Ocean Space Surveillance - Network Beployment Based on Hydrodynamic Modeling

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***Abstract*—The use of hydrodynamic modeling to optimize the placement of sensor nodes with respect to reduction of uncertainty in sea current modeling is demonstrated. This is done under the additional constraint that the nodes should constitute a connected underwater acoustic communication network. For the connectivity analysis a sound propagation model is employed, based on detailed sound speed data produced by the hydrodynamic model. It is found that such a detailed sound speed field is very attractive for obtaining sufficient precision in acoustic modeling. This is particularly important in regions of significant variability in bathymetry and sea currents. In such regions it would be very demanding to obtain sufficiently detailed data by physical measurement, and the use of a hydrodynamic model is virtually the only alternative. In general the model based approach is important for up-scaling the geographical extent of a network, and has a large impact on the economy of its deployment and operation.**

Keywords— hydrodynamic modeling; underwater acoustic network; network deployment; ray tracing;

I. INTRODUCTION

Under the constraint of limited number of nodes in a sensor network it is of high importance to optimize the placement of the nodes. Underwater acoustic sensor networks typically need to obey such limitations, due to high costs of sensors, communication modems and of deployment and maintenance operations. To optimize with respect to the measurement task, knowledge about the process is needed. To optimize with respect to communication, knowledge about sound propagation conditions is needed. The present paper aims to demonstrate the use of hydrodynamic modeling to guide deployment based on both of these criteria together. This is carried out by a simple case study. Though the availability of hydrodynamic model tools is quite widespread, this opportunity seems to have been exploited quite scarcely in the literature, in particular for the joint measurement and communication design.

Our work contributes to the development of an ocean space surveillance concept [1], i.e., to combine underwater sensor networks and ocean modeling in order to obtain improved surveillance capabilities with respect to both real-time situation awareness and model based predictions and assessments. The system architecture is composed of an underwater sensor network, communication links to computers running ocean models, and the ocean models themselves. The latter assimilate measured data from the sensor network in a manner similar to what is done in meteorology.

The measurements that we want to optimize are those that will be used for data assimilation: Time series of current velocity vertical profiles, obtained by upwards-looking profiling sensors close to the sea floor, at geographically fixed locations. In regions of variable bathymetry and external currents, especially coastal region, the process (the current) is very far from uniform in space and time.

In our realization of the concept, and in many related scenarios, cost issues lead to strict limitations in the number of underwater nodes. An optimal deployment is therefore essential to obtaining a sufficient system performance.

There is a considerable body of publications on sensor array design for meteorology and metocean purposes. Our work is based on [2], with extensions according to [3]. Good further references can be found in [2].

Sound propagation is mainly governed by the spatial variability of the speed of sound, together with boundary conditions at the sea surface and bottom. Sound speed variability causes sound rays to curve in space, which may enhance or preclude propagation. In our case, sound propagation translates to connectivity between sensor nodes. Many references consider modelling of propagation based on the assumption that the sound speed field is known [4][5]. This is, however, often only approximately true, and the resulting lack of precision can produce unfortunate deployments if the number of nodes must be limited, with lack of connectivity as a result. Solving the sound speed data issue by using hydrodynamic models seems scarcely studied, in particular in connection with network technology. A few references investigate general sound speed variability prediction from hydrodynamic models [6][7], in [7] including acoustic ray tracing as a means to evaluate the modeling output. Reference [8] combines local hydrodynamic modeling and a parabolic equation model for sound propagation. Reference [9] is an example of the inverse problem: Assimilating tomographic sound propagation measurements in hydrodynamic models. Hardly any references seem to use hydrodynamic models in the context of network connectivity. This is not fundamentally different from the above examples, but the focus largely determines how the hydrodynamics results are exploited. In [10] we consider this topic, but do not include the issue of where to place nodes for optimal benefit of the sensor measurements.

Joint deployment design of sea current sensors and communication network is investigated in [11], but only local

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sea current dynamics and a uniform bathymetry are considered. In the present paper a full scale hydrodynamic model is introduced, in combination with detailed bathymetry information. The subsequent sound propagation analysis is considerably influenced by these inputs.

The paper is organized as follows: Section II describes our deployment-design strategy, including hydrodynamic modelling, optimization of node localization and sound propagation modelling. Section III presents our case-study and section IV the corresponding simulation results. Finally Section V gives a summary and conclusions from our work.

II. DEPLOYMENT-DESIGN STRATEGY

Our strategy is entirely model based: First the hydrodynamic model is used to (i) identify sensor node locations and (ii) provide detailed spatial and temporal sound speed fields. The latter are then input to an acoustic propagation model that evaluates connectivity of the underwater acoustic communication network. If necessary, node locations are slightly modified to ensure connectivity. If larger position-modifications are necessary, relay nodes are added (it is then an issue of incremental benefit and cost whether or not to include sensors also at such locations).

A. Hydrodynamic modeling

Our hydrodynamic model (SINMOD) is based on the primitive Navier-Stokes equations and is established on a z-grid [12]. Each model level has a fixed thickness except for the surface levels and the one close to the bottom. Turbulent vertical mixing is calculated as a function of the Richardsons number and horizontal mixing is calculated according to [13]. The model uses a nesting technique to allow high resolutions in targeted areas. Usually a basin scale model setup having coarse horizontal grid resolution (~20 km) in nested in several steps down to 30-50 m. Usually 8 tidal components are forced on the open boundaries of the basin scale model. The models are then forced by atmospheric fields (wind, pressure and heat flux) and river run-off.

High resolution versions (800 and 160 m) of the model have been applied for various parts of the Norwegian coast. Skill assessment of the model against a data set consisting of 9 Acoustic Doppler Current Profiler moorings placed on the Vesterålen-Lofoten shelf showed that the model was doing well [14].

B. Optimization of node localization

Optimization of the localization of the measuring nodes is carried out so as to minimize uncertainty of the states (current field) of the hydrodynamic model, when including measurement input. This criterion is integrated over a chosen region of interest. Localization of the impact of each sensor is enforced, i.e., influence on geographically distant states is blocked. The procedure starts with a greedy search based on [2], i.e., the nodes are optimized in sequence, at each step considering the others to be fixed. The procedure is iterated, but inevitably produces a suboptimal result. The final output is improved by a tabu search according to [3]. In essence, this strategy systematically searches in the neighbourhood of a sub-optimal solution to find the best measurement locations.

C. Sound propapagation

Sound propagation is modeled by ray tracing, This is the preferred method for frequencies of interest for acoustical communication, above some 10 kHz. Rays have been calculated by direct integration (see [4] ch.3.5). Amplitudes along rays have similarly been directly integrated by the simplified dynamic ray tracing equations of [15]. This is in effect a classical ray tracing system, including (non-physical) infinite amplitudes at caustics. The caustics artifacts are not removed from the results, but caustics are detected in each ray and an ad hoc number of range steps (10) around them are removed from the results. Boundary conditions have been implemented in accordance with [16]. Hence, scattering losses at the rough boundaries are generally lower than the classical coherent reflection coefficient. This, however, means that the reflected arrivals at the receiver are a time spread sum of incoherent contributions.

Rays are terminated when a maximum selected transmission loss (TL) is reached. This termination is the only amplitude information in the present paper: TL is less than the chosen maximum everywhere on the plotted rays. For the present simulations, the selected TL maximum is chosen from a simple transmission budget assessment (corresponding to the sonar equations of [17]): With a source level SL and a receiver noise level NL, the signal to noise ratio at the receiver is given by SNR = SL – TL – NL. The SNR is then required to be at least equal to a detection threshold, DT. The transducers used are assumed to be omni-directional due to the orientation robustness usually required in sensor networks. At 1 m reference distance this gives $SL = 10\log_{10}(\rho cP/4\pi)$, where P is acoustically radiated power, c is sound velocity and ρ is the medium density. Expressed in dB re. 1 μPa rms sound pressure, this amounts to $SL = 170.8 + 10\log_{10}(P)$. The noise level is $NL = 10\log_{10}(N_0B)$, where N_0 is the spectral density of the ambient noise and B is the system's noise bandwidth. Here omni-directional transducers are again assumed. For the present simulations the system is assumed to operate at 12.5 kHz, with B = 300 Hz and N_0 = 48 dB re. 1 μPa/√Hz. The latter corresponds to open sea wind generated noise at Sea State 5 [17]. Furthermore, P = 20 W and DT = 20 dB are assumed. These parameters, then, give a maximum TL of 90 dB (and this value is reached at range 7.7 km for the uniform free space case). The same TL requirement would result for any combination of P, B and N_0, as long as $P/(BN_0)$ is constant.

III. THE CASE STUDIED

The case selected for our study is the area around the Tristeinen islets at the coast of Trøndelag, Mid Norway, see Figure 1.

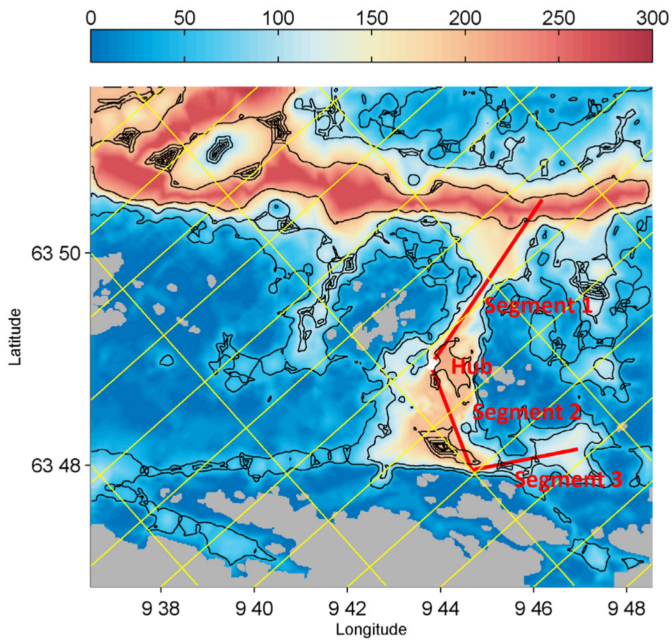

Figure 1 Bathymetry of the deployment area. The color scale shows depth (m). Gray areas are dry land. The yellow coordinates are true north and east. Axis labels refer to these coordinates. The model grid orientation is rotated 48 degrees in relation to true north. Text in red refers to a network deployment case of which Segment 1 is studied in the present paper.

The area is inside the main coastal currents and the currents are relatively weak. This has been confirmed in measurements as well as in the model simulations. The coastal water warms up in the surface during the summer and increases the sound speed compared to deeper waters. In autumn and winter when strong cooling of surface water takes place, the sound speed will decrease towards the surface. Low salinity water near the surface amplifies this cooling as vertical mixing is inhibited.

The location has been used as a test site for aquaculture in exposed areas. The sensor network deployment investigated in the present paper is part of a potential extension of the experimental setup described in [1]: We study in some detail Segment 1 of the two-branch (three segment) configuration in Figure 1. One end of the segment is the hub of the two-branch network. This is identified as $r = 0$ in the following. The other end is 5.2 km away, beyond a shallower saddle point approximately at the midpoint of the segment.

IV. SIMULATION RESULT

A. *Sensor node placement optimization.*

In the present model setup, a basin scale model for the Northeast Atlantic and the Arctic Sea was established with a horizontal resolution of 20 km [18]. High resolution models were nested in 4 steps down to 32 m.

Optimalization of sensor node placement, as described in section II.B is shown in Figure 2. Three nodes were included in the search. White crosses in the figure indicate the output of the greedy algorithm search, while black circles indicate the final locations output from the tabu search (note that the lower-left circle and the upper-right cross overlap). The entire region in the figure was included in the optimization criterion. The result emphasizes the importance of the saddle point region on Segment 1 of Figure 1. This is a region where the basic hydrodynamic model predicts strong currents. The optimization output, then implies that this current is highly correlated with the lower intensity flow in other parts of the region, so that reduction of uncertainty at the sensor locations contribute to a reduction over a wider region.

B. *Network connectivity analysis*

Sound speed fields were simulated in 3D as described in section IV.A for the period August 21st-December 23rd 2010. Sound propagation analyses based on this were then carried out to evaluate connectivity between network nodes along Segment 1. It was decided to keep only one of the nodes in Figure 2 and place a second one at the far end of Segment 1, in order to capture currents that are of general interest, but that do not contribute significantly to the flow in the region of interest for optimization (not providing further information once the currents at the saddle point are known).

A pair of nodes is considered to be connected if there is at least one ray between them with a TL that does not exceed our chosen maximum. This has not been tested by an explicit eigenray search, but simply by checking whether or not a node is enclosed in a fan of rays transmitted from the other one. Sound propagation analysis for the entire network in Figure 1 can be found in [10], using a somewhat more conservative connectivity definition.

Sound speed time variability at the hub is shown in Figure 3. A clear transition from summer to winter conditions is seen in the middle of the period. Figure 4 shows vertical sections along Segment 1 at the start, approximate midpoint and endpoint of the time series in Figure 3. Here spatial variability in the sound speed profile (SSP) is clearly demonstrated. Note that this would be very demanding to measure physically.

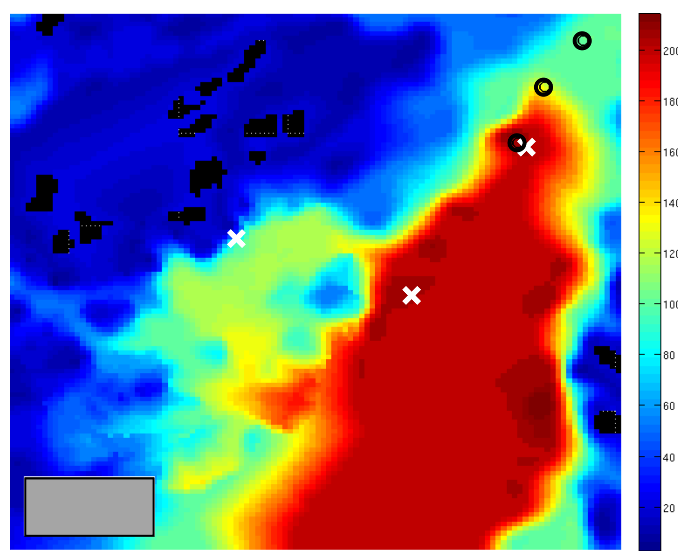

Figure 2 Optimization of sensor node localization: Three nodes included. White crosses are the result of the greedy search. Black circles are final locations after tabu search. Note that the lower-left circle and the upper-right cross overlap. The line from the lower left cross to the upper right circle is approximately the first half of Segment 1 in Figure 1.

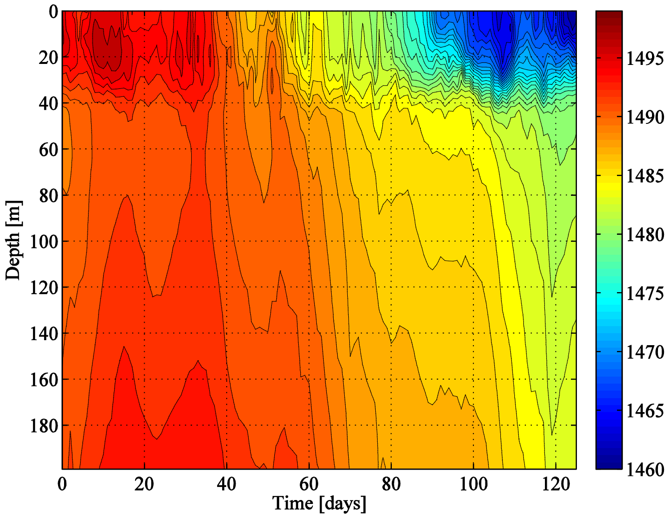

Figure 3 Simulated SSP at network hub. August 21th December 23th 2010. One profile per day

We will now simultaneously demonstrate (i) the use of sound propagation simulations based on modeled sound speed fields – to supplement the above node placement result, and (ii) that very detailed sound speed data are sometimes needed, so that measurement is generally very demanding and the use of modeled input data very attractive.

To this end, vertical sound speed profiles at the hub-location (r = 0) in Figure 4 can be claimed to represent either single point local physical measurements or quite good historical data from the same time of the year. Simulations using such profiles can then be compared to simulations using the complete modeled sound speed field, which is much closer to a true sound field. Hence the differences in simulation results illustrate in a conservative manner the advantage gained by using detailed SSP modeling. The comparison is conservative due to the fact that the single range vertical profiles chosen represent quite good data. Much larger differences would be found if generic, season specific data were used.

Now, consider the connectivity between the hub, the optimal saddle point location and the far end of Segment 1 under winter conditions (see the lower part of Figure 4). Figure 5 shows this connection: Ray tracing from the middle node to each end using the vertical sound speed profile at r = 0. Both end points are required to be located maximum 5 m above the bottom, while middle node is elevated to the minimum height above the bottom that ensures connectivity to the end points. These requirements are introduced due to mechanical robustness and stability issues. The two magenta lines in the figure show all points located 5 m and 10 m above the sea floor. Connectivity in the directions oposite to those shown is given by reciprocity.

The same ray tracing is repeated in Figure 6, now using the full range dependent sound speed field of Figure 4. We observe that the middle node placement is problematic: There is no connectivity between this node and the far end at 5.2 km.

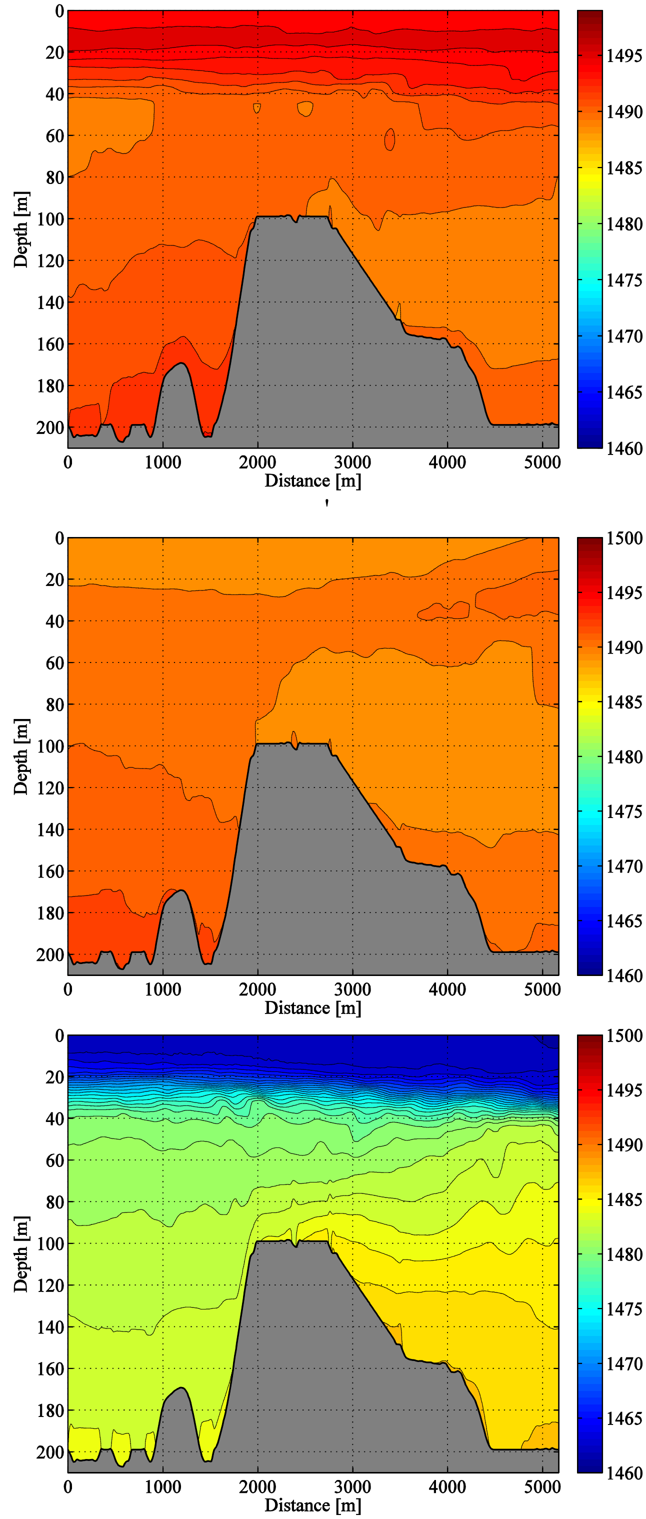

Figure 4 Sound speed range dependent profile. Segment 1. Upper: August 21st. Middle: October 1st.. Lower: December 23rd.

To obtain a connection the middle node is moved around in the vicinity of the position given by the measurement optimization, looking for a position with connectivity. The result is shown in Figure 7, where connectivity in both directions is found.

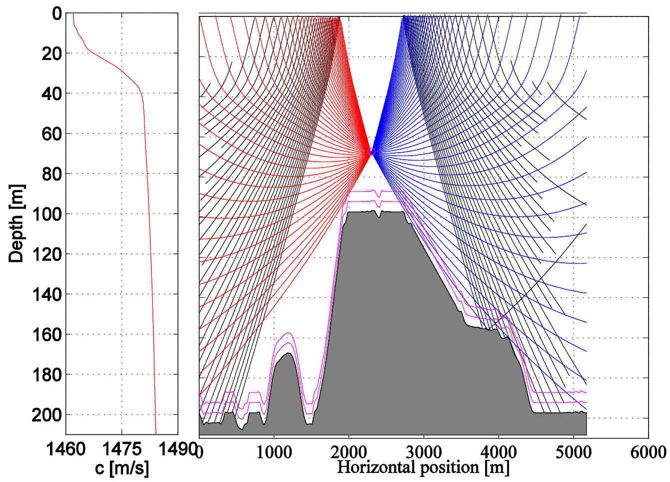

Figure 5 Relay and sensor node 30 m above the bottom. Ray tracing (right) using SSP (left) from hub location, $r = 0$, December 23rd. Colored rays: From relay-towards endpoints, the part before scattering. Black: Ray continuation after scattering in surface or bottom.

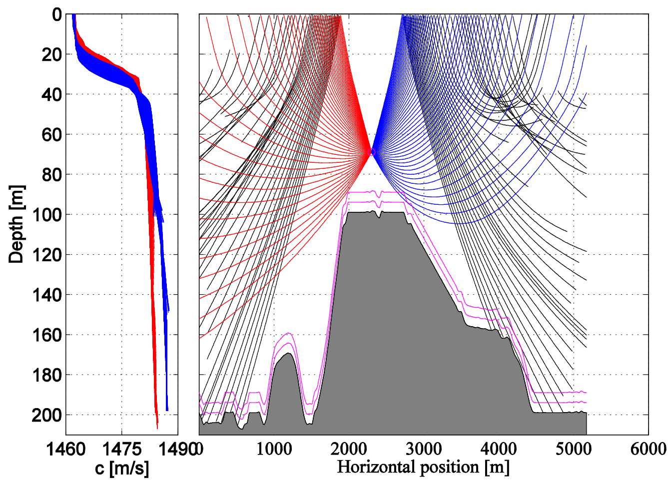

Figure 6 Relay and sensor node 30 m above the bottom. Ray tracing (right) using range dependent SSP (left) – December 23rd. Colors as in Figure 5.

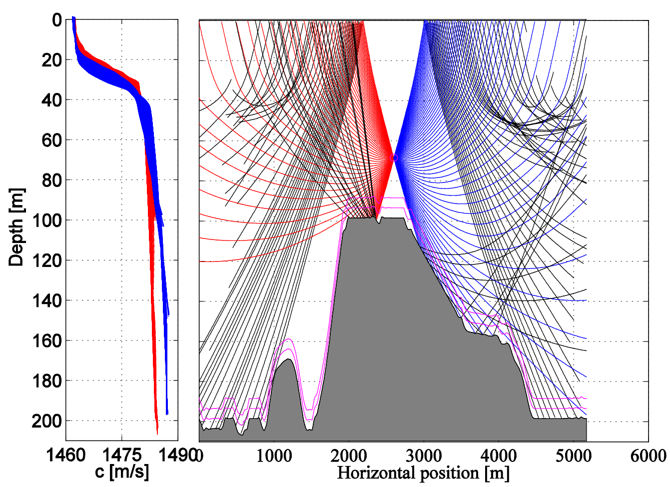

Figure 7 Relay and sensor node moved 300 m right relative to Figure 6. Range dependent SSP from December 23rd. Colors as in Figure 5.

The node in Figure 7 has been moved 300 m away from the start point, a result that is deemed acceptable for the measurement task. The analysis has been repeated for the other two sound speed datasets in Figure 4, with the same positive outcome. Hence, the node location is our final result, and we have demonstrated the two points (i) and (ii) above.

V. SUMMARY AND CONCLUSION

Our case study has demonstrated the use of hydrodynamic modeling to optimize the placement of sensor nodes with respect to uncertainty reduction in sea current modeling, under the additional constraint that the nodes should constitute a connected underwater acoustic communication network. For the connectivity analysis a sound propagation model has been employed, based on detailed sound speed data produced by the hydrodynamic model. Furthermore, it has been demonstrated that such a detailed sound speed field is very attractive for obtaining sufficient precision in acoustic modeling, especially in regions of significant variability in bathymetry and sea currents. It would be very demanding to obtain sufficiently detailed data by physical measurement, and the use of a hydrodynamic model is virtually the only alternative. In general the model based approach is important for up-scaling the geographical extent of a network, and has a large impact on the economy of its deployment and operation.

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