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Application of shallow-water acoustic tomography to measure flow direction and river discharge

Masoud Bahreinimotlagh [a], Kiyosi Kawanisi [b,*], Mochammad Meddy Danial [a], Mohamad Basel Al Sawaf [a], Junya Kagami [a]

[a] Department of Civil and Environmental Engineering, Graduate School of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi, Hiroshima 739-8527, Japan

[b] Department of Civil and Environmental Engineering, Institute of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi, Hiroshima 739-8527, Japan

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ABSTRACT

High-frequency Fluvial Acoustic Tomography System (FATS) was initially used to measure flow velocity and river discharge in a mountainous river. The results showed the high-frequency FATS, not only improves the velocity resolution, but also reduces the minimum operational range from 76 m to 43 m in compare with the previous type of FATS. The analysis of sound wave propagation (Ray tracing) showed the bottom topography can be the reason of multi-ray paths of sound wave in the shallow freshwater rivers. A new formula based on the continuity equation introduced to estimate the variations of the angle between the flow direction and the FATS transmission line. The flow direction was measured using two crossed FATS transmission lines of 53 kHz and 30 kHz. The results compared to the up-looking ADCP (Acoustic Doppler Current Profiler) deployed near the intersection of the two lines which measured the changes in flow direction. The results affirmed the efficiency of the proposed method. Finally, the river discharge was estimated by both FAT systems and compared to the Rating Curve method and moving-boat ADCP estimates. The relative error of the FATS discharge measurements was less than 10%.

1. Introduction

Acoustic tomography systems offer powerful techniques for estimating various water features such as temperature, current velocity, salinity, discharge, and current direction. Ocean Acoustic Tomography (OAT) employs high-powered signals with frequencies less than 1 kHz to measure mesoscale ocean currents [1,2]. Coastal Acoustic Tomography System (CATS) applies OAT to coastal waters. Because CATS transmits signals at frequencies up to 10 kHz, it can be used in smaller water areas. Zhu et al. [3] carried out long-term measurements of river discharge in the Qiantang River located in China. They showed that the CATS is a reliable instrument to measure current velocity and river discharge even during the passage of tidal bores. The tidal current and volume transport were also measured through the Qiongzhou Strait, China. The authors suggested the CATS is a highly viable way to measure volume transport of the residual current in the coastal regions [4]. CATS is widely used to measure mean current, temperature variations, tidal currents, residual currents and strait through flow [5–7].

To use this method in shallow rivers, these systems must transmit sound at much higher frequencies. As a result, Fluvial Acoustic Tomography System (FATS) uses a second-generation - CATS that transmits sound at a frequency of 30 kHz. FATS measures water properties such as discharge and water temperature [8], salinity variations [9], flow velocity [10] in rivers and estuaries.

Razaz et al. [11] measured long-term variations of streamflow in a shallow tidal channel using FATS. They declared that the inaccurate determination of angle between the flow direction and the transmission line of FATS (θ) may lead to very large discharge estimation error. Kawanisi et al. [12] measured flow velocity and river discharge in an estuary using acoustic tomography system. They noted that during the passage of tidal currents, the salinity increases with depth. As a result, the distribution sound speed varied from 1515 m/s in deeper layers to 1485 m/s near the water surface. The ray simulation results showed the salt wedge affects the acoustic ray pattern.

Although previous studies on 30-kHz FATS applications have highlighted advantages, two types of limits still exist. First, the imprecise determination of the angle between the flow direction and the transmission line of FATS (θ) can lead to significant errors in discharge estimation. Therefore, the utilization of another instrument such as Acoustic Doppler Current Profiler (ADCP) is required to measure the angle θ accurately [11]. Second, the velocity

* Corresponding author.
E-mail address: kiyosi@hiroshima-u.ac.jp (K. Kawanisi).

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resolution of FATS inversely depends on the length of the transmission line. In the case of choosing a short length between two transducers, the velocity resolution is low.

In the previous studies, 30-kHz FATS was used to measure river discharge while a moving-boat ADCP was used to determine the angle θ. The present study successfully introduced a 53-kHz FATS that covers the limits of 30-kHz FATS and can be used in shorter ranges than allowable in a 30-kHz FAT system. Moreover, the flow angle is deduced by using a cross-path configuration and a new formula based on the continuity equation.

This paper is structured as follows: Section 2 describes the study area, the acoustic instrumentation and the data analysis procedure; a new mathematical equation is also introduced to estimate the angle θ. In Section 3, the 30-kHz and 53-kHz FATS are compared and explained, and the results of angle estimation and discharge measurement are discussed. The final section summarizes the conclusions of this study.

2. Materials and methods

2.1. Study area

The Japanese archipelago lies between 24° and 46°N latitude. The islands of Japan have several different climatic regions ranging from severe cold to subtropical. Miyoshi City is located in the cool-temperate region where the annually average temperature varies from 8.5 °C to 19.4 °C and the average precipitation is 1492 mm. Field measurements were carried out in a section of the Gono River, located in the Miyoshi City. The length of the Gono River is of approximately 194 km. Basen River and Saijo River are the two main tributaries of the Gono River. These rivers meet approximately three kilometers upstream from the observation site (Fig. 1(a)). A 115-m wide straight reach of the river was selected for the location of the transducers. The bed slope surrounding the observation site was 0.11%. The bed in the observation site is mainly composed of gravel and boulders. The water depth was about 0.55 m and 1 m under low-flow and high-flow conditions respectively. The annual mean discharge at the Ozekiyama gauging station, located 1.1 km upstream of the observation site, was around 73 m^3/s.

The reciprocal sound transmission by FATS was performed between four acoustic stations located on both sides of the river during the period of January 13–20, 2016. The air temperature ranged from 4.6 °C to 22.1 °C and there was precipitation from 18th to 19th. Stations 1 and 2 were equipped with two 30-kHz broadband transducers, whereas Stations 3 and 4 were equipped with two 53-kHz transducers (Fig. 1(b)).

The horizontal distances between the 30-kHz and 53-kHz systems

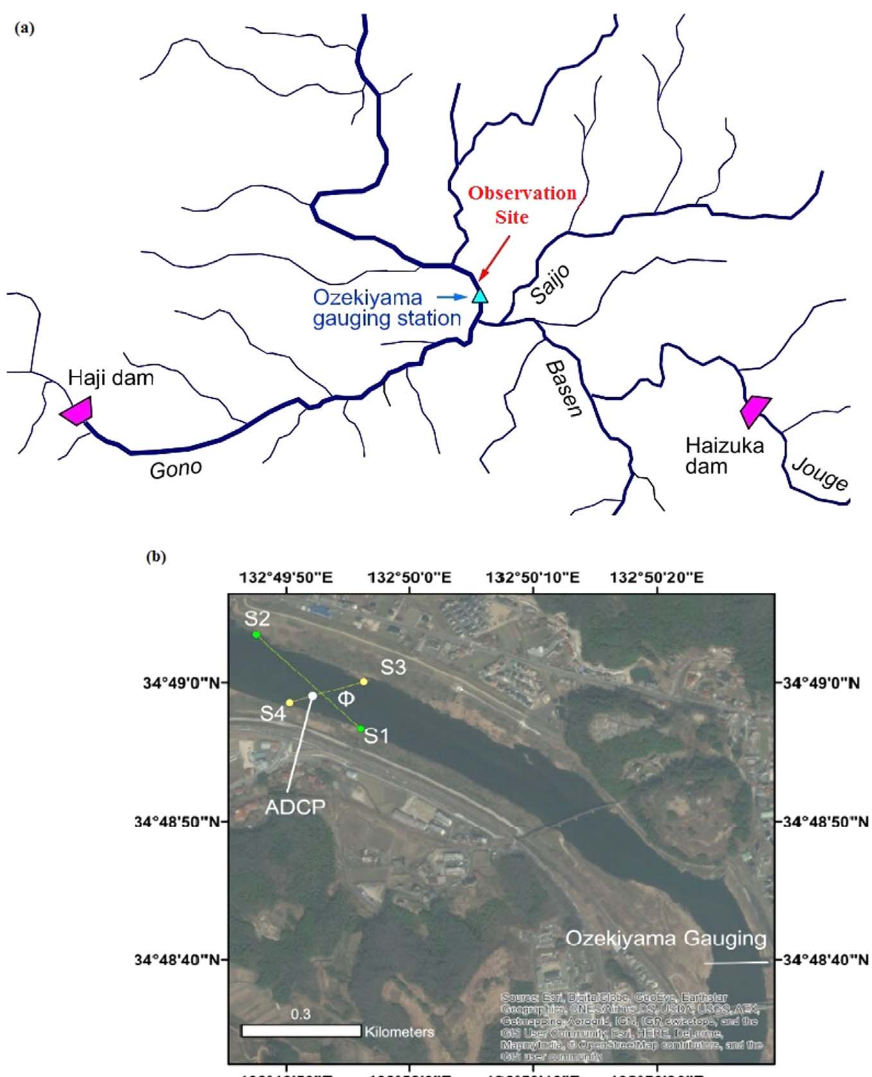

Fig. 1. (a): Map of the river network and observation site; (b): the locations of FATS stations and ADCP.