# Reciprocal sound transmission experiments for current measurement in a tidal river

Chuanzheng Zhang[1], Xiao-Hua Zhu[1,3]*, Arata Kaneko[2], Qingsong Wu[1], Xiaopeng Fan[1], Bo Li[1], Guanghong Liao[1], Tao Zhang[1]

[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
(*Corresponding author: xhzhu@sio.org.cn)

***Abstract* — Six repeat reciprocal sound transmission experiments for current measurement were successful carried out in the upstream region of the Qiantang River in Hangzhou city, about 90 km from the mouth of Hangzhou Bay during April to December 2009. Two Coastal Acoustic Tomography (CAT) Systems were set up at a distance of 3050 m for making a reciprocal transmission between the both banks of the Qiantang River. During the sound transmission experiments, thirty-two repeat shipboard Acoustic Doppler Profiler (ADP) surveys were also performed along the sound transmission line to get a comparison with the reciprocal sound transmission data. Range-averaged current velocities, determined from the travel time differences along the transmission line were in good agreement with those from the ADP, producing a root-mean-square difference of 0.03 m/s .The travel time differences data were well correlated with the river discharge estimated from the ADP data. The time series of river discharge during the experimental period was estimated through an empirical formula, relating to both the parameters. The variations of river discharge caused by tidal bores were well captured. The river discharge changed in the range of -7626 $m^3$/s and 5096 $m^3$/s, with a mean of 1246 $m^3$/s. The above results suggest that the CAT is a powerful instrument for measuring continuously the river discharge in such tidal rivers with quite heavy shipping traffic.**

***Keywords-Coastal Acoustic Tomography; reciprocal sound transmission; current measurement; river discharge; tidal bore; Qiantang River.***

## I. INTRODUCTION

The tidal bore is a positive surge which maintain a step-wise sea level rise over a significant range when it propagates from the offshore to estuary [1]. In the Qiantang River, majestic tidal bores will be formed at flood tides due to the astro-tidal-triggering and the horn-shaped terrain of Hangzhou Bay. The tidal bore at the estuary of the Qiantang River in China is one of the most spectacular bores in the world due to its height and its variety in appearance and shape [2]. The tidal bores in the Qiantang River are also called as “Qianjian waves” in China, which generate around the mouth of Hangzhou Bay and propagate to the upstream along the Qiantang River. The maximum wave height reaches about 11 m at the entrance of the Qiantang River and decreases about 0.9 m in its upstream region belonging to Hangzhou City, about 90 km from the mouth of Hangzhou Bay.

The river discharge is an important hydrological factor in the flood control and the management of water resources. Therefore, the continuous progress of discharge measurement method is an important issue. However, the conventional current measurement methods such as ADCP [3] can only observe the current at a one-point. To get the long-term data of section-averaged velocity and resulting river discharge, the necessary array of currentmeters should be deployed over the stream section of the river. The long-term measurement of river streams has often been prohibited by the heavy shipping traffic especially in large rivers in China. As a traditional method, a water level meter [4] is often operated to measure the discharge of non-tidal rivers. However, in a tidal river like the Qiantang River, water level may not be a good parameter to know the river discharge because of the non-applicability to time varying flows.

In the previous study, the reciprocal sound transmission [5-6] method has been proposed as an innovative technology to measure continuously the cross-sectional average velocities in a tidal channel. However, until now no reciprocal sound transmission experiment was attempted to measure the variation of discharge in tidal rivers in China. This paper reports the reciprocal sound transmission experiments, which was performed in the Qiantang River as the first application in China.

## II. EXPERIMENT SITE AND METHOD

The reciprocal sound transmission experiments for current measurement by use of the Coastal Acoustic Tomography System (CATS) were carried out in the upstream region of the Qiantang River, about 90 km from the mouth of Hangzhou Bay during April to December, 2009 (Fig.1).

Two CATSs [7] were set up at stations E and W with a distance of 3050 m across the Qiantang River. The transducer (Neptune T170) was suspended down up to depth 3 m through a rope from the pier/wharf while the system components such as electronic housing, battery and GPS antenna were put on the pier/wharf. The 5 kHz sound, modulated by one period (0.64 s) of the pseudo random signal, called the $10^{th}$ order M sequence, was transmitted every 3 minutes from the broadband transducer.

During the reciprocal sound transmission experiments, the shipboard Acoustic Doppler Profiler (ADP, SonTek/YSI Inc, 1.5 MHz) surveys were also performed to measure current

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velocities along the sound transmission line with an angle of $\theta$ =25° from the stream axis of the river.

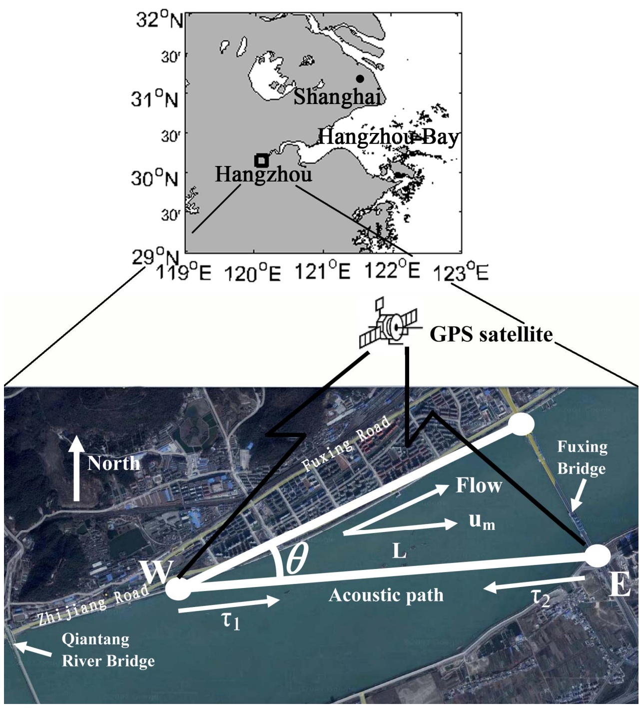


Figure1. Study area and the schematic view of experimental set-up.

## III. MEASUREMENT PRINCIPLES

The travel times $\tau_1$ and $\tau_2$ for the reciprocal sound transmission as sketched in Fig.1 are calculated by the following formulae [8]:

$$\tau_1 = \frac{L}{c_m + u_m} \tag{1}$$

$$\tau_2 = \frac{L}{c_m - u_m} \tag{2}$$

The $c_m$ and $u_m$ are the mean sound speed and range-averaged current velocity along the ray path, respectively. $L$ is the path length. After a simple calculation from (1) and (2), we obtain:

$$u_m = \frac{L}{2}\left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right) \approx \frac{c_m^2}{2L}\Delta\tau \tag{3}$$

$$c_m = \frac{L}{2}\left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right) \approx \frac{L}{\bar{\tau}} \tag{4}$$

Where $\bar{\tau} = \frac{1}{2}(\tau_1 + \tau_2)$ and $\Delta\tau = (\tau_2 - \tau_1)$. Here we assume the ray paths are the same in the reciprocal direction, and $\bar{\tau} \approx \tau_1 \approx \tau_2$. Differentiating (3) and (4), we obtain the relative error of $u_m$ as

$$\frac{\delta u_m}{u_m} = \frac{\delta L}{L} - 2\frac{\delta\bar{\tau}}{\bar{\tau}} + \frac{\delta(\Delta\tau)}{\Delta\tau} \tag{5}$$

The second and third terms in (5) are negligibly small when both systems are synchronized precisely with the GPS clock. The relative error for the ranger-averaged velocity reduces to

$$\frac{\delta u_m}{u_m} \approx \frac{\delta L}{L} \tag{6}$$

In the present experiments of $L \approx 3km$, the GPS distance error of 30 m causes the relative velocity error of $\delta u_m / u_m = 0.01$. The $\delta u_m$ is 1cm/s for $u_m = 1m/s$. This means that the velocity error is negligibly small when the highly accurate measurement of travel time is achieved with synchronization by the GPS clock.

## IV. RESULTS

### A. ADP data

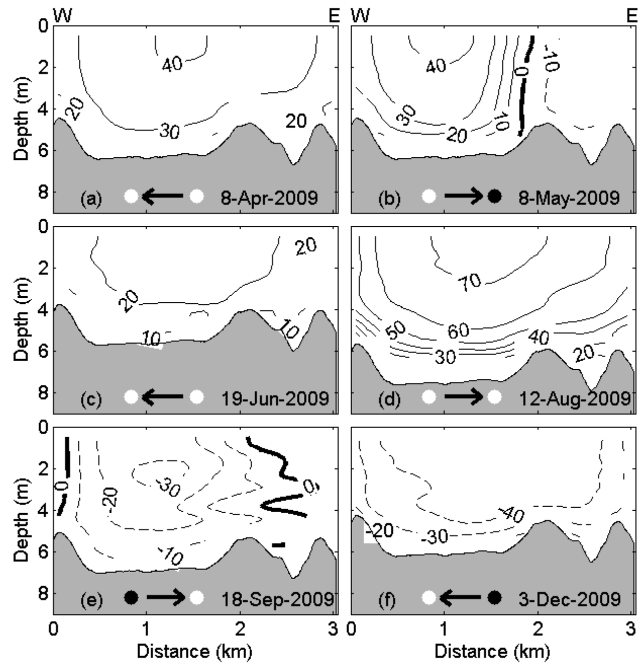


Figure2. Vertical sections of the along-stream velocity measured by ADP. The positive (solid line) and negative (dotted line) values indicate the eastward (W→E) and westward (E→W) velocity, respectively. Contour interval is 10 cm/s. Thick contours show zero velocity. The black arrows show the directions of the shipboard survey. The solid and white circles mark the flood and ebb tide during the shipboard surveys, respectively. The dates of data acquisition are indicated in the bottom-right corner of each panel.

The typical vertical sections of the along-stream velocity obtained by ADP during each reciprocal sound transmission experiment are shown in Fig.2. Current velocities were positive (eastward flow) for Figs.2a, 2c and 2d, indicating freshwater flows from upstream to downstream during the ebb tide. The maximum velocity reached 75.10 cm/s (Fig.4d) on August 12, 2009 just after a rainstorm attack at the upstream of the Qiantang River. Figure 2b shows the velocities, which changed from positive to negative due to the arrival of a tidal bore during the shipboard survey. The currents for Figs.2e and 2f were mainly westward during the arrival of the tidal bores, forming the maximum westward velocity of -48.60 cm/s (Fig.2f).

The vector plots of the depth-averaged current velocity obtained by ADP along the sound transmission line at the phase which corresponds to Fig.2 are shown in Fig.3. The ADP data show the current flows along the Qiantang River almost in parallel to the river bank without meanders. This implies the reasonability of current measurement by reciprocal sound transmission between two CAT stations distributed on both the banks. In an overall view, the depth-averaged currents trace the cross-stream sections of Fig.2. The current directions were the same during each cruise except Fig.3b where the eastward current was gradually decreased and replaced by the slowly increasing westward current during the arrival of tidal bore.

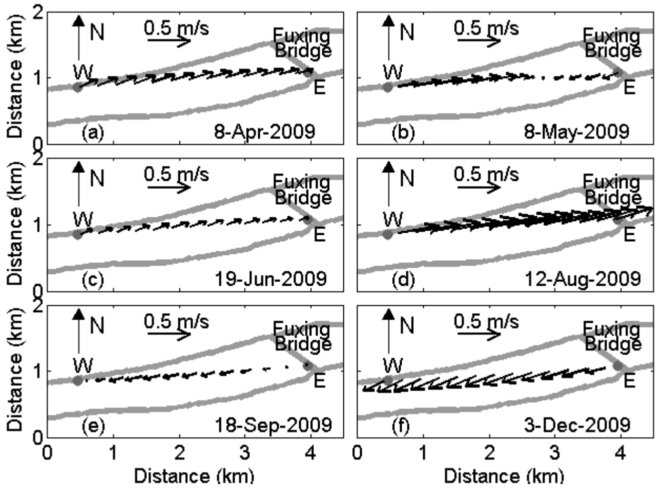


Figure3. Vector plots of the depth-averaged current velocity measured by the shipboard ADP. The upward arrows point out the north. The cross-stream line near the station E indicates the Fuxing Bridge.

### B. *CATS data*

Reciprocal sound transmissions were successfully performed along the sound transmission line. The stack plots of correlation waveforms with the vertical axis scaled by the signal-to-noise ratio (SNR) are shown as typical examples in Fig.4. There were very sharp arrival peaks in the correlation waveforms. The maximum SNRs of the peaks reached about 100-300 (about 20-25 dB). The travel times of sound are determined at the peak point with the maximum SNRs.

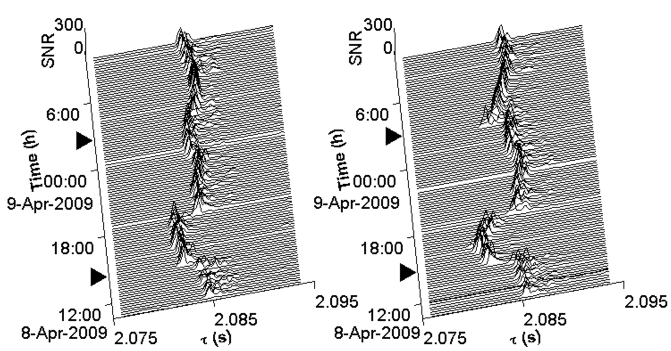


Figure 4. Typical examples of the stack plot, constructed by piling up the correlation waveforms at a successive time. Left panel: W→E, right panel: E→W. Black triangles show the arrival time of tidal bores, based on eye inspection.

The time plots of travel time are shown for the reciprocal directions in Fig.5. The travel time changed in the range of 2.033 s and 2.103 s during the whole experimental period, closing to the expected travel time of about 2.061 s between the two stations (3050m/1480m/s= 2.061 s). The reciprocal travel time decreased suddenly at the arrival of tidal bores as indicated with the black triangles in Figs.5 a, b, d and e, and the travel-time from W to E is larger than that from E to W. On September 18 the maximum change of travel time reached 8.25 ms (Fig.5e) which corresponds to the sound speed change of 5.8m/s or the temperature change of 2.2 ℃. The changes of travel time during the arrivals of tidal bores are caused by the sound speed changes due to the downstream increase of water temperature along the Qiantang River (because salinity is nearly zero). This temperature distribution will be discussed in the future paper.

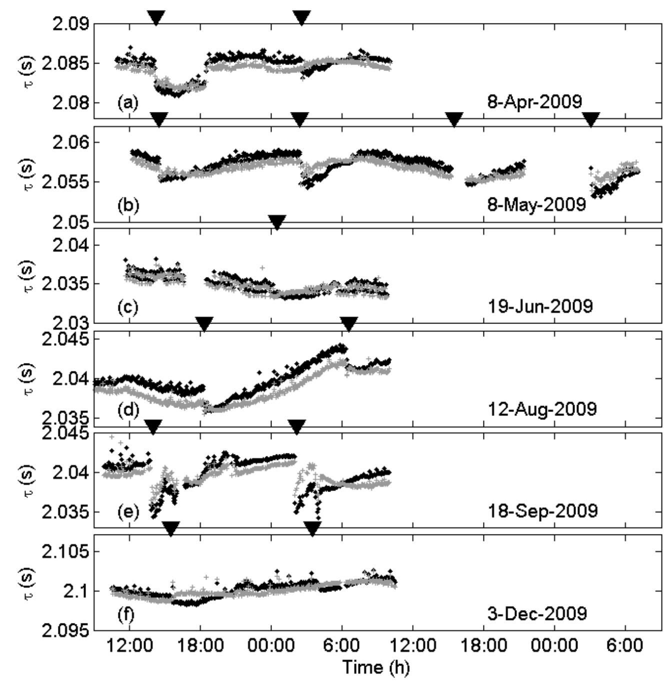


Figure5. Time plots of travel time obtained in the reciprocal sound transmission experiments. The gray and black dots indicate the travel time from W to E and from E to W, respectively. The black triangles at the top of each panel are same as in Fig.4.

## V. RANGE-AVERAGED VELOCITY

The time plots of the range-averaged along-stream velocity ($\overline{V}_{CATS}$) were estimated, using (3) from the travel time difference data. The $\overline{V}_{CATS}$ and shipboard ADP velocities ($\overline{V}_{ADP}$) are compared in Fig.6. The $\overline{V}_{CATS}$ are in good agreement with $\overline{V}_{ADP}$, producing a root-mean-square difference (RMSD) of 0.03 m/s.

The $\overline{V}_{CATS}$ made a dramatic change during the arrival of tidal bores. Before their arrivals, freshwater flowed eastward from upstream to downstream with velocities ranging from 0.25 m/s (Fig.6c) to 0.82 m/s (Fig.6d). The eastward freshwater flow became weak, and then changed its directions form eastward to westward within a short period of about 20 minutes when the tidal surges arrived at the experiment site. This westward flow reached the maximum velocities ranging from -0.11 m/s (Fig.6d) to -1.18 m/s (Fig.6e), and then kept its direction and magnitude for about 100 minutes constant. This westward flow was gradually replaced by the eastward flow, and this "drama" finished in about 5 hours and 20 minutes after the arrival of tidal bores. This "drama" occurred twice one lunar day in a synchronized timing with the semidiurnal tide in Hangzhou Bay.

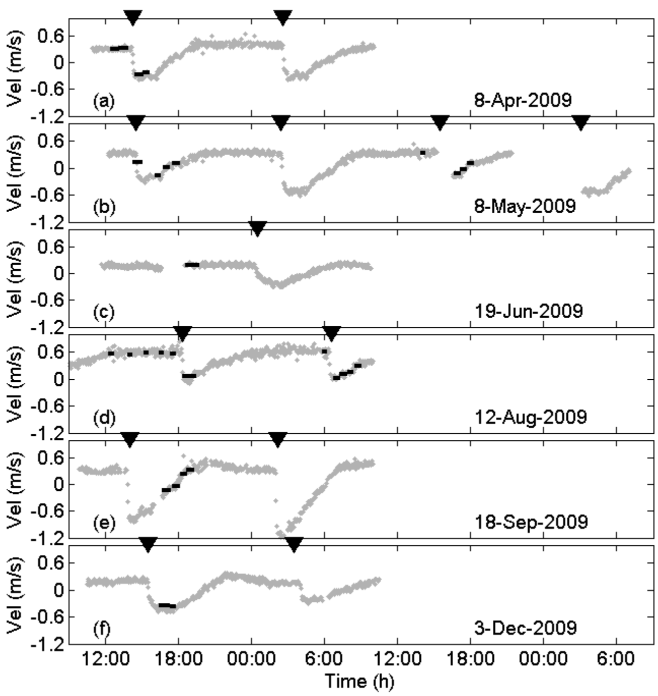


Figure 6. Time plots of the range-averaged velocity measured along the sound transmission line by CATS (gray dots). Horizontal bars indicate the velocity measured by ADP. The black triangles at the top of each panel are the same as in Fig.4.

## VI. ESTMATION OF RIVER DISCHARGE

The relationship of the travel time differences ($\Delta\tau$) to the river discharges ($Q_{ADP}$) calculated by the ADP data is shown in Fig.7. The $\Delta\tau$ data were well correlated with $Q_{ADP}$, with a linear relation. The correlation coefficient is 0.99 and the RMSD from the regression line is 241 $m^3/s$. The empirical formula which connects $Q_{CATS}$ and $\Delta\tau$ may be expressed by:

$$Q_{CATS} = -2400 \times 10^3 \Delta\tau + 179 \qquad (7)$$

The 179 $m^3/s$ of $Q_{CATS}$ at $\Delta\tau$=0, indicates a bias which exists between $Q_{ADP}$ and $Q_{CATS}$. The river discharge during the whole experimental period was estimated in a time series through this empirical formula (Fig.8). $Q_{CATS}$ has a quite good agreement with $Q_{ADP}$. The variations of the river discharge were very similar to that of the velocity (Fig.6). During the arrival of tidal bores, $Q_{CATS}$ changed not only in its values but also in its directions, meaning that the river discharge changed from eastward to westward. The eastward freshwater discharge reached a maximum value of 5096 $m^3/s$ during 0:00 - 6:30 of 13 August when the rainstorm attacks the upstream region of the Qiantang River just before the experiment. On the other hand, the maximum westward discharge of -7626 $m^3/s$ (from downstream to upstream) occurred in the spring tide during 2:00 - 3:40 of 19 September when the tidal bores became the strongest in all the experimental periods. The mean of $Q_{CATS}$ for the whole experimental period was 1246 $m^3/s$ and equivalent to the averaged freshwater discharge of the Qiantang River.

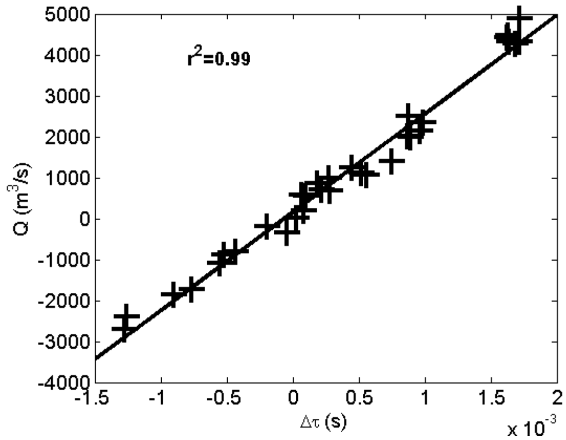


Figure7. River discharge ($Q_{ADP}$) plotted against the travel-time difference ($\Delta\tau$). The solid line indicates the regression line derived from the least square method.

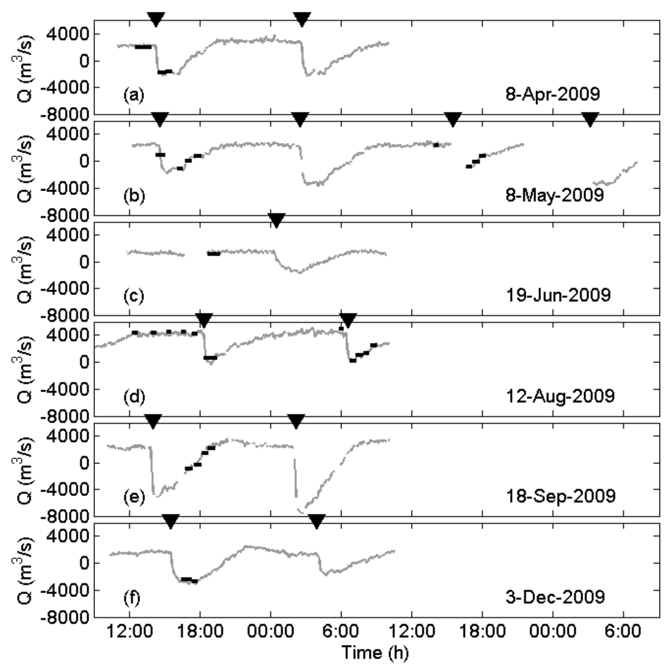


Figure 8. Time plots of the river discharge smoothed through the 9-minute running mean. The triangles and horizontal bars in each panel are the same as in Fig.6.

## VII. ERROR ESTMATION

The estimated error of $Q_{CATS}$ is derived from three kinds of sources and converted to the velocity errors as follows:

The first error is due to the accuracy of river discharge estimated by using the ADP data. The ADP observation accuracy is $v_{ADP}$ =0.005 m/s [9], and the error due to the compass misalignment, corrected by DGPS during the shipboard surveys is $v_{DGPS}$=0.011m/s. The total error for the ADP data results in $\sqrt{v_{ADP}{}^2 + v_{DGPS}{}^2}$ =0.012m/s.

The second error is from the CATS measurement error. The system clock accuracy of 0.5 $\mu s$ [7] causes a travel-time measurement error which corresponds to the velocity error of $v_{CATS}$ =0.000 m/s (using (3)).

The third error occurs in using the regression relationship between $Q_{ADP}$ and $\Delta\tau$, accompanied by the RMSD of 0.032 m/s (241 $m^3$/s) between the observational data and the regression line.

The three error components mentioned above propagate together and generate the resultant error of $\sqrt{0.012^2 + 0.00^2 + 0.032^2}$ =0.034 m/s (correspond to the $Q_{CATS}$ error of 254 $m^3$/s) .

The linear regression procedure makes the major error source which contains about 89% of the total error.

## VIII. SUMMARY

The repeat reciprocal sound transmission experiments for current measurement were successful carried out by using the CATSs in the Qiantang River during April-December 2009. During the sound transmission experiment, the repeat shipboard ADP surveys were also performed along the sound transmission line. The major results of the experiments are summarized as follows:

*1)* The range-averaged along-stream current estimated from the travel time data is in good agreement with that measured by ADP, producing the RMSD of 0.03 m/s. These results indicate the availability of current measurement based on reciprocal sound transmission for the Qiantang River.

*2)* The river discharges for the whole experimental period are estimated through the empirical formula between the travel time and ADP data. The Qiantang River discharge changes in the range of -7626 $m^3$/s and 5096 $m^3$/s, with a mean of 1246 $m^3$/s.

*3)* The total error of river discharge is evaluated as 0.034 m/s after three-component consideration. The linear regression procedure makes the most major source which contains about 89% of the total error.

The present study provides a prosperous way for continuous long-term monitoring of river discharge in large tidal rivers with heavy shipping traffic like the Qiantang River, China.

## ACKNOWLEDGMENT

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