Field Report

Monitoring the Growth of Coastal Algae Blooms in Harsh Weather Conditions Using a Wave-Propelled ASV: Challenges and Lessons Learned

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Abstract: This article presents the experience gathered on a 19-day-long field campaign with the wave-propelled, solar-powered, autonomous surface vehicle AutoNaut. The operation was conducted in Frohavet, a semienclosed sea along the Atlantic coast of Central Norway, as part of a larger field exercise. The objective of the exercise was to observe and quantify the growth and development of algae blooms in the area. The main scientific objective assigned to the autonomous surface vehicle was to monitor *in situ* the levels of chlorophyll-a fluorescence and solar radiation on the sea surface. Several challenges, mainly caused by the harsh weather conditions, are described and discussed. A risk assessment and safety procedures for the crew and the equipment involved are listed so as to provide a starting point for future operations of this kind. The operations in Frohavet lasted for 19 days until a system failure led to the grounding of the vehicle. Although a bloom was not observed during the period of deployment, valuable experience on how to enhance the *in situ* situational awareness and how to improve the navigation capabilities of the vehicle was gathered. The material presented aims to serve as guidance for future operations, helping the operators to avoid committing the same (or similar) mistakes and further improving the autonomy of the vehicle by establishing a standard operational procedure, thereby improving the vehicle's ability to carry out such missions in the future.

Keywords: autonomous surface vehicles, maritime operations, harmful algal blooms, risk assessment, operational experience

1. Introduction

Due to rapid changes in the ocean environment, oceanographic observations of the upper water-column are of high interest. Current ocean monitoring relies mostly on static observation platforms

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(e.g., meteorological buoys) and ship-based observations (Mcgillivary et al., 2012; Dallolio et al., 2021b). In the past few decades, there has been increasing interest in using robotic platforms for remote monitoring. For example, gliders have become an increasingly popular alternative to conventional ocean monitoring platforms (Camus et al., 2019). Wave gliders are a class of unmanned surface vehicles that harvest energy from the waves to propel themselves, making the vehicle suitable for longer missions. Several long-endurance, green energy surface vehicles are available and have already demonstrated their ability to carry out unmanned missions over long periods of time. Liquid Robotics' Wave Glider (Hine et al., 2009), the Sailbuoy (Fer and Peddie, 2013), and AutoNaut (Johnston and Poole, 2017) are all examples of unmanned surface vehicles designed to harvest energy from the environment and therefore increase the time they can operate in the field without human intervention. Extending the time scale for autonomous missions comes with several challenges. For example, the vehicle must be able to continuously navigate, communicate, and detect and mitigate faults while achieving a predefined set of scientific goals (e.g., sampling a specific property). Long-endurance field campaigns are necessary to identify the challenges that arise as the durations of the missions increase.

A harmful algal bloom (HAB) is a rapid increase in the density of algae in an aquatic system (Assmy and Smetacek, 2009). Due to increased human activity near and in oceans, the dynamics of the ocean are changing, potentially increasing the frequency of HABs. HABs can be toxic to aquatic life by causing a depletion of oxygen and eventually increasing fish mortality (Silva et al., 2021). This has severe consequences. In the fish-farming industry, for example, large economic losses are observed as a result of HABs. The dynamics of a bloom is highly complex and is regulated by some key environmental variables, such as ocean currents, light, temperature, and ocean mixing (Fragoso et al., 2019). A bloom appears as peaks in the phytoplankton biomass, often with chlorophyll-a (chl-a) fluorescence exceeding $5\,\mu g\,L^{-1}$. Naturally, one way to detect if a HAB is growing is to monitor the levels of chlorophyll-a fluorescence in the water column. In addition, photosynthetically active radiation (PAR) at the surface can provide information on the occurrence of a bloom, as this can be triggered by the increase in light during spring. According to traditional ocean observation methodologies, *in situ* measurements of this kind were collected from research vessels using manual techniques such as vertical profiling. With the advent of robotic platforms, the human presence at sea and therefore the employment of large vessels has been replaced by autonomous assets capable of operating remotely and continuously, making data collection economically more affordable, reducing the risks to humans, and limiting CO_2 emissions.

This paper presents the experiences and results from a field exercise carried out with an unmanned, wave-propelled, solar-powered vehicle. The scientific goal defined for the vehicle was to monitor chl-a and PAR in Frohavet during the period between mid-March and early April 2021 in order to provide an early warning of a HAB. In addition to being subject to regular ship traffic, the area is exposed to strong and varying environmental forces (e.g., tidal currents and winds), all of which pose a risk to a small unmanned surface vehicle. The objective for the mission was to keep the vehicle operational for as long as possible and minimize the degree of human intervention necessary for long-duration missions and at the same time achieve the scientific objectives.

1.1. Related works, contribution, and article outline

The use of autonomous surface and underwater vehicles in science-driven oceanic exploration and observation of the upper water column has already been demonstrated extensively (Ferreira et al., 2018; Costa and et.al, 2018; McGillivary et al., 2012; Cross et al., 2015; Pedersen et al., 2019). Small autonomous surface vehicles (ASVs) powered by environmental forces have increased in popularity in recent years. The safe operation of ASVs powered by the environment, over longer periods of time, put demands on the guidance, navigation, and control capabilities. Several solutions to guidance, navigation, and control problems have been developed and tested for different environmentally powered ASVs (Liao et al., 2016; Dallolio et al., 2019; Niu et al., 2016; Wang et al., 2019; Dallolio et al., 2021). The long endurance capabilities of ASVs powered by the environment have already been demonstrated. Liquid Robotics' Wave Glider has performed a crossing of the Atlantic Ocean (Goebel et al., 2014; Manley et al., 2017), where at times it was subjected to extreme weather conditions. The Sailbuoy has performed several scientific missions in the Gulf of Mexico for a duration up to 2 months (Ghani et al., 2014).

In this paper, we present the experiences gathered over the course of a 19-day mission with a different unmanned wave-propelled solar-powered ASV, the AutoNaut, whose control-system architecture is designed to achieve enhanced autonomy and safety. A risk assessment was carried out before the mission, and we show how the safety procedures set in place before the start of the mission were crucial in maintaining mission integrity. We further present valuable insight and experience with regard to the operation of autonomous vehicles in extreme weather conditions, and how the level of autonomy can be further improved in such conditions.

The paper is organised as follows. Section 2 presents the system architecture of the AutoNaut. Section 3 presents the risk assessment and mitigation. A set of potential hazards are identified and classified according to likelihood and consequence. Furthermore, a set of control system functions and safety procedures are introduced to mitigate the risks. In Section 4 we go through the results of the scientific mission, and we present a set of cases from the mission. In Section 5 the results and cases are discussed. The paper ends with a conclusion in Section 6.

2. The AutoNaut: overview & system architecture

The vehicle used in this mission is the commercially available AutoNaut (AutoNaut Ltd, 2021) (see Figure 1). The AutoNaut is a 5-m-long solar-powered wave-propelled surface vehicle. It uses only wave power for propulsion, while a set of solar panels charge the onboard batteries that in turn provide power to the sensors and computers. Direction control is achieved with a rudder, while the speed of the vehicle is not controllable since it is dictated by the environmental forces (i.e., currents, winds, and waves). The vehicle is also fitted with a small stern thruster for improving maneuverability in sheltered waters where no waves are present. The combination of wave-powered propulsion, energy harvesting and storage, and electronics with low power consumption make the AutoNaut capable of enduring long missions out at sea ideally without physical human intervention. The vehicle is equipped with a scientific payload consisting of a wide range of sensors. The aforementioned properties make the AutoNaut a viable choice as a persistent observation platform for oceanographic research.

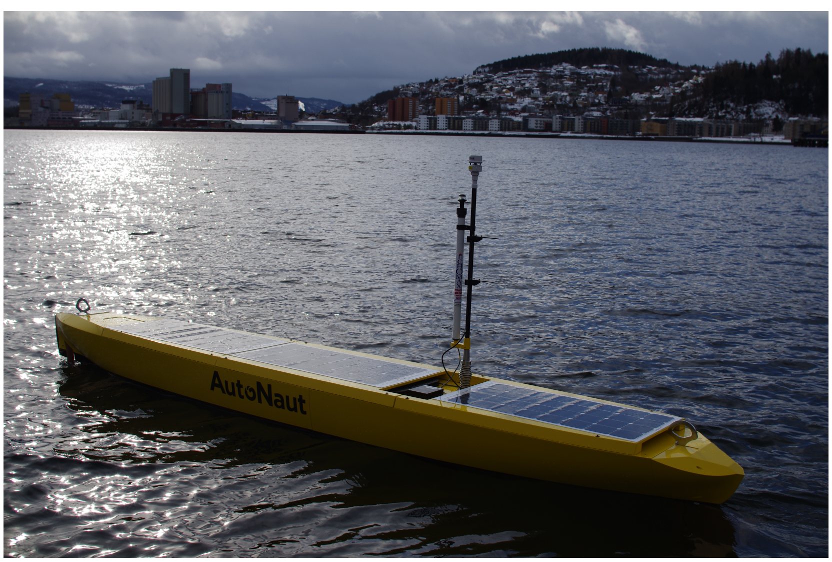

Figure 1. The AutoNaut ASV in Trondheimsjord (Central Norway).

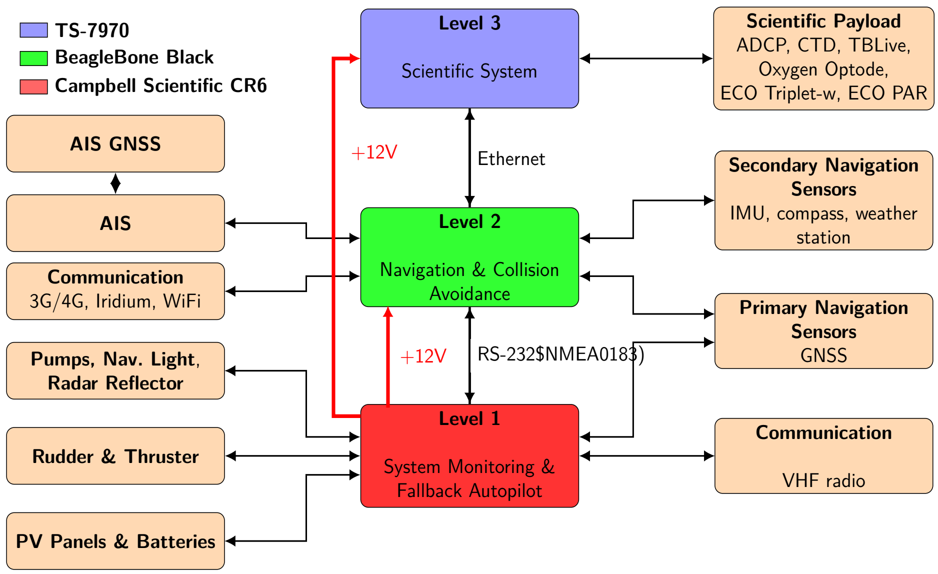

Figure 2. The system Architecture of NTNU's AutoNaut, where each level is implemented using separate hardware and software.

The AutoNaut ASV used in this work is a customized version whose control and communication architecture are designed and implemented at the Norwegian University of Science and Technology (NTNU) (Dallolio et al., 2019). At the software level, the architecture makes use of a modified version[1] of the LSTS toolchain (Pinto et al., 2013).

As shown in Figure 2, the architecture of the AutoNaut is divided into three layers. While the first layer is responsible for monitoring the health of the vehicle and managing the energy harvesting and distribution, the middle level implements advanced navigation functionalities. The vehicle is in fact equipped with a waypoint-based guidance system, a course/heading autopilot, and an AIS[2]-based collision avoidance algorithm. Finally, the third and last layer controls the scientific payload and the data collection. For communication with the operators onshore, the AutoNaut is equipped with a 4G/LTE modem, an Iridium satellite modem, and a VHF radio. While the 4G/LTE modem is the main communication channel for coastal operations, the satellite modem is used whenever the vehicle operates outside the cellular network. The system architecture is described in more detail in (Dallolio et al., 2019).

3. Risk assessment and mitigation

The area of operation (AO) for this mission is along the Atlantic coast of central Norway; see Figure 3. Strong winds and current, high waves, ship traffic, static obstacles such as fish farms and floating debris, constant cloud coverage, and patchy cellular network coverage all represent hazards for navigation. The mission requires the AutoNaut to stay in the AO and take measurements regularly. To achieve this, a navigation plan (typically a list of waypoints) is set to let the AutoNaut run in a loop within the AO. A navigation plan is commanded from the operators onshore using the mission control software, Neptus, from the LSTS toolchain. The navigation instructions are dispatched using the available communication link, and once received onboard the vehicle, the AutoNaut starts executing the plan autonomously. The scientific payload can be set to sample measurements at regular intervals or manually turned on and off from Neptus.

[1] https://github.com/adallolio/dune/tree/AutoNaut-CAS.
[2] Automatic Identification System.

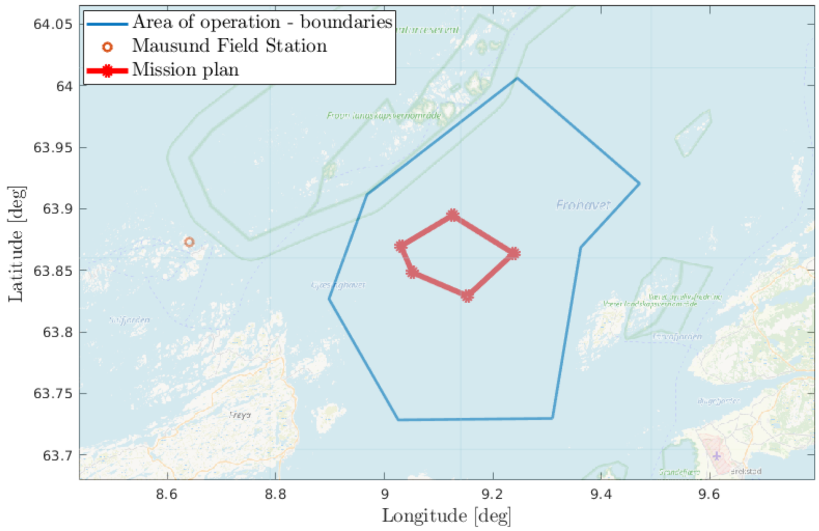

Figure 3. Area of operation (blue) with a navigation plan (red).

3.1. Hazards

A list of hazards is defined and presented below.

1. **Hazard I: collision.** A collision with another vessel poses a risk for both the AutoNaut and other vessels traveling in the AO. Small leisure boats are less likely to go into the AO at this time of year. The local traffic is dominated by larger vessels, for example for fishing, goods transport, tankers, and service for the nearby fish farms. We therefore expect most vessels in the AO to have an automatic identification system (AIS) and thus have the capability to detect the AutoNaut from a safe distance. The AutoNaut is equipped with an AIS-based anticollision system (Hagen et al., 2018; Kufoalor et al., 2020) to prevent collisions with any other vessel equipped with an AIS. Given the small size of the AutoNaut, a collision with another vessel may be fatal to the AutoNaut, but it may result in only minor damages to any other vessel.
2. **Hazard II: loss of control**. In early spring the AO is prone to harsh weather conditions. Winds can regularly get as strong as $30\,\frac{\mathrm{m}}{\mathrm{s}}$ at this time of year. Strong wind in combination with the proximity to the open ocean will likely generate large waves as well. Furthermore, the proximity to islands and shallow waters is likely to generate strong and unpredictable ocean currents. The AutoNaut operates at low speed with low maneuverability, and strong environmental forces can end up dominating the propulsion force and make the vehicle difficult to maneuver, or in the worst case completely uncontrollable.
3. **Hazard III: damage to external equipment**. The sea current pushes floating debris and garbage into the area, which can damage the rudder, foils, and sensors under the hull and antennas on the deck. Breaking the antennas compromises communication with the vehicle and limits the control of the vehicle from land and the monitoring program. Furthermore, contingency plans cannot be executed from shore should a critical situation arise, for example if the vehicle deviates significantly from its main path due to strong winds. A loss of communication also means that the position of the vehicle will be unknown, decreasing the chance of finding the it if a rescue team is sent to recover it. A failure of any of the critical navigation sensors, rudder or foils, will result in a loss of navigation capabilities, which will leave the vehicle uncontrollable.
4. **Hazard IV: harm to rescue team**. The AutoNaut requires a manned vessel to bring it between the deployment site and the AO by towing it. This is done because of the shallow waters with many reefs that are present between the AO and the deployment site. If a recovery

of the vehicle is necessary, the support vessel will have to get close to the AutoNaut in order to attach the tow line. This represents a hazard if the weather conditions are harsh as the recovery vessel may collide with (and eventually damage) the AutoNaut. A recovery of the vessel in harsh conditions will involve a hazard for the crew as well.

5. **Hazard V: low onboard energy**. Even though the vehicle requires no energy to propel itself, it requires energy to power the onboard computers, sensors, and rudder. This power is provided by the battery bank, which is charged by the solar panels. Should the electric energy deplete, critical equipment such as the GNSS receiver and rudder will shut down and leave the vehicle uncontrollable. The vehicle is set to start powering down nonessential equipment if the battery voltage drops below a certain level. The scientific payload is defined as nonessential, thus if the battery voltage drops too low, the vehicle will no longer be able to carry out its scientific mission. It will instead only focus on its survival and keep on navigating the planned route.

3.2. Risk assessment

The hazards, consequences, and mitigating actions are summarized in Table 1, and the risk matrix shown in Table 2 categorizes the various hazards into a red, yellow, and green category. The red indicates an unacceptable risk, and additional mitigating actions must be taken to reduce it. The yellow indicates that further mitigating actions should be considered to reduce the risk. A green status is for acceptable levels, and no action is required.

3.3. Safety procedures

As outlined in the previous section, a number of risks will be present during the mission. We discuss here safety procedures to reduce the risk associated with the hazards.

3.3.1. GPS satellite beacon

All sensors and actuators on the AutoNaut are powered by the onboard battery bank. Sensor information, such as the vehicle's position, is transmitted to land over the vehicle's communication channels, which is either 4G or Iridium. In the event of a failure of the electric system, all sensors, actuators, and communication channels will stop working. This means the AutoNaut will be unable to navigate, but it also means that the onboard GNSS receiver will no longer transmit the vehicle's position to land. In the event of such failure, the position of the vehicle is necessary so that the rescue team is able to locate and retrieve the AutoNaut safely. For this reason a separate GPS satellite beacon[3] was installed on the AutoNaut's deck. The beacon is a self-contained unit with its own power supply, GPS receiver, and Iridium satellite communication antenna. The beacon is completely isolated from the rest of the system, and its sole purpose is to communicate its position over the Iridium satellite network at a fixed interval. The position is transmitted to an independent web service provided by the manufacturer of the beacon. This device would help the operators onshore and the rescue team to locate the vehicle at sea during a rescue operation.

3.3.2. Around-the-clock monitoring

To reduce the risk of collision and grounding, a watch systems was implemented with around-the-clock duty. This ensured that at least one person always was available to assess the situation and take necessary action should the AutoNaut be in danger. During the day the AutoNaut was followed up continuously, while during the night it was watched every two hours. Given the AutoNaut's low velocity, even while drifting with the wind, and the distance to land in the AO, watches every second hour were considered sufficient. Grafana, a web application for data analysis and visualisation, is set up to receive data from the AutoNaut. It provides a good overview of the AutoNaut and its status and is open for the general public. This made it possible to recruit and train a larger team

[3] NOVATECH iSurface delivered by Metocean Telematics.

Table 1. Summary of the hazards presented in this section and their corresponding consequences and mitigations.

#	Hazard	Consequences	Mitigation
1	Collision with other vessels or stationary objects	Leads to material losses and/or third party personal injuries and/or death.	A lantern and radar reflector are fitted to the AutoNaut to increase its visibility. A schedule of manned watches makes it possible to identify dangers and act-on-demand from the moment a danger is identified. An automatic anticollision system based on AIS and digital charts is used.
2	Grounding	Damages to external equipment with the possibility of wreckage. Environmental pollution. Complete stop of the scientific program.	A watch schedule is set so that a human, from land, can follow closely the operation of the vehicle, changes in the local environmental conditions, and traffic. The AO is restricted to deeper waters. The AutoNaut is towed in and out from zones that can compromise the vehicle's integrity.
3	Running out of battery power	Loss of communication channels, actuators, and sensors. Compromises the capacity to control the vehicle remotely. Increases the risk of grounding or colliding.	The navigation plan considers cloud forecasts and live battery-charging data coming from the vehicle. Nonessential equipment may be turned off. If the risk is considered to be too high, the watch can call in the rescue team to retrieve the vehicle and charge the batteries in a safe harbor.
4	Navigating in rough weather, i.e., strong winds and high seas	Compromises the capacity of AutoNaut to follow the planned route. Coming in contact with the vehicle, for instance for recovery and towing, increases the possibility of injuries to the rescue team and/or damages to the rescue vessel and/or AutoNaut	The watch on duty goes in an alert mode and informs the rescue team to stand by. The navigation plan is adjusted on a minutes base to account for the sea current, wind speed and direction, and the geographical conditions around AutoNaut. The rescue team sails only if is considered safe to do so. Experience among the AutoNaut pilots has been built up with several such scenarios, and the rescue team has become more experienced after many recovery rehearsals.
5	Damage to external equipment	Damages to equipment critical for navigation or communication may lead to a loss of control or loss of communication with onshore operators.	The control architecture has redundancy with autopilot functions, several communication links, and an independent GPS beacon. There are foils both fore and aft. The rudder and its servo have no redundancy. A loss of control or communications will compromise the mission and therefore the vehicle should be recovered. The rescue team is on standby and can be deployed within a few hours if the weather permits it.
6	Loss of control due to extreme weather	If controllability is lost, the vehicle can end up colliding or grounding.	Controllability can be regained by altering the mission to align the vehicle better with the environmental forces. A set of contingency plans were made prior to the mission in case of extreme weather. The contingency plans take the vehicle to more sheltered areas to wait out the weather. The plans can be executed based on weather forecasts.
7	Water intrusion	Onboard electronics may fail if they come in contact with seawater. Large leaks may fill the hull with water and result in the vehicle sinking.	The hull is split in three separate compartments and a single leak will not result in the entire vehicle filling with water. Each compartment is fitted with a bilge pump running at a fixed interval to pump out any water in the hull. Critical electronic components are placed in watertight boxes inside the hull. The seals are checked before deployment.
8	Capsizing	May lead to damages to external equipment and waterproof seals. It increases the risk for short circuit and failure of electric components. Communication and control might be lost temporarily or permanently. Internal equipment like batteries and computers may be displaced.	The hull is designed to self-correct. All internal equipment is strapped in place to prevent it from moving in the event of a capsize.

Table 2. Risk matrix identifying the risks associated with the mission. The numbers in the matrix correspond to the hazards identified in Table 1.

Consequence	Likelihood				
	Minimal	**Low**	**Medium**	**High**	**Very High**
Very Critical					
Critical	1,4				
Dangerous		2,5	3		
Relatively Safe		7	8	6	
Safe					

of watchers. If an undesirable event were to happen, the watchers would contact an operator with access to Neptus and the ability to control the AutoNaut.

3.3.3. Contingency plans

In cooperation with the rescue team, contingency plans were made. Areas with more sheltered water were identified such that the AutoNaut could be moved there in case of faults or if the weather made it impossible to operate in the intended area. This reduces the risk of the AutoNaut losing controllability and as a result colliding or grounding.

3.3.4. Monitoring of metocean forecasts

Several services providing tidal and metocean forecasts exist and were closely monitored by the operators on land to anticipate future challenges with navigation due to the weather. A loss of controllability due to strong winds, waves, and currents may not be critical if it can be regained by altering the mission, e.g., moving waypoints to increase the wind angle of attack on the vehicle. Persistently bad weather may increase the risk of the vehicle losing controllability for a long period of time and thereby grounding or colliding with other vessels. In that case, contingency plans may be executed based on the observed forecasts.

3.3.5. Monitoring of ship traffic

AIS online services give information on nearby marine traffic. Operators on land monitored ship traffic in order to predict future possible collisions and take necessary action. If necessary, AIS services can provide the operator with contact information to the vessel, such that the crew can be alerted to the presence of the AutoNaut.

3.3.6. Search and rescue team

A search and rescue team was on standby at Mausund Field Station. If the vehicle was in critical danger, the team could deploy on short notice if the weather conditions permitted it. The assets available for the rescue team were the boat Hunter, a $11 \times 3\,\mathrm{m}$ aluminum vessel, as well as several smaller vessels. Hunter has a cruising speed of about 30 knots, which makes it able to reach any point in the entire AO in about 1 h. Missions are planned such that the AutoNaut keeps a distance of at least 10 km to land. Assuming an average speed of $1.5\,\frac{\mathrm{m}}{\mathrm{s}}$ for the AutoNaut, it will take the vehicle approximately 2 h to move 10 km. This means the AutoNaut will at all times be approximately 2 h from grounding, giving the rescue team a maximum response time of 1 h in the worst case. The crew were experienced in maneuvering the vessel in difficult conditions as well as having extensive knowledge about the area of operation.

3.3.7. Software upgrades

Whenever the vehicle is within 4G cellular coverage, the operators onshore have the ability to update the software running on the navigation computer. This means the navigation and control software can be altered or improved during the deployment if a problem should occur.

March 12. 18:00	The vehicle was deployed at the AO.
March 13. 15:17	First measurement of chlorophyll a fluorescence.
March 15. 20:20	The Iridium satellite communication antenna failed, further described in Section 4.2.2.
March 15. 23:00	The vehicle was towed to land due to the failure of the Iridium satellite communication antenna.
March 17. 19:30	The vehicle was redeployed at the AO.
March 23. 09:00	A contingency plan was executed due to bad weather forecast combined with low battery voltage, further described in Section 4.2.3.
March 23. 19:20	The vehicle was retrieved to charge the batteries.
March 26. 13:20	The vehicle was redeployed at the AO.
March 30. 14:07	Last measurement of chlorophyll a fluorescence.
March 31. 12:55	The vehicles was retrieved to charge the batteries.
April 01. 07:30	The vehicle was redeployed at the AO.
April 01. 08:15	The vehicle had a close encounter with another vessel, further described in Section 4.2.5.
April 04. 06:30	The vehicle capsized, further described in Section 4.2.7.
April 04. 06:45	The vehicle self-corrected.
April 04. 16:05	The vehicle capsized a second time resulting in a loss of GNSS signal, further described in Section 4.2.7.
April 04. 16:15	The vehicle self-corrected.
April 05. 02:15	The vehicle grounded, further described in Section 4.2.7.

Figure 4. Timeline describing the most important events during the deployment.

3.3.8. Data logging

Data are communicated back to the onshore operator at all times, either over 4G if the vehicle is within cellular coverage, or over the Iridium satellite network if there is no cellular coverage. However, all data are also stored on an onboard hard drive. When the vehicle is retrieved, all measurements from the mission can be retrieved by accessing the onboard storage.

4. Results

The goal of the mission was twofold. The vehicle was commanded to monitor levels of chl-a in the upper water column to provide an early warning of a HAB. There is no way to know for sure when a HAB will occur, as it depends on a variety of environmental variables. The fact that the AutoNaut provides updates on the chl-a levels over a long period makes it is more cost-beneficial than conventional sampling methods (e.g., manual sampling from research vessels). Therefore, the second goal of the mission was to keep the vehicle operational for as long a period as possible as it might take several weeks before the bloom starts. In this section, we present the results from the observation of chl-a levels as well as a case study highlighting some of the challenges relating to the operational aspect of the mission. A timeline providing an overview of the major events from the mission is shown in Figure 4.

4.1. Monitoring of chlorophyll-a fluorescence

The main scientific objective of the field campaign was to monitor the surface concentration of chlorophyll-a in the AO. Notable, a HAB is observed when the chl-a measurements exceed $5\,\mu g\,L^{-1}$. The measurements of chl-a were taken using the Sea-Bird Scientific ECO Triplet-w[4]. Algae are subject to nonphotochemical chlorophyll fluorescence quenching (NPQ), a process in which algae

[4] https://www.seabird.com/eco-triplet-w/product?id=60762467721.

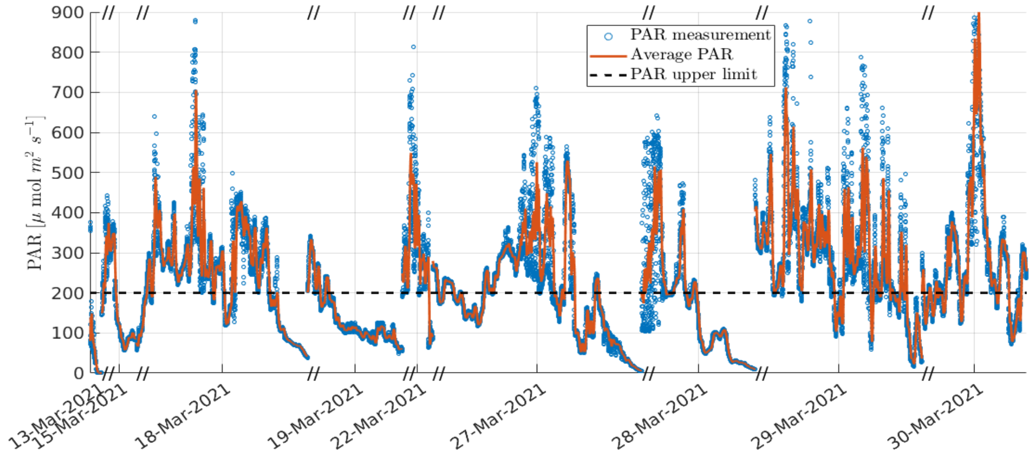

Figure 5. Photosynthetically active radiation measurements taken during the deployment.

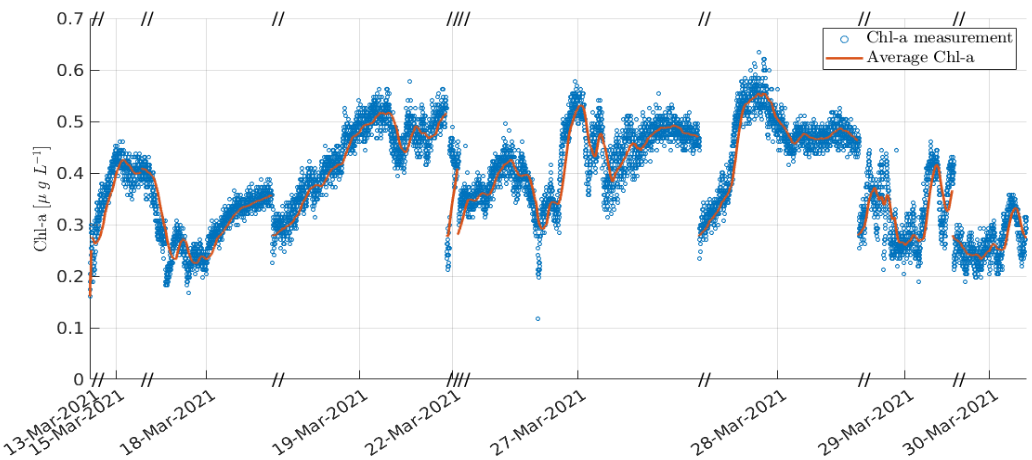

Figure 6. Measurements of chlorophyll-a fluorescence corresponding to simultaneous PAR measurements below 200 μmol m^2 s^{-1}.

exposed to high levels of light will dissipate excess energy in the form of heat. This has been shown to manifest as reduction in chl-a values during daytime when the sun is at its highest. The vehicle is equipped with a Sea-Bird Scientific ECO PAR[5] that measures photosynthetically active radiation. To compensate for NPQ, it is common to discard measurements of chl-a where the PAR is high (Fragoso et al., 2021). Figure 5 shows the PAR measurements taken during the deployment. The upper limit on PAR was set to 200 μmol $m^2\,s^{-1}$. As seen from the figure, a majority of the measurements were taken when the PAR was higher than 200 μmol $m^2\,s^{-1}$, thus giving inaccurate chl-a measurements. Figure 6 shows all measurements of chl-a taken during the deployment where the PAR was within acceptable levels. In Figure 7 we can see all accepted chl-a measurements and their placement in the AO.

4.2. Case study

In this section we describe the challenging scenarios faced during the field campaign. The first four scenarios show situations in which faults were detected or in which the AutoNaut was unable to

[5] https://www.seabird.com/eco-photosynthetically-active-radiation-par-sensor/product?id=60762467733.

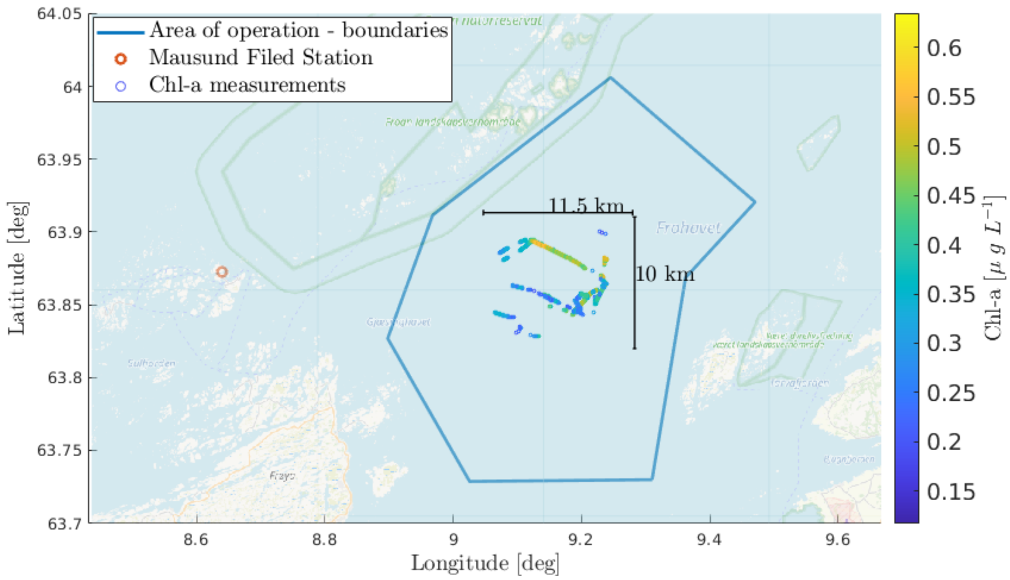

Figure 7. Georeferenced chlorophyll-a measurements corresponding to simultaneous PAR measurements below 200 µmol m^2 s^{-1}. The area of operations is shown for reference (blue polygon).

execute the commanded navigation plan. In each case, a safety procedure was triggered to maintain safety in the mission. The following two cases involve challenging scenarios in which the vehicle was able to handle the situation autonomously without human intervention nor safety procedures being executed. The final case shows a failure that led to the vehicle grounding and the mission being terminated.

4.2.1. Case 1: unfeasible path due to strong wind

As expected, strong winds up to 15 $\frac{m}{s}$ and currents were present in the AO. On such an occasion, the passive wave-propulsion mechanism of the AutoNaut can be overpowered and the planned path can become unfeasible. An example of this can be seen in Figure 8. While maneuvering between waypoints WP 1 and WP 2, the ASV struggles to stay on the desired path. In Figure 9, the wind speed and direction as well as the measured and desired course (over ground) are shown. It can be seen that the wind approaches 20 $\frac{m}{s}$ with gusts up to 30 $\frac{m}{s}$ towards the end. The significant wave height increased to about 3 m. This results in the course oscillating around the desired one. As the wind increases, it eventually overpowers the vehicle and it is no longer able to make any progress towards the waypoint. In this scenario, the wind is directed from southwest towards northeast, hitting the AutoNaut from the front. While the AutoNaut is headed directly into the wind, the lateral force made by the wind is zero, but even a small deviation in heading will make the lateral wind forces substantial and create a moment to turn the vehicle around. This can clearly be seen in Figure 9, where large oscillations can be seen in the course during the last part of the period. In this scenario, the vehicle is not able to reach the waypoint. To continue to make progress on the mission the vehicle was manually set to go to waypoint WP 4 instead, as the wind angle of attack would be larger when heading towards waypoint WP 4.

4.2.2. Case 2: loss of communication

The 4G coverage was weak in some parts of the AO. This was expected and resulted in frequent loss of connection between the ASV and shore. In the event of a 4G communication blackout, the AutoNaut will continue executing the current plan, but it will switch to the Iridium satellite network as its main source of communication with the operators onshore. The bandwidth is decreased significantly and thus the amount of information received by the operators is significantly decreased. This resulted in

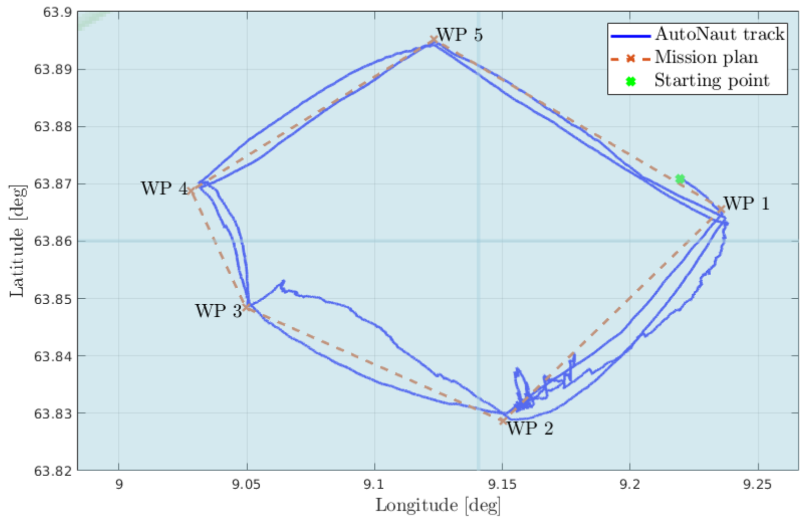

Figure 8. The location of the AutoNaut during a 42-h period during the deployment.

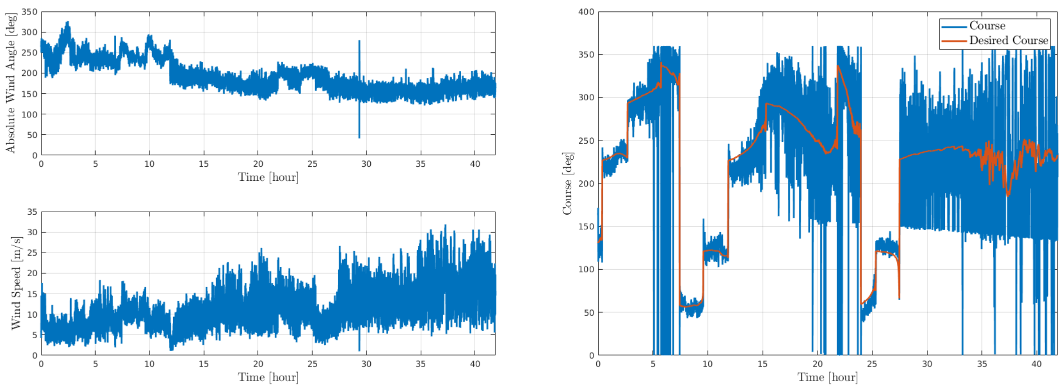

Figure 9. Absolute wind direction (top left), absolute wind speed (bottom left), and measured and desired course (right) for a 42-h period during the deployment.

reduced situational awareness for the operators. The VHF communication link was not used in this mission. Consequently, if the Iridium communication channel fails, the AutoNaut will lose all means of communication, which is a critical situation. Due to water leaking into the Iridium antenna connector, the Iridium antenna suffered a failure during the mission. The fault was immediately detected by an operator onshore. Without any means of communication with the AutoNaut, the decision was made to recover the vehicle to Mausund Field station and the safety procedure was immediately initiated. Although the GNSS device was functioning, the lack of communication made it impossible to transmit the vehicle's location to the operators. By using the location broadcast from the independent GPS beacon, the crew were successful in finding and recovering the AutoNaut. The failure of the Iridium antenna was due to seawater getting into the connector, resulting in a short circuit. The antenna and connector were both replaced. In addition, dielectric grease was added to all connectors to limit corrosion before the vehicle was towed back to the AO and resumed its mission.

4.2.3. Case 3: rerouting due to forecasted strong wind

As stated in the safety procedures, the operators onshore should monitor the weather forecast continuously to predict any hazardous situations. At a point in the mission the AutoNaut was operating nominally in the AO under moderate weather conditions, but the battery voltage was

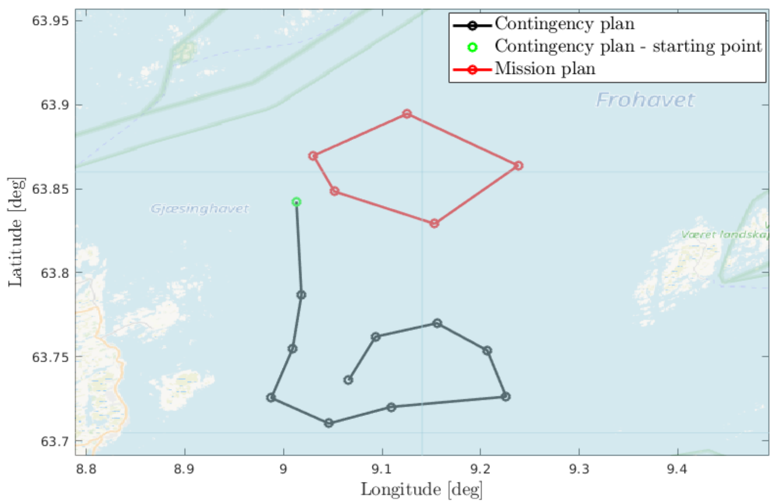

Figure 10. A typical mission plan (red) consisting of a set of waypoints arranged in a loop. A contingency plan is set up (black) to send the vehicle to more sheltered water should it be necessary.

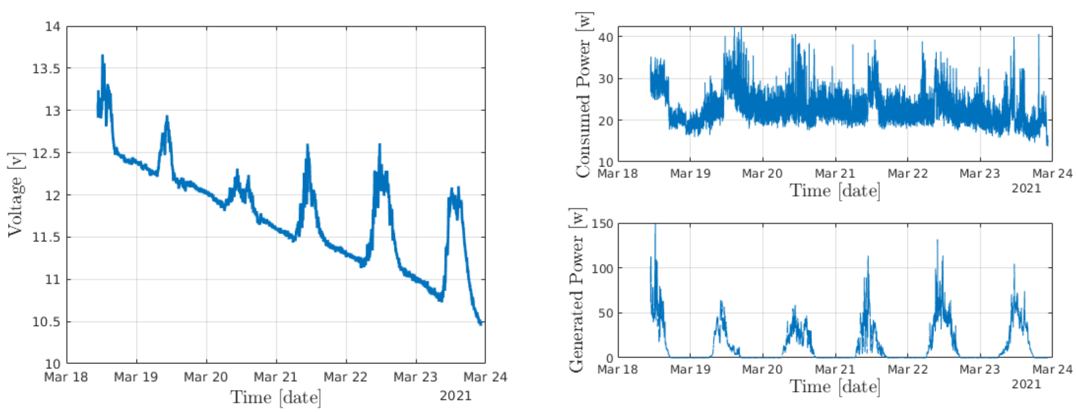

Figure 11. Battery voltage (left), consumed power (top right), and generated power (bottom right) over 6 days.

getting close to the critical level. At the same time the weather forecast showed an upcoming increase in wind and waves. The forecast showed an increase in the winds towards 20 $\frac{\mathrm{m}}{\mathrm{s}}$ and an increase in significant wave height from 2 to 3 m. Low battery voltage would normally trigger a rescue mission, but it was uncertain if the rescue team would manage to retrieve the AutoNaut before the weather conditions worsened. The wave height in particular makes it hard to recover the AutoNaut as it gets increasingly difficult to approach the vehicle. A decision was made to execute a contingency plan where the AutoNaut would navigate south into more sheltered waters. The original plan and the contingency plan are shown in Figure 10. By navigating into more sheltered water, the chances of a successful recovery would increase. While the vehicle was navigating south, the weather unexpectedly calmed down for a while and a window of opportunity opened up for a rescue. The rescue team was dispatched from Mausund Field Station and recovered the AutoNaut successfully. The vehicle was put to charge when back on land and returned to the AO the following day.

4.2.4. Case 4: low battery voltage due to persistently cloudy weather

At the time of the operations, the days were short in the AO and limited sunlight was expected. The short exposure to daylight combined with persistent cloudy weather during the mission caused the solar panels to generate only small amounts of power. Figure 11 shows the evolution of the battery voltage over a 6-day period as well as the consumed and generated power. As seen in the figure, the battery voltage is consistently dropping. During the day the voltage increases as the batteries are charged slightly despite the cloud coverage, but the generated power is not enough to make up for the consumption during the night. At the end of this period the voltage dropped below 11 V, which is considered the critical level, triggering the safety procedures. The recovery team was dispatched from Mausund field station to recover the vehicle. The vehicle was still capable of navigation and was sent to meet the recovery team, while the real time position was transmitted from the AutoNaut to the rescue team via Grafana.

4.2.5. Case 5: collision avoidance

The AutoNaut is equipped with a collision avoidance system based on AIS to prevent collisions with other vessels (Dallolio et al., 2021a). During the mission, a situation occurred where a vessel approached the AutoNaut on a collision course from north-east towards south-west. The speed of the approaching vessel was approximately $4\,\frac{\mathrm{m}}{\mathrm{s}}$ while the AutoNaut had a speed of approximately $0.9\,\frac{\mathrm{m}}{\mathrm{s}}$ at the time. Figure 12 shows the track of the AutoNaut and an approaching vessel. The track shows that the AutoNaut performs an evasive maneuver when the approaching vessel gets too close. The anticollision system is tuned to monitor obstacles within a range of 5000 m, but an action is taken only when the obstacle is within 2000 m. A fault in the anticollision algorithm was detected during the evasive maneuver performed by the AutoNaut, resulting in a suboptimal computed course offset. As can be seen from the track depicted in Figure 12, the AutoNaut acts overly cautious as the obstacle moves fast enough to never pose any real danger. This is desirable, however, as it is desired that the ASV always stays as far away from other vessels as possible. The cautiousness of the AutoNaut will ensure safe operations even if the approaching vessel should start maneuvering more unpredictably.

4.2.6. Case 6: transitioning from 4G cellular communication to Iridium satellite communication

As mentioned in Case 4.2.2, the AO had an unreliable 4G coverage, and at several times during the mission the 4G connection was lost. When this happens, the AutoNaut will use instead the onboard Iridium transceiver to communicate to shore. The Iridium connection has a significantly smaller bandwidth compared to the 4G network connection and therefore the amount of information

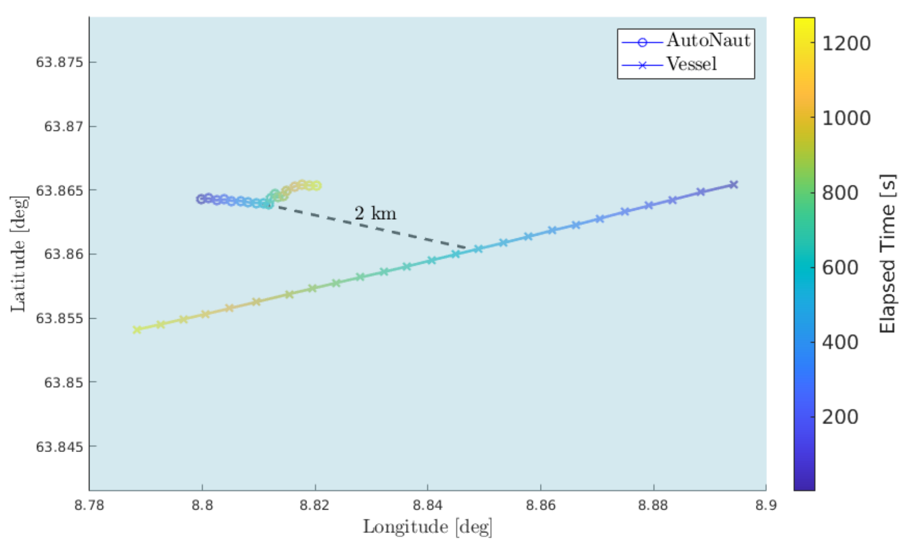

Figure 12. The track of the AutoNaut and the approaching vessel. The black dotted line shows the distance to the approaching vessel as the AutoNaut started its evasive maneuver.

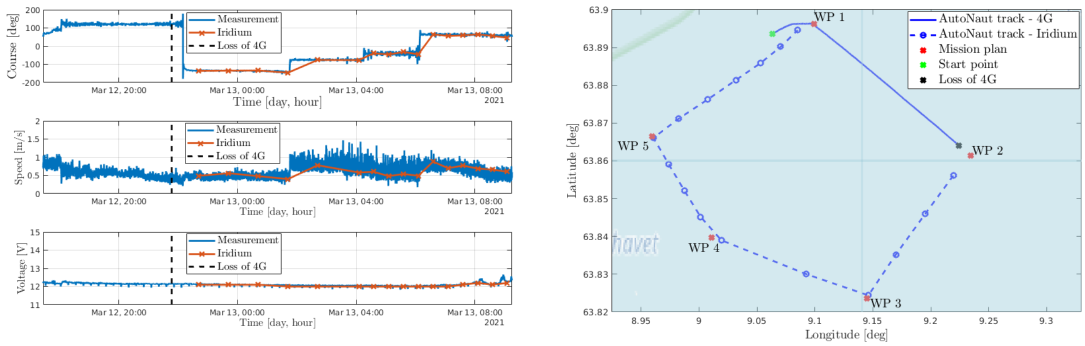

Figure 13. Information on position, wind, course, and battery level broadcast from the AutoNaut via Iridium satellite communication compared to the true measurements.

broadcast is significantly reduced. Figure 13 shows a situation in which the AutoNaut switches from using its primary communication link (4G/LTE) to its secondary one (Iridium). The AutoNaut broadcasts a report at a fixed interval set by the operators. This message contains the most crucial information regarding the status of the vehicle, such as position, battery voltage, speed-over-ground, course-over-ground, mode (e.g., if the vehicle is in standby or maneuvering) and information on what equipment is turned on. The time interval of the reports was initially set to 60 min, but it was decreased to 30 min by the operators once the vehicle lost 4G cellular connection. Figure 13 shows the speed-over-ground, course-over-ground and battery voltage as well as the ASV's track. The true measurements were retrieved from the local storage on the vehicle after the vehicle's retrieval, and, in Figure 13, they are compared to the values transmitted over the Iridium network in real time during the mission. As the figure shows, the vehicle's progress and status can easily be monitored despite the reduced bandwidth.

For more detailed information on the navigation performance of the vehicle, a separate navigation statistic message exists. This message is not sent regularly, but is transmitted by the vehicle when queried by the operator. The message contains information on course, desired course, wind speed and direction, and thruster and rudder usage. During difficult conditions, the message can be queried regularly to ensure the vehicle is navigating nominally, i.e., the course error is small. It is also helpful in ensuring that critical equipment, like the rudder, is functioning properly.

4.2.7. Case 7: capsizing and GNSS failure

19 days into the mission, the AutoNaut was subject to strong winds and large waves. The wind speed was measured to over 20 $\frac{m}{s}$ with gusts reaching 30 $\frac{m}{s}$ and directed towards the west, eventually turning southwest. The strong winds combined with high waves resulted in the AutoNaut capsizing. The AutoNaut is designed to withstand a capsize, and after approximately 10 min the AutoNaut self-corrected. During the capsize, all external antennas and sensors were completely submerged. This resulted in a complete loss of communication and navigation capabilities for the capsizing period. The weather station was not rated to withstand a full submerging and therefore it failed. However, the weather station is not considered critical to the mission and therefore no action was taken and the mission continued as planned.

Approximately 9 h after the capsizing, the AutoNaut once again capsized for another 10 min. This resulted in the GNSS receiver failing. The vehicle is equipped with a second GNSS receiver, however this receiver was in a closed circuit with the AIS and was not set up to provide measurements to the onboard navigation system. Without a GNSS receiver signal for navigation, the vehicle lost its navigation capabilities and started drifting according to the dominating winds and tidal currents. This is a critical failure, and safety procedures were initiated. The recovery team was alerted, but due to the harsh weather condition with waves up to 4 m and winds with gusts up to 30 $\frac{m}{s}$, a rescue operation was not possible without unacceptable risk to the team.

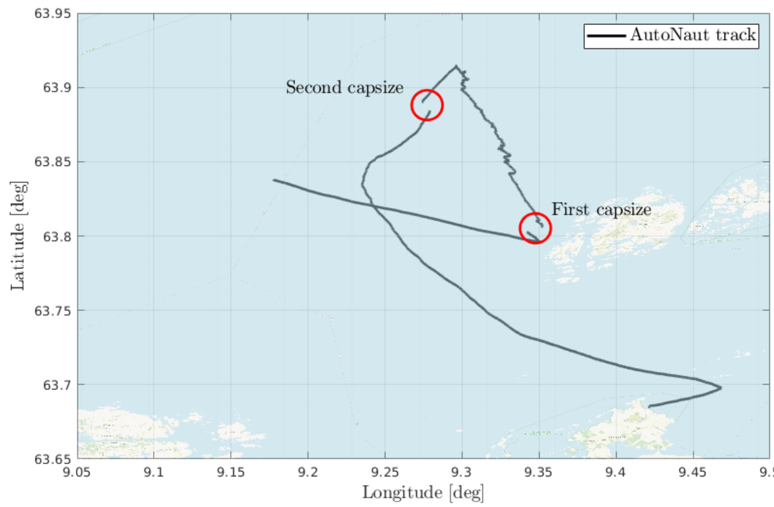

Figure 14. Tracking of the AutoNaut in the hours leading up to the capsizing and grounding. The red lines indicated the places where the AutoNaut was upside down.

After the second capsizing, the vehicle drifted approximately 24 km southeast, passing through a narrow strait between two islands into more shallow waters. Here, it took a turn towards west, most likely due to local variations in the tidal current, and grounded on a beach at the Storfosna island. The track of the vehicle in the time leading up to the first capsize and until it hit land can be seen in Figure 14. As the tides were going out, the vehicle was left on dry land where locals were contacted and they were able to recover it. The grounding had caused only minor damage: two of the submerged foils and a bracket holding the antennas to the mast broke. The hull was completely intact and only suffered small scratches. The GPS beacon was operational during these events and provided some situational awareness to the onshore operators.

5. Discussion

Figure 6 shows chl-a measurements corrected for NPQ from from March 13th to March 30th. During this period, the highest value measured was $0.635\,\mu g\,L^{-1}$. Furthermore, no increasing trend can be observed in the measurements. Due to the difficult conditions with the limited sun exposure, the vehicle had difficulties recharging the batteries during daytime. This led to power management being a key issue during the deployment. The scientific sensors were at times turned off to conserve power, leading to sparse measurements. However, a bloom will last for several days, and we can therefore argue that the amount of measurements we have are sufficient to say that a bloom did not start during the duration of the deployment as all measurements of chl-a are far below $5\,\mu g\,L^{-1}$. Some variation in chl-a can be seen, but this may simply be due to NPQ as the PAR can vary between 0 and $200\,\mu mol\,m^2\,s^{-1}$. Some of the more high-frequency variations may simply be due to measurement noise.

The dynamics of a bloom is highly dependent on some key environmental variables, such as available light and mixing of the surface layer of the ocean. With prolonged calm and sunny weather, the bloom will occur after 2–3 weeks. Stormy weather will deepen the mixing layer, resulting in less light available for phytoplankton. When phytoplankton has insufficient access to light, the bloom will not start (Assmy and Smetacek, 2009). Figure 15 shows the measurement of the absolute wind speed for the deployment. We can see an increase in the wind speed from March 19th and through the rest of the deployment. Blooms typically start in the period from March to early April in Norwegian coastal waters (Sakshaug and Myklestad, 1973). After the AutoNaut grounded, a period with less windy conditions followed. On April 20th, water samples taken close to the AO showed a chl-a

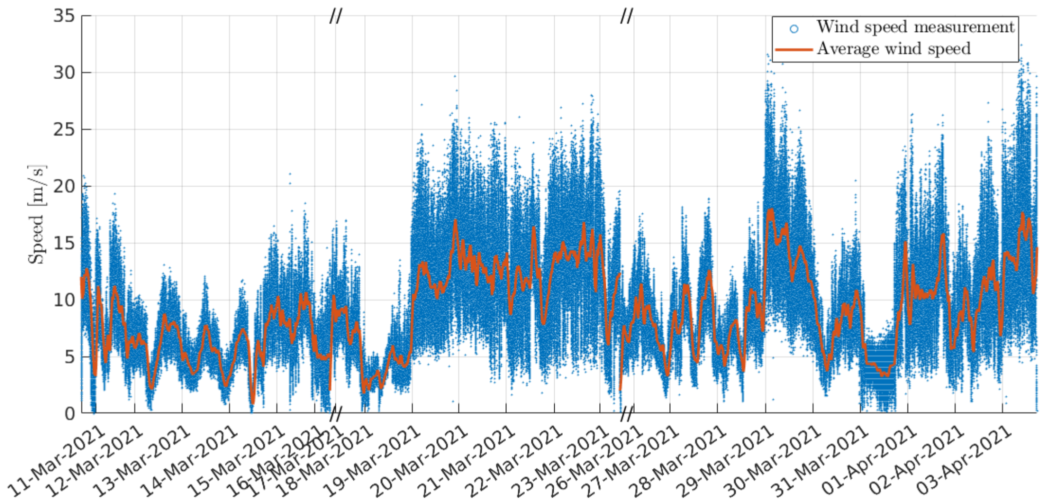

Figure 15. Measurements of the absolute wind speed for the entire deployment.

level of $2\,\mu g\,L^{-1}$, indicating that the bloom had started (Thu, 2022). The strong wind during the deployment likely postponed the bloom, and therefore it did not happen until after the AutoNaut grounded. Nevertheless, by providing *in situ* measurements of chl-a and wind speed, it was possible for the operators not only to follow the state of a bloom, but also to make assumptions of when a bloom would occur, without arranging manned missions.

Several other assets were participating in the mission together with the AutoNaut. Satellites and mathematical ocean models (SINMOD) were both used to give estimates of the chl-a values in the upper water column. Both satellites and mathematical ocean models can give insight into the dynamics of HABs as they provide data on a larger scale compared to, for example, data from manually gathered water samples or drones. In Figure 7 we can observe the spatial resolution of the chl-a measurements from the AutoNaut. A set of measurements on this scale could not easily be obtained with, for example, autonomous underwater vehicles. The data set in itself is valuable when validating both satellite images and mathematical ocean models, thus the data collected will be useful even though a bloom was not detected (Oudijk et al., 2022).

The combination of little solar exposure and strong winds made it difficult for the AutoNaut to operate autonomously over a long period of time. The lack of solar energy harvesting triggered in total two rescue mission so that the vehicle could be recharged on land. In addition, the vehicle was recharged when brought to land to replace the faulty Iridium antenna. The recharging on land caused gaps in the measurements and therefore in the *in situ* temporal coverage. Due to the vehicle's challenges in maintaining a sustainable power usage while deployed, the operators had to make the decision to partly turn off some scientific equipment [e.g., the oxygen optode and the conductivity, temperature, and depth (CTD) sensor]. Measurements of oxygen saturation, temperature, and turbidity can provide valuable insight into the dynamics of a HAB and help provide a better picture of when a bloom will occur. However, all phytoplankton contain chlorophyll-a, and the size of a bloom can therefore be assessed by measuring its fluorescence alone (Assmy and Smetacek, 2009).

The cases presented previously are evidence of the challenges associated with long-endurance autonomous surface vehicle missions. The main challenge for the field campaign described here was the harsh weather conditions that were an underlying factor in almost all these cases. Several technical weaknesses became apparent as a result of the weather conditions and revealed hidden problems previously not seen. Having a recovery team on standby proved to be essential in maintaining the integrity of the mission. In total, the vehicle was successfully recovered by the team three times: two times for charging and once for replacing the defect Iridium antenna. The weather conditions also proved to be a limiting factor for the recovery team as they were unable to go out during the situation that eventually led to the vehicle grounding.

Historically, a bloom occurs some time between March and the beginning of April in this area of the Norwegian coast (Sakshaug and Myklestad, 1973). The AutoNaut was intended to monitor the ocean for a bloom until the middle of April. This mission was unfortunately cut short when the AutoNaut grounded the night of April 5th. The grounding happened due to a failure of the GNSS receiver caused by capsizing. The capsizing was a result of the strong winds and high waves at the time. The risk of capsizing is at its highest when the vehicle heading is not aligned with the wave direction. The wave direction was unknown to the vehicle, and it ended up with waves hitting its side, causing it to capsize. The vehicle is designed to handle a capsize as it is fully enclosed. The wave excitation forces will will eventually self-correct the vehicle due to the shape of the hull and the distribution of mass within the hull. Most of the equipment on top of the AutoNaut is waterproof; however, the weather station was not rated to withstand a full submerging, and hence it failed. In the second capsize, the primary GNSS receiver used for navigation also failed. It is still not fully understood what caused this failure, as the GNSS is rated to withstand being submerged. The weather station was not protected by a fuse, and it is therefore believed that the failure in the weather station may have affected the GNSS receiver, since they are connected to the same power source and controlled by the same computer. After the recovery of the vehicle, the GNSS receiver was tested and shown to be fully functional without any repair necessary. Navigating in the conditions on the day of the capsize would be difficult; however, based on previous experience the vehicle would be able to maintain a degree of controllability by aligning the heading with the environmental forces. Without the failure of the GNSS receiver, a grounding could likely have been avoided.

The vehicle navigates by controlling the course using a PI-controller based on a set of waypoints. Several times strong winds and currents made navigation in certain directions difficult, and sometimes impossible. This required an operator to reassign waypoints in order to make progress on the mission. Because of such challenges, the vehicle was not able to sample chl-a over the entire AO at all times, as seen in Figure 7. Due to the wave propulsion mechanism, the dynamics of the vehicle is strongly dependent on the ocean environment as the speed will vary with the waves. Strong environmental forces can make the nonlinearities in the vehicle dynamics stronger. The linear PI-controller may no longer be sufficient when the speed-over-ground is very small such that a more sophisticated course-controller may be necessary. We have identified that as an area for future research.

Several times during the deployment, the AutoNaut experienced loss in the 4G cellular connection. The Iridium satellite connection proved to provide sufficient information to monitor the status of the vehicle. However, several times the onshore operators were required to manage the missions due to the harsh weather and the possibility of infeasible paths when the wind and currents increased in strength, as described in Case 1 in Section 4.2. The AutoNaut supports changing waypoints using satellite communication, but navigation plans made of multiple waypoints are required to already be stored locally on the vehicle. Hence, new missions consisting of a single go-to command can be uploaded to the vehicle via satellite, but more complex missions require a 4G connection to be started or modified. This means that whenever the AutoNaut is using satellite communication as its primary communication channel, the onshore operators have limited ability to alter missions. Further research should be put into mission planning for the AutoNaut. A mission planner aware of the environmental conditions and forecasts may make plans that prevent unfeasible paths and thereby make the AutoNaut capable of preventing unfeasible paths by itself.

6. Conclusion

In this article, we have presented the results and experiences from a 19-day-long deployment of the ASV AutoNaut in Frohavet. The main objective was to measure the value of chlorophyll-a in the area of operation in order to detect an algae bloom. To do this, the vehicle had to survive for a long period of time in harsh conditions. A bloom was not detected during the deployment. The vehicle measured a maximum chlorophyll-a level of $0.635\,\mu g\,L^{-1}$, which is far below what is expected when a bloom is growing in the area. Stormy weather is known to postpone the bloom by deepening the mixing layer. During the deployment, there were periods when the winds reached speeds as high as $30\,\frac{m}{s}$. Not only did the winds postpone the bloom, they also made the operational aspect of the mission far more complicated. Several faults and weaknesses in the system became apparent as a result of the harsh weather conditions, such as the lack of fuses on all external equipment. This resulted in a critical failure when the AutoNaut capsized and eventually grounded. The harsh weather conditions were a major contributing factor to the challenges experienced during the mission. The winds and currents made navigation challenging, and cloudy weather made the solar panels ineffective, thus the vehicle ran out of electrical power. The mission ended abruptly when a technical failure resulted in the vehicle grounding. However, the damage to the vehicle was minimal. The experiences gained during the mission have highlighted several areas in which further research is necessary to improve the autonomy of the vehicle.

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