Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture

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LONG-TERM GOALS

UNITES is a unique, interdisciplinary team with expertise spanning the environment, ocean acoustics, and tactical sonar systems. The overall goals are to enhance the understanding of the uncertainty in the ocean environment, characterize its impact on sonar system performance, and provide the Navy with guidance for understanding sonar system performance in the littoral ocean.

OBJECTIVES

To: 1) develop generic methods for efficiently and simply characterizing, parameterizing, and prioritizing the physical variabilities and uncertainties arising from regional scales and processes; 2) construct, calibrate and evaluate uncertainty and variability models for the ocean physics and address forward and backward transfer of uncertainties based on the process of end-to-end data assimilation; 3) transfer uncertainties from the acoustic environment to the sonar and its signal processing; and, 4) contribute to overall synthesis and provide scientific guidance for the end-to-end problem

APPROACH

Our technical approach is based on simulating physical fields and high order uncertainties. Data is assimilated in the Harvard Ocean Prediction System (HOPS) using Error Subspace Statistical Estimation (ESSE). Stochastic 4D Monte-Carlo-based simulations of physical fields, parameters and their respective dominant uncertainties are carried out. Dominant uncertainties (error subspace) are initialized, forecast and reduced via data assimilation. Results are analyzed and physical estimates transferred to acoustics/signal processing models. Stochastic error models for unresolved processes, forcing and boundary condition errors, and environmental noise, are further developed and improved. Research for representing and reducing (end-to-end) uncertainty, end-to-end data assimilation and adaptive sampling is carried out. A.R. Robinson (ARR) is one of the two co-leaders of the UNITES team and is the scientific team leader. P.F.J. Lermusiaux (PFJL) carries out the technical research. The Harvard team also coordinates and guides the end-to-end system research.

WORK COMPLETED

ARR and PFJL attended the ONR Capturing Uncertainty DRI Review and Planning Meeting held in Providence in June 2003. ARR presented a summary and synthesis [9] of the status of the fundamental scientific basis for sonar performance prediction and research directions to improve that basis from the

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April 2003 Uncertainty DRI Science Workshop. PFJL's presentation [10] summarized the main tasks completed and technical accomplishments for most of FY03. It included an overview of the achievements of the UNITES team. An invited keynote lecture [7] was given at the Sixth International Conference on Theoretical and Computational Acoustics. The Science Workshop of the ONR Capturing Uncertainty DRI, April 9-10, 2003, was co-chaired by ARR and Ellen Livingston. ARR has drafted a summary and synthesis for the workshop. The plenary presentation [8] of PFJL (modeling working group) is available on the web. Several UNITES sub-team meetings occurred during FY03, including meetings with members of other teams. With Philip A. Abbot and his group we continued to research the end-to-end system [3]. The current focus is on the uncertainties in the ocean physics (e.g. due to unresolved sub-grid-scales) and signal processing (e.g. due to broadband averaging of continuous wave fields), and on the impacts of sonar properties on the end-to-end system. With Prof. C.-S. Chiu, the transfer of ocean physical forecast uncertainty to acoustic prediction uncertainty in the shelfbreak PRIMER environment has continued [1-2].

Two main areas of technical and scientific research for FY03 have been to carry out: i) coupled physical-acoustical data assimilation via ESSE; and, ii) numerical simulations of the ocean physics at accuracies that are suited for useful acoustical computations. Articles on the coupled physical-acoustical data assimilation for simulated examples have been published [2,4]. The approach was exemplified based on twin-experiments using real physical PRIMER data but synthetic acoustical data. Coupled data assimilation involving both real physical data and real acoustical data is currently underway. Substantial efforts were devoted towards achieving numerical simulations of the ocean physics at accuracies suited for useful acoustical computations. This included compiling and studying data sets collected over the large-scale New England shelfbreak region relevant to the (sub)-mesoscale physics. Bathymetric data sets were collected and combined in accord with their uncertainties and biases. Numerical research (i.e. minimize numerical errors due to steep topographies/pressure gradient, non-convergence issues, pycnocline resolution, etc) was carried–out to allow HOPS to run on accurate topographies, with almost no smoothing of the bathymetry (see Fig. 4). Physical representation of boundary influences (e.g. Hurricane Bertha) and their numerics (e.g. OBC) were also improved. The modeling of the largest sources of uncertainties among all of these properties (i.e. ocean physics data sets, bathymetry, initial conditions, parameterized processes, sub-grid-scales and boundary conditions, surface atmospheric forcings, open and closed boundary conditions) is underway.

The ESSE physical results continued to be evaluated in collaboration with WHOI. Bathymetric data, hydrographic data sets, initialization software and physical model outputs were given to Dr. G. Gawarkiewicz. A current focus is on the salting of the AXBT data. PFJL tailored his salting software to the specificities of the shelfbreak front region. The software has been given to WHOI for evaluation using independent data. The ESSE algorithms and software (e.g. [2,4,7]) for physical-acoustical data assimilation and for the computation of interdisciplinary error Probability Density Functions (PDFs), were further improved tested with a series of simplified cases. The definition and computation of the *a posteriori* (after data assimilation) right singular vectors were updated.

Research on uncertainty and predictability evaluations, e.g. [5,6], and on simple rules-of-thumb was carried out with OASIS, NPS and WHOI. Stochastic modeling was further researched with Prof. R. Miller at OSU. An extensive set of references on uncertainty, predictability, (fuzzy) information theory, imprecise probability theory and Bayesian and maximum entropy methods is being studied. Research on visualization of interdisciplinary ESSE uncertainties was continued, with Prof. Alex Pang (UCSC). One objective is to determine techniques that find and visualize the locations where oceanic

PDFs are similar to a target PDF. Another goal is to define features in the context of probabilistic (multi-valued) data sets and to determine techniques that extract such features.

RESULTS

The main results for FY03 involve (i) coupled physical-acoustical data assimilation via ESSE, and (ii) simulations of the PRIMER ocean physics at accuracies suitable for useful acoustic computations.

Coupled physical-acoustical data assimilation for improved sonar predictions - The estimation of ocean physical and acoustical fields was carried out as a single coupled data assimilation problem for identical-twin experiments using PRIMER data [2,4,5,7]. Environmental fields and their dominant uncertainties are predicted using ESSE and transferred to acoustical fields and uncertainties using an ensemble of acoustic propagation model simulations [1]. The resulting coupled dominant uncertainties define the error subspace. The physical and acoustical data are then assimilated such that the total error variance in the error subspace is minimized.
In the identical twin experiment shown here the "true" ocean is a model simulation that assimilates real physical data. After 5 days, a snapshot of the "true" ocean is taken and the corresponding "true" sound-speed field is input to the acoustical coupled-normal-mode model. The acoustical model provides the "true" TL field on day 5. Different synthetic physical and acoustical data were coarsely sampled from this "true" physical-acoustical ocean. These data sets were assimilated using ESSE. Sequential processing of observations is utilized and it was verified that the order of the assimilation (ocean physics before acoustics, or vice-versa) does not matter. In Figs. 1-2, the synthetic physical data are coarsely sampled temperature and salinity measurements: 2 CTD profiles are taken across the shelfbreak front, along a PRIMER acoustical path. The acoustical data are simulated towed-receiver TL data along the same path. An ESSE ensemble of 79 members is used for prior error estimate.

The assimilation results for the sound-speed and continuous-wave TL fields are shown on Fig. 1. The sound-speed (C) residuals are before assimilation (prior fields), after assimilation of the TL data, and after assimilation of both the TL and C data. The true TL, prior TL (i.e. the mean or forecast) and posterior TL (after assimilation of both TL and C data) are shown in the bottom row. Although the sub-sampled data are limited, the posterior C and TL are substantially closer to the true C and TL than the priors. The posterior ESSE ensemble properties (error covariances, etc, not shown) importantly estimate the uncertainty reduction as a result of the coupled data assimilation. To simulate the transfer uncertainties to a broadband sonar system (TL term in a sonar equation), the ensemble of single-frequency TL realizations are processed, using a variable-width running-range average. The prior and posterior histograms of deviations from the mean broadband TL (i.e., the error PDF estimates) are shown in Fig. 2. The prior PDFs are found to be depth and range dependent (Fig. 2a). Near the depth (55 m) of the main wave-guide, the predicted error standard deviation is relatively constant with range and relatively large, around 3 to 4 (db). Above (30 m) and below (85 m), standard deviations tend to decrease with range (down to 2 db), leading to a higher PDF peak. After assimilation (Fig. 2b), the uncertainties are reduced to ± 1db and are more Gaussian at all depths.

Simulations of the PRIMER ocean physics at accuracies useful for acoustical computations **–** The latest numerical ocean simulation is illustrated in Figs. 3-4. Of interest are: the impacts of a large meander of shelf water intruding slope waters at latitudes further south than usual, the corresponding upstream presence of a large slope eddy (confirmed by SST) that is pinching off from the shelfbreak front, and the strong effect of Hurricane Bertha in setting up the basis of the overall regional internal circulation.

The initialization is based on separate objective analyses for the shelf and slope regions, and on a shelfbreak front feature model. A ring visible in the SST is also introduced in the southwestern corner of the domain. Comprehensive calibrations of the numerical and physical parameters of the primitive-equation model of HOPS have been carried out.
It was found that intermittent atmospheric forcing imposes space and time scales on the Shelf Break Front (SBF), mixing/controlling some internal instabilities. Without atmospheric forcing, greater sub-mesoscales are present in the upper-layers, which impact the larger scales on weekly to monthly time-scales. For complete theories, atmospheric forcings must therefore be accounted for. This finding has important consequences for scientific and naval uncertainties. Considering other processes, it was also found that: the SBF is stronger where topography is steeper, the SBF has a tendency to bifurcate at Hudson Canyon, and that this bifurcation, combined with the warm-core rings present in the slope-water, leads to (sub-surface) northeastward flow along the slope. For coupled physical-acoustical processes, the ESSE modes showed that shoreward meanders of the upper-front lead to less loss in the acoustic wave-guide on the shelf. The related thickening of the thermocline at the front induces phase shifts in the ray patterns on the shelf. It can be concluded that numerical mesoscale to sub-mesoscale ocean predictions for acoustic predictions is essential, but that substantial progress is required, both in data and modeling. In particular, for this project, uncertainties in bathymetry, surface atmospheric forcing, un-resolved processes and ocean data are of greatest importance.

IMPACT/APPLICATIONS

Transferring and forecasting uncertainties from the physics, through the acoustics, using ESSE and processing these dominant error estimates to obtain TL uncertainties for a broadband sonar equation is significant. Coupled four-dimensional data assimilation for physical-acoustical fields has the potential to provide important advances in physical and acoustical ocean sciences and fleet applications. A specific impact is the four-dimensional reduction of errors in each discipline based on data from all disciplines. The direct UNITES-team application is to assist the sonar prediction community by providing a probabilistic representation of sonar system performance. Our approach provides a systematic method to incorporate uncertainties due to the environment and to transfer the effects of these uncertainties, in the end-to-end problem through the sonar systems under consideration. The operator can thus use this information to operate the system more effectively and make more informed decisions on search, risk, expenditure of assets (weapons), and assumptions of covertness.

TRANSITIONS

Rules-of-thumb, lessons learned, technical implications for effective environmental sampling strategies for the fleet and other tactical insights are being presented by the UNITES team to appropriate fleet personnel and Navy-ONR working groups or programs, e.g. the ONR Littoral ASW FNC program and the Advanced Processor Build (APB) program. Transfer of knowledge will continue to occur among UNITES end-to-end team members. Transitions to various scientific and applied groups (e.g. NAVOCEANO, MIT, TOMS) are also occurring.

RELATED PROJECTS

This program is closely related to the Harvard 6.1 research "Dynamics of Oceanic Motions" and the 6.2 research "Development of a Regional Coastal and Open Ocean Forecast System". The Multi-Static Active ASW System is currently being transitioned to the Navy through the Advanced Systems Technology Office (ASTO). The predictive probability of detection curves derived from the UNITES Team are being utilized by ASTO in this program.

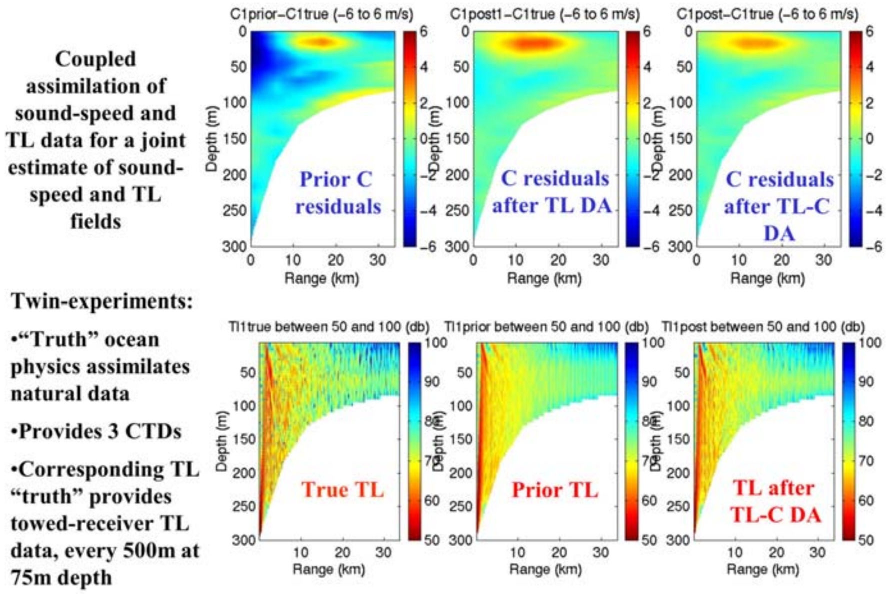

Figure 1. Coupled physical-acoustical filtering via ESSE along one of the Shelfbreak-PRIMER acoustic path (top row, C-residuals; bottom row TL fields).

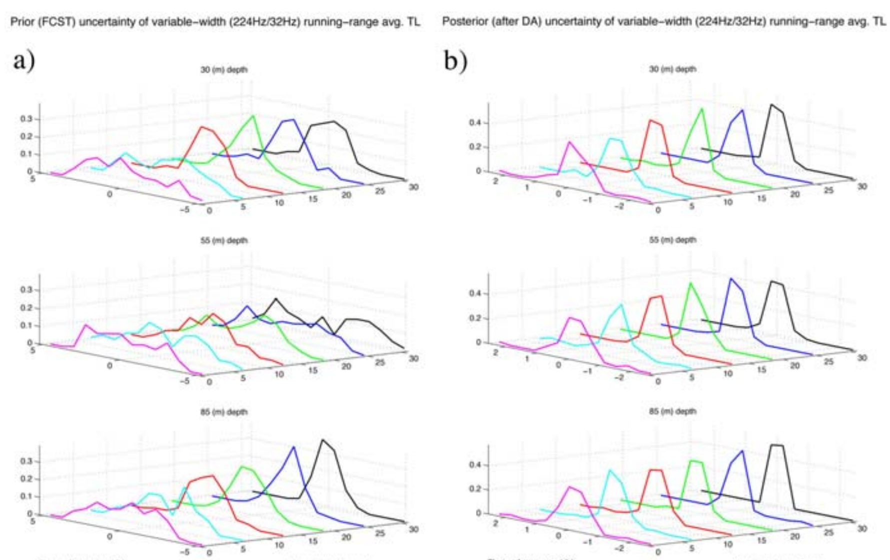

Figure 2. PDF estimates of broadband TL as a function of range and depth, along a PRIMER acoustic path: (a) Prior PDF (predicted by ESSE); (b) Posterior PDF (after ESSE assimilation).

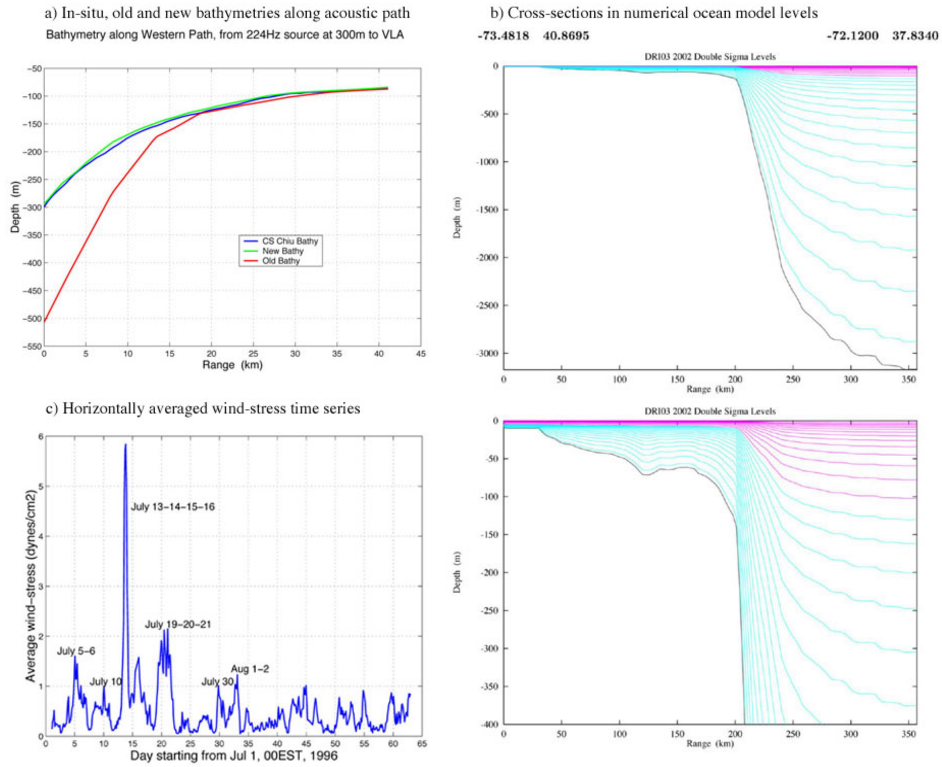

Figure 3. Selected snapshots in central ocean physics simulation: surface temperature after 16, 18, 20 and 22 days of simulation (from 24 to 30 July, 1996).

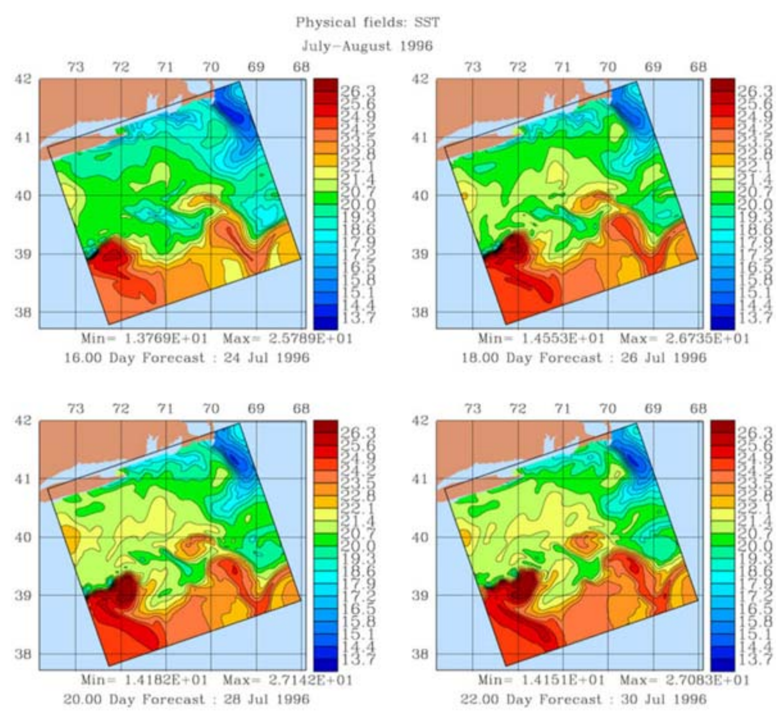

Figure 4. Selected parameters of ocean physics simulation: bathymetry, numerical levels and surface atmospheric fluxes (only averaged wind-stress shown).

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[1] Lermusiaux P.F.J., C.-S. Chiu and A.R. Robinson (2002). Modeling Uncertainties in the Prediction of the Acoustic Wavefield in a Shelfbreak Environment. Proceedings of the 5th ICTCA, May 21-25, 2001, in "Theoretical and Computational Acoustics 2001", E.-C. Shang, Q. Li and T.F. Gao (Eds.), World Scientific Publishing Co., 191-200.
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[2] Lermusiaux, P.F.J. and C.-S. Chiu (2002). Four-dimensional data assimilation for coupled physical-acoustical fields. In "Acoustic Variability, 2002". N.G. Pace and F.B. Jensen (Eds.), Saclantcen. Kluwer Academic Press, 417-424.
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[7] Robinson, A.R. and P.F.J. Lermusiaux (2003). Prediction Systems with Data Assimilation for Coupled Ocean Science and Ocean Acoustics, Proceedings of the Sixth International Conference on Theoretical and Computational Acoustics (A. Tolstoy, et al., editors), World Scientific Publishing. [In press]. Corresponding invited lecture (August 11, 2003) available from:
http://people.deas.harvard.edu/~robinson/PAPERS/robinson_ictca_final.pdf

SCIENCE WORKSHOP AND JUNE ONR REVIEW PRESENTATIONS

[8] Lermusiaux P.F.J. (2003). Deterministic and stochastic modeling of the end-to-end interdisciplinary system, and its errors and uncertainties. Plenary presentation given April 9, 2003, at the Science Workshop of the ONR Capturing Uncertainty DRI, April 9-10, 2003, Alexandria, VA.
http://people.deas.harvard.edu/~pierrel/talk/pfjl_uncertainty_modeling_090403.ppt

[9] Robinson, A.R. (2003). Summary and synthesis of the status of the fundamental scientific basis for sonar performance prediction and identification of research directions to improve that basis. Plenary presentation given April 9, 2003, at the Science Workshop of the ONR Capturing Uncertainty DRI, April 9-10, 2003, Alexandria, VA.
http://people.deas.harvard.edu/~robinson/PAPERS/ARR_synthesis_and_summary_final.pdf

[10] Lermusiaux, P.F.J. (2003). Physical-acoustical data assimilation via ESSE for improved sonar predictions and numerical simulations of the PRIMER ocean physics. Presentation given at the Science Workshop of the ONR Capturing Uncertainty DRI, April 9-10, 2003, Alexandria, VA.
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