Plenary Lectures: Paper ICA2016-485

On the perspective of ocean acoustic tomography for probing ocean currents in the coastal waters surrounding Taiwan

Chen-Fen Huang\(^{(a)}\), Naokazu Taniguchi\(^{(a)}\), Jin-Yuan Liu\(^{(b)}\)

\(^{(a)}\)Institute of Oceanography, National Taiwan Univ., Taipei City 11469, Taiwan
\(^{(b)}\)Dep. of Electrical and Computer Eng., Tamkang Univ., New Taipei City 25137, Taiwan
chenfen@ntu.edu.tw

Abstract
Oceanographic processes in the coastal waters around Taiwan, including wind driven flows, tidal currents, internal waves, eddies, etc., and in particular the Kuroshio, are highly variable in time and space. Among various approaches for studying ocean dynamics, the method of ocean acoustic tomography (OAT) is particularly useful for estimating the spatial distribution of currents. Here we have demonstrated the applications of OAT on measuring the currents with different experimental settings in two particular sites, i.e., the Kuroshio area off the southeast coast, and the Sizihwan Bay area off the southwest coast. This talk will focus on the implementation of the experiments as well as the data analysis for current estimation based upon the principles of OAT in terms of the difference of reciprocal travel times. These studies have developed: 1) the application of the middle-range (about 50 km) OAT technique to study the spatial and temporal variations of a sub-branch of the Kuroshio off the southeast coast of Taiwan; 2) an approach of exploiting the communication signals of distributed networked underwater sensors for ocean current mapping; and 3) an advancement of incorporating a moving vehicle to enhance current estimation. It is our long-term objective to further the OAT techniques to study ocean current around Taiwan, particularly the Kuroshio, which is a prominent western boundary current in the North Pacific Ocean.

Keywords: Ocean acoustic tomography, shallow water, current reconstruction
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1 Introduction

Ocean acoustic tomography (OAT), proposed by Munk and Wunsch in 1979, uses (the perturbation of) acoustic ray travel time to invert and map mesoscale oceanic disturbance in deep oceans [7]. Until recently, most OAT experiments were carried out at sea depths greater than 3000 m, with a complete deep sea sound speed structure from the sea surface to seafloor, and focused on temperature structures because satisfactory results are acquired even when a high precision clock is not available. Recently, coastal acoustic tomography (CAT) was proposed as the application of OAT to coastal seas, with the goal of continuously monitoring the tidal currents in harbors, bays, straits, and inland seas [3, 5, 11, 12]. Coastal acoustic tomography (CAT) studies typically map the 2D (horizontal slice) structure of coastal current rather than temperature. Sources and receivers are deployed in remote areas without risk or inconvenience to shipping, fisheries or marine aquaculture industries.

In this study, we have applied OAT to current estimation in coastal waters around Taiwan. Taiwan is an island surrounded by seas with various geographical characteristics. In the east coast, it faces the western North Pacific Ocean with the Kuroshio flowing northward, while in the west coast, it faces the Taiwan Strait, a shallow water environment with an average depth of sixty meters (Figure 1). Coastal seas around Taiwan exhibit a wide variety of oceanographic processes associated with their complex bottom topography, as well as tides, winds (monsoons and typhoons), and the Kuroshio. The Kuroshio, the western boundary current of the North Pacific Ocean, is swift along the east coast of Taiwan with a maximum speed of about 1–1.5 m s$^{-1}$ and a width of about 100–150 km, and it turns eastward along the shelf break around 26$^\circ$N. A branch of the Kuroshio intrudes steadily and persistently into the South China Sea. Part of the intruding Kuroshio flows out of the South China Sea through the northern Luzon Strait and reunites with the main stream of the Kuroshio [6].

Here we presented results from our OAT experiments. Experiments conducted in 2009 in the Kuroshio area near the southeast of Taiwan demonstrated current estimation using a pair of transducers. Experiments in 2011 in the Sizihwan Bay area adjacent to the southwest of Taiwan demonstrated current mapping using a distributed netted underwater sensors (DNUS) system. Improved current estimation was demonstrated by moving vehicle OAT experiments conducted in 2015, also in the Sizihwan Bay area.

2 Shallow-water ocean acoustic tomography

The time taken by a sound pulse to travel along a ray path in forward ($\tau^+$) and reversed ($\tau^-$) directions between a pair of transceivers is a function of the sound speed $c$ and current velocity $u$ along the path. The small travel-time changes induced by the current are separated
Figure 1: Weekly drifting trajectories observed at 30 m in depth in summer. Derived from climatological mean of shipboard acoustic Doppler current profiler.

from the much larger effects due to sound speed by the sum \[ s = \left( \tau^+ + \tau^- \right) / 2 \] and difference \[ d = \left( \tau^+ - \tau^- \right) / 2 \] of the reciprocal travel times. Using \( s \) and \( d \), one can infer the path-averaged current \( u_m \) as follows [7]:

\[
    u_m = -\frac{R}{s^2}d, \tag{1}
\]

where \( R \) is the distance between transceivers. There exist multiple arrivals of the rays traveling along various paths in the ocean, the vertical profile of the current can be reconstructed using \( d \)'s of all arrival pairs, referred to as vertical slice tomography. When applying vertical slice tomography, it is required that the individual ray arrivals are resolved in their arrival times, are traceable in geophysical time, and the observed arrivals are identifiable to predicted rays.

The above conditions may not be satisfied in shallow waters due to complex arrival patterns resulting from sounds interacting with the sea surface and bottom boundaries. We proposed a ray group method, which divides the received arrival pulses into several ray groups instead of identifying individual rays. The proposed method was validated in [9] using numerically simulated reciprocal acoustic transmission for 170 days in a synthetic ocean. The experimental design and geometry for that validation were taken from a Luzon Strait tomography experiment in 2008 [the green line in Figure 1 for the location map for the station pair]. The sound speed and current in the synthetic ocean were obtained from HYbrid Coordinate Ocean Model (HYCOM) outputs [1]. The series of reciprocal acoustic propagation in the time-evolving synthetic ocean was predicted by the two-dimensional Gaussian-beam ray tracing code BELLHOP [8]. The current effect was accounted for by adding or subtracting the HYCOM current velocity from
the HYCOM sound speed as a scalar quantity. Figure 2(A-1) shows an example of the predicted eigenrays for the one-way transmission. The color of each eigenray indicates its launch angle. Four ray groups were found for the synthetic data; these were chosen based on arrival time in the pulse responses [the time intervals for ray groups are indicated by the shaded areas in Figure 2(A-2)], referred to as grouping, so that these groups could be resolved by these time intervals and traced over 170 days. The reciprocal pulse responses were aligned using the cross-correlation first, and then differential travel times were determined from the nearest peaks, referred to as pairing. There existed multiple peak pairs within the group, thus the corresponding differential travel times were also averaged within the group, referred to as averaging. The ray trajectories of the groups were also averaged within the groups and the ray lengths were obtained from the averaged trajectories [Figure 2(B)].

To obtain vertical profiles of the current, one needs to solve an inverse problem. In [9] the generalized Tikhonov regularization method with a smoothness constraint was used with the assumption that the current profile varies smoothly from the surface to bottom. Figure 2(c) shows the comparison of the reconstructed and HYCOM currents at two layers (0–250 m and 750–1000 m) when the layer thicknesses are 125 m or 250 m. The estimated error in the time series of reconstructed currents is less than 10 cm/s. The derived volume transport in the upper 1000-m layer has a fractional error of 4.5%. The ray group method mitigates the ray identification problem in the bottom-limited environment.

Figure 2: Ray group method. (A) Eigenrays for the transmission from stations T2 to T1 on day 100. (B) Ray lengths and modeling error for each ray group. (C) Time series of reconstructed currents in the surface and bottom layers. [9]
3 Selected results of acoustic mapping for ocean currents

This section provides a brief overview of the authors’ research program with the aim to probe the ocean current field in shallow-water environments via the inversion of measured acoustic travel-time data.

3.1 Vertical current profiling of the Kuroshio southeast of Taiwan

Ocean current profiling using OAT was conducted in the Kuroshio Current southeast of Taiwan from August 20 to September 15, 2009 [10]. Sound pulses were transmitted reciprocally between two acoustic stations placed near the underwater sound channel axis and separated by 48 km [Figure 3(A)]. The ray group method was applied. The differential travel time was determined by three steps: grouping, pairing, and averaging. Based on the ray simulation, the observed acoustic arrivals were divided into three ray groups (Figure 3). The 1st, 2nd and 3rd ray groups were selected to travel through the lower layer (>500 m), the lower to middle layer (>250 m) and all three (lower to upper) layers, respectively. Then, the average differential travel times from the ray groups were used to reconstruct the vertical profiles of currents. Due to the internal clock drift caused by both the clocks equipped in the tomographic system and the programming error of system, the currents were estimated with respect to the deepest water layer via two inversion methods. First, based on the eigenray distribution, the current profile was divided into three depth layers accordingly: \( u_1 \) (500–1300 m), \( u_2 \) (250–500 m), and \( u_3 \) (0–250 m). Since the number of depth layers is equal to the number of ray groups and the layering is consistent with the ray distribution, an explicit solution can be obtained for \( u_1 \) to \( u_3 \). Second, the ocean current was discretized into 10 depth layers with a layer thickness of 125 m. To stabilize the inversion result a second-order Tikhonov regularization was used.

Figure 3(C-1) shows that both methods give similar results; For the comparison the results of the regularization inversion were averaged over two neighboring layers for the upper two layers (0–250 m and 250–500 m) and six consecutive layers for the lower layer (500–1250 m). The observed temporal variation demonstrates a similar trend to the prediction from the HYCOM ocean model [Figure 3(C-2)]. The strong currents (\( u_3 \), red line) were confined to the upper 200 m and rapidly weakened toward 500 m (\( u_2 \), blue line) in depth. The inversion results and HYCOM model outputs exhibit a pseudo 10-day period oscillation in the upper two-layer results.

3.2 Acoustic current mapping using distributed networked sensors

Distributed netted underwater sensors (DNUS) system presents a paradigm change that has generated high interest all over the world. It utilizes many small spatially distributed, inexpensive sensors, and a certain number of mobile nodes, such as autonomous underwater vehicles (AUVs), forming a wireless acoustic network to relate data and provide real time monitoring of the ocean. DNUS systems are expected to provide environmental (oceanographic) monitoring over large areas. As fabrication technology advances, low cost sensors will be available for many applications. The sensors communicate to each other and are networked using acoustic communications. The travel-time data can be extracted from the communication signals between the distributed networked sensors for the inversion of ocean current and temperature.
Figure 3: 2009 Kuroshio pilot experiment. (A) Location maps of the observation site with the positions of two moored stations T1 and T2 (circle). (B) Ray simulation and typical observed arrival patterns. (C) Time series plots of the inverted and HYCOM predicted currents at each layer. [10]

Ocean current mapping using the distributed networked sensors has several advantages compared with the conventional OAT approach based on peripheral sensors: 1) Energy and cost savings: Due to shorter transmission distance between sensors, networked sensors are more energy efficient compared with the conventional approach where sensors are placed at the periphery of the mapping area. 2) In-buoy processing: The local averaged ocean current can be estimated using acoustic signals sent within each Delaunay triangle of the networked sensors. Because the data processing is relatively simple, it can be performed by a computer processing equipment installed within the individual sensors. Results of the local ocean flow estimates for different overlapping clusters are communicated to the base station and are synthesized to produce quasi-tomographic results for a large area.

An Underwater Networking, Communications, and Acoustic Tomography (UNCAT) experiment was conducted in the Sizihwan Bay area in Kaohsiung, Taiwan, in May 2011. Figure 4(A) shows the plan view of the experimental site. Each acoustic unit, designed by NRL, consisted of a surface buoy connected via an electro-mechanical cable to an underwater acoustic modem made by Teledyne Benthos. The surface buoy [the left photo of Figure 4(B)] was constructed...
from a stacked pair of 30” diameter life rings and contained a 900 MHz radio antenna (for the communications between buoys and the control center installed on the R/V Ocean Researcher III (ORIII), a GPS receiver, and a single-board PC connected via an electrical cable to the underwater modem. Each modem was moored to the ocean bottom on a rigid platform [the right photo of Figure 4(B)] so that the travel time measurement is not affected by the sensor motion. For precise travel time measurements, the modem clock is synchronized to the GPS timing signal via the surface buoy. The acoustic units were deployed from ORIII. Once deployed, the modems were anchored to the seafloor and formed a static underwater network.

The travel-time data collected by the distributed networked sensors have been analyzed to reconstruct the local current distribution [4]. The path-averaged currents along T4-T2 and T4-T3 paths [the red solid circle in Figure 4(C)] show a trend similar to the direct measurement from ADCP mounted on the nearby weather buoy (blue circle). A reasonable agreement of the results is obtained when accounting for the placement of the buoy relative to the acoustic path [the white line in Figure 4(A)] and spatial differences between a point location and a path average. Figure 4(D) shows several snaps of the spatial distribution of the current. The current flows along the isobaths from northwest and turns eastwards toward the shore. The spatial distribution of the current field is successfully mapped using the deployed distributed networked sensors.

3.3 incorporating a moving vehicle to enhance current estimation

Moving Ship Tomography (MST) is a method of obtaining high-resolution, nearly synoptic maps of the ocean temperature over large areas [2]. Compared with a traditional tomographic system using only moored sensors, MST uses both moored sensors and acoustic sensors carried by a moving ship to generate a sufficient number of ray paths crossing the water volume, therefore, the spatial resolution is not limited by the number of sensors as in the traditional method.

The concept of MST has been extended to current field reconstruction. A reciprocal sound transmission experiment was conducted in June 2015 in the Sizihwan Bay area [Figure 5(A-1)] using a ship-towed transceiver and two bottom-moored transceivers. The transceiver towed by the ship was continuously moving along a planned route. Due to the relative motion of the towed and moored stations additional signal processing is required to compensate and estimate the Doppler distortions. For constant Doppler (constant relative velocity of the source and receiver), a wide-band delay-Doppler ambiguity function (AF) is computed, i.e., the received data are cross-correlated with the transmitted signal that is time-scaled with different Doppler shifts [Figures 5(B-1)&(B-2)]. The Doppler shift $\Delta f$ with the maximum correlation in the wide-band AF is selected. The delay time series associated with the maximum correlation [the white line in Figures 5(B-1)&(B-2)] is the Doppler compensated arrival pattern [Figures 5(B-3)&(B-4)]. Then, the differential travel time $\Delta t$ is estimated using the cross-correlation between the Doppler-compensated arrival patterns obtained in the reciprocal transmissions.

In the presence of ship motion, current estimation using differential travel time also depends on mean velocity of the two stations. Assuming during the sound transmission (within 0.5 sec) the moored station is static, we can estimate the relative velocity of towed transceiver from the obtained Doppler shift. Figure 5(C) shows that the time series of the relative velocity of
towed transceiver with respective to M1 station estimated from the Doppler shift. The result is consistent with that from the GPS logger on the ship. After correcting the differential travel time for the ship velocity, the path-averaged current speeds between the ship-towed and moored transceivers agree with the ADCP measurements [Figure 5(D)].

4 Concluding remarks and future development

The Kuroshio is an eminent western boundary current in the North Pacific Ocean, and has raised many interests for oceanographers. In the past two decades, there were several large-scale experiments about the Kuroshio studies, including the projects World Ocean Circulation Experiment (WOCE, 1990–2002), Observations for the Kuroshio Transports and their Variations (OKTV, 2012–2015), and the on-going project Study of the Kuroshio-II (SK-II, 2015–2017). Ocean acoustic tomography was originated from the application of oceanographic studies using acoustic means, and has now reached a certain degree of success. Our studies have shown that the estimation of current distributions surrounding Taiwan is achievable using OAT. As more
Figure 5: 2015 MVT experiment. (A) Positions of the moored stations (black circle) and track of the ship-towed transceiver (dots with different colors indicating time). Photo of the developed tomographic system. (B) Wide-band Delay-Doppler ambiguity function of the signal transmitted between the towed and moored stations, and their corresponding Doppler compensated arrival pattern. (C) Relative ship velocity with respect to M1. (D) Path-averaged current speed along the transmission path.

and more attention is devoted to the Kuroshio, not only in academia for many interesting problems such as the current wakes induced by deterred islands, but also in industrial applications such as Kuroshio power generation, it is our hope that OAT applications on the Kuroshio may call for international interests for a large-scale joint experiment, leading to a long-term study for many years to come.

Acknowledgements
We thank Professors Arata Kaneko and Noriaki Gohda of the Hiroshima University, Japan, for long-term collaborations on tomographic instruments, the crews of the R/V Ocean Researcher III of Taiwan for deploying the instruments, and the U.S. Office of Naval Research and the Ministry of Science and Technology (MOST) of Taiwan for supporting our work. The Ocean Data Bank of Ministry of Science and Technology provided the historical shipboard ADCP data.
References


