Whitepaper
YSI Systems & Services • XA00187

# High-Resolution Mapping of a Harmful Algal Bloom

## UNDERSTANDING FINE-SCALE ENVIRONMENTAL FACTORS IN CLEAR LAKE, CALIFORNIA

**Figure 1.** The i3XO AUV staged for its mission at Clear Lake, California.

Harmful Algal Blooms (HABs) have recently been acknowledged as one of the greatest global threats to surface water quality.[1] Freshwater HABs caused by cyanobacteria (a.k.a. "blue-green-algae") occur in drinking water sources, cherished wildlife habitats, popular recreational destinations, and waters of special significance to indigenous people. Their impacts can range from nuisance taste and odor problems to the production of powerful toxins that can sicken or kill animals and humans.

The overarching causes of HABs are well documented. The primary driver in most cases is excessive nutrient loading of water bodies, particularly with nitrogen and phosphorous. In addition conditions exacerbated by climate change, such as warmer water temperatures and water column stratification, can give potentially toxic cyanobacteria a competitive advantage over more-desirable algae.

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a xylem brand

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[1] Plaas HE, Paerl HW (2021) Toxic cyanobacteria: a growing threat to water and air quality. Environmental Science & Technology 55:44-64

While the fundamental environmental triggers are well known, at a finer scale a complex array of hydrological and meteorological factors determine the specific types of algae that will dominate a bloom, as well as the bloom's magnitude and duration. The precise interactions among these environmental factors is difficult to characterize, yet key to understanding bloom dynamics, plankton community structure and toxin production.

High-resolution, temporally- and spatially-integrated data sets aid in understanding of these interactions, and support the goal of building predictive models of HAB events. The sensor technologies for collecting the relevant types of data are well-developed but co-deploying them, obtaining sufficient coverage, and geo-referencing and temporally aligning multiple data sets can hinder analyses.

Autonomous vehicles like YSI's i3XO EcoMapper are part of the solution to this problem (Figure 1). Here we describe deployment of this multi-sensor autonomous underwater vehicle (AUV) for the study of HABs in Clear Lake, California.

## Clear Lake HABs

A team of researchers from the University of Southern California in Los Angeles (USC) and the Southern California Coastal Water Research Project (SCCWRP) chose Clear Lake for study because it is one of the most heavily impacted lakes in the state of California, and indeed in North America.

At an estimated age of 1.8-3 million years, Clear Lake is one of the oldest natural lakes in North America, and it is unfortunately showing its age.

Giusti's treatise regarding human influences on Clear Lake in the 20th century points to at least three activities that have caused major environmental problems in the lake beyond just HABs. Nearly a century of open pit mining resulting in extensive mercury contamination, heavy use of pesticides such as chlorinated hydrocarbons, and significant construction and other landscape alterations have led to watershed erosion and hypereutrophication of the lake.[2]

The increasingly eutrophic state of Clear Lake over the past several decades has stimulated the growth and dominance of cyanobacteria (Figure 2), and with them the toxins that many of these species produce. Cyanotoxin concentrations in Clear Lake routinely place the lake on the state's HAB Incident Reports Map.[3] This is particularly true during summer months when recreational activities and other uses are at their peak, creating serious risks to human and animal health.

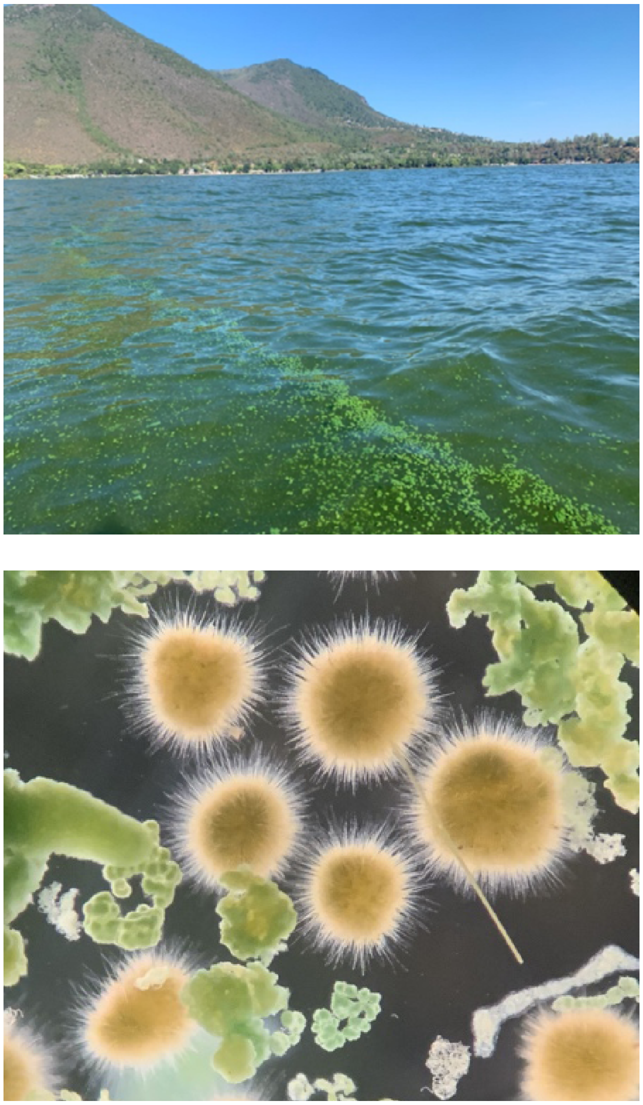

Figure 2. A harmful algal bloom in Clear Lake (left) during the mission discussed in this paper. The light microscopy image on the right shows that *Gleotrichia* (yellowish, round, spiky cells) and *Microcystis* (small green microcolonies) were dominant.

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[2] Giusti, 2009. Human Influences to Clear Lake, California. A 20th Century History. http://celake.ucanr.edu/files/164054.pdf, accessed 7 October 2020.
[3] https://mywaterquality.ca.gov/habs/where/freshwater_events.html, accessed 14 June 2021.

> “If we can tie these disparate pieces of information together through space and time, it will provide unprecedented information on species succession and trophic interactions within the plankton of Clear Lake.”
>
> - David Caron, Principal Investigator

HABs are now so prevalent in Clear Lake that it is one of the most heavily monitored Lakes in North America for this issue. Countless reports and peer-reviewed articles have documented bloom conditions and toxins, and putative causes, but most have arrived at generalized conclusions similar to this statement from Mioni and Kudela (2011):

> “Surface water temperature, nitrogen and phosphorus concentrations appear to be key drivers of cyanoHAB composition and toxicity but additional environmental stressors specific to each system and to each individual [cyanobacterial] taxa may also play a significant role.”[4]

Thus while the general conditions promoting blooms are well known, the details of environmental drivers stimulating the growth of specific cyanobacterial taxa and the production of toxins have been difficult to ascertain, particularly at Clear Lake. A major impediment in achieving that goal has been linking the information gathered from relatively rare discrete water samples that can be collected by hand to the physical processes affecting the location and depth from which the samples are collected. While discrete samples provide vital information on the status of the plankton community at a particular place and time, the physical structure and dynamics of the water column leading to that status are poorly constrained or understood.

A better understanding was sought by scientists from USC, SCCWRP and YSI, with funding from the California Central Valley Regional Water Quality Control Board. The team met at Clear Lake to deploy the i3XO alongside other sensing and sampling methodologies in order to provide new insight into the ecology of cyanobacteria in Clear Lake. Ancillary measurements included analyses of phytoplankton community composition through genetic markers and microscopy, and concentrations of microcystins, a class of cyanotoxins often observed in the lake.

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[4] Mioni et al., 2011. Harmful cyanobacteria blooms and their toxins in Clear Lake and the Sacramento-San Joaquin Delta (California). https://www.lakecountyca.gov/Assets/Departments/WaterResources/Algae/2011+Cyanobacteria+Report.pdf, accessed 7 October 2020.

# Study Objectives and Technical Approach

A major undertaking is to link water column structure and pertinent environmental parameters sensed throughout the lake with information on the plankton community from discrete water samples. Correlating these features across a lake the size of Clear Lake is not easy, yet it is essential for understanding the physical/chemical context (and potential drivers) of the biological processes leading to blooms and toxins.

The study was designed to monitor the lake at two very different spatial scales. The first scale was conducted along the major axes of the three 'arms' of Clear Lake to examine lake-wide characteristics. The second scale was a high-resolution mapping mission of a portion of Konocti Bay in the Lower Arm of the lake to examine small-scale spatial heterogeneity in the distribution of cyanobacteria and their toxins (Figure 3). How mission planning was undertaken with the i3XO AUV is described below, followed by mission details that supported these two spatial scales of operation.

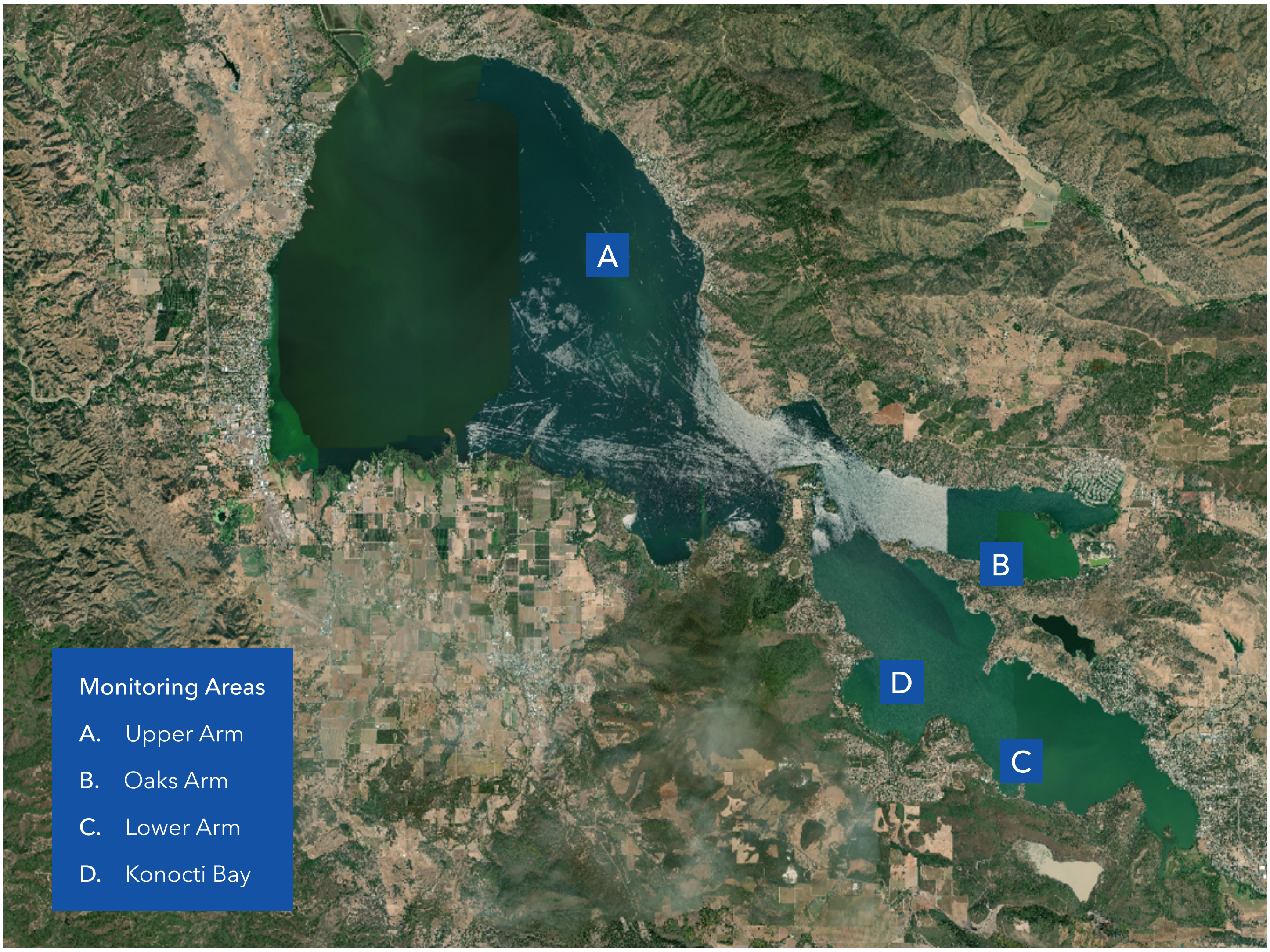


**Figure 3.** Clear Lake, CA, USA at coordinates 39.0216283,-122.9151555.

## Mission Planning with the i3XO

The full sensor capacity of the i3XO was leveraged for the missions. Every i3XO is fitted with a YSI EXO1 sonde that is modified specifically for the AUV (Figure 4). For this project the EXO sonde carried Conductivity/Temperature, Total Algae (for simultaneous measurement of chlorophyll and phycocyanin), Dissolved Oxygen (DO), and pH sensors.

Both multibeam and single-beam side-scan sonar (SSS) were used. Object detection with dual frequency sonar allows the i3XO to quickly identify targets and obstructions in high-resolution. For example, with a single beam running at 10 m from the bottom, the overall coverage one can obtain is <10 m. With the multibeam running at that same height coverage of up to 120 m is possible. This translates to fewer runs to cover the same ground, saving field time (Figure 5).

Figure 4. An EXO1 sonde (top) and the specially modified EXO1 that is in the nose of the i3XO.


The multibeam capability facilitates swath bathymetry, and allows the operator to cover up to **12X** the area of coverage.

Figure 5. Multibeam side-scan sonar for lake bottom mapping and identification of features.

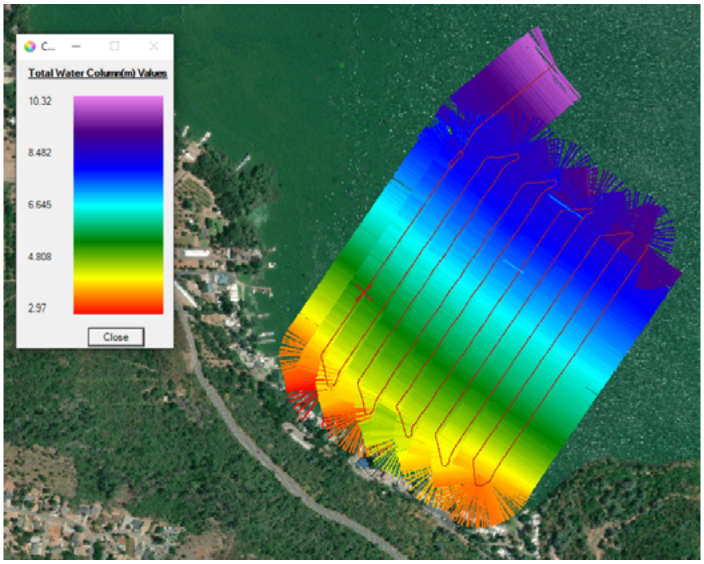
The i3XO has an intuitive software interface called VectorMaps, in which a georeferenced map of Clear Lake was used to create a mission plan. Using a simple point and click method, waypoints were placed at specific areas of interest within the lake. The i3XO was programmed for autonomous operation, using an IP67-rated Getac computer that doubled as a notebook and which also facilitated wireless communication with the vehicle. The vehicle was operated for 6.5 hours without requiring a recharge of the Li-ion battery (though a fresh battery was on hand in case a field swap was necessary).

Following each mission, initial data analysis was carried out using VectorMaps (the same software used to create the line plan). VectorMaps can be used to quickly visualize bathymetry and water quality data for any given mission. The log file from the relevant sensor is imported into the software, displaying the data based off of the recorded GPS position of the vehicle. From there, the individual parameters of interest can be displayed one at a time on the map in a visual format. The data can also be used to adjust and update new line plans for future missions. As an example, Figure 6 shows the depth data for Konocti Bay.

Contour maps could be created for both water quality and bathymetry using a software module that is in development and which leverages Xylem's HYPACK. The log file created by the vehicle was imported into HYPACK using the Mag Editor portion of the software, where one is able to retrieve the data to display. For this study the latitude and longitude recorded by the INS, depth from surface, depth to bottom, total water column, and all of the water quality parameters were retrieved.

Quality Control included removal of outliers from the data set, and then the TIN model portion of HYPACK was used to create contour maps. The contour maps could be displayed directly in HYPACK over the georeferenced map for identifying exactly where points of interest are located. As an example, Figure 7 shows the depth contour data for Konocti Bay, over the exact same region as was surveyed in Figure 6.

HYPACK was also used to process and display the side scan sonar images collected using the EdgeTech2205B unit on the vehicle, the multibeam SSS sensor. After processing the files, georeferenced TIF images were created and overlaid on the map. Such images can be used to identify potential targets. A target report can then be created and supplied for identifying exactly where those targets were found. For example, in Konocti bay an interesting feature was identified and interrogated more closely (Figure 8).



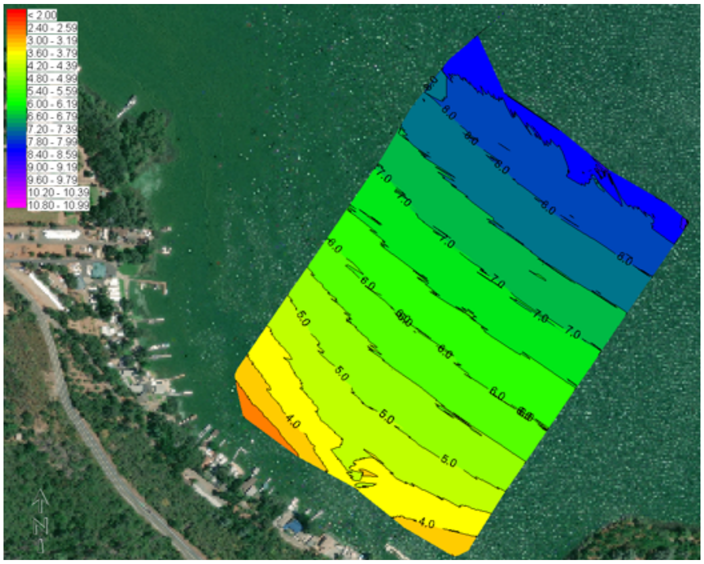


**Figure 6.** Depth in meters for the Konocti Bay mission, visualized in VectorMaps software of the i3XO platform. Data for all the water quality parameters can be visualized in this manner. The i3XO operated at 1.5 m depth from surface for this mission.

**Figure 7.** Bathymetric analysis of Konocti Bay using HYPACK software and data collected by single-beam SSS with the i3XO. Depths are shown in meters.

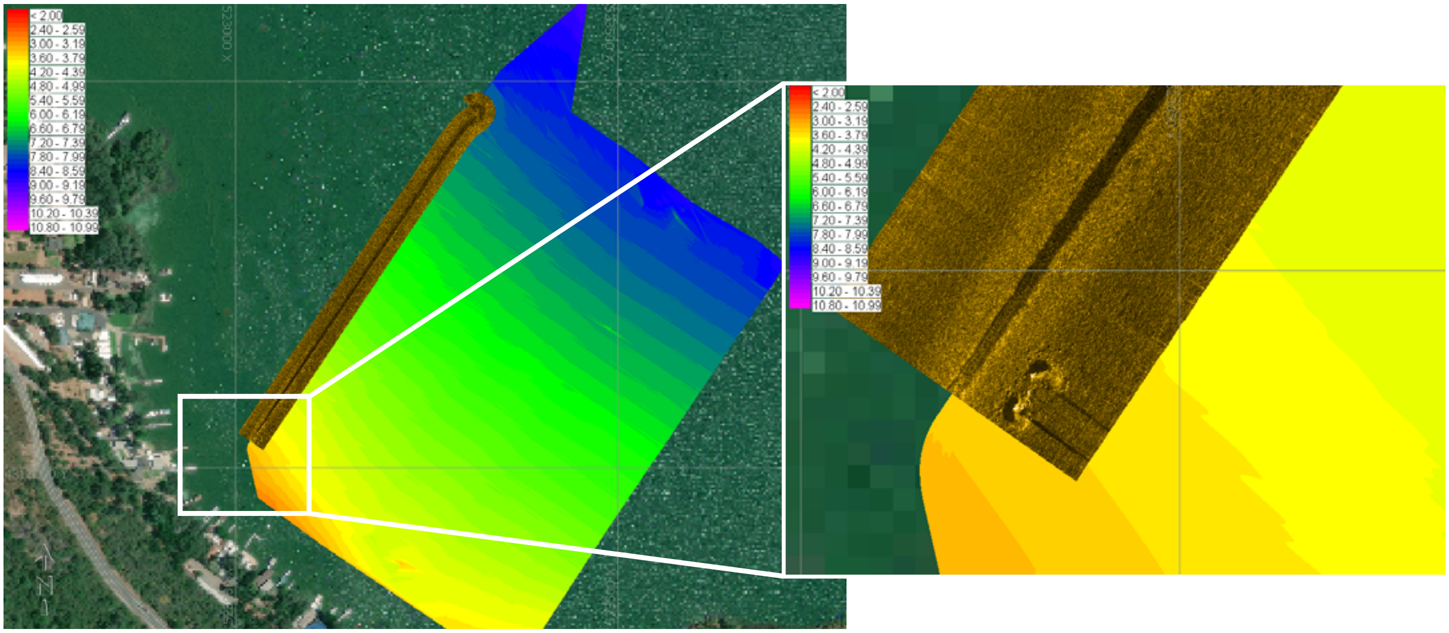


**Figure 8.** The same depth profile in Figure 7 has been overlaid with one of the multibeam SSS tracks (left), with a close up on the right of an interesting feature that may have been a dock piling. The black lines to the right of the feature are shadows.

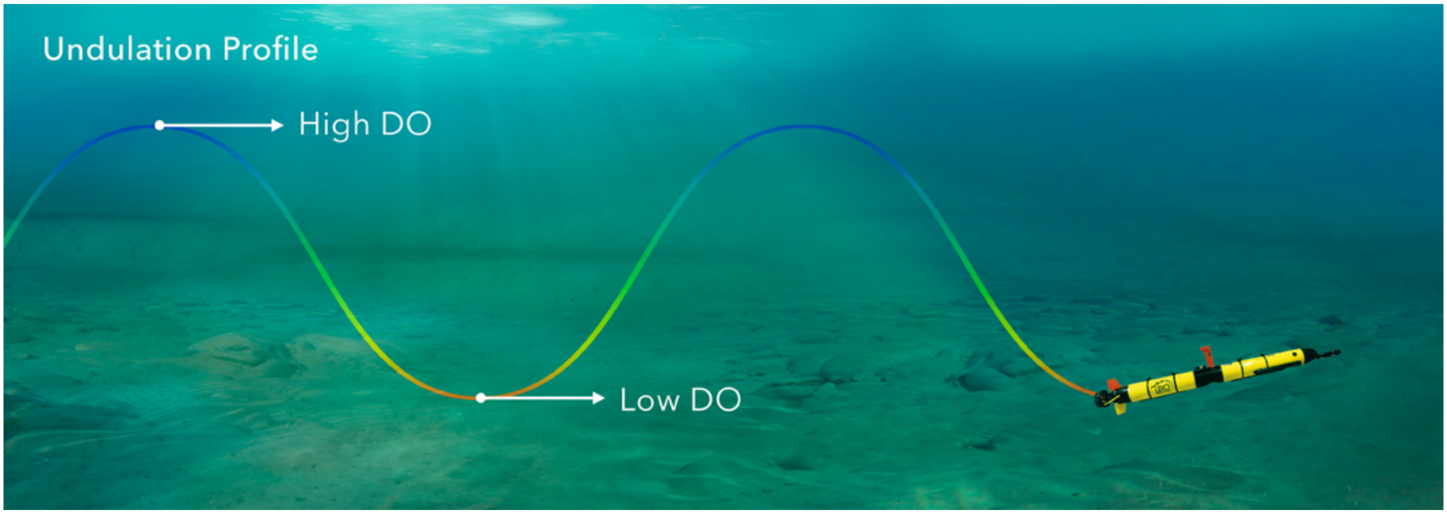


Figure 9. An undulation pattern enables one to profile water quality parameters such as Dissolved Oxygen in this representation. DO at any point travelled by the vehicle can be identified.

## Whole-Lake Survey with the i3XO

For the lake-wide characterization of all three "arms" of Clear Lake (Upper, Lower, and Oaks), the i3XO was used to aid interpretation of the very limited number of measurements and discrete samples that can be collected routinely in most field research programs. The instrument data was used to construct 2D depictions and planar views of the water column along the main axes of the lake.

Four missions employed "undulation" patterns along the main axes of the Upper, Lower and Oaks Arms, with Oaks accomplished in two separate missions. The goal was characterization of lake-wide physical structure of the water column and accompanying chemical and biological parameters. Undulation is the vertical diving and rising of the vehicle as it moves forward, programmed by the operator with a specific dive angle, rising or falling to set distances from both the lake bottom or the water's surface (Figure 9).

Data interpolation yields a two-dimensional view (with depth and horizontally) along the transit path of the instrument line, as will be clear in subsequent figures in this paper. For the undulating missions, YSI's vehicle operator programmed the i3XO to undulate from 1.5 m below the surface to as low as 2 m from the bottom, with a 15 degree dive angle and 2.5 knot speed. It took roughly 6.5 hours to cover over 34 km of Clear Lake.

Note that the shallow areas of the Upper Arm created an interesting conundrum for the vehicle—if it was to always be 2 m from the bottom, but the depth was only 2.8 m, the "dive" cycle actually was higher than the peak of its undulation cycle, which was set at 1.5 m below the surface. The i3XO adjusted its mission such that the vehicle actually was undulating from 0.8 m from the surface to 1.5 m from the surface. This exemplifies the kinds of anomalies that are encountered in the field, especially on initial surveys where one doesn't know what's under the water.

Such anomalies and other unexpected hurdles are why, in practice, one should perform an initial "surface mission" before deploying an AUV like the i3XO. This mission will allow one to understand the depth of the water body across the area of interest, accessing the Advanced Doppler Velocity Log (ADVL). The operator can then set up the primary mission for the safest vehicle operation. The vehicle is also equipped with object avoidance and other safety features that can be controlled by the operator, even during the course of a mission.

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## Fine-Scale Mapping of Konocti Bay with the i3XO

For Konocti Bay the goal was fine-scale mapping of an embayment where cyanobacterial surface scums regularly accumulate as a consequence of wind direction and speed. These accumulations pose particularly dangerous conditions because they often exhibit elevated toxin concentrations. Moreover, the features are spatially heterogeneous and temporally ephemeral, making it difficult for HAB researchers and monitoring groups to collect 'representative' samples from these regions (Figure 10). The overall goal of this mission was to document that heterogeneity thereby aiding groups who must decide where and how to collect samples, and how to interpret the results of their samples.

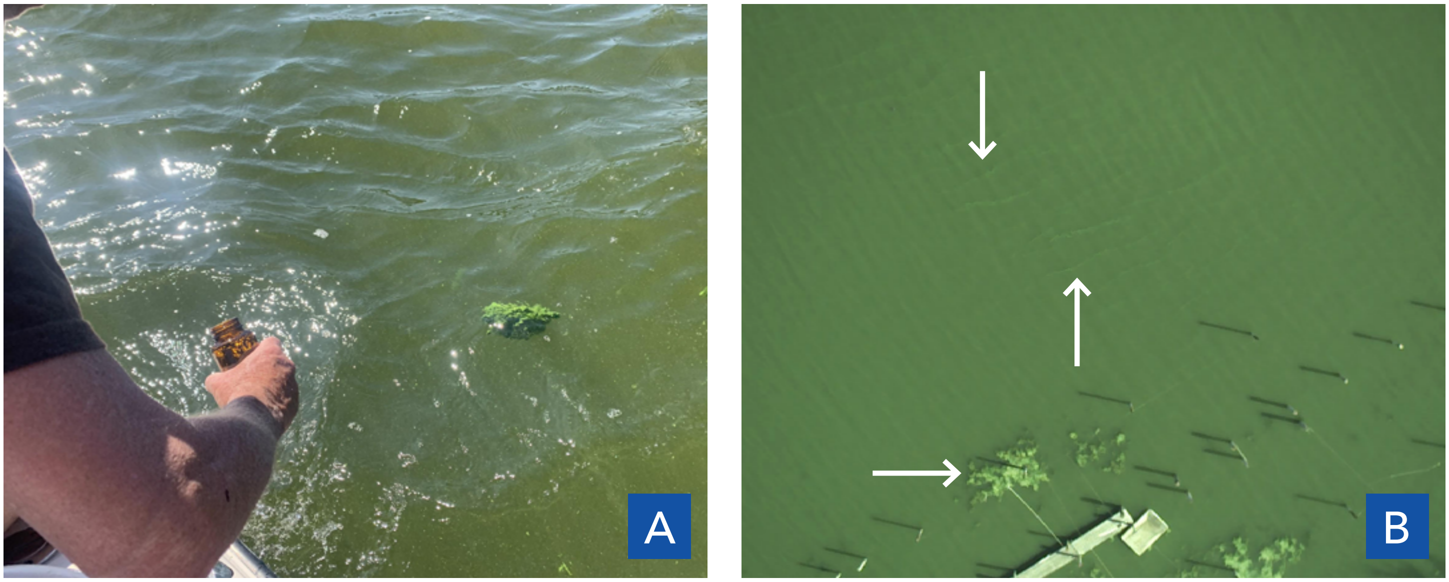


**Figure 10.** Aerial drone footage (B) over an embayment of Konocti Bay shows clustering of phytoplankton. Grab samples in the area (A) were positive for microcystin toxin. Arrows show areas of heavy accumulation of cyanobacterial biomass.

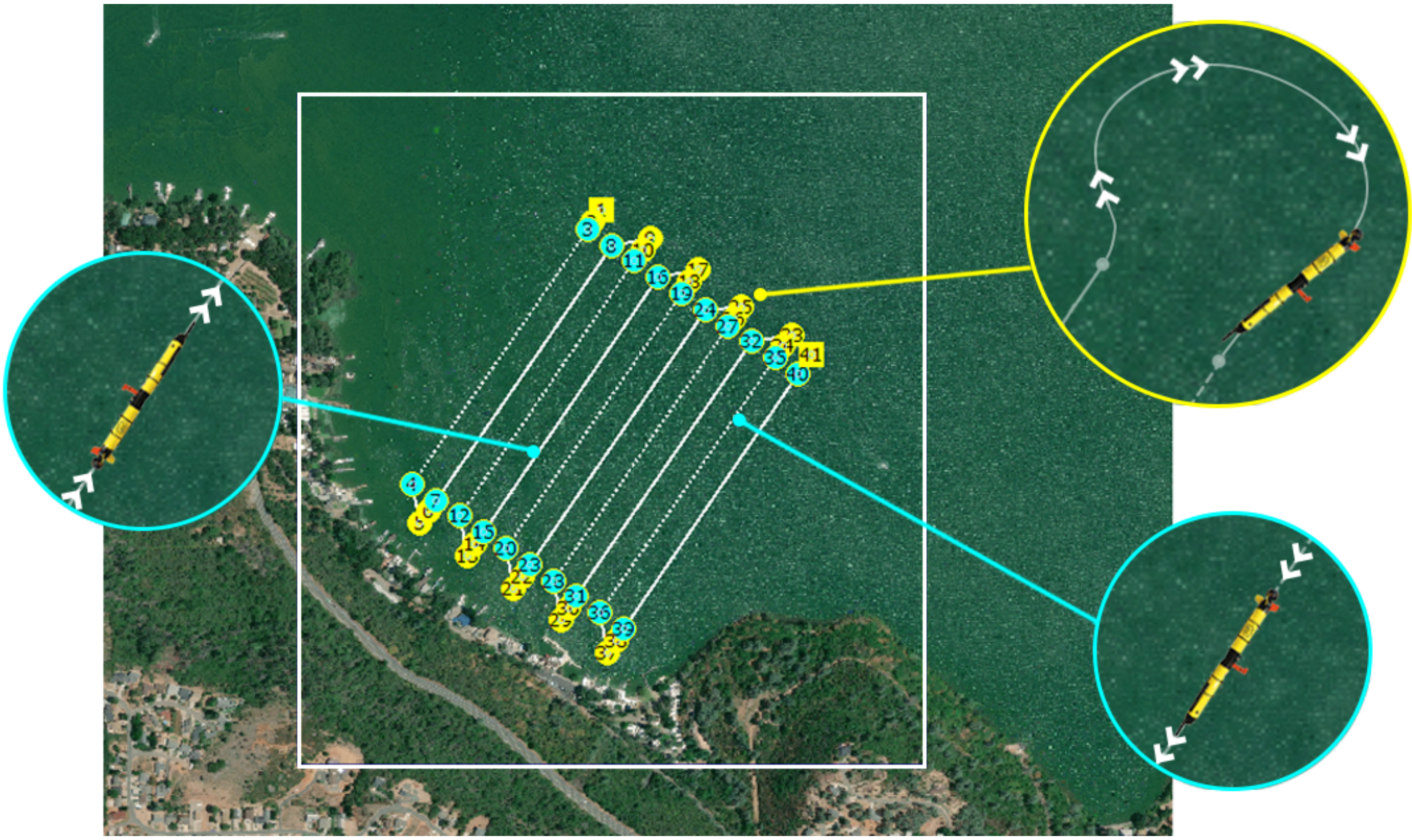


Figure 11. The “lawnmower” pattern in Konocti Bay. Colored circles show the directional waypoints. The turning radius at the end of each line is dictated by the size of the vehicle, but the distance between the lines is user-controlled.

Since Konocti Bay is relatively shallow, the AUV was deployed in a 'lawnmower' pattern at a fixed depth (1.5 m from the surface) and a speed of 2.5 knots. The mission focused on high spatial resolution horizontal coverage, limited only by the turning radius of the vehicle, which is approximately 5-6 m (Figure 11).

With the i3XO always under water, it was possible to maintain highly accurate coordinates for data points because of the AUV's Inertial Navigation System (INS). The INS allows the i3XO to stay underwater for an extended period without coming to the surface for a positional adjustment using GPS. With less time lost to resurfacing and more time to actually run the survey, data collection efficiency is maximized. INS also is highly accurate.

Older AUVs handled positioning with a method known as dead reckoning, which relies on the compass and Doppler Velocity Logs (DVLs) to estimate speed and position.

The typical accuracy for dead reckoning is ~1% of distant traveled: for every 1000 m traveled underwater, one would see an ~10 m error in positioning upon resurfacing. With INS the i3XO is able to get an accuracy of 0.3% distance traveled. Further, the INS aids in avoidance of surface boat traffic, an important consideration in the popular Konocti Bay area.

An example of this exceptional accuracy is demonstrated in Figure 12. This example is from the Upper Arm of Clear Lake, where a single line transect of 12,450 m was planned and took 2 hours and 42 minutes. The total underwater distance was 12,100 m, and at 0.3% predicted accuracy the vehicle should have surfaced within 36 meters of the endpoint. In fact it surfaced 23 meters away from its destination point. This was accomplished without a single resurfacing event to realign the vehicle with its mission plan. Such results can vary; 0.3% is an average accuracy based upon multiple tests conducted by the vehicle's designers.

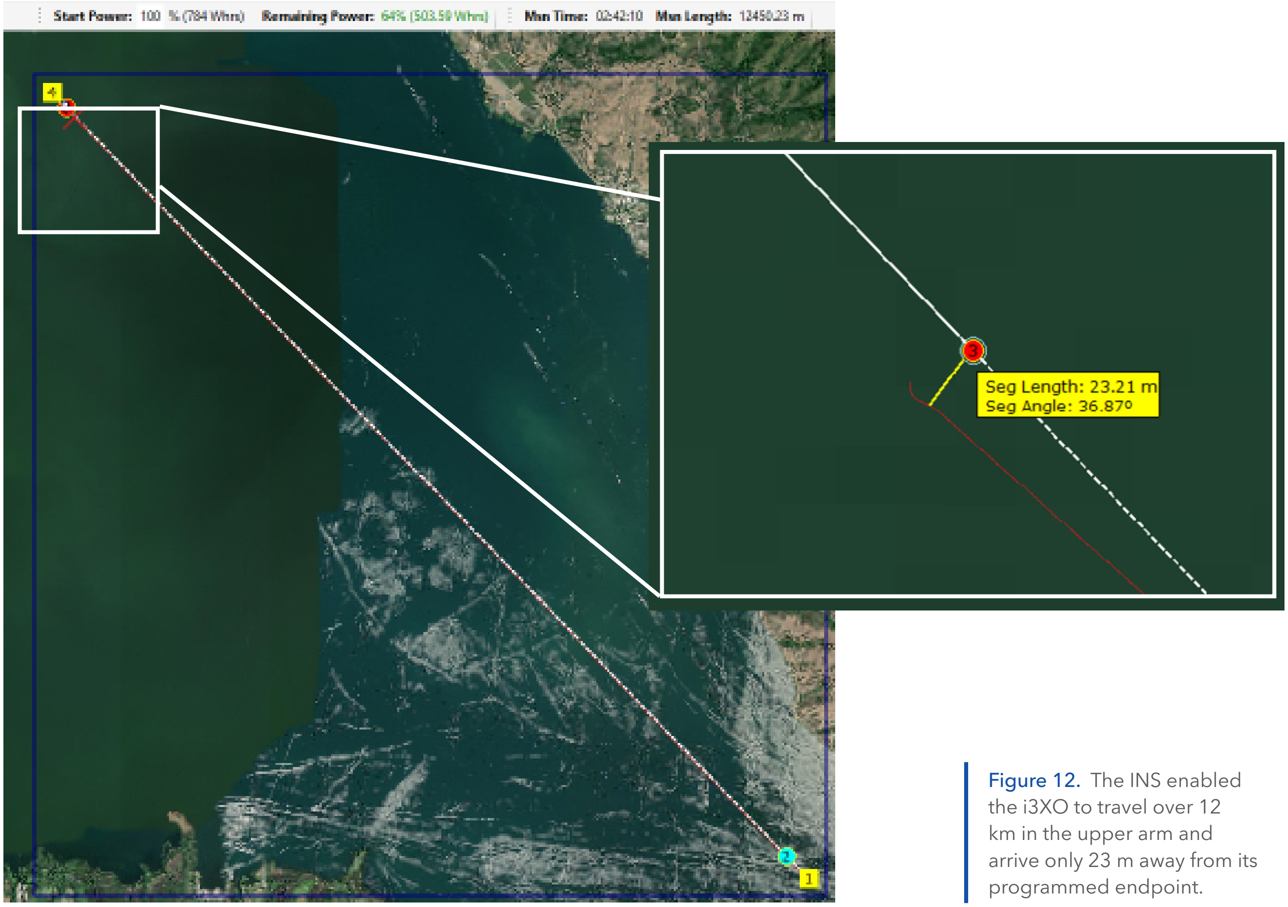

Start Power: 100 % (784 Whrs) Remaining Power: 64% (503.50 Whrs) Msn Time: 02:42:10 Msn Length: 12450.23 m

Figure 12. The INS enabled the i3XO to travel over 12 km in the upper arm and arrive only 23 m away from its programmed endpoint.

## Additional Sampling, Sensing and Imaging During i3XO Missions

The i3XO missions along the main axes of the three Arms of Clear Lake were conducted in conjunction with an instrument package that oscillated vertically at a single location in the lake (deployed at the southeastern end of the i3XO transect line in the Upper Arm of the lake). A separate instrument moored near the confluence of the three arms of the lake moved continuously along a mooring wire from near-surface to near-bottom depths, providing a continuous record of sensed environmental parameters vertically at that location that complemented the spatial coverage obtained using the i3XO.

The environmental data from the i3XO in the lake-wide characterization were also compared to information from ten discrete samples collected near the water surface throughout the open water of the lake and processed for extracted chlorophyll concentration (a proxy for phytoplankton biomass), phytoplankton community composition, inorganic nutrients and the toxin class microcystins.

The whole-lake spatial coverage provided by the i3XO was thus complemented with vertically and temporally-resolved data at a single site, ultimately supporting the study objectives.

Similarly, a drone was employed for the high-resolution study in Konocti Bay to collect imagery of cyanobacterial accumulations and their spatial heterogeneity at the surface of the lake. The information collected by the drone, as well as discrete water samples collected over the sampling grid, complemented sensor data collected at a depth of 1.5 m by the i3XO throughout the study area. Discrete water samples were collected at 1.5 m depth across the same area using a bottle sampler, as well as hand-collected samples at the water surface from inside and outside conspicuous accumulations of cyanobacteria. Water samples were processed for chlorophyll and the cyanotoxin class microcystins in the laboratory.

# Study Outcomes

## Whole-Lake Surveys

The undulation mission in each Arm allowed the team to obtain a synoptic view of chemistry and water column structure throughout the lake.

The Upper Arm mission covered an ~12.5 km stretch in 2 h 42 min. The i3XO operated at a constant undulation between 1.5 m from the surface to 2 m from bottom at a 15 degree dive angle and 2.5 knot speed. The i3XO's ADVL revealed that the depth of the areas covered ranged from 2.8 m to 10.06 m. The water quality data from the EXO sonde can be presented as georeferenced depictions across the lateral expanse of the mission track (i.e. not referenced by depth), as shown here for temperature (Figure 13) and DO (Figure 14).

It is important to carefully consider the data as presented in Figures 13 and 14. A common mistake is to think that one is looking at the data averaged throughout the water column. In fact, it is actual the compilation of all data points from all depths. Each striation represents the data points in one undulation. The data in Figures 13, for example, shows that the northwest corner of the Upper Arm is generally warmer, which would be expected because it is shallower. However, the water column is also relatively well mixed, because the undulations are not demonstrating vastly different temperature ranges.

DO is of special interest in Clear Lake because anoxic conditions promote the release of phosphorus from its sediments (a key element for algal/cyanobacterial growth). Low DO values are known to be common but ephemeral occurrences in the lake, a convergence of conditions that include high organic content for bacterial growth, shallow water depth and strong wind events which induce mixing of the water column. Quiescent conditions promote oxygen demand, especially near the lake bottom, yielding conditions conducive to phosphorus release into the water column.

In general, DO was lower towards the northwest section of the Upper Arm, which was nicely visualized using HYPACK MAX software (Figure 14). Several points of low oxygen were found during the mission, but the lowest was in an ~250 m section towards the north point of the mission. For example, at the point highlighted in Figure 14, DO was at 4.6 mg/L at ~1.5 m below the surface.

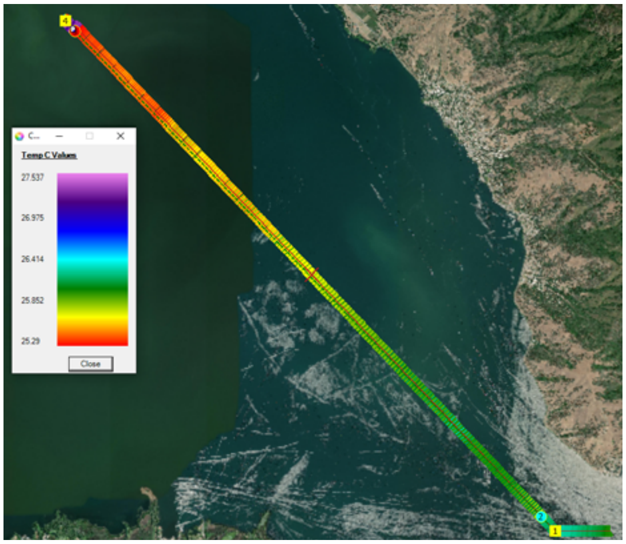
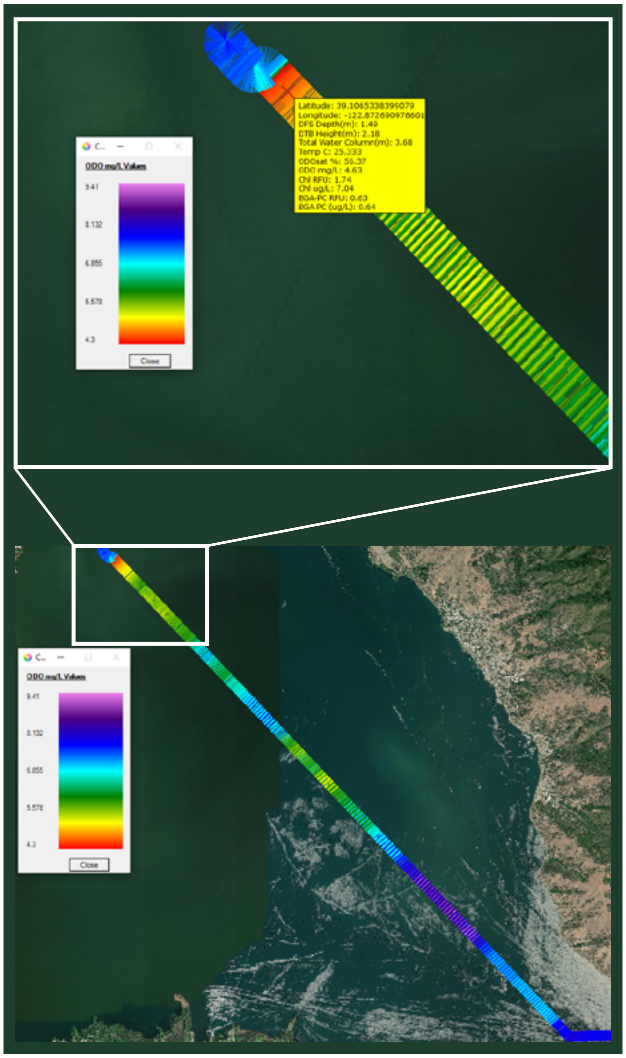


Figure 13. Average Temperature Profile in the Upper Arm.



Latitude: 39.1065338399079
Longitude: -122.87269097660
DFS Depth(m): 1.49
DTB Height(m): 2.18
Total Water Column(m): 3.68
Temp C: 25.333
ODOsat %: 56.37
ODO mg/L: 4.63
Chl RFU: 1.74
Chl ug/L: 7.04
BGA-PC RFU: 0.63
BGA PC (ug/L): 0.64

Figure 14. Dissolved Oxygen in the Upper Arm. Inset shows a single point's

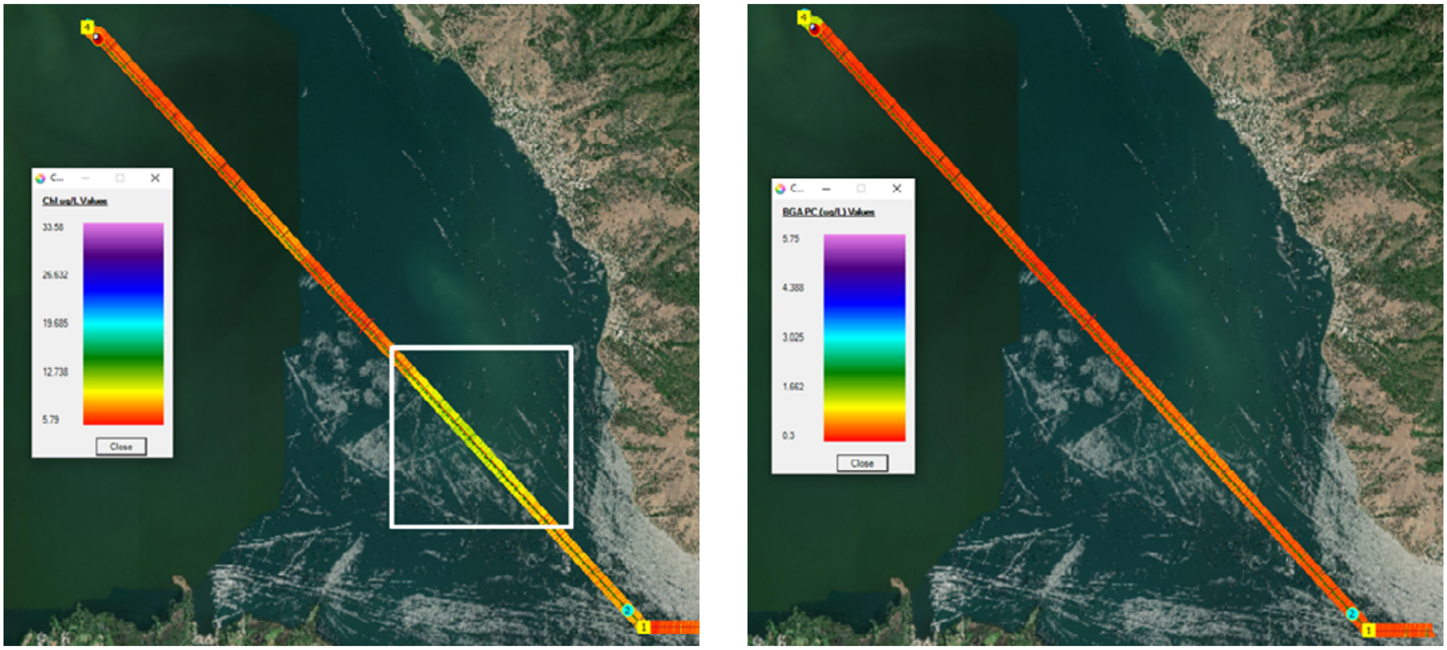


**Figure 15.** Chlorophyll (left) and Phycocyanin (right) in the Upper Arm. These are the same transects shown in Figures 13 and 14.

Chlorophyll (Chl) and Phycocyanin (PC) were measured using an EXO Total Algae-PC sensor (Figure 15). PC was barely considerable in this transect. However when comparing Figures 14 and 15 note that within the area outlined by the white rectangle in Figure 15, chlorophyll is higher than across the rest of the transect. This is also the area of the highest DO activity in Figure 14. This would be an expected pattern in an HAB-impacted lake. Areas of dense algal growth, as estimated with chlorophyll, would yield high percent saturation with DO because the latter is a product of photosynthesis. The peak daylight hours when these measurements were taken would also be peak photosynthetic periods.

Along-transect views of the Upper Arm (Figures 13-15) were informative but greater water column detail can be obtained from the i3XO by exploiting the depth-stamped data collected by the instrument. An example of a preliminary, contoured depiction (a 'heat map') of temperature, DO and chlorophyll fluorescence (a proxy for phytoplankton biomass) along the main axes of Clear Lake is shown in Figure 16.

All Arms of the lake in these depictions are presented on the same scale to illustrate the dramatic differences in phytoplankton standing stocks and chemical parameters among the three Arms of Clear Lake. Data collected by the i3XO allowed immediate comparison of parameters across the entire lake, enabling the identification of salient features, such as phytoplankton 'hot spots' (shown by chlorophyll fluorescence).

Figure 16 revealed that the Upper Arm had substantially less phytoplankton biomass than the Lower Arm, and both had substantially less biomass than Oaks Arm. Massive cyanobacterial blooms and accumulations were visible in the Oaks and Lower Arms during the study period. Overall, water column stability was greater in the Upper Arm as shown by vertical stratification of temperature. This is consistent with what was concluded for Figure 13 above. Dissolved oxygen also was lower overall in the Upper Arm relative to the Oaks and Lower Arms, in part likely due to oxygen production by the cyanobacterial blooms taking place in the latter two locations.

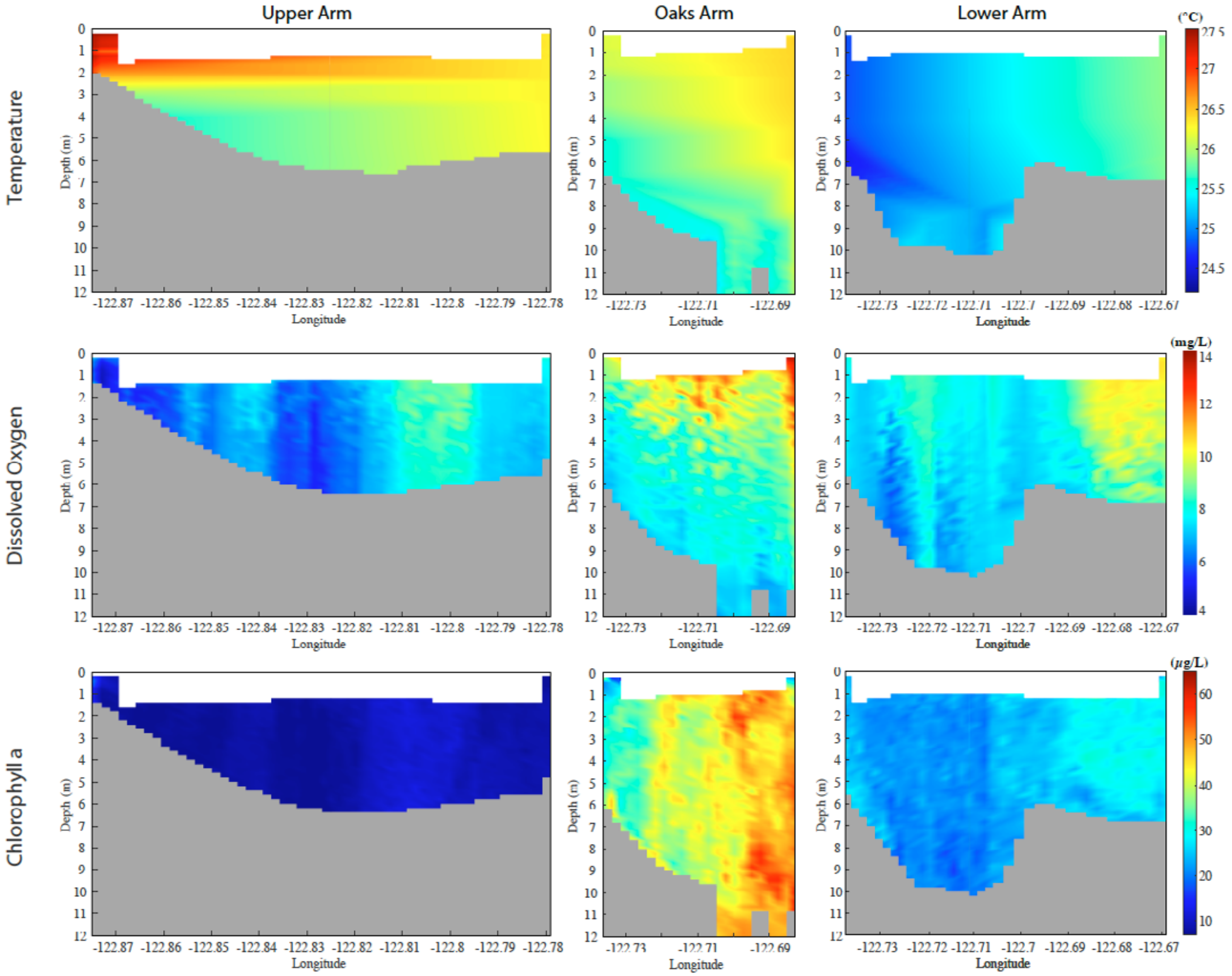


**Figure 16.** High-resolution spatial sampling in Konocti Bay.

*This 'whole lake' snapshot of the water column, captured over three consecutive days, provides near-real-time characterization of water column structure and horizontal heterogeneity that is fundamental in capturing within-lake heterogeneity in such a large lake, and in identifying regions within the lake that warrant further sensor measurements and/or the collection of discrete samples.*

## High-Resolution Spatial Sampling in Konocti Bay

The patterns of environmental parameters above, obtained at the whole-lake scale, provide vital information on where and how to expend limited resources for choosing sampling sites and collecting discrete samples. The Lower Arm was chosen for additional characterization based on the whole-lake patterns of phytoplankton biomass (Figure 16). That said, extreme spatial heterogeneity was observed in the Lower Arm even at the finest spatial scale (Figure 10). That heterogeneity raises questions as to exactly where and how discrete water samples should be collected (e.g. at the surface or subsurface, from an aggregation of cells or away from the aggregation). Such choices have important implications for interpreting the results yielded by water samples.

The high-spatial resolution study using the i3XO in Konocti Bay of the Lower Arm was therefore designed to specifically characterize small-scale, subsurface spatial heterogeneity, and compare it to heterogeneity in the distribution of cyanobacterial accumulations observed at the surface of the water (as shown in Figure 10).

The lawnmower mission (Figure 11) at 1.5 m depth from surface yielded patterns of sensed parameters that differed notably from the extreme heterogeneity of cyanobacterial cells observed at the water surface (Figure 10). For example, the contoured pattern for DO obtained using the i3XO revealed a general trend of higher DO in the shallower portion of the study grid, but modest fine-scale spatial heterogeneity (Figure 17; compare to depth contours in Figure 7). That heterogeneity was less dramatic than surface 'streaks' and 'scums' of cyanobacterial cells that were apparent in the drone images of Figure 10.

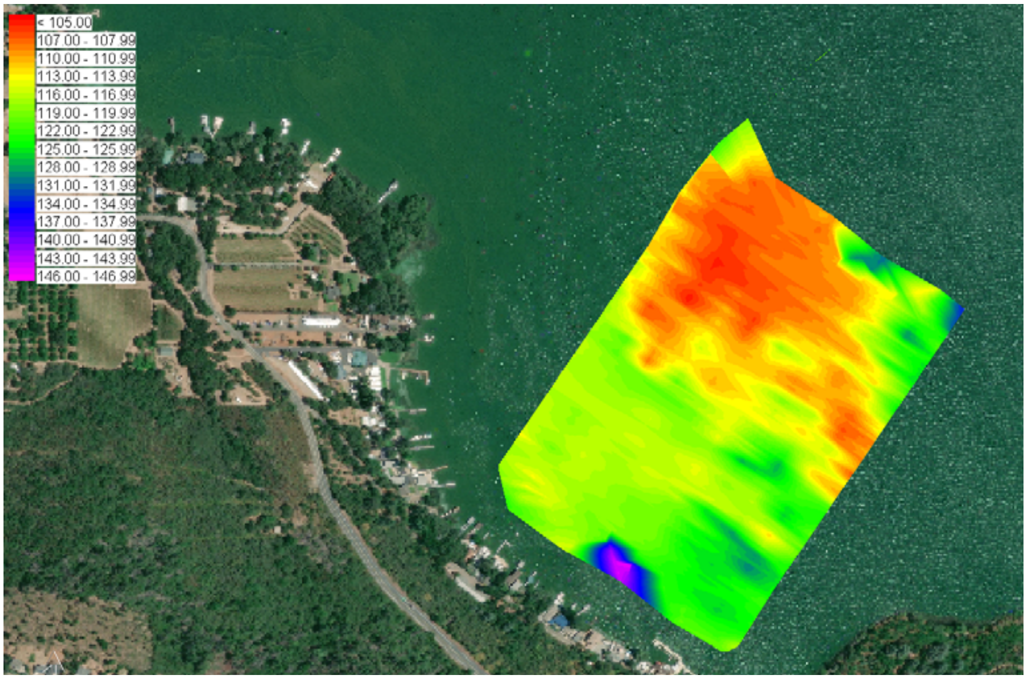


Figure 17. Percent saturation of DO ranged from <105% (red) to over 146% (pink) in Konocti Bay.

The results indicate that obtaining a 'representative' sample in these situations might be better served by sampling subsurface water. On the other hand, samples at the water surface would better characterize fine-scale accumulations of cells and the toxins they may contain (compared to subsurface samples) and might be the target for sampling if maximal cyanobacteria/toxin values are desired. The decision on where and how to collect water sample is therefore dependent on the goal of the monitoring plan, informed by data collected using the i3XO. Additionally, lake bathymetry within the study region was acquired by the i3XO provided contextual information for the interpretation of sensed parameters.

## Discrete Samples Support i3XO Patterns

The data collected with the i3XO suggested that chlorophyll concentrations were lowest in the Upper Arm, with concentrations reaching about 15 µg/L, with higher levels in the Lower Arm reaching about 30 µg/L, and the highest levels in the Oaks Arm, where chlorophyll was measured in excess of 60 µg/L (Figure 18). It is satisfying to note the same trend (Oaks>Lower>Upper) was obtained with the discrete samples collected in those regions on the same day (Table 1). Had the i3XO data been compared to the monthly average, obtained from 8 sampling days, the data in Figure 18 would not have aligned with the data in Table 1. This points to the caution that must be taken when drawing conclusions from a single day's data collected with the i3XO. Thus, while the i3XO enables spatial access as never before possible, long-term continuous monitoring data sets are also very important in the study of harmful algal blooms. Indeed, it is one of the challenges of harmful algal bloom monitoring in general: the temporal dynamics of the bloom cycle, even daily temporal cycles that affect photosynthesis, must always be taken into consideration when comparing data sets.

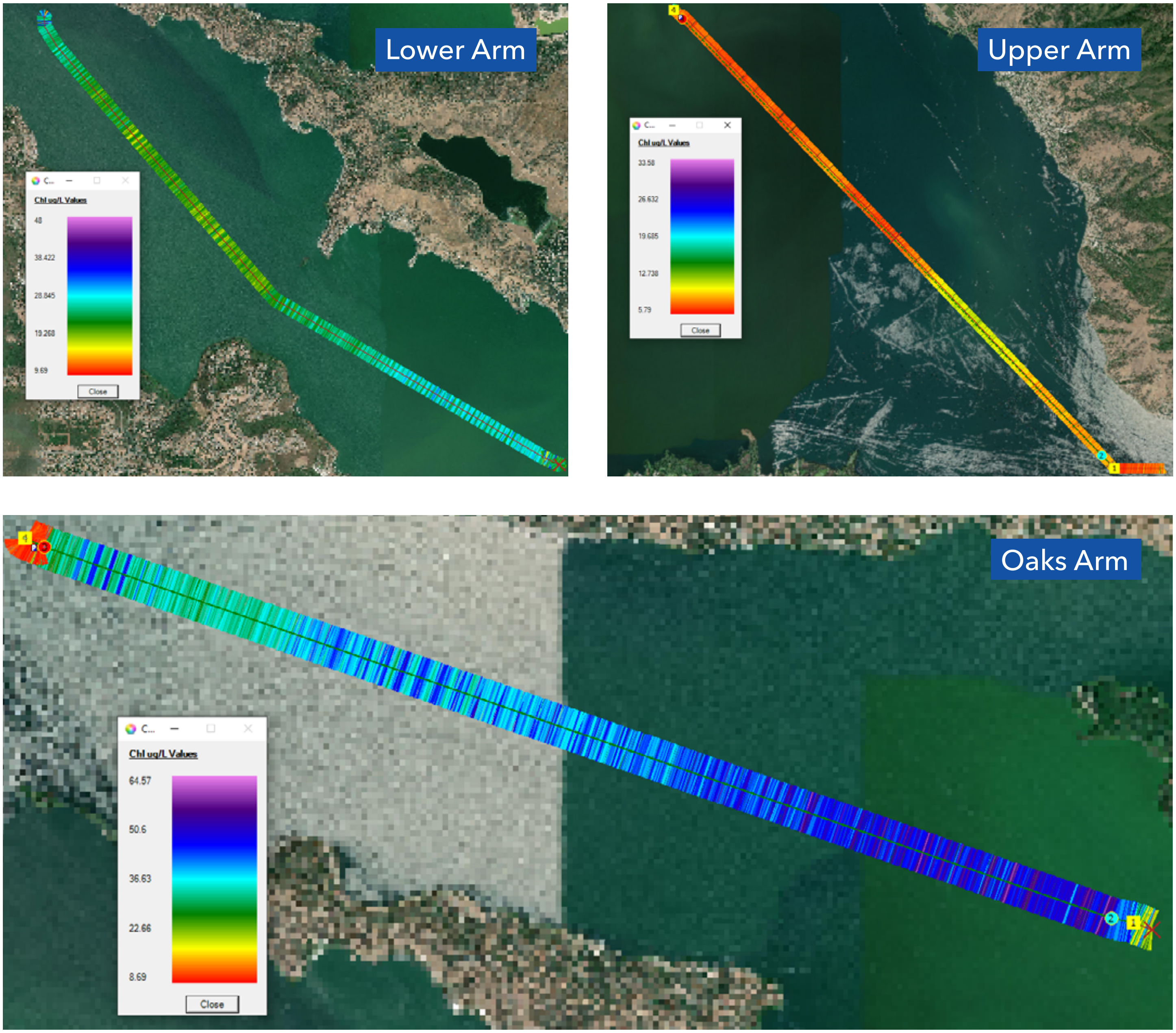


Figure 18. Chlorophyll reading for the i3XO Missions.

| | Sample | Day of i3XO Data | Average for Month |
|---|---|---|---|
| Oaks Arm | 1 | 73.05 | 51.51 |
| | 2 | 75.56 | 56.54 |
| | 3 | 52.97 | 54.92 |
| Upper Arm | 1 | 21.91 | 37.29 |
| | 2 | 12.68 | 39.19 |
| Lower Arm | 1 | 39.63 | 48.95 |
| | 2 | 54.71 | 77.88 |
| | 3 | 60.79 | 63.42 |

Table 1. Comparison of Chlorophyll (ug/L) measured in the discrete samples via extractions. Shown are the samples measured on the same day that the i3XO mission were run, compared with the average of the measurements from the discrete samples collected at the same sites over the month.

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# Closing Comments

The i3XO missions described above provided unsurpassed spatially-resolved sensed data at both the 'whole lake' scale and the high-resolution spatial sampling conducted in Konocti Bay. Follow-on missions are planned to add to the data set presented here, and to continue to dissect the spatial and temporal relationships between water quality and algal bloom dynamics.

The instrument will improve our understanding of water column structure and heterogeneity in Clear Lake. It not only aided in the interpretation of ancillary data, such as community composition and toxin concentrations collected from discrete water samples, but also it helped generate testable hypotheses on those factors most important for driving HAB events.

**These benefits that the i3XO can bring to HAB studies include:**

- Unsurpassed 2D spatial coverage (vertically and horizontally or x-y horizontally) of sensed parameters enables co-location (in time and space) of sensed parameters with biological measurements made from discrete water samples. This enables correlation of the presence of these biological measurements with pertinent environmental physical/chemical features of the water. Correlations aid interpretation of biological data, and identifies features/events for further or future study.
- Sequential repeat missions (i.e. performing the same mission paths multiple times) provides the ability to obtain vertically and horizontal characterizations through time for a given mission path. Ultimately this can facilitate correlation of changes in sensed parameters to response of the water body's biology.
- Multiple onboard sensors allow co-location of multiple parameters. Sensor configurations are flexible and can be adapted to specific needs of a research/monitoring project.
- Integration of data plots obtained using the i3XO with drone imagery, time-course sensed data from vertical profiling instruments, can help to drive sampling regimens.

The small size and ease of deployment of the i3XO makes these advantages accessible to anyone studying HABs or water quality in general. The coverage of tens of thousands of meters in a lake, in a day's time, yields high-resolution data sets that are not obscured by cloud coverage (as with satellite data sets), encompass millions of horizontal and vertical data points that are georeferenced and easily co-located. Future development of HYPACK software for ease of water quality modeling in the same package where missions are planned will advance this technology even further.

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