Acoustic Communication and Navigation in the New Arctic - A Model Case for Environmental Adaptation

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***Abstract*—The particular sensitivity of the Arctic to climate change is well established, and the significance to undersea operations can be dramatic. As part of the recent ICEX16 US Navy Exercise in the Beaufort Sea, MIT deployed an autonomous underwater vehicle with a towed hydrophone array below the ice cover for assessing the climate induced changes to the undersea ambient noise environment. The safe underwater operation depended on navigation updates from the submarine tracking range being communicated to the vehicle for fusion with the onboard inertial navigation.**

However, the changes in the environment severely deteriorated the tracking performance compared to previous deployments. The reason was clearly associated with a previously observed neutrally bouyant layer of warm Pacific water persistently spreading throughout the Beaufort Sea, which severely alters the acoustic environment with dramatic effects for both long and short range acoustic sensing, communication and navigation. This paper describes the effects observed and discusses how robust acoustic connectivity in this environment makes it paramount that the manned or unmanned undersea platforms are capable of adapting to the environment for sensing, communication and navigation.

I. Introduction

Under funding from ONR, the MIT Laboratory for Autonomous Marine Sensing Systems (LAMSS), GobySoft, and Bluefin Robotics participated in the ICEX16 ice camp exercise in the Beaufort Sea in March 2016. This experiment had the technical objectives of demonstrating the deployment, operation, and recovery of an autonomous underwater vehicle (AUV) with a towed array under the extreme under-ice Arctic conditions and the scientific objective of characterizing the climate induced changes in the acoustic environment. Figure 1 shows a snapshot of a video recorded by an underwater camera on the MIT Macrura BF21 AUV during a towed array survey below Ice Camp sargo during ICEX16. Even though the analysis of the data collected during the exercise are still preliminary, the results and the experiences gained during the experiment clearly demonstrated the implications to under-ice operations of both manned and unmanned undersea platforms, and identified critical research needed for achieving a robust and safe undersea operational environment for naval and civilian assets.

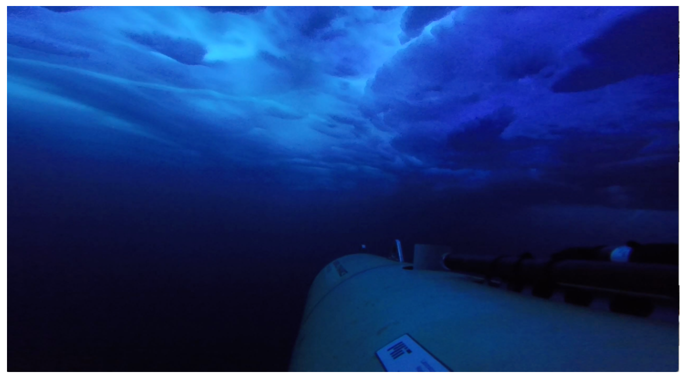

Fig. 1. AUV Macrura during under-ice survey mission at 20 m depth below Camp Sargo during ICEX16.

II. The New Arctic

As was clear from the ICEX16 effort, a particularly critical phenomenon of the new Arctic acoustic environment is the so-called Beaufort Lens, a layer of warm pacific water entering the Arctic through the Bering Strait. This layer is neutrally buoyant at a depth of 70-80 meters in the Beaufort Sea, creating a local maximum in the sound speed profile (SVP) at this depth, as shown in Fig. 2. This warm water severely disrupts the historical, monotonically increasing sound speed with depth, which has been the dominant controlling feature of the Arctic acoustic environment. The phenomenon was observed by Woods Hole Oceanographic Institution in 2013 through the Ice-Tethered Profiler program [1]; its persistent existence has been confirmed each of the following years, and through direct measurements during ICEX16. The effect is spreading geographically and now reaches as far as 300 nm North of Prudhoe Bay, Alaska. An analysis of the long-range acoustic propagation effects has been performed by MIT LAMSS [2], and the results played a major role in shaping

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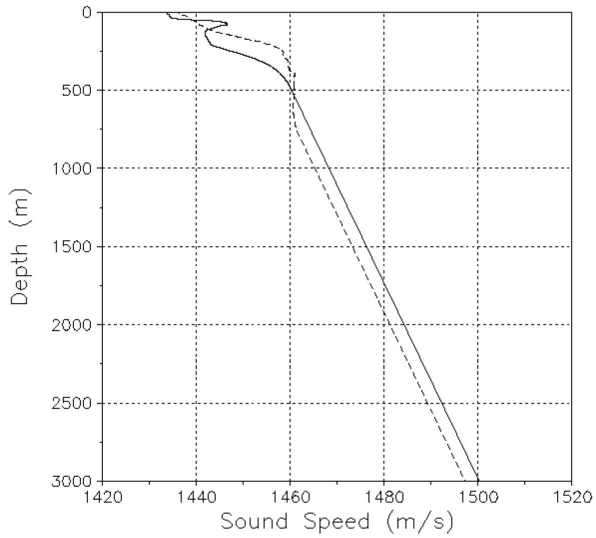

Fig. 2. Sound speed profiles for ICEX16 (solid line), and historical (dashed line). The introduction of the 'Beaufort Lens' at 80 m depth creates a distinct double duct, with the lower duct trapping sound above 350 Hz.

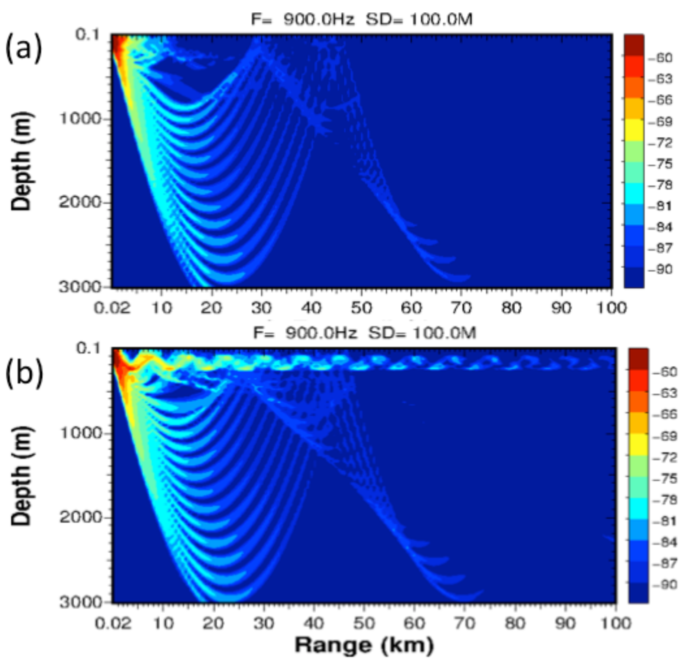

Fig. 3. Propagation effect of Beaufort Lens. Contours of transmission loss in dB for a 900 Hz source at 100 m depth (a) the historical Arctic sound speed profile (dashed line in Fig. 2). (b) Sound speed profile measured in ICEX16 (solid line in Fig. 2

some of the acoustic propagation experiments carried out by the Navy Assets participating in ICEX16. Thus, the analysis showed that the lower sound channel effectively traps sound above 350 Hz, as shown in Fig. 3, with obvious implications to undersea acoustic sensing and communication.

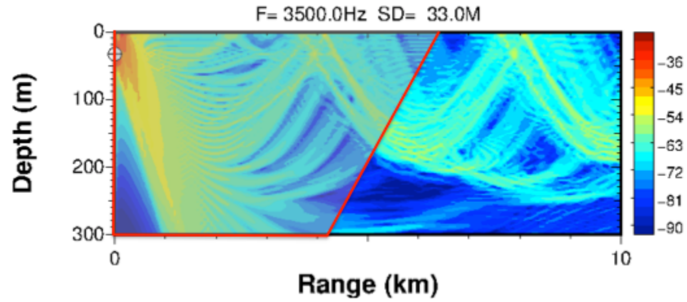

Fig. 4. Transmission loss vs depth and range for a source or receiver at 33 m depth for historical SVP. The shaded area indicates the depth-range domain for which a direct, reliable acoustic path exists without interacting with the rough ice cover.

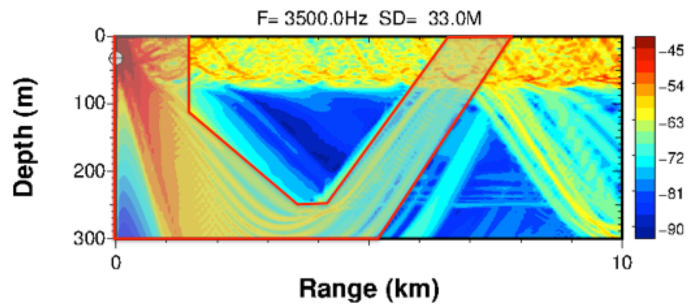

Fig. 5. Transmission loss vs depth and range for a source or receiver at 33 m depth, for ICEX16 SVP. The shaded area indicates the depth-range domain for which a direct, reliable acoustic path exists without interacting with the rough ice cover.

III. ICEX16 Navigation and Communication

Although the effect of the Beaufort Lens was expected to significantly affect long range acoustic propagation, as became apparent in ICEX16, the effect is equally dramatic for short range acoustic communication and navigation systems. Thus, while the historical environment is characterized by a smoothly varying sound intensity versus depth and range from the source, the double-duct SVP creates a dramatic variation in the acoustic channel, with severe implications to the performance of underwater acoustic navigation and communication systems, even at relatively short range. Thus, during ICEX16 the operators of the underwater tracking range observed significant deterioration in the tracking performance compared to historical evidence from before 2014, with highly sporadic and uncertain tracking for shallow sources beyond 1-2 km range. This is in contrast to historical performance where this deterioration was not seen until 6-7 km ranges. [3]. The tracking range provided even more limited range for targets below 80 m depth. A brief improvement in tracking at range 6-7 km was also observed in ICEX14 and 16.

Figures 4 and 5 show the results of a modeling effort using OASES carried out during ICEX16, providing clear theoretical support for this observed behavior. Thus, as shown in Fig. 4, for the historical SVP a reliable acoustic path (RAP) exists in a contiguous range-depth box reaching out to 6-7 km, consistent with the historical observations. In contrast, for the

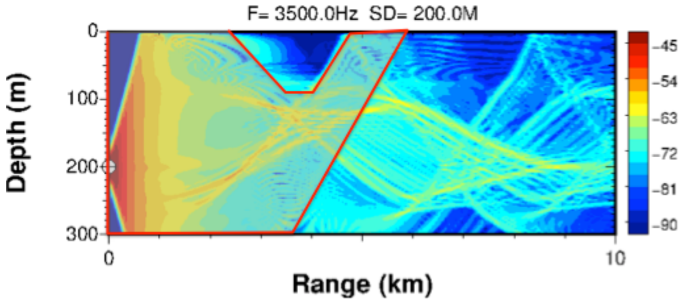

Fig. 6. Transmission loss vs depth and range for a source or receiver at 200 m depth, for ICEX16 SVP. The shaded area indicates the depth-range domain for which a direct, reliable acoustic path exists without interacting with the rough ice cover.

ICEX16 SVP, the double-duct creates a dramatic shadow-zone below the lens at ranges between 2 and 6 km, consistent with the observations. The transmission loss remains low in the surface duct, but here the field is entirely consisting of surface interacting paths, where the rough ice scattering is severely degenerating the signal coherence, resulting in deteriorating navigation and communication performance.

In addition to affecting the signal propagation, the double duct also is expected to affect the spatial composition of the ambient noise, in particular the contribution from distant sources. As part of the ICEX16 effort, MIT LAMSS collected an extensive dataset, deploying the Macrura AUV in a stationary, tethered configuration with the towed array ballasted for creating a vertical aperture. This data is being analyzed, with the objective of creating reliable ambient noise models for the New Arctic.

While it is clear from Figs. 4 and 5 that in the ICEX16 environment the tracking range receiver depth of 33 m is not optimal, generating deep shadow zones and incoherence in the lower and upper duct, respectively. An alternative would be to lower the receivers deeper. Fig. 6 shows the RAP corridors for a receiver depth of 200 m, and it is clear that although eliminating the coherence loss due to ice interaction, a significant shadow zone still exists for shallow targets beyond 3 km range. In fact it turns out that even deploying both shallow and deep receivers does not eliminate the lack of ranging capability at ranges between 3 and 5 km. Thus, to maintain connectivity, it is paramount that the target is capable of changing depth when needed to be tracked or communicated with. Such depth adaptation is described in the next section.

IV. Depth Adaptation with MOOS-IvP

All autonomous underwater vehicles and surface craft operated by MIT-LAMSS are equipped with a common MOOS-IvP Payload Autonomy architecture, with fully integrated sensing, modeling and control [4]. This autonomy-centric Nested Autonomy control paradigm significantly reduces the inter-platform communication requirement to be consistent with the low bandwidth/high latency reality of shallow water acoustic communication.

In addition to the MOOS-IvP autonomy framework, a key component of the nested autonomy paradigm is a unified command and control infrastructure for heterogeneous networks of autonomous underwater vehicles and and surface craft [5], supplemented by autonomous behaviors allowing underwater vehicles to autonomously and dynamically re-configure for optimal acoustic sensing, communication and navigation [6], [7].

Thus, the Macrura AUV used in ICEX16 is directly able to support environmental adaptation using onboard, embedded acoustic modeling in combination with a highly efficient IvP multi-objective optimization algorithm for determining an optimal depth path that allows continuous robust navigation and communication. Also, the MOOS-IvP software infrastructure for autonomously switching between different mission modes enables a platform to choose a path that is optimal for its sensing objectives most of the time, and only seeks a depth that is optimal to communication when needed. An example of such a path is given by Fig. 7.

The navigation adaptation, in particular, is complicated by the fact that the distances to the tracking hydrophones or long base-line (LBL) beacons are different, but here the multi-objective optimization at the core of MOOS-IvP is inherently capable of producing an optimal compromise ensuring robust navigation. In addition to the environmental adaptation, a critical component is the development by LAMSS of a compact communication strategy, which allows the assets to negotiate this re-configuration, without swamping the communication capacity of the network [8].

It is well established that low transmission loss is not a guarantee of robust communication performance. Thus, the multipath channel in the surface duct in Fig. 5 is associated with coherence loss which is not captured by legacy propagation models. Thus, it is crucial to the robustness of the depth adaptation that the embedded channel model accurately represents the loss of multipath coherence, and such models are currently under development, combining legacy propagation models such as Bellhop and Kraken with ice and sea surface scattering models developed at under the ONR Arctic Acoustics Program a couple of decades ago [9], to arrive at a modeling framework that robustly predicts the coherence of the multipath channel response.

V. Conclusion

As part of the recent ICEX16 US Navy Exercise in the Beaufort Sea, MIT deployed an autonomous underwater vehicle with a towed hydrophone array below the ice cover for assessing the climate induced changes to the undersea ambient noise environment. The safe operation was hampered by a significant deterioration in the performance of the acoustic tracking range compared to past deployments. The reason is a neutrally bouyant layer of warm Pacific water persistently spreading throughout the Beaufort Sea, and which severely affects both long and short range acoustic sensing, communication and navigation by introducing a strong double duct environment. In this environment, the propagation from a

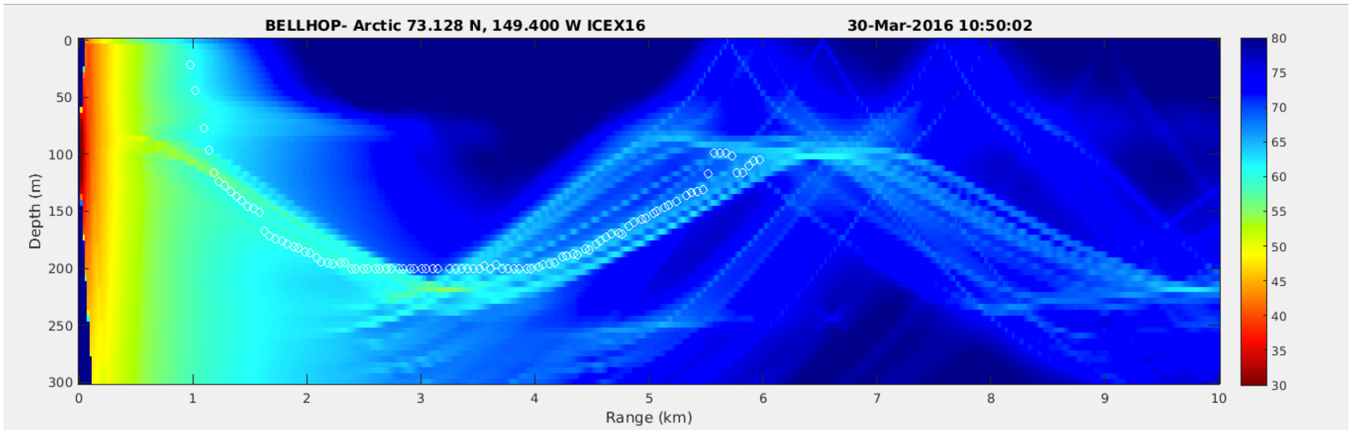

Fig. 7. Demonstration of model-based environmental adaptation of an AUV running MOOS-IvP with the behavior BHV_OptAcoustDepth, using the MIT Virtual Ocean simulator. The behavior forecasts the signal propagation to and from the base modem two minutes into the future and chooses a depth that maintains optimal connectivity. The white circles indicate the path of the AUV as it opens up range with the base modem. Note that the configuration has a maximum depth behavior, keeping the vehicle above 200 m depth.

near-surface source results in significant coherence loss in the upper duct beyond 1-1.5 km range due to interaction with the ice cover, while creating a deep shadow zone in the lower duct. Similarly, a source in the lower duct will have severe shadow zones in the upper duct. Thus, there is no fixed source/receiver configuration that provides contiguous connectivity in this new Arctic reality. The only viable option for maintaining connectivity between an autonomous underwater asset and the operators of a tracking range is to enable the platform to adapt to the environmental situation and the current source/receiver configuration by changing depth when connectivity is required, based on onboard acoustic modeling and forecasting. As demonstrated in this paper, the MOOS-IvP autonomy architecture with its multi-objective optimization kernel is ideally suited for such model-based adaptation.

Acknowledgment

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