Seafloor Cable Based Navigation and Monitoring with Autonomous Underwater Vehicles

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***Abstract*—This study focuses on infrastructure monitoring relevant to offshore power cable inspection. Here we explore the use of an Autonomous Underwater Vehicle (AUV) carrying a small magnetometer to localize and map underwater power cables. By surveying cables with the goal of cable localization, we can circumvent the difficulties associated with AUV based cable-following routines and provide a robust approach to cable localization and characterization that can inform subsequent along-cable navigation, ensuring survey reliability for commercial stakeholders.**

***Index Terms*—REMUS, AUV, WHOI, OFG, Subsea Cables, offshore power cables, Cable Tracking, Cable Monitoring, Magnetometer, Wind Energy**

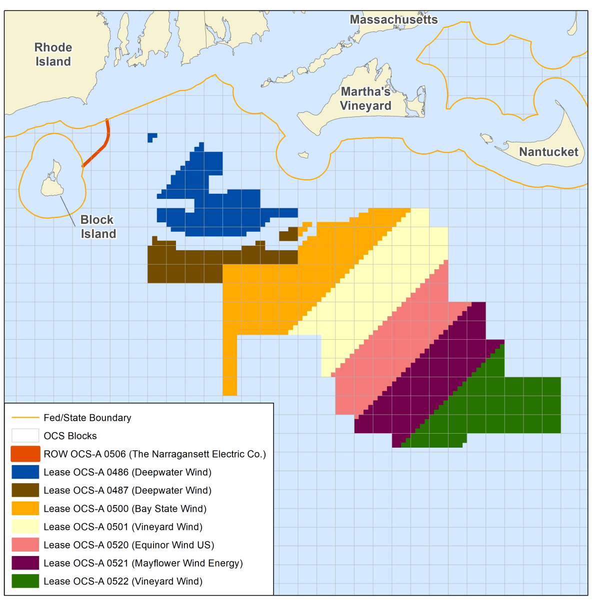

Fig. 1. Map of offshore wind project lease areas south of Martha's Vineyard, www.boem.gov

I. Introduction

This work is inspired by the growing offshore wind energy sector and the associated infrastructure monitoring that will be required as local turbine fields are installed. In 2018, offshore wind companies bid a collective 405.1 million dollars for the rights to develop turbine fields south of Martha's Vineyard [10]. As the industry grows in New England [Fig. 1] there will be an increase in installation of offshore turbines and new opportunities and challenges in monitoring the associated infrastructure. Underwater power transmission cables are used to transfer power to shore and, in the process, produce a strong electromagnetic signature that can be used to localize the cable position even when buried or trenched into the seafloor. By surveying a known cable corridor with a series of perpendicular transects, the local maximum values of the magnetic signature of the cable can be used as a proxy to identify theses cable locations. Based on these local maximums, a series of waypoints can be generated to create a map of the cable routes. This information can inform managers of cable migration while also providing a basis for follow-up missions to map the full cable in a continuous route running parallel to the cable path. AUVs can offer precise navigation and control making them well suited for accurately localizing targets on the seafloor. In this study, a REMUS 600 AUV was equipped with a suit of sensors to detect and image seafloor cables. The power transmission cables between Martha's Vineyard and Falmouth, Massachusetts were selected as a test site due to the accessibility by boat and proximity to the Woods Hole Oceanographic Institution (WHOI). The cables provide power and communication to the island but are vulnerable to failure. Multiple failures have occurred to the existing cables [8] emphasizing the need for a rapid means of cable survey to detect issues that can disrupt power delivery. As offshore windfarms expand it will be critical that the complex networks of inter-turbine cables and power export cables are monitored to ensure reliability and the cost-effective operation of the wind farms. Similarly, the islands and other areas where power is transmitted by seafloor cable can benefit from reliable, cost-effective monitoring.

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II. Cable Inspection and Monitoring

Cable surveys are often conducted from manned surface vessels using towed systems, Remotely Operated Vehicles (ROVs) and divers. Sidescan, cameras and magnetometers can all be deployed as towed systems but cannot always be deployed at the same time in these configurations, necessitating multiple passes over the same area to collect a full data set. Additionally, the navigation and positional accuracy of towed systems can be compromised as current, boat speed and boat motion all contribute to the location uncertainty of a towed system. In recent surveys conducted by a project team for Comcast and Eversource, the most recently installed hybrid power transmission cable to Martha's Vineyard was evaluated with towed systems and an ROV to image the proposed cable route and post-installation of the cable [8]. Bathymetry, Sidescan sonar, sub-bottom profiling and video imagery were collected to document the cable route and demonstrate impact mitigation to "Special, Sensitive, or Unique" (SSU) resources. Local SSUs considered in the Martha's Vineyard power cable installation included intertidal flats, eelgrass, hard and Complex Bottom, N. Atlantic Right Whale, Fin Whale and Humpback Whale core habitat and required efforts such as horizontal drilling and cable burial to minimize the impact to the marine environment. The ecological impacts from electromagnetic fields on marine life are still poorly understood [5] but are of concern to coastal managers and stakeholders necessitating data collection and evaluation impacts. Magnetometers can be used to detect induced magnetic fields that are emitted into the marine environment by power transmission cables. This method presents an advantage over sidescan and camera imaging when a cable is trenched into the sea floor or buried by sediment. In this study the magnetic signal were generated by Alternating Current (AC) power transmission in buried and exposed seafloor cables. The current passing through the cables generates an AC magnetic field with a frequency of 60 Hertz (Hz), which creates a magnetic flux density dependent on current load [9]. The measured magnetic field of such a cable is proportional to distance from the sensor to the source and thus strongest when the distance between the source and sensor reaches a minimum. By evaluating the strength of the magnetic field the cable proximity can be estimated, but variations in field strength due to burial depth or other conditions can present challenges to along-track localization. Therefore, we chose to run transects across the cable path such that maximum values of the induced magnetic field would unambiguously correspond to the intersection of the vehicle path with the cable.

Prior to automated classification algorithms enabling adaptive behaviors, AUVs have been used to inspect seafloor cable routes before installation using sidescan sonars [7]. In some cases, AUVs have even been employed to lay cable themselves [3]. Related work in pipeline following by AUVs has also utilized sidescan sonars since pipelines are typically laid above the seafloor and are not subject to burial [1]. Cable following behaviors have been demonstrated on AUVs using optical feedback over limited ranges [2] but these systems are not effective if infrastructure is covered by sediment. Multiple magnetometers have been used on a single AUV for the purpose of following cables axially [11]. Because seafloor cables are often buried, intentionally or through the movement of sediment, detecting the cable's magnetic field is the most practical sensing modality for reliable cable detection and for developing adaptive behaviors based on cable location.

Fig. 2. REMUS 600 test vehicle and support vessles

III. Survey

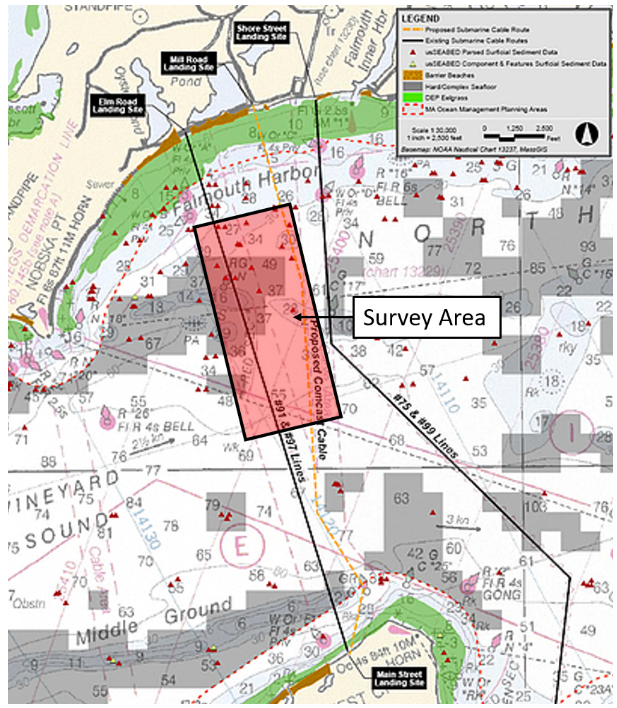

Fig. 3. Map of Martha's Vineyard power transmission cables [8] with overlay of REMUS 600 survey area

Here we demonstrate that a series of transects across a known cable corridor with an AUV can provide valuable data about the cable and the surrounding benthic environment while also generating a series of way-points for cable localization based on the signal maximum detected by a magnetometer. This method of survey can be used to monitor submarine export cable routes, inter-array cables, and the condition of subsea infrastructure as well as the environmental impact of cable installations. The up-front cost and operational overhead of large AUVs are often a barrier for many entities looking to perform survey work. As such, a small magnetometer was selected to enable future work from smaller, lower-cost AUVs. An Ocean Floor Geophysics (OFG) Self-Compensating Magnetometer (SCM) was installed on a REMUS 600 AUV for this study. The SCM is a commercially available system that internally compensates for the attitude of the AUV within the earth's field as well as the effects related to the strength of the electric currents associated with the vehicle propulsion and other vehicle electronics [6]. The use of a REMUS 600 allowed for additional sensors [Fig. 2] to validate the measurements of the smaller SCM. An Edgetech 2205 dual frequency sidescan sonar operating at 230 kHz and 900 kHz and an integrated Edgetech Sub Bottom profiler 424 was used to image below the sea floor. A multi-element gradiometer was used to collect additional high-resolution magnetics data. This data was compared to that of the SCM to further validate the commercially available single-element sensor and characterize the magnetic signature of the power transmission cables. Data was acquired on July 16th and 18th of 2019.

The cable corridor between Martha's Vineyard and Falmouth Massachusetts [Fig. 3] was selected as a test site due to its proximity to the Woods Hole Oceanographic Institution. The AUV was programmed to followed 500m long track lines perpendicular to the cable corridor, with a between-track distance of 100m [Fig. 4]. Transects of the known cable corridor were used to map two parallel offshore power cables. Cables 91 and 97 both lay in the cable corridor as well as portions of the now abandoned 100 cable. Cable 91 was installed in 1986. It has failed 6 times, but repairs have kept it operational. Cable 97 was installed in 1990 and remains operational. Both cables have a 13 MVA capacity rated at 25 kV and continue to provide power to the Vineyard. Cable 100 has been abandoned and no longer provides power to the vineyard but remains on the sea floor [4].

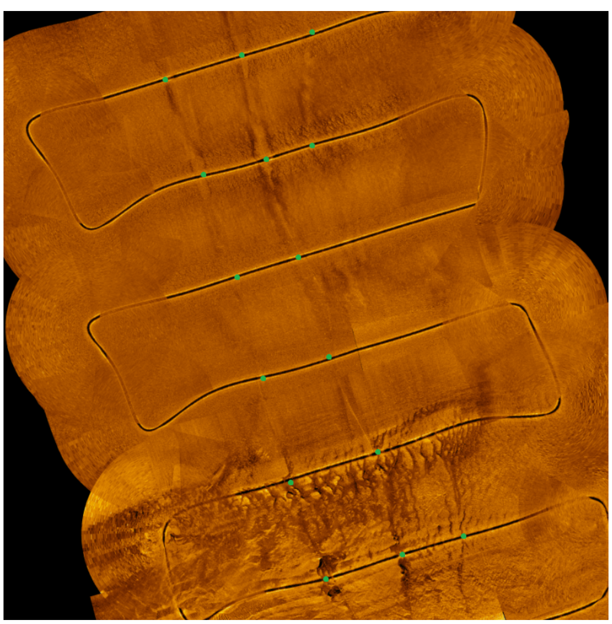

Fig. 4. 230 kHz sidescan mosaic - green dots indicate visible intersections of the cable routs and AUV path of travel

IV. Data Processing and Visualization

The data sets generated by this survey work was analyzed and imported in ArcGIS to generate a geospatial representation of the information that was collected. This allowed for data comparison in the form of overlays and allowed the research team to identify and compare cable route detection between sensors. Multiple data types were obtained including sidescan sonar imagery, bathymetric data, sub-bottom imagery and magnetic intensity data. ArcGIS Pro 2.4.1 and spatial analyst extension (ESRI) software was used to create information overlays and facilitate the rasterization of point data. Along-track bathymetric depth was obtained using the vehicle depth and altitude of the vehicle above the seafloor. Subsequently, a natural neighbor interpolation produced an approximate, continuous bathymetric map. Sidescan sonar imagery was processed and mosaiced using SonarWiz 6 (Chesapeake Technology) and used as a base map in the ArcGIS software where it served to ground-truth and provide a visual representation of the true location of the cable features. The features cannot be continuously detected in these images as the cables are buried beneath sediment in some locations, but even where the cable itself is not visible, the disruption of sediment associated with the cable routes reveal the approximate cable location. The total magnetic intensity acquired by the SCM is automatically corrected by reducing vehicle noise and accounting for the earth's magnetic field. These data points collected by the SCM where turned into a 5m grid by averaging out the points at that location. Each of these data sets were compared in geo-referenced space to provide a visual representation of cable route and surrounding area. To further improve signal detection, The SCM data was clipped to eliminate vehicle turns and processed to evaluate each track-line independently.

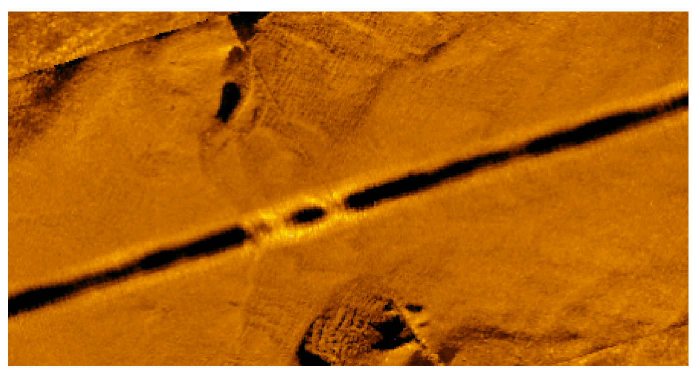

Fig. 5. 900kHz sidescan imagery of a cable transect

V. Results

Visual correlations of the cable location were drawn between sidescan[Fig. 4][Fig. 5], sub-bottom, gradiometer and SCM data. Each high-power sensor was able to collect data that indicate the cable location. This information was then used to validate the detections seen in the SCM data. While the SCM data exhibited noise occurring in the transitions from one transect to the next, we were able to clip the data to

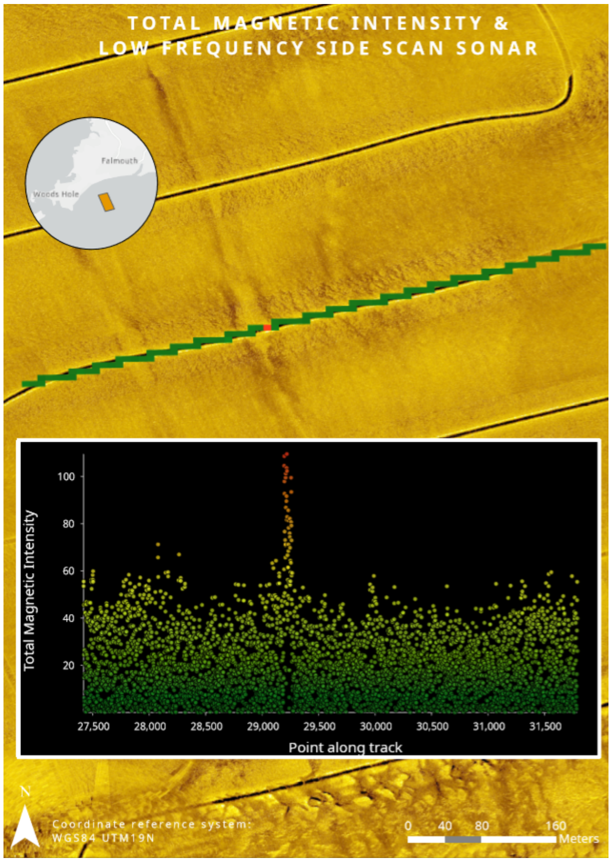

Fig. 6. SCM detection of a power transmission cable - Sidescan mosaic with SCM color chart overlay and SCM along-track signal anomaly measured in nanoTeslas

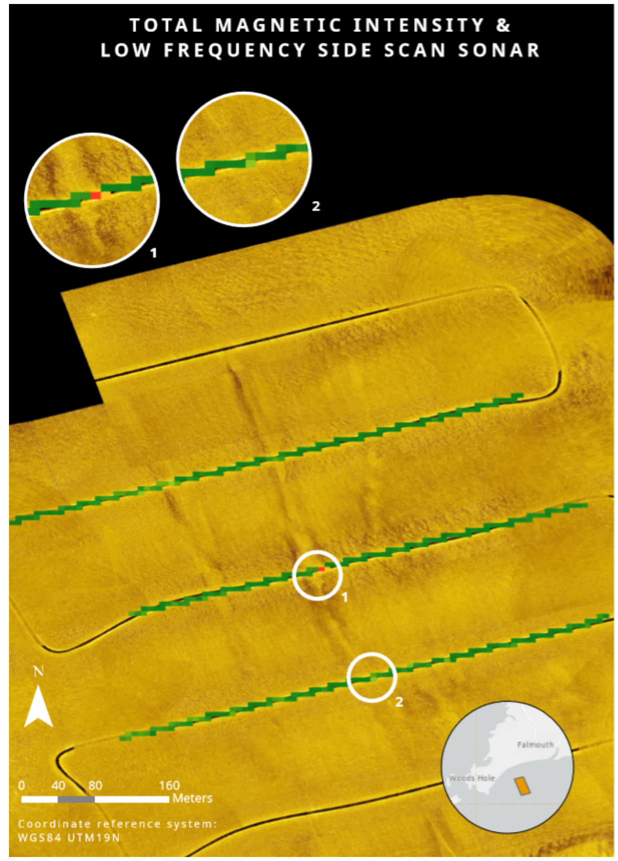

Fig. 7. Self Compensating magnetometer data from REUMS 600 survey of seafloor power tranmission cables

see the cable signature within the individual transects[Fig. 6]. This method provided a reference for cable location within 5 meters of the cable as imaged by the side sonar. In this study, deviations from the mean along-track field value were used to detect the presence of an anomaly for each track line. We were able to correlate multiple detections in the SCM data with cable locations seen in the mosaiced sidescan data. Figure 7 shows SCM data overlaid onto a low frequency sidescan sonar mosaic of the survey area.

VI. Discussion

Future work will seek to replicate similar data sets with a smaller low cost AUV carrying a single magnetometer and other sensors such as sidescan sonar and imaging cameras to detect and document cable routes [Fig. 7]. As in these missions, a series of transects will be conducted to localize the cable. These waypoints will then be used to plan subsequent missions that will follow the cable route based on the point-to-point locations identified from magnetometer data acquired from the preceding transects. In this manner a cable route could be surveyed with full coverage using additional sensors such as sidescan and cameras. It is expected that improved filtering of SCM data will yield higher signal to noise ratios and further increase the reliability of cable detection. We would like to refine the filtering process and explore capabilities in automatic detection. It is our goal to work towards a low-cost system that can be used by industry to monitor sea floor cable infrastructure and relevant environmental conditions of the surrounding benthic environment as improved monitoring can increase awareness of the condition of sub-sea infrastructure and ultimately reduce costs for industry.

Acknowledgment

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