Phytoplankton Bloom Patch Center Localization by the Tethys Autonomous Underwater Vehicle

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Abstract- **The autonomous localization and tracking of the center of a phytoplankton bloom patch by the Tethys Autonomous Underwater Vehicle (AUV) is introduced. This capability is motivated by the desire to separate temporal variability from spatial variability in the observation of phytoplankton dynamics. In effect, by observing the organisms in their own reference frame, we isolate their temporal variability. The small spatial scales and the high temporal variability of phytoplankton patches make strategies that rely on human control challenging, as these strategies must contend with the high latency of intermittent low-bandwidth communications between the submerged AUV and an operator. The autonomous capabilities demonstrated here make much greater use of the responsiveness of the AUV platform to minimize the chance of losing track of the patch and maximize the rate at which the patch center is revisited.**

The ability to characterize the temporal evolution of patches will improve monitoring and predictive efforts that are used to provide warnings for local tourism and fishing industries. In addition, understanding the fine scale environmental conditions associated with bloom formation will increase our ability to predict the location and timing of harmful algal bloom (HAB) formation.

The simple bloom-center localization and tracking algorithm presented here runs on the AUV without operator intervention. In April 2011 field tests in Monterey Bay California, the algorithm successfully localized and tracked the centers of phytoplankton patches. This study not only demonstrates the use of one autonomous platform, but also provides evidence that a nested array of AUVs and moorings equipped with new sensors, combined with remote sensing, can provide an early warning and monitoring system to inform resource managers and mitigate HAB impacts.

I. Introduction

Monitoring a bloom patch may be analogous to monitoring the evolution of an aggregation of organisms, in effect conducting an organism-relative time series experiment. The temporal and spatial variabilities of small marine organisms, particularly micro-organisms, typically exceed the variabilities of the physical processes that are routinely monitored in multi-platform field programs. While physical processes observations can be directly managed via operator intervention from shore, biological observations require autonomy to achieve rapid adaptation of the observation system. Applying the algorithms developed in this study may enable some central assumptions and questions to be tested, including the assumption that the patch correlates to a coherent aggregation of organisms over time, as opposed to a transient density fluctuation of organisms. By tracking patches, we enable investigation of how marine organisms respond to changes in their physical and chemical environment, the strategies they employ to maximize their chances of survival, and the factors that both trigger population explosions of marine phytoplankton, and later cause those populations to crash in a matter of days or weeks.

While phytoplankton blooms support life in the ocean via photosynthesis of organic matter, certain types of blooms cause harm. Far-reaching effects of harmful algal blooms (HABs) – on ecosystem and human health and the viability of fisheries, aquaculture and tourism – motivate greater understanding of natural and anthropogenic factors that modulate blooms [1]. Recently satellite remote sensing has been used to track certain types of blooms. Unfortunately satellite ocean color is limited by cloud cover and low revisit frequency, all of which can lead to extended periods without data. In addition, satellites observe only the water surface, and consequently can miss the existence of a subsurface bloom. As a result, complementary methods are needed to monitor and predict bloom formation and transport, to mitigate their harmful effects on the surrounding ecosystems and local communities.

Figure 1, Tethys autonomous underwater vehicle (AUV)

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II. TETHYS AUV

Tethys (Figure 1) is a medium size (0.30 m diameter, 2 m length) AUV designed at MBARI with the high level of autonomy typical of larger propeller-driven AUVs and the long endurance typical of less capable buoyancy-driven AUVs [2]. The 110kg vehicle has been run for over 1500 hours, and has completed missions exceeding a week in duration. Long term goals for Tethys are to achieve operational deployments of several weeks to months while operating sensors that draw several watts. Via a satellite communication link, the vehicle can be monitored and controlled from shore. Thanks to a powerful and flexible scripting and control system, the vehicle can be safely and easily re-purposed, even at sea [3]. The algorithm described herein was implemented in the Tethys scripting code which leverages simple hard-coded behaviors to build up more complex vehicle interactions.

One important behavior used in this study is a profile maximum detection algorithm designed to continually report the depth of the maximum of a measured quantity in the vertical plane while the vehicle drives up and down in the water column. The algorithm was originally developed for the Dorado AUV [4], and has been applied in a variety of contexts, including hydrocarbon detection [5] and thermocline tracking with the Tethys AUV [6].

III. PHYTOPLANKTON BLOOM PATCH CENTER LOCALIZATION

A key consideration for patch tracking is that a patch is often embedded in a current field, which can move the patch several cm/s even as its center is being estimated. For example, if the current is 0.28 m/s, and the patch size is 1 km, then a geographic point moves from the center to the edge of the patch in about 1800s or 30 minutes. Therefore some methodologies that showed promise for patch center localization in a static field, such as classic "mowing the lawn", spiral center of mass techniques, and analogs to aircraft surveillance techniques such as butterfly patterns were evaluated but dismissed. These approaches take too long to characterize the patch.

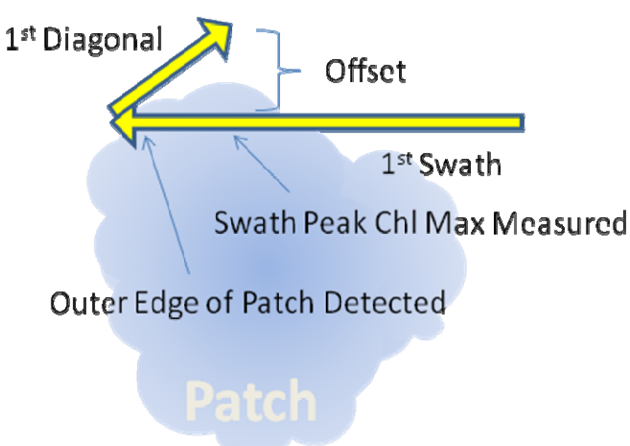

Figure 2, Patch localization, 1st swath and diagonal

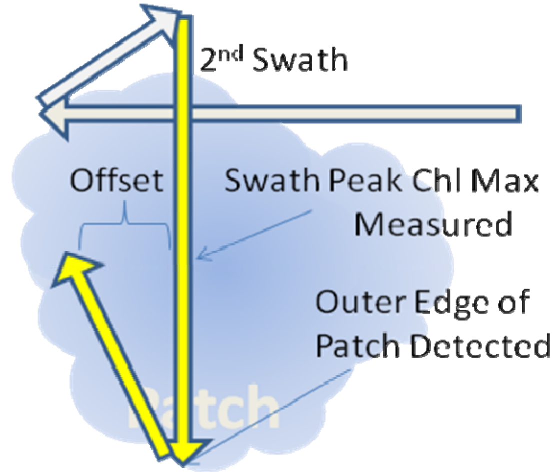

Figure 3, Patch localization, 2nd swath and diagonal

The presented algorithm was inspired by the need to minimize the distance the AUV needs to travel for each successive approximation of the patch center. It is illustrated in Figures 2, 3 and 4. In Figure 1, the vehicle drives through a chlorophyll patch until it reaches the far side of the patch, noting where it has detected the maximum chlorophyll along the way. At the edge of the patch, it drives in a diagonal direction, to a waypoint one "offset" distance away from the point of maximum chlorophyll concentration. In Figure 2, the previous sequence repeats, but rotated by 90 degrees. Figure 3 shows the vehicle's 5th swath, after 4 previous swaths have repeatedly refined the patch center estimate.

Variables determining the algorithm's performance include:

- *Bearing*: heading that vehicle follows while running the center localization algorithm. Decrements by 90 degrees for each pass through the estimated center.
- *MaxTransect*: maximum distance to follow along the current Bearing.
- *ChlMax*: maximum chlorophyll concentration measured in a profile (up or down).

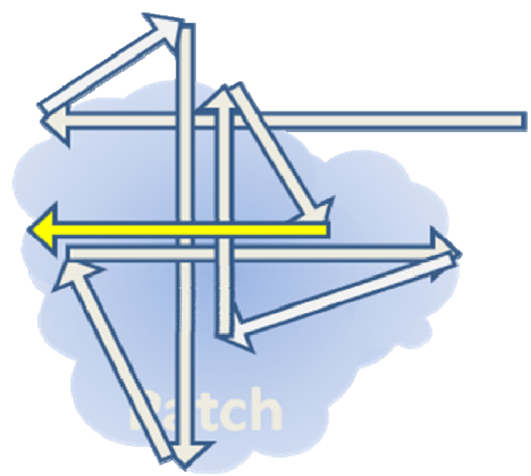

Figure 4, Patch localization, through 5th swath

- *InPatchThresh*: threshold value of *ChlMax* at which the vehicle is considered to be within the phytoplankton patch.
- *OutPatchThresh*: threshold value of *ChlMax* at which the vehicle is considered to be outside the phytoplankton patch.
- *PeakChlMax*: peak value of ChlMax measured along a Bearing, while in the phytoplankton patch.
- *PeakOffset*: a distance from the location of *PeakChlMax*, perpendicular to *Bearing*, to which the vehicle travels diagonally after exiting the patch.

Many other variables are defined and used in the mission script to ensure vehicle safety, define guidance envelopes, and provide periodic surface communications, but these are omitted her for conciseness and clarity. The initial algorithm follows:

1. An Initial value for *Bearing* is set that will send the vehicle towards water where high phytoplankton concentrations are expected, either from other observations or historical trends.
2. As the vehicle moves along *Bearing*, it oscillates from the surface to a specified depth, measuring environmental parameters including chlorophyll fluorescence on each profile. For each profile, *ChlMax* is measured.
3. Once *ChlMax* is greater than *InPatchThresh*, *PeakChlMax* is tracked, along with the location of *PeakChlMax*.
4. If either the vehicle travels more than *MaxTransect* along its *Bearing* or a *ChlMax* lower than *OutPatchThresh* is measured:
   4.1. The vehicle makes a sharp right turn and travels diagonally to a waypoint perpendicular to the original *Bearing*, at a distance *PeakOffset* from where PeakChlMax was measured.
   4.2. Once the vehicle arrives at the "PeakOffset" waypoint, the value of *Bearing* is decremented by 90 degrees, *PeakChlMax* is reset to zero, and the algorithm repeats from step 2.

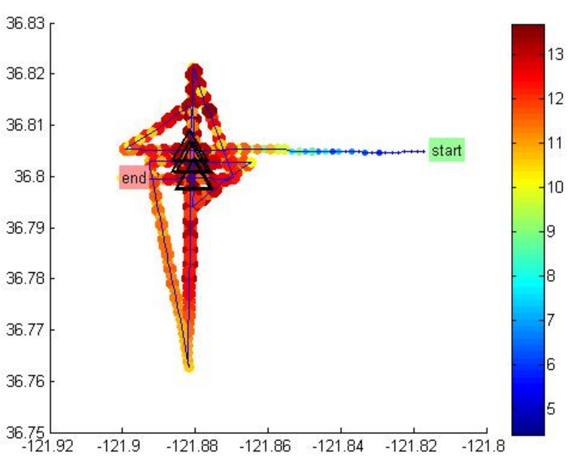

Figure 5, Plan view of example model run. Dot colors and sizes indicate chlorophyll maximum (ChlMax) for each profile. Triangles correspond to bloom center estimates.

IV. Simulation Results

A Regional Ocean Modeling System (ROMS) model run of the Monterey Bay in August 2003 [7] was used to simulate the ocean in several trial runs of the above algorithm. After these initial runs, two preliminary conclusions were reached:

1. The value of *InPatchThresh* can be zero, which will allow the vehicle to approach a patch, even if it can only detect weak signals at its periphery.
2. In order to handle both weak and strong patchs, the value of *OutPatchThresh* should be a function of *PeakChlMax*. In practice, a new constant *OffPeakThresh* was defined such that at all times, *OutPatchThresh* = *PeakChlMax* – *OffPeakThresh.*

The results of an example model run are shown in Figure 5 and Figure 6. Figure 5 is an overhead view of the mission to detect a patch to the west of the starting point. The dot colors and sizes indicate the intensity of ChlMax for each profile. The triangles correspond to patch center estimates.

For each swath through the patch, Figure 6 illustrates the depth and chlorophyll measurements that were made over time. Swath durations varied from just over 2 hours to about 45 minutes. Circles correspond to the *ChlMax* value for each profile, while the triangles indicate the depth and time at which the final value of *PeakChlMax* was measured. The green dashed line represents *PeakChlMax*, while the red dashed line indicates the value of *OutPatchThresh*, in this case 3 µg/l less than *PeakChlMax*.

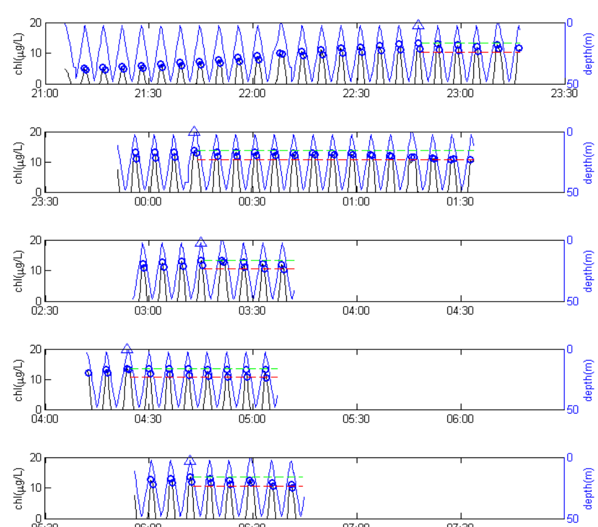

Figure 6, Swaths from example model run. Black (left axis) is chlorophyll concentration; blue (right axis) is depth.

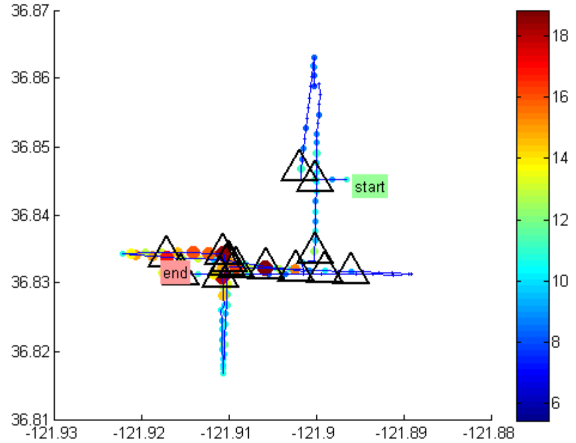

Figure 7, Plan view of 23 April 2011 field test. Dot colors and sizes indicate chlorophyll maximum (ChlMax, µg/l) for each profile. Triangles correspond to bloom center estimates.

The first swath shows that a chlorophyll peak was encountered, but the lower limit of *OutPatchThresh* was never achieved. This occurred because the vehicle traveled 7km west, which was the value of *MaxTransect.* In the second (southerly) swath, the vehicle was able to travel outside the patch without exceeding the *MaxTransect* limit, as case a value of *ChlMax* < *OutPatchThresh* was encountered. Likewise, the 3rd (easterly), 4th (northerly), and 5th (westerly repeat) swaths all managed to pass over the patch peak and out of the patch. The simulation was able to consistently estimate the patch center, which gave us confidence that field tests were an appropriate next step.

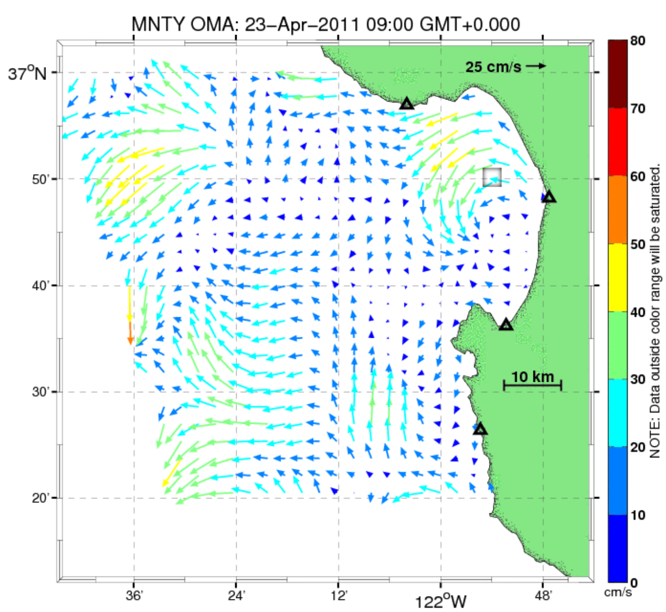

Figure 8, Sea surface currents with location of 24 April 2011 field test in grey box. Image courtesy of the California Coastal Ocean Currents Monitoring Program (cencalcurrents.org)

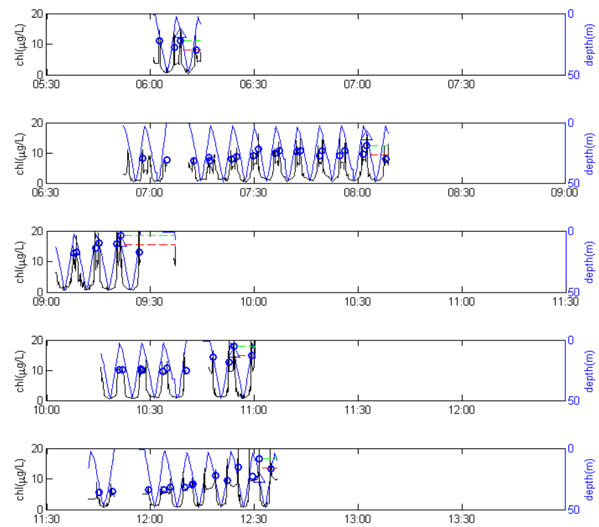

Figure 9, Swaths from 23 April 2011 field test. Black (left axis) is chlorophyll concentration; blue (right axis) is depth.

V. Initial Field Test Results

A series of field tests with the algorithm were carried out in April 2011. Figure 7 shows the overhead view of an early experiment on 23 April 2011. Despite some challenges, the experiment appears to be successful, as the vehicle was able to locate and estimate the center of a patch. Figure 9 illustrates the depth and chlorophyll measurements that were made.

Initially, the vehicle was sent west toward a suspected patch location. After only a few profiles in about 15 minutes (see first swath in Figure 9), it measured a *ChlMax* value less than a relatively low *OutPatchThresh* (possibly due to noise in the chlorophyll concentration signal), and subsequently headed north by northeast in order to cross the detected peak at a right angle. Due to an oversight in the mission script, the peak detection code continued to report *PeakChlMax* as the vehicle headed towards the "PeakOffset" waypoint (hence the extra triangles in Figure 4), but without impacting the algorithm performance.

Along the southerly transect Tethys passed over the initial line with no detection, but eventually found a more intense chlorophyll peak approximately 1.5 kilometers to the south, at which point the vehicle drove west in order to do an easterly pass.

Traveling eastward, the vehicle indentified a strong chlorophyll peak after just 7 profiles and headed south to do a northerly pass, which resulted in peak identification very close to the peak identified in the easterly pass. In the subsequent westward pass, the same peak was identified a 3rd time.

The results for the first five swaths of the early field test were very encouraging. However, in subsequent swaths

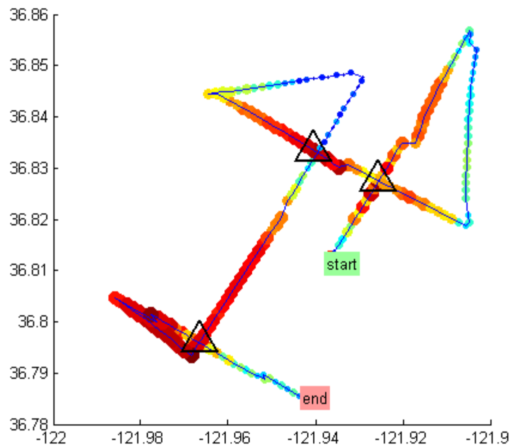

Figure 10, Plan view of 24 April 2011 field test. Dot colors and sizes indicate chlorophyll maximum (ChlMax, µg/l) for each profile. Triangles correspond to bloom center estimates

(omitted for clarity), the peak was lost. Also, we were uncomfortable with the rapid turn after the first swath. The problem seemed to be that the default setting for *OffPeakThresh* (3 µg/l) was too low, possibly on the order of the profile-to-profile noise in *ChlMax*.

VI. Subsequent Field Test Results

A 2nd field test was conducted on 24 April 2011. For most AUVs this would require the AUV to be retrieved, reprogrammed and redeployed. However, the Tethys scripting architecture allows the vehicle operators to adjust script parameters, or even provide a revised or entirely new script from shore.

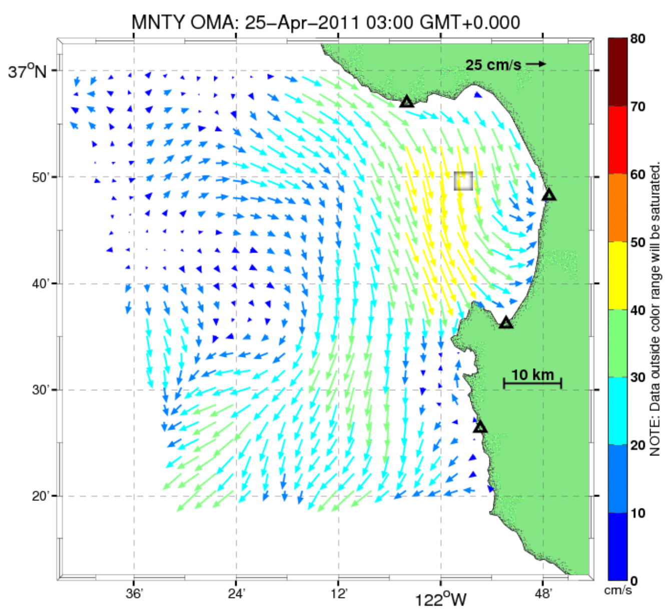

Figure 11, Sea surface currents with location of 24 April 2011 field test in grey box. Image courtesy of the California Coastal Ocean Currents Monitoring Program (cencalcurrents.org)

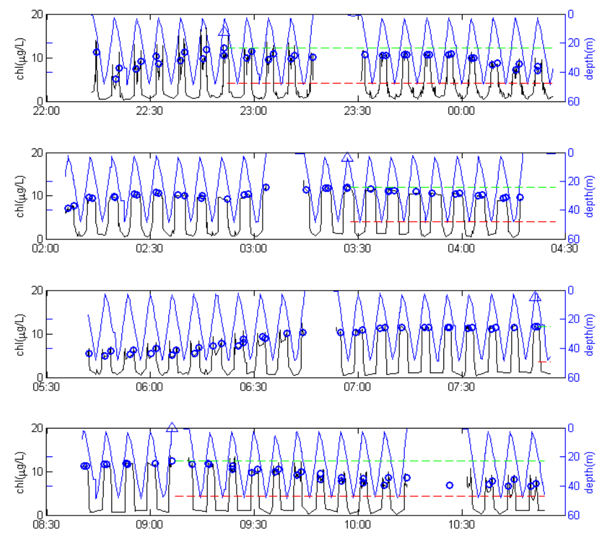

Figure 12 Swaths from 24 April 2011 field test. Black (left axis) is chlorophyll concentration; blue (right axis) is depth.

Modification made for these tests included increase the value of *OffPeakThresh* from 3µg/l to 8 µg/l and changing the *Bearing* parameter. The first ensured that the vehicle would not mistake a local minima for the far edge of the patch. Setting the *Bearing* parameter to a non-cardinal direction tested the capability of the algorithm to work at off-angles.

As shown in Figures 10 and 12, the algorithm was able to track a patch that appeared to be moving to the southwest, despite an *OffPeakThresh* setting that was likely too high, as indicated by the fact that each swath took over two hours. The first transect at a 30 degree bearing seems to have located the patch peak in the first 3rd of the swath. However, the transect continued for the entire 7km (value of *MaxTransect*) since no *ChlMax* values 8 µg/l less than the peak were encountered.

Likely during the extra time that the vehicle continued to follow the 30 degree bearing, the patch was advecting to the southwest. This is suggested by the results of the 2nd pass, which detected much lower *ChlMax* values through the same water, but similar *ChlMax* values further west. On the 3rd (210 degree bearing) swath, the pattern was repeated; lower *ChlMax* in the same water, but higher values toward the end of the transect. Since the *PeakChlMax* value for the 3rd swath was established at the very end of the swath, little time elapsed before the water was measured again, and as one might expect, similar *ChlMax* values were measured in the same water.

VII. Algorithm Improvements

Near future improvements to the patch center localization algorithm described fall into two categories: improving the algorithm's ability to detect a peak with fewer false positives or negatives, and decreasing the overall distance traveled during the localization.

One approach to reducing false positives would be to implement low pass filtering of the *ChlMax* values before comparing them to the *OutPatchThresh* value. Combined with a low OffPeakThresh value, false negatives could also be avoided. Another approach may be to abandon the comparison with *OutPatchThresh* and try to detect a consistent decay in the filtered *ChlMax* values.

Currently, the “diagonal” transects between swaths are straight lines. It may be worthwhile to follow a curve of near-constant *ChlMax* between swaths if it reduces the distance compared to a straight line out to the “PeakOffset” waypoint. Also, information collected during these diagonals is ignored; if a very high *ChlMax* is encountered on the diagonal, then it may be more efficient to treat the diagonal as if it were a swath and loop back on the diagonal’s high *ChlMax* point.

Rather than directly characterize the center of what may be a patchy and indistinct patch, it may be more efficient to characterize the outer extent of the patch, perhaps by setting an in-patch threshold chlorophyll concentration and mapping the line that such a concentration follows. Also, there may be opportunities to further optimize other approaches such as center-of-mass techniques and modifications of aircraft surveillance patterns.

In both simulation and ocean tests using the Tethys AUV in the Monterey Bay, we will continue to test these other approaches as well as versions of the revised center crossing algorithm.

VIII. CONCLUSIONS

The results presented here demonstrate the feasibility of tracking aggregations of marine organisms. Further work is required to optimize performance and to integrate this capability with characterization of the platch and its immediate environment. Further work is being carried out in the context of MBARI’s CANON (Controlled Agile and Novel Observing Network) initiative.

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