Search Methods for an Autonomous Underwater Vehicle using Scalar Measurements

by
Erik Alfred Burian

B.S., Systems Engineering, U.S. Naval Academy, 1989.

Submitted to the Joint Committee on Applied Ocean Science and Engineering in partial fulfillment of the requirements for the Degree of

Master of Science

at the
Woods Hole Oceanographic Institution
and the
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ABSTRACT

The continuing development of the autonomous underwater vehicle as an oceanographic research tool has opened up the realm of scientific possibility in the field of deep ocean research. The ability of a vehicle to travel to the ocean floor untethered, collect data for an extended period of time and return to the surface for recovery can make precise oceanographic surveying more economically practical and more efficient. This thesis investigates several scalar parameter searching techniques which have their basis in mathematical optimization algorithms and their applicability for use specifically within the context of autonomous underwater vehicle dynamics. In particular, a modified version of the circular gradient evaluation in the simulated environment of a hydrothermal plume is examined as a test case. Using a priori knowledge of the expected structure of the scalar parameter contour is shown to be advantageous in optimizing the search.

Thesis Supervisor: Dana R. Yoerger, Ph. D.
Title: Associate Scientist, Deep Submergence Laboratory,
Woods Hole Oceanographic Institution

Acknowledgments

It's interesting to look back on the time here at MIT and Woods Hole. My "shore tour" seemed to go rather quickly, but the time spent was rich with learning, personal revelations and meeting new friends. I come away with an insider's perspective on the scientific community and a fundamental appreciation of the absolute necessity to continue supporting scientific research. There are a number of people who helped make this time both successful and personally rewarding, and it is absolutely necessary to recognize them formally.

United States Navy - for the fantastic opportunity to study full time in the MIT/ Woods Hole program. It's been both an adventure and a challenge, and I wouldn't want any other job.

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My family: Mom, Dad, Chris, Scott and Higgins - you have always been supportive of me in so many ways when I needed it most. I consider it the greatest blessing to be able to enjoy our time together.

Author's Biographical Note

Erik Alfred Burian was born the son of a German immigrant in Bay Shore, New York on July 15, 1967. He grew up on Long Island with brothers Christian and Scott. He attended Longwood High School in Middle Island, New York and was awarded the honor of class valedictorian upon graduation in June 1985. He was sworn into the naval service with the U.S. Naval Academy class of 1989. While a midshipman, he sailed extensively with the offshore training squadron, including a cruise between Annapolis, Bermuda and Newport, RI. He graduated with distinction after completion of a B.S. in Systems Engineering and was commissioned as an officer in the United States Navy.

In preparation for duty in the submarine force, LT Burian successfully completed Naval Nuclear Power School, Naval Nuclear Prototype Training and Submarine Officer Basic Course. He was then assigned duty aboard the *USS Lapon (SSN-651)* stationed in Norfolk, VA. He remained with the crew in various engineering positions until ship's decommissioning at Mare Island Shipyard in Vallejo, CA in June 1992. After a 4500 mile drive across America via numerous national parks with his brother Chris, he joined the crew of the *USS Whale (SSN-638)* in New London, CT. Aboard the *Whale*, LT Burian qualified in Submarines, passed the Nuclear Engineer's exam and held the billets of Communicator and Damage Control Assistant. He participated in a UNITAS deployment that circumnavigated South America and an extensive Arctic deployment, during which the submarine surfaced through the ice on many occasions, including at 90° North. He left the ship in Bergen, Norway in May, 1994 to enter the MIT/Woods Hole Joint Program.

In June 1996, he presented a paper entitled "Gradient Search with Autonomous Underwater Vehicles Using Scalar Measurements", which forms the basis of many ideas contained in this thesis, at the AUV '96 Conference at the Naval Postgraduate School in Monterey, CA. Upon completion of a Master's Degree in Ocean Engineering in August 1996, the author will attend Submarine Officer Advanced Course in New London for tactics and operations training prior to being assigned duty as the Combat Systems Officer aboard the *USS Boston (SSN-703)*.

I dedicate this thesis to my parents, Alfred and Edith Burian,
who have taught me the truly important things,
and to my brothers, Christian and Scott, who have always
been there to enjoy them with.

Bright fame he gat,
Eirik from that.
Eirik o'er sea
Paid the wolves fee.

-Egill Skallagrimsson
Icelandic Viking poet

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Section 1: Introduction

1.1 Motivation

This research project has its origin in the desire of scientists to study ocean processes in an economical and practical manner without the restrictions and difficulty involved with the traditional method of hydrographic casts. The autonomous underwater vehicle (AUV) offers the freedom of being able to measure parameters at almost any depth, the mobility of a free-swimming platform and the ability to tailor the search mission to best advantage based on in situ measurements. The current level of AUV technology permits both pre-programmed missions with the Autonomous Benthic Explorer (Yoerger, et. al.[1996]) and the Aqua Explorer 1000 (Asakawa[1995]) and supervisory control via acoustic commands with the Odyssey II (Altshuler, et. al.[1995]), AMMT Draper vehicle(Zorpette[1994]) and the AUSS(Uhrich and Walton[1993]). The vehicle typically returns to the launching platform to allow operators to download collected data. While some missions may require an exhaustive search, I have investigated situations where it may not be necessary for the vehicle to span the entire search region to accomplish the stated goals of the mission. The value of an AUV as a sampling tool will be even greater when the vehicle can successfully employ sample-based searching algorithms to make movement decisions as it measures. This thesis is directed towards that task.

1.2 Research Objectives

The goal in any engineering effort is to provide the tools and the methods to successfully and accurately accomplish a very specific task. In this thesis, that task is defined as the sampling of a volume of the ocean by an AUV. The particular parameter to be sampled is not the focus, although several will be discussed with respect to missions in the vicinity of hydrothermal vents. The focus of this project is to examine a number of search strategies and evaluate them within the unique restrictions specific to an AUV. The most important constraint is the finite power reserves available on board and thus, particular emphasis is placed on how to make the AUV perform the survey efficiently. The traditional measure of efficiency is vehicle power expended per distance travelled, but moving the vehicle doesn't necessarily mean that additional useful information is being collected. A more meaningful metric would be information gained per energy expended. This idea is discussed extensively by (Singh [1995]).

In order to make sampling practical for the individual scientist with limited resources, the method to accomplish the desired tasks must be conceptually simple to understand and relatively easy to implement in a variety of environments and on various AUV platforms. It is my intention to develop a set of search strategies that the scientist can keep in his or her toolkit and then utilize on an AUV to conduct measurements in a survey region as the need arises. The amount of a priori knowledge available will help to initially define the search.

Some overlaying conditions for the research described in this thesis need to be specified at the outset. It must be understood that oceanographic features are fundamentally patchy and typically are difficult to fit neatly into a hypothetical model. The methods explored have included the premise that an exhaustive search is in fact unnecessary, and undesirable from a scientific perspective, for mission goal accomplishment. The single vehicle will be investigating pseudo-stationary processes based on an expanding on board history of scalar oceanographic measurements. This differs from the idea of using multiple vehicles in coordinated movement (Bellingham and Willcox[1996]; Gage[1995]).

Considerable attention has been focused on the nature, structure and composition of the waters surrounding hydrothermal vent regions. Since these areas are quite localized and are typically found in very deep waters, most of the sampling and observations of the hydrothermal vents has been conducted by manned submersibles, such as *Alvin*, from the Woods Hole Oceanographic

Institution, and by means of hydrographic tows and vertical water column samples. Since manned missions are limited by funds and vehicle availability, considerable efforts have been made to make an AUV mission to the vents complimentary to a manned mission. The capabilities of the Autonomous Benthic Explorer (ABE) will be used to simulate vehicle travel over parameter contours from previous surveys of hydrothermal regions and local bathymetry. Data sets of hydrothermal vent area temperature contours have been collected from various sources and have been used as a testbed to evaluate the performance and efficiency of a number of the search methods.

1.3 The Autonomous Benthic Explorer (ABE)

This thesis was conducted with a specific vehicle in mind as the platform to use when searching. The Autonomous Benthic Explorer was designed by Dana Yoerger, Albert Bradley and Barrie Walden of the Woods Hole Oceanographic Institution. As its name indicates, the vehicle is specifically equipped for investigation of the ocean floor. It was not designed to be a fast vehicle, but rather a slow speed, very stable platform for oceanographic sampling and video and still visual images.

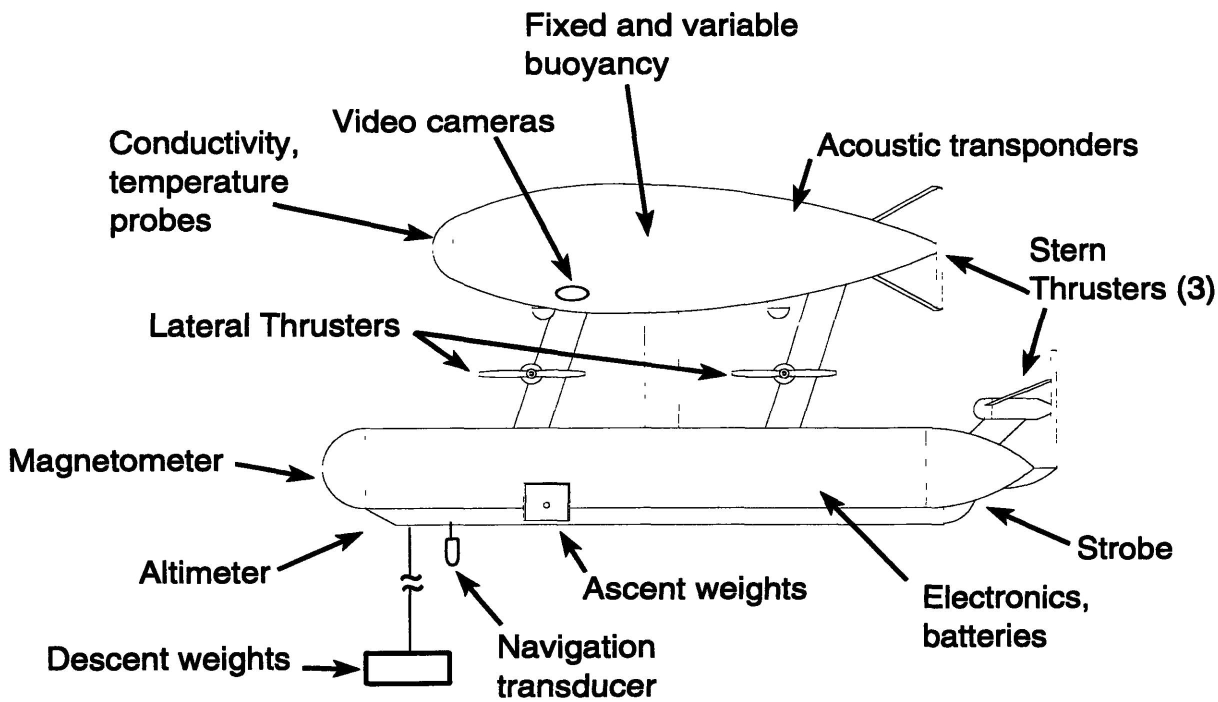


Figure 1. Line drawing of the Autonomous Benthic Explorer (ABE).

It's two upper flotation pods and lower, electronics housing provide ABE with inherent horizontal stability. The vehicle has seven thrusters and is capable of uncoupled motion in the x-, y- and z-axes, as well as being able to rotate in place in the horizontal plane. It is depth rated to 5000 meters and has a conservative range of 10 km with lead-acid batteries.

ABE has already performed missions to the seafloor at the Juan de Fuca Ridge and was able to verify the presence of a hydrothermal feature based on a pre-programmed temperature survey. Magnetic anomaly was measured and video and still images from these missions demonstrated the viability of using an AUV to perform tasks previously only capable with towed instruments (Yoerger, et. al. [1996]).

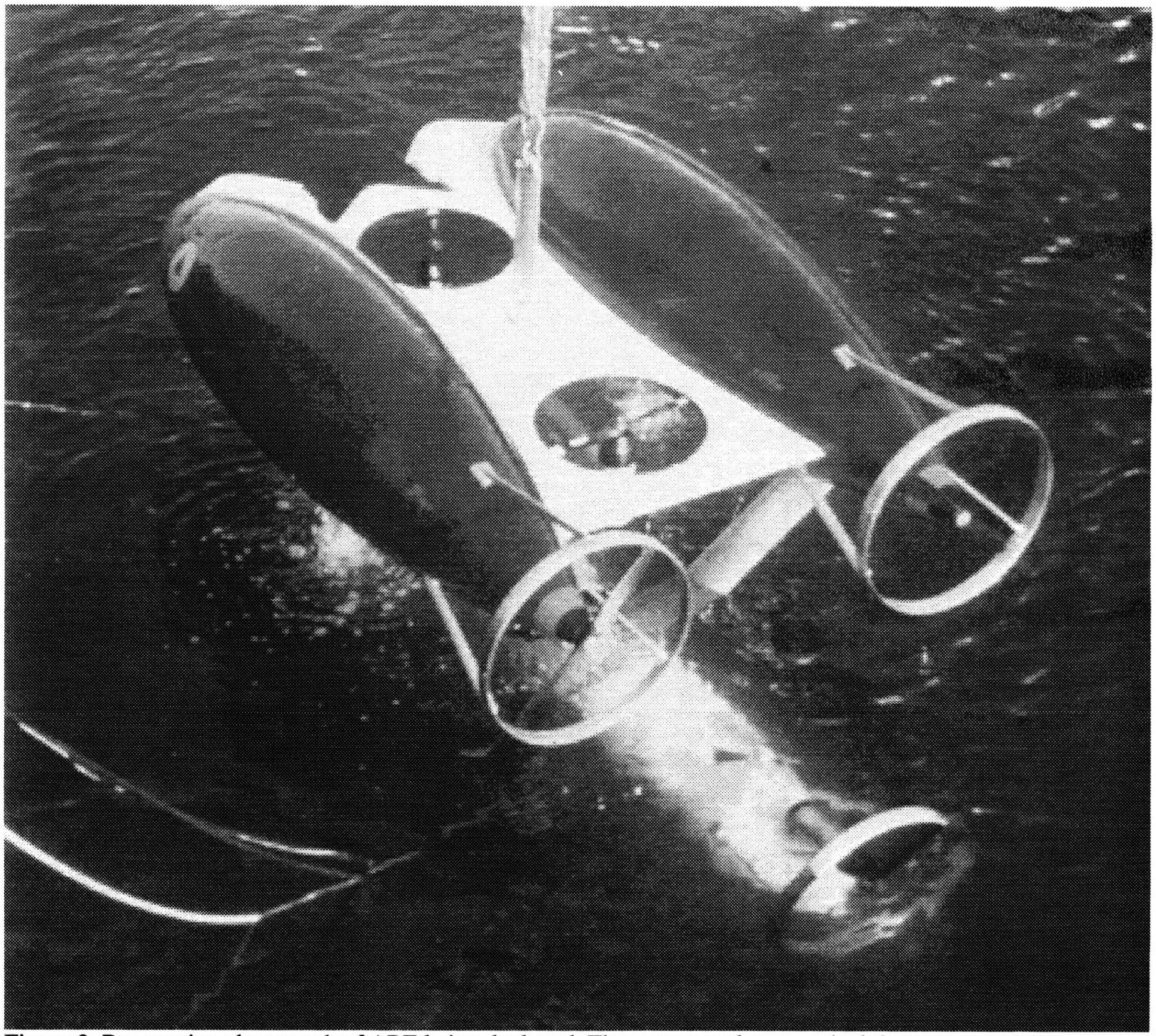


Figure 2. Perspective photograph of ABE being deployed. Three stern and two vertical thrusters are visible. Photo credit: Al Duester, WHOI.

1.4 Outline of Thesis

The thesis develops as the research did. Section 2 examines a number of searching strategies. Some traditional methods, such as the simplex search and simulated annealing, are discussed and compared to some nontraditional methods, such as the taboo search. The concept of the circular gradient evaluation is initially presented as a method more suitable for use by an AUV.

Section 3 contains a discussion of the waters surrounding the hydrothermal vent regions, including their scientific significance, measured and modeled physical structure, typical dimensions, parameter magnitudes and variations, and a discussion of previously collected data.

Section 4 examines the particular value of several search techniques in the vent regions. Specifically, the Direction Set Method and the circular gradient evaluation are studied. The development of a hybrid method is explained and variations on this method are described in detail. Results from numerous simulated runs are presented with discussion.

Section 5 discusses the practical application of the search strategies mentioned earlier. The real challenge of converting the theory of conducting an AUV scalar parameter search to a formal code of instructions to be installed on a vehicle is addressed. Specific questions to guide the search set up are discussed.

Section 6 provides an overview of the research project, a brief conclusion and directions for future work and applications.

Section 2: Search Methods

2.1 A Brief Introduction

The concept of searching for something in the ocean or on the seafloor is centuries old. Yet, the tools to conduct that search have improved dramatically in recent years. Advanced sonar systems such as SHARPS or EXACT and vastly improved optical systems such as the Seatex Laser Profiler have greatly increased the level of precision with which scientists can conduct oceanographic surveys. Both of these instruments are capable of producing results on the order of one centimeter resolution or less. The measurement tools for sampling certain seawater properties have achieved a similar level of sophistication. For example, the advertised performance specifications of the Ocean Sensors OS100 CTD are summarized below:

Table 1: CTD Performance Specifications

Parameter	Units	Range	Accuracy	Resolution
Pressure	decibars	0-5000	0.2%	>0.005%
Temperature	degrees C	-2 to 35	0.020	>0.001
Conductivity	mS/cm	0.5 to 70	0.020	>0.001
Salinity	PSU	0.5 to 45	0.030	>0.001
Time	seconds	1 to 1 year	1	0.1

Now that we have the tools to conduct very accurate searches, the methods of searching can also improve concurrently. The most obvious and inherently thorough type of search is to conduct multiple parallel runs while minimizing both the amount of overlap during the straight sections and the area missed while repositioning for the next run. The U.S. Navy has spent considerable time and effort in addressing this challenge. The four basic parameters to design a search strategy are the effective sensor range, the lane spacing, navigation system error and the distance the survey platform must travel while traversing the lane and during course reversal (Jourdan [1986]). Equations to define the level of coverage can then be developed. The range of sensor effectiveness and navigation accuracy are the dominant factors in determining lane width. The errors introduced by relative motion between the sensor and the survey platform, as in the case of a towed sonar or CTD, and the inherent navigation system positional inaccuracy may make positive overlap a necessity when searching for relatively small features.

Some fundamental guidelines for the design of geophysical surveys have been put forth by (Davis[1974]). These include the provision that the theory should allow estimates of the total variance or mean square error and the spectral content of the sampling error as a function of the survey pattern to be made. The error estimates should be in a format that facilitates their propagation through a variety of linear operations. Davis recommends that the computational burden should be manageable enough to handle with a small scale computer. Fortunately, the accelerating advances in computer technology have reduced the size of quite powerful computers to permit their installation on AUVs.

The probability of detection of an unspecified target by a search platform and has been thoroughly investigated and discussed by (Koopman[1946]). He discusses random searches and "parallel sweeps" with regard to both moving and stationary targets. Although it is generally assumed that the target or object of an oceanographic search is not moving, many AUVs travel at speeds on the order of 1m/s or less and currents can be significant enough so that the vehicle will experience a moving frame of reference when sampling waterborne parameters. For the following explanation, these variables are defined:

p = probability of detection for random search

$P(S)$ = probability of detection for parallel sweeps with spacing S

W = effective search width

L = length of the observer's path

A = area in square dimensions

Several assumptions must be made with regard to a random search. We can expect the target or goal of the search to appear in the search region according to some random distribution. The observer's path must be random in the search area, A, in the sense that it's independent portions should not be placed too near each other in A. On any portion of the path that is small compared to the path length, L, but definitely larger than the range of possible detection, the observer is assumed to always detect the target when it passes within W/2 and never beyond this distance. This results in a formula of random search:

$$p = 1 - e^{-(WL)/A} \qquad (2.1.1)$$

Thus, the probability of detecting the target increases exponentially with path length and approaches one asymptotically. If we were to expand eqn. 2.1.1 into a series and retain only the first two terms, assuming no overlap, a probability function that defines the definite range law remains:

$$p = (WL)/A \qquad (2.1.2)$$

Koopman makes a similar examination of parallel sweeps. In this discussion, the x-axis is perpendicular to the sweeps and the y-axis is parallel. The probability of detecting the target on the nth sweep is given by

$$p_n = 1 - e^{-F(|x - nS|)} \qquad (2.1.3)$$

where F is a potential given by an appropriate formula. The general solution of the detection probability given by a sweep with width S becomes an exponential integral incorporating a sum of potentials

$$P(S) = \frac{1}{S}\int_0^S (1 - e^{-\Phi(x,S)}) \qquad (2.1.4)$$

$$\Phi(x,S) = \sum_{n=-\infty}^{n=\infty} F(|x - nS|) \qquad (2.1.5)$$

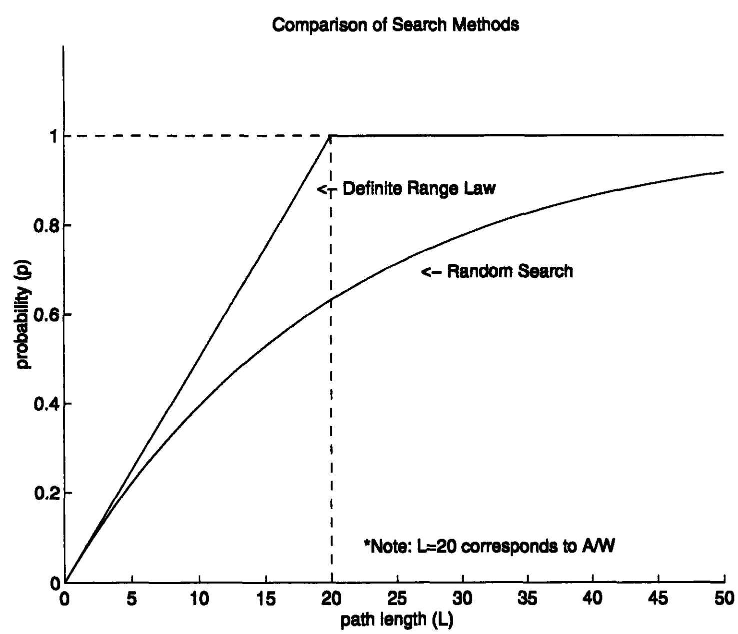


Figure 3. This shows the bracketing of the probability of search success between a no overlap search defined by the definite range law and a purely random search. Variations on the parallel sweeps, including the coordinated multiple vehicle search described by (Gage[1995]), would fall between the two types shown in the figure.

The lines on the plot in Fig. 3 require further explanation. It is important to note that the high probability of detection depends on having perfect navigation, which is not quite possible with an AUV. The random search can be conducted with little or no navigation capability and its detection probability is appropriately lower. The line for coordinated vehicle operation would be a curve of straight line segments that would lie between the two curves. This method has received consideration as a cost effective way of dealing with the mine countermeasures problem (Gage[1995]). The loss of one or more vehicles, out of many, would in this case be acceptable and expected. The cost for these different approaches will vary accordingly and mission requirements for navigation precision and search area coverage will dictate which option is economically and scientifically advantageous.

Many of the early principles of searching for an object were designed with an aircraft or ship in mind as the search platform. An AUV has similar motion characteristics, but possesses a significant advantage when conducting oceanographic surveys. While an aircraft looking for a ship or a ship looking for a submarine travels it only gains information where the target isn't, an AUV measuring a scalar parameter can sense changes in that parameter and detect at least local minima and maxima to guide its motion decisions. Though models for ocean parameters exist and can be incorporated into the search framework, the vehicle is still traveling in an environment undefined by any known function. The difficulty of searching with little or no a priori knowledge of the environment will be addressed by drawing on the improvements in function minimization by a number of mathematical techniques.

2.2 Starting with the Direction Set Method

In order to present the proper context for the vehicle search being studied, a description of the engineering problem and accompanying initial assumptions is necessary. There will be only one vehicle conducting the search. It will not be a multi-vehicle survey. A number of instruments may be installed on the vehicle. Instruments sampling oceanographic parameters will be only capable of making scalar, "along-track", measurements as the vehicle travels through the ocean. I make the assumption that the parameter will be a continuously varying scalar function of x, y, and z. At the outset, this scalar field will be time independent and then later, the complexity of a time-varying scalar field will be discussed.

An initial attempt at solving the problem of driving the vehicle to the minimum is rather intuitive. The Direction Set Method (DSM) or Powell's method is based on an iterative search of successive single leg minima. We want the AUV to drive in the most downhill (or uphill, depending on the parameter being searched) direction toward the goal of the global extrema. However, it is not possible from a scalar point, single-leg search to determine if the vehicle is headed in the best direction to move downhill. An AUV can only tell if it is, in fact, headed downhill. For the vehicle to build up a stored history of the specified search region, successive search legs are required. The Direction Set Method is a practical way to accomplish such a task.

A mathematical representation of the bathymetry of Herring Pond, located just north of the Cape Cod Canal in Massachusetts, was obtained from (Singh[1995]). This data set was used to experiment with variations of the DSM. The basis of the technique is that the vehicle contains memory of the survey region boundaries and is given an initial leg to start the search. It then returns to single leg minima and makes a turn orthogonal to the previous transit and drives to the extent of the survey area. This routine continues until a stopping criteria is reached. The value of the deepest spot is maintained in memory and the change in this value is used as a metric for the improvement of the result. This repetitive path tends to generate a fairly thorough cross-hatching over the area. Of course if the region is purely bowl shaped, the vehicle would rapidly converge on the global value. Unfortunately, this is rarely the case in a natural environment.

Several modifications to the basic procedure were added to improve coverage of the survey area and reduce unnecessary vehicle travel. If, after a required number of full length transits, the change in the global minima is less than the specified value, the length of the legs is shortened and the orientation of the paths is changed. The vehicle now searches in an X pattern rotated slightly from previous legs. After numerous attempts, thirty degrees was accepted to be a useful rotation for the search axis. The search legs were shortened to a fixed value and then incrementally scaled down with each completed X pattern. The vehicle would continue the search by driving directly to the deepest point traversed during the previous X. If the deepest spot was not exceeded or the change did not exceed the required minimum change, the search is terminated.

The Herring Pond bathymetry contour provides some interesting challenges to the method. It contains a definite global minimum while presenting several local minima. There is a deep plain or flat area to avoid and the contours are not "bowl shaped". However, the deep spot happens to be close to the center of the sample space and the algorithm may have been geometrically forced into traversing the center. If the deep spot had actually been closer to one of the corners, it is possible that the method would not have been as successful. A sample vehicle path is shown in Figure 2.

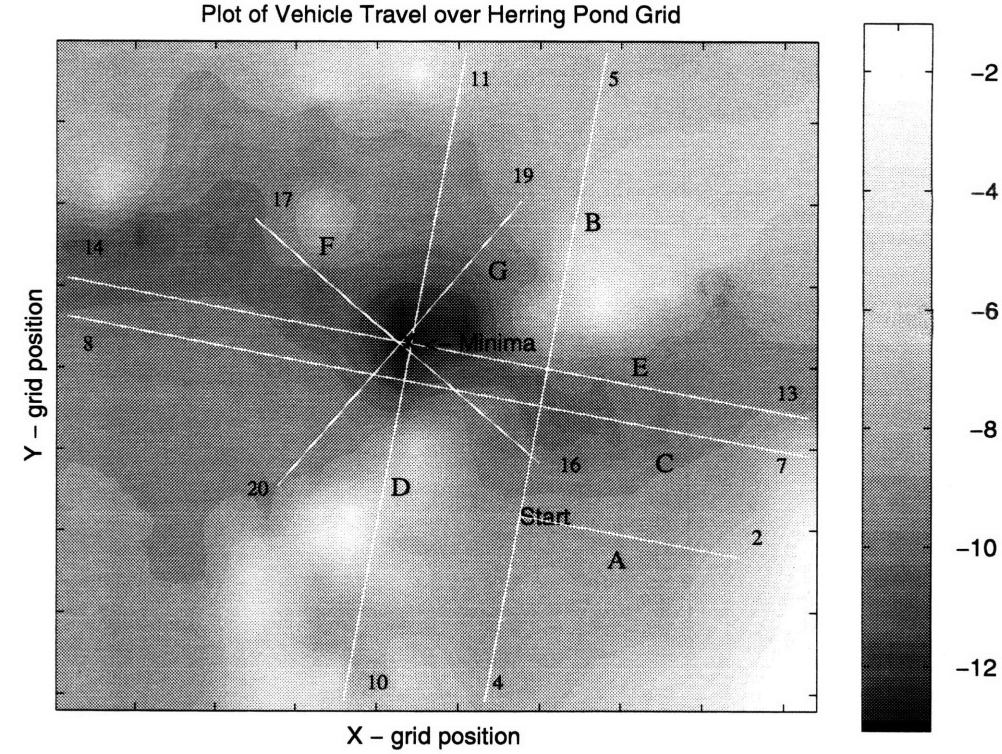


Figure 4. This diagram shows the simulated vehicle travel over the Herring Pond bathymetry contour using a modification of the Direction Set Method for guidance. While there appears to be adequate coverage in the vicinity of the deep spot (dark area), it is easy to see that the corners of the search region have been left untraversed. Legs are in alphabetical order.

The vehicle doubles back on itself during the search to return to areas of interest and it is possible to accomplish this accurately, even in the presence of a prevailing current, with the precision available with a doppler sonar(RDI Workhorse Navigator DVL has a precision of 0.3 cm/s at a vehicle speed of 1.0 m/s). Vehicle turns are not explicitly shown, but would need to be accounted for with regard to the dynamics of the specific vehicle in use.

Despite its limitations, the modified Direction Set Method proved to be quite successful in reliably locating the global minimum. Based on a representative sample of ten runs, the vehicle found the deep spot seven out of ten times (Burian, et. al., [1996]). The instances that the vehicle failed to find the deep spot were typically a result of the vehicle getting caught in deep flat areas. This mode of failure may be overcome by commanding the vehicle to traverse sections of the survey area that were overlooked after the autonomous search has terminated. An examination of the depth record obtained by the vehicle shows how the best depth retained by the vehicle improves with successive legs (Fig. 5). Local minima and inflection points are passed up while the vehicle is commanded to complete the search leg spanning the survey area.

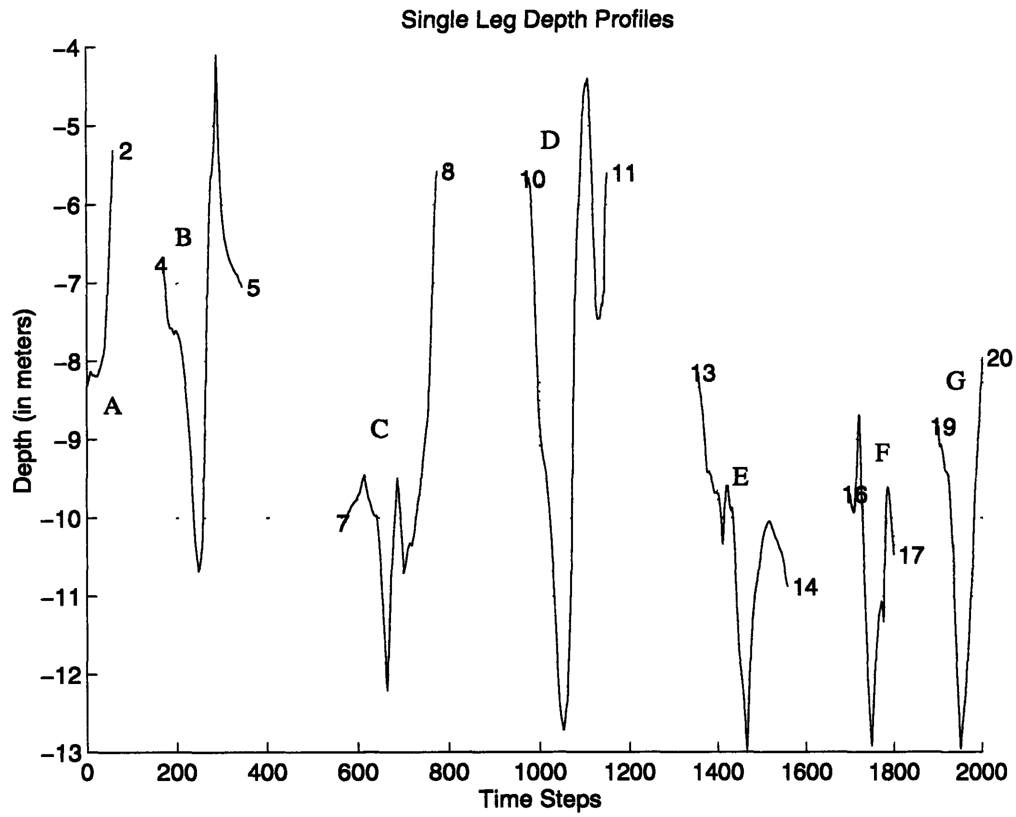


Figure 5. The on board depth record for the numbered legs indicated generated by the path in Fig. 2 is shown. A progressive improvement in the global deep spot is easily seen. The strength of the method is seen in that many local minima along track are avoided. The last two legs shown are taken from the X pattern used to verify the deep spot in the region. Since there is no improvement from the deep spot located on leg 13-14, the search terminates. The search is completed in about 33 minutes. An exhaustive search with 6m track spacing would have taken over 68 minutes.

2.3 Mathematical Search Techniques: Simplex, Simulated Annealing and Taboo

Since the concept of using an AUV as a sampling platform in an unknown yet presumably continuous environment is a mathematical process, I have chosen to draw from several rather non-traditional search methods. The concepts of simulated annealing (Curtis[1994]), simplex method (Nelder and Mead[1964]) and the taboo search (Glover[1990]) all have features that make them appealing in their ability to escape from local extrema and continue navigation through large flat regions. These methods also have the advantage of being able to minimize an unknown function with no information about the derivative of that function. This is not possible with common minimization techniques, such as Newton's Method (Gerald and Wheatley[1989]).

Simplex Search:

The fundamental ideas of the simplex search make it very attractive for use in the realm of AUV's in unknown environments. As described by Nelder and Mead, "the simplex adapts itself to the local landscape, elongating down long inclined planes, changing direction on encountering a valley at an angle, and contracting in the neighborhood of a minimum." A simplex is defined as a geometrical figure that has N+1 vertices when used in N-dimensional space. Therefore, in two dimensions, the simplex is a triangle. An arbitrary starting point is chosen and the highest point on the triangle is reflected through the other side. These reflections are designed to maintain the volume of the simplex. Generally, the triangle is equilateral with a characteristic length scale (λ). If we define P_0 as the starting point and e_i represents one of the N unit vectors, the vertices can be found with

$$P_i = P_0 + \lambda e_i \qquad (2.3.1)$$

However, the real value of the method arises when the lengths of the sides are varied to take larger or smaller steps based on the measured change in the lowest point with each reflection. If the simplex reaches a flat region, the triangle shrinks in the transverse direction and takes smaller steps in the best direction to escape from the valley. If the simplex encounters a very narrow path or saddle in the environment, all legs are shortened about the lowest point and the object squeezes through. When the gradient increases again, the transverse leg is expanded incrementally to take comparatively larger steps downhill.

The question arises how to terminate the search and resolve that the current minima is in fact the global value. Surely, we can make no guarantees about any space that has not been visited, but we can establish a tolerance for minimum movement between successive best solutions and a minimum acceptable change in the measured parameter. The simplex will contract all edges about a minima, whether local or global, and a minimum leg length may also be used as a stopping point. Yet, neither of these criteria prevent the algorithm from getting stuck in a hole during a small number of steps. The simplex method does not have the provision to "see" that a better value of the measured parameter exists somewhere else. The logical solution is to reinitialize the sides of the simplex to their original lengths, keep the minima as the starting vertex and continue the search. This restart should not be computationally or power costly and should maintain a history of where the vehicle has already searched.

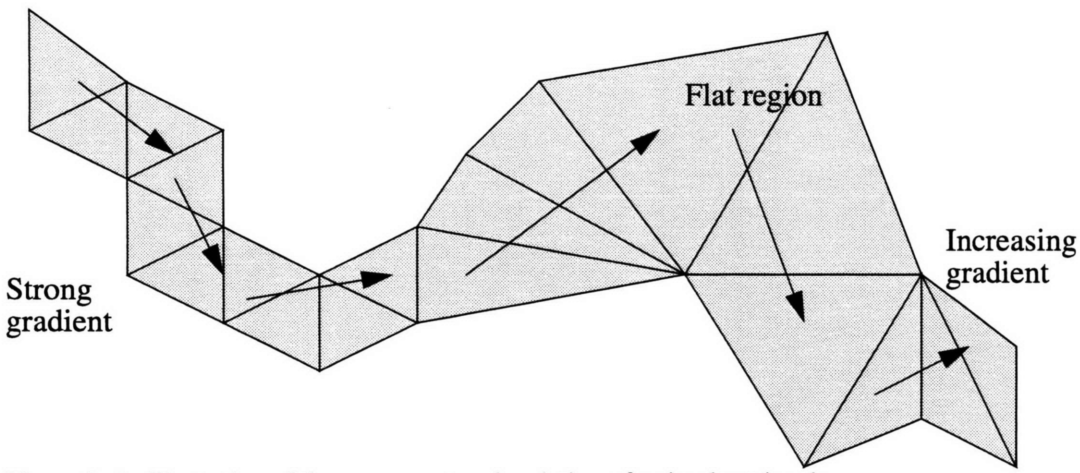


Figure 6. An illustration of the movement and variation of a simplex triangle.

The simplex algorithm, as originally put forth, contains no provisions to keep a history of previously sampled positions, but a travelling vehicle would of course continuously log data. Though it obviously isn't practical to tumble an AUV like a simplex triangle, the concepts of using the two dimensional estimate of the gradient and shrinking and swelling the search length to adapt to the sampled environment has direct application to the idea of the circle gradient search to be discussed in detail later in this thesis.

Simulated Annealing:

While the simplex algorithm accepts all improvements of the current solution as favorable, the method of simulated annealing(SA) is able to conditionally accept detrimental steps in random directions for the sake of expanding the search into regions that would be overlooked with a purely downhill method. The name originates from the metallurgical idea that for a metal to cool without flaws due to residual stresses, an even temperature must be maintained throughout the material and that the temperature not be lowered until all portions have reached that equilibrium temperature. The thermal vibration of particles is likened to random motions within a parameter field. If the vibration is successful in reaching a lower energy state, it is accepted and the particle comes to rest or in the case of a metal, it freezes. The analog in statistical searching is that after a large number of iterations, movement towards improving estimates of the optimum is strongly favored. Yet, the feature of continuing to accept unfavorable steps enables the algorithm to escape local minima without restarting the search. Simulated annealing can be characterized by taking a number of steps in random directions about an acceptable point and progressing from acceptable point to acceptable point towards a global optimum.

A starting point in a two dimensional search field is chosen at random. The routine takes a number of steps of equal length from this point in randomly generated directions. If the step results in an improvement of the parameter, it is accepted unconditionally. If the sampled value is unfavorable, yet deemed acceptable by the criteria explained below, the search anchors this point and proceeds to test further points from there. The percentage of accepted non-favorable steps should be high, as much as 50% or more, to ensure the routine has the ability to escape local minima. The specifics of the routine can be summarized as follows, from Curtis:

$$P(\text{acceptance} \mid \text{detrimental step}) = e^{-\beta(\Delta\Phi)\left(\left|\Phi_0 - \Phi_m\right|^g\right)} \qquad (2.3.2)$$

with: β = positive variable that is inverse proportional to the step size

$\Delta\Phi$ = change in measured parameter from previous accepted step

Φ_m = estimated value at the global optimum

Φ_0 = value of parameter at last accepted step

g = user chosen negative value (-1 or -2) that weights the difference $\Phi_0 - \Phi_m$

After a user specified number of unsuccessful step attempts, the step size shrinks and narrows the search. The size fraction of the subsequent steps and the number of times the step size is shortened are set by the user. This permits tailoring the search to the most practical movements of the individual search platform. The effectiveness of the method is heavily dependent on the proper selection of β and the step distance Δr. If β is chosen to be too small, the search tends to wander and is inefficient. Conversely, if β is chosen too large there is a high likelihood that the algorithm will get trapped in a local minima. The chosen step size should be adequate to escape from a local minima in just a couple of steps. The algorithm also has a fundamental limitation in that it needs an estimate of the global extrema, Φ_m, to establish the measure of conditional acceptability. This can prove difficult to assign in a completely unknown environment. An estimated extrema can be assigned with historical information, but if the estimate comes up short, the search will not proceed beyond it. In the case of an AUV measuring temperature, salinity or other seawater parameters, it should be possible to assign an appropriate value of Φ_m.

During experimentation with the algorithm, the results were found to be very sensitive to search parameter selections. While an AUV cannot afford to waste power on many jumps in random directions, the method of simulated annealing also lends insight to the challenge of evading local minima. The successive sampling at a constant radius about a known acceptable point is easily accomplished by driving in a circle and the radius length and acceptability of the next position can be tailored to suit the sampled environment.

The method was simulated on the Herring Pond data set with interesting results. For clarity, some additional terms are defined, with typical values given:

δ = scaling factor for random step size, (starts at 0.15, decreases to ~0.0375)

β = increases to compensate for smaller average change in cost function between current and next attempted step (starts at 3.5, increases to ~15)

maxshrinks = number of times the step size shortens before the search terminates (3)

shrinkfactor = fraction to multiply the step size with each shrinkage (0.5)

quitreps = maximum number of steps taken at each step length before shrinking (7)

estopt = estimated optimum, Herring Pond's maximum depth of 13 meters was used

The graphical representations of the simulated AUV paths shown in Figure 5 are only considered in terms of raw distance travelled while moving over a sample space. Vehicle dynamics were not considered. The sharp, angular turns appearing in the paths may be rounded into curves in the movement of an actual vehicle. The Odyssey II vehicle is capable of turns with a 5m radius or less and ABE can pivot and rotate in place. In any event, the method is not intended for use as is, but rather to draw on it's advantages in interrogating an unknown environment and to motivate the process of getting an AUV to generate its own motion commands based on in situ measurements.

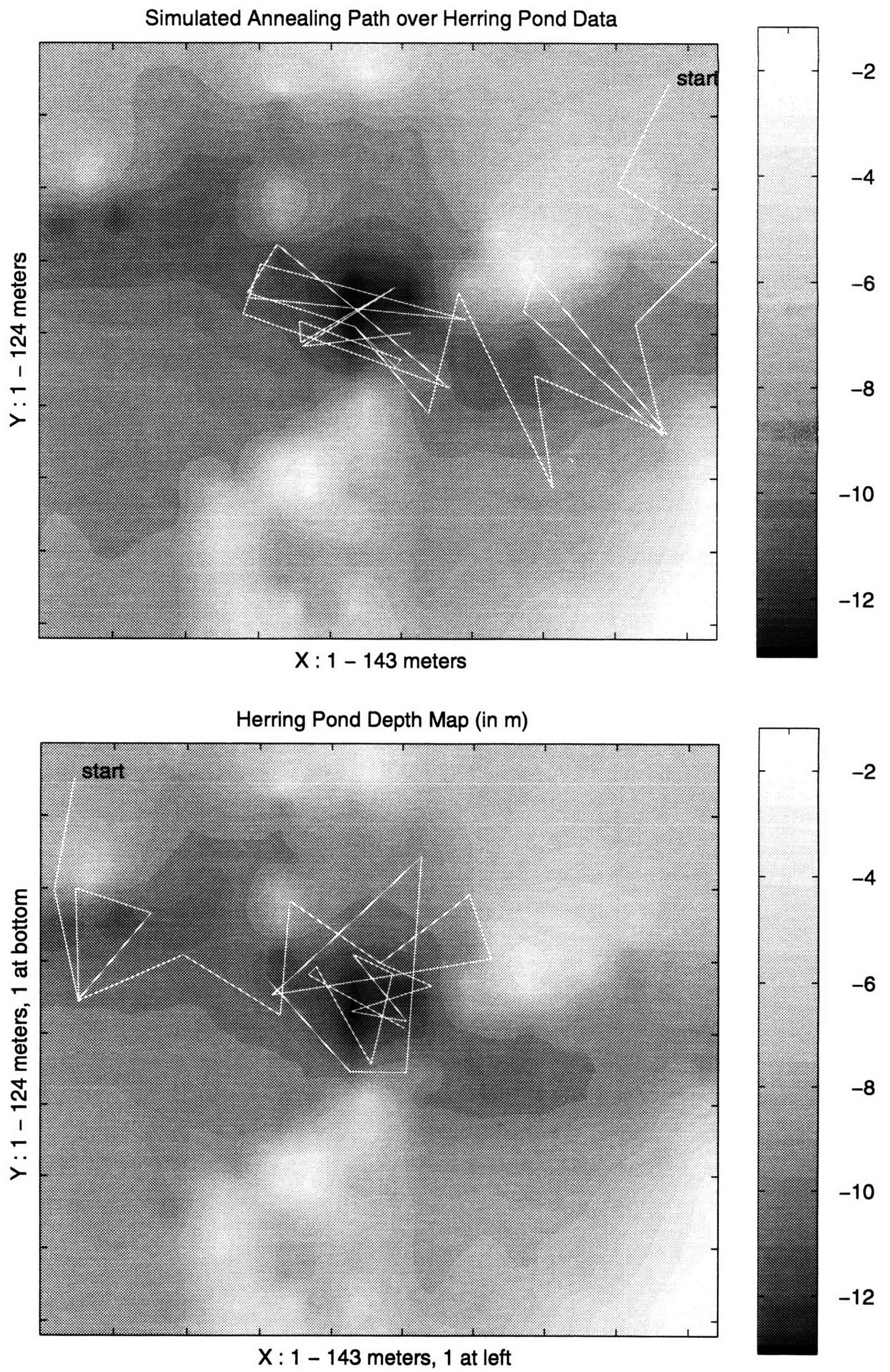


Figure 7. These plots show the path of a simulated annealing routine over the Herring Pond data set. Motion is purely geometric and true to the algorithm without consideration for the vehicle dynamics. Yet, in both cases, it is successful in reaching the global deep spot in the middle of the pond.

Taboo Search:

Since we never know what the next step holds until we get there and measure, it is prudent to retain a short-term memory of recent positions that held favorable values of the search parameter. The taboo (or tabu) search (Glover[1990]) permits us to do this and assign qualifying rules to previous moves and overriding criteria for selection which can further tailor the search. In a sense, we are getting into the realm of imparting the AUV with artificial intelligence, in as much that the vehicle runs through the hierarchy of a complex decision making process much like a person would if faced with the same options. In contrast with purely mathematical algorithms for optimization, the taboo search is logic based and uses qualifying criteria and move weighting to determine the most efficient vehicle path. The user determines the measure of efficiency and is able to change the metric as the mission requires.

The search uses a flexible, attribute based memory structure that permits the merits of previously collected information to be reevaluated with each sample iteration. This allows retention of the information contained in a specified number of past moves among the current options for the next vehicle step. A rigid, overlaying set of rules to confine or loosen the search exists in the form of taboo restrictions and aspiration criteria. These two concepts can be considered additional instructions to the vehicle in the form of: "This is the simple criteria to determine the next move, but also consider these additional intentions with respect to the record of previous moves before accepting the obvious next step." The search can be intensified or diversified by varying the time span of the short term memory.

The imposed restrictions are intended to prevent the search from doubling back on itself and to push the routine beyond local optimas while still taking high quality steps. In contrast to simulated annealing, the taboo search can take a non-optimal step away to escape a local minima, but then is prevented from returning to it during the next few steps by the taboo criteria. In this manner, cycling over the same terrain is minimized as the search expands into new areas to investigate the possibility of a better global minima in another location. As the search lengthens, a greater history of previous moves is established and the decision architecture has a larger database with which to plan the next move.

The candidate moves are evaluated based on their weighting from the taboo restrictions and aspiration criteria. A mathematical value is assigned to the candidate in the form of a penalty or reward, which are negative and positive integers based on the user defined importance of each attribute. The most favorable candidate move is selected and the selection process begins again. If all of the candidate moves are deemed inadmissable, the least penalized move is used to continue the search. This situation may also be used as an indicator that the taboo criteria are in fact too restrictive and perhaps need to be relaxed or modified.

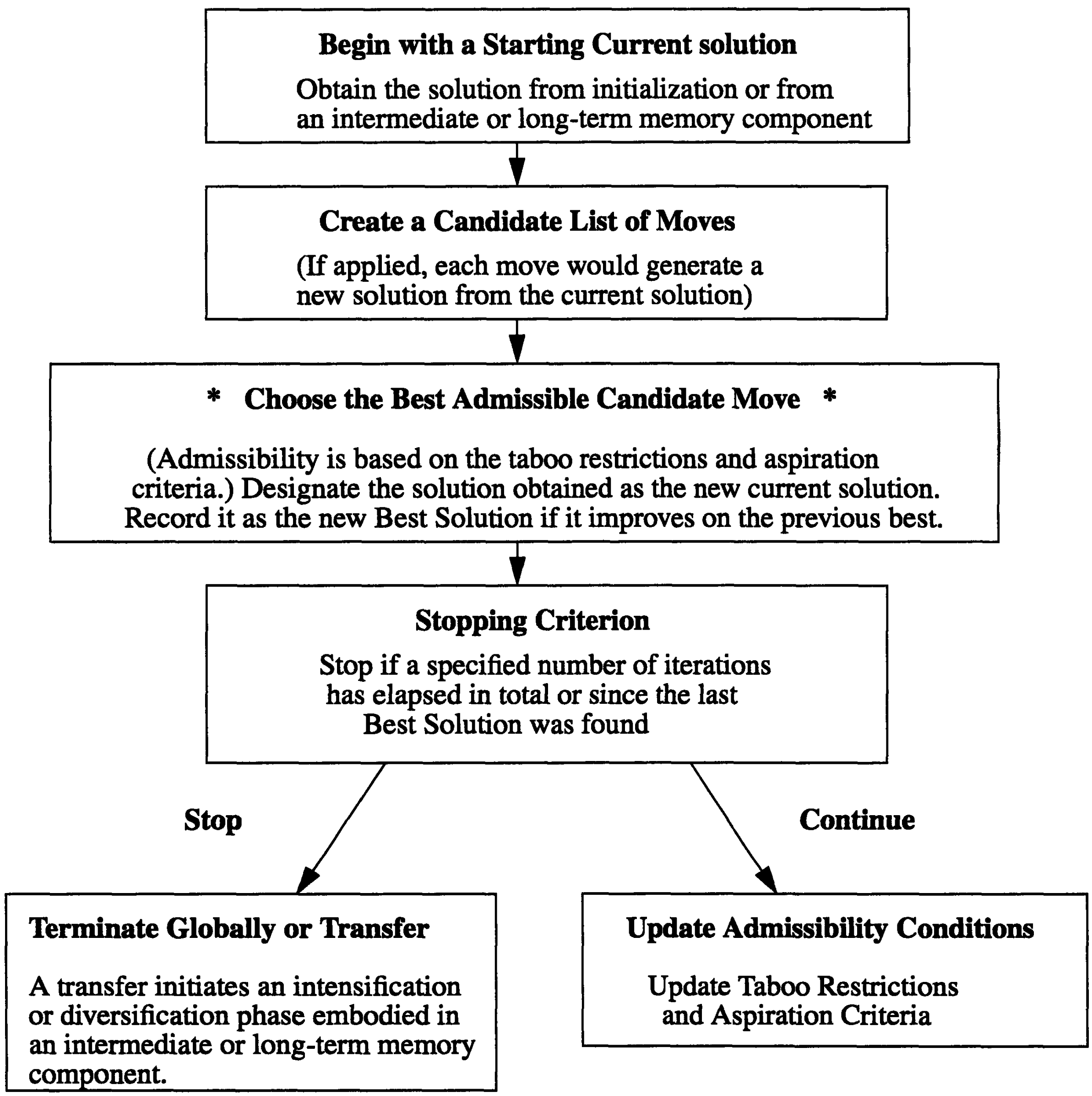


Figure 8. Flow chart from Glover that logically organizes the decisions made during the taboo search process.

Stopping criteria can be established in a way similar to other heuristic methods by limiting the total number of iterations, setting a minimum tolerance on subsequent changes in the optimum value, or by defining a maximum number of steps since the last improvement. The algorithm is defined very loosely and is best represented by a flow chart rather than a set of mathematical strictures (figs. 8,9). This permits the user to custom design the application.

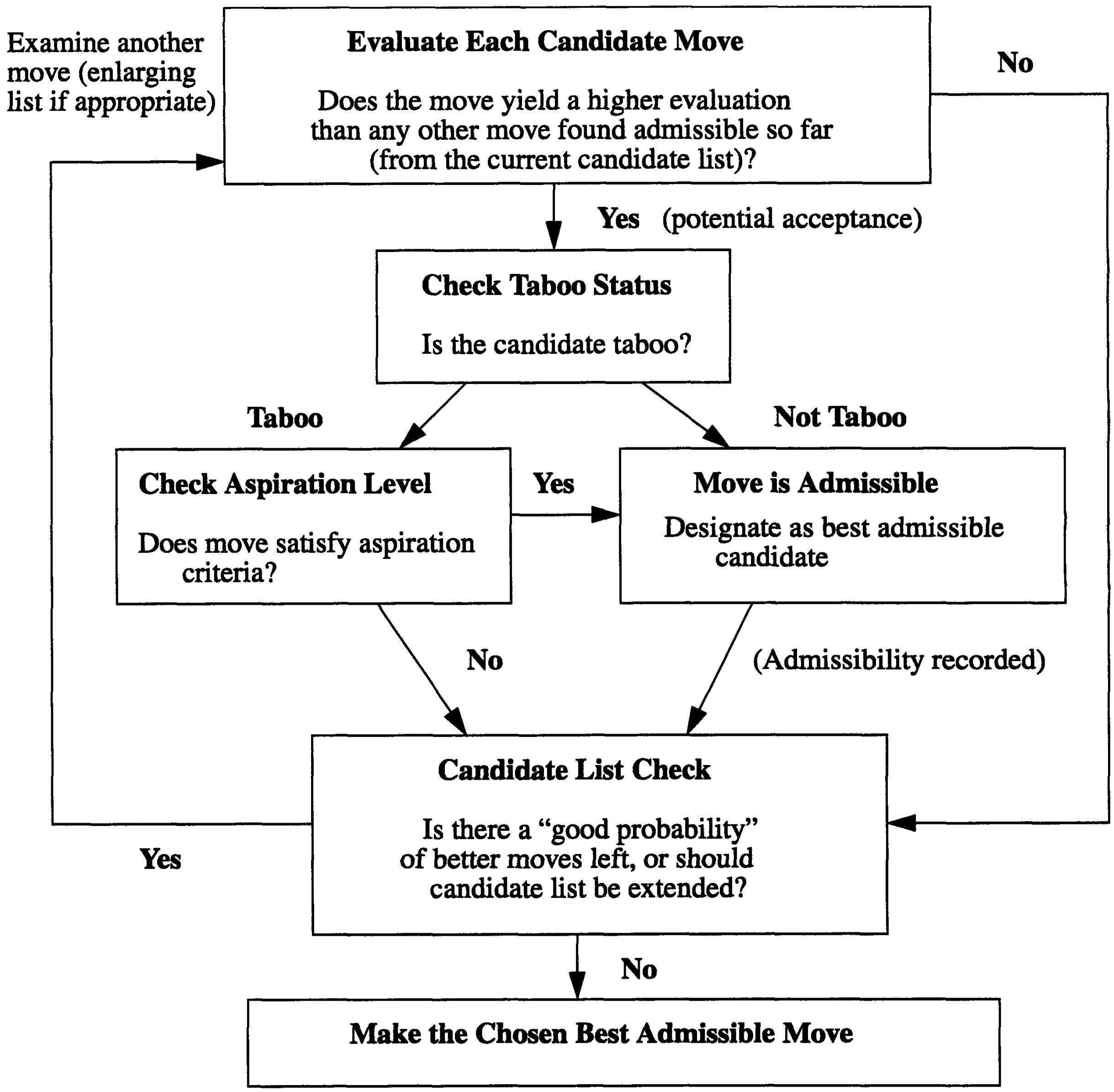


Figure 9. Flow chart from Glover that describes how the taboo search defines the selection process for the next move.

The user develops a list of taboo restrictions. It is possible to turn these on and off as the search progresses. The taboo list should be concise and not overly limit the vehicle's ability to randomly test new terrain. More than about a dozen taboo criteria is likely to make the search too narrow and confuse the search. The same selection process should guide the construction of the aspiration criteria list. These may also be made time dependent and secured when no longer applicable. In all methods that use a flexible memory structure, it is important to resist the temptation to prevent the vehicle from taking steps that without the benefit of a global perspective may appear deleterious. The taboo search has a number of features that make it attractive to use in the guidance of an AUV and it provides the appealing means to overcome what can become a random search. Glover makes the following general remarks:

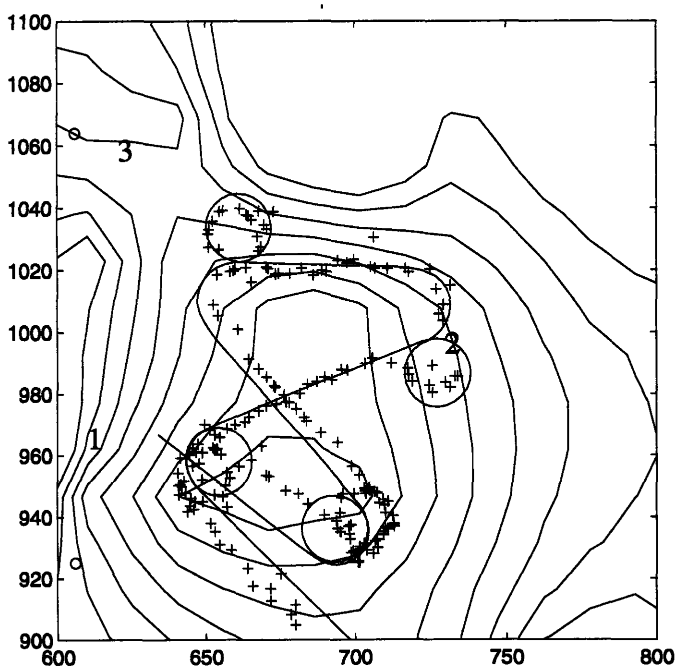
> In the present climate of problem solving methodologies, an instinctive response in this type of situation is to turn to randomization as an attempt to uncover an effective move by the operation of good fortune. Such an approach is certainly possible, but it is also a more haphazard means of achieving diversity than an approach based on the strategic use of memory. Moreover, randomization loses the counterbalancing effect of continuing to pursue good moves, following more than blind selection, in addition to incorporating a diversification objective.(from *Interfaces 20*)

The taboo search can intensify the search by maintaining a history of those candidate moves characterized by attributes that proved to be successful in improving the global solution. A schedule of attributes that have the highest improvement percentage can be used to continually modify the aspiration criteria. In the particular case of escaping from local minima, it will be necessary to make unfavorable moves. These types of moves can be programmed to increase in attractiveness when the search gets repetitive in a small area. The selection of move distances can greatly increase the flexibility and effectiveness of the taboo search. Larger distance moves can quickly remove the vehicle from a cycling search and open up a new area that the AUV had previously not explored. A finite set of large distance moves with specific ranges and purposes in mind can be quite useful. All of these ideas have been drawn upon heavily in the outline of improvements to the basic circle gradient search discussed below.

2.4 Circle Gradient Search

Three mathematical methods that have gained acceptance in surmounting the global optimization problem in two or more dimensions have just been examined. The logical next step is to apply the procedural and conceptual advantages of each of these to the motion of an autonomous underwater vehicle, while removing the features that make them energy inefficient or impractical. Using these techniques in the context of a moving AUV presents particular constraints. The vehicle is confined to a moderate maximum speed, in the case of ABE, slightly under 1 meter/second. It is often difficult to have the vehicle perform sharp, large angle turns at its cruising speed. This complicates the navigation problem and is hydrodynamically inefficient. Purely mathematical methods also do not place an appropriately heavy cost on movement within the search field and tend to positively reach the global extrema typically only after a very redundant search. While this becomes prohibitive when a vehicle must actually drive to all of the points it must sample, the idea of including pseudo-random steps and moving toward the goal via a series of acceptable intermediate positions has much merit.

The simplicity of driving in a circle has been proposed as the preferred basis for determining the next direction to drive the toward the global extrema (Singh, et. al.[1995]). It is easy for any AUV to navigate and it greatly increases the sample bandwidth compared to the one dimensional perspective provided by straight line cuts. The diameter of the circle can be selected to vary the amount of smoothing. This concept was initially employed with success at Herring Pond with a smoothly varying bottom and a fairly well-defined global minimum (Fig. 10). Now, the challenge



Note:
The solid lines are the vehicle dead-reckoned track and the crosses are the LBL positions.

Figure 10. ABE contour following in Herring Pond (from Singh, et. al.[1995])

is to extend the idea into open ocean missions where the search parameter is much more likely to be non-monotonic and the environment contains many false or local extrema. In particular, ABE is being configured to conduct surveys in hydrothermal regions in an autonomous mode and the search methodology to accomplish this will become a primary focus of this thesis.

Since the vehicle can only make measurements along track, it must have a built-in means for determining which way it should proceed after each local evaluation of the parameter being measured. By employing a circular path, the vehicle can cover a relatively large area and obtain a filtered estimate of the two dimensional gradient. A series of samples are taken along the perimeter of the circle, limited only by the vehicle's data collection rate, and then a least squares solution for the overall slope in the x- and y- directions is computed as follows:

Record x and y position & parameter values(z) while circling.

Form $\tilde{x}$ and $\tilde{y}$ by subtracting the mean values from x and y, to center the circle at (0,0).

Solve: $z = g_x\tilde{x} + g_y\tilde{y} + z_0$ for g_x, g_y, and z_0 using least squares. (2.4.1)

Compute direction $\Psi = \mathrm{atan2}(g_x, g_y)$. (2.4.2)

This is only the first part of the subsequent motion commands. The AUV then travels in a straight line, while evaluating the one-dimensional gradient in a recursive least squares sense, to the next area of evaluation.The vehicle must be given rules on how far to travel in the minimum and maximum cases and what changes in the sample parameter are worthwhile enough to stop and perform another circle maneuver. Although this method is only a first order fit to the encircled contour it works quite well on surfaces that are approximately bowl-shaped. Saddle points can be overcome with a sufficiently large radius for the search circle and an adequate number of opportunities to search. In a smoothly sloping environment, it is possible to let the vehicle continue along the straight line path until it detects an inflection point in the slope.

This type of search architecture has significant advantages. Primarily, it reduces the total distance traveled compared to an exhaustive search. Additionally, global navigation is not required since incremental information obtained through dead reckoning can be sufficient, although depending on vehicle dynamics and the presence of currents, a doppler sonar may be needed. By driving the AUV from its filtered sensor input alone, we can assure that it will attempt to converge on the desired minimum or maximum of the search parameter. Yet, it is still susceptible to being trapped in a local minima. As discussed above, the easy-to-drive circle search path suits the vehicle's uniquely limited ability to maneuver and provides the necessary cross-track gradient information to make path planning decisions possible. A good example of a simulated search in

Herring Pond with an improved version of the circle gradient search is shown in Figure 11 below.

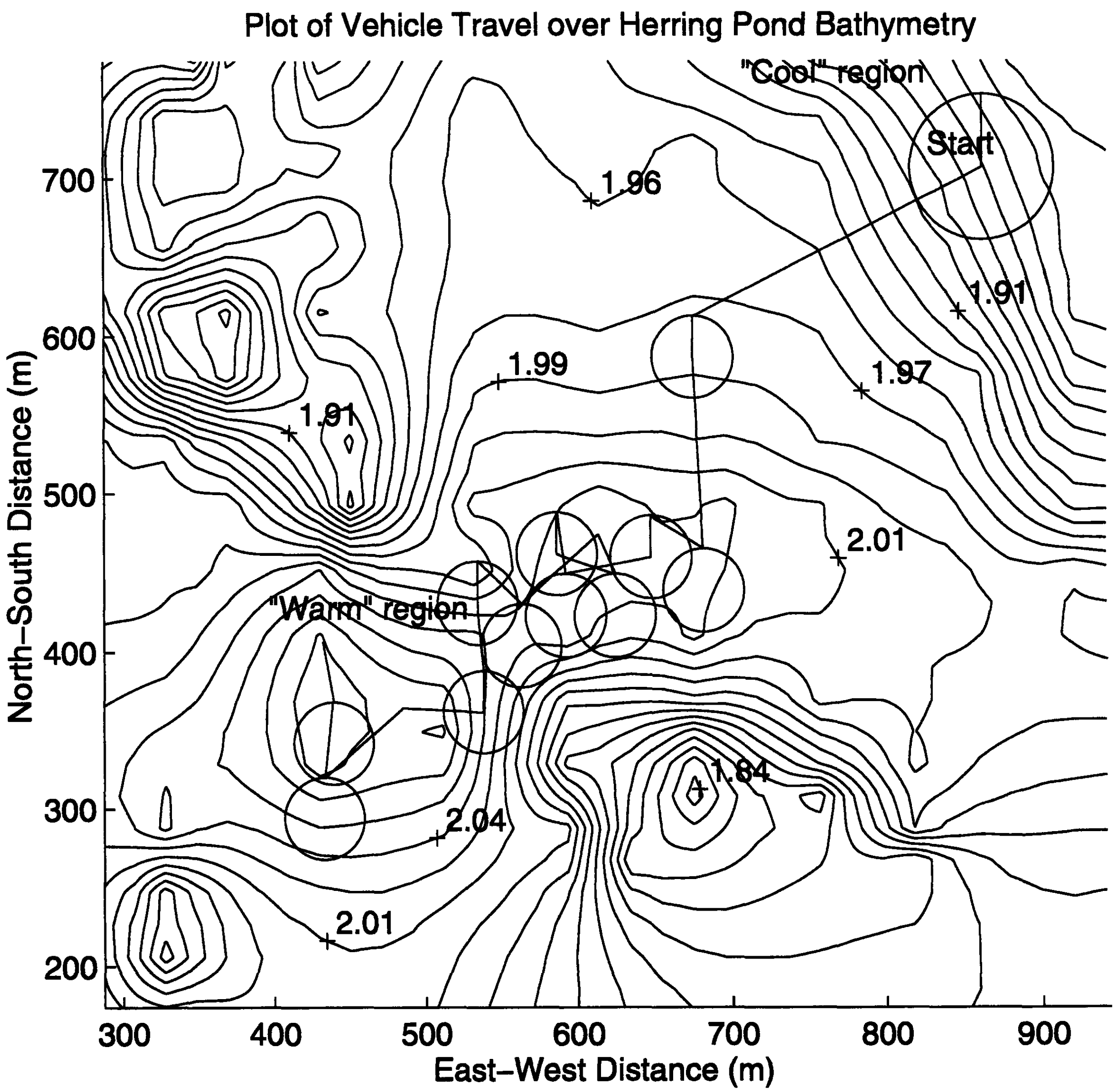


Figure 11. This plot shows the simulated path of an AUV over the Herring Pond bathymetry using the improved circle gradient search method. The bathymetry values have been converted to a range of positive temperatures that can be expected in the vicinity of a hydrothermal plume (1.8 - 2.1 ° C) with the deep spot in the pond substituting for the hot spot in the temperature contour. The vehicle progresses down gradient and squeezes between two cold spots to reach the global hot spot.

2.5 Direct Comparison of Direction Set Method, Simulated Annealing and Circle Gradient Search

In order to provide a quantifiable basis of comparison for several of the methods presented, a single environment was chosen to test the Direction Set Method, simulated annealing and the circle search method. The Herring Pond bathymetry contour was used for the first two methods. The data set was modified to retain the contour but use representative temperature values, in the range of 1.8 - 2.1° C, when used with the circle search method. If the vehicle were to perform a rectangular search in the 125m by 143m search region with 6m spacing between track centers, it would take 68 minutes to complete the pattern at the standard speed of 0.7 m/s. It is assumed that the global maximum would be found with this method.

Table 2: Comparison of Search Methods

Run #	Direction Set Method	Success	Simulated Annealing	Success	Circle Search Method	Success
1	26.6 min	Yes	89.3 min	Yes	8.6 min	Yes
2	22.9 min	No	116.5 min	No	11.6 min	No
3	29.0 min	No	67.0 min	Yes	3.8 min	Yes
4	33.0 min	Yes	187.7 min	Yes	7.4 min	Yes
5	33.7 min	Yes	83.7 min	No	9.3 min	Yes
6	40.4 min	Yes	122.4 min	Yes	5.2 min	Yes
7	41.1 min	Yes	101.9 min	Yes	5.2 min	Yes
8	34.8 min	Yes	93.5 min	Yes	5.9 min	Yes
9	23.5 min	No	63.4 min	Yes	5.0 min	Yes
10	28.9 min	Yes	46.3 min	Yes	6.3 min	Yes
Mean	31.4 min	70%	97.2 min	80%	6.5 min	90%

Table 2 provides a comparison of a representative set of ten runs in each of the three methods. Time expended during the search was chosen as the metric. The criteria for success was locating the global maxima. All runs were conducted over the same search area and contour, from different starting positions and at a vehicle velocity of 0.7 m/s. Many more runs were conducted than those represented and some specific observations of each search can be discussed.

The Direction Set Method proves to be adequate in positively verifying a minima, but takes a rather long time to do so. DSM sufficiently spans the sample space, but large areas can easily be missed due to the geometry of the search area and the orientation of the search legs. Having some historical knowledge of the survey region can avoid this. In conducting tests in the sample space apparent to the experimenter, attempts were made to be as objective and unbiased as possible when selecting a starting leg length and orientation. DSM also seems to make a significant amount of extra travel after the global optima has been located. This feature could be improved by shortening the legs after the 30° rotation of the search legs has begun. However, a point is reached where the search may again miss opportunities to escape a local minima.

The simulated annealing runs confirm the fact that this a valid method only when the cost on travel between sample points is negligible. The method is satisfying in that it can be tuned to positively locate the global optimum value on every search. However, the potential cost in vehicle power and time on station makes this method prohibitive. In fact, when locating the global value is only one of several goals of an oceanographic survey, it is too costly to consider. The ideas behind the search still have merit and applicability in developing a hybrid search method.

Tests of the circle search have demonstrated that it reaches the goal significantly faster than both the Direction Search Method and simulated annealing. The circle search uses a larger bandwidth sample of its immediate surroundings to make subsequent move calculations. It drives in the best estimate of the up or downhill direction. This method does have the disadvantage of leaving large sections of the search region untraveled though it is tempting, but not prudent, to make the assumption that the global optimum value has not been overlooked. For this reason, a logical combination of strategies is to initially scan the area using the Direction Search Method until the region of interest has been adequately located and then take a closer look using the circle search method.

Section 3: Hydrothermal Plumes

3.1 Scientific Interest

The scientific community has been intrigued with the characteristics and surrounding ecosystems of hydrothermal vents on the ocean bottom since their discovery nearly two decades ago(Francheteau, et. al., [1979]; Crane and Ballard[1980]). These areas are believed to be primarily located at the meeting of the major tectonic plates of the earth's crust, such as mid ocean ridges and the Pacific Rim. Sites in the Juan de Fuca Ridge, East Pacific Rise and the Mid-Atlantic Ridge have been the location of numerous scientific observations. The seafloor surrounding the vents has been found to be rich in marine life that survives in this otherwise cold and dark environment by employing chemosynthesis. Some physical oceanographers also suspect that the heat flux into the ocean from within the earth via these plumes may be the "missing heat" to even the balance in current models of global hydrothermal circulation and convective heat removal (Rudnicki and Elderfield[1992]). Plumes may also disperse the larvae of hydrothermal vent fauna (Lupton[1995]).

To support continuing research in these areas and others, there has been a concerted effort at the Deep Submergence Laboratory at WHOI and other institutions to use remotely operated and autonomous vehicles to more closely survey regions of known or suspected hydrothermal activity. Although temperature seems the obvious parameter to guide the search, some surveys indicate that optical backscatter or chemical tracers such as iron, manganese, methane, hydrogen and helium-3 may actually provide a more distinct and longer range indication of the presence of hydrothermal venting (Nelsen, et. al. [1987]; Baker, et. al. [1995]).

The current understanding of hydrothermal plume structure has its origin in the classical discussions of entrained buoyant fluids, such as hot gases rising from a smokestack. In an otherwise static fluid environment, the plumes rise vertically and entrain ambient fluid as they do so. Once the source fluid has attained a buoyancy equivalent to its surroundings, it decelerates in the vertical direction and begins to horizontally stratify. There is an overshoot above this buoyant level called the "plume cap" and may be as large or larger than the layer. The Atlantic and Pacific have similar but subtly different common plume structures due to varying ambient temperature and salinity profiles. Pacific plumes tend to be warmer and saltier than the surrounding conditions and stabilize at around 200m off the bottom, while those in the Atlantic rise to approximately 350m altitude and are colder and fresher than ambient (Speer and Rona [1989]). Various studies have been conducted on plumes in the presence of prevailing cross currents. Their structure is fairly well understood and has been modeled extensively. These plumes tend to bend over in the down-stream direction and stabilize at comparable altitudes in a roughly parabolic shape (Trivett[1991]; Middleton and Thomson[1986]).

The cost of a manned submersible dive to the vent regions is considerable. Even with a vehicle as capable as *Alvin,* time on the bottom to sample and observe the hydrothermal vent environment is limited by the endurance of life support systems. An unmanned, autonomous vehicle is significantly less expensive to build and operate, has greater availability and can perform missions of much longer duration. The technology of battery power is fast making week or even month long missions a possibility. Sampling instruments for many measurements of ocean parameters have been reduced in size, weight and power requirements such that their installation on an AUV is practical. When the decision making architecture aboard an AUV can mimic the in situ desires of the scientist, the unmanned mission will be the preferred means to collect data. An AUV is most likely to encounter the type of temperature and chemical anomaly described above. It is my intention to exploit this knowledge of the plume structure to construct the vehicle search strategy.

3.2 Hydrothermal Plume Types: Diffuse and Discrete

Hydrothermal vents are found typically at depths between 800m and 4000m. They are divided into low temperature (<200° C) and high temperature (200° - 400° C) categories. The water emerging from hydrothermal plumes is believed to originate at the seafloor within a reasonable vicinity of the sources. It then settles, possibly a kilometer or more into the earth, to the level of mantle magma. The water is heated to temperatures of several hundred degrees centigrade, but remains in the liquid phase due to the tremendous pressure from water above. There is a forced hydrothermal circulation set up by the evacuation of buoyant rising fluid and the sinking of cool, dense ambient seawater. As the water approaches to the seafloor it accelerates from the decrease in density due to heating and takes on many properties unique to the particular hydrothermal vent system. Particulate matter of high iron and sulfur content becomes entrained with the fluid as it makes its way vertically out of the seafloor. Often, the specifics of temperature, salinity and chemical composition serve as a particular signature to an individual vent or cluster of vents.

The physical geologic structure of the vents is indicative of the type of plume it produces. The chimney type vents appear to develop over relatively short periods of time as the heavier particles are pushed out of the seafloor and settle and collect close to the vent opening. These sites are characterized by the usually high temperature black or white smokers that they produce. Such sources are called discrete, since their flow is localized to a single or a couple of openings and exits the vent with a high velocity. The source fluid rises vertically through the stratified surrounding bottom water and entrains ambient fluid in the process. The discrete plume decelerates vertically as it is rises to the buoyant level and then disperses downstream once its buoyancy equilibrates.

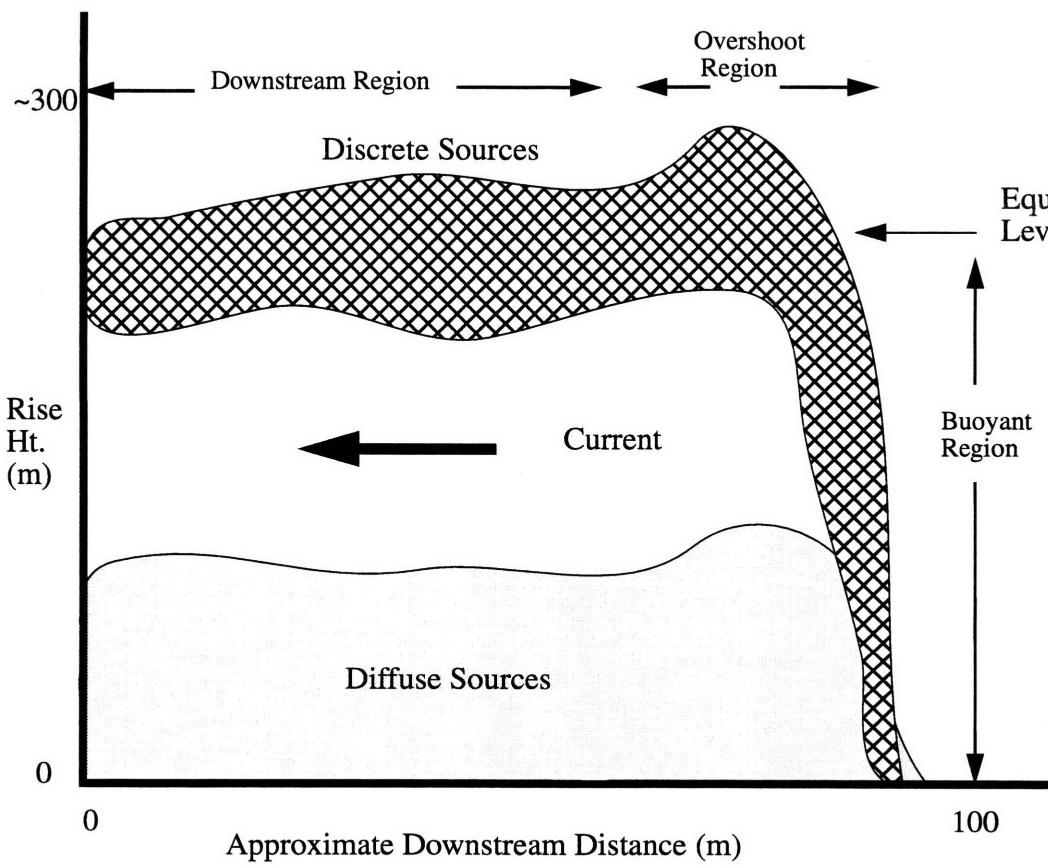


Figure 12. A graphical representation of the two major types of hydrothermal plumes. The specific dimensions vary with the individual source, but the physical structure is consistently displayed. The specific regions of the plumes will be referred to in the text and the search strategy will differ in each. (after Trivett[1991])

A diffuse source differs from a discrete source in that the water leaves the seafloor over a larger area, usually seeping at a slower speed from an extensive collection of cracks and fissures.

Since the tortuous flowpath slows the water emerging from the surface, there is time for more cooling with ambient seawater to take place. Diffuse sources tend to be cooler than discrete sources and do not rise as high off the bottom. It has been observed (Trivett and Williams[1994]) that the boundary layer type flow produced by diffuse plumes may remain attached to the seafloor as they disperse downstream. The detectable portion of such plumes may only rise to several tens of meters. Such a feature forces inspection by a free-swimming submersible or by placing a fixed sampling platform in the vicinity of the source, which is deployed by dropping it from the sea surface. It is not possible to tow instruments at so low an altitude without great risk of their colliding with the bottom. An appropriately configured AUV is ideally suited as a lower cost means to accomplish a survey of a diffuse hydrothermal vent field. ABE is quite capable of following even dramatic bottom topography (Yoerger, et. al.[1996]) and due to its size can access venting sites not possible with *Alvin*.

3.3 Hydrothermal Plume Structure

In order to design an AUV search strategy to locate sources in the vicinity of hydrothermal activity it is essential to have a solid understanding of how entrained waterborne parameters can vary in the presence of a cross flow. A mathematical representation of both an Atlantic and Pacific plume has been developed that provides an idealized model of the structure of a hydrothermal feature(Speer and Rona[1989]). The characteristic variation with depth of temperature and salinity in each basin determines at what level it will reach equilibrium and the type of anomaly with respect to the surroundings. It is the combination of both parameters that determines the density of the ambient water and sets up the buoyancy relationship with the vent effluent. For example, in the Pacific, salinity generally increases with depth and potential temperature decreases with depth. As a result, the hydrothermal plume stabilizes vertically at a level where it is warmer and saltier than its surroundings. Though counterintuitive, the opposite situation is the case in the Atlantic, where hydrothermal plumes are cooler and fresher than their surroundings (Speer and Rona[1989]). The plume structures represented in Fig. 13 below are drawn without the influence of a predominant cross current. Although the deep ocean basins are generally stable and stratified, semidiurnal tidal currents on the order of ~0.2m/s do exist and over time, will tend to bend the plume outwash over in the downstream direction around the buoyant level as displayed in Fig. 12.

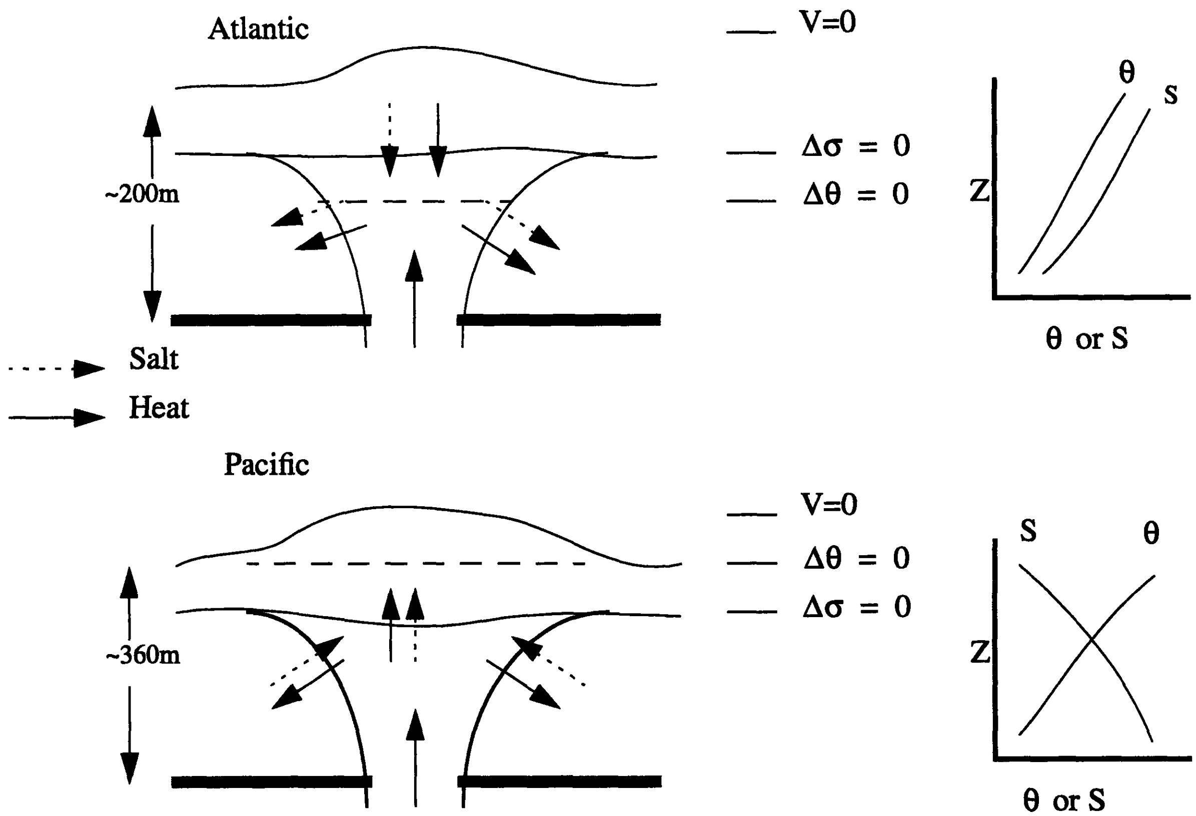


Figure 13. Schematic representation of typical Atlantic and Pacific plume structures.The hash marks to the right of the plume diagrams delineate the approximate heights where velocity(V), potential temperature (θ) and salinity (S) reach equilibrium with the surrounding waters. (after Speer and Rona[1989])

(Middleton and Thomson[1986]) have put forth equations which define a buoyancy function and describe the change of buoyancy with respect to height above the source of hydrothermal fluid. The following parameters are defined in their equations:

z = vertical axis of an axisymmmetric plume

b = plume radius

w = mean vertical velocity of the vent effluent

α = entrainment constant

β = coefficient of thermal expansion

ε = coefficient of haline contraction

$\rho_e(z)$, ρ_0, ρ = environmental, reference and plume densities

Equations for the conservation of mass and momentum within a plume are given by

$$\frac{d}{dz}(b^2 w) = 2\alpha b w \qquad (3.3.1)$$

$$\frac{d}{dz}(b^2 w^2) = b^2 g\left(\frac{\rho_e - \rho}{\rho_0}\right) \qquad (3.3.2)$$

Oceanographic buoyancy is represented by (T and S are temperature and salinity)

$$\left(\frac{\rho_e - \rho}{\rho_0}\right) = \beta(T - T_e) + \varepsilon(S_e - S) \qquad (3.3.3)$$

Conservation of buoyancy with respect to temperature and salinity are given by

$$\frac{d}{dz}[b^2 w g \varepsilon(S_e - S)] = -b^2 w g \beta \frac{dT_e}{dz} \qquad (3.3.4)$$

$$\frac{d}{dz}[b^2 w g \varepsilon(S_e - S)] = b^2 w g \varepsilon \frac{dS_e}{dz} \qquad (3.3.5)$$

(Rudnicki and Elderfield[1992]) have expanded on the work of Speer and Rona and developed a finite difference model of hydrothermal plume that incorporates the changes in a trace parameter. This is particularly useful for generating a mathematical framework in which to simulate AUV movement. In their system of equations, A is the cross-sectional area of a horizontal plume slice, W is the vertical velocity, Z is the height above the vent, E is the entrainment constant, S and T are the salinity and temperature respectively, C is the concentration of a tracer, g and ρ are the acceleration of gravity and density. The subscripts z and 0 represent background at height z and initial vent conditions. For the forward finite difference system of equations, changes in each parameter (X) can be considered in the following manner,

$$\frac{dX}{dZ} \approx \frac{X^{i+1} - X^i}{\Delta Z} \qquad (3.3.6)$$

The matrix representation of the buoyant hydrothermal plume is given by

$$\begin{bmatrix} W & 0 & 0 & 0 & A \\ SW & AQ & 0 & 0 & SA \\ CZ & 0 & AW & 0 & CA \\ TW & 0 & 0 & AW & TA \\ \rho_0 W^2 & 0 & 0 & 0 & 2\rho_0 AW \end{bmatrix} \begin{bmatrix} A^{i+1} \\ S^{i+1} \\ C^{i+1} \\ T^{i+1} \\ W^{i+1} \end{bmatrix} = \begin{bmatrix} \Delta Z(EA^{1/2}W) + 2WA \\ \Delta Z(S_Z EA^{1/2}W) + 3SAW \\ \Delta Z(C_Z EA^{1/2}W) + 3CAW \\ \Delta Z(T_Z EA^{1/2}W) + 3TAW \\ \Delta Z g(\rho_Z - \rho)A + 3\rho_0 AW^2 \end{bmatrix} \qquad (3.3.7)$$

The above matrix equation is solved for (i+1) values which are the parameter values at a height of $Z + \Delta Z$. Values of ΔZ can be varied to make more calculations at the heights where parameters are changing more rapidly, such as the opening of the vent and the region of overshoot or "plume cap". The system can be easily solved with any matrix math package, i.e. Matlab.

A more sophisticated, time-dependent model of a buoyant plume has been developed by Lavelle at NOAA Pacific Marine Environmental Laboratory (Lavelle[1995]). This model accounts for the effects of a rotating frame of reference and subsequently features the presence of vorticity (ζ) couplets. A three dimensional matrix of a fully developed discrete hydrothermal plume was obtained by the author from Lavelle and used in the development of AUV search strategies.

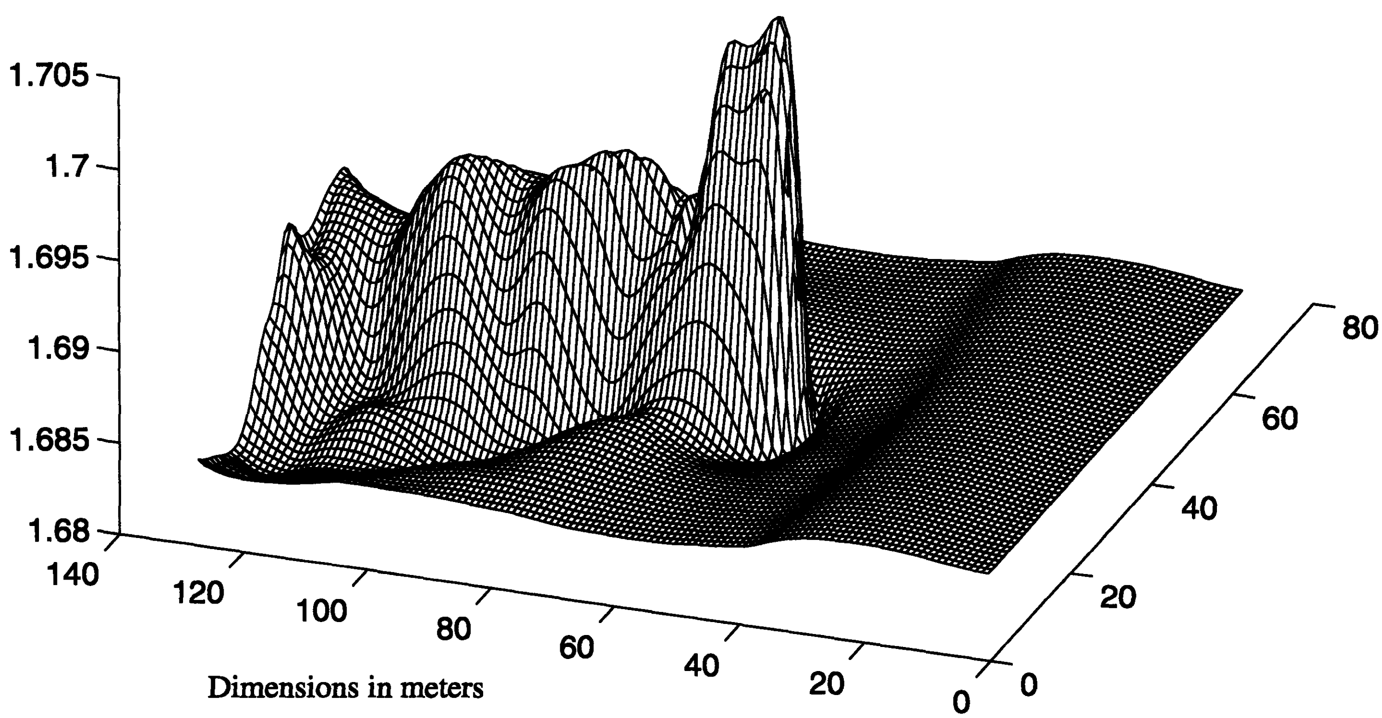


Figure 14. The above contour uses temperature ($^\circ C$) as the vertical axis. The data was taken from a horizontal slice of a three dimensional model of temperatures in a fully developed hydrothermal plume in the presence of cross flow and rotational vorticity developed by Lavelle and supplied to the author. Note the presence of multiple local peaks distinct from the global peak in the wake of the plume source and the fact that the entire grid spans only 0.025 $^\circ C$. This slice is taken from a 13MW discrete source in the presence of a 1.5 cm/s cross flow 150m above the vent.

The structure of diffuse plumes is conceptually simpler than that of discrete plumes. These sources tend to develop a laminar profile with respect to the seafloor (see Fig. 12). Analysis, modeling and actual measurement of diffuse plumes has been accomplished by Trivett and Williams in the ASHES vent site in the Juan de Fuca Ridge. For the discussion of their model, the x-direction is downstream, z is vertical, y is across the current and the following variables are identified:

D = vent field source diameter on the seafloor

N = local buoyancy or Brunt-Väisälä frequency

U,V,W = velocities in $\hat{x}$, $\hat{y}$, and $\hat{z}$ directions

o,e,u = subscripts referring to source, entrainment and upstream quantities respectively

Entrainment velocity can be understood as the ambient velocity in the absence of the motion generated by the diffuse source. The parameters of interest are again, the physical dimensions of the anomaly and the variation of source parameters within the plume outwash. The solutions for the diffuse plume are given as a function of downstream position (x). The maximum rise height is given by

$$Z(x) = -\frac{2g}{N^2}\rho'_0\left(1 - e^{-\beta x \frac{\sin(\lambda x + \phi)}{\sin\phi}}\right) \quad (3.3.8)$$

where

$$\rho'(x) = \frac{(\rho_u - \rho)}{\rho_u} \quad (3.3.9)$$

$$\tan\Phi = \frac{2\lambda\beta}{\beta^2 - \lambda^2} \quad (3.3.10)$$

and

$$\lambda = \frac{N}{U} \quad (3.3.11)$$

The distribution of downstream parameter concentrations with density as an example is expressed as

$$\rho'(x) = \rho_0' e^{-\beta x} + \left(\frac{N^2}{\beta g U}(W_e + V_e) + \rho'_0 \frac{W_0}{\beta U D}\right)(1 - e^{-\beta x}) \quad (3.3.12)$$

While the equations described above offer no guarantee of similarity to what may be sensed by an AUV traversing an unknown region of hydrothermal activity, they provide a definite framework with which to develop methods to direct vehicle motions in such an environment. What happens to the effluent of hydrothermal vents is still the subject of considerable research. Indeed, this research project is intended to help expand that knowledge. Though it may not be efficient to install them on a vehicle, these idealized models of hydrothermal plumes are quite useful in defining expected variation in sensed parameters. If a vehicle can correlate changes in measured temperature, salinity, optical backscatter or chemical tracer strength with the typical structure expected for a plume, then it can make decisions on where further measurements may yield scientifically interesting data.

3.4 Hydrothermal Plume Parameters and Dimensions

In order to establish the scope of a search specifically tailored to locate and map regions of hydrothermal activity, it is necessary to include a discussion of the physical scale and range of measured parameters within the boundaries of the thermal and chemical anomaly. At the vent opening, temperatures and chemical compositions are at their greatest values and then rapidly decrease with the rise of buoyant fluid as ambient seawater is entrained in the uptake. However, clouds of hydrothermal fluid several hundred meters in thickness have been observed to be detached from the seafloor half a kilometer or more, with only a slight indication of the feature near the bottom (Baker, et. al.[1995]). Although it is expected that the plumes will remain near their sources on the seafloor, it is often difficult to correlate a single feature to a specific vent source in regions of high hydrothermal activity due to the tendency of currents to permutate the plumes (Harrington and Helfrich[1995]). Traces of temperature and chemical anomalies can be detected as far as 15km away (Roth Franks[1993]). However, the range of reasonable probability of detection is more likely on the order of one or two kilometers (Trivett[1991]). Measured buoyant plume clouds often will be composed of several individual layers of thermally and chemically distinct fluid with near ambient seawater between them. These combined stacks can vary from several hundred meters to a kilometer or more in thickness. Typically, the highest layer will be marked by having the highest heat flux, the greatest vent volume flux, the lowest entrainment ratio and the largest temperature and salinity anomalies (Rudnicki and Elderfield[1992]).

It is likely that temperature, salinity and optical backscatter will be the parameters to be interrogated by an AUV equipped with a CTD. The instrument is easily mounted within the hydrodynamic flowlines of a vehicle and CTDs have become commonplace tools among the oceanographic community. Measures of both parameters have shown to be useful in identifying the presence of a hydrothermal plume, although the anomalies may be relatively small in magnitude.

Maximum temperature differences on the order of $0.2°C$ have been observed with the ABE vehicle (Yoerger, et. al.[1996]) and reported by other studies (Roth Franks[1993]; Baker, et. al.[1995]), but many measured plumes have shown temperature differences on the order of a few hundredths of a degree celsius (Trivett and Williams[1991]). An interesting feature of buoyant plumes is presented in the model proposed by Lavelle and confirmed by data recorded by ABE at the FLOC site in the Juan de Fuca Ridge. This is the presence of a negative temperature spike, below the level of ambient potential temperature, just downstream of the plume source. This feature may be less than a tenth of a degree celsius, but is detectable. Two explanations for this have been suggested. First, the temperature dip could be caused by upward advection of cooler water at the edges of the vertical plume flow due to a partial blockage of ambient flow. Secondly, the buoyant plume fluid overshoots the equilibrium level and has net downward velocity just downstream of the plume stem. It continues to drop below the equilibrium level and then cycles back up drawing cooler ambient fluid with it, causing an apparent temperature drop when sampled in a horizontal plane (Lavelle[1996]). Although the physics for this dip in temperature may not be fully understood, it is generally recognized as being a real feature and may be used as indicator of the proximity to a vent source. The difficulty arises in having the AUV establish a representative background temperature in situ to compare with a negative temperature spike.

It is important to note that a straight measurement of temperature is considered inadequate to describe the temperature anomaly $(\Delta\theta)$. A more appropriate measure is presented by Lupton as

$$\Delta\theta = \theta - k\sigma_\theta - b \qquad (3.4.1)$$

with θ = ambient measure of potential temperature

σ_θ = potential density

k, b = slope and intercept of the background θ vs. σ_θ line

In areas of widespread hydrothermal activity, both discrete and diffuse plumes are found. The diffuse plumes produce a cloud of low lying warm fluid around the base of discrete vent and may mask the background temperature profile when attempting to survey the buoyant plume. An AUV will be able to detect the presence of a disturbance, but probably not be able to discern between sources.

Salinity anomalies of 0.016 psu have been reported by Roth Franks in the Endeavor Ridge. Speer and Rona conducted a cast within a few hundred meters of the TAG site in the Atlantic. In comparison with their model, the salinity anomaly was ~0.01 psu. The salinity data computed in

Lavelle's model displayed an anomaly which was coincident with the temperature anomaly and had a magnitude on the order of 0.06 psu. The locally sampled salinity excursions are smaller probably due to the difficulty of establishing a background salinity and overcoming the time lag of ambient flow past the CTD. Salinity varies with depth and temperature and setting a constant value for reference becomes complicated with a moving vehicle.

Recent studies suggest that parameters other than temperature and salinity may also be useful in serving to provide evidence of hydrothermal activity on the adjacent seafloor. Results of a water column profile taken on the Endeavor section of the Juan de Fuca Ridge show a strong correlation of anomalies of light attenuation, helium-3, manganese, methane and radon with temperature anomalies (Lupton[1995]). The usefulness of the last three is exemplified by the dramatic increase, often several hundred percent, of these chemical tracers not typically found in any significant level in the deep ocean. Hot smoker plumes introduce great amounts of suspended material into the surrounding waters. The colloidal-sized grains are mostly manganese and iron, and appear to make up the majority of total suspended material (TSM) in the vicinity of hydrothermal vents (Nelsen, et. al.[1986]). The preferred means to measure TSM has been the use of a nephelometer to measure optical backscatter. Nelsen, et. al. recorded increases in backscatter in the vicinity of known vent sites at the TAG site in the Mid-Atlantic Ridge from a background of 20 nephels to a maximum of 70 nephels. The magnitude of per cent parameter change makes sensing of chemical tracers and optical backscatter attractive options for use in detecting and mapping plumes. An optical backscatter meter (or turbidity sensor) is a relatively inexpensive instrument that is simple to operate and quite sensitive to parameter changes(Seapoint Sensors).

For an AUV search strategy to be effective at recognizing a hydrothermal feature, it must be able to recognize what constitutes an unexpected deviation in the measured parameter as opposed to a temporary variation. Setting threshold parameter changes for recognition and motion decisions becomes advantageous. How the search is conducted will be shaped by the mission. If detection and localization of hydrothermal features is the goal, it is desirable to have the vehicle proceed expeditiously to the target. If gathering survey data over a relatively larger area is preferred, the vehicle should attempt to optimize information gained per distance travelled. Attempts at possible solutions to this problem will be discussed and demonstrated in Section 4.

Section 4: Testing of Search Strategies

4.1 Challenges of the Search

In any attempt to direct a sophisticated robotic vehicle to perform a task more complicated than a pre-programmed mission, the machine will inevitably uncover possibilities that have eluded the programmer. When that task is the exploration of an underwater environment that is still far from being fully understood, the difficulty of completely successful accomplishment increases several notches. However, in the context of a scientific endeavor, collecting data that increases understanding is the measure of success, and good, though not necessarily exact, results are certainly acceptable.

Measurements of the hydrothermal regions have been conducted, as described in Section 3, by fixed platforms, hydrographic casts, deep towed sensors and manned and unmanned submersibles. Although fixed and mobile surveys in the hydrothermal regions have been extensive, these devices physically cannot provide the complete picture. The majority of the data sampled at the vent sites used by the author was generated by tracks of another vehicle, *Alvin* for instance, or a towed sensor and then built into contours to "drive" a simulated vehicle over by interpolating values into the empty spaces. While these contours are useful in testing strategies, it is fully understood that a large number of artifacts surely exist and prominent features within the regenerated field may have been missed entirely. Models, such as those proposed by Speer and Rona, Trivett and Lavelle are useful in visualizing the shape of a plume in the very general sense, but a vehicle will naturally encounter something different. However, I believe the sampled and modeled data to be valid enough to used when simulating vehicle sampling and motion. With such a disclaimer behind us, let us proceed to possible solutions by expanding on the ideas presented in Section 2, combined with the knowledge of hydrothermal plumes discussed in Section 3.

4.2 Description of the Hybrid Search Algorithm

While the Direction Set Method appears to be quite successful in locating global minima in a search region, the faster convergence and improved search flexibilty of the circle gradient search (CGS) was chosen as the basis of the hybrid search algorithm(HSA). The basic ideas of the CGS were presented in Section 2.4 and a discussion of the modifications drawn from the other methods examined is presented here. The HSA takes advantage of the efficient gradient evaluation of the CGS, the variable search scale of the Nelder-Mead simplex method, and the layered logic of the taboo search. However, as always, proper search parameter selection will prove to be critical to the usefulness of the method.

Certain preliminary assumptions are made before the HSA is initiated. Starting the vehicle in a flat parameter space is unlikely to produce desirable results. In that type of environment, it would be necessary to use the Direction Set Method or a widely-spaced version of the traditional "lawnmowing" technique to identify the specific locale within the defined search boundaries that contains adequate parameter topography for the vehicle to infer a true gradient from a circle maneuver. Otherwise, the least squares disk fit to the plane of the search circle will drive uphill on the scanty information it has sampled, which may or may not be above the level of sensor noise. Therefore, it is preferable to give the vehicle the advantage of a good head start.

HSA begins with a large first circle to give it a general evaluation of the gradient at that particular point on the search region. The starting point in the circle is the north or 12 o'clock position. It evaluates the two dimensional gradient from this first circle. The vehicle maneuvers to the center of the circle and starts the straight run from there to remove the offset error in the gradient due to the radius. If the new straight line run is computed to be within 60 degrees of the top of the circle, the vehicle takes off from that point to prevent wasted travel time due to a sharp turnaround at the center. This criteria is applied to all circles. The size of the standard search circle is supplied by the user at the beginning of the mission. The larger and smaller circles produced by various situations during the search are all scaled versions of this standard circle. It became apparent in the course of testing that choosing a circle radius that was comparable to a representative plume length scale was crucial. This length scale is derived empirically and naturally varies between plumes according to their source strength and physical size. This parameter needs to be chosen based on dimensions of expected or historical hydrothermal features in the search area.

The vehicle drives a specific minimum distance in a straight line up the gradient and away from the circle until it records three consecutive decreases in the search parameter. The specific number of decreases can be varied according to the time between samples, but three was chosen as a reliable measure of a downward inflection point. The third point becomes the top of the subsequent circle maneuver. The method continues in this manner for a specified number of search circles or until another stopping criteria is satisfied.

One of the taboo search ideas that was incorporated into the HSA is a means to prevent the vehicle from repeating circles in the same position or very near previous circles. This is done by maintaining a record of the location of all previous circle centers and checking each new circle in its proximity to the previous ones. The most frequently used "taboo distance" was 1.5 times the standard circle radius. This usually seemed to be adequate in preventing the vehicle from surveying the same area twice while not pushing it unnecessarily far past the inflection in the measured search parameter. When the search lands within the taboo radius of a previous circle this has been termed a "bounce" and will result in a "breakout" or a run "up current".

Since the shape of the hydrothermal plume parameter contour expands horizontally in a wedge about the axis of predominant current flow, it is desirable to force the vehicle to continue along the best estimate of what it determines is "up the plume". A breakout is a typical example of the aspiration criteria involved in the taboo search. If a breakout is initiated, the vehicle will continue on a new straight line path, vice circling. That path is determined by a least squares fit to a number of previous circle centers or another advantageous direction.

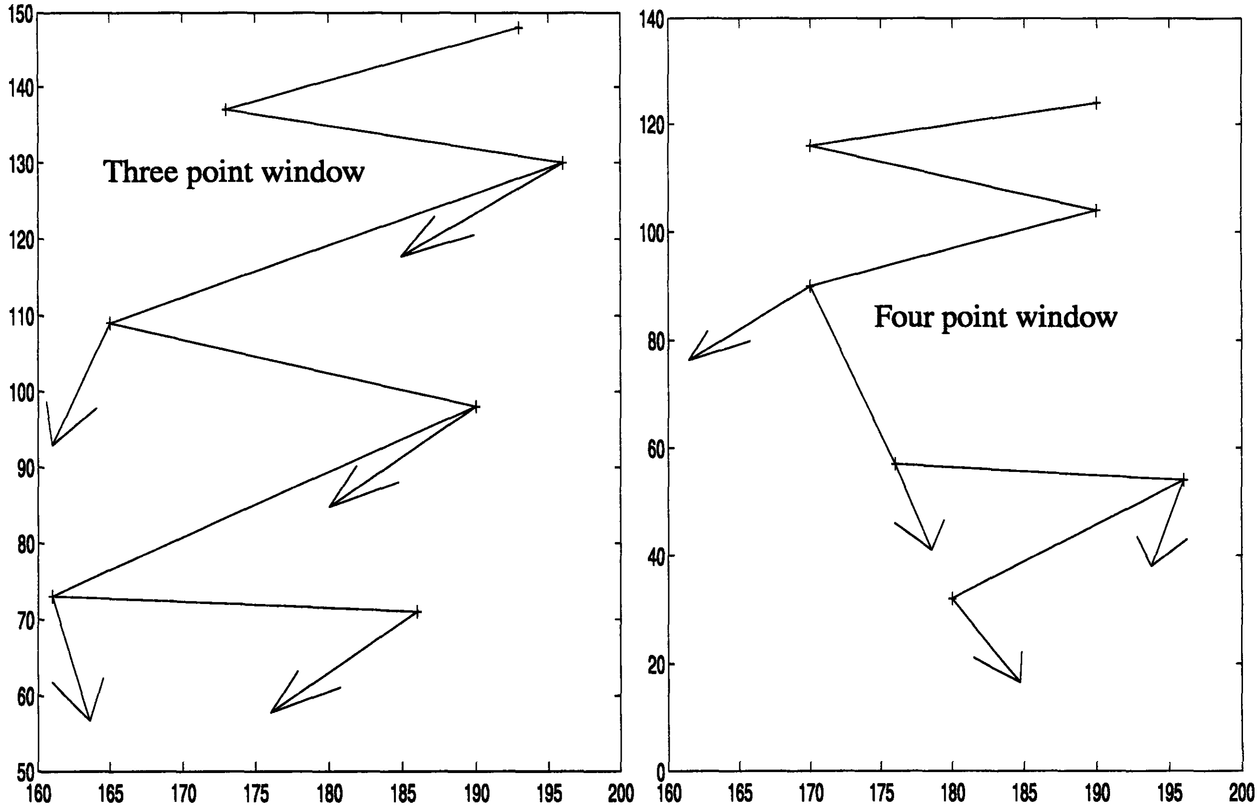


Figure 15. This diagram shows the difference between two vehicle paths with different least squares windows. Each of the nodes (+) represents a circle center. The arrows represent a least squares direction at that point, computed over three or four previous positions as indicated. The method is workable but shows obvious limitations.

A sliding window follows the vehicle as it progresses along the survey. Each of the points is equally weighted by the square of its orthogonal distance to the best fit path. To keep the search flexible, a window of three or four positions appeared to be the most effective.

Again, the vehicle relies on this estimate of best direction when the gradient drives it back to a location that it has already surveyed. A three position window generally forms a "V" shape, with the anchor or oldest position sometimes pushing the result away from the direction of the most recent leg. A four position window keeps a lot of the path history, but at times too much, and can slow down the adaptation to a new and better direction. The effects of both windows can be seen in Figure 13 above. The minimized cost function to determine the least squares path is given by

$$C = \sum_{n=1}^{N} r_n^2 \sin(\theta_n - \theta_w) \qquad (4.2.1)$$

where n = index previous circle centers

N = number of points in the window

r_n = radial distance from current to oldest point in window

θ_n = radian angle between current point and oldest center

θ_w = radian angle of least squares path that is minimized

On occasion, the search will bring the vehicle back to a common location. After a specified number of breakouts, it is desirable to expand the search into a new area to preclude further repetition. There are several ways to deal with this. One way is to program the vehicle to take a large straight run in the "upstream" direction as best determined by a doppler sonar or LBL fixes and delay looking for an inflection point until it has travelled a distance deemed adequate to clear the area of previous searches and local peaks in the parameter. Another means to expand the search into new directions is to have the vehicle complete a large circle and either use that expanded sample of the contour gradient or simply traverse to the highest point on the circle and continue the search.

An increase in the slope of the contour is likely to be indicative of a corresponding increase in the spatial variability of the parameter. I have found it to be preferable to reduce the size of the circle to obtain a more local estimate of the gradient. The circling part of the HSA computes the normalized magnitude of the gradient and returns this information to the main program. When this magnitude exceeds a pre-determined level, the subsequent circle is reduced in radius. What that pre-determined level will be must be generated empirically from the magnitude of the anomaly.

One method to determine this value could be to use the median of a trailing window of previous gradient magnitudes. During experimentation, the gradient cut-off value was selected and set a priori based on results from numerous runs over the same contour. To perform this task autonomously in situ, a delay would be necessary to hold off shrinking the search radius until a representative number of samples was obtained.

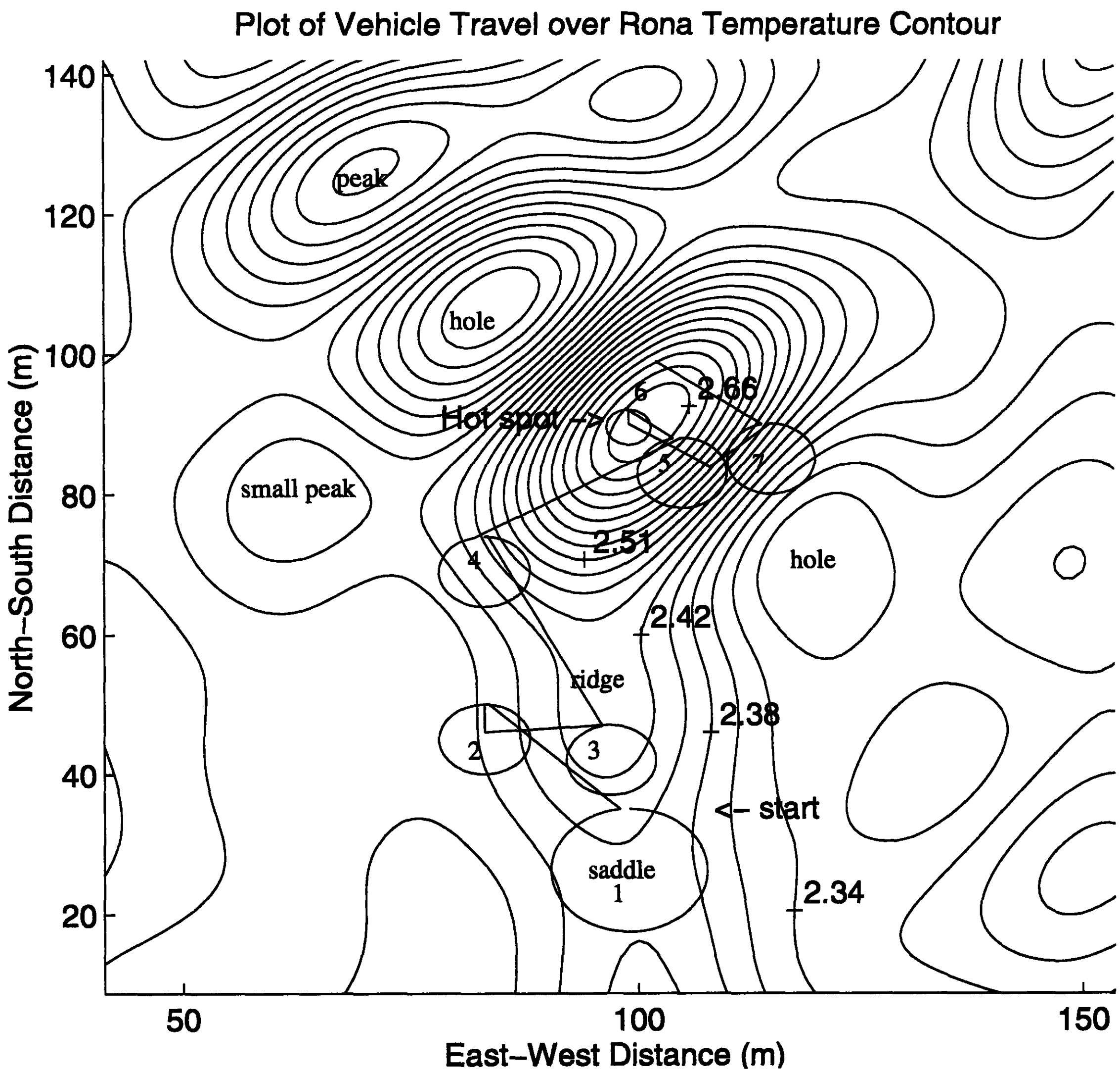


Figure 16. The contour in the above figure was generated by a FTT-inverse FFT algorithm developed by Trivett. The temperature data was collected during *Alvin* tracks over the ASHES site in the Juan de Fuca Ridge (Trivett and Rona[1995]). Selected contour lines are labeled with temperature ($°C$) values. The vehicle path begins at the top of the larger circle at the bottom of the plot. The vehicle starts in a saddle and the resulting direction is off to the left of the ridge. The vehicle recognizes the down turn and circles again to correct the path. This directs the vehicle back up the ridge and the next circle drives it along the ridge. The vehicle senses it is driving past the peak and stops to get a new direction which sends the vehicle directly up the temperature gradient(4). The vehicle accurately locates the hot spot and shrinks its search radius on the sixth circle due the large gradient magnitude of the fifth circle. The gradient evaluated on circle 6 pushes the vehicle back to within circle 5, causing a breakout and the last circle drives the vehicle back up the temperature gradient toward the peak.

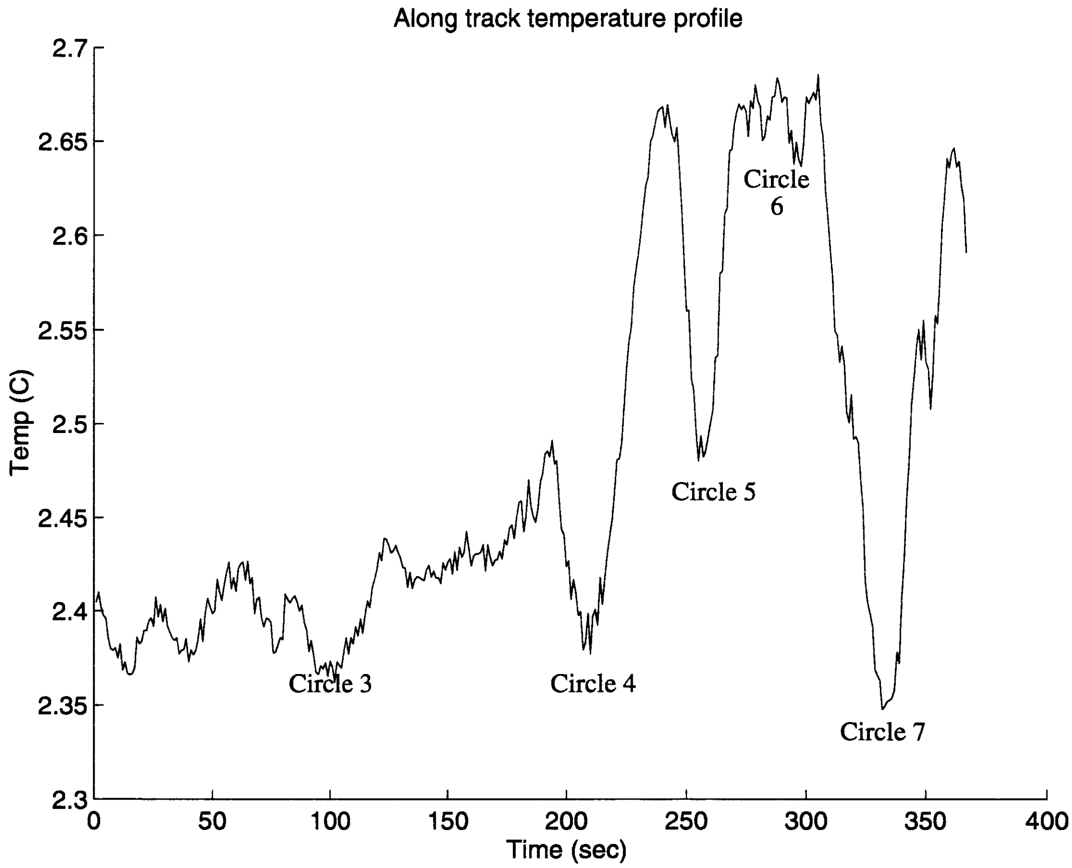


Figure 17. This plot is a representation of sampled temperature from the vehicle travelling the path shown in Fig. 14. The prominent features of the circling maneuvers are identified. A positive trend in temperatures is evident. Random noise has been imposed on the smooth contour prior to sampling in order to examine the robustness of the algorithm. The profile also reinforces the necessity of driving away from the purely uphill direction to verify that the result is characteristic of the vicinity, not just the path covered by the vehicle.

4.3 Data sets used in the testing of the Hybrid Search Algorithm

It was necessary to use temperature and salinity data in the vicinity of hydrothermal vents collected during other experiments. As there was no control over the method, dimension or resolution of the data obtained, I adapted the information to make it useful for simulating the movements of an AUV conducting samples. When real data became available, it was apparent that the parameters had not always been sampled as densely or systematically as I would have preferred. My unrealistic expectations were appropriately adjusted and the process of interpolating data as needed continued. The testing program for the hybrid search algorithm required that the data be in a two dimensional matrix of evenly spaced positions. Random noise was added to smoothed data in order to provide a more realistic assessment of the algorithm. The noise was added using the "randn" function in Matlab at a magnitude of 50% of the smallest decimal place (i.e. 0.0005 for an average temperature of 1.650).

The first temperature profile was obtained from D. Andrew Trivett and Peter Rona(personal communication[1995]) which they collected aboard the DSRV *Alvin* while surveying the Axial portion of the Juan de Fuca Ridge in September 1987. The temperature was sampled over a 150m square section containing several discrete vents. Two surveys were made over the site at 1m and 20m altitudes. The tracks were fairly far apart and contained a significant amount of open space. The resulting contours were produced by a FFT-inverse FFT routine to build a grid at evenly spaced intervals. The contouring algorithm unfortunately imposed an undulating appearance to the data that probably did not exist.

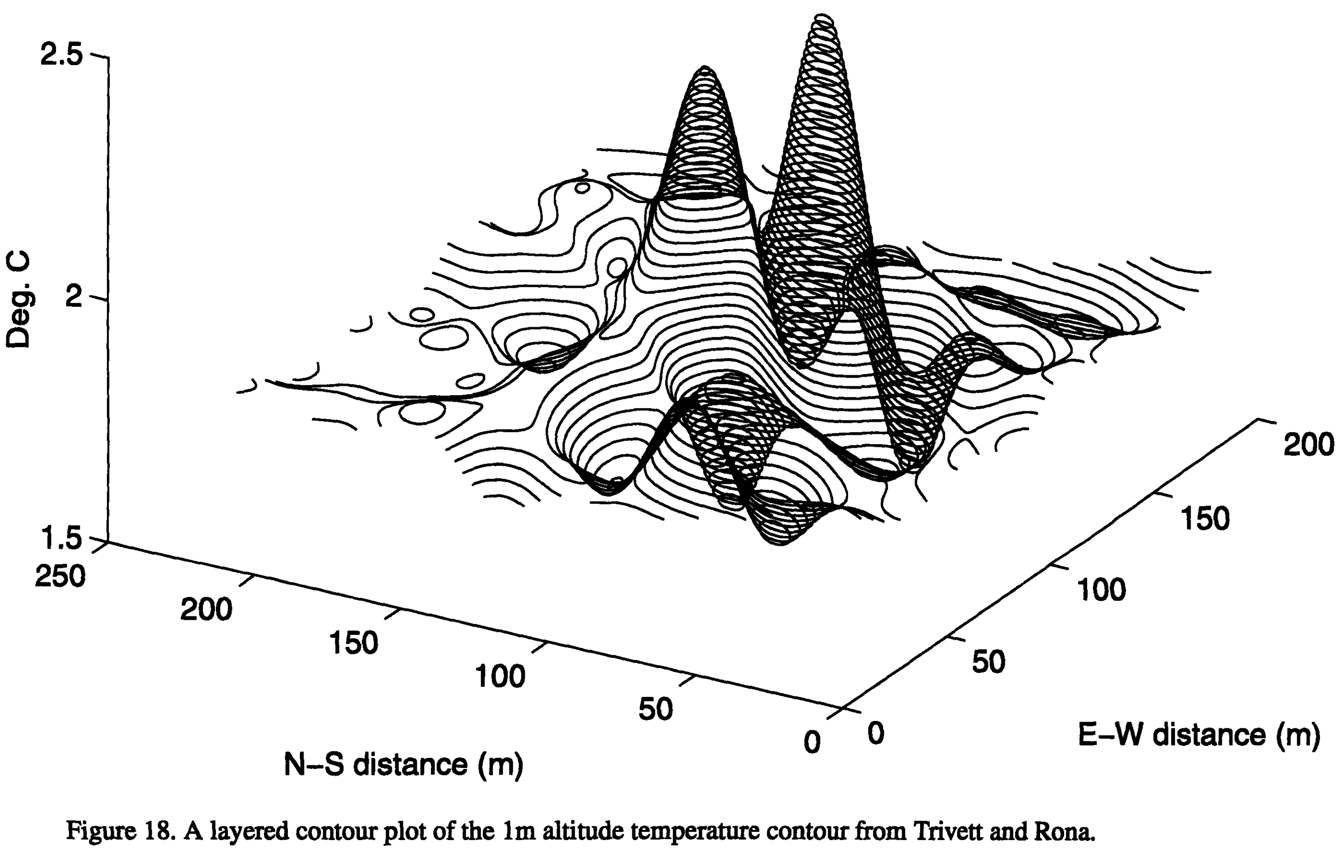


Figure 18. A layered contour plot of the 1m altitude temperature contour from Trivett and Rona.

Other *Alvin* dives that were useful for their temperature samples at the vents were identified during correspondence with scientists from NOAA's Pacific Marine Environmental Laboratory (PMEL). The data from *Alvin* dives 2429-2443 (Robert Embley, chief scientist) was retrieved from the Woods Hole Oceanographic Institution archives in the raw form. These dives were centered about 44° 53′ N, 130° 15′ W, also on the Juan de Fuca Ridge. Vehicle position and depth for each dive was plotted to determine adequacy of coverage at the site. The data was examined for bad data samples and obvious outliers. These points were removed and replaced with interpolated values to smooth the contours.

Although vehicle depth obviously varied during the course of the dives, portions where the vehicle appeared to fly horizontally near the seafloor were retained. Dives that did not provide sufficient coverage were discarded. However, several dives were apparently conducted for the purpose of creating a temperature contour (see Fig. 19 below). About four of the dives were actually usable in terms of generating a reasonable temperature profile.

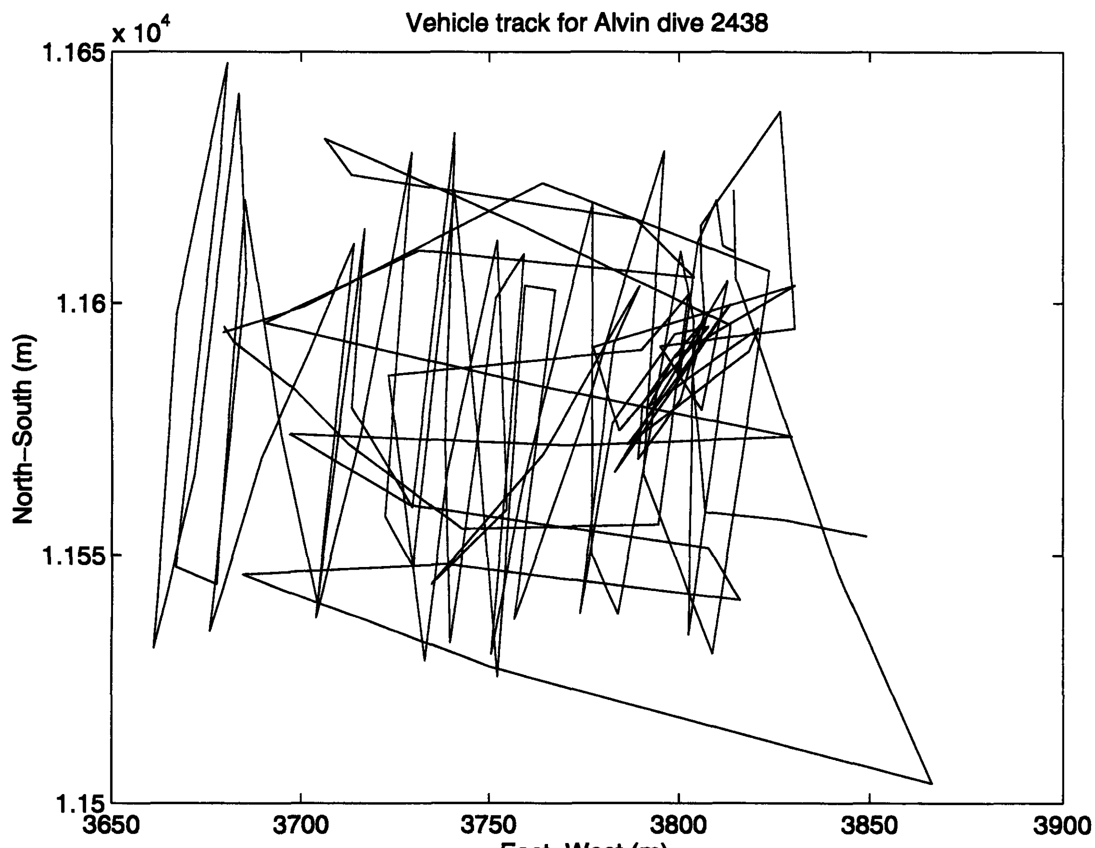


Figure 19. Reconstructed track of *Alvin* on dive 2438 shows extremely good coverage of search area.

Other methods to impose the data on a regularly spaced grid were unsuccessfully attempted and Trivett's FFT contouring routine was again used to produce gridded data to drive the simulated AUV over. Due to the heavy coverage in the survey area the artifacts from the FFT routine were deemed acceptable. A second set of field data was obtained from Stephanie Harrington which was sampled on the Southern Cleft segment of the Juan de Fuca Ridge in April 1994. The data consists of temperature, salinity and attenuation at each kilometer in a 20km square grid, at every 25m between 1800 and 2300m. The sample space is centered about 130.2079° W, 44.9621 N. In order to facilitate use in the searching program, the slabs were interpolated onto a grid of 210x210 positions. The data was collected via surface tows using the tow-yo method of rasing and lowering the sampling instrument while traversing the search area to add vertical variations to each swath. The ridge runs from the northwest to the southeast in this region and several tracks were conducted in an asterisk pattern centered about the vent field. Due to the method of sampling and the amount of data manipulation necessary to get it into usable form, a large amount of artifacts exist. These have been partially accounted for by starting the vehicle in portions of the grid suspected of being most representative of actual conditions.

A model generated data set was supplied by Wm. Lavelle of NOAA PMEL(personal communication[1995]). The data as given simulated a 13MW discrete buoyant source in a 1.5 cm/s cross flow (see Fig. 14 for plot). The temperature and salinity were mapped onto a grid of 640x320x300m at one meter intervals. Since each point in the grid was specifically assigned a value this data did not need to be adapted or interpolated before use. The contours generated from this model conform more closely to what is expected from the equations describing parameter variation in Section 3. Instead of the roughly symmetric peaks and valleys produced from the *Alvin*-sampled data, Lavelle's model produces a laterally expanding, ridge shaped anomaly that has a significant peak in the vicinity of the source and smaller local peaks as the fluid is advected downstream. Modifications to the hybrid searching routine were largely motivated by the simulated vehicle's response to this environment.

4.4 Modifications to the HSA and variations of the search parameters

Although it is possible to custom parameterize the searching program to each contour, this does not necessarily lead to a robust algorithm. Instead, I attempted to find values that seemed to work well in a number of similar environments. It is important to restate the goal of the algorithm as the localization and verification of hydrothermal anomalies. Changes were evaluated on their ability to guide the vehicle more directly toward the region of interest. Specific parameters that were frequently addressed include starting, shrink and enlarged circle radius, taboo distance between circle centers, minimum travel distance for normal straight line runs and breakouts. The specific maneuverability of the ABE vehicle was not included in the searching algorithm, but did not need to be (see Fig. 10). ABE has demonstrated the ability to stably drive in constant radius circles and is capable of stopping and rotating in place if necessary, though this is not preferred.

Gradient circle radius:

The original idea behind the concept of driving the vehicle in a complete circle while measuring the scalar parameter was to increase the amount of across track information during the search. There are bounds on the length of a useful radius. Although ABE is capable of rotating in place, it is not hydrodynamically efficient and provides little useful information to do so. There are times, however, when a small circle is preferred and almost necessary for the proper evaluation of a hydrothermal feature. The characteristics of the individual plume will determine what is an effective search radius. Since vehicles are usually a meter or more in length, a minimum radius of three or four meters is realistic. In simulations, the standard radius chosen varied between 5 and 10 meters. The idea is to balance the information gain versus time, distance and energy expended. Too large a circle may miss important variations in the search parameter by encircling them, while too small a circle does little to make the search dynamic.

The selection of the standard radius is done at the start of the mission. All modifications of the search circle are scaled versions of the standard search circle. The large starting circle is designed to take a large cut through the search region and increase the smoothing properties of the least squares routine to fit a gradient disk to the surface. In experiments, the starting circle radius was selected to be 1.5 to 2 times the standard radius. While this search parameter was not that critical, it appeared to be preferable to have the initial circle to be larger than the standard circle. It is important to reiterate that the vehicle most likely arrived at that location by means of a lawnmower search or the Direction Set Method, so it shouldn't be necessary to drive the vehicle too far away at first.

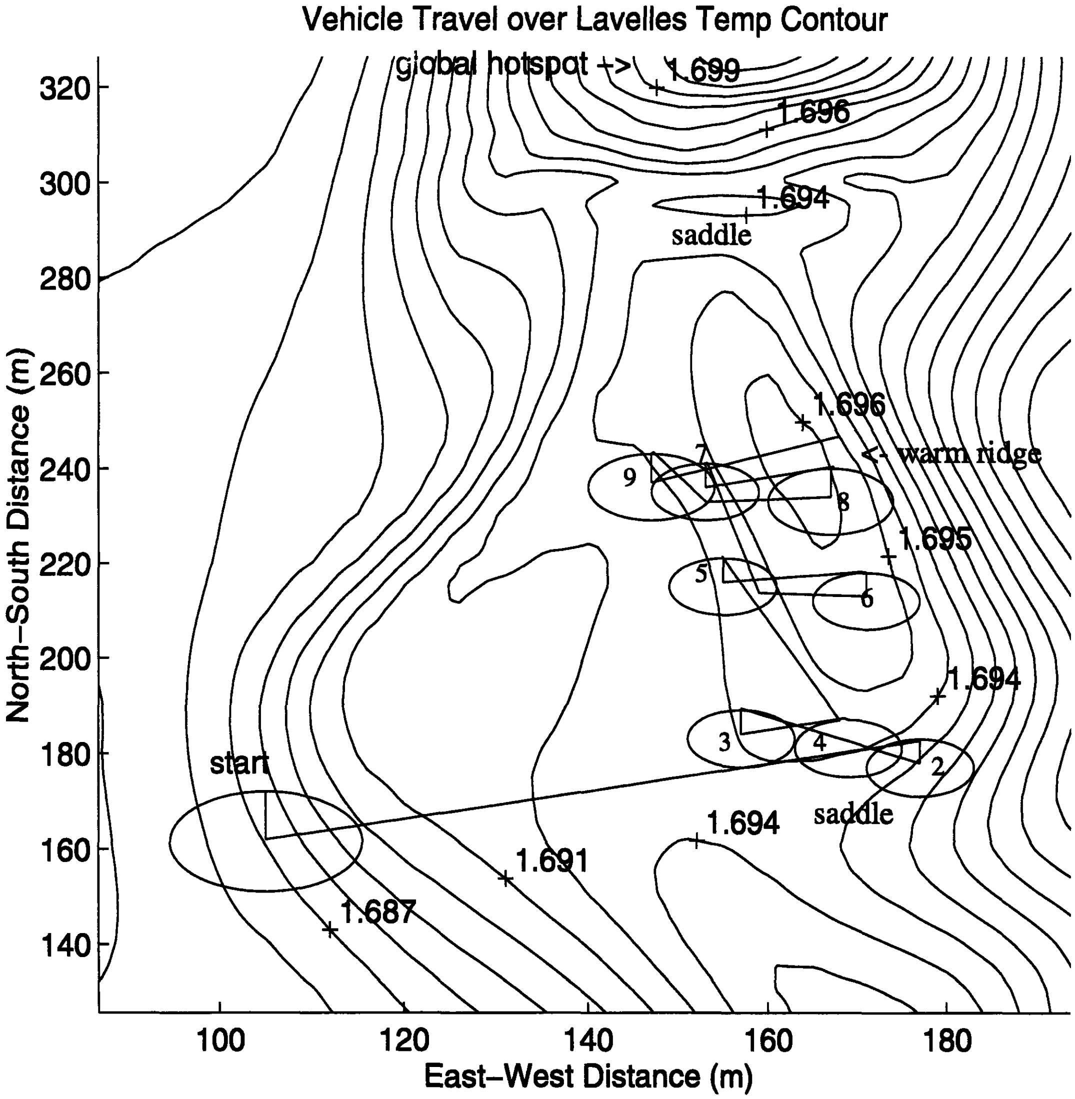
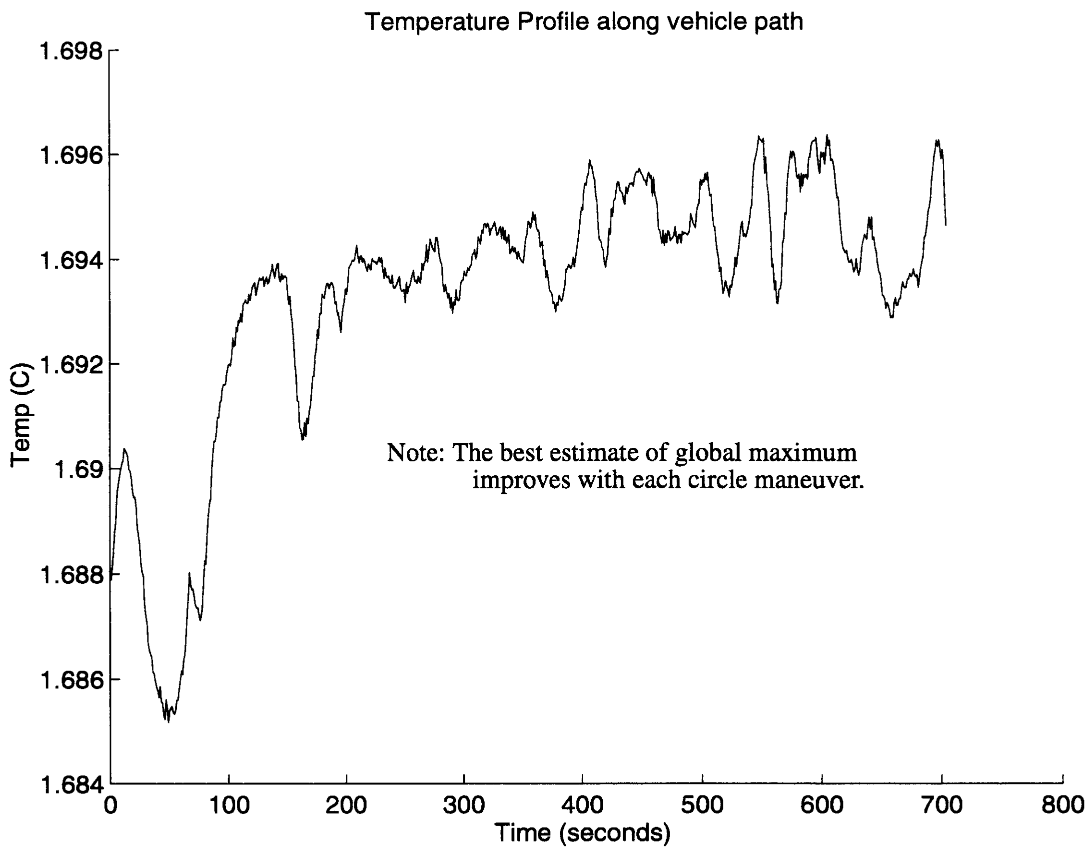
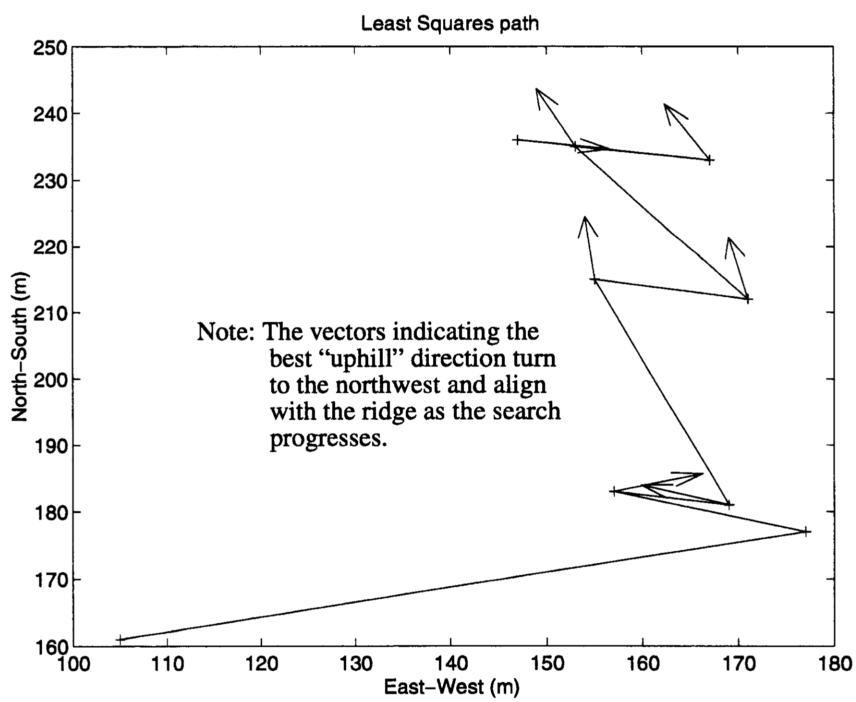


Figure 20. This plot demonstrates the operation of the hybrid search in the Lavelle's contour plot. This particular horizontal slice was taken at 180m above the plume source. The vehicle starts off to the left of the plume ridge axis and drives smartly uphill until it detects a dip in the ridge. The vehicle conducts three quick circle maneuvers (2,3,4) at the base of the ridge and then turns uphill to drive parallel to it. An inflection forces a circle (5) and a bounce following circle (6) sends the vehicle further up the ridge due to the least squares gradient evaluation. Evaluation of circle (7) sends the vehicle up the ridge again. Since circle (8) is basically on the ridge the gradient pushes it off the ridge, the downturn is recognized within circle (7), so it bounces. Circle (9) drives the vehicle back up the slope to verify the local peak. The global peak is just off the top of the plot. The ridge continues through a saddle to point of steep gradient in the same northwest direction. This mission was only programmed for nine circle maneuvers. For the vehicle to reach the global peak, had the mission continued, an aspiration criteria of a sufficiently long straight line run during a breakout, upstream run or a large search circle due to multiple breakouts would be necessary to overcome the saddle. Later versions of the algorithm have shown that driving upstream is generally advantageous.



Figures 21 & 22. These plots detail the increase in sampled temperature and least squares gradient path fm. Fig.20.



When the magnitude of the gradient computed while circling exceeds an empirically selected or automatically computed value, the vehicle reduces the search radius to tighten the search and more closely follow the parameter contour. It is desired to make this reduction significant but not remove the ability to measure across track. Therefore, a shrink ratio of 0.5 was accepted. If the characteristic length of the plume region is large and the standard radius is appropriately lengthened, a greater reduction for high gradient regions is warranted. A shrink ratio of 0.3 times standard radius was employed.

After a selected number of breakouts it is assumed that the search is getting redundant or has located a peak in the parameter. The search can be pushed to new areas by drastically increasing the size of the search circle. This serves to look for higher values in the vicinity of previous searches or verify the maximum by returning to it. The size of this big circle was chosen to be three or four times the standard circle. This distance appeared to be adequate to encircle previous circles or drive an arc through them, depending on the starting point and at the same time sample untraversed regions.

This large circle extends information gained during previous circles. The circle starts at the point where a standard size circle would have taken place. The center is then fixed at a "large" radius away in the computed least squares path direction. If the path vector is uphill towards the thermal or chemical source, this large circle is out in front of previous circles. If the path vector is erratic the circle will arc through the congested region. (See figure 23.) An alternate way to deal with the problem of the search becoming redundant is to drive straight away from the area where the search has concentrated for an extended distance. The difficulty with this method is in choosing an effective direction. Using the last circle gradient is not useful since the result in the vicinity of a peak is likely not consistent with the axis of the plume. The algorithm has arrived at this point because the vehicle does not have a good idea where to proceed. It was decided that a large circle was a reasonable way to pick up the trail again.

Taboo distance:

A fundamental premise of the gradient directed search is that it will be more efficient due to less wasted vehicle travel. In order to limit the amount of resampling of the survey area, the concept of a taboo distance was incorporated into the hybrid search. This can be understood as a stand off distance between circle centers. As mentioned previously, 1.5 times the standard radius was selected as an acceptable compromise.

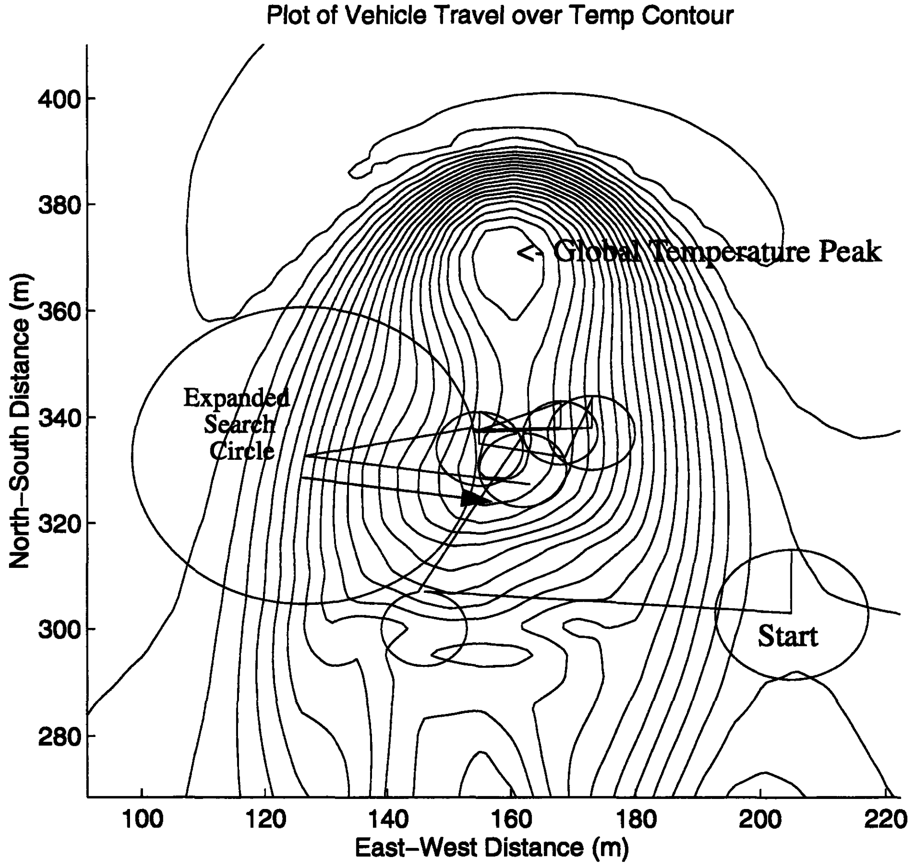


Figure 23. This plot shows the necessity of the large circle. The vehicle is started to the side of the plume outwash axis. It drives uphill and evaluates again as it detects an inflection in the saddle at the base of the peak. It conducts four circle evaluations in close proximity, leading to two breakouts and then an extended search radius. The least squares path vector pushes the large circle off to the left of the temperature peak. The gradient measured over this enlarged circle forces the vehicle back toward the temperature sub peak in the direction indicated by the arrow. The search terminated at this point, but would have continued to circle and attempted to maneuver toward the global peak. The contour is a close up taken from Lavelle's model at 180m above the plume source.

For the circles to have no overlap, the distance would obviously have to be twice the standard radius. It was decided to use less than this since some overlap in a rapidly changing environment appeared to be advantageous and the algorithm did not account for the occasional shrinks due to gradient magnitude. Taboo distances up to 2.5 times the standard circle were attempted. By greatly expanding the prohibited region around each circle, the vehicle was pushed away from areas that it should have stopped to circle and measure.

Minimum travel distance and breakouts:

In order to keep the algorithm moving through new sections of the survey area, a minimum travel distance is set before the vehicle is permitted to act on an inflection point. This length is also a scaled value of the standard circle radius. During normal runs, this distance is twice the standard radius if it starts from the center of the circle and one radius if the run starts at the top of the circle. Both distances are adequate to push the vehicle beyond the most recent circle, but not limit its ability to evaluate the contour. A breakout occurs when the inflection point of a straight run lands within the taboo distance of another circle. The inflection point is most likely not exactly in the center. The minimum travel distance from this inflection point has been selected to be 1.5 times the standard radius. Since we know that an evaluated gradient was used to return the vehicle to this location, it is not desirable to push it any further away than necessary.

Upstream travel distance:

An intuitive approach to localizing the source of a hydrothermal fluid is to search until the plume outwash is detected and then track the parameter by means of travelling upstream. The upstream direction can best be determined in situ by using the vehicle as a langrangian current float. ABE is stable when unpropelled and a doppler sonar or LBL fixes should be able to provide a good estimate of the predominant flow. This may be a better means of directing the vehicle after a bounce than the least squares path method when the current information is reliable. The distance to drive upstream is selected according to the characteristic length for the plume environment being surveyed and will also be a multiple of the standard search radius. The characteristic length is based on estimated source magnitude and historical tidal current magnitude. In simulation with the plume contours supplied by Lavelle, an aspiration criteria of upstream travel for ten standard radii appeared to be sufficient to clear the area of previous circle searches and escape prior local temperature maxima. The ideal distance may need to be modified based on local conditions, but the idea is to drive the vehicle far enough away from local peaks so that it won't return to them, but not so far that it misses significant features or the source entirely, for that matter, in one jump.

The current set and drift from Lavelle's model is known and was used as the vehicle's measured estimate. This method of avoiding repetition and pushing the vehicle further towards the source of hydrothermal fluid can be used in the place of a breakout. As soon as the vehicle returns within the taboo distance of a previous search circle, it is directed to travel upstream at least the specified minimum distance and then stop to conduct a circle gradient evaluation when it has detected an inflection point.

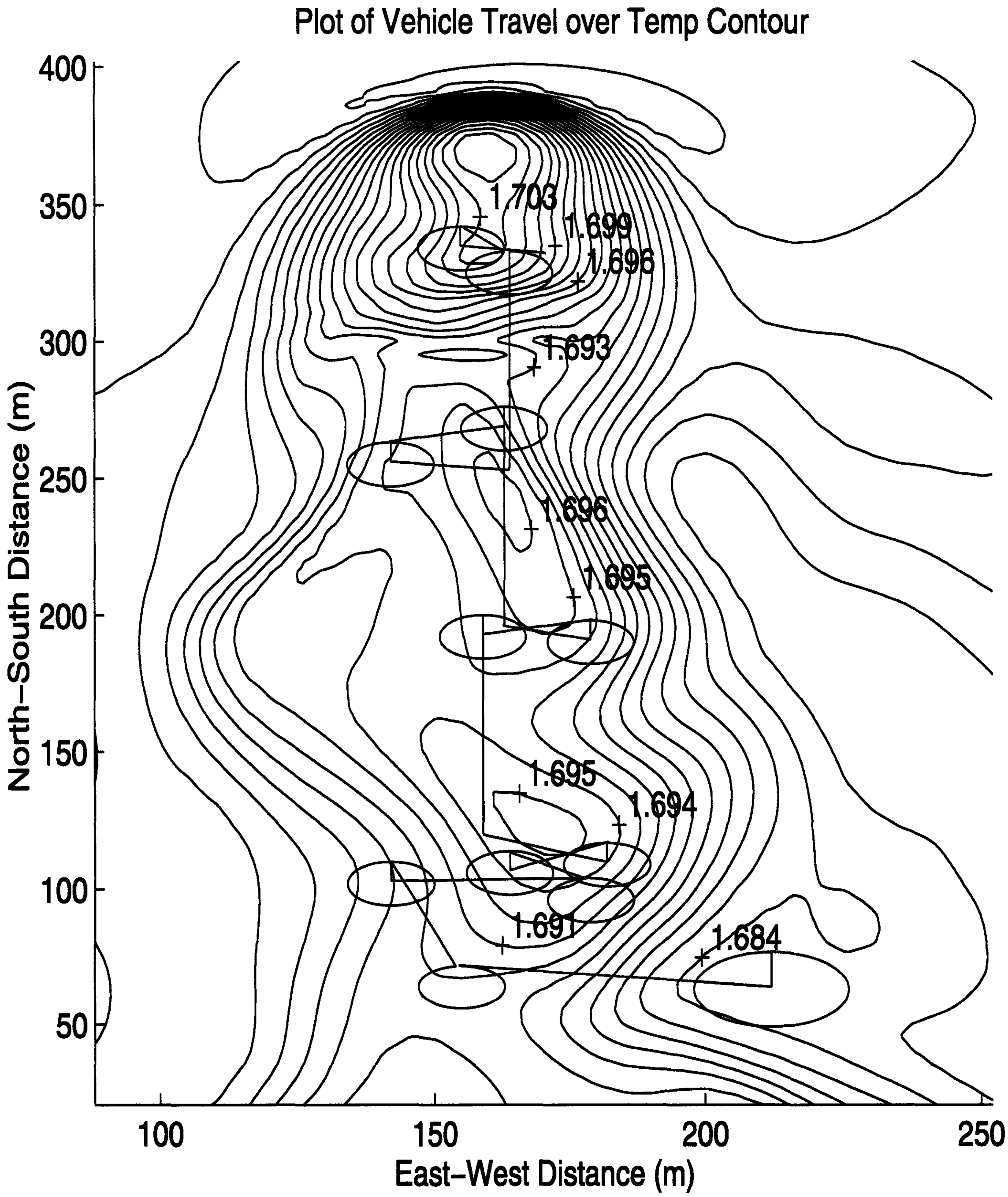


Figure 24. This simulated vehicle path uses the "driving upstream" aspiration criteria instead of the breakout method when the vehicle returns to a location within the taboo distance of a previous search circle. Saddles and local maxima are avoided and the vehicle progresses upstream toward the source of hydrothermal fluid seen as the oval at the top of the contour plot. The contour is from Lavelle and the modeled current flows down from the top of the diagram.

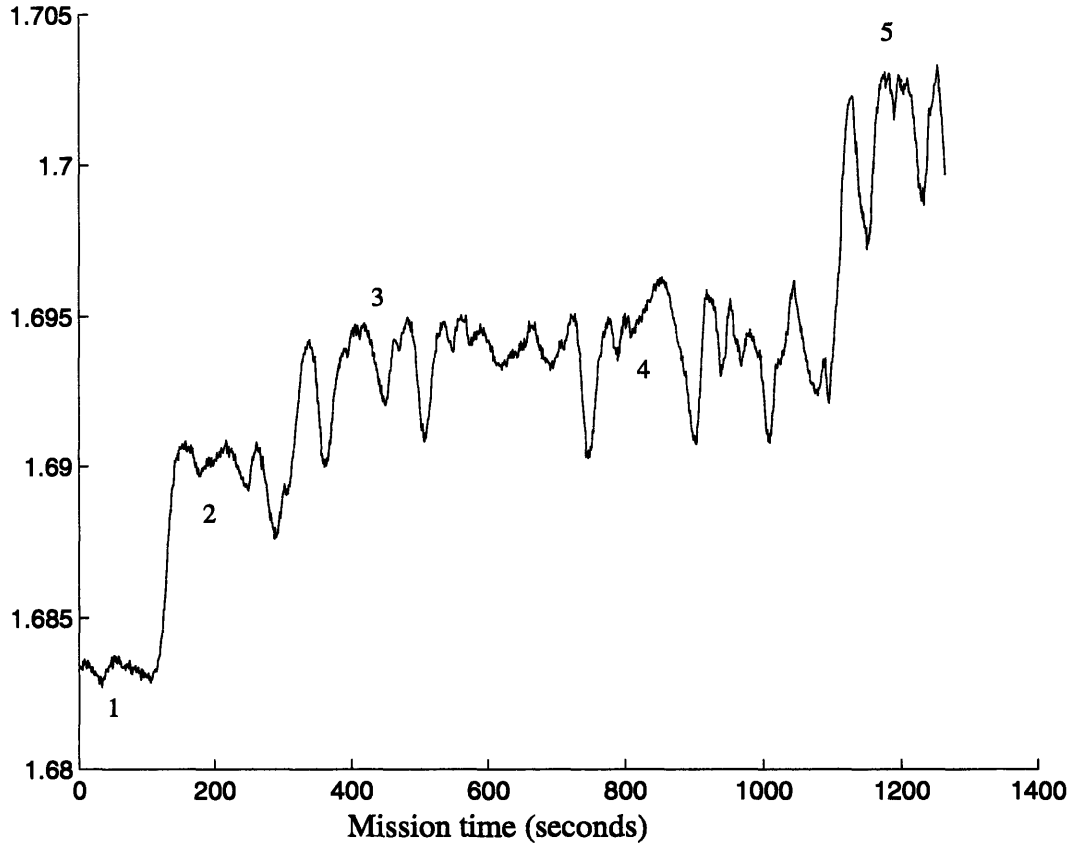


Figure 25. This graph shows the mission temperature profile for the path shown in Fig. 22. The lower temperature is the off-axis ambient(1). The vehicle tracks up the temperature ridge(2) and conducts a few circular evaluations. To avoid some of the local minima and advance the search toward the source of hydrothermal fluid, the vehicle defaults to its drive "upstream" mode(3). Despite dips in the temperature profile, it continues upstream until the minimum travel distance has been satisfied(4). The strategy proves to be effective as the source of the warmer fluid is localized at the end of the run, as seen by the jump in measured temperature(5).

The vehicle continues working its way upstream until the stored maximum temperature seen during the search is not exceeded after circling. At that point the vehicle can traverse back down the plume outwash, switch search modes, travel to another suspected region or terminate the search and return to the surface. The starting point of the hybrid search can be used as a marker to terminate the vehicle travel downstream.

Section 5: A Consolidated Search Strategy

5.1 Addressing the search problem

In order to make practical use of the theorizing described thus far, a formal set of guidelines needs to be applied in the various search situations. The needs and desires of the scientist conducting the survey must be intrinsic to the plan. The explicit purpose of the survey must be identified. The methods described in this thesis are primarily designed as a means to optimize the path the vehicle takes to locating the parameter minima or maxima. Non-directed surveying, such as parallel line tracks, has been studied extensively (Jourdan[1986], Koopman[1946]) and works well when coverage alone is the measure of effectiveness. However, this thesis has shown that a gradient based search may be significantly more direct.

The parameters being measured are defined and the sensors to sample them are incorporated into the vehicle physical structure and electronics package, the latter often being a non-trivial process. The search area coordinates are set and a means of navigation is chosen. Typically, a net of sonar transponders will be placed on the seafloor to provide for a fixed global reference. Although, the algorithms described above should be robust enough to drive the vehicle with only dead reckoned position in the presence of minimal currents. It should be expected that the search will be an iterative process, with each mission providing more information on plume "characteristic length" to decide the standard circle radius, taboo distance, and minimum travel distances for straight line and "upstream" runs.

5.2 A plan for using the methods

The choice of search plan can be made after answering several fundamental questions:

Does previous survey data exist for this parameter and location (assume it is valid)?

Does there exist any knowledge of the expected structure of the parameter?

Will global navigation be available and reliable over the entire search region?

Are currents significant with respect to vehicle speed and parameter variation?

Is there a good understanding of expected oceanographic conditions?

It is imperative to have a solid understanding of the survey environment. For instance, the temperature and salinity anomaly caused by Atlantic plumes is cooler and fresher than ambient at the buoyant level. This condition is counterintuitive. If previous survey data is available and not outdated, as parameter variation around hydrothermal sites can vary dramatically over weeks or days, it is obviously useful to focus on and initiate the search near where significant anomalies exist. This serves to remove large sections of the area that possibly contain minimal parameter variation. When basing a search plan on previously assembled data, the instrument and methods used to collect it must be taken into consideration. It may be prudent to do some verification of the historical data by hydrographic casts or, preferably, with the vehicle to be used for the survey. In all likelihood, the search strategy will evolve during multiple runs in the same search area. As mentioned in Section 3, the buoyant plumes reach an equilibrium layer and then disperse horizontally and downstream. The largest anomalies in temperature, salinity, optical backscatter(OBS), etc. will occur at this depth. The first mission through the length of the water column will reveal much about the ambient environment. It is expected that if the vehicle is in the relative vicinity of a hydrothermal vent, there will be a distinct increase in OBS and that the buoyant plume depth is near this water column maximum. It would therefore be advantageous to search horizontally at that depth.

If significant currents exist, this will affect both parameter variation and the vehicle's ability to maneuver and navigate. Parameters with a discrete introduction point will develop a definable structure in the presence of a predominant cross flow as seen in Lavelle's model and data retrieved by ABE at the FLOC site on the Juan de Fuca Ridge in August 1995 (Singh, et. al.[1995]). This plume structure was successfully incorporated into the hybrid search algorithm, with the aspiration criteria of searching upstream when the vehicle becomes "confused" being pivotal to it's success. It turns out that the existence of a relatively steady cross flow is quite advantageous to the vehicle's ability to locate the discrete source of a particular parameter. For example, the outwash from a hydrothermal plume can serve as a pointer in the ocean to the vent opening. However, the greater the current, the more challenging the vehicle navigation and control problem. The fact that the vehicle cannot easily include a current vector in it's estimation of position makes either a long baseline (LBL) navigation net or an effective doppler sonar necessary for the vehicle to account for a non-stationary sampling environment.

If the ambient currents are negligible and the parameter, such as suspended particulate matter from a hydrothermal vent, assumes a mushroom cap shape, the Direction Set Method may be just as useful in evaluating the roughly monotonic parameter contour. Since much of the real, horizontally collected temperature contours tend to be splotchy, having the vehicle perform a verification run at the end of a mission may be necessary. A verification run can be a set of widely spaced parallel tracks or an asterisk pattern, depending on the physical dimensions of the vent field. Iterative missions in a common search area will build empirical knowledge of the environment and will serve to determine which method works best.

An interesting challenge for the vehicle to overcome will be dealing with a necessary change in depth due to bottom avoidance while in the midst of a supposedly horizontal search. Changing depth changes the ambient potential temperature and takes the vehicle to a different level of the plume structure. Buoyant plumes will typically rise to a height above the seafloor that makes obstacle avoidance unnecessary, but the possibility exists that a depth excursion may be needed for vehicle safety. In this instance, the vehicle should be forced to maintain as flat a profile as the bathymetry permits to make parameter sampling as uncorrupted by depth changes as possible. Provisions for this behavior already exist in ABE but have not been specifically addressed in the testing algorithm.

5.3 Searching realities

The circle gradient search has already proved it's worth during the ABE Herring Pond tests in the summer of 1995 (see fig. 10). Bathymetry was sensed with a reasonably accurate altimeter and depth sensor. The vehicle dynamics for ABE fit easily within the boundaries of the simulated runs conducted with the DSM, CGS and modified hybrid method. The instruments that will be used to measure parameters particular to hydrothermal vents have been used successfully on fixed and lowered platforms (Trivett[1991]; Lupton[1995]; Nelsen, et. al.[1986]). The logical progression is to adapt and conform these instruments for use on a capable AUV, such as ABE. Their sensitivity and accuracy is sufficient to permit the vehicle to make motion decisions based on an adequate parameter sampling rate and spatial coverage and perform missions that are close to being truly autonomous.

Section 6: Conclusions and Future Work

While considerable academic energy has been expended to address the problem of mathematical optimization of an unknown parameter field, little application of these methods has been made to the unique problem of incorporating into these strategies the vehicle dynamics or motion limitations imposed by an autonomous underwater vehicle. This thesis has examined the feasibility of using simulated annealing, the Direction Set Method, the simplex search and, primarily, variations of the circle gradient evaluation to produce a workable means to make an AUV truly autonomous in an unknown parameter environment. It was shown that using knowledge of the expected physical structure of the parameter can improve the efficiency of search from the random probability of "lawnmowing" to a highly directed gradient search that responds to in situ measurements of the search parameter.

The waters surrounding the hydrothermal vent sites were selected as the primary testing environment because of the significant scientific interest concerning the impact of hydrothermal activity in all fields of oceanography. Several models of the plume effluent flow(Lavelle[1995]; Trivett[1995]; Middleton and Thomson[1986]; Speer and Rona[1989]) were available to design a testbed for evaluating potential search strategies. Actual data collected aboard the deep submersible *Alvin* was also used. As more information about the parameter scale and structure of the vent physics becomes available, the searching routine described in this thesis can become more efficient at locating features of interest. It is likely that existing models are already adequate to give the vehicle a sufficiently sophisticated framework to conduct the search. The focus should be on matching the scale of vehicle search routine to that of the particular feature being surveyed.

It is the intention of the Deep Submergence Laboratory to use ABE on a return mission to the Juan de Fuca Ridge in the Fall of 1996 to conduct surveys in the waters surrounding the hydrothermal vents. Parameters to be measured will include temperature, conductivity, optical backscatter and magnetic anomaly. The vehicle will be run on pre-programmed missions and in a fully autonomous mode based on the hybrid search algorithm described in this thesis. The results of those runs will provide significant information on the usefulness and limitations of hybrid circle gradient search.

Several potential projects may expand the work completed in this thesis. ABE has been successful in mapping the magnetic anomaly during pre-programmed missions(Yoerger, et.

al.[1996]). Since the dimensions of the anomaly are not precisely known, it may be possible to use the vehicle in a gradient search mode to more accurately define the boundaries of the magnetic feature. The particular feature being investigated by Maurice Tivey of the Geology and Geophysics department at WHOI is approximately ellipsoidal in shape. ABE has conducted a "lawnmowing" search over the site during the 1995 cruise. Since the edges of the variations in the magnetic strength are sharply defined, it may be possible to have the vehicle traverse the feature from edge to edge and map the anomaly more precisely. The vehicle could perform a cross-feature survey similar to that employed by the Direction Set Method and conduct a single leg evaluation of maximum magnetic anomaly at the end of each traverse leg. The approximate orientation of the feature is known and would be incorporated into the search routine. In the vicinity of new lava flows, measured magnetic field strength is actually lower than unaffected areas. Within the boundaries of the feature the field strength varies significantly (Tivey[1996]).

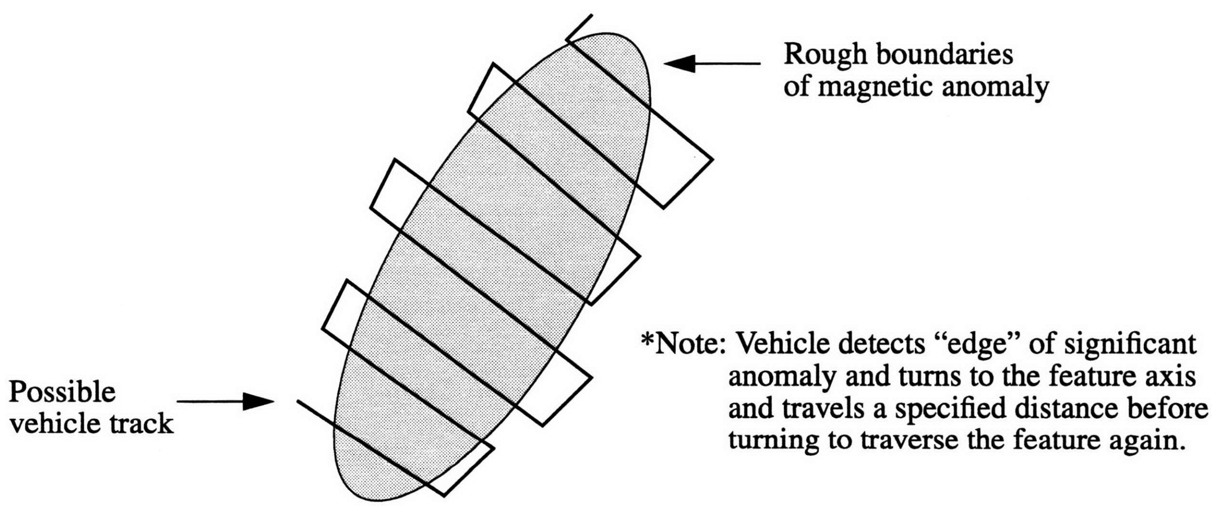


Figure 26. Proposed vehicle tracklines for interrogation of magnetic anomaly.

Another possibility for locating the sources of plumes will be made possible with the installation of an optical backscatter sensor on ABE. Since the scale of the anomalies in suspended particulate matter is on the order of tens of kilometers, long duration missions covering significant distances may be possible to locate as yet undetected sources of hydrothermal fluid. A version of the hybrid search algorithm with the search parameters appropriately adjusted may be very useful for such missions.

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