Measurement of Yangtze River Flow Based on Coastal Acoustic Tomography

Zhengwei Chen, Hong Zheng, Yunfeng Tang*, Chao Chen
Marine Acoustics and Remote Sensing Laboratory, Zhejiang Ocean University, Zhoushan, 316000, China
Email: 1072492830@qq.com

Abstract. River flow is an important hydrological element for river management, and it can be used to detect the profile of river water resources. Coastal acoustic tomography technology, is a novel flow measurement technology, can continuously observe flow changes compared to the acoustic Doppler velocity profiler (ADCP) flow measurement. In this article, our experiment has arranged two acoustic tomography stations on both banks near the Datong Hydrological Station in the Yangtze River. Each station is equipped with a coastal acoustic tomography system. The depth of the transducer placed underwater is about 7 meters, the frequency of the transmitted signal is 50kHz. Knowing the distance between the two stations, calculate the average flow velocity between the stations according to the reciprocal propagation time difference between the stations, and then obtain the average velocity of the section according to the geometric relationship between the flow velocity between the stations and the section velocity. Finally the cross-sectional velocity multiplied by the cross-sectional area is the cross-sectional flow, and the calculation result of the river flow is compared with the official data. Experimental results prove that coastal acoustic tomography technology has broad prospects in monitoring river flow.

1. Introduction
Ocean Acoustic Tomography (OAT) is an emerging technology that uses acoustic methods to detect large-scale ocean environments based on experimental verification by American scientists Munk and Wunsch in the 1990s [1]. Compared with traditional anchoring or ship-borne flow measurement, the acoustic tomography method requires only a small number of acoustic stations to be deployed to obtain a large-scale vertical and horizontal distribution of complex flow fields, which is suitable for monitoring the shallow sea marine environment such as Harbors and channels [2, 3]. Later, scholars from Hiroshima University in Japan proposed Coastal Acoustic Tomography (CAT) on the basis of ocean acoustic tomography. Coastal Acoustic Tomography is suitable for small-scale measurement in offshore waters, compared to ocean acoustic tomography. The measurement accuracy is higher. Coastal acoustic tomography is also widely used in coastal waters measurement in our country [4].

The research in this paper is to use the superiority of coastal acoustic tomography system in flow measurement, and use it to measure flow in inland river channel. The measurement of river flow is an important hydrological parameter in monitoring water resources. However, the current measurement method is difficult to continuously measure the average flow velocity of the section under complicated water flow conditions or extreme weather. For example, current meter (Current Meter), Acoustic Doppler Current Profiler (ADCP) and so on. Their main shortcomings are to measure the water flow through frequent sampling points, so that the average flow velocity of the section can not be fully...
estimated [5]. And their measurements will be affected by the frequent ships passing by on the Yangtze River. Coastal Acoustic Tomography is a new technology, and very suitable for measuring environmental changes in coastal and inland waters where fishing activities are frequent [6]. This is the application of mesoscale ocean acoustic tomography technology in coastal areas [7].

Datong Hydrological Station is the closest hydrological control station of the Yangtze River to the estuary and the last important hydrological station in the Yangtze River. It is the upper boundary of the river that has the furthest rise in ocean tides. Therefore, the Datong Hydrological Station can represent the size of the Yangtze River’s inflow into the sea, and it is also a hydrological station with long-term observational data in the lowermost reaches of the Yangtze River [8]. Through the measurement of the flow of Datong, the research on the flux of the Yangtze River into the sea can be monitored, and other parameters such as carbon sources, sediment, biomass, etc., can be used to provide a very valuable reference for the monitoring of the flow of the estuary coast area.

2. Location and Method of Experiment
A reciprocal sound transmission experiment using the CAT systems was carried out between two sound transmission and reception (acoustic transceiver) stations (K1 and K2) on both sides of the river near the Datong Hydrological Station in the Yangtze River. K1 is located on a small boat docked along the north bank of the Yangtze River, and K2 is located at the tourist wharf on the south bank of the Yangtze River, as shown in figure 1. The positions of two stations are shown in table 1. The distance between the stations is 2,628 meters. The layout of the site CAT system and the schematic diagram of the acoustic signal between K1 and K2 propagating along the sound line are shown in figure 2. Calculate the time of receiving the signal at each station, and calculate the average flow velocity of the sound ray path based on the reciprocal propagation time difference.

![Figure 1. Schematic diagram of acoustic tomography site location.](image)
Table 1. GPS coordinates of the experimental site.

| Stations | Latitude (° ′) | Longitude (° ′) | Latitude (°) | Longitude (°) |
|----------|----------------|----------------|--------------|---------------|
| K1       | 30 47.2022 E   | 117 38.2051 N  | 30.7867E     | 117.6368N     |
| K2       | 30 45.9686 E   | 117 37.3961 N  | 30.7661E     | 117.6233N     |

Figure 2. Schematic diagram of CAT system site layout.

In addition, on the day of the experiment, we also paid attention to the official data of the Datong Hydrological Station released by the Yangtze River Hydrological Network (http://www.cjh.com.cn/, which releases the water level and flow of the hydrological station on the hour). Record the water level and flow information released at each time point of the Datong Hydrological Station during the experiment as a reference for our calculation results. Obtain the official real-time measurement of the water level of the Datong Hydrological Station from the Yangtze River Hydrological Website, and then according to the topographic data of the bottom of the hydrological station, the area S of the section can be obtained.

3. Process the Signal Data to Obtain the Average Velocity of Sound Rays

3.1. Extract the Signal Arrival Times

First, perform correlation calculations on the original data, and perform correlation calculations between the serial number of the M10 sequence used by the transmitting site and the original signal of the receiving site, and read the results obtained from the correlation calculation to obtain the signal amplitude and signal-to-noise ratio. And select the time at the maximum amplitude as the arrival time of the signal. The former K1-K2 transmits signals, and the latter receives the peak value and time obtained by data processing. Fig.3 shows the reciprocal propagation time between K1 and K2 stations. From the results, it can be seen that the reciprocal time is similar but not the same. This is because the flow velocity has a certain influence on the speed of sound propagation.

Each graph in figure 3 is a three-dimensional rectangular coordinate system diagram, the lower abscissa is propagation time, the right column ordinate represents time, and the left column represents the signal-to-noise ratio. Generally speaking, only SNR>5 is considered as Valid value.
3.2. Calculation of Average Flow Rate

The principle of the coastal acoustic tomography system is to derive the average flow rate through the time difference of the signal received by a pair of transceiver transducers. The key to the accuracy of the coastal acoustic tomography inversion results is whether the signal arrival time can be accurately extracted [10]. At present, sound ray propagation time tomography is a relatively mature method used today [11, 12]. The schematic diagram of reciprocal propagation of stations T1 and T2 is shown in figure 4. Let the speed of sound \( C_m \) be the sum of the reference speed of sound \( C_m \) and disturbed sound velocity \( \Delta c \). The reciprocal propagation time of acoustic signals at stations T1 and T2 can be expressed as [13]:

\[
\begin{align*}
   t_1 &= \int ds \frac{d}{C_m + V_m} \approx \frac{L}{C_m + V_m} \\
   t_2 &= \int ds \frac{d}{C_m - V_m} \approx \frac{L}{C_m - V_m}
\end{align*}
\]

in the formula, \( t_1 \) and \( t_2 \) respectively represent the propagation time from T1 to T2 and T2 to T1, \( L \) is the horizontal distance from T1 to T2, and \( V_m \) is the flow velocity.

From formulas (1) and (2), the basic equations of time chromatography are obtained:

\[
\begin{align*}
   V_m &= \frac{L}{2} \left( \frac{1}{t_1} - \frac{1}{t_2} \right) \approx \frac{C_m^2}{2L} \Delta t \\
   C_m &= \frac{L}{2} \left( \frac{1}{\bar{t}_1} + \frac{1}{\bar{t}_2} \right) \approx \frac{L}{\bar{t}}
\end{align*}
\]

where, \( \Delta t = (t_2 - t_1) \), \( \bar{t} = (t_2 - t_1) \), \( \bar{t} \approx t_1 \approx t_2 \). It can be seen from the above formula that the average flow velocity and average sound velocity can be calculated by obtaining the propagation time of the acoustic signal between two stations [14].
Then, we find the location of the cross-section on the map and measure the angle $\theta$ between the cross-section flow velocity and the station flow velocity, as shown in figure 5. In this way we get the average flow velocity of the section:

$$v_a = \frac{v_{12}}{\cos \theta}$$  \hspace{1cm} (5)

Where $v_{12}$ is the average flow velocity between stations; $v_a$ is the average flow velocity of the section; $\theta=35^\circ$ is the angle between $v_{12}$ and $v_a$.

According to formula (3), the flow velocity between the two stations can be calculated. From formula (4), we can obtain Speed of sound. Since the signal propagation process inside the water body will be affected by complex environmental conditions or uncertain factors such as system emission signal abnormality, it is normal that a small amount of abnormal values will occur. In this case, we can adopt methods such as moving average data, sampling at equal intervals, and deleting the signal-to-noise ratio of the received signal to reduce the impact of these abnormal data. Figure 6 shows the flow velocity obtained by the inversion between K1 and K2. From the figure, it can be seen that the inversion results of the signals obtained at the two time points have a large deviation from the overall. The results of other signals all perform well, and the average flow velocity range is between
1.1 and 1.3m/s. From the relationship of formula (5), the average velocity of the section is calculated, as shown in figure 7.

4. Calculate Section Flow

Finally, the flow rate of the cross-section $Q$ is the product of the velocity of the cross-section and the cross-sectional area:

$$Q = v \times S$$  \hspace{1cm} (6)

Where $S=43000\, m^2$ (take the cross-sectional area when the water level is 14.4m, because the water level changes little in a short time, and the cross-sectional area does not change much).

| Time | Water level (m) | Qa(m$^3$) | Q(m$^3$) | error (%) | Qmean(m$^3$) | error(%) |
|------|----------------|----------|----------|-----------|--------------|----------|
| 12   | 14.44          | 66200    | 66132    | 0.1027    | 65821        | 0.5725   |
| 13   | 14.44          | 66200    | 57652    | 12.9123   | 63633        | 3.8776   |
The river flow can be calculated according to formula (6). We compare the calculated flow of Datong Hydrological Station with the results recorded on the Yangtze River Hydrological Network. As shown in figure 8, the green line $Q_a$ represents the flow volume recorded at points 12 and 13 published on the Yangtze River Hydrological Network. The blue line $Q$ for us to calculate the results of the flow of the Yangtze River, the red line $Q$ average is a moving average of $Q$. It can be seen from the figure that the calculated average of the flow results in this period is generally close to the official data, and the result is highly reliable. Table 2 is an error analysis table. The results show that the error in calculating the flow rate is small, and the error can be reduced to less than 10% through the calculation of the average flow rate.

6. Summary and Outlook
At present, most of the methods adopted by domestic hydrological stations to measure flow are to carry instruments on ships to measure cross-sectional velocity, and then read the current water level and its relationship with the cross-sectional area to obtain the real-time cross-sectional area, thereby calculating the flow. However, such measurement needs to be carried out every hour, which is time-consuming and costly for a long time, and it will also be disturbed by the frequent ships on the river. The coastal acoustic tomography system used in this article measures the flow velocity. It only needs to set up a suitable station on both banks of the river and install the acoustic tomography system to achieve continuous measurement (every 3 minutes). The measurement results in this article show that the use of acoustic tomography technology to measure flow can meet the requirements of hydrological stations. In the follow-up, we can continue to improve the measurement parameters and algorithms according to the actual conditions of the river to obtain more accurate results. The use of acoustic tomography to measure river flow is just a simple attempt. In the future, continuous improvements can be made, and the technology will become more mature, and eventually be applied to more river flow measurements.

Acknowledgment
Thanks to the Chizhou Municipal Maritime Safety Administration of Anhui Province for their strong support for this work and the Yangtze River Hydrological Network for providing data reference. This work was supported by the National Key Research and Development Program of China (No. 2019YFC1408404) and the Open Foundation from Marine Sciences in the First-Class Subjects of Zhejiang (No.11104060218/001)

References
[1] Razaz M, Kawanisi K, Kaneko A, et al. 2015 Application of acoustic tomography to reconstruct the horizontal flow velocity field in a shallow river Water Resources Research 51(12): 9665-9678.
[2] Liao G H, Zhu X H, Lin Ju, et al. 2010 Observation technology and methods of ocean acoustic tomography Acta Oceanologica Sinica 32(3): 14-22.
[3] Liu X D, Lin J, Wang H, et al. 2016 Determination of inversion current field in the Jiaozhouwan Bay based on coastal acoustic tomography data Marine Sciences 40(1): 101-111.
[4] Dong M H, Zhang C Z, Zhu X H, et al. 2015 Research progress of coastal acoustic tomography for current measurement Journal of Ocean Technology 34(6): 112-119.
[5] Yao Z M 2002 Application of acoustic doppler flow profiler in river flow measurement Pearl River (6): 23-24, 31.
[6] Kawanisi K, Razaz M, Kaneko A, et al. 2010 Long-term measurement of stream flow and salinity in a tidal river by the use of the fluvial acoustic tomography system Journal of Hydrology 380(1-2): 74-81.
[7] Zhang C, Kaneko A, Zhu X H, et al. 2016 Acoustic measurement of the net transport through the Seto Inland Sea Acoustical Science & Technology 37(1): 10-20.
[8] Zhang R, Wang Y P, Pan S M 2006 Analyses with wavelet and hilbert-huang transform on monthly water discharges at Datong Station, Yangtze River *Journal of Nanjing University (Natural Sciences)* (4): 423-434.

[9] Chen M M, Lin J, Chen P, et al. 2014 The ocean current field inversion method based on coastal acoustic tomography *Proceeding of Western China Acoustics Academic Exchange Conference*.

[10] Lv L G, Yuan L Y 2002 Two intriguing topics of ocean acoustic tomography *Journal of Oceanography of Huanghai & Bohai Seas* 20(2): 133-138.

[11] Zhu Y, Lv L G 2002 Basic principle and application of ocean acoustic tomography *Advances in Marine Science* (4): 70-75

[12] Liao G H, Zhu X H, Lin J, et al. 2008 Overview of the applications and observations of ocean acoustic tomography *Progress in Geophysics* (6): 1782-1790.

[13] Munk W, Worcester P and Wunsch C 1995 *Ocean Acoustic Tomography* Cambridge: Cambridge University Press.

[14] Guo Y J, Zhang Y, Zhao Z X 2015 Study of river discharge observation based on high frequency acoustic tomography technology *Journal of Nanjing University (Natural Sciences)* (S1): 60-63.