 2013)(Edward, Osmer, Mazour, & Hover, 1981). Previous land SAR research has focused on different searcher/sensor types (Koester, Gordon, Wells, & Tucker, 2013), search object types (Koester et al, 2014), and environments (Koester, Cooper, Frost, & Robe, 2004)(Chiacchia & Houlahan, 2010). Baseline W values from these experiments could be adjusted with correction factors to account for other variables that may affect POD (and therefore W). Correction factors include target color, searcher fatigue, searcher morale and other aspects of a searcher's ability to locate a target, such as colorblindness and the searcher's height (Koester, Cooper, Frost, & robe, 2004).

Despite the frequency of land SAR operations conducted at night, to date no published W estimates or correction factors exist for land SAR tasks that occur at night. By determining both a daytime and nighttime sweep width value for the same sensor, environment, and search object it is possible to calculate a correction factor. This becomes critical since all baseline land search W values have been determined during the day.

Searching at Night

Searching at night presents numerous challenges to searchers. While human vision has the ability to adapt to low-light conditions, certain aspects of vision such as color and depth perception are more limited than they are in daylight (Barbur & Stockman, 2010). These differences are due to two distinct parts of the retina known as rods and cones. Cones are used for vision when light is readily available, and offer sharp images and color clarity. This is known as photopic vision. In contrast, rods are used when light levels are very low (e.g., starlight), which picks up very low resolution detail and no color. This is known as scotopic vision. In mid- to low-light level conditions (e.g., driving at night using headlights, outdoor lighting, search tasks at night) rods and cones can both be activated for use in what is known as mesopic vision (Barbur & Stockman, 2010)(Khan & Bodrogi, 2015).

In visual-based search tasks, the reduction of color and depth perception that occurs with mesopic vision leads to decreases in object detection and recognition (Kan & Bodrogi, 2015)(Bullough & Rea, 2000). While land SAR tasks conducted at night may involve mostly mesopic vision, measuring human perception in the mesopic range is complicated and beyond the scope of this study. Nonetheless, it is important to account for the effects that decreased visual perception may have on W and POD values for land SAR operations conducted at night.

Handheld flashlights or headlamps are the primary source of light for land SAR operations at night. In wilderness environments, the desire for the brightest light possible is tempered by the need for portability and duration. Recent advancements in small, high-lumen flashlights have resulted in many choices of light sources for searchers. Results of experiments comparing cool white LED sources (LEDs that emit somewhat bluish light) to incandescent or regular white LED suggest that object detection and recognition are improved with the cool white LED sources (Khan & Bodrogi, 2015)(Lewin, 2001). Despite these choices, no standard recommendation exists regarding luminance or spectrum of light that the light source emits. Thus, any experiment that considers W values at night would also need to consider the effect of the searcher's flashlight.

Literature Review

A comprehensive review of search theory was conducted by Benkoski et al. (1991). Since then additional contributions to POD in search theory have been numerous. Washburn has recently addressed detection models, different sensors, LRC, stationary targets, moving targets, multiple targets, and false alarms (Washburn, 2014). In Stone et al. (2016) the focus was on moving targets. Iida (1993) discusses an inverse N^{th} power detection law based upon the lateral range curve. Stone et al. (2014) have also showed how prior POD from different sensors changes the *a priori* in the search for AF447. Frost (1999a, 1999b) has also published a series of articles on general search theory that was directed at a land SAR audience.

The development of formal search theory, especially POD, in the land SAR discipline has not paralleled the aeronautical or maritime discipline or its use in other fields such as archaeology (Stewart, Banning, Edward, Hitchings, & Bikoulis (2015), fishing (Mangel, Marc & Clark, 1983), mining (DeGeoffroy & Wignall, 1985) or weed control (Baxter & Possingham, 2011). Cooper et al. (2003) provide a comprehensive review of the use/non-use of search theory in land SAR. One of the earliest land SAR texts by Bridges makes no mention of search theory (Bridge, 1960). This is not too surprising since Koopman's (1946) work was not declassified until 1956. The first mention of search theory is by Kelley in (1973) who cites Koopman (1956b). Wartes (1974) conducted the first land-based POD experiments during the day and at night. His methodology precludes a direct comparison of results to this experiment since he did not produce a lateral range curve, counted detection opportunities differently, and mixed different types of search objects. However, for a “spacing” of 30.5 meters between searchers a POD of 51% was obtained during the day and 19% at night for an “unconscious” human subject. Wartes (1974) reported that much of his POD results was based upon the spacing of the searchers. While not in his original report, his results were summarized as a formula that gave a POD based upon searcher spacing for all conditions in the land SAR textbooks of the time (LaValla, Stoffel, & Jones, 1981). Bownds et al. (1981) conducted a POD experiment in the Arizona desert using a helicopter search crew as the sensor looking for non-high-visibility people on the ground. The speed, altitude, and spacing was varied and decided on by each helicopter crew. POD values were given for sunny (29%) and overcast days (69%). A similar experiment was conducted in mountainous terrain in Arizona by Bownds & Harlan et al. (1991) with the helicopter flying either a descending contour search or a route search pattern. They reported POD values for three conditions: motionless subject (0%), upright waving (60%), and lying down moving spread eagle (81%). Perkins (1989) described a method of determining POD called “Critical Separation” whereby a spacing between searchers at twice the maximum detection range while moving away from the intended search object results in a POD of 50%. This paper also provides a graph that is linear for critical separation distances less than 1 and then inversely proportion for greater spacings. This was the first technique in land SAR to account for the search object and the environment. However, it did not account for search effort. In the paper Perkins (1989) noted he conducted empirical testing, spacing the searchers at one critical separation but allowing the searchers to wander within their lanes to investigate any features. They reported an actual POD of 80%, which can be accounted for by the extra effort in the trackline which would result in a greater coverage. Colwell (1992) also conducted POD experiments in the Pacific Northwest and reported POD results based upon different spacings. He also reported different curves depending upon the search object or sensor (sound sweep, high visibility sweep, standard sweep, and low visibility sweep). It is somewhat understandable that the land SAR discipline was not aware of formal search theory and how it handled POD since even in 1996 the USAF National Search and Rescue School Inland SAR Coursebook (1996) did not address lateral range curves, sweep width, coverage, or detection models.

Robe and Frost (2002) were the first to conduct an effective sweep width experiment on land demonstrating that even in the highly variable land environment distance between the searcher and the search object is the most important factor. They also introduced the use of the cross-over technique to obtain the actual sweep width value from the often highly variable LRC. The methodology was improved and a series of five additional experiments were carried out in different types of terrain and times of the year. These experiments by Koester et al (2004) determined sweep width values for different sizes of search objects, different visibility classes of search objects, and looked at several different potential correction factors. In addition, the study clearly demonstrated that searchers were not able to self-evaluate their individual POD. Chiacchia and Houlahan (2010) collected sweep width values for different search objects and noted some correction factors involving youth in SAR. These experiments also involved improvements to the methodology and the first use of IDEA which automates the experimental design, data collection, and data analysis for land-based sweep width experiments (Koester, Guerra, Frost, & Cooper, 2006a, 2006b). While in most experiments the search sensor was visual detection during the daytime, experiments have been conducted to determine the sweep width value for mounted searchers on horses (Koester et al. 2004), for air-scent dogs representing olfactory search (Chiacchia, Houlahan & Hosterrer, 2015), and for auditory search (Koester, Gordon, Wells, & Tucker, 2013). Koester et al. (2014) reviewed land-based visual effective sweep width experiments. In this review, the authors showed how a simple field procedure called the Range of Detection (Rd) could be used to estimate the sweep width, while accounting for the search object and environment. It also applied a correction factor based upon the search object visibility class to account for the difference between an alerted searcher (during the Rd procedure) and an un-alerted searcher (during an actual search or long-term ESW experiment. All of these experiments were conducted during the daytime. While no previous studies have determined a visual effective sweep width at night, Koester et al.(2013) examined sound and light at night and determined an effective sweep width of 306 meters for the two-way search problem of a subject hearing the searcher's whistle-blast and the searchers hearing the subject's shout. In addition, the ability to spot a flashlight in a heavily forested area produced a sweep width of 277 meters. Land SAR POD research is now consistent with search theory.

Most of the search theory literature talks about the detection models from a theoretical point of view and how Koopman (1980), originally derived the three major models (Stone, 2007). The USCG SAROP and USN NODESTAR certainly use the models in their search software (Wysokinski, Marcjan, Dajda, 2014)(Stone & Corwin, 1995). However, the question remains: what empirical data supports the models in land SAR? Currently no land-based experiments have been conducted to test the detection models. Edwards et al., (1980) using data from USCG R&D Center experiments, plotted the actual coverage against the POD from maritime experiments with 16-foot boats and life rafts as the search objects. They reported that for coverages 0.8 or less the inverse cube law model was a good predictor. For greater coverages the empirical data fell between the inverse cube and exponential curves. A best fit of the empirical data resulted in the following equation.

$$\mathrm{POD} = 1 - e^{-1.3C} \qquad (6)$$

They also looked at the empirical curves during good conditions with a peaked LRC curve and poor conditions with a flat LRC. They reported the empirical curve for good conditions was closer to the inverse cube curve than during poor conditions. This paper represents support for the detection models without a clear indication of which one might be the best match.

Methods

The methodology used was similar to visual land based effective sweep width experiments previously described (Koester, Cooper, Frost, & Robe, 2004). An important tool used to set up experiments is the Integrated Detection Experiment Assistant (IDEA) which is built using MS Excel. The calculator determines the total number of targets required, expected length of course, expected time to complete the course, and the random locations to place search objects (representing subjects). In addition to setting up the experiment, IDEA displays the results after inputting raw data (Koester et al, 2006a, 2006b).

Modification to Methodology for Night experiments

In order to conduct the nighttime experiments, a few changes to the previously described methodology were necessary. In addition to collecting Average Maximum Detection Range (AMDR), the Range of Detection (Rd) was also determined using the procedure previously described (Koester et al, 2014). Target placement was based upon the daytime AMDR results and the targets were left in the same location for the nighttime trial (secured with a tent peg). Lateral target placement was measured with a Laser Range Finder (Nikon Aculon AL11) from a well-marked trail which was measured with a measuring wheel (Keson Roadrunner, model RR3M). Medium visibility (blue) adult-sized manikins (stuffed Tyvek coveralls)(**Fig 2**) were used along with both low-visibility (green) and high-visibility (orange) clue-sized objects (gloves and socks that were spray-painted). The clue-sized targets were placed directly on the trail as previously described (Koester et al, 2013).

Fig. 2. Medium-visibility adult sized manikin (Stuffed Tyvek coveralls) placed 6 meters track offset from path. During the day 100% of searchers detected this subject, during the night 70% of searchers detected the subject. Photo taken from path at eye level.

Search Participants and equipment

Search participants were attending a Virginia Department of Emergency Management Ground Search and Rescue College training event. Classes consisted of entry-level search team member, search team leader, introductory tracking, and introductory search management. Both students and instructors participated in the experiment. Searchers participated in either the day or night trial but not both. Participation was voluntary except for those in the search team member class; who are required to go through a clue awareness exercise as part of the class. The collection of individual data however, was still voluntary for this class. Data was collected by the research team and instructors who assisted with the debriefing process. For the nighttime trial, participants used their own flashlights and/or headlights. The lux of the lights were determined at the end of the course using a lux meter app (Lux Meter by Not Quite Them), measured one meter away from the light source in a darkened area outside after the light source had been turned on for 30 seconds. The measurement was taken from the brightest part of the beam with the beam focus set as it had been used during the search trial. The measurement was made at the end of the course. Some participants indicated they had replaced batteries while out on the course. No participants replaced batteries just for the measurement.

Calculation of actual probability of detection

Individual data sheets were scored by the principal investigator to determine if each search target had been detected or missed. This data was entered into IDEA along with the characteristics of each searcher. IDEA was then used to generate the LRC and calculate the half sweep width for both the day and night experiments. IDEA automatically sorts the data by the lateral range distance from shortest to longest distance and also displays the actual percentage of searchers who detected each target. In order to ensure a uniform distribution of potential targets, the LRC was used to interpolate the POD of targets for every meter of lateral range where no actual targets were placed. Since the course was laid out on a linear path with searchers looking both left and right and the sweep width was known, it was possible to change the coverage by simply changing the working definition of the size of the search area. The length of the search area remained fixed; only the width needed to be adjusted for different coverages. With a fixed length and fixed effort the formula for coverage can be simplified as shown below where *w* is the width of the intended search area:

$$Coverage = \frac{\mathrm{W}}{w} \quad (6)$$

For each sized search area the actual POD was calculated using the following formula for both the day and night experiments:

$$POD = \frac{\text{\# of Targets Detected}}{\text{\# potential Targets}} \quad (7)$$

Adjustment for adjacent tracks

Since the experiment was conducted using a single track in the middle of the search area all of the POD values based upon different coverages are based upon the LRC from the single track. However, the inverse cube equation is based upon parallel tracks. Therefore, the adjacent parallel track LRC was simulated based upon the one actual LRC generated for the nighttime experiment for coverages of 0.5, 1, and 2. For each coverage the actual POD determined for the single track, including the adjacent tracks (cumulative value), and the predicted POD from the inverse cube equation [4] are reported. The cumulative curve was calculated in the same manner as calculating additional coverage from multiple tasks (National Search and Rescue Committee, 2011).

Statistics

All statistical measurements consisted of an ANOVA: Single Factor with the *P* value shown in the appropriate table conducted using Excel Data Analysis. Chi-square analysis of fatigue was carried out using GraphPad Software (La Jolla, CA).

Results

The overall experimental conditions and results are summarized in **Table 1**. A total of fifty-four searchers participated in the experiment during what could be described as ideal search conditions. The day and night lateral range curves are shown in **Fig. 3**. Additional night correction factors based upon flashlight brightness (**Table 2**) and searcher experience (**Table 3**) are summarized. The actual percentage of clues detected based upon various coverages are shown in **Fig. 4** for both the day and night experiment.

	General Course Characteristics		
Location	Appomattox 4-H Center, Appomattox, Virginia, USA		
EcoRegion Division	SubTropical		
Season	Winter		
Length of course	1900 meters		
Course type	Road and trail		
Elevation change	43 meters		
Topography	Hilly		
Vegetation	Mixed Deciduous and evergreen. Limited ground cover		
	Day		**Night**
	Environmental		
Temperature (Celsius)	2-7^{o}		-4 – 4.5^{o}
Wind (kph)	0 – 5		0
Light intensity (Lux)	$\bar{x}$ = 35,000 (15,000 – 50,000)		0
Precipitation	0		0
Cloud Cover	$\bar{x}$ = 50% (0 – 80%)		0
Meteorological visibility	unlimited		unlimited
Time (Local)	09:30 – 17:30		20:00 – 00:20
	Demographic		
n	31		23
Age (years)	$\bar{x}$ = 43.4 (23- 64)	P=0.47	$\bar{x}$ = 41.0 (20-71)
Years in SAR	$\bar{x}$ = 7.6 (0.25 – 40)	P=0.04	$\bar{x}$ = 2.7 (0 – 21)
# Searches in field	$\bar{x}$ = 23.7 (0 – 150)	P=0.59	$\bar{x}$ = 17.6 (0 – 200)
Time searching (hours)	$\bar{x}$ = 1.32 (0.45 - 2.25)	P=0.06	$\bar{x}$ = 1.47 (1.0 - 2.0)
Speed (kph)	$\bar{x}$ = 1.4 (0.8 - 4.2)	P=0.06	$\bar{x}$ = 1.3 (0.95 – 1.9)
Fatigue (% Drowsy)	6%	P=0.75	4%
	Outcomes		
Detection % (High Vis clue)	$\bar{x}$ = 100% (92 – 100%)	P<0.001	$\bar{x}$ = 94% (67 – 100%)
Detection % (Low Vis clue)	$\bar{x}$ = 80% (50 – 100%)	P<0.001	$\bar{x}$ = 42% (0 – 79%)
Detection % (Med Vis adult)	$\bar{x}$ = 74% (47 – 88%)	P<0.001	$\bar{x}$ = 32% (6 – 53%)
ESW (Med Vis adult)	64.0 meters		22.0 meters

Table 1 Shows the general course characteristics, environmental, searcher demographics, and outcomes between the day and night experiment. The night time experiment was colder, less windy, and dark. No statistically significant difference was found between the group of searchers participating in the day or night experiment except for the number of years in SAR. Night resulted in significantly less detection of both high and low visibility clues on the path, overall detection of medium visibility targets set away from the path and effective sweep width value. Averages, ranges, and where appropriate *P* values are shown.

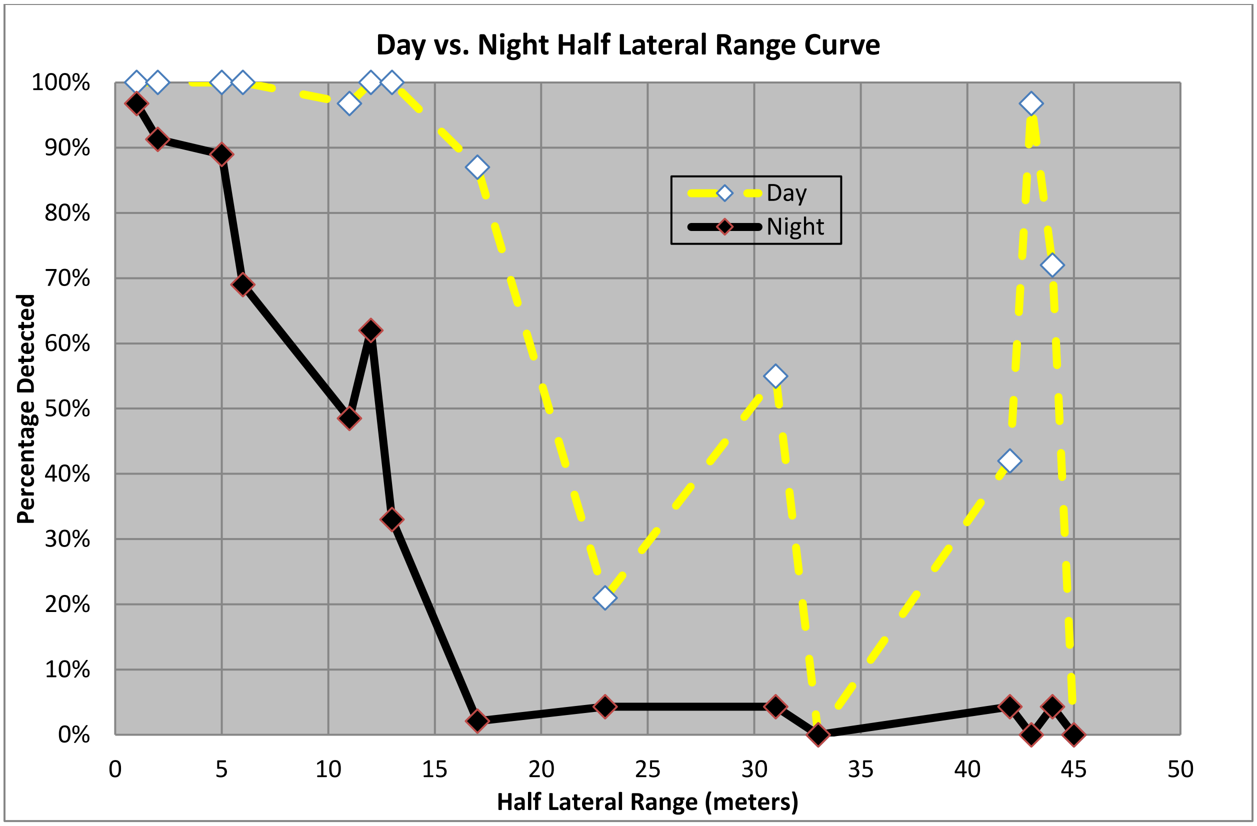


Fig 3. Half Lateral Range Curve (LRC) which combines both left and right of path. Diamonds indicated lateral range of the actual search targets (Blue adult sized manikins). The same targets placement was used for both the day and night experiment. Targets detected at 43 and 44 meters were 20 meters uphill and not obscured by ground vegetation.

Flashlight Lux @ 1 m	ESW (m)	n	% Detected	Correction (*Cf*)
< 200	12	6	21%	0.5
200-500	22	3	33%	0.92
>500	24	14	37%	1.0

Table 2. Flashlight corrections. The table provides the ESW for different lux values of the flashlights used. The ESW of all flashlights over 200 lux was 24 meters which would bring the n value up to 17 and allow correction of 0.5 for only those flashlights less than 200 lux.

	Night				**Day**			
# Searches	**n**	**ESW (m)**	**% Detected**	***Cf***	**n**	**ESW (m)**	**% Detected**	***Cf***
>10	6	26	43%	1.0	16	64	73%	N/A
≤ 10	17	22	28%	0.85	15	64	75%	
≤ 10 + >200lux	11	22	33%	0.85				

Table 3. Searcher experience at night. Searcher experience had no significant difference during the day. At night searchers with more than ten searches in the field had an ESW = 26m. Night searchers with ten or less field searches had an ESW = 22m even after correcting for weak flashlights. Based upon the total number of targets detected this was statistically significant (*P*=0.04).

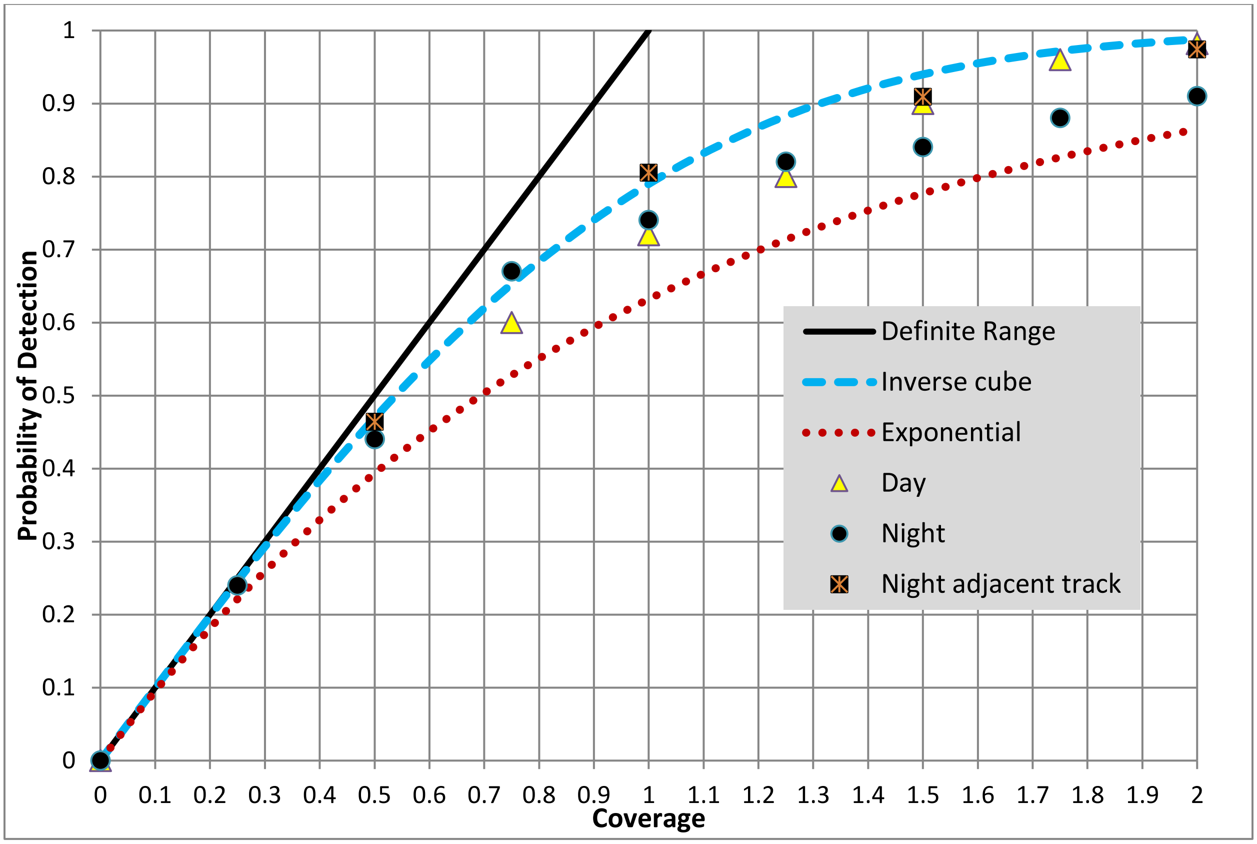
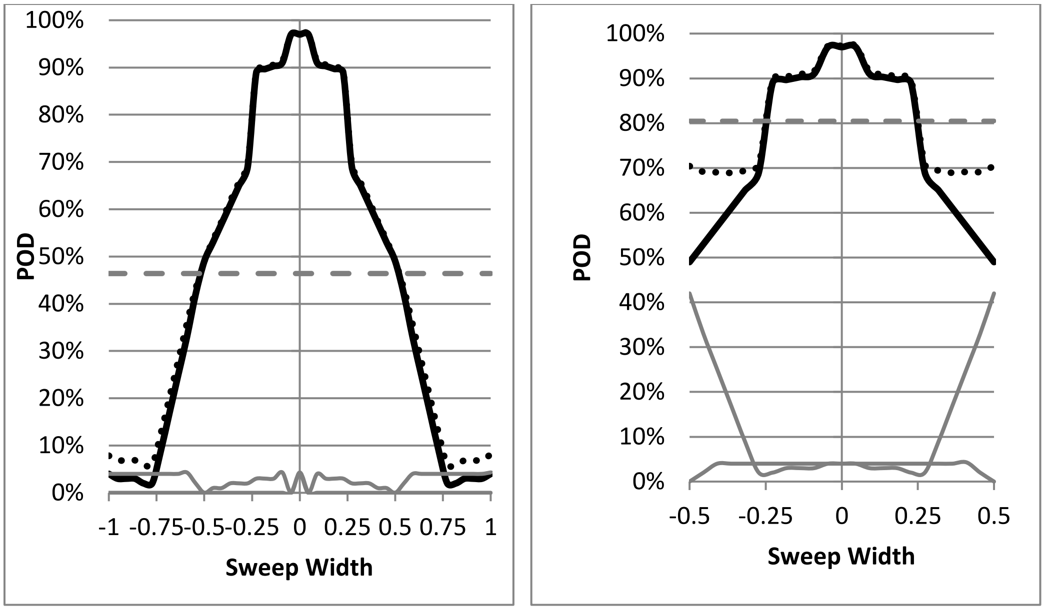
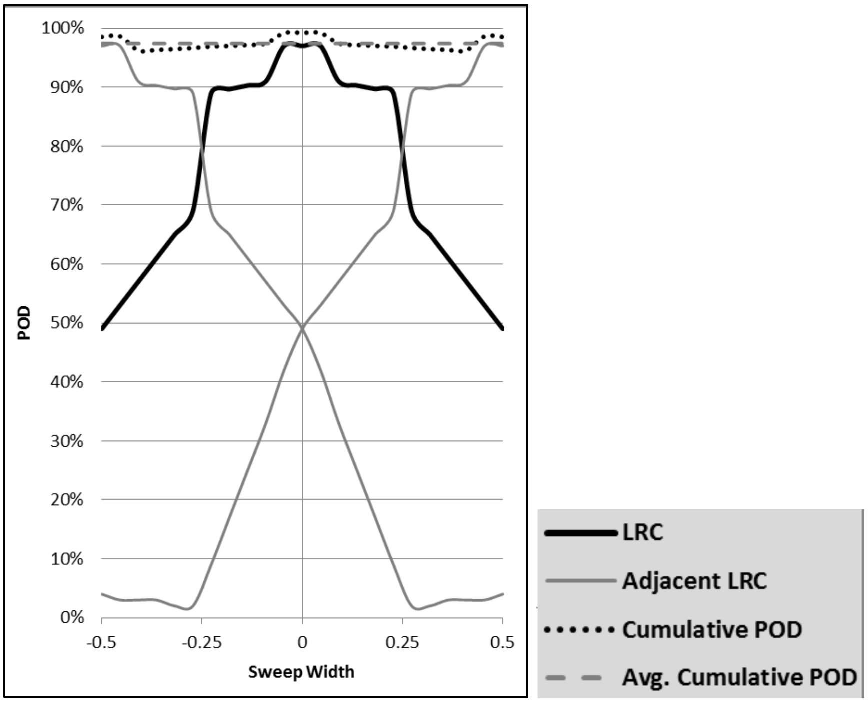


Fig 4. Shows both the three detection functions and the coverage vs POD from the day and night experiments. The Exponential detection curve is also known as the Random Search curve and the Inverse Cube is sometimes referred to as the Inverse Cube Law. Additional points are shown for the night search after adjusting for the presence of an adjacent track based upon parallel track spacing at that coverage (also see Fig 5.).



A. 0.5 Coverage

B. 1.0 Coverage



C. 2.0 Coverage

Fig 5. Each graph is based upon a different coverage using the same LRC from the night experiment. The light gray line shows the LRC from the adjacent track. These are used to determine the cumulative POD curves and the overall average cumulative POD for each particular coverage using empirical data.

Discussion

Searching at night is an essential part of search and rescue. In fact, it represents on average half of the time available for searching. Yet we are not aware of any sweep width or correction factor studies available for night visual searching in the land environment. We are also not aware of any land sweep width experiments specifically carried out to determine correction factor reductions to a sweep width distance based upon secondary factors. The results from the day and night experiments were clear and left little doubt that searching at night is much more difficult. This study determined the sweep width value for a subtropical mixed deciduous and softwood forest during the winter time during both the day and night. The experimentally derived lateral range curves were markedly different. During the nighttime experiments the need for a flashlight brightness correction factor and searcher experience factor was determined. The detection of clues on the actual trail had some similarities and differences to a previous experiment conducted in New Zealand.

Day versus Night Search Participants

Participants for both the day and night trials were recruited from the same pool of instructors and students. Both were given the choice to select the day or night trail. Both the day and night groups were similar in age, level of fatigue and SAR experience. The only statistically significant difference between the two groups was the number of years in SAR. However, no statistical difference existed in the number of searches in the field, which is perhaps a more relevant measure of SAR experience. Previous sweep width experiments (all conducted during the day) have shown that cloud cover, age (once >19), gender, years in SAR or SAR experience do not affect sweep width (Koester et al, 2004). Chiacchia and Houlahan (2010) showed that sweep width values from searchers under the age of 19 are significantly lower than adults. During this experiment no participants were under the age of 20. Therefore, no particular effort was made to control for these factors. However, fatigue levels have been found to have a significant impact on land visual searching, with a correction factor of 10% for high-visibility and 50% for medium and low-visibility search subjects (Koester et al., 2004). While it was hypothesized that searchers at night might be more fatigued than daytime searchers, no significant difference was found between the two groups. Since the experiment took place in January, all of the nighttime searching was conducted between 20:00 and 00:20. Since experiment participants could self-select if they wanted to search during the day, night, or not participant, it is possible that already fatigued participants would decide not to participate in the nighttime trial. Even without any attempt to randomize the day and night cohorts, both groups were essentially the same.

Day versus Night results

While common sense might suggest that daytime searching is more productive than nighttime visual searching, this is the first study to quantify the difference. The daytime effective sweep width for the medium visibility adult was 64 meters; the nighttime value was 22 meters for a day-to-night correction factor of 0.34. Looking at the lateral range curves (**Fig. 3**), it can be observed that all of the search objects that were detected during the day were also detected at least once at night. However, at 18 meters and beyond subject detection never exceeded 5% while many of these same subjects (>18 meters) were detected more than 50% of the time during the day. Therefore, while it was possible to illuminate the more distant search objects to a sufficient level to make the detection, the low illumination associated with mesopic vision made detection much more difficult. The illumination or lux at the search object would also be conditional on the flashlight's throw level. Throw is a measure of how far away a flashlight will "usefully" light an object. Useful is defined by ANSI/NEMA FL 1-2009 standard as being at least 0.25 lux (about a full moon) (ANSI, 2009). The throw distance is not necessarily proportional to the overall lumens generated by the flashlight since it varies with the characteristics of the focused beam (Gawthrop, 2005). Typically, the brighter the illumination, the more cones are activated, and thus more clarity and color vision is achieved (Fotios & Cheal, 2009).

The lateral range curves (**Fig. 3**) also reveal another important difference between the day and night experiments. The day time LRC shows nearly 100% of the targets were detected by the searchers to a distance of 13 meters then the probabilities start dropping off. While for the night experiment some searchers missed a target one meter off the trial and probabilities steeply dropped off immediately beyond even one meter. Targets were not placed directly on the path to test a lateral range of 0, since the path was used by the general public and would have posed a safety hazard. Koopman (1980) describes a LRC that conforms to the inverse cube law as approaching or reaching 100% POD at a lateral range of 0, staying at or near 100% POD for some lateral range, then dropping off. Frost (1996) states that in US Coast Guard experiments with deteriorating search conditions the sweep width becomes both smaller and the peak drops below a POD of 100%. Under these conditions he suggests the exponential curve should be used. This appears to be a good description of the shape of the night experiment's LRC.

The detection of the medium-visibility adult-sized search objects was used to test distance searching and generate a lateral range curve. The placement of clues (glove-sized) along the path required the searchers to shift attention between distant and near searching, as required on actual searches. During the daylight, 100% of the high-visibility clues were detected versus 94% at night (a statistically significant difference). For the low-visibility clues, 80% were detected during the daylight and 42% at night. A similar daytime experiment conducted in New Zealand found 99% of high-visibility clues and 53% of low-visibility clues detected (Koester et al. 2013). The two experiments differed in that Appomattox was conducted on a trail (1 meter in width) with a single searcher and New Zealand had a pair of searchers along a dirt road (3 meters in width). Even with these differences the results are compatible. In searching linear features such as roads or trails it is suggested that these Probability of Detection values for clues can be used directly as a guideline. Low-visibility gloved-sized clues can be missed even when placed directly on the trail and even high-visibility clues can be missed during the night.

The steps required to go from a sweep width value to the actual Probability of Detection (POD) value are well described (Koopman, 1980)(Stone, 1989). The application of a correction factor is a straight-forward adjustment (IMO/ICAO, 2013). If a search segment has a sweep width value derived from a previous daytime ESW experiment or daytime Range of Detection experiment adjustment (Koester et al, 2014), then the night correction factor of 0.34 is multiplied by the daytime sweep width to obtain the corrected night value. If the daytime value was 100m, the area was searched at night (*Cf*=0.34), by a fatigued (*Cf*=0.5), inexperienced team (*Cf*=0.85), and they all had weak flashlights below 200 lux (*Cf*=0.5), then the corrected sweep width would fall to 100m*(0.34)(0.5)(0.85)(0.5) = 7.2m. It is still possible to obtain a high POD, but it would require at least ten times the effort compared to a daytime search with a team that was not fatigued. This begs the question: is night searching even warranted? A lack of any nighttime searching produces a POD of 0%. In addition, we can deploy a non-fatigued experienced team with brighter flashlights and the correction factor becomes 100m*(0.34) = 34m. The team would be expected to detect 94% of high-visibility clues and 42% of low-visibility clues on a trail and potentially hear the subject (night auditory sweep width = 306m) or see a light source (night light detection sweep width = 277m) (Koester et al, 2013). The ultimate tactical decision is up to the planning and operational needs of the incident and types of resources available.

Flashlight illumination effects

In designing the experimental methodology some thought was given to controlling differences in flashlights by issuing a standard flashlight with fresh batteries. However, it was eventually decided to let searchers use the flashlight they currently use on actual searches and measure the light output of the flashlights (night exercises are a regular part of the class curriculum). Searchers used just handheld flashlights or headlamps or a combination of the two. If they used a combination, then the brighter light was recorded. The light output from the flashlights used ranged from 30 lux (LED headlamp) to 8919 lux (tactical flashlight). It was noticed while scoring results that the searchers with the five weakest flashlights (30 – 130 lux) also had the three lowest detection rates (6% - 18%). Looking at the range of flashlight illumination levels, cutoff values of 200 and 500 lux were selected. Searchers with flashlights below 200 lux had a sweep width value half of what bright flashlight (> 500 lux) searchers obtained (12m vs 24m). Only three searchers had flashlights in the intermediate range of 200-500 and they had an intermediate sweep width value of 22m. If the thresholds are changed to simply less than 200 lux or greater than 200 lux then the sweep width values stay at 12m versus 24m. This may be a simpler paradigm to apply in the field. It is hoped all searchers would have a strong flashlight that generates at least 200 lux at one meter; for those that don't have a strong flashlight a correction factor of 0.5 is applied. A better brighter tactical flashlight with a good throw distance is perhaps the quickest, least expensive, and easiest way to improve nighttime searching.

Searcher experience

One of the more surprising and controversial findings from previous daytime sweep width experiments was that experience at SAR (as measured by years in SAR or number of field searches) did not correlate with a higher detection rate (or sweep width value) (Koester, et al, 2014). This was again confirmed during the daytime experiment where those with ten or fewer searches had the identical sweep width value as those with more than ten searches. In fact, the individual with the greatest detection rate had never been on a single SAR incident. Instead, he had led a Marine reconnaissance unit for over twenty years. It has previously been observed that participants with occupations that require daily “searching” out to visual infinity are far more predictive of successful detections than actual SAR experience. However, for the nighttime searching a difference in the sweep width value for those with ten or fewer searches (ESW=22m) versus those with more than ten searches (ESW=26m) was observed, a difference of 15%. The raw number of subjects detected was 43% for the experienced group and 28% for the inexperienced group. A possible confounding factor was the brightness of the flashlights between the two groups. No one in the experienced group had a flashlight that measured below 200 lux while 35% of the inexperienced group had weaker flashlights. In an effort to control for this, if the weak flashlight results are removed from the inexperienced group as shown in **Table 3** the inexperienced group still has an ESW value of 22m. Since the raw number of detections of the experienced group (43%) is still significantly greater than the raw number of detections (33%) of the inexperienced group with brighter flashlights, a correction factor of 0.85 is reported. It is hypothesized that the difference might still be a result of the confounding factor of the flashlight’s illumination and/or improper use of flashlights and/or a higher level of anxiety among the inexperienced group of searching alone at night.

Detection models

The working hypothesis of this experiment was that daylight coverage versus POD would follow the inverse cube model while the nighttime experiment would follow the exponential curve. Previous experience with land-based visual LRC for medium-visibility search targets looked similar to LRC associated with the inverse cube model. Searching at night represents an adverse environmental condition that was expected to have a smaller sweep width value and a lower POD at a lateral range of zero, resulting in the exponential curve. Both of the experiments resulted in curves between the inverse cube and exponential curves as shown in **fig. 4**. Between the coverage of one and two the day curve starts approximating the inverse cube curve and the night experiment the exponential curve. The empirical land-based day and night data also closely match the empirical maritime data reported by Edwards et al. (1980). However, clearly more experiments are needed to draw any conclusion other than that the experimental data confirms they are between the inverse cube and exponential.

It is not too surprising that the empirical data fell between the inverse cube and exponential curve. The methodology used to define the search area created by a single track perfectly centered in the search area gives: no navigational errors, no duplication of effort, no large gaps, and no mobile search objects. Therefore, results better than the exponential curve might be expected. However, both the day and night results generally fell below the inverse cube curve. This can also be partially explained by the methodology used by this experiment which placed a single track in the search area. However, the inverse cube formula is based upon integrating an infinite number of parallel tracks within the search area. Washburn (2014) has shown that a search with five parallel tracks that provides coverage of 1.0 would actually have a POD of 67% instead of the predicted 79% from the inverse cube equation [4]. The difference is caused by the lack of overlapping coverage at the two sides of the search area. Looking at the actual empirical data is even more insightful. Using the LRC from the nighttime experiment and the coverage of 0.5 very little overlap of the adjacent track occurs as seen in **fig 5a**.The nighttime single track POD was 44.3% and when the adjacent tracks are added it increases slightly to 46.4%. The inverse cube equation predicts a POD of 46.9% for the coverage of 0.5. The coverage of 1.0 with a single track down the center of the search area results in a POD of 74.7% using the empirical nighttime data. However, when the LRC is added from the adjoining tracks (**fig. 5b**) the cumulative LRC shifts upwards. The new integrated POD then becomes 80.5% which for empirical data is close to the predicted 79.0% of the inverse cube equation. The amount of overlap significantly increases when the coverage is increased to 2.0 as shown in **fig 5c**. The nighttime empirical POD data for a single track at the coverage of 2.0 was 91.0%. When the overlapping adjacent tracks are added the empirical data achieves a POD of 97.4% compared to the predicted POD of 98.8% from the inverse cube equation. Once the correction is made for adjacent tracks, even the nighttime data best matches the inverse cube curve. However, it is important to keep in mind that adjacent tracks would not occur if the land tactic being used was a single linear or hasty task.

Since a single track linear task is perhaps the most common task in land SAR what is the best approach? The conclusion certainly cannot come from a single experiment. The best answer most likely lies between the exponential and inverse cube curves. From a strictly empirical perspective a curve fit of the data would suggest the same empirical equation that Edward et al. reported and is shown in equation 6.

A requirement for the definite range and inverse cube models are searching along perfect parallel paths. Since the experiment was carried out along a linear path and the actual search area was defined by lateral ranges from the linear path, it creates a situation similar to perfect parallel tracks. A fair question: Are perfect parallel paths operationally possible in the land environment? One of the most common search tactics is a linear task (also sometimes called a hasty) along a road, trail, hydrological feature or other linear features. When assigned such a task the team is often not only assigned to search the feature but also a specific distance from the feature. In this circumstance the operational search area would match the experimental setup. It would also mean that the POD would not benefit from an overlapping adjoining search track. Therefore, the POD would always be expected to be less than the inverse cube curve. Another common method used to cover area is the sweep or grid search tactic (National Search and Rescue Committee, 2011). The tactic differs from maritime and aeronautical parallel search in that several searchers typically line up well within visual sight of each other and attempt to maintain uniform spacing. Depending upon training, experience, and terrain it may be easy or difficult to maintain equal spacing during a task. In addition, some searchers may receive tasking instructions to "wander" within their spacing lanes in order to check out obstacles or other points of interest. Therefore, operational reality for land SAR ranges from always being able to maintain a "parallel" path during linear tasks to a situational ability during sweep or grid tasks.

No error bars are shown for the two experiments (**fig. 4.).** The coverage is directly related to the sweep width as shown by equation 6. Combined data from all search participants is required to generate the LRC which involves determining the POD at various lateral ranges. Since the W value is the area under the LRC (equation 2), it therefore also requires all participants to determine the W value. This precludes error bars around the W value even though individual detection rates and total targets detected varied from searcher to searcher since the W value integrates the efforts of all searchers. This also precludes error bars around the plots of the coverage versus POD since it took the entire searcher population to determine the POD. Therefore, any interpretation of the data is limited since it represents only two experiments for a single visibility class of search object in one particular type of terrain and vegetation during the winter.

The furthest a target was placed was a lateral range of 45 meters, therefore the smallest possible coverage was 0.71 for the daytime experiment. The lowest coverage shown for the day experiment is 0.75 and then coverage is shown in increments of 0.25 up to coverage of two. Operationally, coverage of two represents a reasonable upper bound for land SAR. For the night experiment, two additional coverages could be determined since the W value was much lower. At coverages below 0.5 it becomes more difficult to distinguish between the definite range, inverse cube, and exponential models.

Limitations

The chief limitation is that this paper reports two experiments (day and night), in a single environment, with a limited range of search targets. It is unknown if the correction factor of 0.34 applies during summer conditions, in a dry domain, with child or clue-sized objects, or even with different visibilities of subjects. This paper did not discuss illuminated signal devices such as flares, fires, lights, or laser flares that might be detected from kilometers away. Nor does it discuss high visibility retro-reflective material. Searching for these materials along with a flashlight with a good throw distance could result in detections better than daytime results, based upon some preliminary field data. However, the use of retro-reflective material by missing subjects is generally rare for most land-based searches.

This paper suggests a nighttime correction factor for searcher experience. However, these results were confounded by weaker flashlights. While an attempt was made to control for this effect it is still possible that brighter flashlights might have accounted for all of the differences in nighttime searcher experience. Flashlights clearly affect what can be detected at night with the complex relationships of throw distance, total lumens, beam width, lux at fixed distances, battery life, color output, and portability. It would take considerable research to find the best combination. Ultimately, user preferences are a large factor. The methodology calculated values for a single searcher. This is operationally relevant given that when calculating the coverage obtained by a team conducting an area task, it is critical to know the sweep width value for each individual sensor (searcher). However, for a linear task where the interest might be limited to finding clues along a path, the typical minimal tactical deployment would be two people.

This research provides some validation for the use of the inverse cube or exponential search curves. With essentially only two experiments it is impossible to make any definitive statement. As previously stated the results only represent a medium visibility (blue) subject, in a winter forested environment with moderate terrain.

Conclusions

This study, using search and rescue trained resources, provided an objective correction factor of 0.34 for the sweep width between daytime and nighttime searching. It showed that while more distant targets were still illuminated and detectable, mesopic vision makes it difficult to make an actual detection. Clue-sized objects placed directly on the trail were also more difficult to detect at night. Once again it was shown that searcher experience (measured by number of searches) did not affect the sweep width value during the day but resulted in a correction factor of 0.85 at night. The brightness of the flashlight was also significant with flashlights dimmer than 200 lux at one meter resulting in a correction factor of 0.5. The study also validates the use of detection models in the land environment to predict a POD value. Once the empirical data was corrected for adjacent tracks, the inverse cube equation was a good predictor of the POD. However, in situations such as linear or hasty tasks with a single track the POD is expected to fall between the inverse cube and exponential curves.

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About the Author

Robert J. Koester first joined the Appalachian Search & Rescue Conference in 1981 and since then has participated in hundreds of searches, including over a hundred as Incident Commander. He holds a Ph.D. from the University of Portsmouth in search theory and a MS and BA from the University of Virginia in biology (neurobiology). His contributions to search and rescue include seminal research on search theory and lost person behavior along with creating the International Search and Rescue Incident Database (ISRID). He is an instructor for the Virginia Department of Emergency Management since 1988 and past-president (15 years) of the Virginia Search and Rescue Council, Robert has also worked for the USCG (conducting visual sweep width experiments), NASA (conducting missing aircraft radar research), NPS (responding to major searches and writing the draft NPS *SAR Field Manual*), FEMA (as an instructor and disaster reservist), and SAR Institute of New Zealand (conducting sound and light sweep width experiments). He is currently developing SAR software called FIND, for the US DHS S&T directorate. He also developed courses for DCJS and was a Cardiac Technician for twelve years with CARS. He is the CEO of dbS Productions which provides research, software & publications, and training services. He is also a visiting researcher at the University of Portsmouth. Robert has authored dozens of books and research articles on search and rescue, including *Lost Person Behavior,* and is widely cited.

Abbreviations

AMDR	Average Maximum Detection Range
ANOVA	Analysis of Variance
C	Coverage
Cf	Correction Factor
ESW	Effective Sweep Width
IDEA	Integrated Detection Experiment Assistant
LED	Light Emitting Diode
LRC	Lateral Range Curve
M	meters

MS	MicroSoft
OPOS	Overall probability of success
POA	Probability of Area
POC	Probability of Containment
POD	Probability of Detection
R	Range
R&D	Research & Development
Rd	Range of Detection
S	Spacing
SAR	Search and Rescue
USCG	United States Coast Guard
USN	United States Navy
VDEM	Virginia Department of Emergency Management
Vis	Visibility
W	Sweep Width

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