The First Chinese Coastal Acoustic Tomography Experiment

Xiao-Hua Zhu[1,3], Arata Kaneko[2], Qingsong Wu[1], Noriaki Gohda[2], Chuanzheng Zhang[1] and Naokazu Taniguchi[2]

[1]State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China
[2]Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima 739-8527, Japan
[3]Department of Ocean Science and Engineering, Zhejiang University, Hangzhou, 310058, China

***Abstract*-The first Chinese coastal acoustic tomography (CAT) experiment was successfully carried out during July 12 to 13, 2009 with seven acoustic stations for mapping the tidal currents in the Zhitouyang Bay near the Zhoushan Island. The CAT results showed the strong eastward tidal current which entered into the tomography site from the Loutou Channel at the western part of the bay, and separated into two branches, flowing into the Laoshumen Channel, Qingzimeng Channel and Fodu Channel during the ebb tide. On the other hand, the strong westward tidal current, joined with the currents from Laoshumen Channel, Qingzimeng Channel and Fodu Channel, went back to the Loutou Channel during the flood tide. A clockwise tidal vortex of diameter about 5 km was generated in the eastern part of the bay in the transition phase from the ebb to flood. No tidal vortices were generated in the weak tidal currents in the transition phase from the flood to ebb, changing the current direction from westward to eastward. The range-averaged current obtained along the transmission lines after the inverse analysis was in agreement with the acoustic Doppler current profiler (ADCP) results, producing the root-mean-square difference (RMSD) of 1.77 cm/s. The horizontal distributions of tidal current calculated by the inverse analysis were in rough agreement with that of the shipboard ADCP velocity. The RMSD is 11.70 cm/s for the eastward current and 16.50 cm/s for the northward current. It is suggested that the CAT is a powerful instrument for continuously mapping the horizontal tidal current structures in coastal regions in China with heavy shipping traffic and active fishing.**

Keywords: Coastal Acoustic Tomography; field experiment; tidal current; inverse analysis; Zhoushan Island.

I. INTRODUCTION

The ocean acoustic tomography (OAT) was proposed by Munk and Wunsch in 1979 as a powerful acoustic technique for mapping mesoscale oceanic features [1-2]. The coastal acoustic tomography (CAT) was also proposed as an application of OAT to the coastal sea, aiming at continuous monitoring of tidal currents in ports, bays and semi-enclosed and inland seas without disturbing shipping traffic, and fishing and marine aqua-culture activities [3].

The CAT system has been developed by Hiroshima University and successfully applied to current structure measurement in coastal seas around Japan since 1995 [4-9]. However, until now no CAT application experiments were carried out outside Japan. This paper reports the coastal acoustic tomography experiment which was attempted first in China.

II. EXPERIMENT SITE AND METHOD

The tomography experiment with seven CAT systems was carried out during July 12-13, 2009 in the Zhitouyang Bay near the Zhoushan Island, facing the mouth of Hangzhou Bay, China (Figure 1). The Zhitouyang Bay was composed of four channels, the Loutou Channel, Fodu Channel, Qingzimen Channel and Laoshumen Channel. The water depths are deeper than 40 m in the southwestern part of the bay and shallower than 20 m in the northeastern part of the bay. The maximum and minimum water depth is 91 m and 3 m inside the tomography domain, respectively. The area of the tomography domain is about 11.4 km×11.5 km.

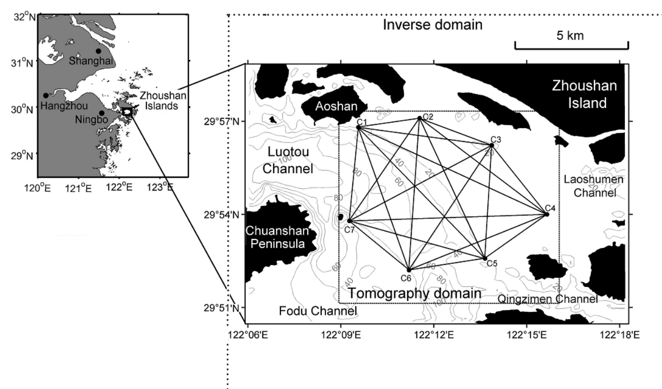

Figure 1. Location maps of the experimental site. The positions of the CAT stations C1-C7 are shown with the solid circles. The thick solid lines connecting the CAT stations indicate the sound transmission lines. The interval of bathymetric contours is 20m.

Seven CAT systems numbered from C1 to C7 were set up, using the fishing boats, anchored at the periphery of the bay. The transmitter/receiver was suspended down up to 5-10 m depth through a rope from the boat while the major components of the system such as electronic housing, battery, and GPS antenna were put on the boat. The 5 kHz sound, phase-modulated by the 10^{th} order M sequence, was transmitted every 3 minutes from the broadband transducer (Neptune T170). The M sequences with different codes were assigned for each of acoustic stations to resolve multi arrivals. One period of the M sequence was transmitted with the pulse

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

width of 0.64s. As a result, one station receives transmission signals from other six stations with resolvability.

The shipboard acoustic Doppler current profiler (ADCP, RDI 600-kHz) surveys were also performed during the CAT experiment inside the tomography domain and collected the data for comparing with the CAT data. Five CTD casts were executed during the shipboard ADCP surveys.

III. Inverse analysis

In the inverse analysis developed by Park and Kaneko[10], travel-time differences, obtained from the reciprocal sound transmission between the paired CAT stations, are adopted as data to reconstruct the tidal current distributions. The inverse domain is extended to 23 × 23 km which is twice the tomography domain. The relationship between the travel-time difference vector $\boldsymbol{y}$ and unknown velocity vector $\boldsymbol{x}$ may be expressed by the form [1, 3]:

$$\boldsymbol{y} = \boldsymbol{E}\,\boldsymbol{x} + \mathbf{n}, \quad (1),$$

where $\boldsymbol{y}$ is the column vector of order 21 (the total numbers of station pair), $\boldsymbol{x}$ the 23-element vector of Fourier function series, used to simulate the velocity distributions, $\boldsymbol{E}$ the 21 × 23 matrix, estimated from the location data of seven CAT stations and $\mathbf{n}$ the noise vector which represent both the measurement error and other uncertainties in the model. The inverse solution is obtained by the "tapered least squares" method described by Yamaoka et al. [6].

IV. Results

A. Ray pattern

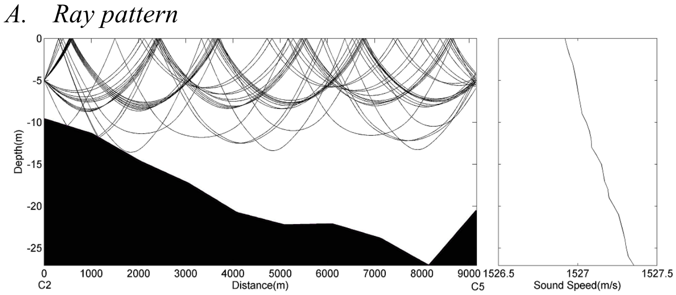

Figure 2. Ray pattern between the CAT stations C2 and C5, simulated by the ray tracing method. The range-averaged sound speed profile used in the simulation is presented in the right panel.

Figure 2 shows the typical ray patterns obtained between C2 and C5 by the ray-tracing method which uses the range-averaged sound speed profile determined from the CTD data. Water in the observation region was well mixed due to strong tidal currents. As a result, the sound speed was gradually increased with depth. Almost all the ray paths are confined to the upper 10 m, forming a three-time surface reflection or a one-time bottom reflection near C2. The travel time for these rays makes the mean and standard deviation of 5987.1221 ± 0.0053 ms with the variation range from 5987.1045 to 5987.1315 ms. This means that transmission signals are received, forming multiple arrivals within a quite short range of travel time.

B. Received data

Reciprocal sound transmissions were successfully performed along the 21 transmission lines which connect the seven CAT stations. Data lacking due to traffic or anchored ships frequently occurred in the experiment. The received signal between C1–C5 is shown with the unit of signals-to-noise ratio (SNR) as a typical example in Fig.3a. The correlation waveform of received signals makes a sharp arrival peak with a large SNR. The maximum SNR reaches about 730-879 (28.6-29.4 dB). The travel time is determined at the peak point with the maximum SNR.

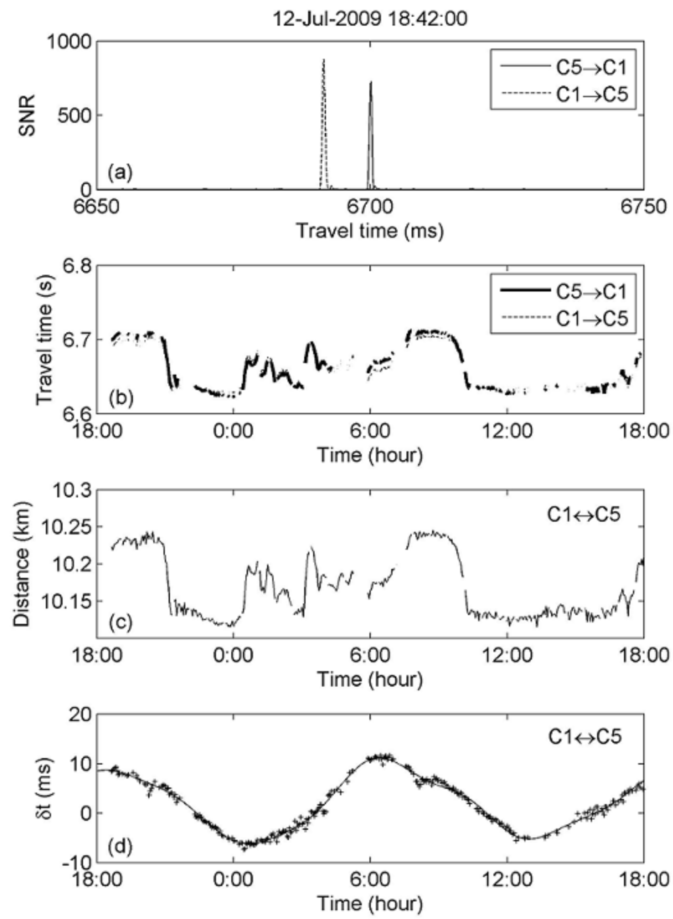

Figure 3. (a) Typical correlation waveforms, and time plots of (b)travel time, (c) station-to-station distance and (d) travel-time difference. These data are acquired between C1 and C5.

The 3-minute interval travel-time data obtained between C1–C5 vary between 6.6 and 6.7 s (Fig.3b). It was caused by the ship drift of about 150 m due to tidal currents (Fig.3c).

The travel-time difference (δt) data show the prominent semidiurnal oscillation, as seen with dots in Fig.3d. The δt predicted by the harmonic analysis, which considers the 8 major tidal constituents of K1, M2, M3, M4, 2MK5, M6, 3MK7 and M8, traces the plotted δt quite well (see the solid line in Fig.3c). The RMSD between the raw δt and its predication is 0.637 ms. This RMSD value results in the velocity error of 7.3 cm/s under the sound speed of 1527m/s and the station-to-station distance of 10200m. The predicated

δt is also useful to reproduce the lacked data by the smooth functions.

C. Inverse results

The inverse results provide the continuous mapping of horizontal tidal current distributions at a 3-minute interval. The typical horizontal tidal current structures are shown with the vector plots in Fig. 4. The strong eastward tidal current with a maximum velocity of 2.34 m/s entered into the tomography site from the Loutou Channel at the western part of the bay, and separated into two branches, flowing into the Laoshumen Channel, Qingzimeng Channel and Fodu Channel during the ebb tide (Fig.4a). On the other hand, the strong westward tidal current, joined with the currents from Laoshumen Channel, Qingzimeng Channel and Fodu Channel, went back to the Loutou Channel during the flood tide (Fig.4c).

A clockwise tidal vortex of diameter about 5 km was generated in the eastern part of the bay in the transition phase from the ebb to flood (Fig.4c). No tidal vortices were generated in the weak tidal currents in the transition phase from the flood to ebb, changing the current direction from westward to eastward (Fig.4d).

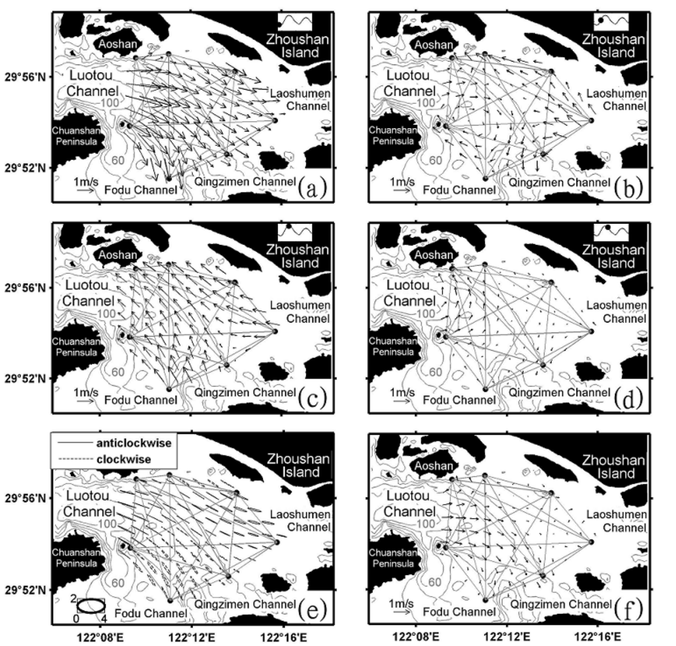

Figure 4. Horizontal current distributions, obtained at (a) 18:00 (b) 22:00 of July 12, (c) 01:00 and (d) 03:00 of July 13 by the inverse analysis. The tidal level is shown at the top-right corner in each panel. (e) Distributions of M2 tidal ellipse, and (f) residual current vectors.

The semi-major axes of the tidal ellipse were directed in the east-west direction, and separated into two directions on the eastern side. The mean semi-major and semi-minor axes of the tidal ellipses were 1.51 m/s and 0.13 m/s, respectively. The rotation of the tidal vector was anticlockwise in the northern part of the bay while it was clockwise in the southern part of the bay (Fig.4e). The vector plot of residual current obtained by removing the tidal component from the original data through the harmonic analysis is shown in Fig.4f. The residual current was strong near the Luoto Channel and became weak in the eastern part of the bay. The residual current flowed eastward from the Luotou Channel, and then turned southward along the 40 m bathymetric contour line.

The distributions of current across the four transects C1-C7, C5-C7, C3-C5 and C1-C3 which form a closed box, are shown in Fig.5 at the same tidal phases as for Fig.4. During the ebb tide, the eastward tidal current was the strongest at the center of the C1-C7 transect, and at the northern part of the C3-C5 transect. The current flowed into the closed box from the C1-C7 and C1-C3 transects and went out from the other two transects (Fig.5a). The westward tidal current was the strongest at the northern part of the C1-C7 transect during the flood tide (Fig.5c), and the current was directed opposite to that during the ebb tide. The cross-transect currents were weak in the transition phase of tides (Figs.5b and 5d).

The volume transports across the upper 10 m of the four transects and their residuals for the closed box in the same four tidal transition phases as for Fig.5 are summarized in TABLE I. The residual volume transports were only 0.5 and 2.6% of the total inflow and outflow volume transports from the box during the ebb and flood tides, respectively, showing a good mass balance.

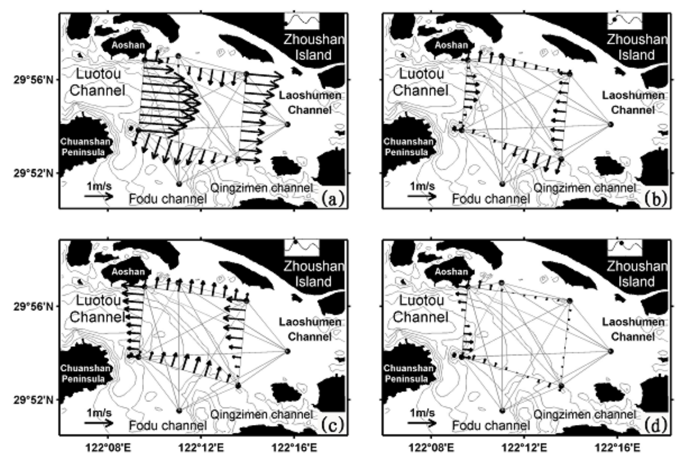

Figure 5. Distributions of current across the transects C1-C7, C5-C7, C3-C5, and C1-C3, obtained at the same tidal phases as for Fig.3. (a) 18:00 (b) 22:00 of July 12, (c) 01:00 and (d) 03:00 of July 13. The tidal level is indicated at the top-right corner in each panel.

TABLE I Volume transport across the upper 10 m of the transects[a]

Time	18:00	22:00	01:00	03:00
C1-C7	95082	11946	-32529	1695
C1-C3	13208	-17844	-30796	-3640
C3-C5	-63591	25550	31680	763
C5-C7	-44198	-18668	32186	1917
Residual	501	984	541	735

[a] Unit: m^3/s, Positive values mean the inflow volume transports to the box.

V. EVALUATION OF THE INVERSE RESULTS

The range-averaged current velocity (post-inversion result), obtained along the transmission line of C1-C5 by the inverse analysis is shown in Fig.6, together with that (pre-inversion result), obtained by substituting the travel-time difference data into the formula [4] :

$$u_m \approx \frac{c_m^{\ 2}}{2L}\delta t \quad (2)$$

where C_m is the rang-averaged sound speed and L the range between C1 and C5. The post-inversion result showed a prominent semidiurnal oscillation and was in good agreement with the pre-inversion result with the RMSD of 3.70 cm/s (Fig.6). Furthermore both the range-averaged current velocities agreed well with the ADCP results, and their RMSDs are 1.59 cm/s for the post-inversion result and 1.77 cm/s for the pre-inversion result.

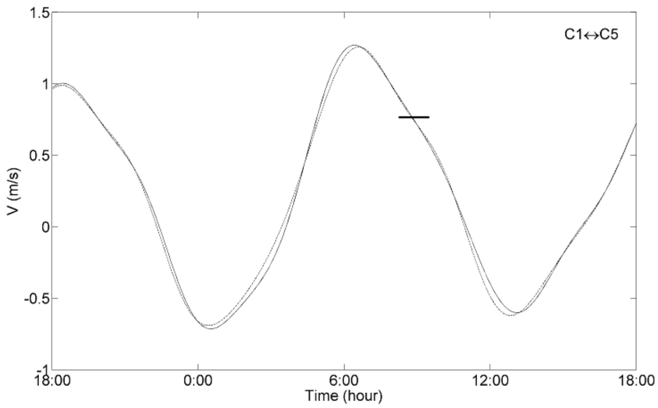

Figure 6. Time plots of the-range-averaged current velocity, estimated along the transmission line C1-C5 before (solid line) and after (dotted line) the inverse analysis. The upper 10m average velocity, obtained by the shipboard ADCP is indicated with the thick horizontal bar.

The horizontal distribution of tidal currents obtained from the inverse analysis is in rough agreement with that of the shipboard ADCP velocity, smoothed though a 10-minute running mean (Fig.7). The RMSDs are 11.70 cm/s and 16.50 cm/s for the eastward and northward currents, respectively.

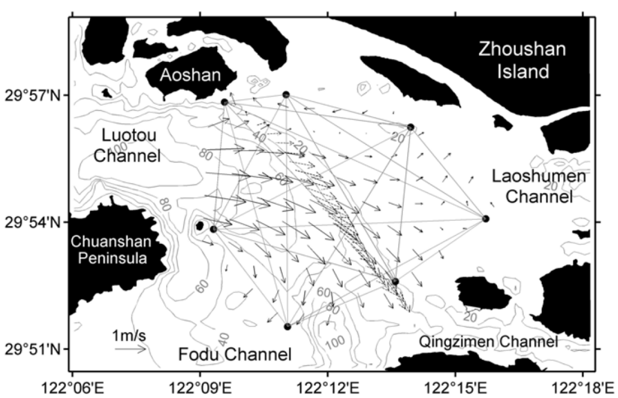

Figure 7. Comparison of the CAT (solid line) and ADCP (dotted line) velocities along the ship track.

VI. SUMMARY AND DISCUSSION

The first Chinese CAT experiment for mapping tidal currents in the coastal seas was successfully carried out with seven acoustic stations, located in the Zhitouyang Bay near the Zhoushan Island. The horizontal tidal current fields are reconstructed by the inverse analysis of reciprocal travel time data. The strong eastward tidal currents with two branches during the ebb tide and the reverse currents during the flood tide are well reconstructed. The clockwise tidal vortex of size 5km at the eastern part of the bay is also reconstructed in the transition phase from the ebb to flood.

The observed travel time difference (δt) is well simulated by the harmonic analysis which considers the 8 major tidal constituents K1, M2, M3, M4, 2MK5, M6, 3MK7 and M8. This result is so useful not only for interpolating and smoothing the raw δt, but also for predicating δt for the future time. This is a new proposal that makes it possible to predicate tidal currents inside the tomography domain by the inverse analysis from the predicated δt without the tidal circulation model or data assimilation method.

The above results suggest that the CAT is a quite powerful instrument for continuously mapping the horizontal tidal current structures in coastal regions with heavy shipping traffic and active fishing.

ACKNOWLEDGMENT

This study was supported by the scientific research fund of Second Institute of Oceanography, SOA (No.JT0903), the National High Technology Research and Development Program (2006AA09Z102), the Zhejiang Provincial Natural Science Foundation (2007R10G3050004) and National Natural Science Foundation of China (40776021 and 40706017). We thank Mrs. Wen Y. Z., Zeng D.Y., Lin Y., Xu L.J., Ding Y. B. and Zhou Z. J. for their supports in the shipboard work during the experiment.

REFERENCES

[1] Munk W, Worceser P F, Wunsch C. Ocean Acoustic Tomography, Cambridge: Cambridge University Press, 1995, 1-433.

[2] The ocean tomography group. “A demonstration of ocean acoustic tomography”, Nature, 1982, 299, 121-125.

[3] Elisseeff, P., H. Schmidt, M. Johnson “Acoustic tomography of a coastal front in Haro Strait, British Columbia”, J. Acoust. Soc. Am., 1999, 169-184.

[4] Zheng, H., N. Gohda, H. Noguchi, T. Ito, H. Yamaoka, T. Tamura, Y. Takasugi and A, Kaneko, “Reciprocal Sound Transmission Experiment for Current Measurement in the Seto Inland Sea. Japan”, J. Oceanogr., 1997, 53, 117-127.

[5] Yamaoka, H., A. Kaneko, J.- H. Park, H. Zheng, N. Gohda, T. Takano, X-H. Zhu and Y. Takasugi, “Coastal acoustic tomography system and its field application”, IEEE J. Oceanic Eng., 2002, 27(2), 283-295.

[6] Kaneko, K. Yamaguichi, T.Yamamoto, N. Gohda, H. Zheng, S. Fadli, J. Lin, H.Q. Nguyen, “Coastal acoustic tomography experiment in the Tokyo Bay”, Acta Oceanologica Sinica, 2005, Vol.24, 86-94.

[7] Lin J., A. Kaneko, N. Gohda and K. Yamaguchi, “Accurate imaging and prediction of Kanmon Strait tidal current structures by the coastal acoustic tomography data”, Geophys. Res. Lett., 2005, 32, L14607, doi: 10.1029 /2005GL022914.

[8] Yamaguchi K, J. Lin, A. Kaneko, T. Yamamoto, N. Gohda, H.-Q. Nguyen and H. Zheng, “A continuous mapping of tidal current structures in the Kanmon Strait”, J. Oceanogr., 2005, 61, 283-294.

[9] Nguyen, H., A. Kaneko, J. Lin, K. Yamaguchi, N. Gohda and Y. Takasugi, “Acoustic Measurement of Multi Sub-Tidal Internal Modes Generated in Hiroshima Bay, Japan”, IEEE Journal of Oceanic Engineering, 2009, 34(2), 103-112.

[10] Park, J. -H. and A. Kaneko, “Assimilation of coastal acoustic tomography data into a barotropic ocean mode”, Gophys. Res. Lett., 2000, 27, 3373-3376.