Acoustic Data Assimilation: Concepts and Examples

Liling Jin, Wen Xu, Jiamin Huang and Jianlong Li

Abstract The ocean is a complicated hydro-dynamic system, showing various interdisciplinary processes of multiple interactive scales. Such processes as internal waves, eddies, and fronts make the ocean acoustic environment drastic changes in time and space. Understanding and modeling physical-acoustical processes are essential for ocean acoustic applications as well as ocean field prediction and parameter estimation. The acoustic data assimilation (ADA), which melds instant observed data of different natures and various physical models, has recently been developed as a new technique for forecasting both ocean and acoustic fields. The general framework of ADA includes three major parts: (1) an observational network for data measurements; (2) a suite of interdisciplinary ocean physics models and the sound propagation model; and (3) data assimilation schemes. Hence it is expected to provide ocean acoustic predictions with higher resolution and better accuracy, compared to those only using the observation data or the physics model. In this paper, we discuss the concepts and framework required to develop the coupled physics-acoustical data assimilation schemes, and review some typical ADA systems and their filed-testing results. It is shown that both the theory and related experiments are advancing steadily.

Keywords Acoustic data assimilation · Ocean acoustic predictions · Parameter estimation · Physical-acoustical processes

---

L. Jin (✉) · W. Xu · J. Huang · J. Li
College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China
e-mail: wxu@zju.edu.cn

J. Li
e-mail: jlli@zju.edu.cn

L. Zhou et al. (eds.), *Underwater Acoustics and Ocean Dynamics*
DOI 10.1007/978-981-10-2422-1_4

1 Introduction

In the ocean, interdisciplinary processes, involving physical, biological, chemical, sedimentological, acoustical, and optical processes, are now known to occur on multiple interactive scales in space and time. These processes cover a wide range of space scales from 1 mm to 10,000 km, and of time scales from 1 s to 100 years and more [1]. Understanding and modeling these processes are essential for ocean field prediction and parameter estimation. However, conventional oceanographic measurements cannot carry out a large area and long-term observation with sufficient temporal and spatial sampling, especially for the sub-mesoscales processes [2]. Recent research on coupled oceanographic and acoustic data assimilation (ADA) is concerned with melding instant observed data of different natures and various physical models. A large number of simultaneous physical, biological, and acoustical measurements and physical models are combined by ADA to study the physical-acoustical-biological processes. Importantly, efforts of ocean field prediction and parameter estimation are enhanced by integrating acoustical measurements. ADA is becoming a common technique for forecasting both ocean and acoustic fields.

In this paper, we first discuss the concepts and framework required to develop coupled physics-acoustical data assimilation schemes, and then review some typical ADA systems and their field-tested results. In the end, we draw some conclusions and introduce a number of future trends based on our understanding toward the problem.

2 Concepts of Acoustic Data Assimilation

ADA melds estimates of data and models for field and parameters with three major parts: (1) an observational network for data measurements; (2) a suite of interdisciplinary ocean physics models and the sound propagation model; and (3) data assimilation schemes. The diagram of the ADA is shown in Fig. 1, which illustrates

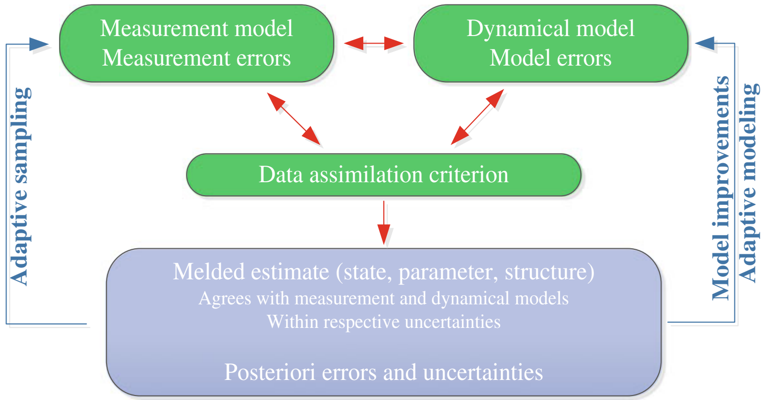

Fig. 1 Diagram of the acoustic data assimilation (reprinted from Ref. [3])

the system components and their interactions, including two feedbacks [3]. Data measurements are linked to the state variables and dynamical model via measurement models. Dynamical models represent the interdisciplinary ocean physics models and the sound propagation model. Then, based on the data assimilation criterion, data and dynamics are melded with inverse weighting related to their relative errors. Finally, the melded estimates are used to improve the model predictions and optimize the resource deployment of an observational network.

2.1 Data

Presently, advanced measurement techniques present powerful opportunities for the acquisition of extensive data sets. The platforms can be used to organize an observational network, such as ships, underwater vehicles, etc. The data required by the ADA system include the following data of different characteristics:

(1) in situ dynamical data, e.g., profiles of temperature, salinity, and current velocities from XBTs, CTDs, ADCPs;
(2) remotely sensed data, mostly satellite data;
(3) acoustic data, including sound pressure, travel time, and transmission loss.

2.2 Models

Ocean dynamics are governed by Newton's equations of motion expressed as the Navier–Stokes equations. Many ocean models have been developed to numerically solve the governing equations (which are also referred to as the primitive equations), such as Harvard Ocean Prediction System (HOPS) [4], Princeton Ocean Model (POM) [5], Regional Ocean Model System (ROMS) [6], and The Unstructured Grid Finite Volume Coastal Ocean Model (FVCOM) [7]. For computational economy, the primitive equations are often solved under the hydrostatic and Boussinesq assumptions. However, for some special dynamical processes, the assumptions may become inappropriate. Taking internal waves as an example, the governing equations should be replaced by non-hydrostatic primitive equations or dedicated internal wave equations. Although the ocean models have become powerful tools for marine environment simulations, the errors caused by numerical calculations and the uncertainty of the boundary conditions and atmospheric forcing are still inevitable. Therefore, assimilation methods should be employed to calibrate the ocean models using the measurement data.

2.3 Assimilation Methodology

A number of methods are available for coupled oceanographic and ADA, which can be divided into four classes [8]

(1) estimation theory, such as the Kalman smoother and optimal interpolation;
(2) control theory, such as the adjoint method;
(3) direct minimization methods, such as the steepest descent, conjugate gradient, simulated annealing, and genetic algorithms;
(4) stochastic and hybrid methods, such as the Error Subspace Statistical Estimation (ESSE).

3 Current Status and Main Results

In this section, we introduce a few typical ADA systems and their field-tested results.

3.1 MIT Ocean Acoustic Tomography Framework

A general framework of ADA was first proposed at MIT to reduce the environmental uncertainty and estimation the true environment parameters [9]. In this approach, a variety of information sources are exploited, including a direct local sound speed measurement model, an oceanographic dynamic model of the sound speed field, and a full field acoustic propagation model as well as other various measurements. These four sources of information are described as

$$\tilde{c} = Mc + c_n, \quad c_n \sim N(0, R_c) \tag{1}$$

$$A(c) = v, \quad v \sim N(0, Q_a) \tag{2}$$

$$B(p, c) = w, \quad w \sim N(0, Q_b) \tag{3}$$

$$\tilde{p} = Lp + p_n, \quad p_n \sim N\left(0, R_p\right) \tag{4}$$

where Eq. (1) denotes the local sound speed measurement model and c_n is the measurement error of the local sound speed, Eq. (2) denotes the oceanographic dynamic model and v is the error of the model, Eq. (3) denotes the full field acoustic propagation model and w is the modeling error, Eq. (4) denotes the acoustic pressure measurement model and p_n is the measurement noise. $\tilde{c}$ and $\tilde{p}$ denote the local sound speed measurements and the local acoustic pressure measurements; c and p denote the true sound speed field and acoustic pressure field; M and L are the mapping matrices; and R_c, Q_a, Q_b, and R_p denote the covariance matrices. All the additive error terms are modeled as a Gaussian random distribution. Then, the paper introduces a variational method to solve this inverse problem, through minimizing the misfit (also called the cost function) between the measurements and their predictions calculated from the available models

$$\hat{c} = \arg\min_{p,c}\{J(p,c)\} \tag{5}$$

where the cost function J can be described as

$$J(p,c) = c_n^{\mathrm{H}} R_c^{-1} c_n + v^{\mathrm{H}} Q_a^{-1} v_n + x^{\mathrm{H}} Q_b^{-1} x + p_n^{\mathrm{H}} R_p^{-1} p_n \tag{6}$$

This article is the first time toward the assimilation of acoustic data into ocean models, which is referred to as an ADA. However, Ref. [9] just verifies the feasibility of the proposed framework, and the oceanographic dynamic model was not included. Following the approach in Ref. [9], a modified GM internal wave model for the specific shallow-water environment is included as an oceanographic dynamical model in the framework of ADA [10]. In the numerical examples, the true environment parameters can be estimated more precisely with the iterative implementation of the inversion process. Analyzing the simulation results, we find that the inversion performance is quite well, which further verify the validity of the ADA approach in ocean environmental inversion.

3.2 Harvard Ocean Prediction System

The interdisciplinary ocean observing and prediction system developed at Harvard and presently in scientific and operational use is HOPS [4]. HOPS is an integrated system of data assimilation schemes. The PE physical dynamical model is utilized in HOPS, as an oceanographic dynamic model. Three coordinate transformations are available for the vertical coordinate, including sigma, hybrid and multiple sigma coordinate transformations. In the horizontal dimension, multiple two-way nests are included. The entire system includes a data analysis and management module, data assimilation, dynamical consistent model initialization, and model-driven adaptive sampling with feedbacks.

During July and August of 1996, the US Office of Naval Research (ONR) Shelfbreak PRIMER experiment was carried out in the Mid-Atlantic Bight south of New England. The main objective was to study the effects of oceanographic changes on the sound propagation. We found that the posterior TL is substantially closer to the true TL than the prior, and the estimation performance of the assimilation of the TL and sound speed data is better than the assimilation of the TL data alone [11].

3.3 Focused Acoustic Forecasting-05

For limited environment measurements and computational capabilities, oceanic acoustic predictions cannot be provided in high resolution and with enough

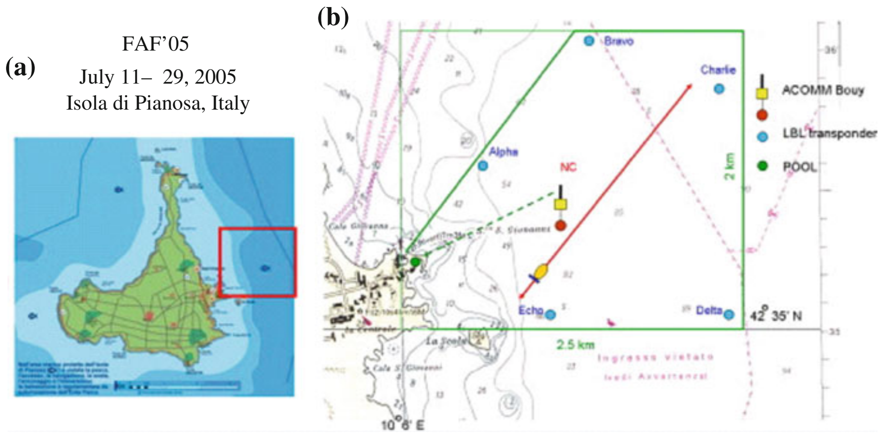

Fig. 2 **a** Geographic location of the FAF05 experiment; **b** General schematic of the FAF'05 experiment [12]

accuracy. Adaptive Rapid Environmental Assessment (AREA) is an adaptive acoustics-environment sampling approach being developed. By assimilating in situ measurements sampled adaptively and optimally, AREA can dramatically improve the estimation performance. In 2005, the Focused Acoustic Forecasting-05 (FAF'05) exercise was held to illustrate these concepts. FAF'05 was carried out in the northern Tyrrhenian sea, on the eastern side of the Corsican channel (Fig. 2). The Autonomous Underwater Vehicle (AUV) domain covers an area of about 2.5 km × 2.5 km. The main realization for the FAF'05 exercise simulations can be summarized in three steps: (1) HOPS/ESSE was used to predict ocean environmental daily; (2) acoustic forecasts were computed by various scenario predictions of sound speed using a sound propagation model; (3) sound speed and acoustic forecasts were input into an adaptive sampling, and an optimal prior AUV path was forecasted based on optimization algorithm, via which the corresponding uncertainties of the predicted acoustic field were reduced. The results of the FAF'05 simulations clearly demonstrated the validity of the AREA methodology.

3.4 Battlespace Preparation 2007

The real-time coupling data assimilation system of a nested ocean model and an acoustic propagation model were carried out at sea for the first time, as a part of the Battlespace Preparation 2007 (BP07). The operational region of BP07 was southeast of the island of Elba (Italy) in the Tyrrhenian Basin, east of Corsica and Sardinia. During BP07, a new real-time working process chain was developed prior to the exercise, as shown in Fig. 3. It consists of the following parts: (1) in situ ocean data collected based on oceanographic forecasts; (2) the in situ ocean data

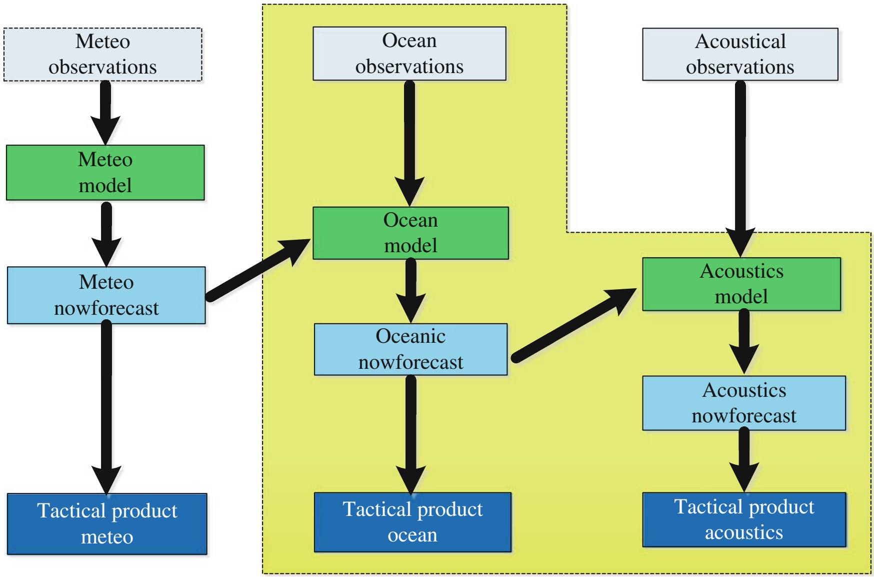

Fig. 3 Working process chain of the data-driven oceanographic acoustic modeling system [13]

and external meteo-data assimilated into an oceanographic modeling system to provide oceanographic forecasts; (3) sound speed forecasts then used as inputs to the acoustic model for acoustic propagation forecasts. Some of the results are given in Ref. [13]. We can find that the ocean environment variability can highly influence sound propagation properties and the probability of detection. The coupling of at-sea acoustic modeling to real-time ocean forecasting is essential.

3.5 *Quantifying, Predicting, and Exploiting Uncertainty*

The 2008 Quantifying, Predicting, and Exploiting Uncertainty (QPE2008) pilot experiment was carried out on the continental shelf and slope of northeast Taiwan, China [14]. The QPE2008 was designed to (1) develop real-time methods to forecast the ocean, the seabed, and the acoustics; (2) compare predictions from such coupled systems to in situ data; (3) study and quantify the influences of the ocean and geo-acoustic uncertainties on the coupled predictions. In Ref. [14], the authors quantified the dynamic mechanisms and the sensitivity with acoustic transmission data collected from the QPE2008. From that paper, one can obtain that the sediment properties lead to larger but isotropic variations on the shelf and smaller but anisotropic variations over the shelfbreak, and internal tides on the shelf lead to the largest TL sensitivity. In general, those results are useful for improving the real-time modeling of coupled physics-acoustical data assimilation and optimum sampling network.

4 Conclusions and Future Trends

Coupled oceanographic and ADA has received increased attention in the most recent ten years, and significant progresses have been achieved. Both the theory and related experiments are advancing steadily. Although ocean computations are restricted to a lower resolution volume grid, ADA can get high vertical resolution estimates of state variables and parameters by melding high-resolution environmental data. However, high-resolution environmental data inverted from the acoustic measurements have yet to be explicitly included as a new effective data source for data assimilation.

There are several future research trends related to ADA, which can be summarized in four aspects: (1) develop solving systems of the non-hydrostatic ocean model for the estimate of the dominant physical processes that affect the acoustic field; (2) incorporate atmospheric adaptive sampling to improve specification of wind stress, heat flux, etc., to ocean models; (3) exploit techniques of adaptive sampling, such as network building and path planning of moving platforms; (4) design algorithms for real-time ADA, such as rapid algorithms and methods of parallel computing.

Acknowledgments This work was supported by the National High Technology Research and Development Program of China (grant No. 2012AA090901), the Fundamental Research Funds for the Central Universities (grant Nos. 2011XZZX003 and 2013XZZX011), and the National Natural Science Foundation of China (grant No. 61171147). The authors want to thank all the researchers in this area for their outstanding work.

References

1. Dickey, T.D.: Technology and related developments for interdisciplinary global studies. Sea Technology, 47–53 (1993)
2. Dickey, T.: Emerging ocean observations for interdisciplinary data assimilation systems. J. Mar. Syst. **40**(1), 5–48 (2003)
3. Robinson, A.R., Lermusiaux, P.F.J.: Prediction systems with data assimilation for coupled ocean science and ocean acoustics. In: The Sixth International Conference on Theoretical and Computational Acoustics (ICTCA), Honolulu, HI, Aug 2003
4. Robinson, A.R.: Forecasting and simulating coastal ocean processes and variabilities with the Harvard Ocean Prediction System. In: Mooers, C.N.K (ed.) Coastal Ocean Prediction. AGU Coastal and Estuarine Studies Series, American Geophysical Union, pp. 77–100 (1999)
5. Mellor, G.L.: Users guide for a three dimensional, primitive equation, numerical ocean model. Program in Atmospheric and Oceanic Sciences, Princeton University, 1998
6. Shchepetkin, A.F., McWilliams, J.C.: The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography following-coordinate oceanic model. Ocean Model. **9**, 347–404 (2005)
7. Chen, C.S., Liu, H.D., Beardsley, R.C.: An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. J. Atmos. Oceanic Technol. **20**, 159–186 (2003)

8. Robinson, A.R., Lermusiaux, P.F.J., Sloan, N.Q.: Data assimilation. In: Brink, K.H., Robinson, A.R. (eds.) THE SEA: The Global Coastal Ocean. Processes and Methods, vol 10, pp. 541–594. Wiley, New York (1998)
9. Elisseeff, P., Schmidt, H., Xu, W.: Ocean acoustic tomography as a data assimilation problem. IEEE J. Oceanic Eng. **27**(2), 275–282 (2002)
10. Li, J.L., Jin, L.J., Xu, W.: Inversion of internal wave-perturbed sound speed field via acoustic data assimilation. IEEE J. Oceanic Eng. **39**(3), 407–418 (2013)
11. Lermusiaux, P.F.J., Chiu, C.S.: Four-dimensional data assimilation for coupled physical-acoustical fields. In: Pace, N.G., Jensen, F.B. (eds.) Acoustic Variability, pp. 417–424. Kluwer Academic Press, Saclantcen (2002)
12. Wang, D., Lermusiaux, P.F.J., Haley, P.J., Eickstedt, D., Leslie, W.G., Schmidt, H.: Acoustically focused adaptive sampling and on-board routing for marine rapid environmental assessment. J. Mar. Syst. **78**, s393–s407 (2009)
13. Lam, F.P.A., Haley Jr., P.J., Janmaat, J., Lermusiaux, P.F.J., Leslie, W.G., Schouten, M.W., te Raa, L.A., Rixen, M.: At-sea real-time coupled four-dimensional oceanographic and acoustic forecasts during Battlespace Preparation 2007. J. Mar. Syst. **78**, s306–s320 (2009)
14. Lermusiaux, P.F.J., Xu, J.S., Chen, C.F., Jen, S., Chiu, L.Y., Yang, Y.J.: Coupled ocean-acoustic prediction of transmission loss in a continental shelfbreak region: predictive skill, uncertainty quantification, and dynamical sensitivities. IEEE J. Oceanic Eng. **35**(4), 895–916 (2010)