Event response using AUVs in NEPTUNE

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Note: this is a draft, questions to be resolved are highlighted□

1□Introduction

Autonomous Underwater Vehicles (AUVs) can provide crucial capabilities for responding to events□ An AUV docked to a NEPTUNE node could reach a new hydrothermal plume long before we could mount a response with a ship and perhaps quicker than could an AUV launched from an aircraft□In addition to being close to an event, an AUV docked at a node could be ready to run at a moments notice, requiring only information relevant to the event to be downloaded□

AUVs can be built in a variety of shapes and sizes, which translate into a wide range of capabilities in terms of speed, range, manueverability, and payload□This paper will use an event response example to motivate a discussion of how AUV characteristics and capabilities will effect our ability to achieve scientific goals□Specifically, we will examine the following AUV attributes:

- range
- speed
- maneuverability
- payload capability
- battery characteristics

At a system level, we will examine the following:

- navigation infrastructure
- docking station capabilities
- number of vehicles per node
- number of docking stations per node

Event response also will require that we solve some interesting management problems□what decisions will we need to make? who will make them? how long will they take?

As an example response, we will consider the mapping (and perhaps sampling) of a new hydrothermal plume created by a tectonic or volcanic event□The goal of the mapping exercise will be to localize the plume, then determine its size, shape, and composition, and to watch the plume evolve for a length of time (HOW LONG?)□We would like to make a standard suite of oceanographic measurements (conductivity, temperature, optical backscatter) as well as other in-situ chemical measurements that are just now emerging□

2□Event detection strawman

As a strawman approach, the event response scenario might procede in the following steps:

1□We identify and localize an event using remote sensing techniques (hydrophones, seismometers, etc)□

2□We decide to respond, download relevent event description to the nearest AUV(s), and launch it (them)□

3□The vehicle transits to the site

4□The vehicle attempts to determine the precise location the event plume, starting at the most likely location then expanding out□This initial part of the survey would take place at the optimum detection depth, approximately one hundred meters off the bottom□Initial detection could be accomplished with a simple suite of sensors, including temperature, optical backscatter, conductivity, etc□

5□Whether or not an event is detected, the vehicle heads back to its home node when the "come home" battery level is reached□

6□If the plume is detected, the vehicle then executes a survey strategy designed to determine the size, shape, and composition of the plume, mostly up high in the water column□The sensor suite would consist of the same sensors used for detection, possibly with the addition of other sensors more appropriate for detailed examination of the plume□The AUV could conceivably take water samples□

7□The AUV might also attempt to localize the plume source□This might require flying closer to the seafloor, which could complicate navigation, require more responsive dynamics, and possibly a complete bottom-following capability□

8□Other AUVs could start transitting to the site□The next nearest AUV might procede directly to the event, while AUVs from nodes further out might work their way to the nearest node by stopping at intermediate nodes for recharging□

9□Acoustic communications capability from the AUVs back to the nearest node would allow a much better coordinated multi-AUV response□The range requirement coupled with limited power would necessitate the use of low data rates, which should be sufficient to transmit brief updates on the progress of the survey□

10□After completing its survey, the AUVs would return to the nearest node□They would dock, download data, and start recharge□

11□Depending on how many vehicles we are able to include in the event response, battery recharge time could be very important□Most advanced batteries can be charged in about 2 hours□However, we may not have sufficient power at the node or the ability to transmit the power to the vehicle could be a limiting factor□

Currently, we have an impressive capability for detecting events on the Juan de Fuca plate through the use of the SOSUS system□(summarize briefly how this is done)□Given the capabilities of NEPTUNE, our ability to detect and localize events will improve (is this true?, will it depend on the quality of the acoustic infrastructure we install?), as we will have more hydrophones located closer to the event□

*I*f the processing of the hydrophone data is fully automated, detection, localization, and characterization of the event could happen almost immediately *(IS THIS TRUE?)*□However, events can be complex and often move over time (*how long, how far typically*?)□

We need to determine how we would judge an event as worthy for a full AUV-based response□The penalty for a "false alarm" will depend on the reliability of our AUV systems□Also, information of the approximate location would be required, and information about the expected size of the plume, as well as projections of currents would be useful for AUV mission planning□Would an automated response be appropriate? or would human decision-making be required? If human decision-making will be required, our response may be delayed and the data set diminished in value□

PARAMETER: time between detection of event and decision to deploy AUV(s)□

SCIENCE NEED: We need to understand how rapid our response must be□Marv Lilley has told me that any delay after the plume starts would result in loss of important data□However, the plume may not start up immediately□Simply stated, engineers need a definition of "rapid"□How long a delay can we tolerate between the detection of the initial acoustic data and the arrival of the AUV at the scene? These questions impacts many technical issues such as node spacing and AUV range/ speed tradeoffs□

PARAMETER: Expected distance of event from nearest node

PARAMETER: Expected delay between event detection and emergence of the plume

PARAMETER: Allowable delay between emergence of the plume and arrival of AUV to start survey□

In terms of distance required for a single AUV, the worst case location for an event would lie equidistant between nodes□Somelocations, such as the NEMO site on Coaxial Seamount, would likely have events quite nearby to a node□But we certainly want the ability to respond to events in less predictable places□

If events could occur anywhere along the network backbone, and we assume worst-case (midway between two nodes), then we can make a simple conclusion about vehicle range: we need sufficient range to reach the event, conduct a meaningful survey, then return to the node with a sufficient margin of safety□For our current preliminary design of 100 km node spacings, the vehicle of the size and shape of Odyssey considered in my AUV white paper, would fit□With either lithium ion or pressure-tolerant lithium polymer batteries and a modest hotel load, the vehicle would have sufficient range□Note that this range corresponds to a survey and travel speed of 5 km/hr, i n the worst case the vehicle could take up to 10 hours before it starts reach the vicinity of the event plume□The only way to improve upon this delay is to either hope for an event closer to a node, decrease the node spacing, or travel faster□Depending on the propulsor design, the vehicle would likely go faster but at a fairly stiff price□As the vehicle would be operating in the regime dominated by quadratic drag, doubling the speed would require 4 times the power for 1/2 the time (net doubling of the energy requirement)□

CONCLUSION: a vehicle the size and shape of Odyssey with a realistic battery pack would have sufficient range to respond to any event along he or near the backbone of the network, provided we can accept a delay of up to 10 hours to reach the vicinity of the event□A substantially smaller vehicle could only reach the event if it travelled slower or had batteries with high energy density□To reach the event more quickly, we have several options:

- plan the nodes to be closer to events (NEMO for example)
- make the initial transit at higher speed, resulting in lower efficiency and loss of survey time
- station vehicles between nodes□Perhaps vehicles could be woken up and directed acoustically, then return to a node for power/data offload
- use larger vehicles that could travel the required range at higher speed□

If the AUVs have sufficient range to travel to an event midway between the nodes, perform a meaningful survey, then return, then AUVs from the node on each side of the event can respond to the event□The AUV from the farther node would have sufficient range to reach the event, survey, then transit to the closer node. This requires multiple docks at each node.

3. System level considerations

In this section, we will consider elements of our overall system design that are somewhat vehicle independent. These will include the navigational infrastructure and the characterstics of the docks.

3.1 Navigation infrastructure

We will probably require the vehicle to localize itself continuously during its transit to the event and during the event localization and mapping. We will consider several options for navigation.

Currently, most AUVs rely on traditional (7-15 khz) long-baseline acoustic navigation, nearly identical to that used by Alvin and most ROVs used by the scientific community. We could conceivably use LBL transponder in our conventional manner if we restrict our event response to a region near the network backbone. By placing the transponder on long (200-400 meter) tethers, we have tracked ranges well over 10 km even during bottom survey, as long as acoustic "line-of-site" was maintained. At long ranges we would probably lose line-of-site when approaching the bottom in rugged terrain. When the direct path is lost, we often get surface bounces. These could certainly be used to help with a navigation solution, although misidentifying them results in a bad fix.

Placing 10 transponders in a line running parallel to the backbone and several kilometers to one side would cost about $60K for purchasing the transponders and would require several days of ship time to install and survey. The transponders would last several years, depending on how often they were pinged.

Provided that the needed paths exist, we could improve the range by using lower frequencies and longer transponder tethers. COTS transponders that work below 7 khz are not common, but this limit is not fundamental. Someone who has easy access to the appropriate modelling capability should check the propagation to test the viability of lower frequency, longer range transponders.

To maintain proper geometry, some of the low-frequency beacons should be placed far off the back-bone axis (1/4 baseline length or more).

If we can obtain good ranges out to 40 km (possibly with the restriction that we stay well off the bottom), we could put one transponder near each node with only two between 100 km-spaced nodes. If we can obtain ranges out to approximately 60 km, we could get by with only one transponder between nodes. These options are summarized in figure 1.

A doppler navigator (or doppler velocity log, DVL) can greatly enhance transponder navigation. Our community has had great success using these from AUVs, ROVs, and manned submersibles. If the doppler can maintain bottom-lock, then accuracies better than 0.2%-1% of distance travel can be obtained (although this figure must be treated carefully, as the quality of the heading reference also plays a significant role. A working doppler fundamentally changes the role of transponder navigation, as the transponder fixes are used only to keep the position estimate from drifting. One manufacturer, RD Instruments, builds a 300 khz unit, for which they claim 0.4% accuracy with a maximum range of 200 meters off the bottom.

We also need to consider some more exotic navigation options. The possibility of dropping off one or more beacons after finding the plume is a possibility, although one that will require a larger vehicle. Surveying such transponders will require some careful thinking, especially in a fully autonomous context□Another possibility would be to build inexpensive "pathfinder" vehicles that are essentially mobile transponders□One on each node with sufficient range would allow a 2 transponder net to be created at any point between the two nodes□These vehicles might be used only once, which could simplifiy their design considerably□

3□2 Dock characteristics

A dock will allow the vehicles to be recharged, to offload data, and to be reprogrammed□Data transfer will not be a limiting factor□In the context of this discussion, we need to consider the charging capability and especially how long recharge may take□

Connections for recharging may be achieved by a direct, wet-mate electrical connection (like an OD Blue wet mate connector used on subsea installations such as H2O) or by an inductive couple□Inductive couplings may have significant advantages in terms of reliability and low mating forces, but may impose power limits□

Recharge time may be limited by several factors□Our strawman Odyssey-like vehicle has a 3□3 kwhr Li Ion battery, which ideally can be charged to its full capacity in about 2 hours (like the lithium ion batteries in a notebook computer)□But to achieve the full charge in two hours requires that we deliver approximately 2 kw to the vehicle, accounting for charging inefficiencies□Also, a large AUV sized pack might have to be charged more conservatively (exotic batteries do not presently scale up simply)□Another limiting factor might be the coupling mechanism□If we connect with a wet-mate connector, 2 kw could be achieved, but an inductive coupling might have only a few hundred watt capacity□Finally, the power available at the node might be the limiting factor□Present preliminary designs for Neptune will provide for several kilowatts at each node, so node power will likely not be a limiting factor if the majority of the power at a given node can be directed to AUV charging (recall that system demands will be high for many functions during an event)□ We might be limited in terms of how many AUVs could be charged at a time□

In summary, for a 3 kwhr battery, recharge time will be limited by the coupling mechanism if we chose an inductive link Coupling considerations aside, depending on how agressively we can charge the battery, charge times could be as short as 2 hours, although presently we cannot charge a large pack of high-density batteries at this rate□

While budgetary considerations may limit us to one AUV per node, putting additional docks at each node might be very valuable□If the AUVs have the range and navigational ability to move from one node to another, then AUVs from nearby nodes could converge on the node nearest to the event provided multiple docks were available□

4□Vehicle characteristics

For water column survey or bottom survey in gentle terrain, a shape similar to an MIT Odyssey II vehicle would be appropriate (figure 2)□These vehicles have low drag and have sufficient manueverability for most response tasks□While these vehicles would be completely reengineered for a Neptune effort, they represent a good starting point for a deep-water survey vehicleThe Odyssey vehicles are approximately 1□6 meters long, weigh 165 kg□in air□

By gathering a number of our own experimental data points, we can project the performance of an

Odyssey-like vehicle if proper attention was paid to hydrodynamics, propulsion, and power management□ To travel at 5 km/hour, such a vehicle would require approximately 100 watts for propulsion (extrapolated from Fast Fish hydrodynamic tests and ABE propulsor results)□If we add 14 watts for a carefully designed "hotel" load (from ABE), add another 20 watts for fin actuators (estimate), add 15 watts for a basic science payload, we arrive at a total load of 150 watts□Assuming a battery pack weighing 30 kg (either in air or in water, depending on whether the battery is in the dry one-atmosphere volume or run at pressure in the wet volume) and depending on the battery type chosen, we obtain a range of 110 km with lithium-ion cells□ These cells are currently available, although the small size of available cells requires that large numbers be assembled into packs□If pressure-tolerant lithium polymer cells become available, 30 kg on in-water weight of batteries would provide a range of 220 km□Finally, a lithium thionyl chloride (primary, non-rechargable) pack weighing 30 kg in-air would provide 380 km range□

Figure 4 summarizes the range-speed tradeoff for an Odyssey like, with a somewhat optimistic performance projection□The fixed load includes the computer power, sensor power, and the average power for tthe steering actuators□The optimum is a bit broadbetween 3 and 5 km/hr, but range drops from a peak of about 160km to under 100 km at 10 km/hr□If the propulsor and power systems were designed appropriately, we could use more power to reduce the time before the first AUV reaches an event□

5□A response timeline

For discussion purposes, consider a Neptune AUV setup with the following characteristics:

1□We will consider a 3 node system lying in a straight line, each initially with one AUV
2 The spacing between neptune nodes is 100 km
3 The vehicles have a cruising and survey speed of 5 km/hr
4 The vehicles have a maximum range at their cruising speed of 150 km, enough to travel to the midpoint between nodes, perform 10 hours of survey, and return□Likewise, the vehicle could start at one node, survey, then proceed to the next node for recharging and data offload□This range would also allow vehicles to transit from one node to another, arriving at the next node with a partially charged battery
5 Each node has multiple docks, accomodating up to three vehicles
6 Battery charge time is 5 hours for a fully depleted pack, proportionally less if the vehicle arrives with a partially charged pack□
7 The vehicles can determine their own position sufficiently for transiting, survey, and for docking□
8 An event occurs 30 km from the center node (see figure 4)□

Figure 5 shows the timeline for each of the three AUVs, along with the number of AUVs surveying the plume at any given time□AUV2, the closest to the event, starts immediately toward the event, reaching it in 6 hours□AUV3 also transits directly to the event, reaching it in 14 hours□AUV1 transits to NODE2, where it will charge up its batteries, then proceed to the event□Each AUV returns to NODE2 for data offload and recharge after depleting its batteries to the appropriate level□We assume that NODE2 can accomodate at least two vehicles at once□

Figure 6 shows an improved schedule that provides continuous coverage after the initial gap while AUV2 transits to the event□AUV3 is delayed by 5 hours (or perhaps could go slower during the initial transit and save power, depending on its optimum speed)□

Further fine-tuning of the scheduling can reduce the initial delay in surveying the event□For example, AUV2 could make its initial transit to the event at a faster speed□While this would force it to return earlier, this might only reduce the overlap with the arrival of AUV3□Also, AUV1 coudl make its initial transit to NODE2 at a higher speed that would nearly deplete its batteries on the 100 km transit□Allthough this would require a longer recharge time, AUV1 would still arive at the event sooner□More sophisticated scheduling algorithms would ultimiately provide optimum results, and would be a big asset in real-time□

6□Conclusions

1□A single Odyssey-sized vehicle on each node could provide viable capability for event response anywhere along the backbone, provided nodes are spaced at 100 km□

2□For events randomly distributed along the Neptune backbone, minimum response times will be as large as 10 hours worst-case (10 hours at 5 km/hr to cover a distance equivalent to half the node spacing), unless we compromise total survey time by running faster□Realistically, we could not reduce this time by more than about 1/3 without building a larger vehicle

2□the ability to dock at least two vehicles, preferably three, at each node would allow vehicles from adjacent nodes to converge on the nearest node□

3□If we coordinate the vehicles from the 3 nearest nodes, we can obtain continuous survey coverage following an initial gap due to finite transit speed□

4□Battery recharging times on the order of several hours, presently obtainable in small high-performance battery packs, are likely for AUV-sized packs with improvements in batteries and charging techniques□For sustained event response, quick recharge times will improve coverage by putting an AUV back in play more quickly□Especially if we consider multiple docks on each node, fast recharge could translate into a major driver for node power□Battery packs with energy capacity of 3-5 kwhr are quite realistic, charging them in two hours would require 2-3 kw for each vehicle during charging□

5□These analyses would benefit from a more detailed dialog between scientists and engineers concerning the attributes of events

6□Vehicle navigation coverage for the entire region between nodes may be difficult, although Neptune's acoustic infrastructure should be helpful□Dialog between those interested in AUVs, event response, and those planning Neptune's core acoustic systems is needed□

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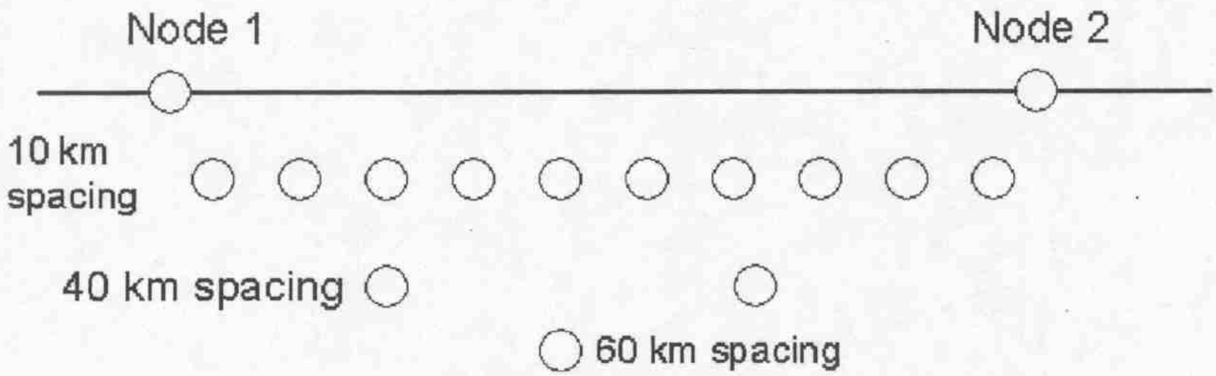

Figure 1Potential transponder layouts. The 10 km spacing scenario is commonly used today with towed sleds, rovs and auvs. The 40 and 60 km spacings must be supported by analysis of likely acoustic propagation conditions.

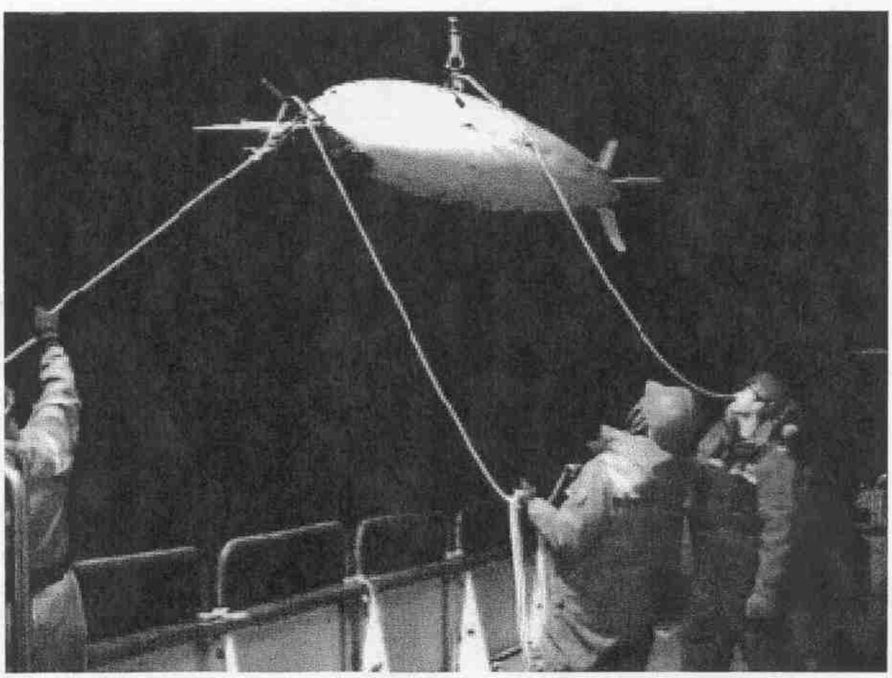

Figure 2. The Odyssey 2B AUV. This shape features low drag. An event response vehicle based on this design could travel nearly the required distance on 30 kg of currently available batteries.

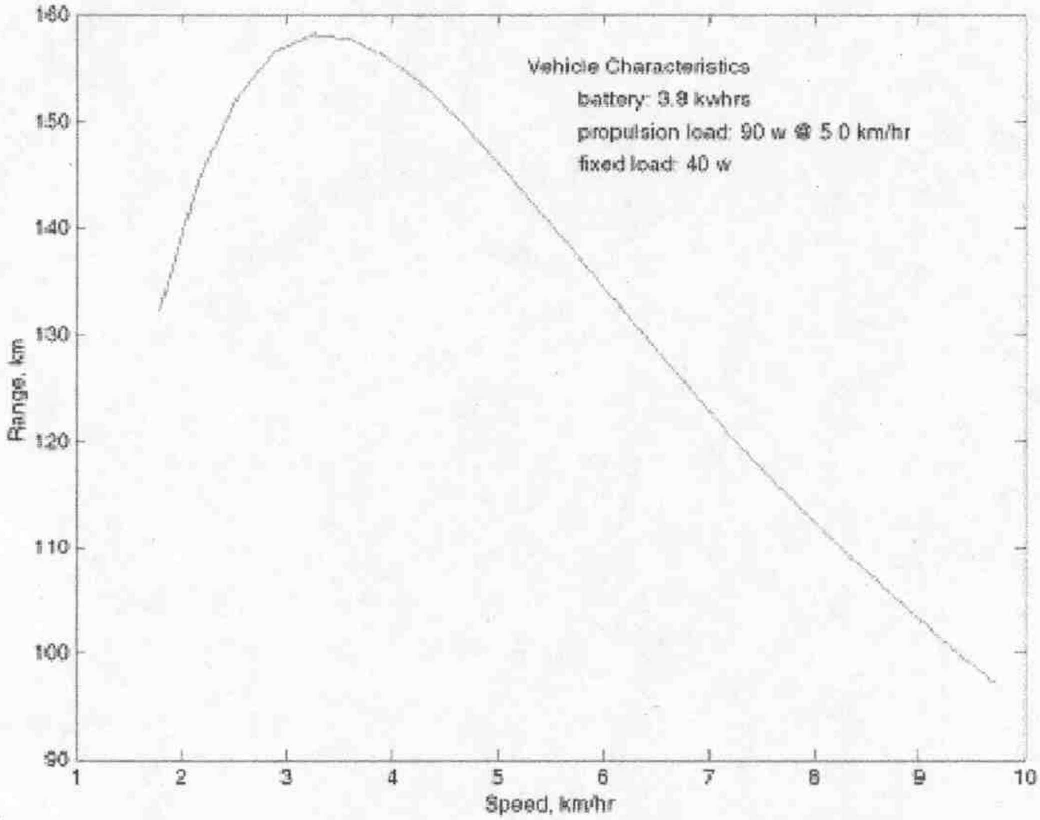

Figure 3 This plot shows the range-speed tradeoff for a slightly optimistic projection of an Odyssey-like vehicle. Due to the substantial fixed power load (control computer, science sensors, and steering actuators), slowing down below 3 km/hr results in decreased range. Increasing the speed to 10 km/hr (possibly unrealistic from a propulsor perspective) reduces the max range by about 40%.

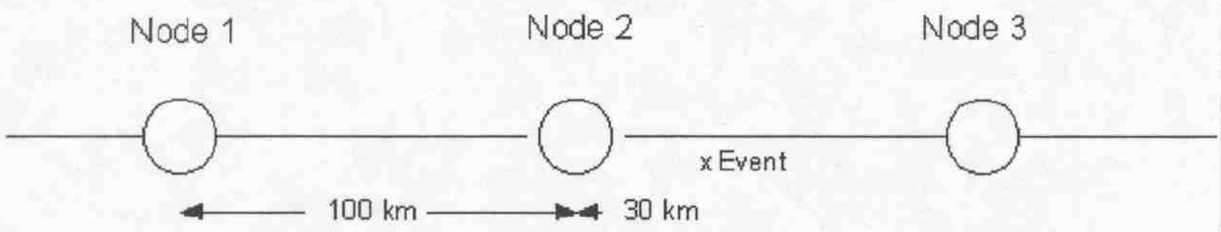

Figure 4 Node layout for the response scenari The nodes are spaced at 100 km, the event occurs near the backbone, 3 km to the east of the center node

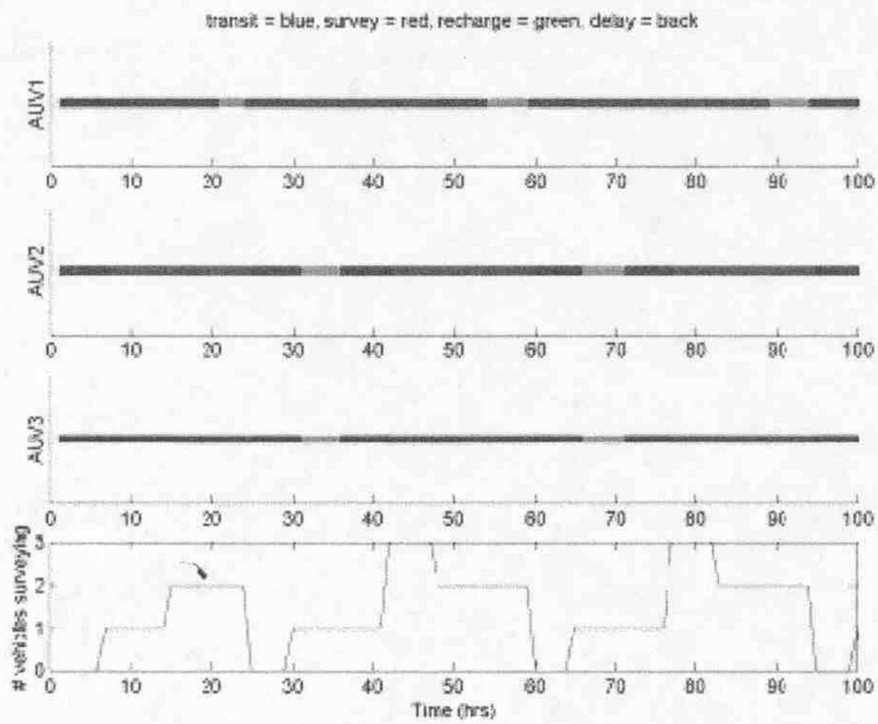

Figure 5 These plots show a possible schedule for the 3 AUVs given the constraints described earlier AUV2 heads directly to the event, as does AUV3 which arrives later AUV1 transits to NODE2 for recharging, then heads to the event Note that AUV2 and AUV3 become synchronized following the first survey period, as they both exhaust their batteries to the same level before heading to NODE2 For 41% of the time, at least two vehicles are surveying the plume, 21% of the time no vehicles are surveying the plume

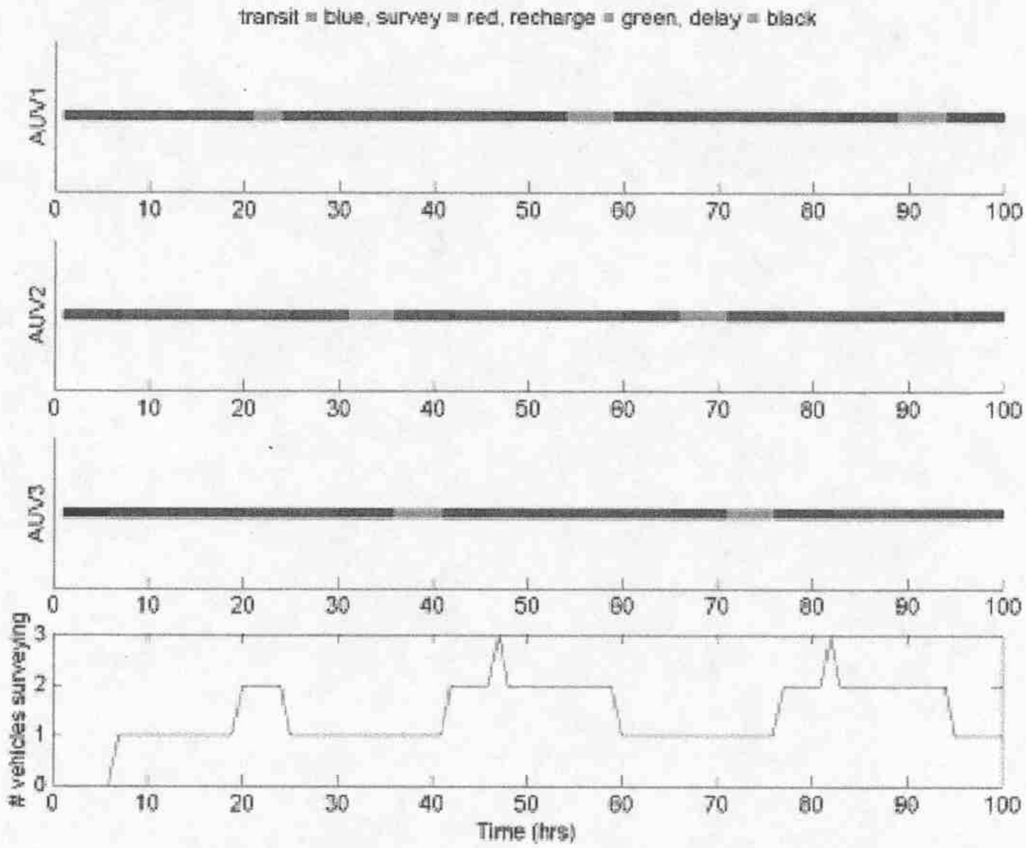

Figure 6. An improved schedule provides continuous plume survey after the initial vehicle arrives. In this case, AUV3 is delayed by 5 hours. The periods with 3 vehicles are shorter, but the gaps in coverage are eliminated