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**Flow velocity mapping in a circular  
experimental wave/current basin with small scale  
underwater acoustic tomography method**

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A thesis submitted in fulfilment of the requirements  
for the degree of Doctor of Philosophy  
to the  
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# Abstract

Several researches normally use the rectangle tank for ocean device testing in laboratory trails. Rectangle experimental tanks, however, can only generate normalized flow in one or some fixed directions with limited testing area. Meanwhile, the appearance of the flow will be in large extent affected by boundary. This thesis study flow details in a 25m diameter circular testing facility Flowave TT, which can generate combined wave and current in any relative direction. The spatial of flow current velocity obtained by fixed point direct measurement is insufficient if the quantity of test points is not enough. Acoustic tomography is used here for flow internal structure visualizing in the experimental basin by transmitting sound wave with acoustic transducer. Using acoustic tomography method, one could get real-time mapping of parameter variation by installing detect devices outside or at the boundary of interested region without interrupting original field.

Two sets of underwater acoustic tomography system that developed in cooperation with Hiroshima University were used for sound wave emitting and acoustic signal receiving. Travel time of acoustic signal in the interested region is analysed to reconstruct flow velocity by solving inverse problems. Multi-path arrivals that propagated by different ray paths are identified by ray tracing. Flow details in the circular basin is studied in a horizontal plane and along a vertical slice using acoustic method. Besides acoustic tomography experiments in the Flowave, a field work was conducted in the Bali Strait, Indonesia. This trail explores the remote sensing of tide progress in the Bali strait with coastal acoustic tomography systems. This study is for the first time to conduct multi-station acoustic tomography experiment for flow velocity reconstructing with only two stations. This study demonstrates that small scale flow profiles in the experimental tank can be reconstructed with acoustic tomography method. The real time monitoring of small-scale flow details can be accomplished with multi-station network, which is one of the further research topics for small scale underwater acoustic tomography research.



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## **Declaration**

This project is proposed by my supervisor Prof David Ingram based on the developing requirement of the FloWave Facility. Acoustic tomography technique is used here for flow details profiling in the state of art circular experimental basin that built in University of Edinburgh. Besides the acoustic tomography experiment in the FloWave TT, a field work is conducted in the Bali strait cooperated with Hiroshima University and Badan Pengkajian dan Penerapan Teknologi (BPPT) in Indonesia. The field work is supported by Office of Naval Research (ONR) from America.

I declare that the work in this thesis is accomplished by the author except where otherwise stated. Significant contribution is made by author where the work is done in collaboration with others. This work hasn't been published for any other degree qualification.

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# Chapter 1

## Introduction

### 1.1 Motivation

Scaled model testing of newly designed devices is an essential progress for offshore renewable energy system research. Several researchers have focused on the use of rectangular tanks for offshore energy systems testing in the laboratory [1-3]. Model scale testing in a laboratory reduces the risk associated with full scale deployment [4-7]. Rectangular experimental tanks, however, can only create flowing water in one or some fixed directions leaving a limited testing area. In real ocean environment, wave and current may come from different direction with various velocities and interact with the device in various modes. FloWave is an all-waters testing facility that can generate combined waves and current in any relative direction [8-10]. Multi-direction flow is created by controlling the velocity of 28 impellers that are installed around the perimeter of a circular area underneath the testing floor. The 25m diameter, circular, experimental basin can generate steady and repeatable flow across a large central testing area. It is, therefore, suitable for offshore array system testing and renewable energy farm designing.

Flow velocity in an experimental basin can be measured using fixed point direct measurement devices, e.g. using an acoustic Doppler velocimeter (ADV). If a spatial mapping is required a large number of point measurements must be taken. This is a time-consuming process, since multiple ADVs can interfere with each other. Acoustic tomography provides a promising alternative for mapping the flow.

Acoustic tomography can be used to visualize the internal structure of regions of interest by transmitting sound waves between acoustic transducers [11-15]. Travel time of the acoustic signal between stations is used to reconstruct current velocity map by solving an inverse problem. Different arrival could be separated by ray tracing propagated by different ray path. The acoustic tomography technology has been developed for ocean climate change monitor, weather forecast and Geological exploration. Ocean acoustic tomography is initially promoted to climate change monitor by measuring ocean water temperature variation, which is a result of global warming. Acoustic tomography has been developed to small scale in coastal area in



recent decades. This study will demonstrate flow current profiling with multi-station acoustic tomography method. This study offers another method for renewable energy structure test condition monitoring in experimental basin. Acoustic tomography technique could also be used in offshore turbine farm flow condition and devices monitoring.

Ocean Acoustic Tomography is used to study ocean temperature change over large regions at the beginning. Sound speed in the ocean could be affected by various parameters including temperature gradients, pressure and salinity variations. By measuring the travel time it takes for a sound pulse to propagate between sensors at known positions, we can calculate the average sound speed between the source and receiver locations. Changes in sound speed can then be related to the temperature change of ocean water. Meanwhile, if the water between the sound sources and receivers is not stable, the travel time will change due to the fluid velocity. The smaller scale turbulent and internal-wave features that usually dominate point measurements are averaged out, so the large-scale dynamics is better determined. Fluid velocity measurement in rivers and straits have also been done for many years to explore acoustics tomography at smaller scales.

The FloWave TT emulates real-Ocean tidal and wave conditions [16]. The use of Underwater Acoustic Tomography (UAT) in small-scale dynamics has great benefit, in fluid velocity measurements over the flow basin. This could offer assistant with tide and wave energy devices under test in the FloWave TT, before they are deployed in the real ocean environment.



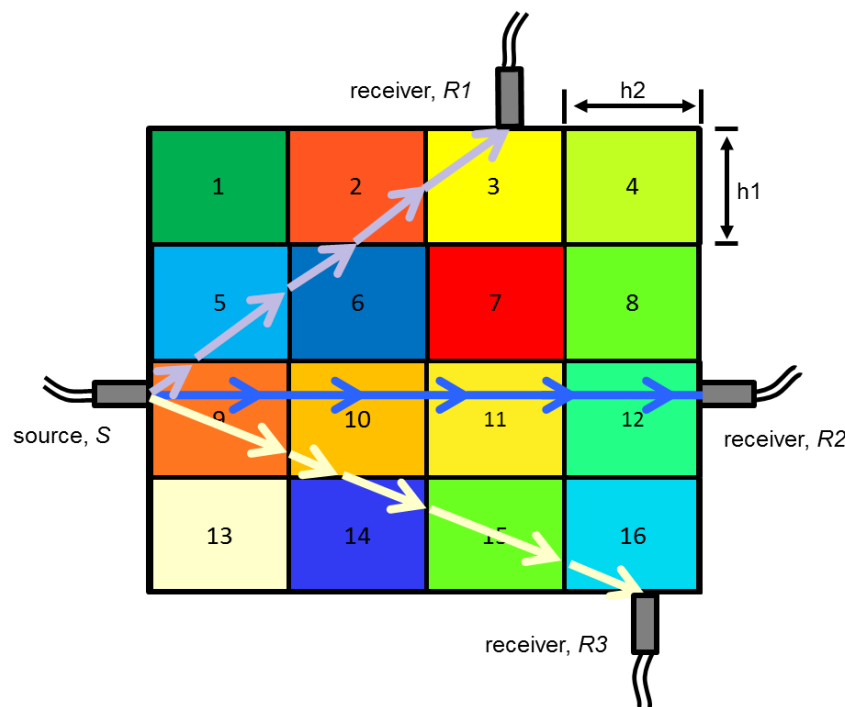
**Figure 1.1:** Side view of the FloWave Facility. The picture is taken from the working space.

Measuring the flow patterns in the basin is critical to understanding the interaction of waves and currents with tidal and wave energy machines [17-18]. Currently technologies exist for point and small area measurements. This project seeks to extend the ideas developed in ocean acoustic tomography to make wide area measurements in the basin. We aim to develop wide area current measurement techniques that can be implemented and tested in laboratory test

basins. The successful introduction of such techniques would allow a detailed characterization of the flow patterns in test basins, particularly involving the interaction between waves and currents. This project is broken down into the following stages: Introduction of the FloWave Facility and acoustic tomography technique; remote sensing of tide in the field work using acoustic tomography system; inverse problem in small scale and data processing; mapping of flow details in the basin.

## 1.2 Internal structure measurement with tomography method

Tomography is used to get the internal details of obstacles by sections imaging [19]. The tomography technique has been used in many areas through the use of different kind of wave. Sound wave is used as transmitting medium in the acoustic tomography research. The travel time, attenuation and signal arrival angle of transmitting wave are the information used in the tomography application. For this research, the travel time of sound wave passing through interested area are used to reconstruct internal details of interested area. The example of acoustic tomography system is as the following figure shows:



**Figure 1.2:** Scheme of acoustic tomography, it uses travel time of sound wave passing through interested area to reconstruct internal details.

The transducers are installed outside of the interested region without interrupting original field. Transducers and receivers are installed at fixed position. Sound sources sends out acoustic

signal at known time, the travel time of acoustic signals travelling through testing area is determined by recording arrival signals with receivers.

In this research the travel time of sound wave is used for flow details reconstruction in a circular experimental basin. The fluid velocity detail is mapped by combining signal information from all the acoustic sensors. We deploy some acoustic sensors in the basin to measure current velocity by transmitting sound in opposite directions through the flow. The modified coastal acoustic tomography systems were used for system control. By solving the inverse problem flow current velocity profile in the whole experimental tank could be mapped by acoustic tomography.

### **1.3 Thesis overview**

The main objectives of this research are to use small scale underwater acoustic tomography method to map flow current details. The acoustic tomography technique and its development history is introduced firstly. The small scale underwater acoustic tomography is origin from the ocean acoustic tomography, which is promoted for remote sensing of ocean water parameter variation. The underwater acoustic tomography is designed based on the coastal acoustic tomography system that developed by acoustic tomography group in Hiroshima University. High frequency acoustic sensor is used here for short distance sound wave transmission. The use of high resolution of sound wave travel time makes small scale acoustic tomography possible. The underwater acoustic tomography experiment is conducted in the circular all-water basin FloWave facility, which is specially designed that could generate complicate flow condition in all directions. It makes multi-station network sensing possible with only two underwater acoustic tomography stations. Acoustic tomography method is used here for flow detail mapping in the FloWave facility. Ray tracing programming is used for multi-path arrival signal identification. Acoustic tomography experiment is conducted in the circular basin for the flow velocity analysing. The flow velocity is mapped in a horizontal plane with multi-station network firstly. Vertical layered velocity is analysed along the ray path in a slice. The flow details in the whole tank is structured with combination of horizontal and vertical layered analyse. The underwater acoustic tomography result is verified by fixed point measurement with ADV. The work of the research is structured as follows:

- **Chapter 2 Background**

The circular experimental basin, FloWave Facility, is introduced by modelling and flow simulation. The development of acoustic tomography technique is discussed and it is

also compared with other type of tomography method. The underwater acoustic tomography system that modified based on former design by Hiroshima University is also presented in this chapter. The acoustic tomography system is used in the FloWave testing, which will be discussed in the latter chapters.

- **Chapter 3 Acoustic Tomography technique**

Sound propagation in water could be traced with ray simulation. The travel time of sound wave is used in underwater acoustic tomography research here. This chapter introduces the forward and inverse problem for the acoustic tomography method. Flow velocity is analysed from three aspects: horizontal plane mapping, vertical layered averaged study and the three-dimensional flow detail reconstruction.

- **Chapter 4 Remote sensing of tide in the Bali strait---the application of coastal acoustic tomography system in the field work**

Acoustic tomography system can be used for remote sensing of ocean circulation, tide variation and water column transport. This chapter demonstrates the application of coastal acoustic tomography system in the Bali Strait for tide monitoring. Flow current in the strait is studied. It founds a base for the small scale underwater acoustic tomography experiment in the following chapters.

- **Chapter 5 vertical layer averaged current velocity reconstruction**

Flow condition is affected by surface and the bottom floor. This chapter explores flow current details in different depths. Sound wave reciprocal transmission experiment is accomplished in the FloWave facility. Uniform flow is generated along the sound propagation path with two opposite directions. Though reflected by boundary, steady signal is detected with clear arrival peaks. Multi-path arrival signals that propagate along different paths are identified with ray tracing in the circular experimental basin. Besides path averaged velocity analysing, this chapter also study layer averaged velocity in different depth.

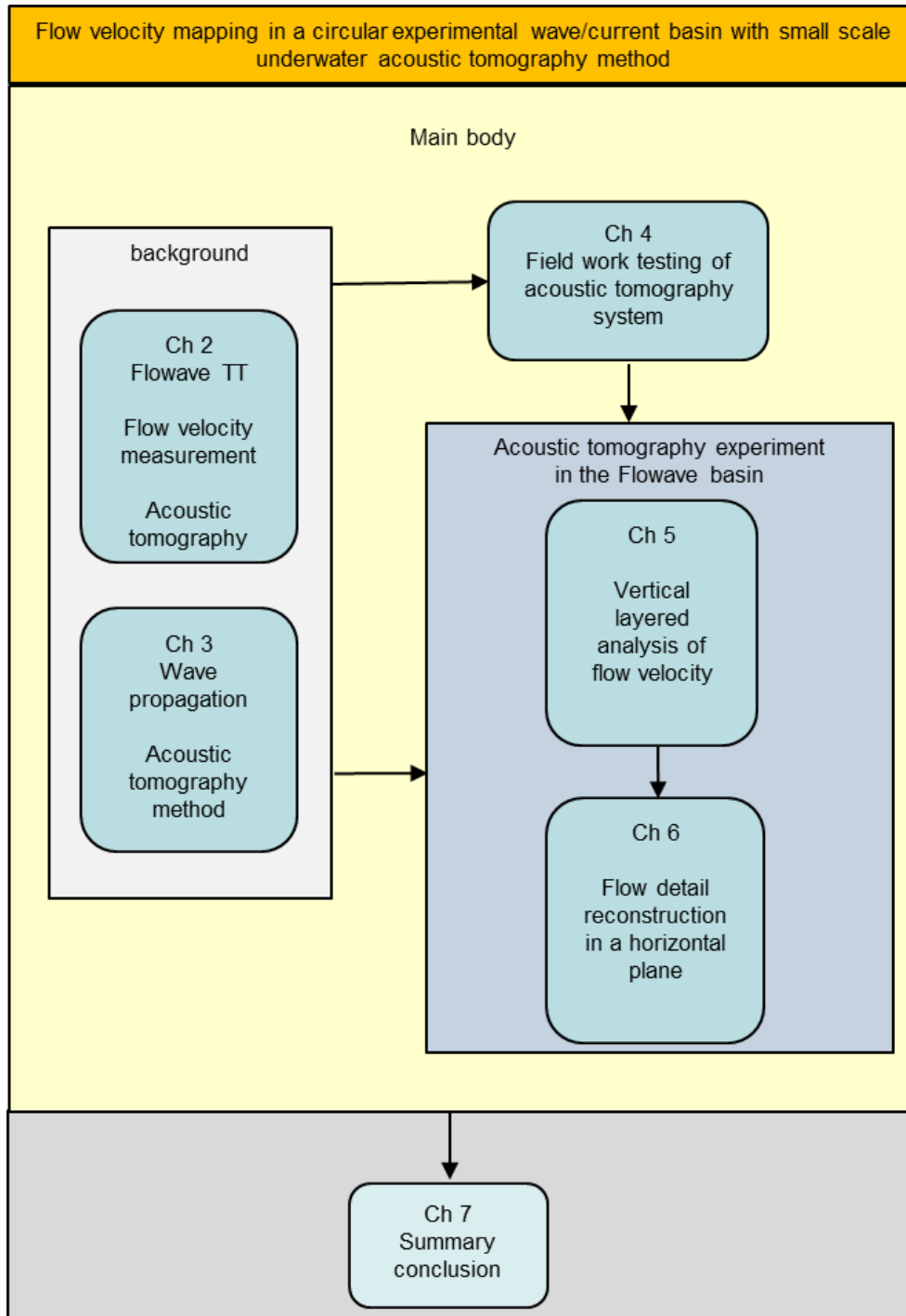
- **Chapter 6 Flow current mapping with acoustic tomography method in the horizontal plane**

Flow velocity in the circular basin is analysed with acoustic tomography method in this chapter. A 7-station sensing network is constructed with two underwater acoustic tomography systems. Normalized flow is generated in the basin for velocity testing. ADV is installed in the testing area during the experiment. Flow velocity in the horizontal plane is reconstructed with sound wave travel time by solving the inverse problem. The inverse result consistent with the ADV measurement.

- **Chapter 7 Conclusions**

The content discussed in the former chapters is summarised. The outcomes and challenges about this research is concluded. Some particular concerned topics are discussed in detail for further development of small scales underwater acoustic tomography.

The structure of this thesis and the links of each chapter are shown in the following figure



**Figure 1. 3:** Overview of the thesis. The links of chapters shows the structure of this thesis and how is this research combined by these different parts.

## Chapter 2

# Background

### 2.1 Introduction

This research explores the detailed profiling of small-scale flow details using underwater acoustic tomography method. Except for the field work conducted in the Bali Strait, all the experiments are conducted in the circular basin of the FloWave Ocean Energy Research Facility. This all-waters experimental tank is constructed for model testing of ocean engineering device. Different from traditional rectangle testing tank, this circular basin could not only simulate almost all the flow conditions in the ocean, some complicate flow that only exist in computer simulation for former research can also generated in the tank. The state-of-art facility will be introduced in this chapter with model construction and flow simulation. During working the flow velocity needs to be measured in detail in order to explore the working condition of testing devices in the tank. By doing this the working progress of the testing device could be monitored. Acoustic Doppler Current Profilers (ADCP), Acoustic Doppler Velocimetry (ADV) and Particle Image Velocimetry (PIV) are normally used for flow velocity measuring. All of these flow velocity profiling devices either only measure the flow velocity at one fixed point or over a small area. Meanwhile, ADCPs transmit sound beams within an angle and cannot measure flow details over the whole experimental basin. Flow current measuring devices will also be introduced and compared in this chapter.

Besides fix point measurements, the flow details in the target experimental area can be mapped using the acoustic tomography method, which gets flow details by transmitting sound waves across the target area. In the tomography system the sensors are installed either outside of, or on the boundary of testing area. It can be used to detect the internal structure and details of the target using non-contact methods. Tomography has been applied to many applications in different areas. This chapter introduces some applications of the tomography method, especially using acoustic signals. The underwater acoustic tomography used in this research origins form ocean acoustic tomography, which was promoted by America oceanographers for the mesoscale (100 km) ocean water parameters sensing [20-24]. After being developed in the deep sea for two decades the acoustic tomography method is introduced to coastal area by acoustic tomography group in Hiroshima University [25-32]. They also design a coastal

acoustic tomography (CAT) system to better analyse flow condition in coastal area. The CAT system has also been used for river water volume transport monitoring in recent years [33-39]. The underwater acoustic tomography system used in this research is based on the CAT system. The system used was designed and tested is completed in cooperation with the acoustic tomography group Hiroshima University. The main different from CAT system this underwater acoustic tomography system uses high frequency broadband sonar sensor. The tomography method and development history of acoustic tomography will be presented in the following sections. Furthermore, the underwater acoustic tomography systems design and its testing will be described in detail.

## **2.2 Experimental tanks and the FloWave Facility**

### **2.2.1 Experimental tanks**

Wind tunnels are of great importance to aircraft designing, they make a big contribution to the development of aviation industry [40-41]. They can simulate air condition anywhere in the world, even for air flows that not exist on earth. An airplane model is tested in wind tunnel to check its performance. Meanwhile, newly designed aircraft also needs model tests in the wind tunnel for its shape variation [42]. In a similar way, model testing also make sense in the shipping industry, and in the assessment of ocean structures. Boat models are tested in the tanks before the real full-scale boats are used. Scaled model testing of new designs for offshore structures is also essential, given the large capital investment in their construction. Experimental testing is sometimes used for offshore renewable energy systems [43]. Test methods were originally designed for wave energy devices but are now being applied to tidal and offshore wind turbines.

Experimental tanks and basins are built for ocean structure model testing. These facilities provide a controlled environment where specified met ocean conditions are available on demand in a repeatable way, allowing both the performance and survival to be characterised [44-48]. Condition requiring flowing water can also be simulated in some experimental tanks and basins. Such facility can be used for fluid mechanics studies, vehicle model testing and ocean structure testing. Model testing also decreases the risk of failure in the real ocean environment. As all ocean conditions can be simulated and reproduced in the laboratory, the ocean structure model can be tested in the tank and check its working condition. This progress is normal for almost all the structure development. To meet particular requirement experimental tanks are designed with different shape, depth and have many ability of flow generating.





**Figure 2.1:** Wide tank that ever in service in the Edinburgh University. It was constructed for in wave condition simulation in ocean and structure testing. It has been teared down after working 24 years.



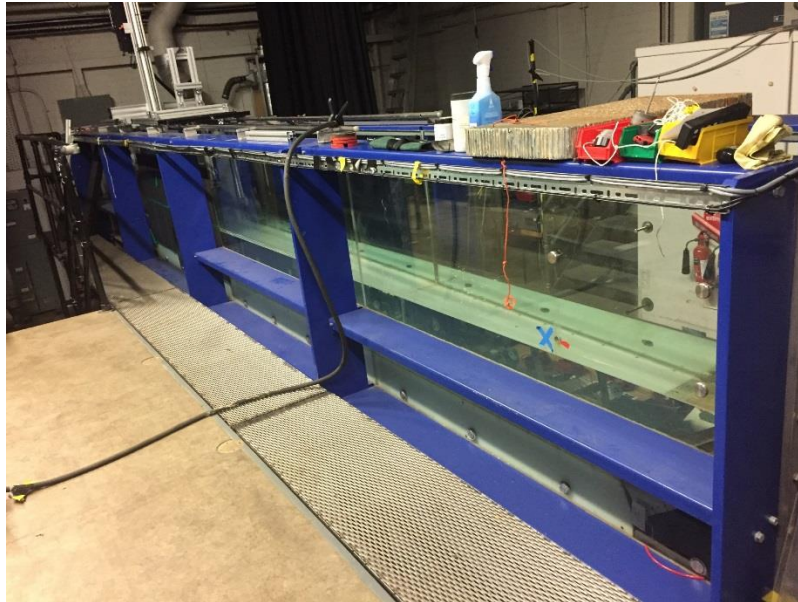
**Figure 2.2:** The curve flow testing tank in the Edinburgh University. The sea state curve tank can generate wave from different direction and can be used for wave condition exploring. It can also be used in ocean structure testing and analyse its interaction with waves.

Offshore renewable energy system testing in the experimental tank is of great importance to the energy system developing. Several researches have focused on the rectangle tank for offshore energy system model testing in the laboratory. The rectangular experimental tank, however, could generate only bidirectional flow with limited testing area. Moreover, the performance of the flow is affected by the boundary conditions in a large extent. In the actual ocean environment, the wave and current may come with various velocities from all directions and interact with ocean devices in various modes. The devices will therefore not interact tidal current along one single direction. To get multi-direction effect, the model must be rotated or reloaded to simulate the real tidal current. It may be impossible to get this situation for large arrays. Real site conditions, however, normally include multi-directional waves and complex currents in any relative direction.

Many experimental tanks are designed as a rectangle so they can generate steady wave or flow current in the testing area [49-50]. Steady uniform wave can be created in the rectangle tank for wave condition study and wave energy system testing. To reduce the effect of reflected waves some tanks introduce wave absorbers or beaches on the opposite side from wave maker. The length of waver tanks can be hundreds of meters, so that the effect of wave reflections is decreased, or so that tests involving towed models can be conducted. Rectangular tanks have a limited capability to create multi-directional waves and currents. In the real ocean environment, however, the waves and flow interacting with the structure under test come from many directions. Testing multiple directions, thus normally requires, the repeated recovered and installed of the device in order to change direction. The Wide Tank (figure 2.1), was designed to generate wave at angles of up to 30 degrees using a bank of wave makers along one side. It is constructed by Edinburgh University in 1977 [51]. It was the first multi-direction wave tank to use a bank of absorbing, force-feedback, wave makers to create waves. It able to generate multi-directional, poly-chromatic, seas representative of those found in the ocean.

The Curve Tank was built by Edinburgh University in 2001. It was a direct development from the wide tank and made use of many of the original components as well as the control system [45,52]. Unlike rectangle tanks, the curve tank was built using a 90-degree arc of wave makers. This design increased the range of multi-direction wave states that could be created improving the tanks ability to simulate realistic sea-states. As shows in figure 2.2, the waves generated in the tank are absorbed by a bank of vertical “beaches”, installed along a long side of the tank. Model tests can be monitored through the clear side wall next to the work station.

The wide tank and curve tank were designed for wave-structure analysis. Tidal research is also of great importance of offshore renewable energy systems. A wave-current flume was built to generate combined waves and current. It was designed as a very small (circa 1:100) scale facility. It is equipped with a PIV system that has been used for detail flow measurement. The side walls of flume are glass, to allow laser light to pass through.



**Figure 2.3:** The Flume testing tank in the Edinburgh University. Flow can wave can be generated in the tank for flow analysing. A PIV is introduced in this system for flow current detail profiling.

The curve tank was designed to generate complicate wave in some different directions, it offers a relatively larger testing area than wide tank. A rectangle tank, however, cannot generate the same flow from all directions and avoid the problem of rotating and reinstalling devices. The need to create such complex conditions in the laboratory led to the development of the FloWave facility at the University of Edinburgh. FloWave is the first circular experimental tank in the world that can generate waves and flow current in any relative direction [8]. FloWave is a state-of-the-art ocean research facility that designed to provide a testing facility for large scale (circa 1:30) modelling services for wave and tide research. It has the ability to generate complex multi-directional waves and flow currents in the 25m diameter circular tank (figure 2.4). This circular basin permits to generate steady, reproducible flow in the central area [8-10,46]. The risible floor in the central area is designed for installing and removing the devices easily. It is, therefore, suitable for offshore array platform testing and renewable energy farm designing. Waves are created using a bank of 168 wave makers around the outside of the basin, while

currents are created using 28 separately controlled by controlling the rotating speed of impellers installed underneath the test floor. By controlling rotational speed of the impellers, FloWave can generate steady flow up at up to  $1.6 \text{ ms}^{-1}$  (in current only mode) and up at up to  $1.0 \text{ ms}^{-1}$  when combined with waves [8-9]. Table 2.1 shows summarises the experimental facilities built at the University of Edinburgh.



**Figure 2.4:** Section of the FloWave Facility. Steady flow is generated by the impellers that installed underneath the testing floor along the perimeter.

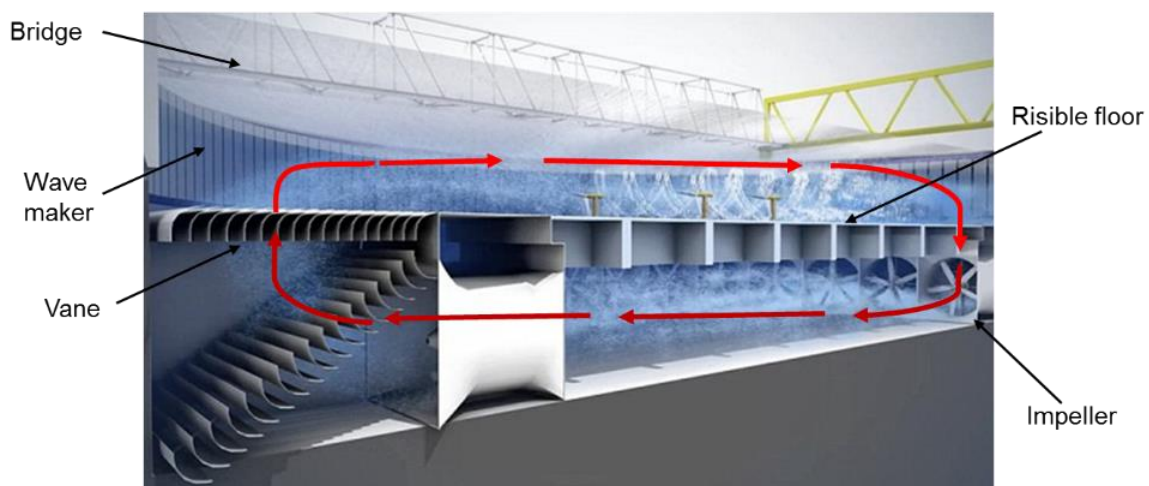
**Table 2.1:** Flow tanks in the Edinburgh University.

	Wide tank	Curve tank	Flume	FloWave
Construct time	1977	2001	2011	2013
Tank shape	rectangular	arc	rectangular	circular
Flow type	wave	wave	wave/current	wave/current
Flow direction	$-30^\circ$ to $30^\circ$	$0$ to $90^\circ$	$0^\circ$ or $180^\circ$	any direction
Dimension	$10\text{m} \times 27.5\text{m}$	$14\text{m} \times 9\text{m}$	$10\text{m} \times 0.4\text{m}$	$25\text{m} \varnothing$
Depth	$0.6\text{m}$	$1.2\text{m}$	$0.5\text{m}$	$2\text{m}$
Scale	$1/100$ to $1/150$	$1/70$ to $1/100$	$1/40$ for ocean structure $1/100$ for wave	$1/20$ to $1/40$



### 2.2.2 Model simulation of the FloWave facility

The circular experimental wave/current basin is designed to simulate the coastal environment in the laboratory for ocean structure testing. It could also be used for wave and flow interaction research to explore how the ocean works. The water depth of the testing area in the tank is 2m, another 2m depth water is underneath the testing floor (figure 2.5). The risible plate in the centre of the floor can be lifted out of the water for instrument and model installation and lowered for testing. It offers a convenient way for testing device installing and recovering with high efficiency. 28 pumps are installed under the testing floor along the circumference. The turbines are all controlled in the work station. This basin could generate steady flow in all directions by combined controlling of all the impellers' speed. A group of vanes are used to regulate inflow and out flow directions, which makes repeatable steady flow in the testing area. The flow direction could be changed quickly within 7 min. The wave makers allocated along the circumference can make waves from all directions. The bridge above the tank can move along the rail, which make it possible to get access to all the positions in the testing area.



**Figure 2.5** Vertical section of the FloWave facility. The turbines are installed along the perimeter of a circular area underneath the testing floor for flow generation. The bridge across the whole tank moves along the track.

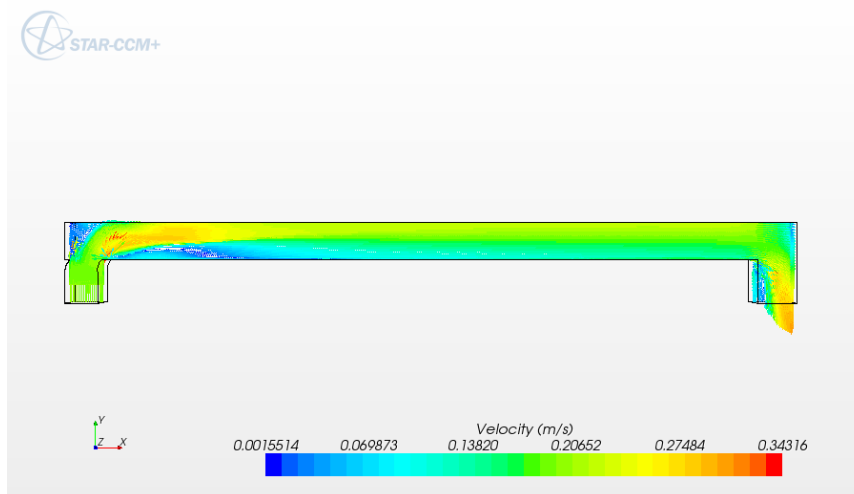


**Figure 2.6:** Vanes in the Flume. The sub-vane is used in the tank for flow direction restriction. Steady uniform flow can be created in the flume without strong interaction with water surface near input flow.

The FloWave facility generates waves at 2s period and 0.4m height and the fastest flow reaches a velocity of 2m/s. It can offer a model test tool for most renewable energy devices. The test area above the floor is 2m deep (Figure 2.5), the water depth underneath the floor is also about 2 m in depth. The 168-segmented wave makers are installed around the circumference of the tank. The wave makers generate steady wave and absorb the wave by active controlling, which diminishes an interaction of the incident and reflected waves. These wave makers not only create regular waves, but also generate multi-mode ocean states from different directions. Here in this study only flow construction is taken into account, and wave makers keep no motion when the impellers push steady flow.

To explore flow generation theory in the circular tank, the inlet vanes that combined with 20 vanes (figure 2.5) should be analyzed to the better controlling of inflow direction and speed [10]. As shows in figure 2.5, water is moved using 28 impellers installed under the floor of the tank. Steady flow is generated by controlling speed of the impellers individually. Since flow is moved across the tank floor with impellers either pumping or providing suction, the vanes must cope with either inflow or outflow. Careful design of these vanes is critical to ensure fully developed flow is crated efficiently. The inlet vane design was tested in the wave-current flume (Figure 2.6).

Computational Fluid Dynamics (CFD) simulation is a powerful tool that can be used in tank designing, flow modelling and experimental design in the tank. Initially, a model of the wave-current flume has been constructed. The flume is  $10\text{ m} \times 0.4\text{ m} \times 0.5\text{ m}$ . The inlet uses 20 vanes to control the flow angle, which are also present at the outlet. The mean inlet velocity is  $0.2\text{ ms}^{-1}$ . The inlet velocity through each channel between the vanes is individually controlled to give the correct flow angle. The floor of the flume is modelled as a no-slip wall and a two-dimensional model has been used. As shown in Figure 2.7, the angle of the vane ranges from  $25^\circ$  to  $37^\circ$ . To ensure an accurate simulation, the grid is finest around the inlet surfaces. This study neglects the effect of gravity on the water in the flume. There results (Figure 2.7) show that there is a strong shear layer around the inlet flow, the purpose of which is to ensure the wave maker is not affected by the flowing water [53]. The testing area, downstream towards the outlet has the required uniform flow profile (Figure 2.7). Generating a usable test section from (3m-8.5m) in the flume.

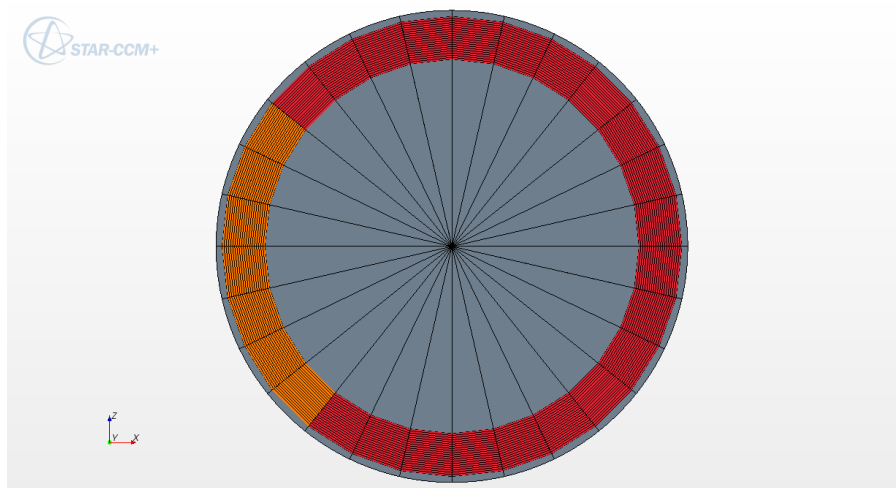


**Figure 2.7:** CFD simulation of a wave-current flume with multiple inlet vanes, using STAR-CCM+.

After constructing a model of the flume, the same approach has been used to construct a CFD model of the FloWave facility. Initially, a three-dimensional model of the circular basin was built using the solid edge 7 CAD system. The diameter of this circular basin is 25m. The 28 equally spaced vanes are placed around the circumference. The model is combined up by 28 sectors. Each sector contains a flow guide, divided into 20 vanes, once again with varying flow angles. Each sector can act as a flow inlet or outlet. Effectively, the circular basin works like 14 flumes merged together. In this study, 7 sectors were specified as outlets (with the pumps

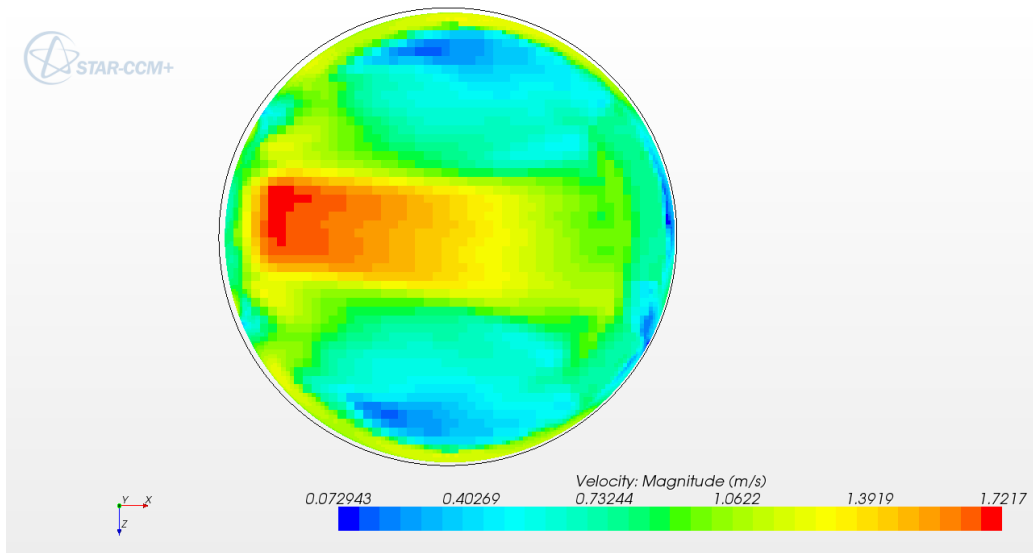
providing suction) and the rest as inlets (Figure 2.8) [9-10,54]. The model was bounded by a circular wall to represent the wave makers. This model was used to simulate uniform flow in the FloWave basin using STAR-CCM+.

This simulation intends to demonstrate that steady, uniform flow with a velocity of  $0.8 \text{ ms}^{-1}$  can be created across the central test area. The flow direction is from left to right, parallel to the x-axis of the model (figure 2.9). In the central area, quasi-uniform flow offers a testing space for ocean renewable devices. Moreover, the test region is large enough to allow for the array testing. The flow field near boundary is much more complex, with recirculating flow regions. The CFD simulation shows that a circular tank can generate a uniform flow, and that the flow field is similar across the central area. More complicated case can be also simulated with CFD, showing the powerful practicality of this tank. Some direct measurement of flow have also been made to understand its working performance [9].



**Figure 2.8:** Three-dimensional model of the circular tank constructed by solid edge. The yellow and red areas indicate the inflow and outflow sectors, respectively.





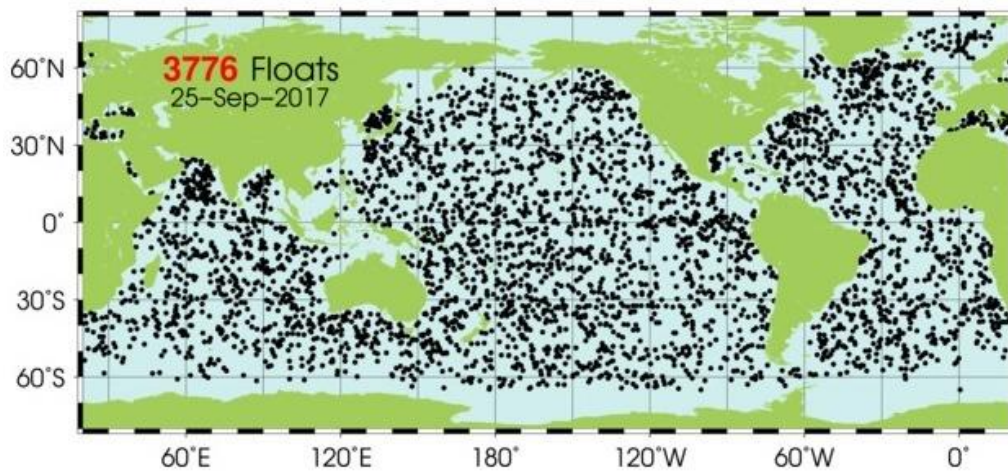
**Figure 2.9:** Flow velocity field simulated in the circular tank. The flow is from right to left with a nominal input velocity 0.8m/s.

### 2.3 Flow velocity measuring technique

Ocean current sensing is of great importance to global circulation [55-57]. Surface wave and upper layer current can be measured with satellite, high frequency radar (HF radar) and aerial photography [58-61]. Those devices use remote sensing system for flow detail mapping. Other devices can be deployed in water to measure flow velocity in a small scale. Floating bottle and drifting buoy can also be used for flow current measuring, track trajectory of them is plotted to trace ocean current [62-63]. Figure 2.10 shows the distribution of ARGO in ocean. It is a kind of drift, which can dive to deep sea (about 1000m) and flow with ocean current. It can rise up to water surface for data transporting and communication. Other devices that used for flow current measurement will be introduced in the following content.

Ocean structure model testing in the experimental tank can decrease the risk than installing full scale device directly in field. During tests in flowing currents, the velocity field across the tank need to be properly characterised so that the conditions the device is subjected to are fully understood. Flow details in experimental tank and basin can be profiled with flow measuring devices. Local flow conditions can be mapped in detail over a small area using particle image velocimetry (PIV) [64-65]. To characterise the flow detail over larger area a large number of direct fixed-point measurements is normally needed. The flow detail can be mapped using acoustic Doppler velocimetry (ADV) or electromagnetic flow meters [66-67]. The spatial resolution in such cases is restricted by the number of direct measurements that taken in the

tank. Acoustic Doppler current profilers (ADCP) can be used in flow detail measurement in a certain area. The flowing water within sound wave beams of ADCP can be profiled.



**Figure 2.10:** ARGO floats in use for global sea water parameter measuring. They are distributed in most sea regions on the earth. This data is got from Argo project.

Acoustic Doppler Current Profiler (ADCP) works like sonar. It transmits sound waves in water column and the echo wave is received. Doppler shift is obtained when particle moves in the water column by analysing scattered sound wave [68]. The frequency of sound wave used in this system is from 38 kHz to some Megahertz, which determine the working distance (meters to hundreds of meters) of ADCP. This device can not only used for flow velocity mapping, it also used for wave monitoring in ocean. ADCP can not only be fixed on surface plat to sense water volume bellow it, it sometimes installed on the sea bottom to measure water parameter of wave height variation [69-70].

Acoustic Doppler Velocimetry (ADV) uses sound wave pings for flow velocity measuring [71]. A transmitter sends high frequency sound wave continuously, which is received by receivers. The Doppler Effect is observed when particles pass through the sound field of ADV. The vector velocity of the moving particle is acquired with this method, it is treated as flow velocity at this position. The ADV is widely used in laboratory testing and field work, it sometimes is fixed to other moving plat for flow parameter sensing [72]. An ADV (Vectrino) is used in this study for fixed point flow velocity measurement, which is used to verify the reconstructed result by underwater acoustic tomography method.

Laser Doppler Velocimetry (LDV) also use Doppler shift of laser beam to measure the velocity of fluid flows [73]. Not like ADV, this device use laser beam as a media instead of high frequency sound waves. The measurements of velocity are taken at a point or small area where

two laser beams meet. Light is scattered when a particle passes through the intersection volume, the scattered light is received with a detector. The frequency of the scattered light is proportional to the velocity of moving particle. Accurate and reliable moving velocity of particle in flow field, including turbulence, can be measured as high frequency laser beam is used in the system. It can also be used for measuring small vibration of solid surface and get the frequency of the movement.

Particle image velocimetry (PIV) is used as a method for small scale flow detail visualization in the experimental tank [64-65,74]. The flow fluid is seeded by tracer particles, which are assumed to have same velocity with the flow current. The movement of the seeding particles is used to track flow current. Position of particles are acquired with camera continuously; velocity of particle can be calculated by analysing position change of them within a fix time zone. Flow details in a region can be mapped with this method, it can even get three-dimensional vector field by slice analysing [75].

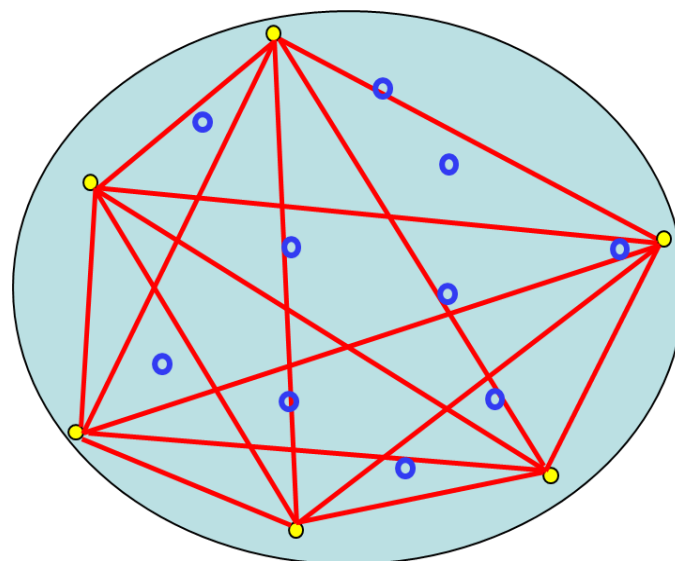
ADP, LDV and ADCP use the Doppler shift of energy wave when the target particle is moving in water. Seed (particle) is needed if use Doppler Effect for the flow detail mapping in clean water. Water in river, lake and sea is 'dirty', small particle is used as seed in those environments. ADV and LDV can only measure flow velocity in a certain position. ADCP can map flow details in a horizontal plane or three-dimensional water volume [76-77]. It transmits sound wave beam within an angle like a flashlight, there will has dead area that sound wave cannot reach. ADV and ADCP is widely used in ocean surveys, they are always installed on platform or boat [78-79]. LDV and PIV take Laser beam as a media to measure flow velocity. It needs laser machine for this system, which is costly and needs training for the laser machine using. Meanwhile, LDV and PIV have high requirement of the experiment environment. The laser beam needs pass through the container of flow, where glass wall is always needed. This requirement restricts the application of those devices. It is hard to use them for flow detail measuring in the outdoor field surveys. Though buoy can be used for flow velocity measuring lonely, it always used together with other flow velocity measuring equipments [80-81]. It is always a combined water parameter measuring plat, which also get water temperature, salinity, oxygen density, water pressure etc. Meanwhile, the discrete flow velocity measuring devices are also always fixed to vehicle (USV, UUV, ROV, sea glider etc.) [82-85].

As shows in table 2.2 flow velocity measurement equipment presented here can only measure flow details in a one position or very small range. The multi-station sensing network using

sound waves transmission in a certain distance will be introduced in following sections, it can map flow details in a large area. This method can get flow velocity map in an interest region by one transmission.

**Table 2.2:** Flow velocity measurement methods and their application.

Measure range	Device	Occasion	Theory	Typical Application
Trajectory tracking	buoy	Outdoors	Position change	Ocean current tracing
Fix point measurement	ADV	Laboratory/ Outdoors	Doppler Effect	Flow velocity measuring at a point
	LDV	laboratory	Frequency shift of Laser beam	Flow research, Blood flow in medical, navigation,
Profile flow details within a range	PIV	laboratory	Particle move	Flow detail visualization
	ADCP	Laboratory/ Outdoors	Doppler Effect	Topography mapping, flow progress monitoring



**Figure 2.11:** Compare of discrete measuring and multi-stations network sensing with tomography method. Blue circles are discrete measurement of the field parameter. Yellow circles are tomography stations and red line are kind of wave energy transmission path through original field.

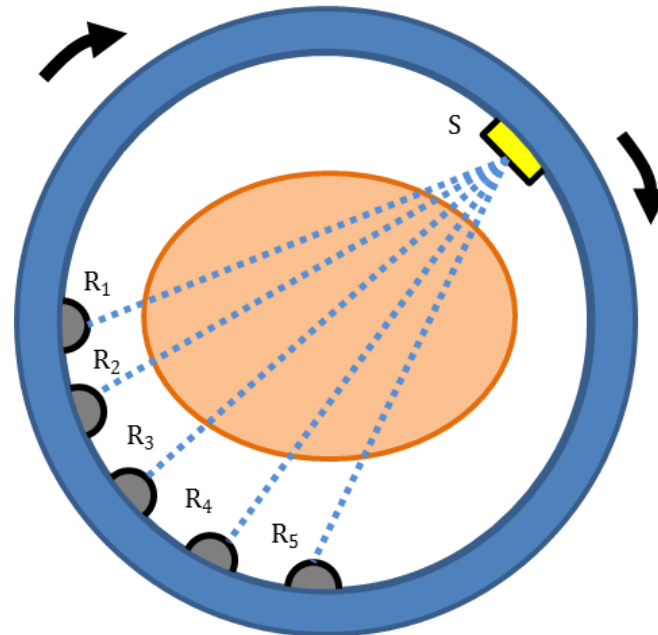
The network sensing system can use non-contacting method for internal structure mapping without affecting original field. This method is particularly important when it not allowed to insert measurement devices in the target. Such measurements became particularly useful for investigating the transportation of water through channels, straits, and ocean basins. The flow details in experimental tank also need real-time monitoring to get working progress of testing devices. This research explores using network sensing system for small scale flow detail sensing in the circular experimental basin by installing sound stations in the basin. The sound stations are deployed near boundary of the circular basin to avoid interrupting original flow field that generated in the flow tank. The flow details in the central testing area can be reconstructed with the multi-station sensing network. The original flow field will more or less affected by flow detail measurement devices if they are distributed in the original field. Moreover, the efficient of discrete measurement is much lower than network sensing system. The internal structure if target can be mapped with one measurement using the sensing network, which is of time and cost effective. One can get  $N \times (N - 1) / 2$  measurement result when the station number is  $N$  in the network sensing system. As shows in figure 2.11, 15 measurements are acquired when only 6 stations are used in the network sensing system. Discrete measurement method gets same number of data with the discrete station. Spatial of the measurement is highly improved with network sensing.

## **2.4 Acoustic Tomography and its development in small scales**

### **2.4.1 Tomography**

Tomography is a technique used for internal imaging of target object with sectioning by transmitting some kind of wave energy in the target area [86]. Different type of wave energy or partials are used as media in various type of tomography research. The information about internal structure or interest area is obtained by wave transmission or partial travel time within it. The obtained information is used for inverse problem solving, which bring a solution of interested parameter. Different from discrete measurement, the tomography method use field sensing by constructing network sensing system. Sensors are fixed near the boundary of target object or interest zone; detailed image of internal structure can be presented with this non-contacting method. The resolution of the imaging in the tomography field is largely depend on measurement taken in the multi-station sensing network. The most famous tomography technique is computerised tomography that used in human body internal structure imaging. Figure 2.12 shows a typical example of the computerised tomography system. A transmitter and 5 receivers are fixed to the ring, which rotate around the target. Meanwhile, the underwater

acoustic tomography method used in this research is also a multi-station sensing network. The main difference between this small-scale acoustic tomography and normal acoustic tomography research is the sound wave frequency.



**Figure 2.12:** A typical example of tomography system. A transmitter and 5 receivers are fixed to the ring, which can rotate around target area. Phasic field in the ring is affected by target product, the parameter of target can be reconstructed by solving the inverse problem.

Computed tomography (CT) is a well-known medical device that used in medical application [86]. X-ray transmitter and receivers are installed in a ring, which rotate around human body. The attenuate of X-ray is used for internal structure mapping as the absorption is different when the energy pass through different organ, it works as shows in figure 2.12. X-ray CT scanner is widely used in disease diagnose for bones, soft tissue, flow blood and organ checking [87-89]. CT scanner can provide 2D mapping of the organs, three-dimensional internal structure of body and structure can also be obtained with “adding” of all slices. This technique can make the internal structure of body visible, the image can monitor with screen, printed on film and saved.

Atom probe tomography (APT) is a technique three-dimensional imaging of atom distribution and chemical materials analysing [90]. Ion is sent by atom in the highly voltage electric field, the travel time of ion is used in atom position reconstruction. APT is up to now the only technique that can get high resolution mapping of internal structure analysing in atom scale. The position of different kinds of atom can be mapped with this method, which is applied in

material surface atom structure analysing. It is the only technique that used in small scale atom distribution study [91]. This technique is also used in chemical composition analysis.

Electrical tomography is main part of process sensing method in the industry development [92-93]. Electrical tomography mainly includes three kinds: electrical capacitance tomography (ECT), electrical impedance tomography (EIT) and electrical resistivity tomography (ERT). ECT measures internal dielectric permittivity distribution of target object from capacitance change of the electrical field that created by electrodes [94]. The resolution of ECT is relatively low than other progress tomography method due to restrict of electrode numbers. It is widely used in industrial process sensing, including internal distribution of mixed objects [95]. Electrical resistivity tomography is used for sub-surface structure detailing in geophysics survey, it is some kind like the acoustic tomography method used in this field [96]. Electrodes are inserted in earth and used for current injection; the variation of electrical resistivity is used for inverse problem. Sensor arrays are normally inserted in the boundary of interested area and acquired data is used in the ERT surveying. Electrical conductivity and impedance of a tissue that measured with surface electrode is used for tomography image plotting in the EIT. This technique based on the principle that electrical conductivity is different of various tissues and movement of gas and fluid in the tissue. EIT can be used in medical examination for internal structure analysing of body and another organ together with CT.

Sound wave is used as media for internal structure mapping and process monitoring in the acoustic tomography. Acoustic tomography technique is used in weather forecasting, geography surveying and sea water parameter sensing [97-99]. The frequency of sound wave is different according to its application field. Acoustic stations are allocated around the interest area, sound wave is transmitted with transmitters. Acoustic signal is received with receivers after a certain distance propagation. The information of internal structure is obtained with the sound receiving, sound wave propagation along different path. Travel time of sound wave is normally used in the acoustic tomography, the attenuate of sound energy and phase variation of sound wave are also used in the acoustic tomography research. Meanwhile, ambient noise can also be used as input for passive acoustic tomography [100-103]. Figure 2.13 is an acoustic tomography system that designed to measure air temperature distribution [104]. As shows in this figure, sound transmitters and receivers are allocated in the ring. They are deployed in the boundary around interest area, which can avoid the sensors' disturbing of the original field. Transmitters send sound waves simultaneously and the propagating acoustic signals are received by receivers. The air temperature field can be reconstructed with this tomography



system. The air heating progress can also be monitored with this tomography system by continuously transmitting of sound waves. This method is widely used in progress tomography, which play an important role in industry development.



**Figure 2.13:** Air temperature sensing system using acoustic tomography method [104]. The sensing system consists of 12 sound transmitter and 12 receivers. The sensors are installed along the circumference of 1m radius circular ring. A heat source is placed under the sensing network for air temperature heating.

Optical tomography (OT) uses light beam for internal structure profiling [105]. It works like computed tomography and can also be used in medical application. According to the information used in this method optical tomography can be divided to two types: optical projection tomography and diffuse fluorescence tomography. The travel time of light and light energy attenuate are used as information in optical tomography inverse problem solving. The three-dimensional structure of objects is reconstructed with stack of a series of 2D tomography slice. This technique can be used in breast cancer detection and cerebral measurement. The internal structure of tissue can be mapped by slice analysing in the optical tomography [106].

Tomography method has been developed to many different types, all of them are used in internal information obtaining of structure and progress monitoring. This technique is used in different scale and applications, from nanometre to thousands of kilometres. The table 2.3 presents a compare of those tomography method, they are applied in various field. Atom probe tomography the atom distribution mapping technique, it is up to now the smallest scale tomography method. It is can be used in chemical composition analysing and mapping of atom



distribution in a structure. The atom probe tomography is the only technique in tomography field that use ion particles for atom distribution mapping. The variation of wave field in the interest area or target is used in the inverse problem-solving progress for all other tomography method. The development of tomography technique is in some extent origin from requirement of medical application. Computed tomography is widely used in medical tissue surveying and disease assuring by internal structure mapping of body. This technique is the most famous among all tomography method, it is awarded a Nobel Prize for its contribution in medical application [107]. Many diseases can be assured conveniently with assistance of computed tomography imaging. Electrical tomography is also applied in medical checking. It is also a practical method for small scale flow progress monitoring in progress tomography. Optical tomography use laser beam as media to detect internal information of tissue. Plenty of sensor node is used in the optical tomography, it can create detailed mapping of tissue for medical use. Acoustic tomography method can also be used in medical check, a good example is the breast cancer checking. The acoustic tomography is widely used in industry development. It is a useful technique in earth surveying as sound wave can propagate in earth, water and in the air with small attenuation. The underwater acoustic tomography technique that will be presented in this study is a research field of acoustic tomography, which use different frequency of sound waves as media for internal structure mapping. Travel time of sound waves is used in the underwater acoustic tomography research in this study.

**Table 2.3:** Comparison of tomography methods.

Tomography type	Medium	Theory	Application
Computed Tomography	X-ray	Attenuation variation	Internal detect in Medical use
Electrical Tomography	Magic-electricity	electricity field	progress monitor, sub-surface structure mapping
Atom probe tomography	Ion	Ion flight time	Chemical analyse, atom distribution
Optical Tomography	Infrared light	Coherence of light	Medical imaging
Acoustic Tomography	Sound wave	travel time, phase or attenuation	Weather forecast, geometry survey, flow detail sensing

Flow dynamic research is a main work of ocean engineering structure designing and testing. The model of ocean structure can be tested in the experimental tanks. To better explore the working condition of the testing devices, the flow fields and testing progress should be monitored continuously. As discussed in the former section the CFD simulation has been frequently used for the offshore renewable energy research. It caters for complicated flow fields and boundary conditions. In the real testing conditions the fixed-point measurement is normally used to monitor the small-scale flow fields. Direct measurement of flow detail and water parameters is also used in the open water experiments. Beside the fixed-point measurement, the acoustic tomography method can also reconstruct the flow fields in the experimental tank and open waters.

Acoustic tomography techniques that based on sound wave transmission between pairs of sound stations provide a promising way of characterising the flow test conditions. Acoustic tomography is an advanced technique that can map the structure of flow in an observation domain by transmitting sound waves through water between a set of acoustic transceivers. When an acoustic signal is transmitted between two fixed stations then the signals travel time is affected by the fluid velocity component in the travel direction. If the signal is transmitted in both directions, then the fluid velocity can be found using the reciprocal travel times. Since sound waves from the transmitter is scattered, multiple signals will arrive at the receiving station with sound rays being reflected from the water surface and the bottom and walls of the basin. Consequently, a multi-path analysis of sound transmission can be performed allowing the velocity profile to be reconstructed. The acoustic tomography sensing network can be constructed with certain number of stations.

#### **2.4.2 Ocean acoustic tomography**

Acoustic tomography method is used in ocean for water parameter sensing. Sound stations are installed deep in the sea with a certain distance. Low frequency sound wave is transmitted with sound source, the sound waves are received with hydrophones after long distance propagation. The sound source is deployed in a certain depth (around sound channel axis) for long distance propagation. Sound wave will propagate according to sound propagation principles, which will be presented in the following chapter. Multi-path propagation acoustic signal can be observed at the receiving station. Sound speed is determined by water temperature, salinity and water pressure. Sound travel time is affected by sound speed variation. Meanwhile, the average sound speed is also involving the current information along ray path. The travel time of sound waves

are used as input information in the inverse problem. Sound speed variation and current velocity can be reconstructed using sound travel time between sound source stations. Sea water temperature can also be reconstructed as the sound speed is affected by it. The water parameter in an interest area can be profiled with network sensing with acoustic tomography method by solving inverse problem.

Ocean acoustic tomography (OAT) was initially proposed by Munk for mesoscale ocean parameter monitoring in the ocean [11,20]. Ocean acoustic tomography is used in deep sea for water temperature sensing, which a result of global warming. It has been applied to the study of mesoscale oceanic eddies and monitoring climate change [21,108-109]. The reconstructed result can be used in climate change monitoring, it is a useful method for ocean internal structure profiling. Since the 1980s ocean acoustic tomography technique has been used to map flows in oceanic and coastal waters. A series of acoustic tomography experiments have been conducted in the open waters [11,110], which shows a good application of this method for water parameter variation sensing. Using the acoustic tomography method, we could reconstruct the unknown ocean parameters (salinity, temperature, sound speed, flow details) by studying travel time of sound that propagate through the considered field.

Low frequency sound source is used in the ocean acoustic tomography for high power sound wave transmission. The sound waves are normally modulated to get high SNR at receiving station, its bandwidth is broadened in this way. The broadband sound waves can be obtained with hydrophone arrays after a long-distance propagation. Sound source is normally fixed to vertical rope, which is moored in the sea floor. The sound source will be affected by ocean internal current, the position of sound source is always not fixed. The accuracy of sound source's position is of great importance in the ocean acoustic tomography research. The long baseline positioning system is used for sound source position tracking. Hydrophone arrays are used for sound wave receiving, the SNR will be improved with array signal processing. Meanwhile, multi-path propagation can be observed with vertical hydrophone arrays, which receive arriving sound wave separately and add them up with time shifting method. Control system for ocean acoustic tomography is normally kept on boat as power supply for low frequency sound transmission is of high requirement. Self-contained system can be developed for sub-surface deploying, the power supply is achieved with battery. The ocean acoustic tomography systems are synchronised with GPS signal, this signal also offer assistance to sound station positioning. Quartz clock is always used as timing system for sub-surface station.

As sound waves is a kind of energy that transmitted in water, it has effect on ocean livings. Transmission of high-power sound waves in open waters needs take sea mammals and other livings into consideration. Low frequency sound waves are used in the ocean acoustic tomography research for its few attenuate in long distance propagation. Low frequency sound wave is also used by marine mammals for long distance communication, it is also used for sea mammal navigation. Working frequency of ocean acoustic tomography need to avoid affecting ocean living, ultra-low frequency can be considered for long distance sound wave propagation in the deep sea.

### **2.4.3 Coastal acoustic tomography**

The coastal acoustic tomography technique that applied in coastal area is originated from ocean acoustic tomography. It is a remote sensing method of water parameter changing and the flow details in the coastal areas (Shallow Ocean, near offshore area, strait). This technique can sense water parameter in harbours and bays with busy shipping. The acoustic tomography has been extended from deep sea to the coastal seas around the East Asian countries [25,27,31,36,111-113]. Over the last two decades coastal acoustic tomography (CAT) has been developed as a refinement of OAT and applied to shallower coastal waters at smaller geographic scales [25,27,31]. The acoustic tomography research was introduced to the coastal area by the acoustic tomography research group of Hiroshima University that leaded by Prof Kaneko in the 1990s [31]. The coastal acoustic tomography method was used in the lake and strait for flow detail profiling [32,114-115]. Coastal acoustic tomography systems are also used for sound transmission in inland sea [32,115]. The shallow water sound transmission using coastal acoustic tomography shows a good performance of the self-contained system. As shows in chapter 4 the acoustic tomography method has been used in water properties profiling in the Bali strait for tide monitoring. While OAT and CAT have normally been used to map the velocity in a 2D horizontal plane, Taniguchi et al., [23] studied the vertical profile of the Kuroshio Current southeast of Taiwan using acoustic tomography stations moored below the surface. Acoustic tomography has also been applied at smaller scales still for monitoring flow in rivers [116-117] by using higher frequency sound waves. The acoustic tomography systems are installed at both sides of river for high frequency sound wave transmission. Water volume transport and water height can be monitored with the remote sensing method. Meanwhile, the flow details in river can be reconstructed with multi-station sensing network.

A commercial coastal acoustic tomography system is developed in Hiroshima University and has been used in many coastal acoustic tomography researches [27]. The land-based coastal

acoustic tomography device is a self-contained system, it can be installed in the open field and transport received data with satellite. The reliability of CAT system was validated by the field experiments in coastal areas [26,118]. Mirror-coastal acoustic tomography system (M-CAT) is also designed in Hiroshima University, this self-contained device is used in deep sea for flow detail sensing. The M-CAT system transmit received raw data to land-based station, through with the underwater information can be processed. The flow details in deep sea can be monitored with this sub-surface moored network sensing system.

The boundaries will have strong interact with propagating acoustic wave in the shallow water. Multi-path propagation will be overlapped at the receiving station as sound waves are reflected with water surface and bottom floor. The topography of shallow water has big effect to bottom floor reflection of sound wave. Scattering is also much stronger compared with deep sea sound wave transmission. All of those factors make sound transmission of coastal acoustic tomography more complicate. Higher frequency sound wave is used in the shallow water acoustic tomography, which make time resolution much higher. Hydrophone arrays can be used in the coastal acoustic tomography research to get higher SNR with array signal processing. Multi-path propagation can also be obtained with the vertical sensor array, the arrival signals can be used for layered analyse in the vertical section. The three-dimensional mapping of water parameter distribution can be obtained by combining of vertical layered analyse and horizontal plane mapping. This method will be presented in the following chapters.

#### **2.4.4 Small scale acoustic tomography in experimental tank**

Normally new technique is developed from laboratory to the field work in open area, this is because model testing is needed before the full-scale model get in use. The acoustic tomography method is used for water parameter sensing in open waters for the last forty years. As the development of acoustic tomography technique, this method is used in smaller scales. The coastal acoustic tomography is used in lake and river for water transport sensing. Coastal acoustic tomography system is also designed and applied in coastal area. This method can also be used in much smaller scale for water parameter sensing. Philippe Roux explore water temperature variation with two vertical transducer arrays in a rectangular tank using double-beam forming method [119-121]. This method is tested in the experimental for water temperature changing with two sensor arrays. Plenty of high frequency transmitter is used in this experiment, the sound transmission paths offer enough information in the inverse problem solving. This method can also be used in field work for vertical water parameter sensing, especially in the shallow water. Meanwhile, hydrophone arrays are always used in shallow

water acoustic tomography. The SNR can be improved by array signal processing, multi-path propagation sound waves can be observed with sensor arrays. At the same time, the double beamforming acoustic tomography method will be affected with ambient noise in the open water testing.

Underwater acoustic tomography was originally developed as a method for global sea water temperature monitoring in deep sea. Small scale sound wave propagation is normally conducted in shallow water, the underwater acoustic tomography research is combined with some sound transmission between each sound station. High power sound source is needed for shallow water sound wave propagation, as the acoustic signal is received before complicate boundary reflection. Underwater acoustic tomography research also has high requirement of sonar sensor, the transmitter and receiver need to be Omni-direction. The arrivals cannot be received is the directional of receiver is too narrow. Meanwhile, all direction transmitting assure sound waves propagate to all sound stations in the sensing network. The acoustic tomography system used in small scale flow detail sensing has high requirement of hardware. The time synchronise is also achieved with GPS signal, it can also use the timing system in computer for the integrated system. The frequency of sound waves is much higher in the small scale underwater acoustic tomography, which bring high time accuracy. The resolution of the reconstructed result in the acoustic tomography also depend on time accuracy besides number of sound stations. High frequency sound transmission also brings high requirement to hardware system in the acoustic tomography research. The speed of control system needs to be much faster and the working frequency of sonar sensors needs to be higher. As the M sequence sound wave is broadband signal, the working bandwidth of sonar sensors need to be wide enough. As small-scale flow detail sensing is normally conducted with point measurement in the laboratory. The successful use of acoustic tomography at these smaller scales motivated this study which seeks to apply underwater acoustic tomography in an experimental basin for the first time.

Details of the flow in the tank is normally obtained by discrete point measurement or small area mapping with ADV, PIV and ADCP. Direct measurement needs instrument to be installed within the flow, which will interact with the original field. The small scale underwater acoustic tomography, however, could map detailed flow fields in the whole region of the tank, which is suitable for ocean device testing. Small-scale acoustic tomography can be used for the flow details mapping in the experimental tank. The circular tank can also offer an ideal sound transmission bed as the sound channel is steady, sonar sensors can receive steady signal after boundary (water surface, tank floor and wave maker) reflection. The reciprocal travel time of

acoustic signal is different when it transmits along and opposite the flow current. Steady flow velocity can be measured by the acoustic signal travel time difference when the distance is fixed. The vertical layered flow current velocity can be reconstructed if the multi-path propagation signals that transmitted along the vertical slice between two stations are picked out. The horizontal flow details however could be mapped with multiple station networking in the interested area by acoustic tomography method. By constructing multi-station networking the acoustic tomography method could get much higher resolution mapping of parameter variation in the target area quickly compared with distribute measurement. The boundaries will have strong interact with propagating acoustic wave in the shallow water. Acoustic tomography is developed to small scale for flow detail profiling in this study. It is used for flow detail profiling in the circular experimental basin. This method is developed to much smaller scale in this study, more detailed mapping of flow velocity can be obtained with multi-station network. Meanwhile, two new underwater acoustic tomography systems are developed for the sound transmission in the basin, it will be presented in the following sections.

## **2.5 Conclusion**

This chapter reviews recent development of small-scale fluid detail sensing methods, experimental tank technique, acoustics tomography and its signal processing methods. Simulation of fluid dynamic in the FloWave Facility are analysed to explore its flow conditions. Tomography method and its development in the flow parameter sensing is also introduced here. Acoustic tomography is an efficiency method for remote sensing of flow progress in different scales. Three-dimensional model of the FloWave is constructed using STAR-CCM+, flow condition in the circular basin is also simulated.

Small-scale acoustic tomography experiment in this research is conducted in the circular experimental basin, FloWave Facility. The FloWave design and its application is of great importance to the ocean engineering device testing. It can simulate reproducible real ocean condition continuously by model scaling, which is a key procedure of ocean structure designing. To explore the working condition of this newly constructed testing facility sub-vane simulation of the inlet is used in this study, it offers a good direction of flow simulation in the experimental tank. The simulation shows that this circular basin can generate steady and repeatable straight flow, it offers a testing bed for ocean structure models. The flow conditions in the circular basin is simulated with STAR-CCM+, more complicated flow situation can be simulated in this facility.

Flow velocity measuring methods and devices are discussed here, the acoustic tomography system is presented as a network sensing method of flow parameter especially. Acoustic tomography system uses multi-station networking for the flow detail mapping within the sensing network. The efficiency of networking sensing with acoustic tomography system is much higher than discrete measuring. Acoustic tomography can be used for field surveying and in experimental tank/basin testing. By installing sensors around interested area this non-contact method allows for more accuracy profiling of steady flow without interrupting the original flow field. This method is particularly important when ocean engineering device is being tested in the experimental tank.

The development of acoustic tomography technique is discussed in this chapter. Tomography method is used in many fields. Underwater acoustic tomography method that studied in this research is developed from ocean acoustic tomography. The development history of acoustic tomography for flow detail profiling is discussed in this chapter. The underwater acoustic tomography system is used in the flow velocity measuring that will shows in the following chapters.



## Chapter 3

# Acoustic Tomography technique

### 3.1 Introduction

Underwater acoustic tomography can be used in the sea to measure the water temperature, profile the sound speed and to investigate ocean circulation patterns at different scales. Underwater acoustic tomography uses information about sound wave propagation between stations in an array to parameter variations. The method is best explained by considering a plane wave propagate through the water. As with light in air, underwater sound waves travel in a straight line when sound speed remains constant. The route travelled by sound rays becomes curved when the sound speed changes (e.g. with depth). It is important to know the sound speed distribution for real time ocean dynamic monitoring, as it's the initial requirement of ray tracing. If the sound speed distribution is not known, however, ray tracing can be simulated. It is also possible to simulate sound wave propagation information (attenuation, absorption, reflection travel time and angle) in the water for experimental designs based on the sonar equation [122]. The sound wave model including travel time, phase variation and arrival angle data are used to solve inverse problems to determine the oceanographic parameters of interest.

The acoustic tomography techniques in this study only focus on the flow velocity using travel time information from sound waves. Travel time based acoustic tomography is also widely used in geophysical survey work [123-125] and in atmospheric weather forecasting [126-129]. The transmitting stations use a single frequency sound wave with phase modulation. The receiving stations make use of pulse compression to improve both the SNR and the time resolution (see chapter 2). The travel time of sound wave that propagated along different ray paths can be used for flow details monitoring by solving the inverse problems.

This chapter mainly deals with the forward and inverse problems of the acoustic tomography method. The path averaged flow velocity is discussed initially. By dividing the water into a number of layers at different depths, the layer averaged flow velocity can be determined. Using multiple transceiver stations, fluid flow patterns can be mapped in a horizontal plane by using grid-based methods. A method for three-dimensional flow reconstruction is also discussed in

this chapter. In addition to describing analysis methods, sound propagation in sea water is discussed. Ray tracing is introduced for sound wave propagation simulation, a key technique for acoustic tomography research.

## 3.2 Underwater sound wave transmission

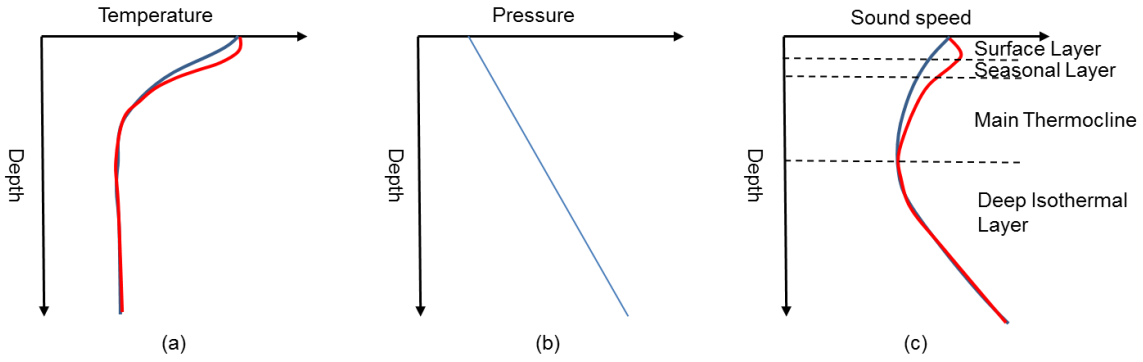
### 3.2.1 Sound speed

Magneto-electric waves can only propagate for a very short distance in the ocean as water is an electrically conductive media. Losses occur as the magneto-electric wave propagates in water, as energy is transformed into thermal energy. Light, on the other hand, is absorbed and scattered by the water, preventing propagation over long distances. This makes acoustic waves the only practical way of propagating signals over long distances under water. Underwater sound, however, is used by marine mammals for detection, communication and navigation. While fish and shrimps use high frequency acoustic waves for short distance communication and target detection. Shipping is a major source of acoustic underwater noise, primarily from propulsion systems. These constraints effectively limit the frequency range that can be used in the ocean for acoustic tomography.

The sound speed in water is about 1500m/s, which is about 4.7 times faster than in air. The sound speed at a specific location depends on the local pressure, temperature and salinity. Salinity is normally considered to be constant in a particular oceanic region, away from sources of fresh water. Pressure in water increases linearly with depth,  $P = P_0 + \rho g z$ , where  $P_0, \rho, g$  are atmospheric pressure above sea level, sea water density and gravity. All of them are treated as constant. The sound speed profile (SSP), therefore, could be presented as a function of temperature  $T$  ( $^{\circ}C$ ), salinity  $S$  (psu) and depth  $D$  (m): Mackenzie's formula [130]

$$\begin{aligned}
 C = & 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 \\
 & + 1.340(S - 35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^{-2} \\
 & - 1.025 \times 10^{-2}T(S - 35) - 7.139 \times 10^{-13}TD^3
 \end{aligned} \tag{3.1}$$

The validity range of this equation is temperature 2-30 $^{\circ}C$ , salinity 25-40 psu, depth 0-8000m. Sound speed is affected by water temperature ( $\Delta 1^{\circ}C \sim 4m/s$ ), salinity ( $\Delta 1\% \sim 0.114m/s$ ) and depth ( $\Delta 1m \sim 0.0175m/s$ ).



**Figure 3.1:** Temperature, Pressure and Sound speed profile in the deep ocean [131].

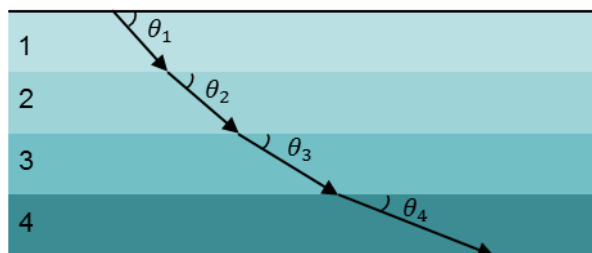
Seawater temperature varies significantly with depth as shows in Figure 3.1 (a). Sound speed profile is divided into 4 layers: surface layer, seasonal layer, thermocline layer and the deep-water layer. Surface and seasonal layers form a mixed zone that affected by waves, tidal and wind driven currents and sunlight. Bellow this layer is the thermocline, where seawater temperature decreases rapidly. In the deep-water layer seawater temperature is quite low and assumed to be constant ( $4^{\circ}C$ ) [132]. In the deep-water region the sound speed is mainly influenced by pressure, increasing with depth. Daily changes in weather conditions have a big effect on the surface layers. The thermocline itself is a kind of ocean weather whose strength and depth vary in time (and space).

### 3.2.2 Sound wave propagation

Sound speed is an important factor for sound waves propagating in water. When a sound wave is transmitted through different water layers at an angle,  $\theta_i$ , it propagates according to Snell's law [133],

$$\frac{\cos(\theta_1)}{c_1} = \frac{\cos(\theta_2)}{c_2} = \frac{\cos(\theta_3)}{c_3} = \frac{\cos(\theta_4)}{c_4} = \text{constant} \quad (3.2)$$

where  $c_i$  is the sound speed in the  $i^{\text{th}}$  layer.



**Figure 3.2:** Sound wave refraction in the water.

As figure 3.2 shows, the increase in sound speed with depth, i.e.  $c_1 < c_2 < c_3 < c_4$ , leads to a decrease in the sound transmitting angle, so  $\theta_1 > \theta_2 > \theta_3 > \theta_4$ .

When acoustic waves propagate in an incompressible medium, they can be modelled using the Wave Equation [134]:

$$\nabla^2 \Phi = \frac{1}{c^2} \frac{\partial^2 \Phi}{\partial t^2} \quad (3.3)$$

where  $\Phi$  is the acoustic wave pressure,  $\nabla^2 = \left(\frac{\partial^2}{\partial x^2}\right) + \left(\frac{\partial^2}{\partial y^2}\right) + \left(\frac{\partial^2}{\partial z^2}\right)$  is the Laplacian operator and,  $c$  is the sound speed. In deep water this is normally combined with Snell's law.

For a single frequency plane wave, the sound pressure can be written as a harmonic wave:

$$\Phi = \phi e^{-i\omega t} \quad (3.4)$$

where  $\phi$  is the time independent sound pressure,  $\omega$  is the angular frequency,  $\omega = 2\pi f$ , and  $f$  is the frequency of the sound wave. Inserting this harmonic wave in equation (3.3) we can derive the Helmholtz function:

$$\left( \nabla^2 + \left(\frac{\omega}{c}\right)^2 \right) \phi = 0 \quad (3.5)$$

The Harmonic wave can be written in three ways:

$$\begin{cases} \phi = F(x, y, z) e^{iG(x, y, z)} & \text{(a)} \\ \phi = F(z) \cdot G(r) & \text{(b)} \\ \phi = F(r, \theta, z) \cdot G(r) & \text{(c)} \end{cases} \quad (3.6)$$

In the first equation (3.6a), water pressure is presented as a multiply of amplitude  $F(x, y, z)$  and harmonic waves with range dependent phase function  $G(x, y, z)$ . Ray theory discussed below is obtained by substituting (3.6a) in (3.5) and solving the Helmholtz function. Normal Mode, Multipath Expansion and Fast Field Models [134] are obtained by solving (3.6b). Finally, Equation (3.6c) leads to a Parabolic Equation (PE) model solution of the Helmholtz function. So-called PE models make use of this parabolic approximation of a sound wave.

For ray theory, the Harmonic wave can be rewritten as:

$$\phi(r, \omega) = \phi(r) e^{-i\omega t(r)} \quad (3.7)$$

where  $r = (x, y, z)$  is a function of position,  $\phi(r)$  is a slowly varying pressure envelop function that is affected by attenuation and geometrical spreading,  $t(r)$  is a fast changing phase function, known as the Eikonal. High frequency approximation is considered with the assuming of  $\nabla^2 \phi(r)/\phi(r) \ll k^2$  [133,135]. Considering real part and imaginary part of Helmholtz Equation, the Eikonal Equation and Transport Equation are:

$$(\nabla t)^2 = \frac{1}{c^2} \quad (3.8)$$

$$2(\nabla A \cdot \nabla t) + A \nabla^2 t = 0 \quad (3.9)$$

To get solution of Eikonal Equation one need solve the equation given by [136]:

$$\frac{dr}{ds} = c\sigma_r(s), \quad \frac{dz}{ds} = c\sigma_z(s), \quad \frac{d\sigma_r}{ds} = -\frac{1}{c^2} \frac{\partial c}{\partial r}, \quad \frac{d\sigma_z}{ds} = -\frac{1}{c^2} \frac{\partial c}{\partial z} \quad (3.10)$$

where  $s$  is the travel distance of sound wave and  $\sigma = 1/c$  is sound slowness. The initial condition for sound wave propagation is:

$$r(0) = r_0, \quad z(0) = z_0, \quad \sigma_r(0) = \frac{\cos(\theta_0)}{c_0}, \quad \sigma_z(0) = \frac{\sin(\theta_0)}{c_0} \quad (3.11)$$

where  $c_0, z_0$  and  $r_0$  are sound speed and position at source position,  $\theta_0$  is launching angle of sound ray.

By considering boundary condition and initial environment at source position sound ray tracing can be conducted by solving the Eikonal Equation in water. In the Gaussian Beam approximation, the amplitude of the rays is given by solving Transport Equation [135]:

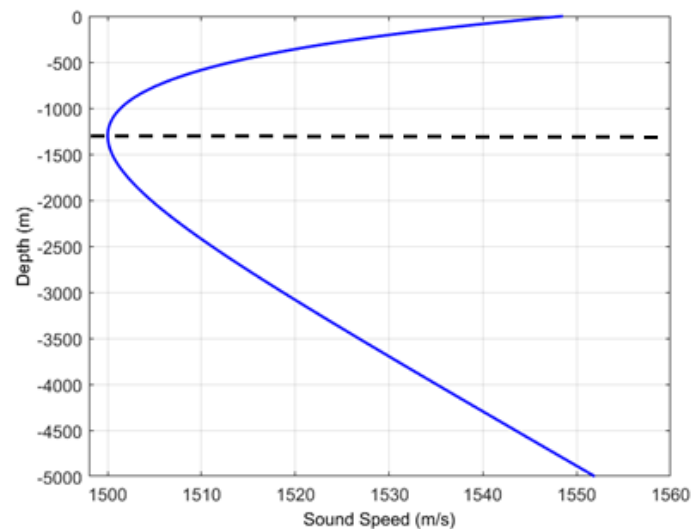
$$P(s, n) = \frac{1}{4\pi} \sqrt{\frac{c(s)}{c_0} \frac{\cos(\theta_0)}{q_\perp(s)q(s)}} e^{-iw \left[ t(s) + \frac{1}{2} \frac{p(s)}{q(s)} n^2 \right]} \quad (3.12)$$

where  $p(s)$ ,  $q_\perp(s)$  and  $q(s)$  are auxiliary function, they are derived by solving equations around sound axis [137], the auxiliary parameter determines the width of Gaussian beam.  $n$  is normal distance to the beam axis.

### 3.2.3 Ray tracing

In deep sea, there has a depth (at 1000-1500m) that the sound speed is minimum. That depth is the sound SOFAR (Sound Fixing and Ranging) axis. When the sound wave propagates along SOFAR axis it will be trapped in the channel. The sound wave can transmit for a long distance with small attenuation as it has few interactions with surface and sea floor.

As shown in Figure 3.3 the SOFAR axis is at 1300m for the Munk sound speed profile (SSP) [138].

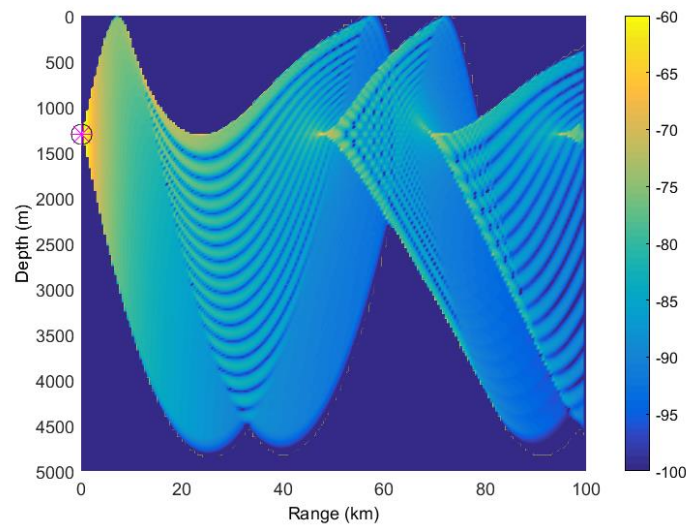


**Figure 3. 3:** Munk SSP in the deep sea. The SOFAR axis is at a depth of 1300m.

Sound wave propagation simulation is of great importance for ocean research. There exist several mathematical/numerical models based on different approaches [129]. Many of the most used models are based on ray theory, modal expansion and wave number integration techniques. Ray theory is widely used in range independent sound propagation simulation. After continuous developing there exists many ray tracing models, some of them focus on specific applications, and other models however are more general. The ray tracing simulation in this research all uses TRACEO, which developed by OC Rodriguez in University of Algarve [135]. This ray tracing method is partly developed based on Bellhop ray tracing model [137]. The TRACEO model can better process sound wave propagations in following conditions: sensor array is used in the simulation, obstacle exists in the sound wave propagation domain, range-dependent boundary conditions.

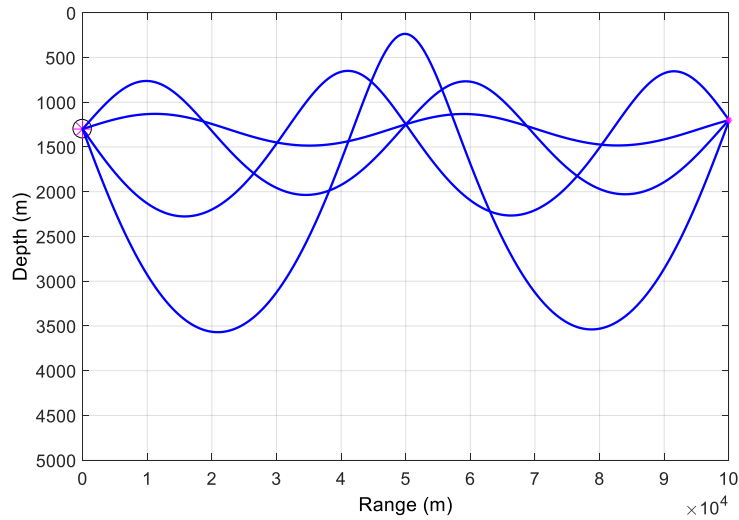
As shows in figure 3.4 sound wave launched with an angle and transmit in ocean with refraction effect. Supposing a target (marine mammal) sends sound waves at the source position, a

detecting ship moving across the sea surface from 0 to 100km will only be able to detect the animal at specific positions. In this case the target may be detected at 10km, 50km and 70km away from sound source. If an active sonar was used in the source position, targets (submarine and military ships) cannot be detected if they hide in the shadow areas. Sound speed profile is range dependent over a long distance. Range dependent sound speed profiles must be used for ray tracing simulations in field work and for sound wave propagation over long distances. The CTD data can be found on some website or measured by oceanographer.

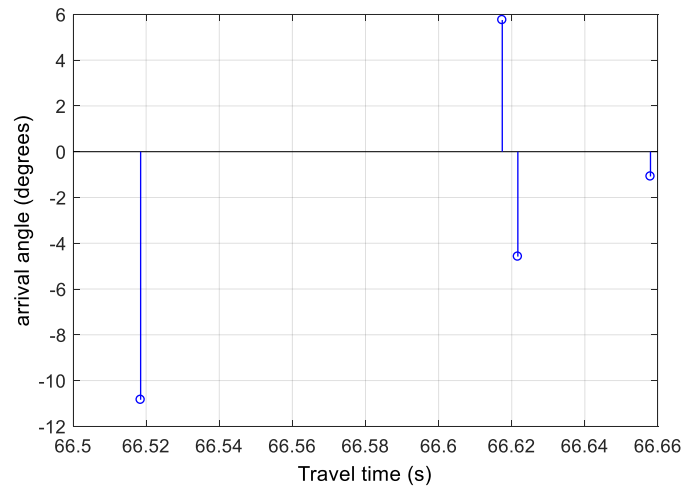


**Figure 3.4:** Sound transmission loss in deep sea with the Munk SSP. The sound source is deployed at the sound channel, number of colour bar indicate source level in dB (re  $\mu\text{Pa}$  at 1m).

In the sound wave propagation simulation, all the transmitted sound rays that can be received at receiver station are eigenrays. Exhaustive method is always used by dividing the transmitted sound waves into a range of rays with different launch angle. Eigenrays can be found after numerically calculate of each transmitted acoustic ray based on sound wave propagate theory that discussed in former section. The sound ray is assured as eigenray if it propagates along receiver, it always has litter error tolerance. As shows in figure 3.5, two sound transceivers are installed around SOFAR axis (1300m and 1200m separately) with a distance of 10km. Four eigenrays can be identified in this simulation.



**Figure 3.5:** Eigen-ray transmission in the deep sea. The transmitter and receiver are deployed at 1300m (sound propagation channel) and 1200m with a distance of 10km.



**Figure 3.6:** Travel time and arrival angle of different Eigen-ray.

Peak matching method can be used after receiving sound wave data from sound source. Sound wave phase, arrival angle and signal strength are all information that can be used for peak matching. Figure 3.6 is an example of arrival angle and travel time of different Eigen-ray that propagate along different ray path. The information used here is travel time of different signal. The received data will contain arrival signals propagate along different ray path. By ray tracing simulation, the arrival signal can be identified according the real travel time and simulated result. There may has some error as the simulated result is not absolutely accurate as the water environment is not steady. The travel time of sound wave can be used for inverse problem solving in the acoustic tomography research.



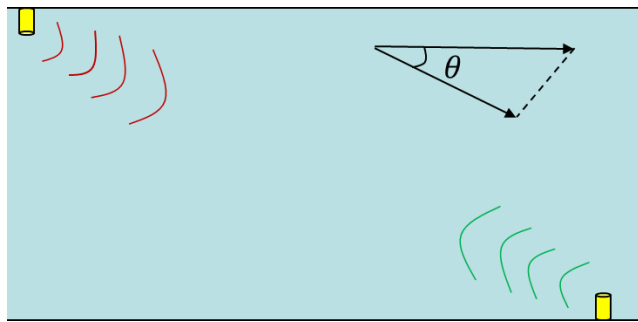
### 3.3 Sound Reciprocal Transmission

When short sound pulse propagate in flowing water between two transceivers the travel time is determined by the sound speed  $c$  and the current velocity  $\bar{v}$  along the path. Reciprocal travel time along and against the flow are given by:

$$t_+ = \frac{L}{c+v}, \quad (3.13)$$

$$t_- = \frac{L}{c-v}. \quad (3.14)$$

Where  $v$  is the component of the current velocity that has same direction of the sound transmission path;  $L$  is the distance between the transceivers.



**Figure 3.7:** Sound reciprocal transmission in river. Two sound transceivers are installed in opposite bank with a distance of  $L$ , the angle between flow current direction and sound transmission path is  $\theta$ .

The measured sound speed in the water  $c_m$  is normally about 1500m/s, the measuring flow current velocity  $v_m$  along sound wave propagate path is small relative to the sound speed.

Therefore, averaged sound speed and current velocity along the ray path could be written as

$$c_m = \frac{L}{2} \left( \frac{1}{t_+} + \frac{1}{t_-} \right) \approx \frac{L}{t_m}. \quad (3.15)$$

$$v_m = \frac{L}{2} \left( \frac{1}{t_-} - \frac{1}{t_+} \right) \approx \frac{R \Delta t}{2 t_m^2} \quad (3.16)$$

where  $t_m = (t_- + t_+)/2$  and  $\Delta t = t_- - t_+$  are mean and differential of the reciprocal travel time respectively. The angle between sound wave path and flow direction is  $\theta$  (figure 3.7), flow velocity along river is

$$v_r = \frac{v_m}{\cos(\theta)} \quad (3.17)$$

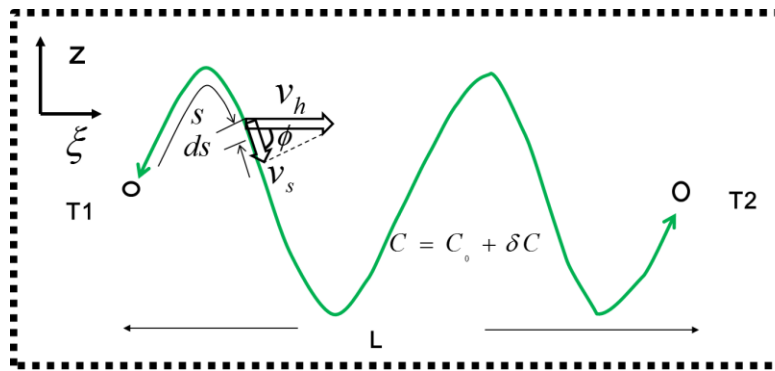
As equation 3.1 shows, sound speed is a function of temperature, depth and salinity. Depth averaged temperature along ray path is fixed when salinity, sound speed is obtained. Thus,

path averaged water temperature in all depth is determined combining equation 3.16 and equation 3.1.

### 3.4 Flow velocity analysis with sound wave transmission

#### 3.4.1 Forward problem

As discussed in this chapter, sound wave can propagate a long distance around sound axis in deep sea. Figure 3.8 presents a side view of an example of sound wave transmission in deep sea. Two transducers are deployed in ocean with a distance of  $L$ , the angle between sound ray path and horizontal axis is  $\phi$ , flow velocity along ray path is  $v_s$ . Sound speed  $C_0$  is affected by ocean environment with a variation  $\Delta C$ .



**Figure 3.8:** Side view of sound reciprocal transmission in deep sea. Two sound transceivers are installed in deep sea with a distance of  $L$ , the sound speed is affected by sea water parameters.

Travel time of sound wave along real ray path  $\Gamma_i^\pm$  is

$$t_i^\pm = \int_{\Gamma_i^\pm} \frac{ds}{C_0(z) + \delta C(x, z) \pm v_s(x, z)} \quad (3.18)$$

Where  $\pm$  indicate sound wave transmit along and opposite the direction of T1 to T2.  $C_0(z)$  is range-independent sound speed,  $\delta C(x, z)$  sound speed variation and  $v_x(x, z)$  is flow current along and opposite ray path from station T1 to T2.

Sound wave is transmitted from one station and received by receiver after a long-range propagation in water. In the field work, it's impossible to get the real sound ray path. Ray tracing simulation is chosen as an alternative way. Sound speed profile is calculated with CTD measurements around source for the range independent case. The simulated sound wave propagation time  $t_{0i}$  between two stations is

$$t_{0i} = \int_{\Gamma_{0i}} \frac{ds}{C_0(z)} \quad (3.19)$$

Where  $\Gamma_{0i}$  is simulated ray path with acoustic propagation programming.

Sound speed is relatively much larger than sound speed variation and flow velocity along ray path ( $C_0(z) \gg \delta C(x, z)$  and  $C_0(z) \gg v_s(x, z)$ ). By taking subtraction of equation (3.18) and (3.19) and using Taylor expansion, the difference of travel time of sound wave and simulated result is

$$\begin{aligned} \tau_i^\pm &= t_i^\pm - t_{0i} = \int_{\Gamma_i^\pm} \frac{ds}{C_0 \left( 1 + \frac{\delta C(z) \pm v_s(x, z)}{C_0} \right)} - \int_{\Gamma_{0i}^\pm} \frac{ds}{C_0} \\ &= \int_{\Gamma_i^\pm} \frac{ds}{C_0} \left( 1 - \frac{\delta C(z) \pm v_s(x, z)}{C_0} + \frac{(\delta C(z) \pm v_s(x, z))^2}{(C_0)^2} - \dots \right) - \int_{\Gamma_{0i}^\pm} \frac{ds}{C_0} \\ &= \int_{\Gamma_i^\pm} \frac{ds}{C_0} \left( 1 - \frac{\delta C(z) \pm v_s(x, z)}{C_0} \right) - \int_{\Gamma_{0i}^\pm} \frac{ds}{C_0} \end{aligned} \quad (3.20)$$

High order Taylor expansion term is neglected here. Simulated ray path is similar with real sound wave propagation path,  $\Gamma_{0i}^\pm \approx \Gamma_i^\pm$ . Thus, the travel time can be approximated as

$$\tau_i^\pm \approx - \int_{\Gamma_{0i}} \frac{(\delta C \pm v_s)}{C_0^2} ds \quad (3.21)$$

The subtraction and summation of round way sound wave travel time are

$$\Delta \tau_i = \tau_i^+ - \tau_i^- = -2 \int_{\Gamma_{0i}} \frac{v_s}{C_0^2} ds \quad (3.22)$$

$$\delta \tau_i = \tau_i^+ + \tau_i^- = -2 \int_{\Gamma_{0i}} \frac{\delta C}{C_0^2} ds \quad (3.23)$$

The subtraction and summation travel time are the input information of acoustic tomography inverse problem. In the following content, flow details are reconstructed by acoustic tomography method using round way travel time difference  $\Delta \tau_i$ .

### 3.4.2 Horizontal flow current velocity reconstruction using sound travel time

For incompressible flow, velocity in horizontal plan can be expressed by the stream function,  $\psi$  [139-140]:

$$\vec{v} = \nabla \times (-\psi \hat{z}) = \left( -\frac{\partial \psi}{\partial y}, \frac{\partial \psi}{\partial x} \right) \quad (3.24)$$

The stream function can be expanded by Fourier series:

$$\psi(x, y) = \sum_{k=0}^N \sum_{l=0}^N \left\{ A_{kl} \cos 2\pi \left( \frac{kx}{L_x} + \frac{ly}{L_y} \right) + B_{kl} \sin 2\pi \left( \frac{kx}{L_x} + \frac{ly}{L_y} \right) \right\}, \quad (3.25)$$

Where  $A_{kl}$  and  $B_{kl}$  are Fourier coefficient,  $L_x$  and  $L_y$  are size of inverse domain. To avoid periodicity of the Fourier series, the inverse domain should be larger than observation area.  $N$  determines the wave number of stream function, it is chosen according observation data and spatial requirement of inverse result. Equation (3.27) can be rewritten as:

$$\psi(x, y) = \sum_{j=1}^{(N+1)^2} P_n Q_n(x, y), \quad (3.26)$$

where  $P = [A_{00}, B_{00}, A_{01}, B_{01}, \dots, A_{NN}, B_{NN}]$ ,

$$Q(x, y) = \left[ 1, 0, \cos \frac{2\pi x}{L_x}, \sin \frac{2\pi y}{L_y}, \dots, \cos 2\pi \left( \frac{Nx}{L_x} + \frac{Ny}{L_y} \right), \sin 2\pi \left( \frac{Nx}{L_x} + \frac{Ny}{L_y} \right) \right]$$

Project ray path to horizontal plan and substitute equation (3.28) to (3.22), the round way travel time difference is

$$\Delta t_i = 2 \sum_{j=1}^{(N+1)^2} P_n \int_0^{R_i} \frac{\frac{\partial}{\partial y} Q_j(x, y) - \frac{\partial}{\partial x} Q_j(x, y) \tan \phi_i}{C_0^2} dx \quad (3.27)$$

Where  $R_i$  is the distance between two sources along  $x$  axis,  $\phi_i$  is angle between  $x$  axis and  $i^{th}$  ray path. The travel time can be reduced as

$$\mathbf{y} = \mathbf{E}\mathbf{x} + \mathbf{n} \quad (3.28)$$

Where

$$\mathbf{y} = [\Delta t_1, \Delta t_2, \dots, \Delta t_{N_r}]$$

$$E_{ij} = \int_0^{R_i} \frac{\frac{\partial}{\partial y} Q_j(x, y) - \frac{\partial}{\partial x} Q_j(x, y) \tan \phi_i}{C_0^2} dx$$

$$\mathbf{x} = \mathbf{P}^T$$

The error vector  $\mathbf{n}$  is introduced by time taking and random error, it also contains model error that caused by truncated Fourier series number and limited measurements.

To determine the unknowns, a damped least squares method is used to balance the model parameters and the error. The objection function could be given

$$J = (\mathbf{y} - \mathbf{E}\mathbf{x})^T (\mathbf{y} - \mathbf{E}\mathbf{x}) + \alpha^2 \mathbf{x}\mathbf{x}^T, \quad (3.29)$$

The  $\alpha$  is the weighting factor. The expected solution  $\tilde{\mathbf{x}}$  is found by minimize the objection function  $J$

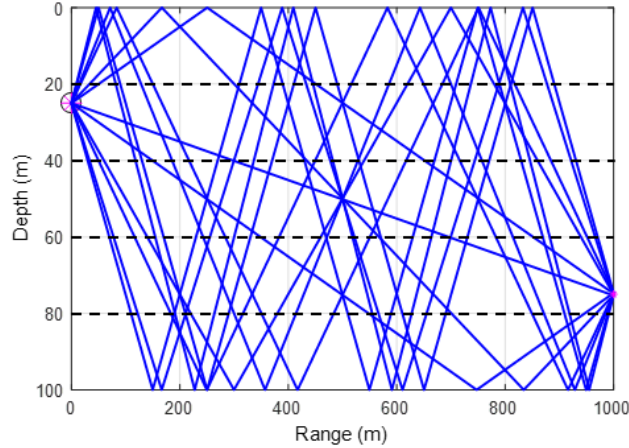
$$\tilde{\mathbf{x}} = \mathbf{E}^T (\mathbf{E}^T \mathbf{E} + \alpha^2 \mathbf{I})^{-1} \mathbf{E}^T \mathbf{y} \quad (3.30)$$

The solution of (3.30) is layer averaged velocity in the ray path slice.

### 3.4.3 Vertical layered inversion

Flow detail can be analysed in different depth layer using multi-path propagation acoustic signals. The vertical slice of ray path can be divided into different layers. Travel time of sound rays pathing through different layers is used for inverse problem solving. Considering the flow current estimating, travel time of round-way transmission signal is used in this research as input information.

Figure 3.9 shows a shallow water sound wave propagation example. Two acoustic transceivers are deployed in a depth of 25m and 75m separately, 1000m apart. The 100m depth water is divided into 5 layers, 20m for each layer. Sound speed is treated as constant in this simulation. Multi-path propagation appears in this case as water depth is shallow and transmitted signal reflected by water surface and sea bed. The multi-path propagation signal can be used for vertical layer averaged velocity reconstruction.



**Figure 3.9:** Eigenrays in shallow water. Sound source and receiver are at a depth of 25m and 75m separately, sound speed is 1500m/s of all depth.

For  $M$  sound rays through  $N$  layers, the travel time for  $i$ -th acoustic ray along and against the flow ( $t_i^+$  and  $t_i^-$ ) are

$$t_i^\pm = \sum_{j=1}^N \frac{l_{ij}}{(c_j \pm u_j)}, \quad j=1,2,\dots,M \quad (3.31)$$

The  $c_j$  is the path-average sound speed for j-th layer, and the sound speed is taken uniform for the whole depth in this study. The  $u_j$  is the flow velocity for j-th layer. The  $l_{ij}$  is the length of i-th ray crossing the j-th layer.

The flow velocity is small compared to the sound speed in water. Thus, the reciprocal travel time difference  $\Delta t_i$  is expressed by

$$\Delta t_i = (t_i^+ - t_i^-) = -2 \sum_{j=1}^N \frac{l_{ij} u_j}{c_j^2} \quad (3.32)$$

In the matrix form it becomes

$$\begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \vdots \\ \Delta t_M \end{bmatrix} = \begin{bmatrix} -2 \frac{l_{11}}{c_1^2} & -2 \frac{l_{12}}{c_2^2} & \dots & -2 \frac{l_{1N}}{c_N^2} \\ -2 \frac{l_{21}}{c_1^2} & -2 \frac{l_{22}}{c_2^2} & \dots & -2 \frac{l_{2N}}{c_N^2} \\ \vdots & \vdots & \ddots & \vdots \\ -2 \frac{l_{M1}}{c_1^2} & -2 \frac{l_{M2}}{c_2^2} & \dots & -2 \frac{l_{MN}}{c_N^2} \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_N \end{bmatrix} \quad (3.33)$$

Considering the travel time errors  $\mathbf{n}$ , Equation (3.33) is reduced to

$$\mathbf{y} = \mathbf{E}\mathbf{x} + \mathbf{n} \quad (3.34)$$

where  $\mathbf{y}$  is the travel time difference vector,  $\mathbf{E}$  is the transform matrix and  $\mathbf{x}$  is the layered current vector.

According to the regularized inverse method, the cost function is

$$J = (\mathbf{y} - \mathbf{E}\mathbf{x})^T (\mathbf{y} - \mathbf{E}\mathbf{x}) + \lambda \mathbf{x}^T \mathbf{H}^T \mathbf{H} \mathbf{x} \quad (3.35)$$

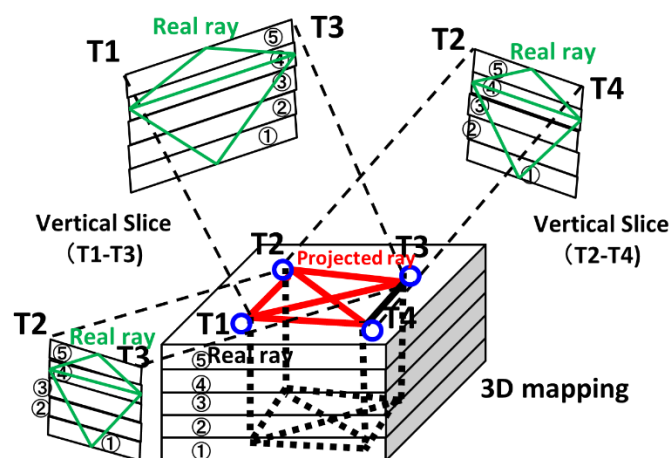
Where  $\lambda$  is the Lagrange multiplier, superscript  $T$  is the transpose of a matrix.  $\mathbf{H}$  is the weighting matrix to regularize the solution. By minimizing the costing function the optimal solution  $\tilde{\mathbf{x}}$  is

$$\tilde{\mathbf{x}} = (\mathbf{E}^T \mathbf{E} + \lambda \mathbf{H}^T \mathbf{H}) \mathbf{E}^T \mathbf{y} \quad (3.36)$$

The solution of (3.36) coefficient is truncated Fourier series. The stream function is obtained from (3.25) and flow velocity of each grid is obtained.

### 3.5 Three-dimensional flow detail reconstruction within the whole area

Surface wave can be monitored by remote sensing with radar, high speed camera and satellite. Inner flow details in water is always detected by fixed point direct measurement or floating buoy. As discussed in former content, sound wave is the only found medium that can propagate a long rang with small attenuation in water. The 2D flow details can be obtained with acoustic tomography method, which use travel time of sound wave as input information. The flow velocity can be mapped by solving inverse problems. The three-dimensional flow details, however, can also be monitored with acoustic tomography technique. Flow detail monitoring of a water volume can be accomplished by combining vertical layered analyse and horizontal 2D mapping of target parameter. Flow velocity is analysed in different layer in the ray path slice. The flow velocity detail in different layer can be mapped using layer averaged velocity along each ray path.



**Figure 3. 10:** Scheme of three-dimensional acoustic tomography research. Layered averaged velocity of flow current in vertical slice is analysed, flow details then can be reconstructed in different layers.

As shows in figure 3.10, the interested water volume is divided into 5 layers. Four acoustic tomography stations are installed in the middle of 4<sup>th</sup> layer around target area. 6 sound propagation route slices are formed for this multi-station sensing network. Take the vertical slice that contain T2 and T3 as an example, multi-path arrival signal can be received at both station. As shows in section 3.4.2, layer averaged flow velocity can be acquired by solving inverse problem in slice that contain station T2 and T3. Layer averaged flow velocity of all those 6 vertical slices can be used for horizontal flow detail reconstruction. The assimilated sound wave round-way travel difference is determined by layer averaged flow velocity and

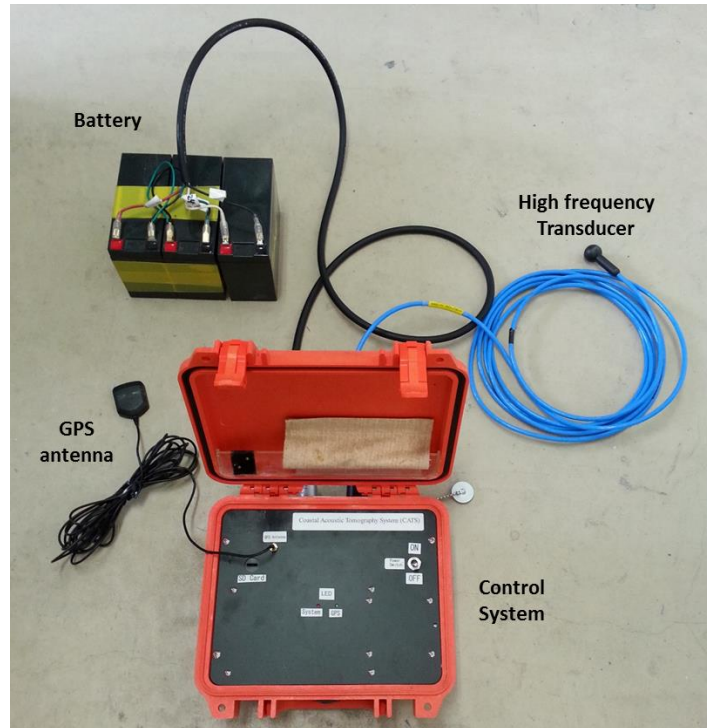
travel distance. As shows in section 3.4.3, sound wave travel time is used as input information for the travel time in the acoustic tomography research. In each layer, the flow velocity can be mapped with acoustic tomography method. The three-dimensional mapping of flow velocity in the interested area is obtained with 5 horizontal mapping.

For three-dimensional acoustic tomography research, flow details in each layer is mapped using sound wave travel time along different ray paths. To get better sensing result passive acoustic tomography [102,136,141-142] can also be used in the three-dimensional ocean parameter sensing. For the deep-sea acoustic tomography sound source and receiver are deployed around sound axis, it's difficult to transmit received data to onshore station. By adding time domain to the three-dimensional mapping of ocean parameter, the real-time sensing of ocean progress can be accomplished. If acoustic tomography station can communicate with onshore station with radar or satellite, the real-time acoustic tomography measurement can also be used in ocean environment forecasting. The real-time monitoring of flow details can also benefit to model testing in experimental tank, which is a main target of this research.

### **3.6 Underwater acoustic tomography system**

Like normal sonar system this underwater acoustic tomography system also contains two part: dry and wet part. The underwater acoustic tomography presents here mainly consist of three parts: power supply, central control system and the high frequency broadband transducer (figure 3.11). The transceiver is wet part, control system and power supply are dry part. The self-contained deep-sea acoustic tomography system that being developed by Hiroshima University put all three part in one glass ball. All parts of the system can be treated as wet part in this case. The main difference between this system and coastal acoustic tomography system is the working frequency. Short distance sound propagation uses high frequency sound waves for much higher time resolution. Low frequency sound wave can be received after long distance propagation in ocean. In the small-scale flow detail sensing research time accuracy is of great importance. Transducer is chosen according to the frequency of sound wave. As this study mainly explore small scale flow details in experimental tank, high frequency transceiver is used in the new system. The underwater acoustic tomography is developed based on the coastal acoustic tomography system that designed in Hiroshima University. This system modifying work is completed in cooperation with acoustic tomography group in Hiroshima University.

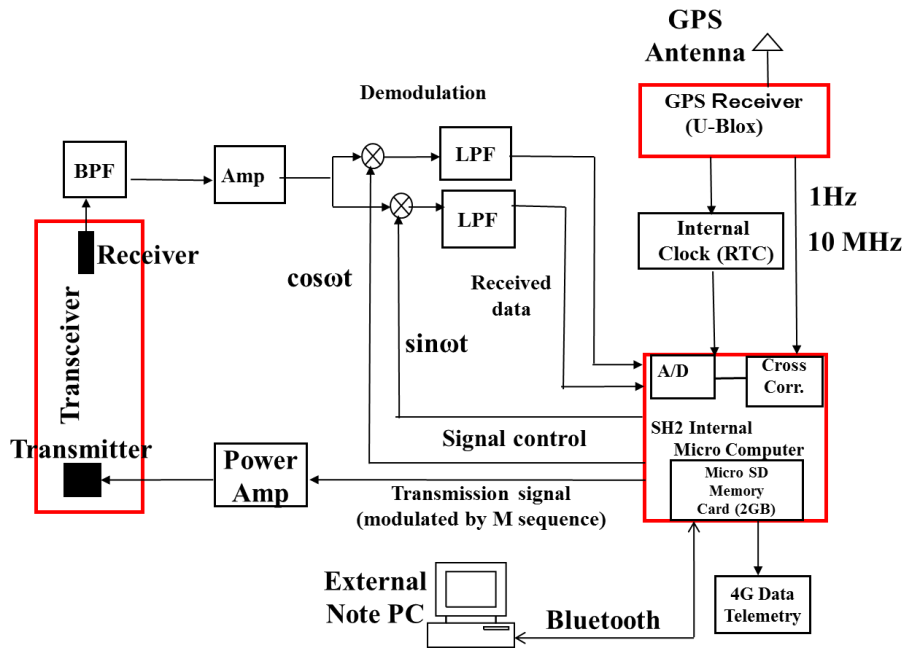




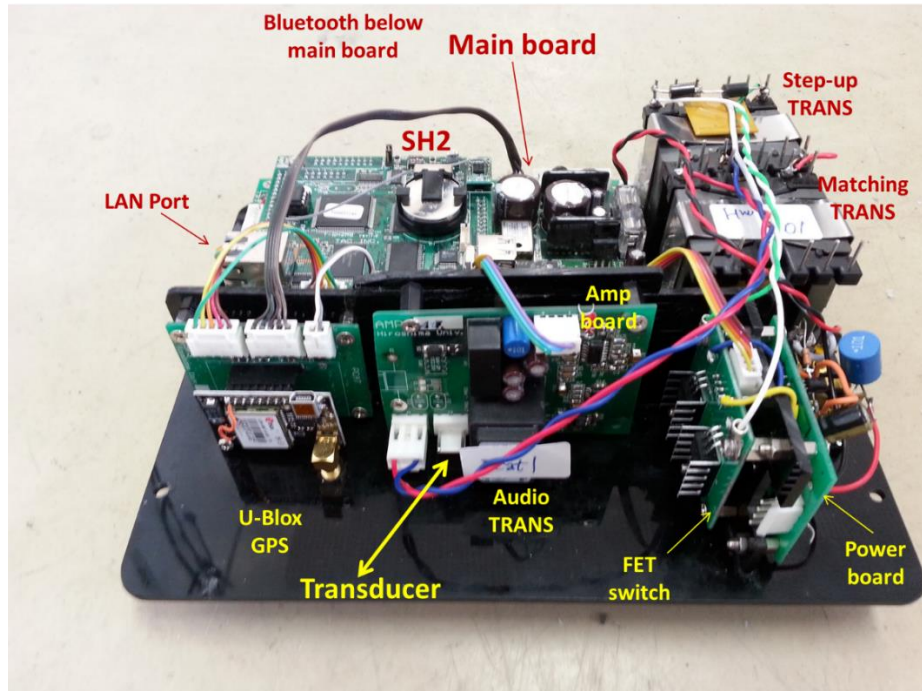
**Figure 3.14:** Newly constructed underwater acoustic tomography system. It mainly consists of central control system, power supply and high frequency broadband sonar sensors. The system receives GPS signal for time synchronize, this signal can also be used for station positioning.

### 3.6.1 Control system

The acoustic tomography system used in this study is a modified based on coastal acoustic tomography system that originally designed by Hiroshima University [27,31,118]. The system is powered by a 12V power supply, while the acoustic sensor is powered with 24V. GPS signal is used by the systems for time synchronisation. In the laboratory environment a GPS repeater can be used to provide a signal inside the building. Besides, sound station positioning also use GPS signal in the open water experiment. The originally transmitted signal and received raw data are all stored in the central control system on a high-speed memory card. It shows the block diagram of the acoustic tomography system in Figure3.12. The system can be controlled with PC by Bluetooth of cable, a LAN port is reserved for this using. System transmit modulated sound wave through transmitter after power amplifying. Sound wave is received by receiver after propagation in water. The received raw data is modulated with transmitted sine sound wave and stored in the system. The system can also transport received data to onshore work station with telecommunication technique for field work.



**Figure 3.15:** Block diagram of the underwater acoustic tomography system. Sonar sensor is fixed in the left red box. The system received signal is separated into two channels. GPS antenna is used in the system for time synchronise and station positioning.

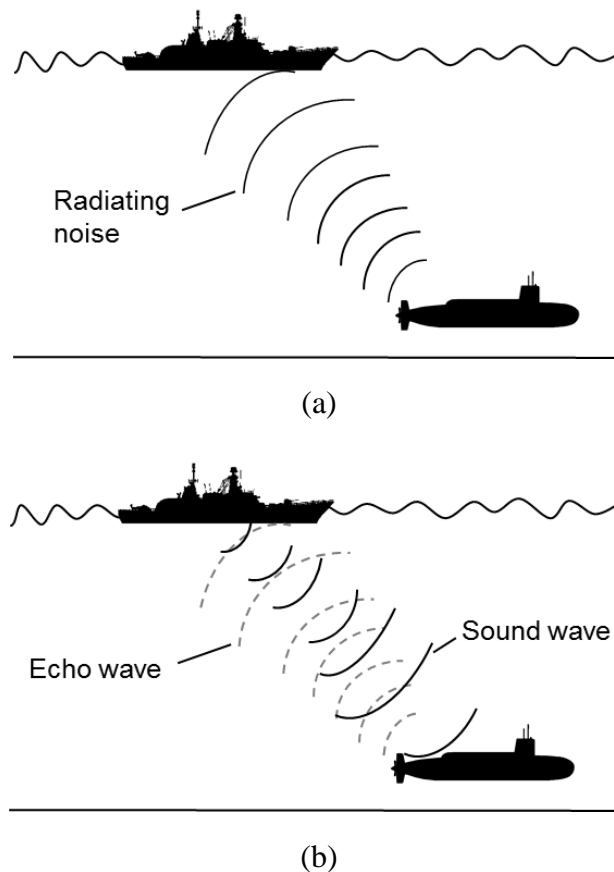


**Figure 3.16:** Circuit of the acoustic tomography system. It mainly contains transmit matching, power board, U-Blox, amp board and main board. Bluetooth board is also used in this system for remote controlling.

The time resolution is determined by the frequency of the carrier wave. High frequency sound wave must be used to get sufficient time resolution over short distances. Meanwhile, the attenuation of sound wave increases quickly with high frequency. This is the reason for low frequency sound transmission in ocean for the large-scale acoustic tomography research. The newly constructed underwater acoustic tomography system is developed based on the coastal acoustic tomography system. Except for using new high frequency broadband sonar sensor, this new system also modifies the control system for higher frequency. The transmit power (figure 3.13) transfer is changed based on the performance of the chosen sonar sensor. As shows in figure 3.13, the arriving sound wave is received with receiver. The raw data is divided in two channel and multiplied with transmitted sine wave and phase shifted sound wave. Those data are stored in the system after low pass filter. The low pass filter in the control system is changed as it has different cut-off frequency for the high frequency acoustic tomography system. The sampling frequency for the new system is much quicker than normal acoustic tomography system. Much higher processing speed is required of the main control system, the speed of main board is of great importance in the system. The hardware system for the small-scale acoustic tomography research is also modified based on the requirement of the chose transceiver, DualSense 115, which will be presented in the following section.

### **3.6.2 Sonar sensor**

Sound wave is up to now the only founded media that can be used for long distance propagation in water. Like using radar for communication and target detecting in air. Sound wave is a popular language for the underwater world. Plenty kinds of marine mammals use low frequency sound wave for long distance communication. Sonar is used for underwater sound wave transmitting and receiving, it is a device that needed for ocean surveying. Sonar is the acronym for SOund NAVigation and Ranging, it is used for underwater target detecting, navigation, communication and ocean surveying. Sonar system mainly contain sound transmitter, receiver, control system. The central control system can not only maintain the work progress of the sonar system, it also transmitted sound wave and the received acoustic signal. Sound speed in water is about  $1500\text{ms}^{-1}$ , which is much quicker than that in air. Take a simple example, sound waves are transmitted with sonar. Transmitted sound wave reaches a target and bounced back, the echo sound wave is received with sonar. The distance between sonar and target can be established by calculating the round way travel time of sound wave.



**Figure 3.17:** The working principle of active sonar (a) and passive sonar (b) system. Active sonar use target echo wave as input information by transmitting sound wave in water. The passive, however, get information by detecting radiate noise of target.

According to the working intention and its function sonar system can be divided into two types: active sonar and passive sonar. Figure 3.14 shows the typical active sonar (figure 3.14 (b)) and passive sonar (figure 3.14(a)) system. The biggest difference between active sonar and passive sonar is whether the sound energy is transmitted out in water. Active transmit sound wave or pulse into water. It listens to the echo wave and use the received acoustic signal for navigation, target detecting and so on. Passive sonar, however is a listening device that only receive sound wave that produced by other products. Passive sonar doesn't transmit sound wave in the water environment, it thus doesn't disturb the marine life. It always used in the submarine for military intention. The direction and distance of the target can be founded when hydrophone array is used for passive sonar system. Meanwhile, the frequency spatial of different target is also not same. Passive sonar can be used for marine mammal detecting by analysing the frequency of received "voice". Passive and active sonar is always used together for combined detecting in ocean engineering systems. This underwater acoustic tomography system uses sonar transceiver for sound wave transmitting and receiving, it is a kind of active sonar system.

The received acoustic signal should be with enough strength after a long-distance propagation. Sound energy loss for underwater sound transmission mainly contains geometric spreading loss, absorption loss, reflection and scattering. Acoustic energy is spread over a surface, the surface will become much larger as it propagates as the total energy is fixed after a sound wave is transmitted. The energy density will decrease with sound propagation, this process is the geometric spreading loss of sound propagation. As a media, water will absorb energy of sound wave when it transmits through it. Meanwhile, sound wave will be reflected and scatted in water. The most important factor that impact the sound transmission is the frequency of sound wave. Sound attenuation  $\alpha$  is a affected with frequency  $\alpha$  as:  $\alpha = \frac{0.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.003$  . As shows in table 3.1 sound energy decrease rapidly with the increase of frequency.

**Table 3.1:** The distance it takes sounds of different frequencies to travel in the ocean before half of the sound energy is absorbed [143].

Frequency (kHz)	Range (km)
0.1	3000
1	30
10	3
40	0.3
300	0.03

This new small scale underwater acoustic tomography system uses the DualSense 115 transducer as sonar sensor. This producer is a broadband transceiver that can not only used to transmit sound wave and it can also receive the arriving acoustic signal with high sensitivity. It can transmit sound wave in a large range (10 Hz to 150 kHz), which is needed for acoustic tomography research as the transmitted sound wave is modulated to broadband. Another reason for choosing this transducer for the system is its Omni-direction character (table 3.2). This transducer can transmit and receive sound wave in all directions. It can be used in the multi-station network sensing system.

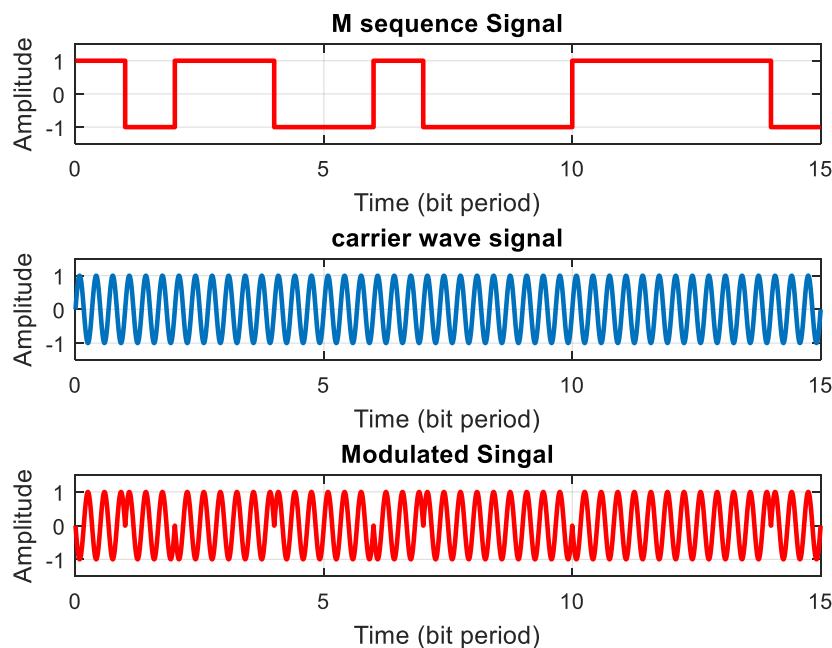
**Table 3.2:** The parameter of Dual Sense 115 transducer. It is used in the small-scale flow detail profiling in the underwater acoustic tomography system.

Technical specification	
Nominal resonant frequency	115kHz
Receiving Sensitivity @116kHz	-204 dB re 1V/uPa
Recommended receive frequency range	10Hz-150kHz
Linear frequency range	10Hz-75kHz
Maximum acoustic input @116kHz	+250 dB re 1μPa
Transmit sensitively @116kHz	+150 dB re 1V/uPa
-3dB bandwidth	22kHz
Quality Factor	5.3
Recommended transmit frequency range	85kHz – 120kHz
Maximum source level @ 116kHz	+196 dB re 1μPa/V at 1m
Maximum applied voltage at resonance	200Vrms
Low Frequency capacitance (@ 1kHz)	11nF
Horizontal beam pattern Omni-directional	+/- 1.5 dB at 75kHz
Vertical beam pattern	>270°
Mechanical specification	
Dimensions	Maximum outer diameter 25mm, Length 61mm
Transducer head weight in air	Approximately 40g
Transducer head weight in water	Approximately 30g
Maximum recommended operating depth	1,000 m
Survival depth	2,000 m
Operating temperature range	-5 to +35°C

### 3.6.3 Acoustic signal

Sound wave is used in the underwater target detection, communication and navigation with sonar system. Suitable kind of sound wave is of key importance to the performance of sonar. The sound wave propagation in ocean environment is affected with ambient noise that brings with boating, fish, marine mammal, surface wind, rain, geography activity and other ocean livings. The mixed noise is sometime treated as white noise for simplify. White noise is broadband signal, whose power density is constant and spread in all frequency range. The white noise has no correlation with efficient signal and its auto-correlation is a sharp pulse, which

means it has ideal auto-correlation. White noise can be produced with simulation and it exist in real environment. The ideal white noise cannot create by any sonar sensor as there has working frequency band for all sonar sensor. The white noise is an ideal signal for multi-station network sensing by using correlation. Pseudo noise, however, is a good choice for signal identifying. This underwater acoustic tomography system needs use high SNR signal for travel time identifying. Meanwhile, the multi-station sensing network has high requirement of acoustic signal used in this research. The received signal from different station need to be identified and separated. Acoustic signal used in the underwater acoustic tomography system here is M sequence modulated high frequency sound wave.



**Figure 3.18:** Phase modulation of M sequence signal. Two cycles of sine wave are multiplied in one digit, 5 order of M sequence is used here. The carrier wave (sine wave) is phase modulated with M sequence.

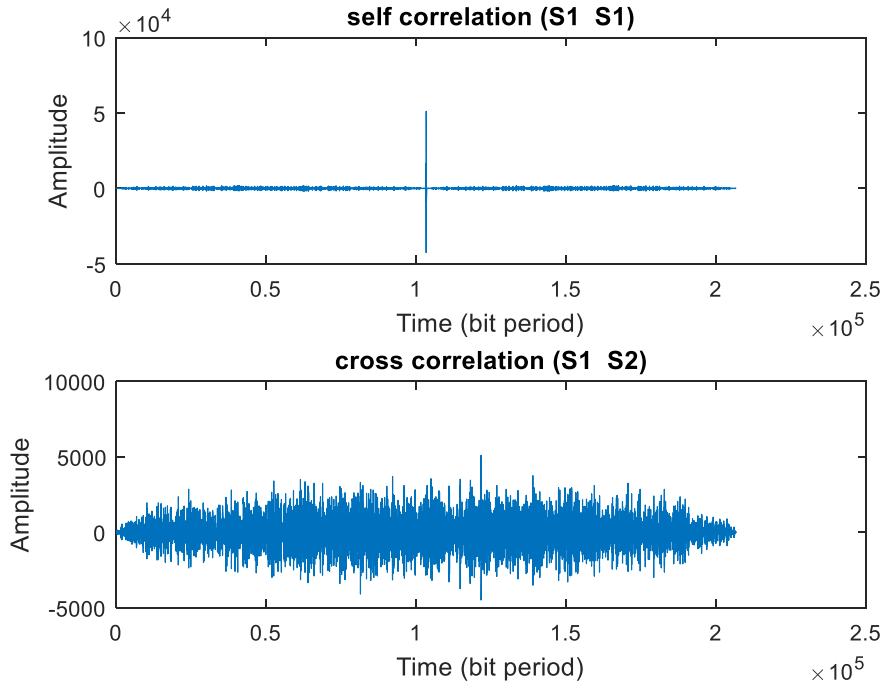
Maximum length sequence (MLS) is a kind of pseudorandom binary sequence, it is also named as M sequence. This sequence is created with linear feedback register, its bit is generated with shift of register. The sequence is repeatable, the period of this sequence is  $2^m - 1$  if the number of registers is  $m$ . Figure 3.15 Shows a progress of M sequence modulated sound wave, the order of this M sequence is 4 and the modulate depth (cycle per digit) is 2.

Since the received signal will be mixed with ambient noise a pseudo-random M-sequence is used to modulate the carrier signal, which provides a strong anti-interference ability to the

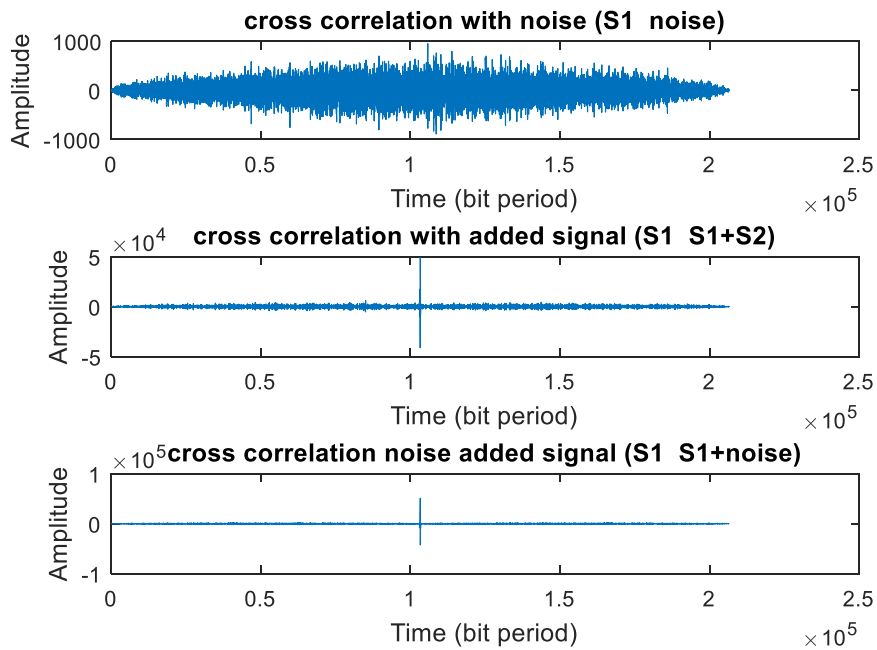
acoustic signal. It can be shown that the signal to noise ratio (SNR) of  $n$ th order M-sequence phased signal increases  $2n-1$  times. Precisely travel times can be estimated using correlation of received data and transmitted M-sequence modulated signal. This is because the auto-correlation of an M-sequence modulated signal appears like an impulse response. Figure 3.16 and figure 3.17 Shows the correlation of  $10^{\text{th}}$  order M sequence modulated sine wave, the modulate depth is 2. Two M sequence signal  $S_1$  and  $S_2$  are of the same order and the amp of noise is also same as M sequence used in this simulation. It shows M-sequence signals have no correlation with ambient noise and cross-correlation between two M sequence is also very low, which can be neglected. M sequence modulated signal is suitable to Multi-station network, where one station can receive signals from all other stations in the network without overlapping.

The sound wave is modulated with M sequence, whose frequency band is broadened with phase modulation. This progress brings a strict requirement of sonar sensors, especially for transceiver. The sonar sensor is normally designed as sound transmitter (sound source) or receiver. The sensitivity of the sonar sensor is of great importance for sound transmission and receiving. The bandwidth of M sequence is 25 kHz if the central frequency  $f_0$  is 50 kHz and the modulate depth  $Q$  is 2 as the frequency band of M sequence sound wave is  $f_0/Q$  [144]. It will be difficult to find suitable transceiver for the M sequence sound wave transmission and receiving. The transmission and receiving sensitivity are a big restrict for broadband sonar sensor. Broadband transceiver is needed for the underwater acoustic tomography system. There will be distortion for long distance transmission of broadband signal in water, especially in shallow water. Sound wave is reflected by water surface and bottom, with has different feedback to each frequency. Single frequency sound wave can propagation long distance, the performance will be much better if the frequency is low. That is why researchers choose large  $Q$  number for M sequence in ocean acoustic tomography research. Time resolution is determined by frequency of sound wave that transmitted by sound source.





**Figure 3.19:** The auto-correlation (a) and cross-correlation (b) character of M sequence modulated signal. No correlation peak appears of different M sequence, two signals are of same order.

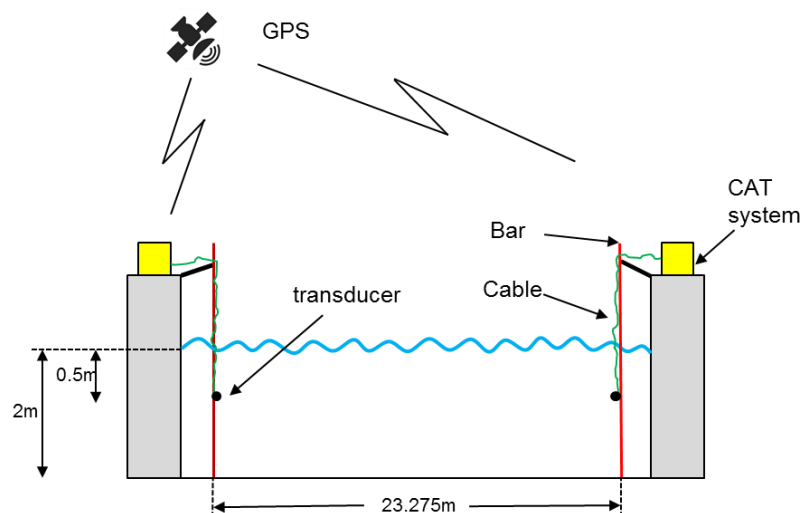


**Figure3.17:** The robust of M sequence. An M sequence signal has no correlation with noise and other M sequence signal. The strength of noise is same as M sequence signal.

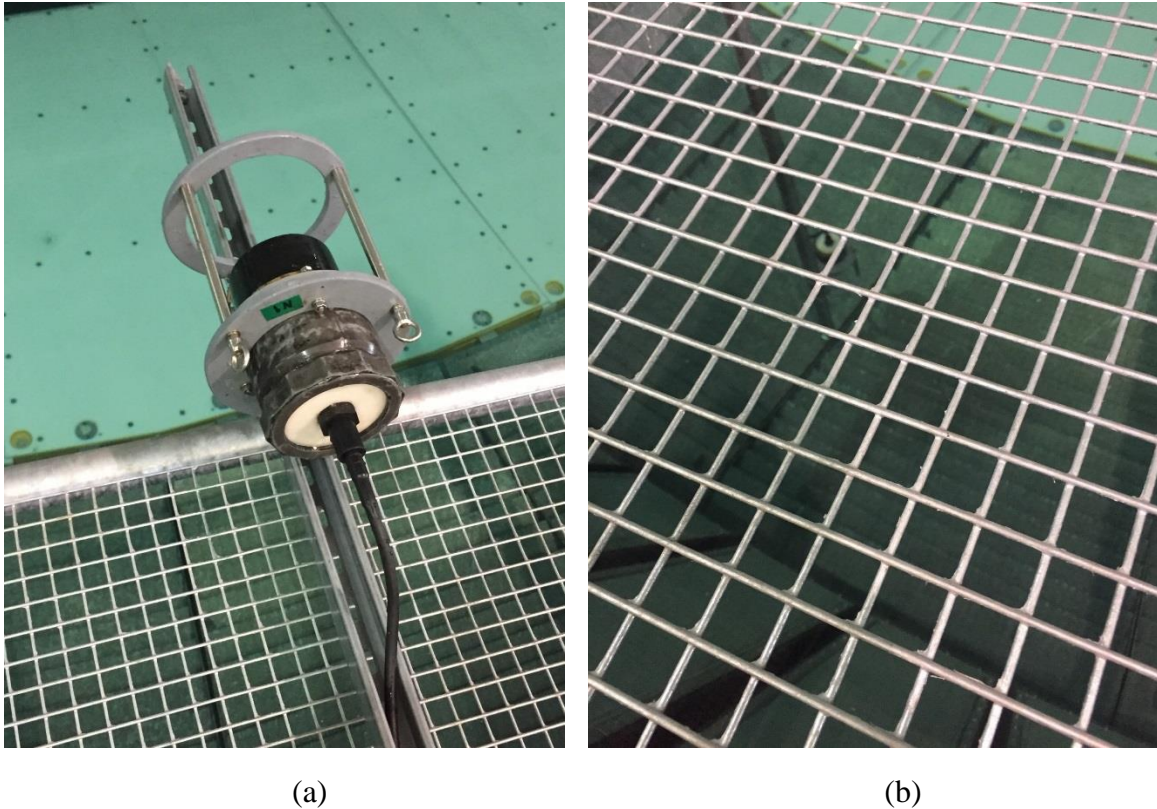
### 3.6.4 Sound transmission in the circular experimental basin

The acoustic tomography method is normally used for large scale flow condition or water parameter monitoring for recent researches [21,145-147]. This research is for the first trail to use the acoustic tomography method in small scale test, experimental tank, for flow current monitoring. To explore the performance of acoustic tomography in the short distance sound wave transmission a pilot test was conducted in the experimental tank before the acoustic tomography experiment. The acoustic tomography system is used in this experiment for sound transmission within 25m. The intention of this experiment is to study the sound propagation characteristics in the tank.

A pair of transceivers were installed 0.5m below the surface with a distance of 23.275m (Figure 3.18). The depth of the water in the experimental area is 2m. Fresh water is mixed in the circulatory system in the shallow experimental basin, the sound speed thus is taken as a constant here. The sound rays will interact with the boundary in the shallow water. The bottom of the tank is flat and the surface is also taken as a flat plane. The sound sensor is controlled with acoustic tomography system, which manages the testing progress. The received acoustic signal is pre-processed with acoustic tomography system and stored in SD card in the system. GPS signal is used for positioning of acoustic stations in the open water acoustic tomography research. Small scale sound transmission has high enquiry for the time accuracy, GPS signal was used for the system time synchronize.



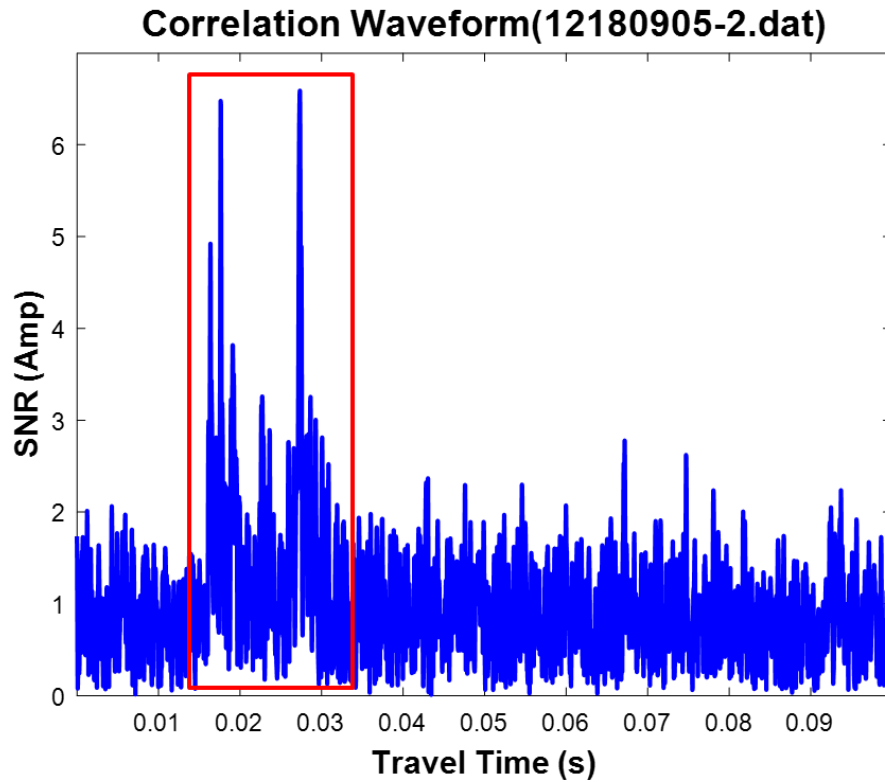
**Figure 3.18:** Experiment design scheme for the reciprocal sound transmission. The CAT system uses GPS signal for time synchronize.



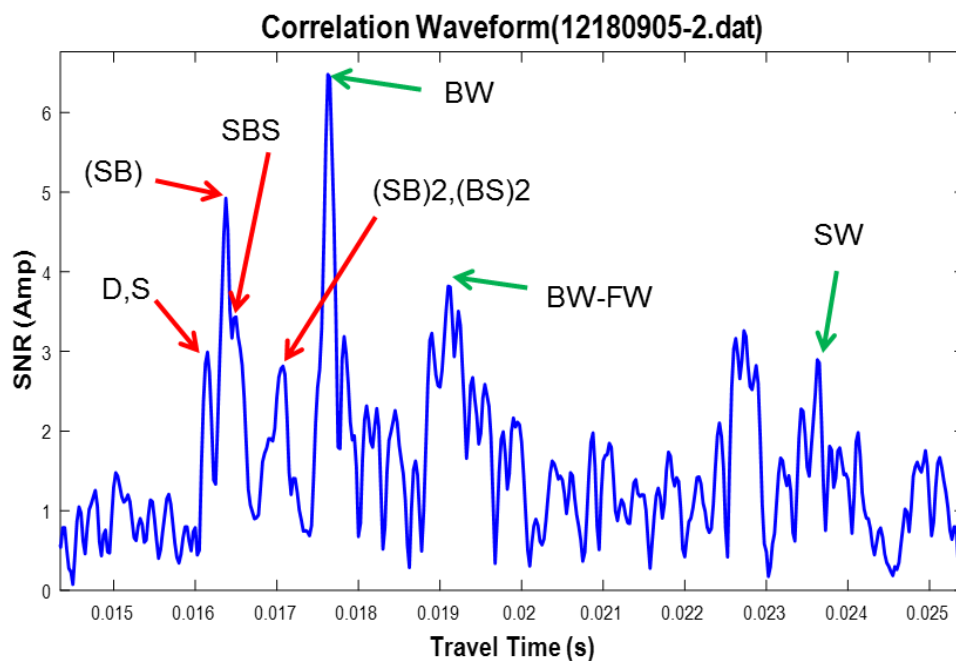
**Figure 3.19:** sonar sensor used in this experiment. The broadband transceiver is fixed to a bar. The bar is inserted to the gap of vanes.

Two broadband acoustic transceivers are fixed on a bar facing bottom of the basin (figure 3.19). The Omni-direction sonar sensor can transmit sound waves in all direction with same strength, which is of key importance to multi-station network sensing. It can assure all other stations to receive sound waves from the transducer. The transceiver cannot only transmit sound waves in all directions and can receive multi-path propagation signals. The first arrival signal is from direct propagation in the short distance sound transmission experiment. Boundary reflections will also be received by Omni-direction transceivers. The multi-path propagations can be used in vertical flow detail profiling. Meanwhile, the flow progress in the whole water column can be monitored by using all the received acoustic information, which will be discussed in the following chapters.

The sonar sensor is controlled by acoustic tomography system for sound wave transmitting and acoustic signal receiving. It is connected with the system with electric cable. Power supply of the transceivers and acoustic tomography control system are 24V and 12V separately. The bar is fixed to the working net of FloWave facility, it is inserted in the gap of two neighbouring flow vanes.



**Figure 3.20:** Correlated result of received data and transmitted signal. Only ambient noise was recorded before 0.015s. Multi-path transmitted signal was received at the range of 0.015-0.035s (in the red box).



**Figure 3.21:** Different arrival signals propagated from different ray path (zoom in of peaks in the red box of Fig.3.20). Boundary reflected signal were picked out by peak searching.

The 12 order M-sequence modulated acoustic signal was transmitted in turns with an interval of 1min. The central frequency of the signal is 20 kHz and sampling frequency is 40 kHz. Two cycles of sine wave are treated as one digit in the M sequence signal. The received acoustic signal is pre-processed and stored in the acoustic tomography system. The received data was correlated with the transmitted signal (Figure 3.20). Only ambient noise was recorded before 0.015s. The ambient noise level in the tank is about 2dB when the 0.8m/s steady flow is generated. Acoustic signal can be used in this experiment was received at the range of 0.015-0.035s (within red box of Figure 3.20). The following signal still contain boundary reflected sound waves, which can be used in more detailed analysing. It is out of the range of this research. The SNR of received acoustic signal reaches up to 6.5dB, it shows the noise suppression character of M sequence. Boundary reflected sound waves are also received with sonar sensors except for direct arrival signal. The arrival peaks can be identified with mirror reflection theory and ray tracing programming. Travel time of sound wave in water is determined if the travel distance is determined as sound speed is constant. The effect of flow current to travel time is neglected in arrival peak identifying. The multi-path propagated signal was Labelled as follows, D: direct arrival; B: bottom reflection; S: surface reflection; BW: backward wall reflection; FW: forward wall reflection; SW: side wall reflection. The direct arrival signal is combined with surface reflected signal due to the relatively low time resolution. As the sonar sensors are installed at the same depth the direct arrival signal can be used for 2D horizontal slice flow current velocity mapping for the multi-station network. Surface and bottom reflection signal path through the whole depth range in the tank, the travel time for these ray path could be used for the vertical layered current analyse. The sound wave will also be reflected at the vertical wall (green arrows in Figure 3.21), the wall reflection signal was picked out by ray tracing. High frequency sound waves are transmitted in the basin and they are received after short distance propagation. The strong boundary reflection makes multi-path propagation signal received with two acoustic stations. The M sequence modulated sound wave assure high SNR at the receiving station. This trail demonstrates that sound transmission in the experimental basin with the acoustic tomography system is possible. The frequency of sound waves is of great importance to the time accuracy, which determine the resolution of reconstructed result. Omni-direction transceiver is needed for multi-station sensing network. Meanwhile, the acoustic tomography system is tested in the short distance sound wave transmission, it is normally used in coastal area. The modified underwater acoustic tomography system can be used in small scale flow detail profiling.

### 3.7 Conclusion

The basic theory of underwater acoustic tomography method is introduced in this chapter. Sound speed profile in the interested area is calculated using water temperature and salinity at different depth. Sound propagation simulation is conducted with ray tracing to determine transceiver depth and distance using sonar equation. Round way transmission time of sound wave along ray path is used as original information for inverse problem. Flow details in horizontal plane and vertical slice can be reconstructed by solving the inverse problem.

Underwater acoustic tomography method is also presented in this chapter. Compared with coastal acoustic tomography system and ocean acoustic tomography, the underwater acoustic tomography system uses higher frequency acoustic signal for small scale flow detail charactering. High-frequency acoustic tomography system are constructed based on coastal acoustic tomography system that developed in Hiroshima University for small scale flow detail profiling. Higher time resolution makes it much easier for multi-path propagation signal identifying. The steady multi-path propagating acoustic signal shows a steady sound channel in the testing area, the stability is verified for the continuous steady transmitting. The acoustic tomography system is used in the circular basin for sound channel testing. Steady acoustic signal is received in the round way sound wave transmission experiment, which show the basin is suitable for short distance sound transmission.

According to flow details obtained in the experiment the parameter sensing can be divided into five different dimensions:

- 0D: fixed point direct measurement of flow velocity
- 1D: path averaged sensing of flow velocity with sound wave reciprocal transmission or depth averaged flow velocity along sound propagate path.
- 2D: layer averaged analyse of flow current in the vertical slice; flow detail plotting in a vertical slice using grid method; reconstruct the flow details in a horizontal plane.
- 3D: water parameter sensing in water volume by combing 2D horizontal and vertical analyse.
- 4D: real-time monitoring of flow details in interested water volume area.

Real-time monitoring of water parameter is a hot topic for acoustic tomography research [148], especially in the ocean environment remote sensing. Besides flow current reconstruction, water temperature and sound speed distribution in target area can also be monitored with acoustic tomography method. Ocean acoustic tomography is proposed firstly for mid-scale sea water

temperature sensing [11,97,149]. Flow detail sensing research will be discussed in the following chapters using acoustic tomography method.

## Chapter 4

# Remote sensing of tide flows in the Bali strait: an application of coastal acoustic tomography system in the field work

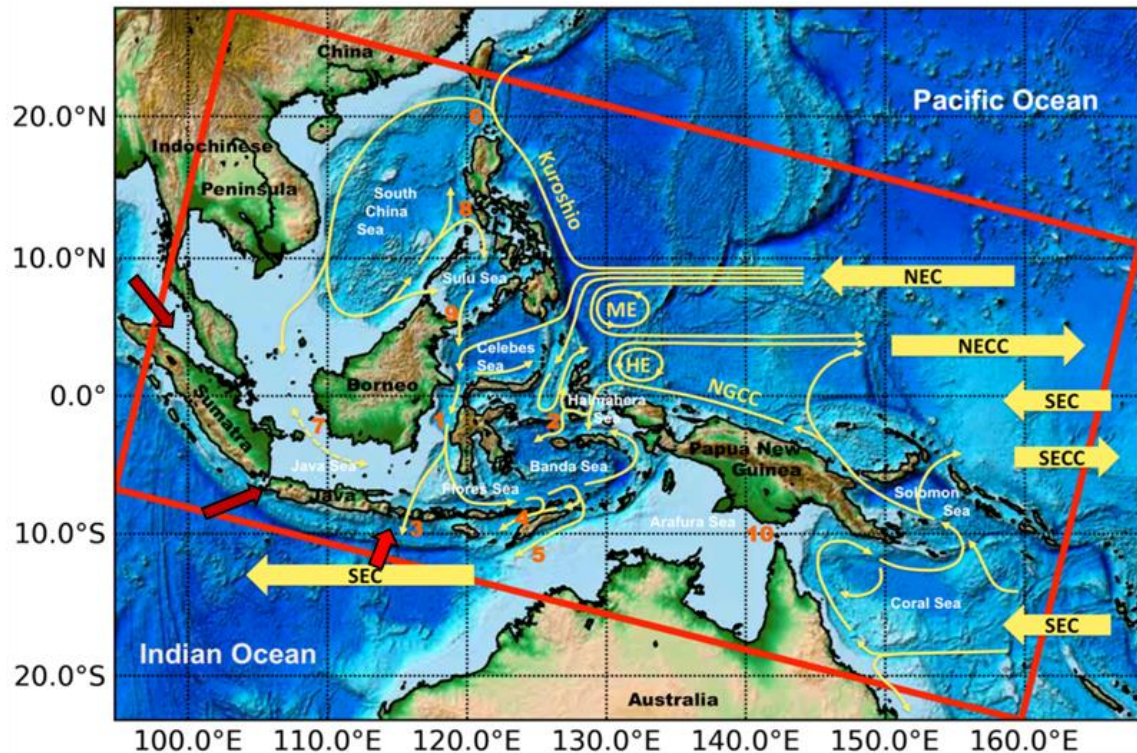
### 4.1 Introduction

The Indonesian Sea is an important link of Pacific and Indian Ocean, it offers a channel for water volume and heat transport [150]. The Indonesian Throughflow (IFT) however is part of ocean flow current recirculation, which affect global climate. Sea level of Pacific Ocean near equator is about 300 millimetres higher than Indian Ocean as a result of heating and trade winds. The Indonesian Throughflow mainly exchange upper warm sea water from Pacific Ocean to the Indian Ocean. The throughflow enter Indonesian Sea from west part of Pacific Ocean and make its way through the Indonesian archipelago to the west part of Indonesia islands (figure 4.1). The Lombok Strait that facing south Indian Ocean offers a path of the mass transport. Bali strait is near Lombok strait and also an important channel for water exchange between Indian Ocean and Java Sea. The flow detail sensing in the Bali strait can offer important information of flow conditions neat east island chains of Indonesia.

Demonstration trail of flow current measuring in the Lombok strait has been conducted using acoustic tomography method with cooperation with BPPT in Indonesia and Hiroshima University [111,150-151]. Acoustic tomography technique is used here in the Bali strait for flow detail monitoring. Four acoustic tomography stations constructed a sensing network in the strait. Travel time of sound waves is used in the inverse problem-solving progress. The first arrival signal is of high SNR and multi-path propagation sound waves can also be identified with ray tracing programming. Strong water surface and bottom sea floor reflected sound waves are received at all four stations. Only the first arrival signal is used here for path averaged flow current reconstruction in the strait. The experiments conducted in the Bali strait and the Lombok strait shows that the coastal acoustic tomography technique can also be used in the Lombok strait for three-dimensional profiling of flow. Deep sea acoustic tomography will be developed in the near further for real time sensing of internal water parameter sensing. The



acoustic tomography method developed in coastal area can also be used in small scale flow detail sensing in experimental tanks and basins.



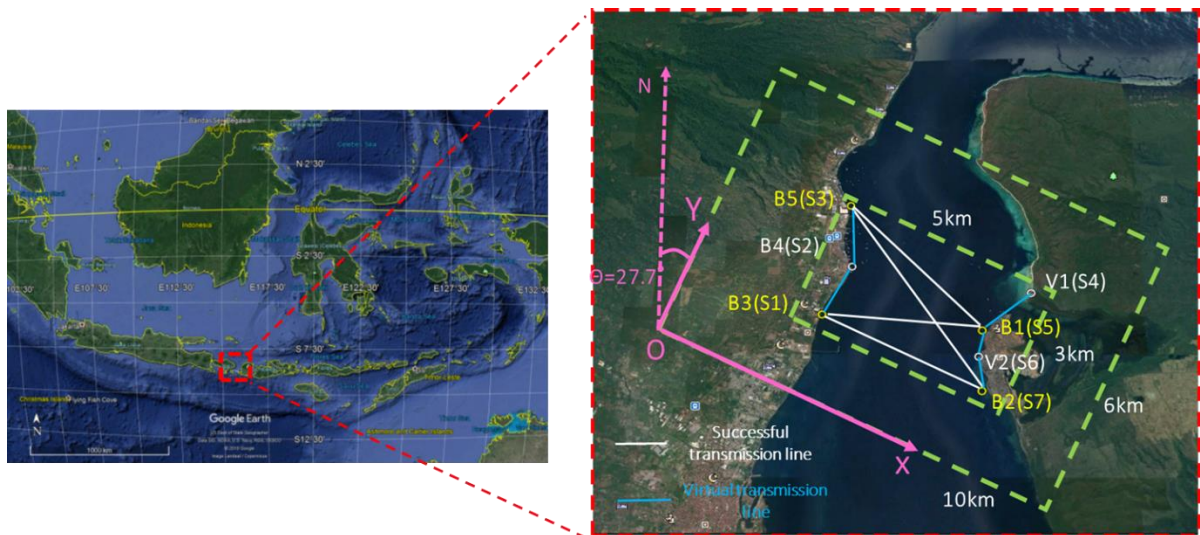
**Figure 4.1:** Indonesian throughflow and the straits in Indonesia that connecting Pacific Ocean and Indian Ocean [152-153].

## 4.2 Experiment configuration

Indonesia is a big country that composed with plenty of inlands (more than a thousand), it lays in the middle of Pacific Ocean and Indian Ocean. Flow currents that passing through straits in Indonesia have great impact on global climate. The Bali Island locates in the middle of an island chain at the wet boundary of Indonesia. The Bali strait is an important channel for water exchange between Java Sea and Indian Ocean. The left figure in figure 4.2 shows position of the Bali strait in the world, it lays at the west side of Indonesia and the strait faces the Indian Ocean. The Bali strait is like a loud speaker mouth at two sides, it restricts flow current passing through this narrow strait. The boundary at two sides of this strait will reflect the coming current, the flow details in this strait is complicate.

The flow details in the strait is measured with acoustic tomography method by sound transmission in this study. The coastal acoustic tomography systems developed by acoustic group in Hiroshima University are used in this testing for sound wave transmitting and acoustic

signal receiving. The system works as the progress described in chapter, a broadband Neptune transceiver (figure 2.22 (a)) is used at each sound station. All stations are synchronized with GPS timing signal. Low frequency sound waves are transmitted in the strait, the travel time along each path is used as input for inverse problem solving.



**Figure 4.2:** The experimental scheme of the tide progress sensing test in the Bali strait. Four sound stations (B1, B2, B3, and B5) are used in the experiment to construct a remote sensing network, three virtual stations (V1, V2 and B4) are also added in the system to restrict boundary conditions.

Four sets of coastal acoustic tomography systems are installed at two sides of the strait (figure 4.2 (b)), two stations (B3 and B5) at the Java island site and another two stations (B1 and B2) located at the Bali island site. These four acoustic stations construct a sensing network in the strait to monitor tide flow progress. The number of sound transmission path in the 4-station sensing network is 6. The sound transmission path B1-B2 and B3-B5 is interrupted with shore, the sound transmission along these two paths is impossible. Four sound transmission paths (white line in figure 4.2 (b)) are used in this experiment for flow information sensing. The distance along sound propagation path B1-B3, B1-B5, B2-B3 and B2-B5 are 4020m, 4955m, 4454m and 6210m separately. The depth of the transducers at station B1 and B2 are 14m and 27m separately. Station B1 is deployed in a navigation signal tower near the Shore of Bali Island. The coastal acoustic tomography system is kept on the working plat, the transducer is laid down in water with rope. Figure 4.3 shows the site of station B2 and B3. The station B2 is located at an abandoned oil platform. The depth of station B2 is larger than that of station B3 as the station B2 lays near shore. The depth of transducers used in station B 3 and B5 are 4m

and 10m separately. The station B3 is installed at a pier near a hotel and station B5 is installed at a pier of a petroleum factory.

Besides four acoustic stations another three virtual stations (V1, V2 and B4) are also added to the multi-station sensing network to restrict the boundary condition. All stations used in this sensing system are used for sound transmission. As shows in figure 4.2 (b) all the seven stations are named as  $S_i$  ( $i = 1, 2, \dots, 7$ ). The complicate flow near shore is treated as still water. The flow velocity along the shore at two side of the strait (S1-S2, S2-S3, S4-S5, S5-S6 and S6-S7) is set as zero. The reconstructed flow details will be largely improved by introducing more information in the multi-station sensing system. Meanwhile, the inverse problem will be underdetermined as limited number of information (travel time of sound wave) is used in this problem. Broadband sound wave is used in this experiment, the frequency of carrier wave is 10 kHz ( $f_0$ ). The 10<sup>th</sup> order of M sequence signal is used for sine wave modulate in the sound transmission. The modulate depth of this signal is 3 ( $Q=3$ ) in this experiment. The bandwidth of this broadband sound wave is 3.3 kHz ( $f_0/Q$ ). The Inverse zone of this experiment is set within a  $3km \times 5km$  rectangle (small green dash box in figure 4.2 (b)), all sound transmission paths are in the inverse region. The computing zone is in a  $6km \times 10km$  rectangle region. The computing region is set double length of inverse zone to avoid the periodic of the stream function. The angle between the Y+ axis of computation coordinate and north direction of earth coordinate is  $27.7^\circ$ .



(a)



(b)

**Figure 4.3:** Site picture of station B2 (a) and B3 (b). Station B2 is installed at an abandoned oil platform near the shore of the Bali Island and station B3 is deployed near a pier at the Java Island.

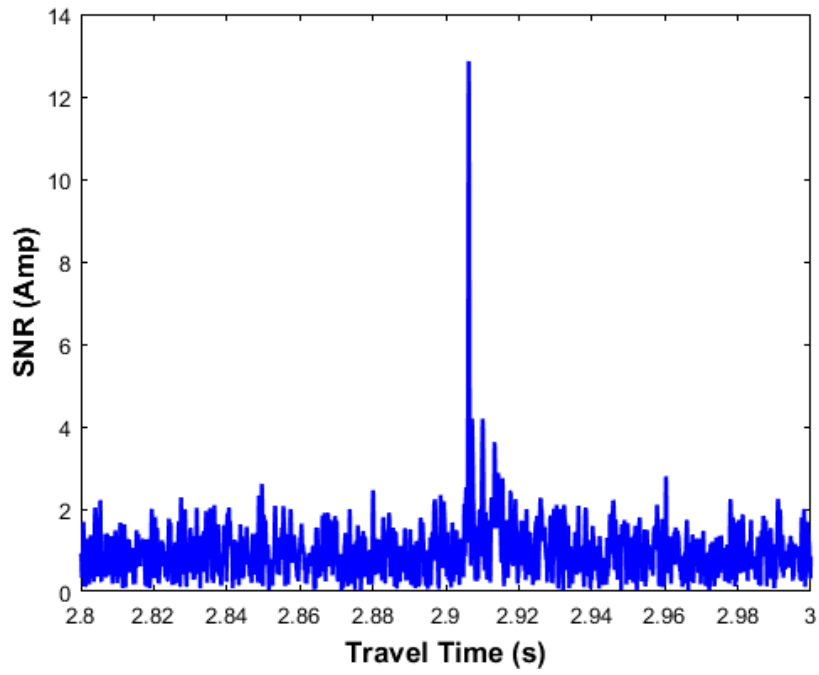


## 4.3 Experimental data

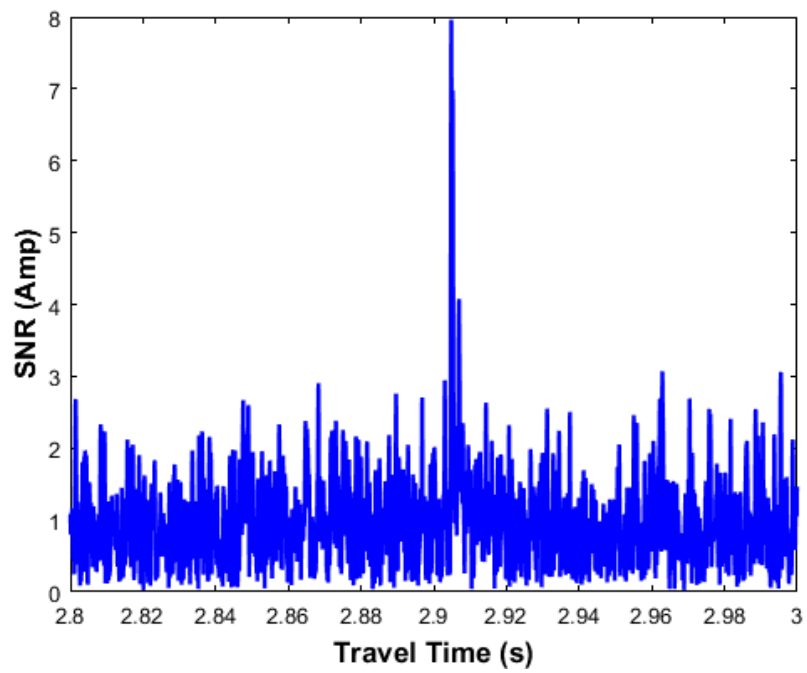
### 4.3.1 Received acoustic signal

The coastal acoustic tomography systems show in chapter 2 are used for sound transmitting and receiving with sound transceivers. The sound waves are received with the broadband transducer after a long-distance propagation. Multi-path propagating sound wave is acquired with the coastal acoustic tomography system and stored in the SD card. The received data is correlated with transmitted M-sequence modulated acoustic signal. As discussed in chapter 2, the M sequence modulated signal has good performance of auto-correlation. High SNR peaks appear when sound waves reach sound receiver, the travel time of sound waves is determined with this method.

The correlation result of received data with the transmitted M sequence modulated acoustic signal at station B2 and B3 are shown in figure 4.4. The travel time of sound waves along ray path between these two stations is at a time zone of 2.9-2.92s. The SNR of correlation result at station B2 is about 13 dB, which is a little higher than that of data received at station B3 (8 dB). M sequence modulated broadband sound waves are transmitted at one station and received at other stations in the network. The acoustic signal received for sound transmission between station B2 and B3 is shown here. Ambient noise is acquired before sound waves reach sonar receiver; the ambient noise is below 3 dB for the sound transmission in the strait. Multi-path propagated sound waves are received for both stations, travel time for these signals can be used in flow details analysing in the vertical section between two sound stations, which will be discussed in the chapter 5. The multi-path propagated sound waves can be identified with ray tracing programming. The correlated result is zoomed in to explore travel time of sound waves for this reciprocal sound transmission (figure 4.5). The threshold is set to 3 dB as all the SNR of ambient noise is below this level, received sound waves can be picked out in this method. As shows in figure 4.5 the first arrival signal has high SNR level for acoustic signal received at both sound stations. Multi-path propagations come following the first arrival signal. Only the first arrival signal is analysed in this study to explore depth averaged flow details in the strait. To better analyse the slow changing progress of tide in the strait the received data is analysed using moving average method, through which small random error is filtered out. The flow progress in the strait can be profiled using the multi-station network sensing method, neglecting small turbulence in small regions. The travel time identifying analyse using moving average method will be presented in the following section.

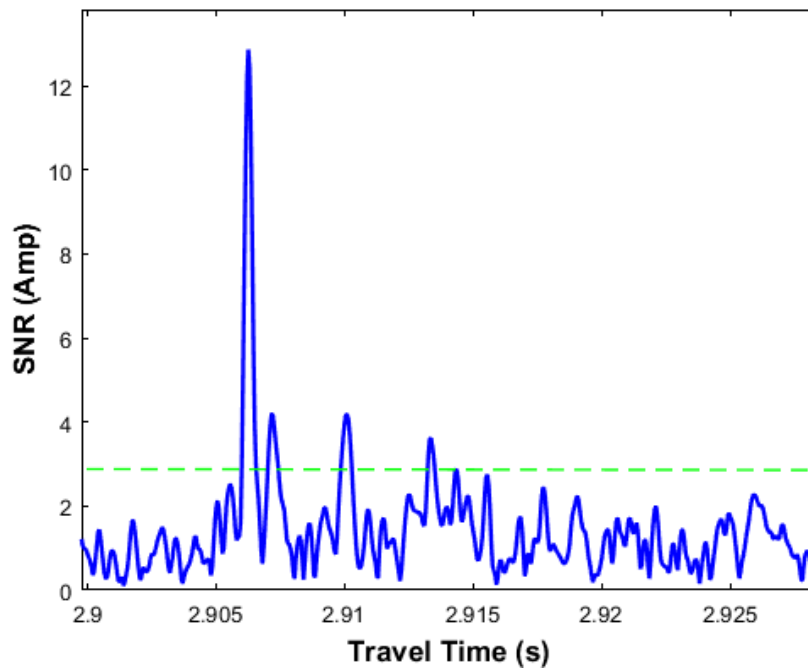


(a)

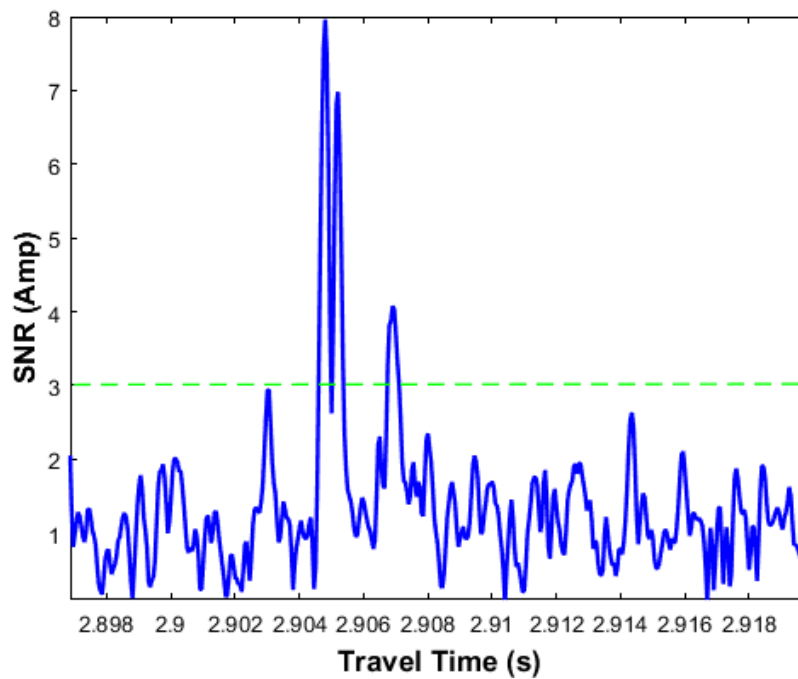


(b)

**Figure 4.4:** Correlation of received data with transmitted acoustic signal. The data are received at station B2 (a) and B3 (b).



(a)

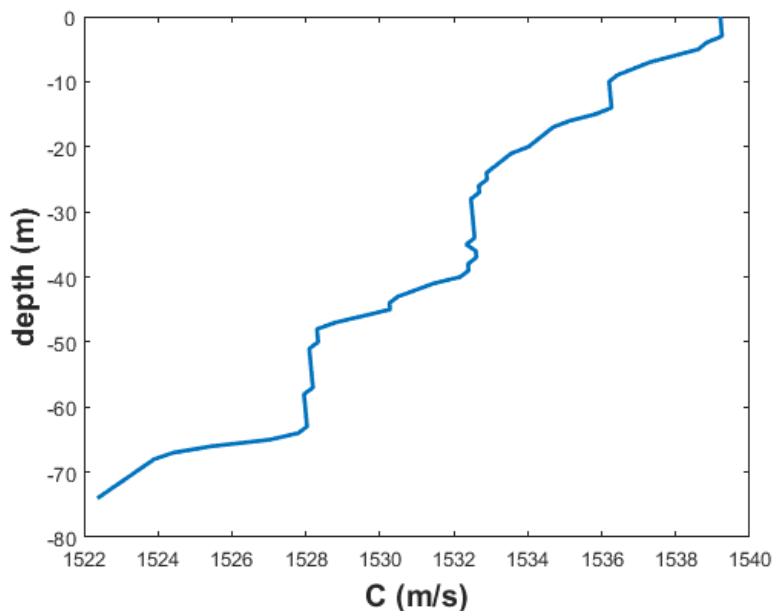


(b)

**Figure 4.5:** Zoom in of the correlation result. The SNR of first arrival peak is high enough for sound propagation ray tracing. Three peaks can be used in this signal for multi-path propagation sound waves identifying.

### 4.3.2 Sound speed profile

Travel time of sound waves in ocean can be fixed when the sound speed is fixed for the sound transmission between two sound stations. Sound speed profile is of great importance for sound transmission no matter in deep sea or shallow waters. Sound speed profile can be used for ray simulation in the multi-path propagation identification. The sound speed profile in the Bali strait is measured with a CTD, which helps calculate sound speed profile by measuring temperature, salinity and pressure of water [150]. It is a typical inverse sound speed in shallow water (figure 4.6), where sound speed decrease with the depth. This sound speed distribution is caused by water heating with strong solar energy as Indonesia is a low latitude country. The salinity in the shallow water (less than 100m) is treated as constant here within a small region. As discussed in chapter 3, sound speed in water is affected with water temperature and pressure. Sound speed is mainly affected with water temperature for shallow water. The water temperature in upper layer is higher than lower water. Meanwhile the sound speed is not smooth, the changing rate of sound speed is not a constant. It demonstrates that water temperature in the strait changes with the increase of depth, mix of warm water and cold water happens. The sound speed in the Bali strait is between  $1522\text{ms}^{-1}$  and  $1540\text{ms}^{-1}$ . The depth averaged sound speed can be used in the depth averaged flow detail reconstruction with acoustic tomography method. The average sound speed in the Bali strait is  $1531\text{ms}^{-1}$ .

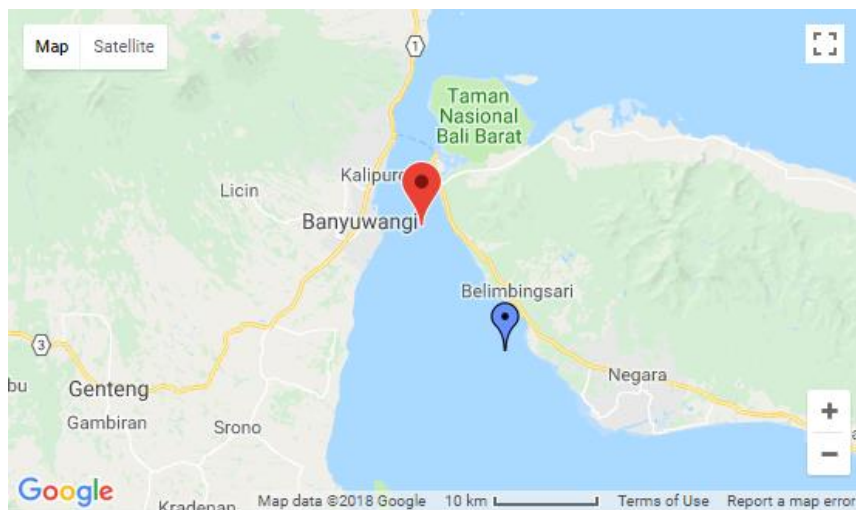


**Figure 4.6:** Sound Speed Profile (SSP) in the Bali strait. It is calculated with measurements of CTD.

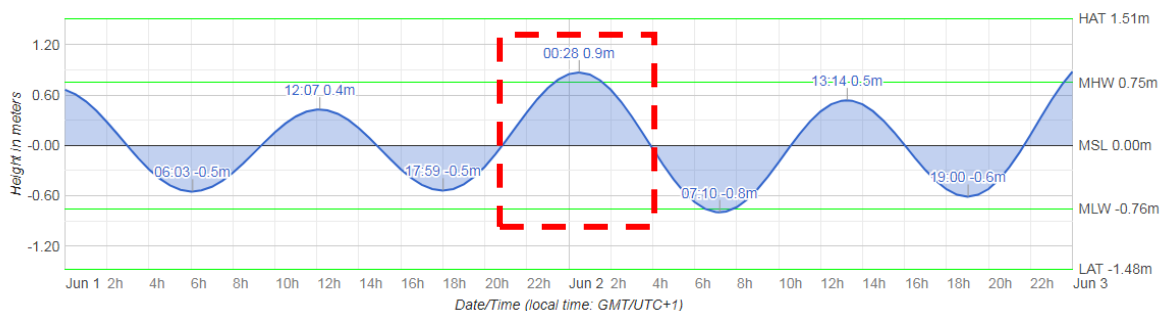


### 4.3.3 Sea level changing

The tide progress in the Bali strait can also be described with sea level changes during the sound transmission experiment. As shows in figure 4.7 and 4.8 Tide data in the Bali strait is obtained, the tide data is from WorldTide [154]. The coordinate of expected position and actual measurement point are (-8.224, 114.425) and (-8.333, 114.500) separately. The tide progress predicted by WorldTide is consistent with the measurements using pressure sensor. Water level rise up to peak and lower down during this experiment. The tide in the Bali strait reach highest level to 0.9m at 00:28 am of 2<sup>nd</sup> June 2016. The flow velocity will change direction after tide peak appears, this tide progress can be used for flow velocity reconstruction result using acoustic tomography method.



**Figure 4.7:** Tide progress monitoring. The red mark is in the experimental region. The blue mark shows the actual position of the tide progress.

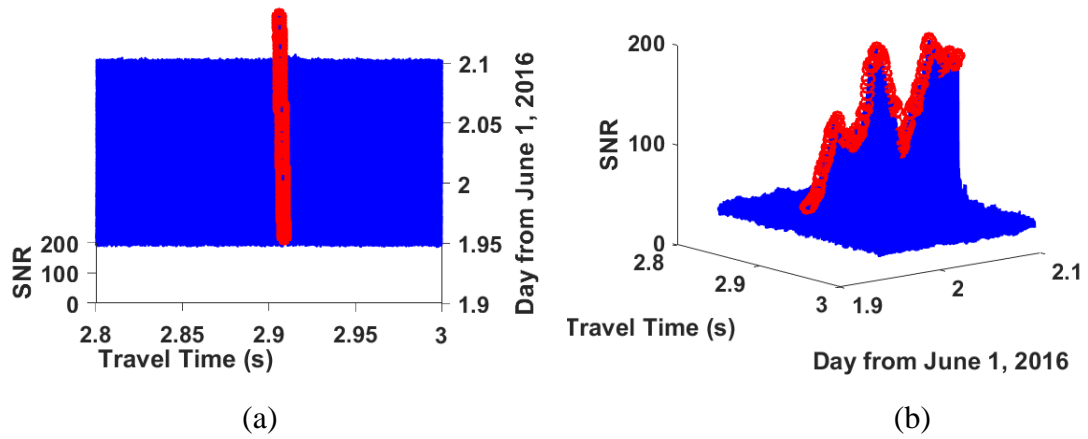


**Figure 4.8:** Tide progress prediction in the Bali strait during the sound transmission experiment. The red dash box indicates the time range of flow detail reconstruction in this study. This data is obtained from the WorldTides Developer Information.

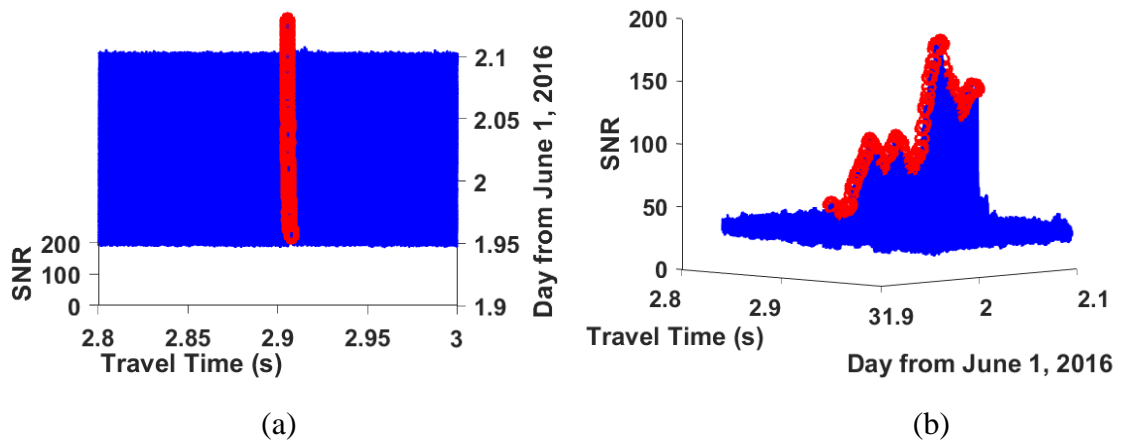
## 4.4 Signal processing

Low frequency sound wave (10 kHz) is used in this experiment for flow detail detecting in the Bali strait. The coastal acoustic tomography systems are installed near the shore of this narrow strait for sound transmission and receiving. Broadband sonar sensors are used here to transmit sound waves in water. As the target of this multi-station system is to monitor flow progress in the strait sound wave is transmitted continually. The sound transmission in within short time zone is similar for the slow changing progress in the strait. The time difference between two neighbouring transmissions is quite small compared with the travel time along sound propagation path. The signal used in this experiment is M-sequence modulated sine wave. The received acoustic signal is stored in the coastal acoustic tomography systems for post-processing. The received sound data can also be transported to land-based computing station using telecommunication technique. As presented in chapter 2, the M sequence has no correlation with ambient noise and other M sequence even with same order as it. That is the reason to use M sequence modulated sound waves for flow detecting in the multi-station sensing network. The received data is correlated with original transmitted M-sequence modulated signal. The highest peak appears when the first sound wave arrives to receiving station as shows in the figure 4.5, multi-path propagating sound waves comes following the first arrival signal. The correlation of received data at each station is filtered using moving average method of thirty transmissions. All the correlation result are stacked together to get higher SNR of the received sound wave. The changing trend of travel time and SNR of the signal can be identified using this method.

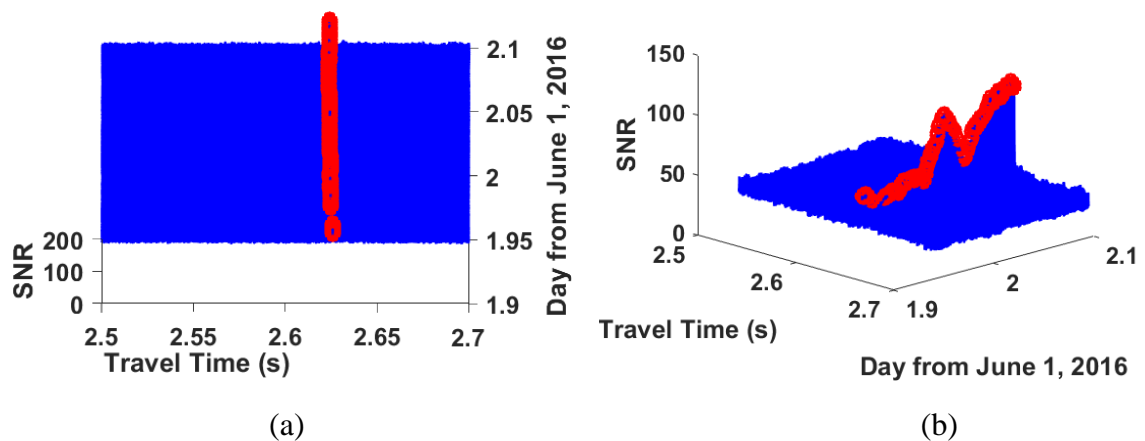
Figure 4.9 and figure 4.10 shows the correlation of received data and transmitted acoustic signal for sound transmission between station B2 and B3. The highest peaks are marked with red circles to confirm the travel time of sound waves along propagation path. The travel time of between station B2 and B3 is in the range of 2.9-2.92s as show in figure 4.9 and 4.10. The SNR of signal received at two station is almost the same for the reciprocal sound transmission in the strait. The SNR of highest peak for acoustic signal received at station B2 and B3 is of similar height, the changing trend of two signal is also same (figure 4.9 (b) and figure 4.10 (b)). Three peaks appear for the acoustic signals received in both stations; the strength of signal received by the transceivers are affected by flow current in the strait. The tide progress can also be monitored with the variation of signal strength when only one-way sound transmission is conducted. Meanwhile, the travel time variation of sound transmission in the strait also shows the tide progress.



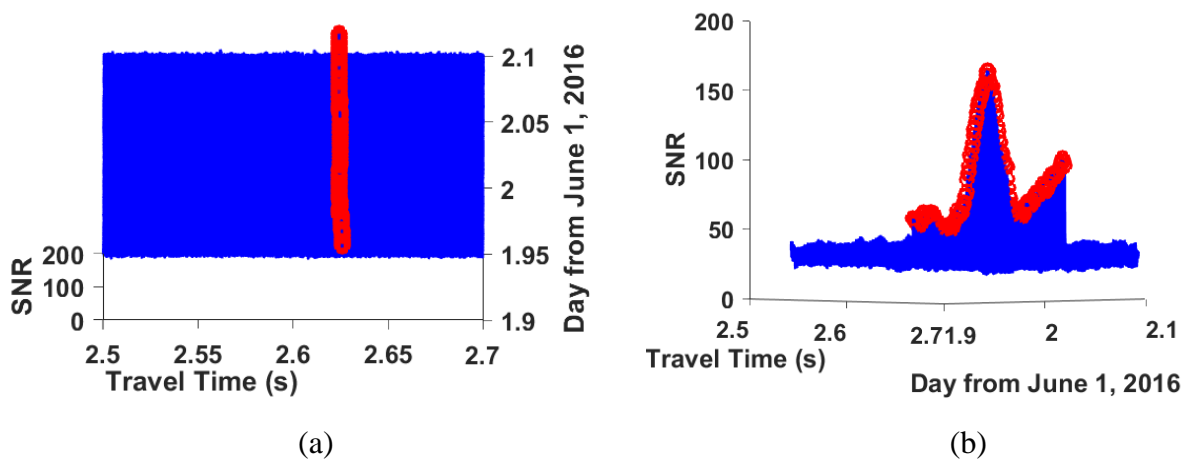
**Figure 4.9:** Peak identifying of acoustic signal transmitted from station B3 to station B2.



**Figure 4.10:** Peak identifying of acoustic signal transmitted from station B2 to station B3.



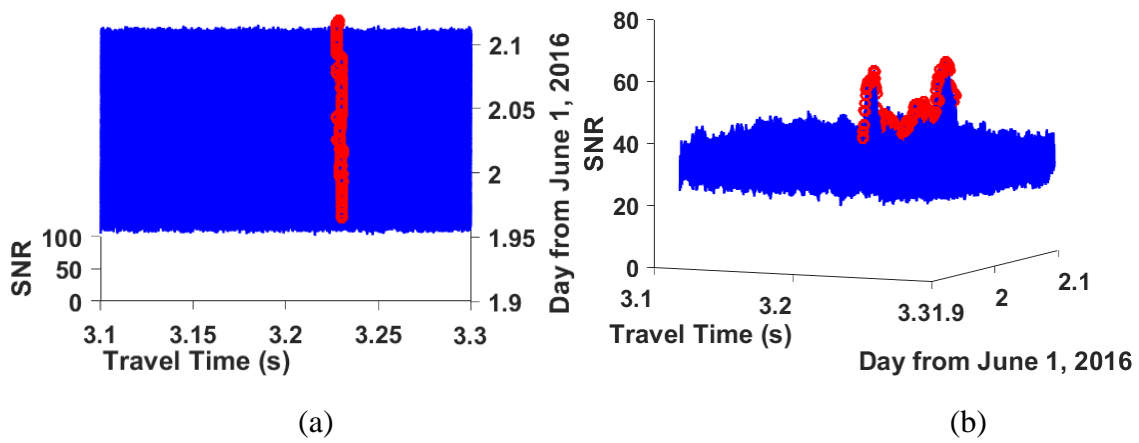
**Figure 4.11:** Peak identifying of acoustic signal transmitted from station B1 to station B3.



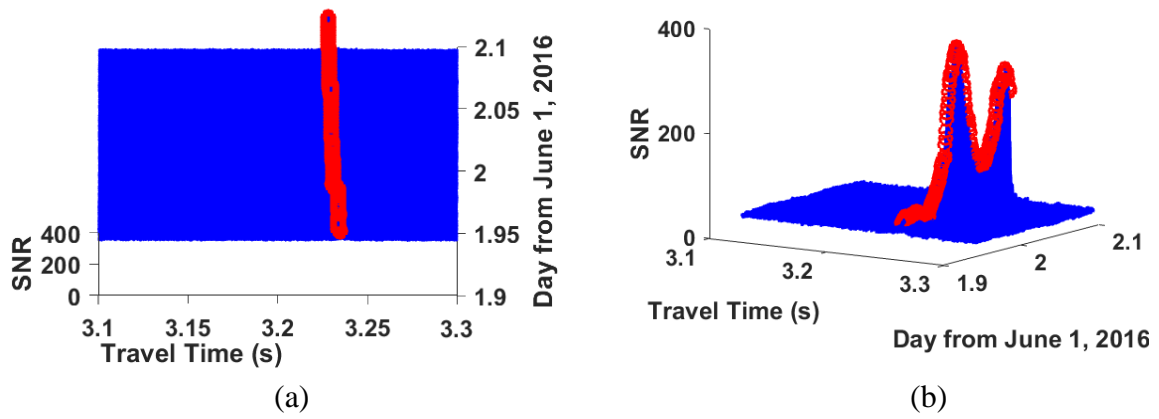
**Figure 4.12:** Peak identifying of acoustic signal transmitted from station B3 to station B1.

Sound transmission between station B1 and station B3 is also conducted in the experiment. The received data is correlated with the transmitted sound waves used in the sound transmission in these two stations. The received acoustic signal is correlated with transmitted M sequence signal at two stations as shows in figure 4.11 and figure 4.12. The signal received at two stations is both has high SNR for first arrival peak. The travel time of sound waves along ray bath is at range 2.62s to 2.63s for the sound reciprocal transmission (figure 4.11(a) and figure 4.12(a)). The strength of first arrival signal at station B3 is higher than that of station B1. The highest SNR for signal received at station B1 is about 175 dB, which of station B3 is less than 150 dB. Meanwhile the changing trend of signal received at two stations are similar, both of them have two peaks (figure 4.11(b) and figure 4.12 (b)).

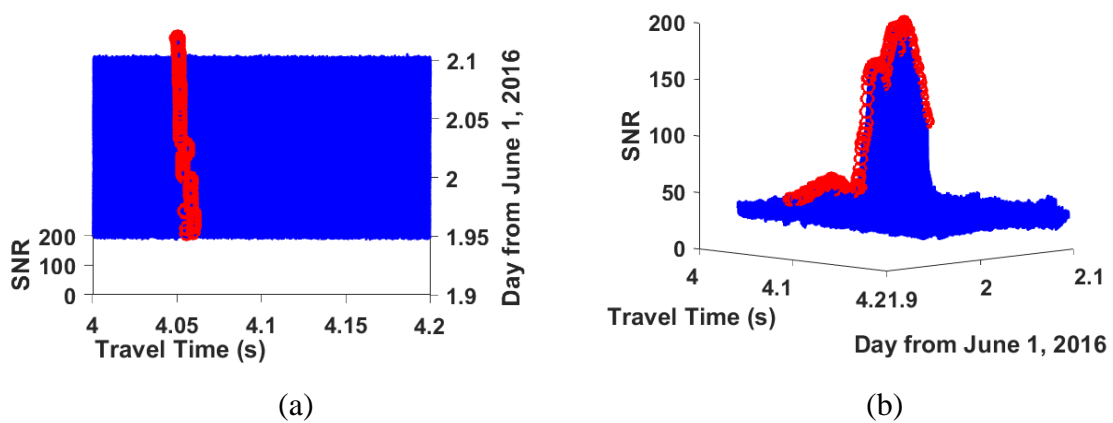
Each sound station used in this multi-station network sensing system can receive acoustic signal from all other stations. The received data can be identified by correlating with different M sequence transmitted in each station. The signal used for phase modulation of carrier sine wave in Station B1, B2, B3 and B5 are 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> and 5<sup>th</sup> sequence of the 10 order M sequence. As the M sequence has no correlation with other sequence of same order. The travel time between each pair of station can be obtained with peak searching in the correlation result. The sound transmission along B2-B3 and B1-B3 are both concern with the sound station B3 at the Java Island site. The sound station B3 works well after its installation, it can transmit and receive sound wave continually. Sound transmission along other two paths (B1-B5 and B2-B5) are concerned with station B5, which is installed at the pier of a petroleum factory. The received data is also correlated with the transmitted acoustic signal to identify travel time of sound waves along each sound transmission path.



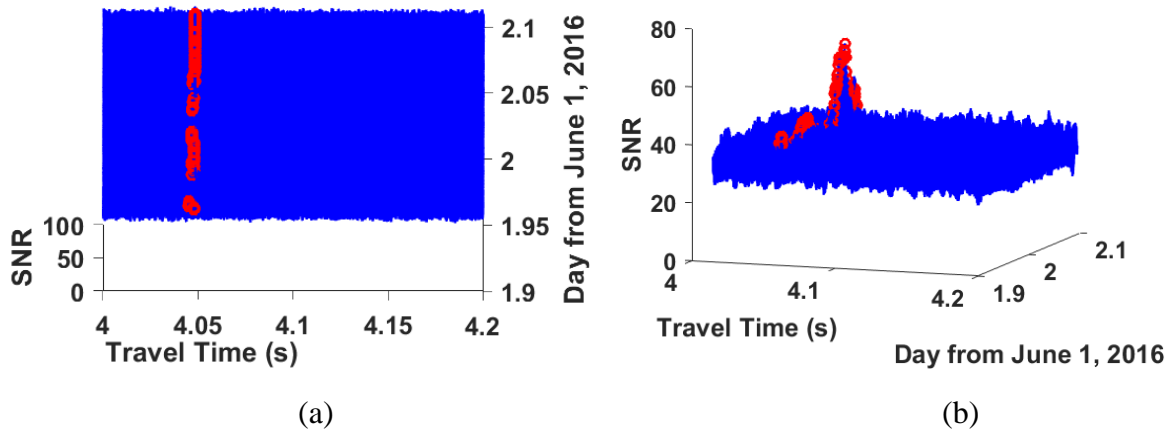
**Figure 4.13:** Peak identifying of acoustic signal transmitted from station B1 to station B5.



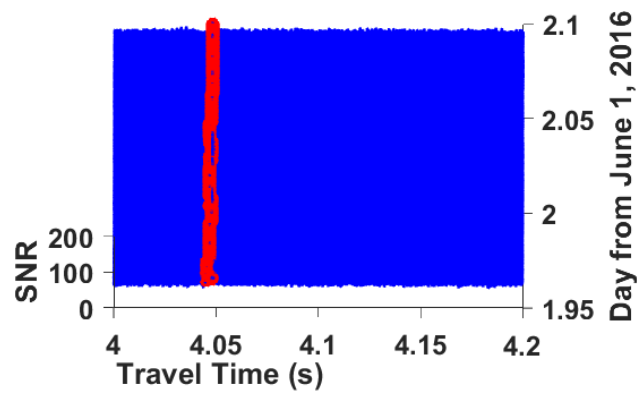
**Figure 4.14:** Peak identifying of acoustic signal transmitted from station B5 to station B1.



**Figure 4.15:** Peak identifying of acoustic signal transmitted from station B5 to station B2.



**Figure 4.16:** Peak identifying of acoustic signal transmitted from station B2 to station B5.



**Figure 4.17:** Peak identifying of acoustic data between 4.04s and 4.05s received at station B5, the sound wave is transmitted from station B2.

The Omni-direction transducers used in this experiment can transmit broadband sound wave in all directions with same power strength. Multi-station network is constructed with sound transmissions between each station that installed at two sides of the Bali strait. The sound transmission performance of station B5 is not affected by complicate turbulence around the pier. The sound waves transmitted with station B5 are received with two stations in the side of Bali Island (B1 and B2). As shows in figure 4.14 and 4.15, high SNR acoustic signal is received at station B1 and B2 for the sound transmission from station B5. The travel time of sound waves between station B1 and B5 is at a range of 3.2s to 3.5s (figure 4.13 (a) and figure 4.14(a)). The SNR for first arrival signal reaches up to about 400 dB for sound transmission from station B5 to station B1, which is higher than that of sound transmission from station B5 to station B2. This is because the sound transmission distance between station B5 and B2 is much longer than the distance between station B5 and B1. The sound transmission time between sound station B5 and B1 is about 4.05s (figure 4.15(a) and figure 4.16(a)).

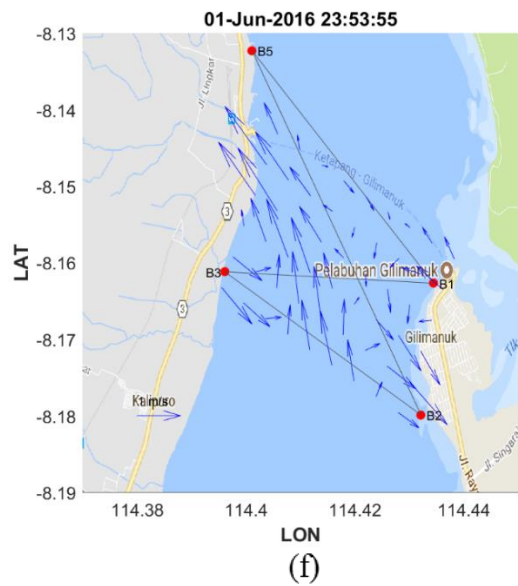
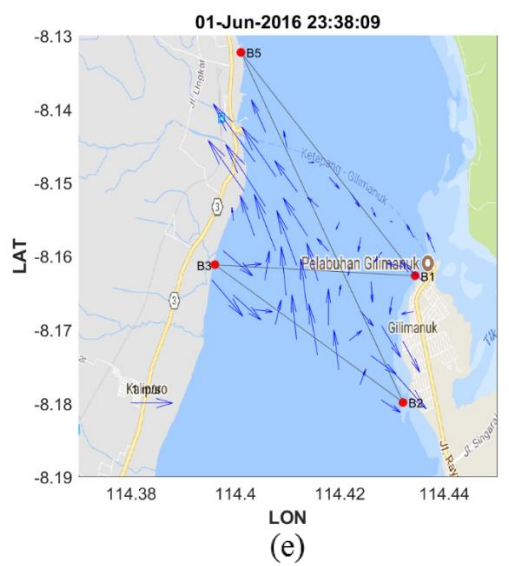
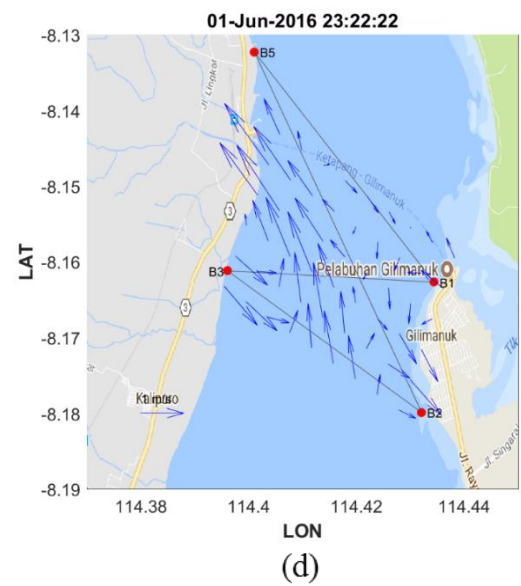
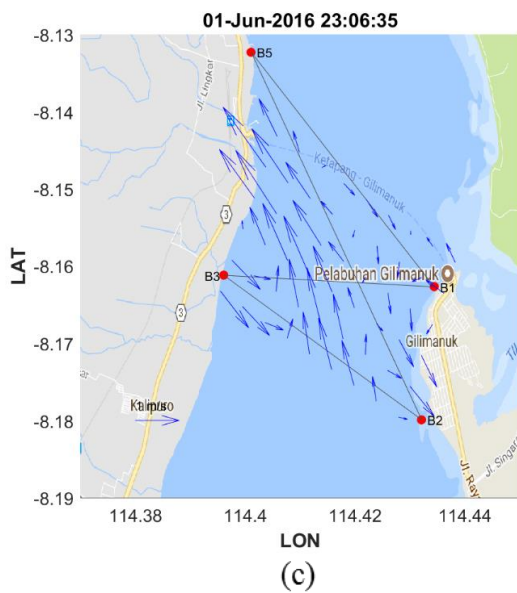
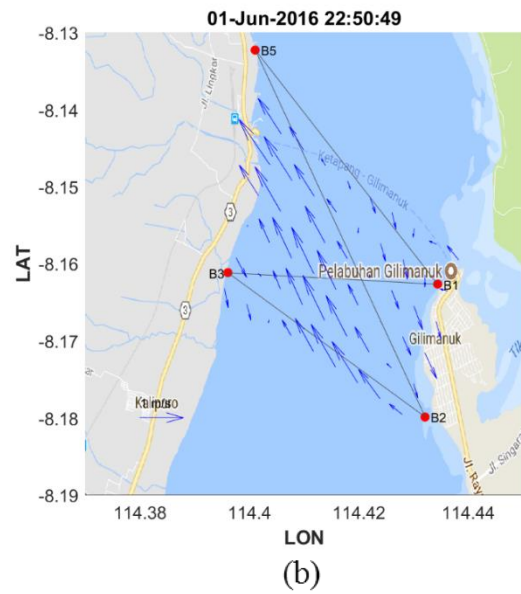
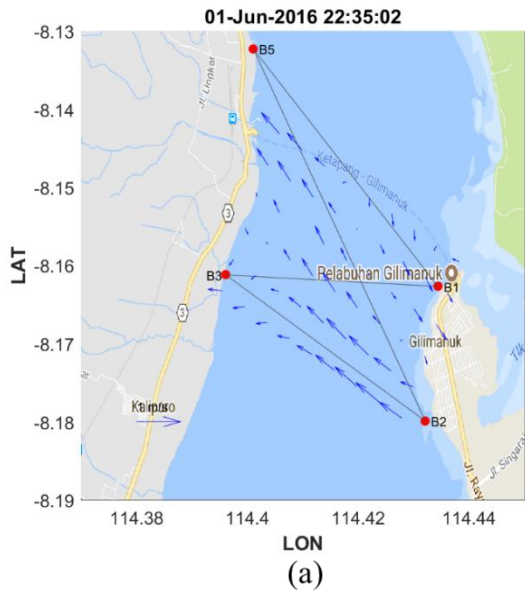
The flow condition near the pier at station B5 is complicate as it has strong interaction with boundary. The coming flow will be reflected when it reaches the boundary. The accuracy of position in station B5 is affected also by turbulence flow, it will shake around the expected position. Meanwhile, a relatively small stone is used as the anchor in this station. The anchor is not lowered down to the bottom, it is laid near sea floor and can sway around. The received data in station B5 is affected by turbulence near the pier. The sound transmission from station B5 to station B1 is affected with the shaking of transducer. The SNR of first arrival signal is less than 120 dB (figure 4.13(b), which is much lower than the sound transmission from station B1 to station B5. The ambient noise level is also higher for this sound transmission compared with other sound transmission from B5 to B1. At the same time, the correlation result at the sound station B5 is also affected with the boundary condition for the sound transmission between sound station B5 and B2. The SNR of first arrival acoustic signal is less than 80 dB (figure 4.16 (b)). The low SNR of received acoustic signal is partly due to longest sound wave propagation distance in the sensing network. The sound receiving at station B5 is affected with boundary condition around pier for the sound wave transmission from station B2. As shows in figure 4.13 and figure 4.16, the correlation result of acoustic signal received at station B5 is lower than other stations. Advanced signal processing method can be used in the peak identifying for sound wave propagation in shallow water. Figure 4.17 shows the peak identifying result around 4.05s. The highest peak searching progress is conducted around the expected arrival time instead of in all the time zone.

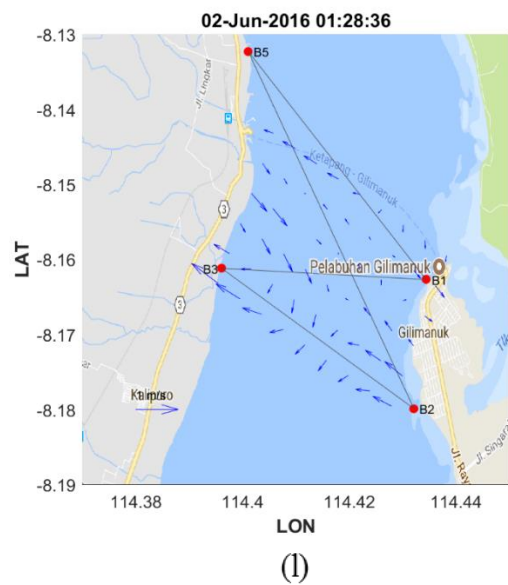
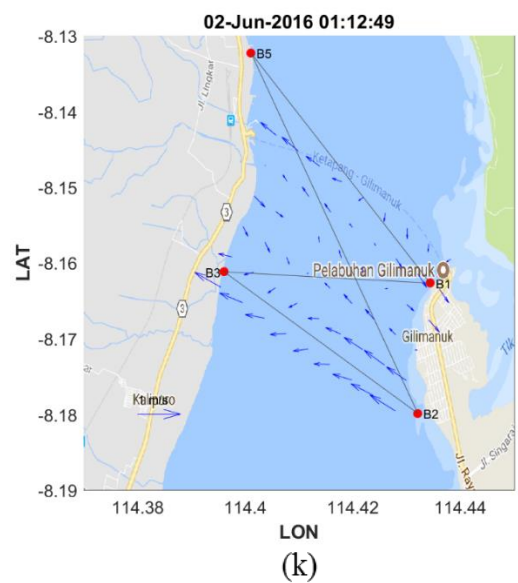
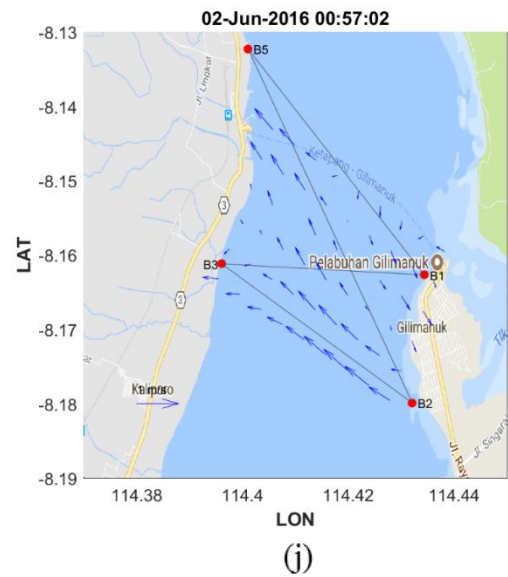
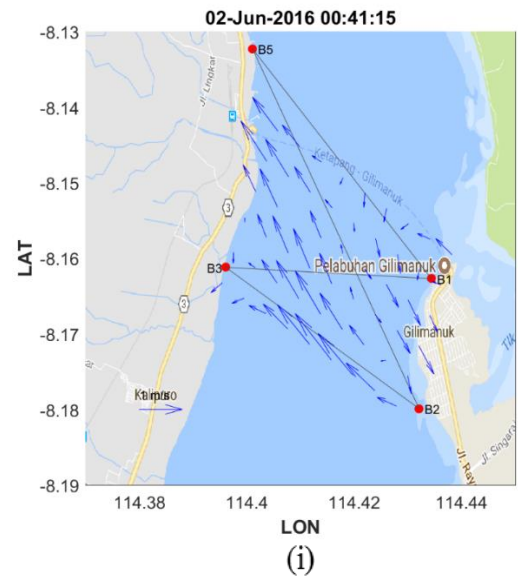
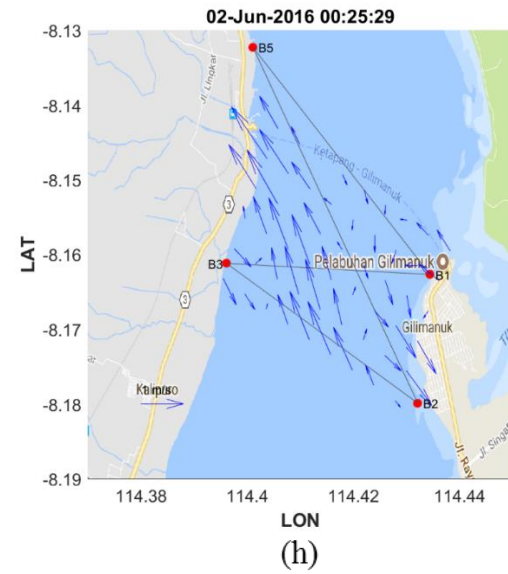
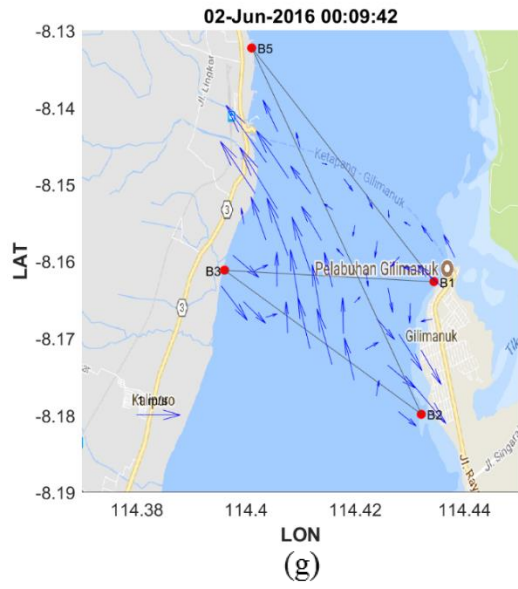
## 4.5 Depth averaged tide progress in the Bali strait

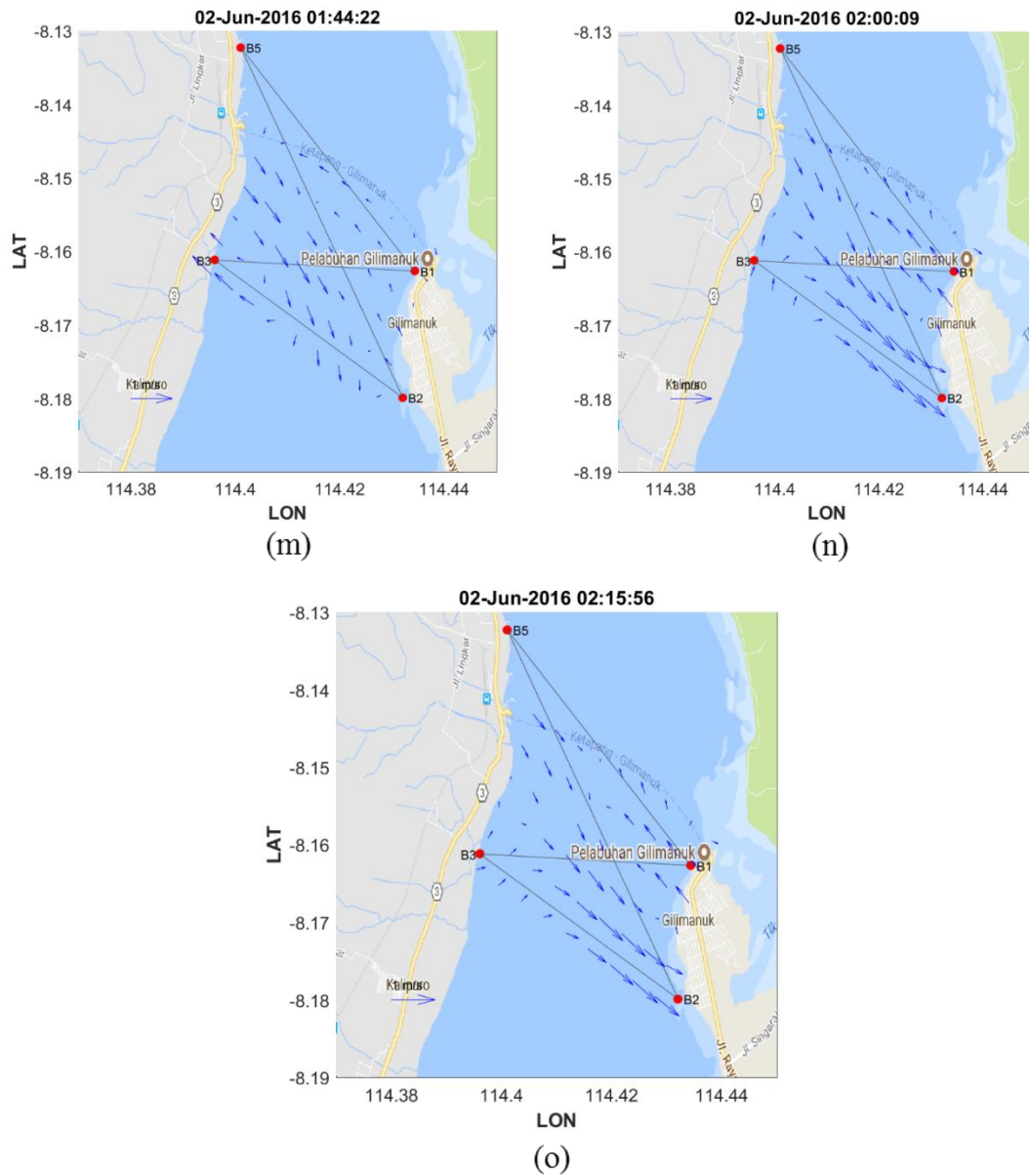
This experiment explores flow details in open waters with sound waves. Acoustic signal is used as a media to calculate flow velocity along sound transmission paths. A total of 7 stations are used in this multi-station system, travel time difference along 21 sound transmission paths are used in the system. As shows in former section, flow velocity along shore is set to zero. Four coastal acoustic tomography stations transmit sound waves continually in the strait. The travel times for sound transmission along four paths (black solid line in figure 4.2) are obtained with post-processing of recorded data at all four sound stations (B1, B2, B3 and B5). The travel time along all other paths that no sound transmission occur are set as Nan (not known), which makes this inverse problem underdetermined. Inverse problem is solved in the computing zone with travel time of sound waves along 21 paths. The result is restricted with boundary conditions to get reconstructed result in the experimental area. The reciprocal travel time of sound waves along the sound paths are input information of inverse problem solving. As shows in section 4.4, the travel time of each sound transmission is identified with peak searching for correlated data. The received sound data is correlated with transmitted M sequence modulated acoustic signal from each station, travel times of sound waves from other station are determined in this method. Sound transmission by all stations in the multi-station network are used in this flow reconstruction progress. Travel time difference along each ray path is calculated as input information for inverse problem solving in the acoustic tomography research for flow velocity reconstruction. The flow velocity component is calculated with stream function in the experiment region. The coefficient of 3 order truncated Fourier series is calculated by solving the inverse problem with travel time. Flow velocity in the experimental can be calculated with the stream function as shows in chapter 3.

As shows in figure 4.2 the position original point in the new coordinate system is (114.36, -8.165). The flow velocity in the Bali strait is reconstructed with acoustic tomography method in this study. This multi-station sensing network is used in shallow water (less than 100m) flow progress profiling here, more sound stations can be installed in the multi-station sensing network to get higher resolution result. Small scale flow detail profiling in experimental tanks and basins can also use this remote sensing system, which will be discussed in the following chapters. The frequency of sound waves used in the small-scale flow velocity sensing system needs to be improved to a much higher range. High time accuracy is required for short distance sound transmission. Meanwhile the resolution of reconstructed result is affected by time resolution.









**Figure 4.18:** Flow details reconstruction results in the Bali strait using coastal acoustic tomography systems. Four sound stations in two sides of the strait are marked with red points. The flow velocity in experimental region is shown with blue arrows. Four sound transmission paths are presented with black solid line.

Flow details in the Bali strait is reconstructed with acoustic tomography method by solving inverse problems. The flow progress is monitored by continuously sound transmission with four broadband transceivers that controlled with coastal acoustic tomography system. The time zone of the data analysed in this experiment is from June 1<sup>st</sup> 22:35 to June 2<sup>nd</sup> 02:15 of 2016, the time gap of each plot is 15min 47s. The flow details reconstructed in this experiment shows flow progress of tide in the 4h period in the strait. North direction flow comes from Indian Ocean to Java Sea at first three hours, the tide reaches highest level around 01:20 (figure 4.18 (k)) of June. It changes direction after high water level appears, the strong flow current goes to Indian Ocean from the Java Sea. Flow velocity increase when water level is rising up quickly, the increase rapid become smaller when water level reaching high level. At the same time, the current velocity also increases from small level to a relatively large range when water level lowering down. This performance consistent with tide theory in ocean. Tide current increase rapidly with a large velocity, the velocity reaches its peak when water height reaches average level. Flow velocity will decrease from largest level to zero until water height reach highest level in one tide period. The tide progress reconstructed with coastal acoustic tomography systems is consistent with the result from WorldTide. Water level rise from 22:35 at June 1<sup>st</sup> and reach high level at about 01:20 of June 2<sup>nd</sup>. As shows in figure 4.18, the direction of flow changes from northward to southward after 01:20 of June 2<sup>nd</sup>.

The reconstructed flow details in the strait profile the changing progress during this tidal period. As shows in figure 4.18 flow direction is not along shore of this strait. The Bali strait has a shape of northeast toward southwest direction at the experiment area. The flow direction in this strait, however, is with northwest toward southeast direction. This is a result of boundary restriction of the strait. The input and output of this strait both like a loudspeaker mouth, which restrict flow direction in the middle of this strait. Flow current come to this channel and reflected with shore and affected with sea floor and surface wave, complicate flow conditions exist in the shallow channel. At the same time, flow details near shore is much more complicate than that in the middle area of this strait. Flow condition is affected with boundary and has strong interaction with shore. This condition will also appear for flow details in the experimental tanks and basins, where only restricted testing area exist. The number of sound station used in the multi-station sensing network determines the resolution measurement, this also works in acoustic tomography research. Meanwhile, real-time monitoring of flow progress in the strait can be achieved if received data is transferred to land-based working station for inverse problem solving and result presenting.

## 4.6 Discussion and Conclusion

Indonesia lays in the middle of Pacific Ocean and Indian Ocean, it is an important channel for water and heat exchange. Water exchange in straits of Indonesia has great effect on global climate changing. The Bali strait is an important passageway for water exchange between Indian Ocean and Java Sea in Indonesia. This research explores flow details in the Bali strait using acoustic tomography method. The acoustic tomography method shows in chapter 3 is applied in this chapter for flow detail profiling in the Bali strait. The depth averaged flow velocity in the strait is measured with four acoustic tomography stations that installed at two side of the shore. The flow detail of tide is consistent with pressure sensor measurement, which shows acoustic tomography can be used for flow details profiling in the coastal area and has potential for small scale flow progress sensing.

Meanwhile, water exchange progress in different layer is presented in the chapter, which contribute to the ocean condition forecast around Bali strait. The flow velocity differs with the increase of depth in the strait. Flow velocity is reconstructed in the Bali strait during 4h tide flows. This research shows acoustic tomography system can be used in coastal area for flow current reconstruction and water temperature monitoring. It offers a good idea for flow progress monitoring in the open waters. This method can also be used in small scale flows in experimental tank and basin, which will be discussed in the following two chapters.

## Chapter 5

# Vertical layered analysis of flow velocity using acoustic tomography method

### 5.1 Introduction

As shown in chapter 4 the acoustic tomography method has been used in water properties profiling in the Bali strait for tide monitoring. Understanding the conditions under which an ocean energy device, vessel or maritime structure being tested in the laboratory is critical to properly interpreting experimental data. While wave conditions can be determined effectively using arrays of wave gauges, the velocity profile of flowing is more problematic.

As shown in chapter 2 velocity maps can be produced over small areas using laser Doppler velocimetry, but if a larger area is to be mapped then a series of fixed, point, measurements must be taken using either acoustic Doppler velocimetry (ADV) or electromagnetic flow meters. Accurately mapping the flow field in this way can be extremely time consuming. In this chapter a pair of underwater acoustic tomography stations have been deployed, 23.56 m apart, in the University of Edinburgh's FloWave Ocean Energy Research Facility and used to characterise, steady, unidirectional flow at  $0.8 \text{ ms}^{-1}$ . By transmitting M-sequence signals the reciprocal travel times of multiple sound paths can be identified, combining this data with ray tracing simulations the vertical velocity profile between the stations can be identified. The working frequency suitable for CAT experiments is increased with decreasing station-to-station distances. As a result of recent progress in accurate velocity measurement, the maximum frequency of CAT reached 50 kHz, forming the minimum distance of 100 m.

In this chapter we report the use of two underwater acoustic tomography stations modified to operate at a higher frequency than normal to construct a vertical velocity profile in the FloWave basin. This work demonstrates the use of underwater acoustic tomography in a hydrodynamic laboratory, the reconstruction of a 2D planar velocity map will be described in chapter 6. The flow velocity reconstruction method using reciprocal sound wave transmission is briefly explained. Ray tracing is used to identify sound paths and discuss how the resulting travel time data is used to determine the average velocity in each layer. It also presents the results from the

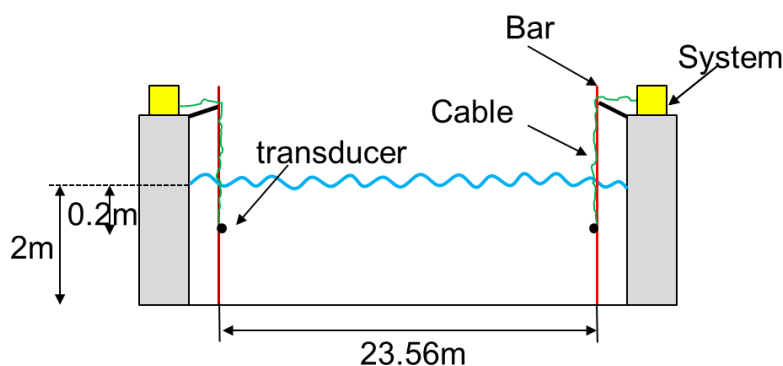


experiment and compares the velocities with data obtained using a series of point measurements taken with an ADV. Good agreement is shown between the acoustic tomography velocity profile and a detailed velocity map obtained using point ADV measurements. Underwater acoustic tomography is shown to be a promising technique for mapping the velocity in experimental tidal current basins, where more detailed flow profiles and velocity maps could be produced using a multi-station network.

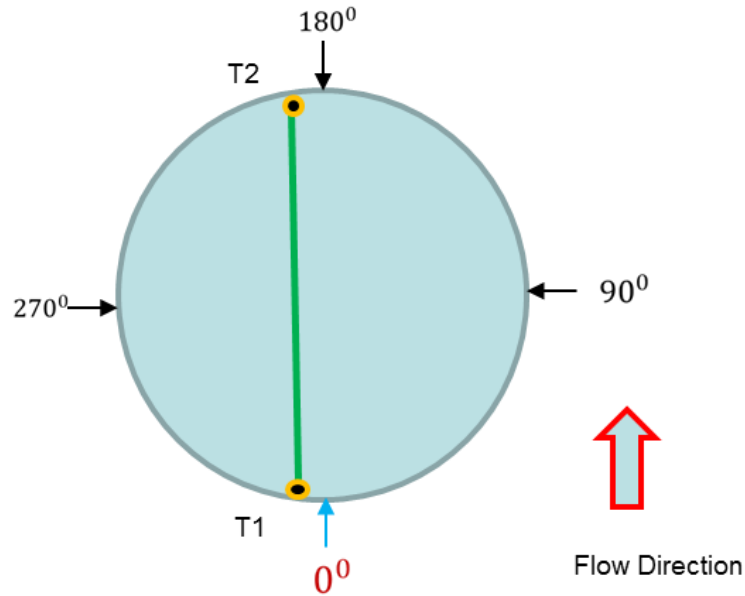
## 5.2 Sound reciprocal transmission in the circular basin

### 5.2.1 Flow velocity measurement with sound waves

As described in former section, the FloWave facility can generate plenty kinds of steady flow, including linear flow, from all combined directions. Big testing zone in the central area can offer a test bed for ocean structure array, which is often used in offshore renewable energy systems. The circular basin is an ideal testing bed for ocean engineering devices and mainly for structure model testing with scaling. Linear flow can simulate the water conditions in open waters, especially for tide energy system. The testing devices are installed in open water to get its working condition and interaction with ocean environment. Flow details (velocity distribution) can be monitored during its testing using flow velocity measuring equipment. The flow details of deferent depth in the circular basin is not same as the flow has interaction with boundary. The flow velocity analysing in the basin of different is quite important to ocean structure working condition testing. Instead of direct point measurement, this study use sound waves transmission in water for path averaged flow velocity measuring across the basin. The small scale underwater acoustic tomography technique is used in the FloWave facility for flow detail profiling.



**Figure 5.1:** Section of the FloWave facility. A pair of broadband sound transceivers is deployed 0.2m from the surface in the 2m depth water, the distance between the stations is 23.56m.



**Figure 5.2:** Experiment design of the sound transmission in the circular basin. The direction of this steady uniform is from station T1 to station T2.

A pair of DualSense 115 transceivers (T1 and T2) were installed, 0.2m below the water surface (figure 5.1). These two broadband high frequency transceivers are fixed on vertical stanchions, facing each other to have high transmitting and receiving efficiency. Every 30 seconds the station T1 transmitted a 12th order M-sequence modulated sound signal to station T2, T2 then sent its signal to T1 providing reciprocal travel times. The phase modulated sound signal uses 2 cycles per digit (Q2) so the bandwidth of the transmitted signal is 25 kHz. As shows in chapter 2, the working frequency range of this transceiver is up to 125 kHz, which can transmit and receive the sound waves used in this experiment. By using high frequency sound waves as media in the flow velocity sensing, this system gives an effective time resolution of 0.04 ms. Normally, high frequency sonar transmitter is used in short distance sound transmission. The strength of this high frequency sound source is relatively low though power transfer is used in this modified acoustic tomography system. In order to acquire a high SNR, 40 repeats of the M-sequence signal were transmitted in a single burst and summed at the receiving station prior to performing the autocorrelation. Using a GPS time signal at each station ensures the clocks on the CAT stations are synchronised to within 10 ns. The indoor GPS signal is weaker than open area due to building reflection, the indoor positioning system needs to be used to get accuracy positioning result. A repeater is used in this experiment to strength the GPS signal, an antenna is installed outside the FloWave facility and a signal repeater is used to transmit received GPS pulse. Each underwater acoustic tomography system starts to record received

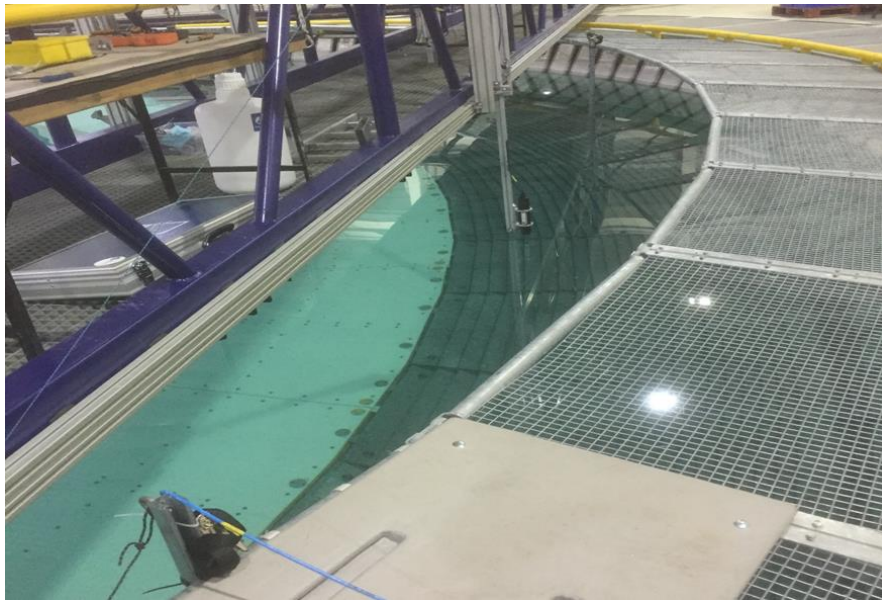


signal data 0.01s ahead of the transmission time and continues to record until 0.09s after the start of the transmission, making each the length of each transmission record 0.1s. The depth-averaged current velocity along each ray path is calculated using the arrival times of the each signal that determined from the cross correlation of the received signals and the transmitted M-Sequence.

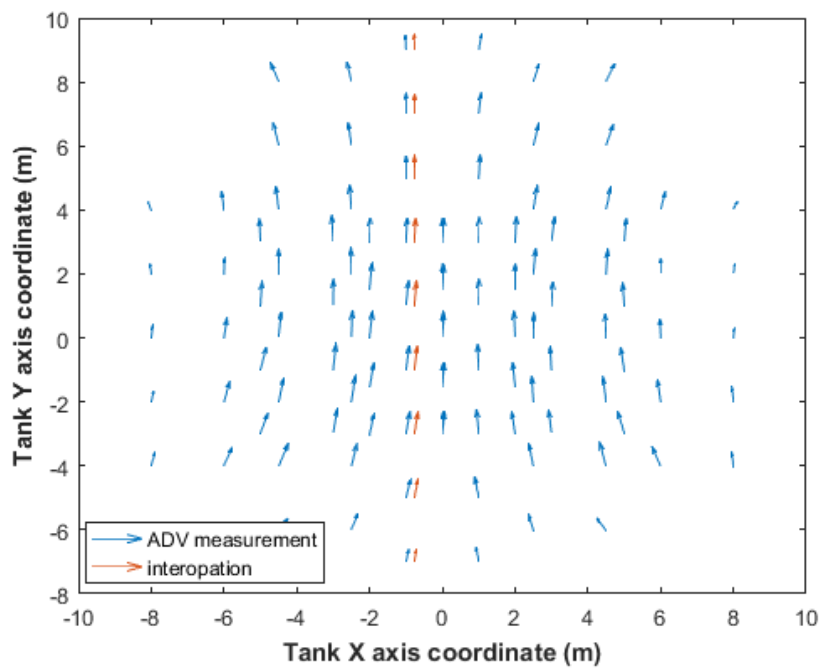
### **5.2.2 Discrete point measurement with Vectrino**

FloWave facility is designed to provide repeatable steady flow conditions across the central testing area for ocean structure testing. This flow condition was characterised as part of the calibration of the FloWave basin. A steady uniform flow is generated in the FloWave facility. The designed flow velocity of this uniform flow is  $0.8\text{ms}^{-1}$ , which is same with the flow condition used in this acoustic tomography research. The real flow details in the basin can be measured with flow velocity measuring devices. As described in chapter 2, the bridge can move across the surface of this circular experimental basin, any position within this basin is accessible. Steady flow conditions can be used for model testing in the basin, the flow condition is much more complicated near wave maker paddles. The flow velocity in the central testing area is measured with the ADV. The ADV is installed in discrete positions within the FloWave facility with the assistance of the moving bridge across this circular basin (Figure 5.3). The ADV is fixed to movable working bridge, which can move on the rails. It takes long time to complete this discrete flow velocity measurements in the steady uniform flow as it is time consuming for ADV installing.

It provides a detailed set of point ADV measurements which can be compared to the tomography measurements. As shows in figure 5.4 the centre of the circular basin is used as origin of the coordinate system with the X axis in an east-west direction. Unfortunately, the ADV measurement positions do not align exactly with the direct path between the acoustic tomography stations so the velocities along this path (shown in red) have been interpolated using discrete measurements of the flow velocity. As the flow system (Figure 1b) has induction and subduction zones with turning vanes the velocity is lower at the edges of the tank. Consequently, the mean velocity along the direct path (based on the ADV measurements) is  $0.65\text{ms}^{-1}$ , with a maximum velocity of  $0.8\text{ms}^{-1}$ . The measured flow velocities are presented in figure 5.4 (blue arrow). The path averaged flow velocity can be measured with sound transmission between two sound stations in the circular basin. This interpolated result can be used for the acoustic tomography invers result verifying.



**Figure 5.3:** Flow velocity measurement in the circular basin, the flow velocity along sound transmission path is interpolated with direct measurements.

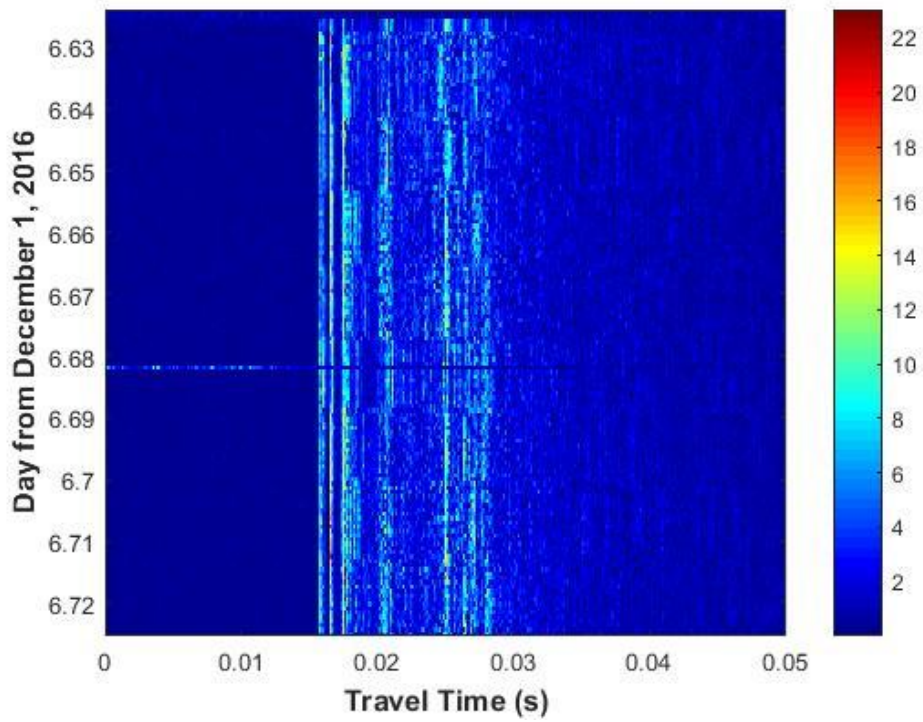


**Figure 5.4:** Flow velocity measurement in the circular basin, the flow velocity along sound transmission path is interpolated with direct measurements.

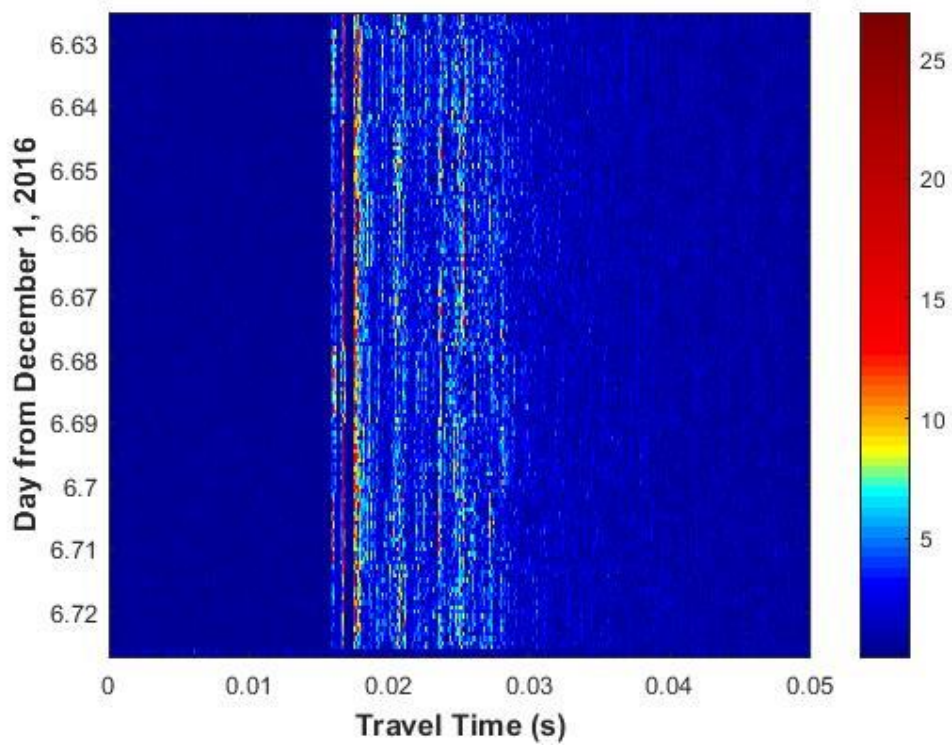
### 5.3 Received data and signal processing

Arrival acoustic signals are acquired with transceivers and stored in the control system continuously. Figure 5.5 shows the received data of this experiment, the raw data is presented at a zone of 0-0.05s. It clearly shows that direct propagation sound waves arrived at about 0.015s, and the boundary reflected signal followed the first arrival sound wave. Ambient noise is acquired before sound waves arrive. Boundary reflection signal last about 0.015s (0.015-0.03s), which means the longest sound transmission length is as long as 45m. Strong reflection signal can be used for flow detail profiling using quite limited acoustic tomography station. It offer a good research direction for flow detail profiling in experimental tank and other small water area. Meanwhile, clearly multi-path signal is also a key factor for flow parameter sensing in open water, which make three-dimensional mapping of flow detail possible with single sonar sensor at each station. This experiment also shows that the FloWave facility is an ideal testing basin for sound transmission experiment, its sound channel is steady for acoustic signal propagation. Different arrival signal can be identified with geometry sound transmission theory in this study as the circular basin is specially designed, its bottom is flat and has regular shape. The water surface and bottom floor are both treated as a plane, where sound waves will be reflected when they arrive. The sound reflection can be calculated with reflection theory. The ray tracing programming is used here for arrival signal identifying, which is widely used in oceanography research. It will be discussed in the follow section. The colour bar shows SNR of the correlation result, the SNR of data received at station T2 is higher than that of station T1.

Only first few arrival signals are used in the acoustic tomography analyse here in this study. Figure 5.6 shows the cross correlations of the transmitted and received M-sequence signals at T1 and T2. Several peaks can be clearly identified in the signal starting with the first peak which is associated with the direct sound path, prior to this only noise is detected. The strongest response is over a time span of 0.015-0.02s, which will be used in this study for sound wave multi-path propagation. After this time zone weak arrivals associated with sound reflected from the wave makers around the edge of the tank are detected. Although these weaker signals are not of interest in this study and are disregarded, they can be used in further research for flow detail profiling in the circular basin with few acoustic tomography station. It is the research topic for further research about small scale acoustic tomography in the experimental tank and other small-scale waters. More detailed flow details can be reconstructed by using more information of arrival signals. As shows in figure 5.6, SNR before 0.015s is below 2 dB. Therefore, a SNR threshold of 2dB is defined as the cut off for ambient noise.

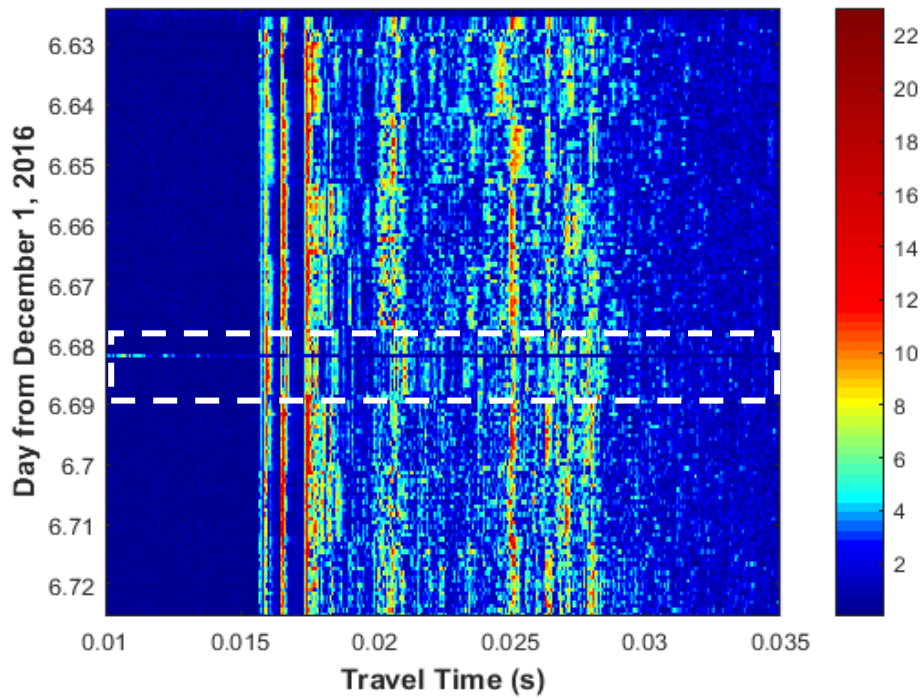


(a)

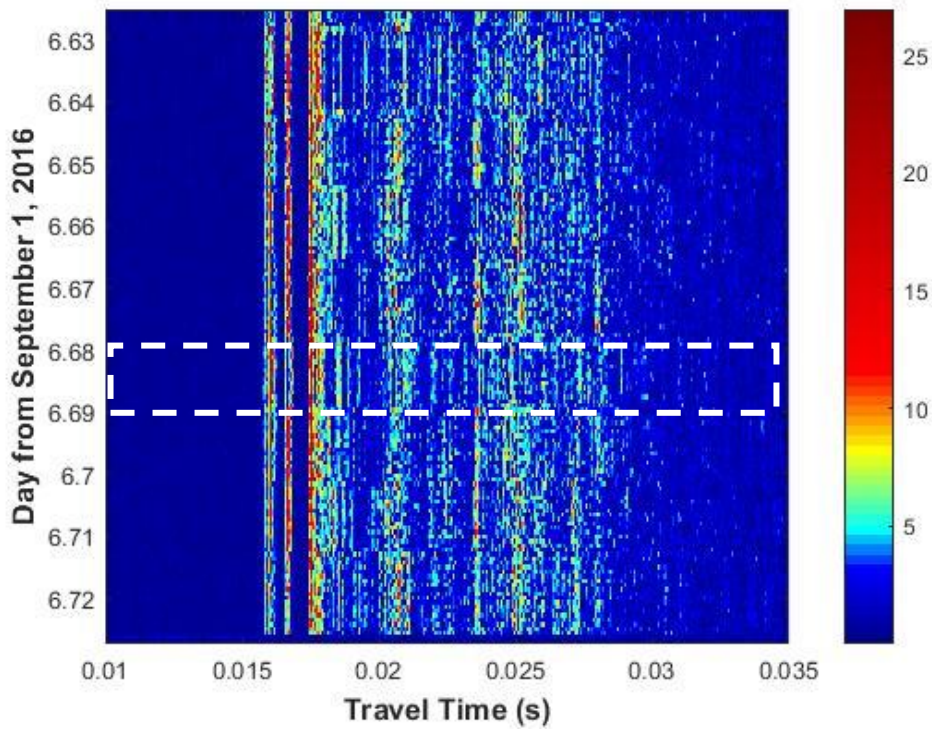


(b)

**Figure 5.5:** Received data at station T1 (a) and T2 (b). Signal arrived at 0.015s and main sound information is at the time range 0.015-0.03s.



(a)



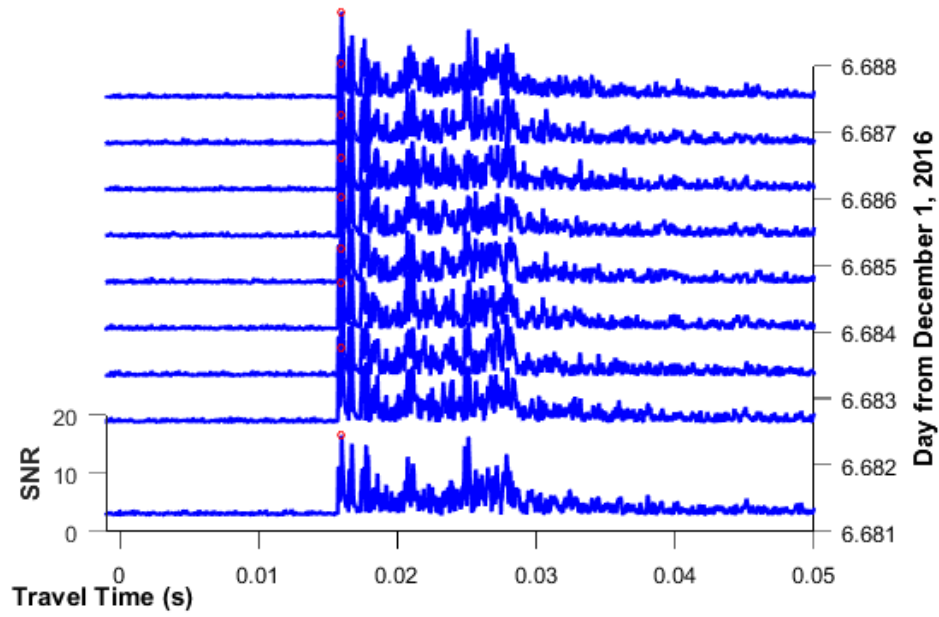
(b)

**Figure 5.6:** Zoom in of received data of station T1 (a) and T2 (b). The received data for this study is at the range from 6.68 to 6.69 of the Y axes that fixed within the dash white block.

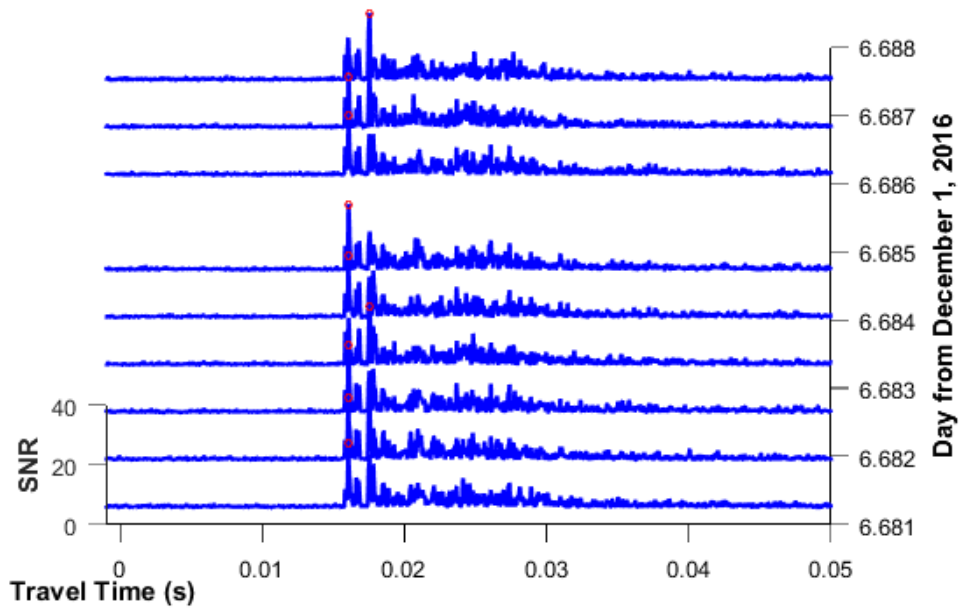


As presented in former section the steady uniform flow is generated in this circular basin for flow detail profiling in this study. A total of 10 periods of signal is transmitted for each transmission, the time gap between two transmissions is 30s. The round way transmitted sound waves propagated across steady flowing current, which will affect the travel time of multi-path propagation acoustic signals. As presented in chapter 2 M sequence modulated signal has strong auto-correlation. The received data are correlated with transmitted M sequence, high SNR peak appears when sound wave is received. In each transmission the most significant SNR peaks are identified with red circles (figure 5.7). The arrival peak with highest SNR is normally associated with the first arrival, which has no boundary reflection. The peaks that identified between 0.015s to 0.02s are used for the vertical layered flow velocity inversion. The arrival peaks between 0.02s and 0.03s are arrival signal that reflected by the surface and floor, these arrival signals can be used to increase the detail in the flow inversion by adding more layers. There also exists some arrival peaks come after 0.02s, which are due to vertical wall reflections. This information can be used to add details to the 2D horizontal flow inversion, the resolution of inverse result will be much higher with more identified arrival signals. The 2D horizontal flow mapping is not considered in this chapter, thus arrival signals after 0.02s is not considered in this analysis.

This research explores flow velocity in the vertical section between two sound stations. Ray tracing is conducted to identify multi-path propagation sound waves, first few arrival peaks are analysed to determine the ray path. The correlation result of received signal is zoomed in at the range of 0.015-0.02s to get more detailed analyse of former arriving (figure 5.8). Peaks appear when the multi-path propagation sound wave arrive to receiving station. The sound transmission is steady in the circular basin, where repeatable flow condition is kept. The first arrival signal corresponds to direct propagation that has no interaction with boundary. As shows in figure 5.8, the highest peaks are not the first arrival signal, which is not consistence with acoustic tomography survey in open water. This is because the sound transmission path in this experimental tank is clear. The water surface and bottom floor can be treated as plane, where mirror reflection occurs at the boundary. The sound propagation ray length is same for the paths that with same number of surface and bottom reflections. The travel time of these arrival signals is same if no flow exists in the testing area. These arrivals combined together for one peak, appears like one arrival signal with a high SNR. Three groups of arrival signal are shown in the zoomed in figure. These peaks will be identified with ray tracing programing for propagation path identifying.

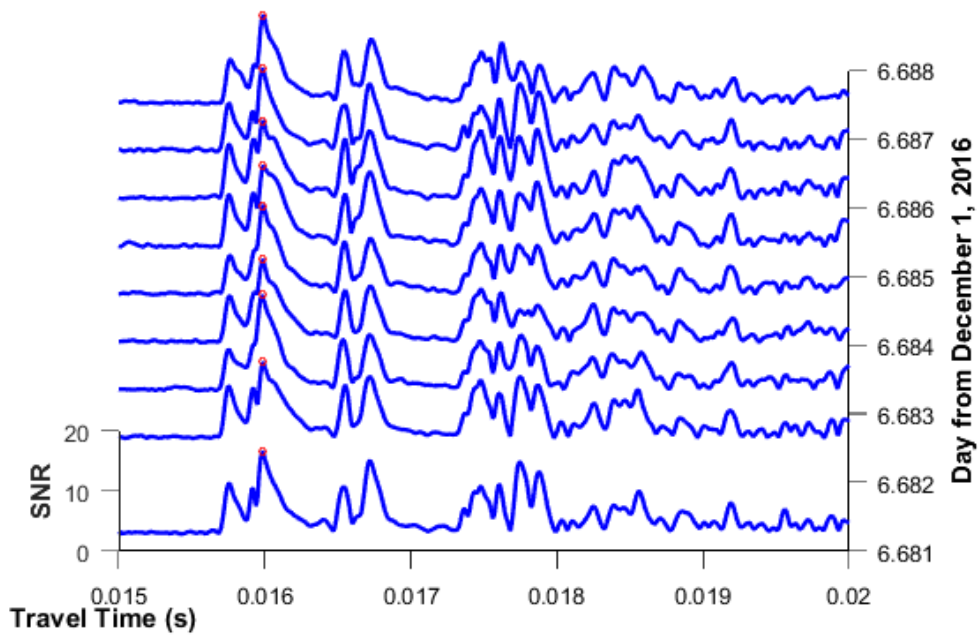


(a)

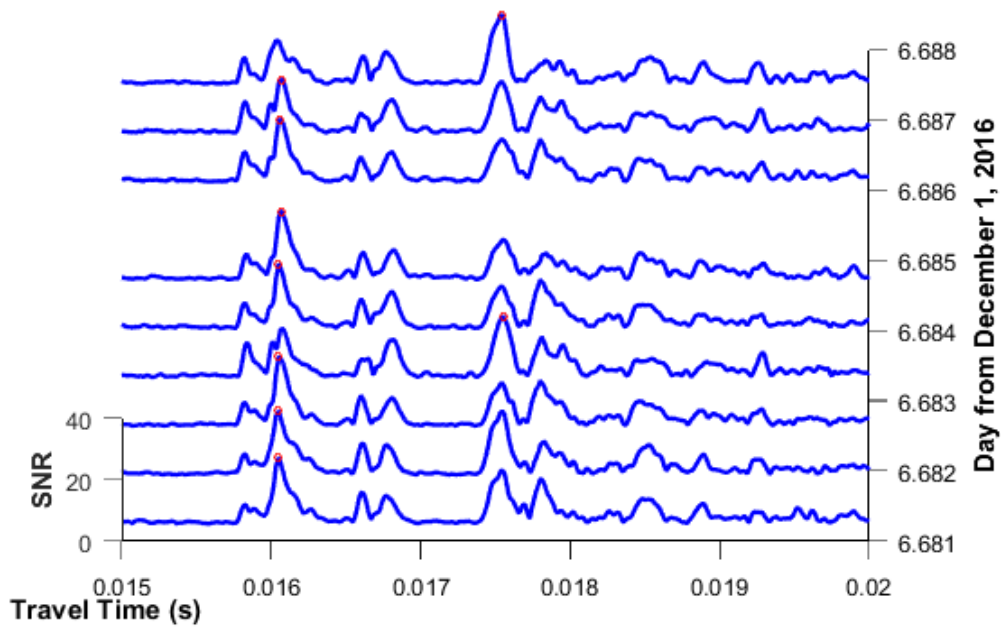


(b)

**Figure 5.7:** Stacked diagrams of the received data correlated with the M-sequence used in transmission at (a) T1 and (b) T2. The red circles show the largest SNR peaks of the data.



(a)



(b)

**Figure 5.8:** Arrival peaks are mainly in the time span of 0.015-0.02 s that shows in (a) and (b) for T1 and T2, respectively. Multi-path propagation signal are clearly shown with different peak.

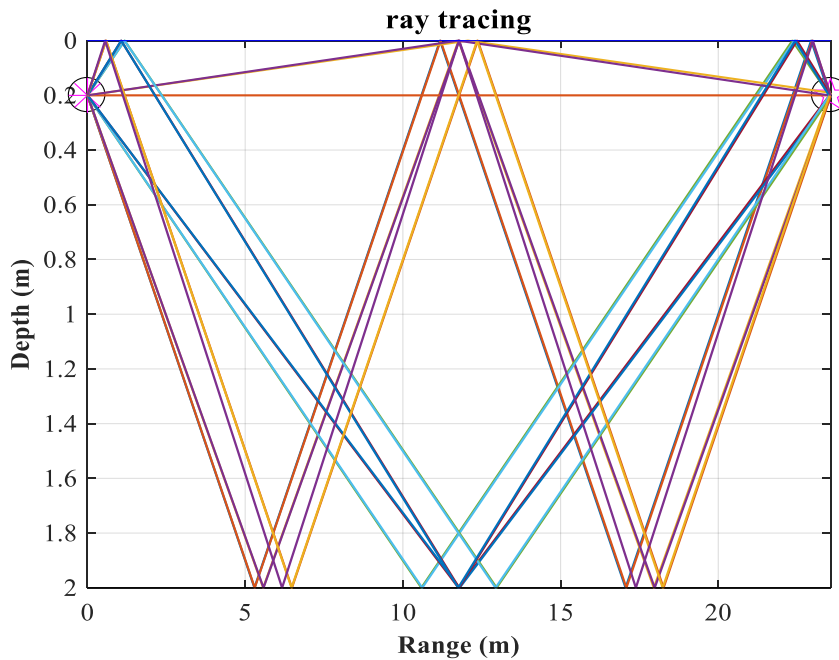


## 5.4 Arrival Peak Identification with Ray Tracing Result

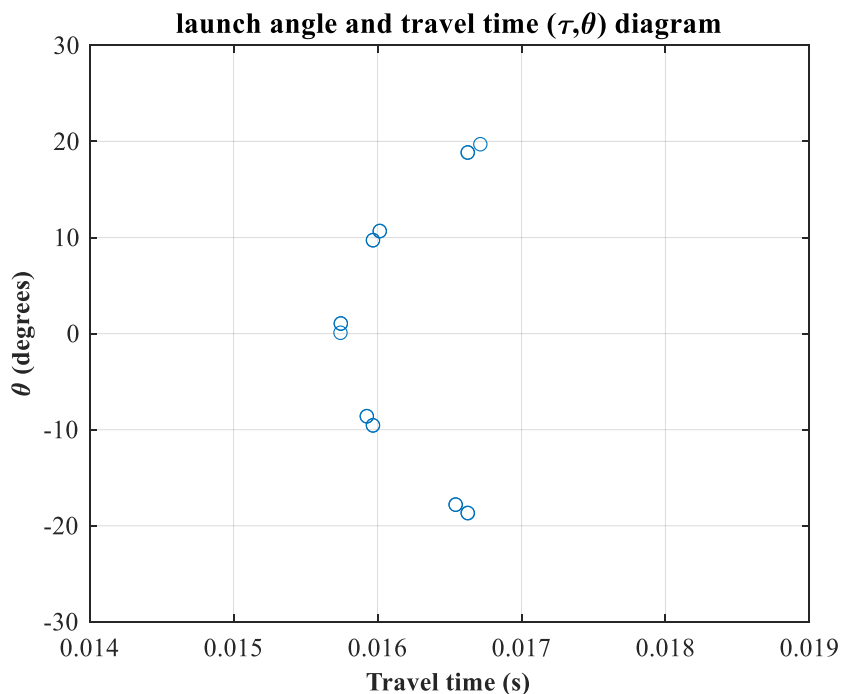
Sound waves passing from one isotropic media to another media will have refract at the boundary according to the Snell–Descartes law. In deep ocean sound speed changes due to depth, temperature and salinity also cause refraction. Ray simulations are used to calculate the sound ray trajectory based on sound wave propagation theory presented in chapter 3. The TRACEO ray tracing program [134,155-156] was used to identify the acoustic ray path associated with different arrival times through a vertical slice between two acoustic stations in the FloWave. In still water conditions FloWave has a uniform 2m depth across the whole experimental area. FloWave uses fresh, rather than saline, water which circulate quickly and is well mixed over the whole basin. Consequently, a constant sound speed of 1496 ms<sup>-1</sup> was calculated for use in the ray tracing simulation. This value is in agreement with the sound speed measured by Vectrino ADV used for the velocity profiling. FloWave’s floor is flat and smooth, and although it is capable of generating waves with current a flat free surface was assumed for these tests since no waves were being created. TRACEO identified ten eigenrays between the transmitter and receiver (Figure 5.9). The ray tracing results along the slice shows that the sound wave propagated along different ray paths in the tank. The identified launch angles (Figure 5.10) in the vertical slice correspond to different sound wave propagate ray paths. The simulated travel times provide a very useful assist in identifying the arrival peaks in the acquired data. The ray tracing results also shows that the direct arrival signal and the surface-reflection signal cannot be separated due to the very small difference between their arrival times. Higher time resolution is needed to identify those two arrivals, the time gap between direct arrival and surface reflection will be smaller if the sonar sensor depth is bigger. The ray tracing result are same for station T1 and T2 as the transceivers were deployed at the same depth, the reciprocal sound transmission path is same for each multi-path propagation.

Ray tracing shows that the earliest signals are expected at around 15.7ms and prior to this ambient noise will be detected. Furthermore, Figure 5.10 shows that the travel times can grouped into four distinct groups, (shown in Figure 5.11). Group-1 is composed of direct (D) and surface reflected (S) rays. Group-2 contains rays with one bottom reflection (SB and BS). Group 3 contains rays with two bottom reflections and one surface reflection (BSB). Finally, Group 4 contains rays with two surface, and two bottoms, reflections, SBSB and BSBS. Within these groups the travel time differences are too small to be resolved. However, since these groups each have distinct arrival times the form a basis for a layered vertical inversion. As

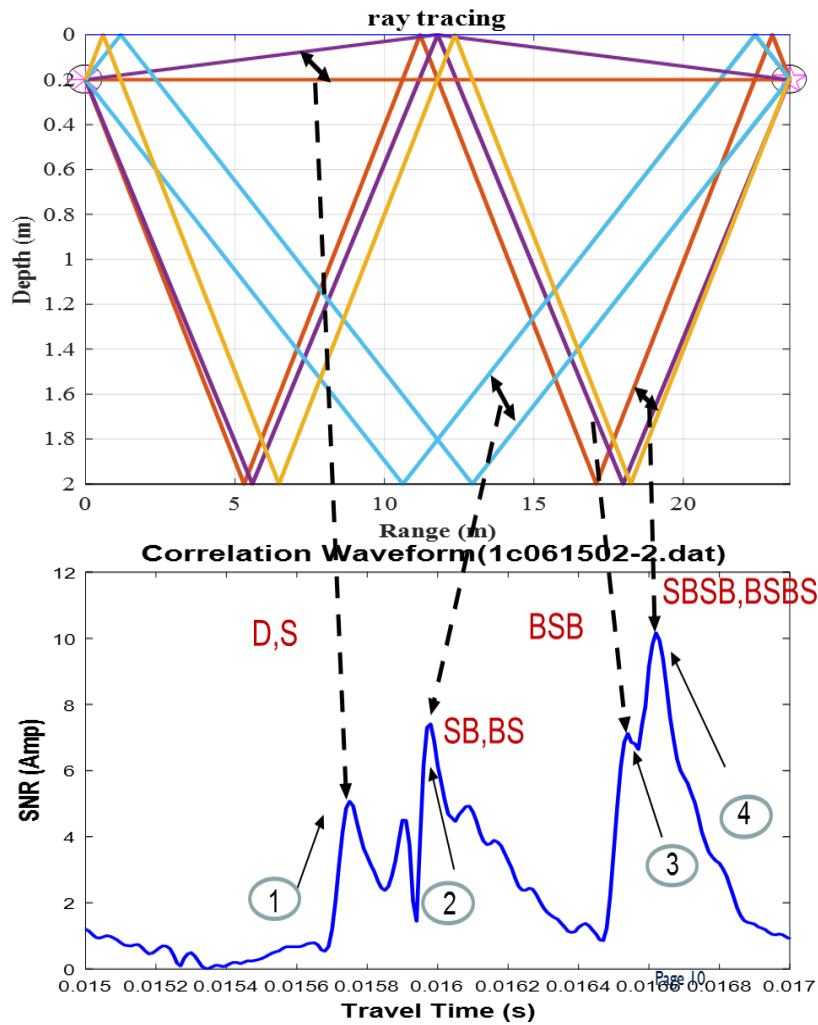
previously mentioned, arrival peaks later than group-4 also contain signals from side wall reflection which are useful for horizontal inversions.



**Figure 5.9:** Eigenray tracing along the slice between two stations, the number of surface and bottom reflection is less than 5.

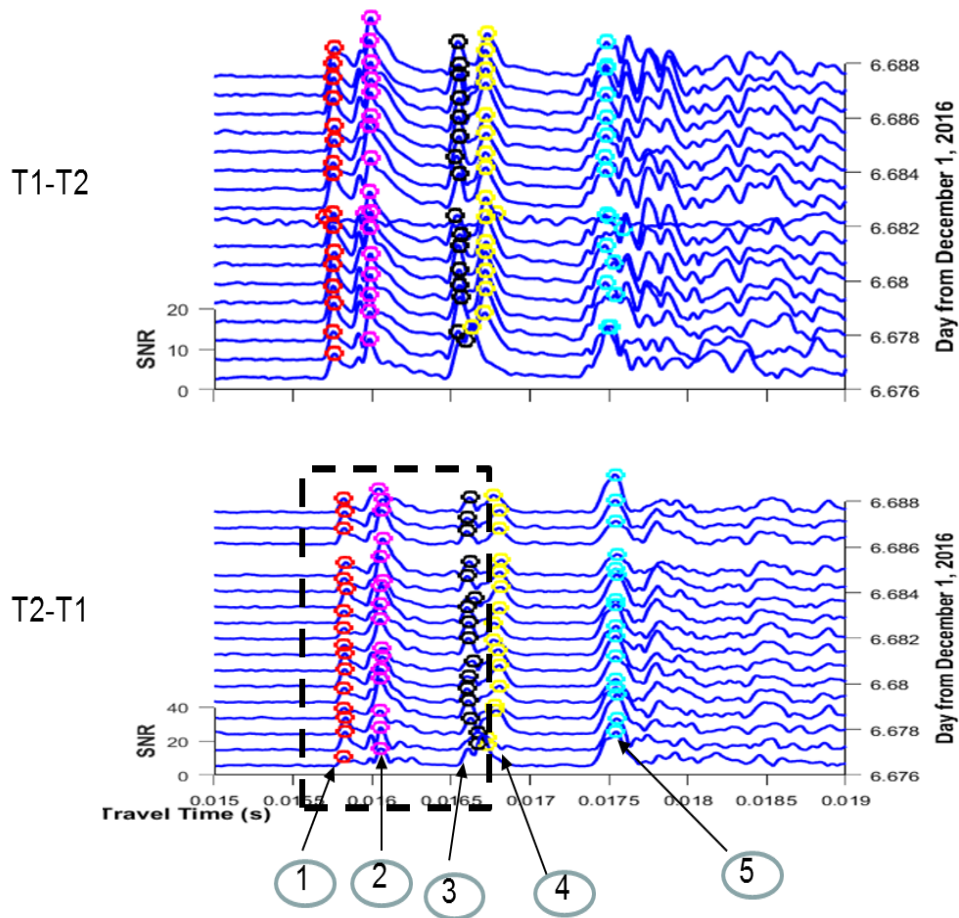


**Figure 5. 10:** Launch angle and the travel time of different eigenrays. The launch angle can be used together with eigenrays to identify peaks of arrival signals of that propagate along each ray path.



**Figure 5.11:** Arrival signal identify by comparing the received signal and ray tracing result. 4 group of rays are picked out here based on the travel time and sound wave launch angle.

The multi-path propagation acoustic signals are received at the receiving station, they are identified with ray tracing programming. 5 group of arrival peaks are identified and used here in this study for flow detail reconstruction. Figure 5.12 shows 1-minute ensemble averages of the correlation signals with SNR peaks identified using coloured circles. The first four arrival times are those associated with the groups discussed above. The 5th group is associated with the ray which is reflected of the back wall behind the transmitting station before traveling directly to the receiving station. Ensemble averaging is often used in oceanic measurements to improve the SNR but has not proved necessary in FloWave where the background noise is less than 2 dB. Under the steady flow conditions created we expect that every transmission time will be the same during a test, this is clearly observable in the plots where the arrival peaks occur at the same times.

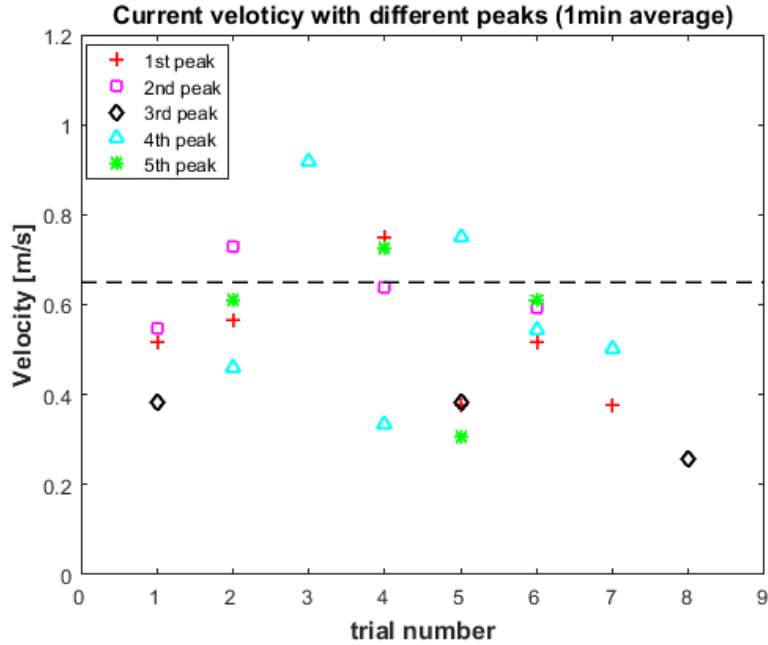


**Figure 5.12:** Peak searching for the received data when transmitting from station T1 (top) and T2 (bottom). 5 peaks have been identified using ray tracing (see Fig 5.9 and 5.10).

## 5.5 Flow velocity analyses along the ray path

### 5.5.1 Path-average velocity

As discussed in section 5.2, when the sound wave travel time between station T1 and station T2 is known for each group, the path averaged flow velocity can be calculated using equation (3) as the ray lengths have been determined. Figure 5.13 shows flow velocities calculated using sound waves round-way travel times between two stations using 5 group of arrival signals. The 1-minute interval signal is affected by ambient noise and surface waves, arrival signal has small shift for some particular transmission. The flow velocity calculated using each sound wave propagate ray path can be averaged as the flow generated in the circular basin is steady. The direction of flow current generated in this experiment is from T1 to T2. Flow velocity along T1-T2 is calculated in this study, positive axis of velocity is chosen same direction as flow current.



**Figure 5.13:** Path averaged flow velocity calculated with arrival signals propagate through different ray paths, black dash line indicates ADV measurement ( $0.65\text{ms}^{-1}$ ) of flow velocity in the tank.

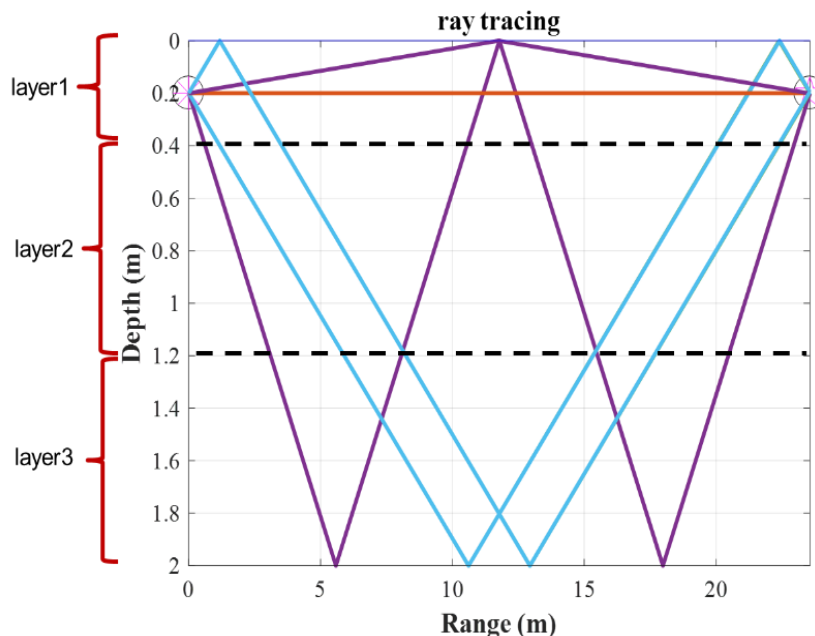
Path averaged flow velocity along sound wave propagation paths is between  $0.33\text{ ms}^{-1}$  and  $0.92\text{ ms}^{-1}$ . The reconstructed flow velocity for each trial has small difference caused by travel time variation for each arrival group. Travel time of sound waves is affected by local flow current when propagating across, path averaged flow velocity is, thus, different for each arrival peak. The mean velocity averaged over all five ray paths is  $0.54\text{ ms}^{-1}$ . As discussed previously the ADV measurements give a mean flow velocity along sound propagation path of  $0.65\text{ ms}^{-1}$ . The ADV was installed  $0.5\text{m}$  from surface when taking direct measurement of flow across the central area of the basin. These results show that velocity measured using sound transmission is in good agreement with the results obtained using direct measurements. In order to make a better comparison between the two approaches an analysis must be made to determine the depth averaged velocity profile over a number of layers in the basin.

### 5.5.2 Vertical layered velocity

Layer averaged velocities in the sound transmission plane can be reconstructed by solving the inverse problem as described in chapter 3. This is done using the travel times of multi-path sound waves. As discussed in section 5.4, 3 distinct groups of arrival signals were identified using ray tracing programming. The flow detail near bottom floor and surface is affected by boundary, flow velocity is not constant of different depth. The vertical slice of whole water

depth in the circular basin can be divided into three layers (0-0.4 m, 0.4-1.2 m, 1.2-2.0 m) as shown in Figure 5.14. Five eigenray are included in first three arrival signals. When sound wave propagates through a layer, the travel time is affected by flow velocity in this layer. The layer averaged flow velocity can be reconstructed using sound wave travel time in the basin. To get layer averaged flow velocity in different depth steady sound transmission is needed. Small variation is weakened when moving average is used around a time range. As shows in figure 5.12, arrival peaks are steadier when moving average is used for received signal. Steady arrival peaks ignore quick changing small-scale flow details in the interest region. The unidirectional flow generated in this circular basin is steady, flow condition (including flow velocity) for each sound transmission is same. For each arrival signal all the trial data are averaged to get path averaged flow velocity.

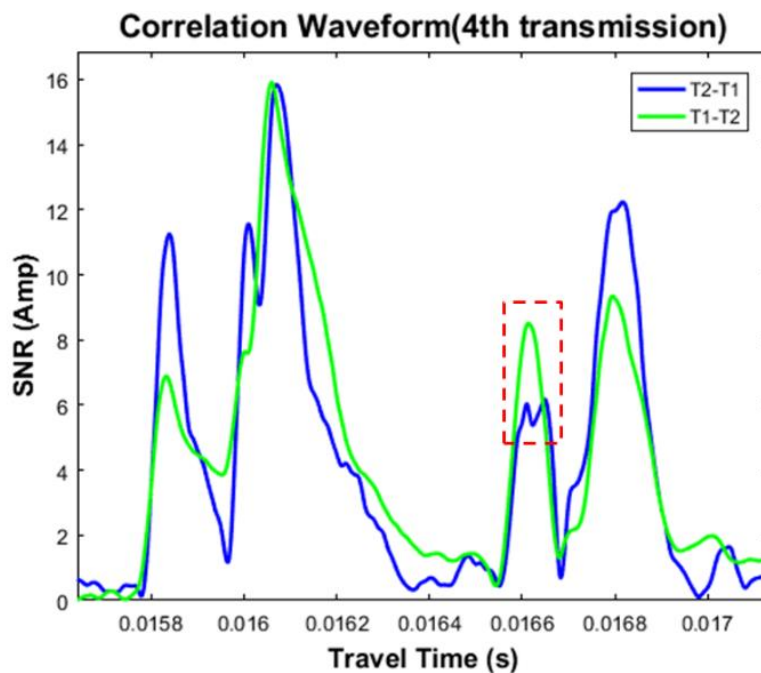
Path averaged flow velocity is calculated using first 3 arrival signals (Table 1). Flow velocity for 3rd arrival peak is biggest compared with other two signals. In order to calculate the steady state travel times in Table 1 the arrival times from each transmitted burst are averaged. In some signals, however, peak 3 and peak 4 are indistinct and cannot be clearly identified. In this case the signal is excluded from the averaging process. Figure 5.15 shows a signal where peak 3 is too indistinct to be used. The burst signal of this kind was excluded from the T2-T1 and T2-T1 average in determining the arrival times of peak 3.



**Figure 5.14:** The vertical slice is divided into 3 layers (0-0.4m), (0.4-1.2m) and (1.2-2.0m). Five Eigenrays are traced for the first 3 peaks.

**Table 5.1:** Ray lengths and travel times used in the calculation of steady state, layered, depth averaged velocity.

Peak number	Ray path	Ray distance (m)	t+ (s)	t- (s)
1	D,S	23.56	0.15824	0.15833
2	BS,SB	23.90	0.16057	0.16067
3	BSB	24.76	0.16607	0.16624



**Figure 5.15:** Correlation signal for forth sound burst for T2-T1 (blue line) and T1-T2 (green line), red dash box fixes the 3<sup>rd</sup> arrival peak of this study. It shows that the arrival time of peak 3 cannot be resolved sufficiently to be included in the averaging process.

The vertical layered inversion was performed on 3 layers using the averaged arrival times. Solving the inverse problems gives velocities of 0.8063 ms<sup>-1</sup>, 0.4989 ms<sup>-1</sup>, and 0.2147 ms<sup>-1</sup> in the 1st, 2nd and 3rd layers respectively. The velocity in the surface layer is very close to the flow speed expected from the drive settings used in the experiment. The middle and bottom layer velocities are lower showing the expected boundary layer across the floor of the basin. The Vectrino was deployed 0.5 m from the surface in the upper part of the middle layer. Since this layer is quite deep (0.8 m) the average value should be lower than that measured using the Vectrino. In order to make a comparison with the measured velocity it is possible to estimate velocity at 0.5 m by taking a weighted average of the upper- and middle-layer velocities. Using

weights of 67% and 33% for the upper and lower layers respectively gives an estimate of the velocity 0.5 m below the surface as 0.6014 ms<sup>-1</sup>. As discussed in former section, the path averaged velocity obtained using the Vectrino is 0.65ms<sup>-1</sup>. The error between the reconstructed result from the upper two layers using acoustic tomography and the ADV measurements is 7.48%.

## **5.6 Summary and discussion**

Acoustic tomography method has been applied in this chapter to profile path averaged fluid velocity in the circular experimental basin, FloWave facility. In addition to calculating flow velocities based on individual sound travel times the depth averaged flow profile has been reconstructed over three vertical layers (0-0.4m, 0.4-1.2m and 1.2-2.0m). A pair of high frequency broadband sonar transceivers were installed, 23.56 m apart, on opposite sides of the circular basin in this experiment. Two underwater acoustic tomography systems, operate at 50 kHz, were used to measure the arrival times of M-sequence acoustic signals transmitted across the basin. Compared with previous acoustic tomography research in open waters, high frequency acoustic signal is needed to identify multi-path propagating signals in short distance sound transmission. Meanwhile, the travel time difference of round way sound wave transmission in short distance is small, high time resolution can decrease the model error of this acoustic tomography system. M-sequence modulated sound wave broaden the frequency band, using broadband acoustic transceivers guarantee high sound information acquiring. The ambient noise was found to have a SNR of less than 2 dB while the received M-Sequences have SNRs of about 20 dB. This difference is sufficient for the arrival peaks to be easily identified.

Analysis of the received signals shows prominent, multiple, arrival peaks that correspond to sound rays reflected by the floor of the basin and the water surface. The ray tracing programming, TRACEO, was used to simulate these rays and to calculate ray lengths, launch angles and expected arrival times. Data from the simulations was used to identify the peaks observed in the experimental data. The multiple arrival peaks were divided into 3 distinct groups of rays and the path averaged flow velocities were reconstructed. Using a regularized inverse method, the layer averaged current velocity was determined from the ray data. Besides the acoustic tomography analyse, fixed-point measurement was carried out in the central test area of the tank. The flow velocity measurement by ADV monitored fixed-point flow condition continuously. The reconstructed average currents show very good agreement with velocity measurements made directly using an ADV.



This experiment is the first trial of acoustic tomography in an experimental laboratory basin with station-to-station distances shorter than 50 m. The study shows the potential of acoustic tomography as an analysis technique for small scale flow monitoring. The higher frequency acoustic signals used in this study would allow smaller scale flow details to be reconstructed in either the horizon plane or the vertical plane using a multi-station networking. Underwater acoustic tomography therefore provides a useful tool for real-time monitoring of flow in both experimental tanks and open water areas. This method can be used in flow detail sensing in small experimental tank in laboratory.

## Chapter 6

# Mapping of flow details in the circular experimental basin with underwater acoustic tomography method

### 6.1 Introduction

As discussed in former section the circular experimental basin can generate complicate flow conditions for ocean structure testing. To explore flow details in the basin path averaged flow velocity is analysed in chapter 5 with a pair of underwater acoustic tomography systems. Strong water surface and bottom floor reflected sound waves make layer averaged analyse possible. The velocity distribution in the horizontal plane is also of great importance for the flow field in the circular experimental basin. The flow details can be obtained by CFD simulation with three-dimensional modeling of the circular tank as discussed in chapter 2. The flow velocity in the experimental tank can also be acquired with discrete measurement using ADV. The CFD simulation cannot agree with real complicate flow ideally and it takes time for this work. Meanwhile, it takes long time to get flow velocity mapping with limited number of discrete measurement devices. This research studies the uniform flow velocity mapping in the basin with underwater acoustic tomography method. A pair of acoustic transceivers was installed at the periphery of the FloWave facility for flow field mapping by solving the inverse methods. A 7-stations network was attained with only two acoustic tomography units by changing the uniform flow directions. A uniform flow is generated in the basin by the linked control of inflow velocity for different vanes. A set of travel times obtained along the 7 transmission lines was used to solve the inverse problem for flow field detail mapping. In collaboration with Hiroshima University, the multi-repeat transmission program and the ring-buffer summation program for received data are newly constructed to increase largely the signal-to-noise ratio (SNR) of received data. The flow fields are reconstructed by the inversion of the acoustic tomography data. Fixed-point data of flow velocity was acquired in the central testing area by ADV. The discrete measurement has good agreement with the reconstructed result. The flow-

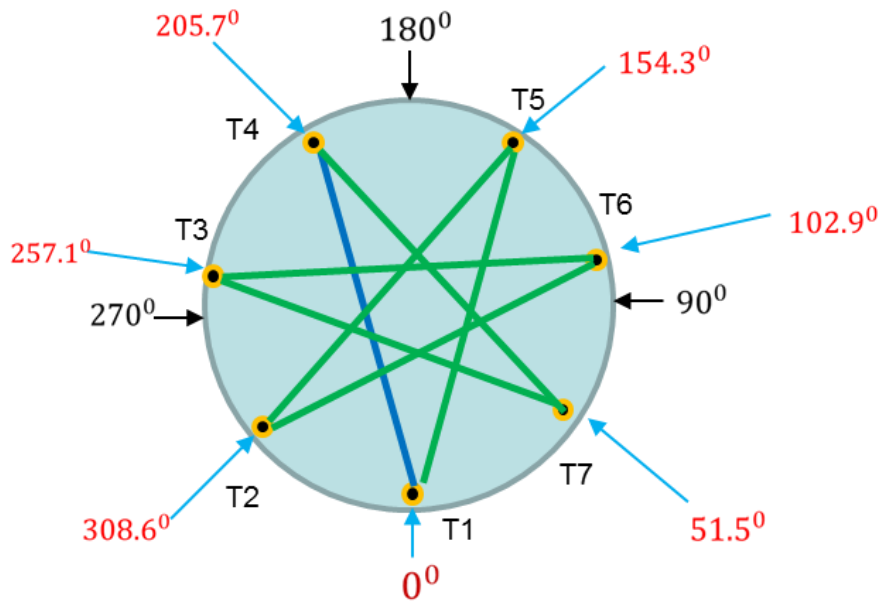
field mapping results by the acoustic tomography methods showed that the FloWave is an ideal test facility for offshore renewable energy platforms which can construct a steady, uniform flow. This study demonstrates a method for flow field details reconstruction in the circular basin.

## **6.2 Underwater acoustic tomography experiment in the circular basin**

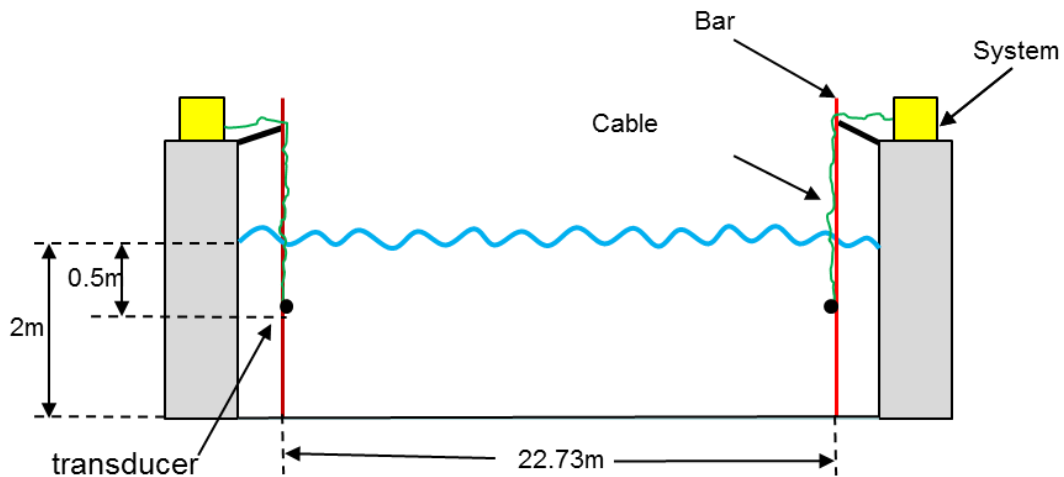
### **6.2.1 Sound wave transmission**

This research is for the first time to use acoustic tomography method for small scale flow detail profiling. Meanwhile, no previous research is conducted about flow velocity mapping with acoustic tomography system in the experimental tank. The high frequency sound waves are used in this testing as a media for flow velocity measuring. To explore working condition of the circular tank and get flow details in the testing area uniform flow is generated in the basin. The newly developed small scale underwater acoustic tomography systems are used in this research for flow details profiling in the circular experimental basin. Two set of underwater acoustic tomography stations are installed in the circular basin for sound wave transmission. Multi-station sensing network is constructed for velocity reconstruction in the experimental basin with a pair of underwater acoustic tomography system.

Normally the most continent method to get flow details in the FloWave facility is install some sound station in the circular basin and construct sensing network. Meanwhile, flow velocity distribution can be obtained by discrete measurement using ADV. One can get discrete measurements at different positions in the continuous steady flow field. Repeatable steady flow can be used in the experimental tanks and basins if the number of measuring devices is limited. It takes long time to get flow details in an interested area in this way. The multi-station network sensing system, however, is achieved by changing flow directions in the circular basin with only two sets of acoustic tomography systems. As discussed in chapter 2, regular flow tank is designed to rectangle for steady flow generating. The circular flow simulation basin is designed to a circular shape, which can push flow with different directions. Plenty of CFD simulation and experimental tests shows that repeatable flow can be generated in the FloWave facility. Moreover, nearly same flow conditions can be generated in the circular basin with different direction. The excellent performance of the flow basin makes this experimental scheme possible, which use limited number of sound stations for multi-station network sensing. The multi-station sensing network can also be constructed with limited stations by changing station positions around target area.



**Figure 6.1:** Experimental design of the underwater acoustic tomography test. Two acoustic tomography station are installed at T1 and T4. The uniform flow is generated from  $0^\circ$  with a velocity of  $0.8\text{ms}^{-1}$ . To simulate a 7-station network with only 2 acoustic tomography stations flow direction is changed to other 6 different degrees as shows in the figure.



**Figure 6.2:** Vertical section of flow velocity mapping with underwater acoustic tomography system in the FloWave facility. Two sonar sensors are installed in water with a distance of 22.73m. They are deployed 0.5m from the water surface in the 2m depth water. Sonar sensors are controlled with the acoustic tomography system, which synchronised with GPS timing system.

Sound transmission in the circular basin described in chapter 5 shows that high SNR sound wave can be received after short distance propagation. Acoustic tomography technique can be used here to reconstruct flow velocity like the coastal acoustic tomography research in open waters. Only two acoustic tomography systems are developed in this research due to the restriction of fund. Specially designed experimental scheme is conducted in the circular basin to get multi-station network with only two acoustic tomography stations. Other than moving station position in the circular basin, the flow direction is changed to get different sound transmission path. All the sound transmission in the network sensing are assumed in the basin with 7 different flow directions (figure 6.1). Flow direction changing in the experimental basin is conducted by combined controlling of the turbines that installed underneath the testing floor. Each flow condition is assumed with same flow velocity distribution, where only the direction is changed.

Two set of underwater acoustic tomography systems are used in this research. High frequency Sound wave was reciprocally transmitted between two sonar stations (T1 and T4) in the tank for flow current velocity measuring. As the circumference of the testing area is divided equally into 7 segments, the angle difference between each nearest station is  $51.5^\circ$ . The sound transmission paths in Figure 6.1 have same distance as the circumference of the tank is equally divided. The original flow direction is assured as  $0^\circ$  directing to the central of the circular basin from T1, which is the lowest point in the new coordinate. The uniform flow in the circular basin is generated by combined control of 28 impellers underneath the testing floor, velocity of the flow is  $0.8\text{ms}^{-1}$ .

When two sound station is installed in the original position, uniform flow is generated for sound transmission. The reciprocal transmission travel time is used in the inverse problem solving for the tomography research. Keeping original position of acoustic stations, flow direction is changed to  $51.5^\circ$ . The flow works like generated from station T7, directing to the central point of the circular basin. The sound transmission between station T1 and T4 continues. Changing the coordinate to  $51.5^\circ$  counter-clockwise, it works as the uniform flow is from direction  $0^\circ$ , where the flow generated from station and directing to the central point of the basin. The sound transmission between T1 and T4 is changed to T2 and T5 after the coordinate rotation. The flow direction is changed to  $51.5^\circ$   $102.9^\circ$   $154.3^\circ$   $205.7^\circ$   $257.1^\circ$   $308.6^\circ$  separately. Then all the sound transmission between 7 stations is achieved in the circular basin. This experiment assume the condition is the same for the steady flow from each direction.

The water depth of the circular experimental basin is 2m in the testing area and the sound transceivers are installed 0.5m from the surface (Figure 6.2). Same depth of the sonars can assure sound wave transmission stay in a horizontal plane, which is main task of this study. The flow details in a horizontal plane needs to be reconstructed with the sound transmission method in the basin. The horizontal distance between station T1 and station T4 is 22.73m. The transceivers were fixed to the bars facing to the centre of the tank, which assure sound transmission to other stations in the network. As shows in chapter 2, the sound sensor has a property of Omni-direction, which means sound wave can be transmitted in all directions around. It is means multi-path propagations in the experimental area is possible. Meanwhile, the all-direction sonar can also receive acoustic signal that come from different direction. The floor of circular basin is a cement plane, which has strong reflection of sound waves. Neglecting the roughness of the surface, the surface and bottom are treated as a flat plane. Sound reflections can be traced easily in the regular boundary environment using mirror-reflection method or ray tracing programming. The sonar sensor is deployed in water for underwater sound wave transmission and receiving. It is controlled by the underwater acoustic tomography system, which is connected with the sonar sensor using cable.

Uniform flow is generated in the circular basin for flow velocity reconstruction. In this study, 21 vanes are assured as input and other 7 vanes are output. The input velocity of each sub-vane is different, all impellers works together to create the uniform flow in the testing area. Real flow condition is quite complicate, especially in the boundary area. The flow near boundary is affected by vanes and the vertical wave makers. This research explores flow velocity distribution in the experimental and sound transmissions all cross the central area of the basin. The devices testing in the circular basin is all conducted in the central area, mainly above the risible floor. Figure 6.3 shows the uniform flow in the circular basin, quite complicate small-scale flow detail neat wave makers is neglected in this study. Steady repeatable flow is generated with different in the basin. As shows in figure 6.4, the high frequency broadband sonar sensor is fixed on the bar, which is attached to the boundary of the working net. The bar is relatively thin in the boundary of the flow field, the effect to the original field is also neglect. It is inserted into the gap of two vanes to assure it vertically fixed firmly in water. Meanwhile, fast changing small scale flow details in boundary area are also neglected in this study. It can be observed in real-time monitoring system using net multi-station networking. It is out of the research area of this study and it is a task for further underwater acoustic tomography research in the experimental tanks.

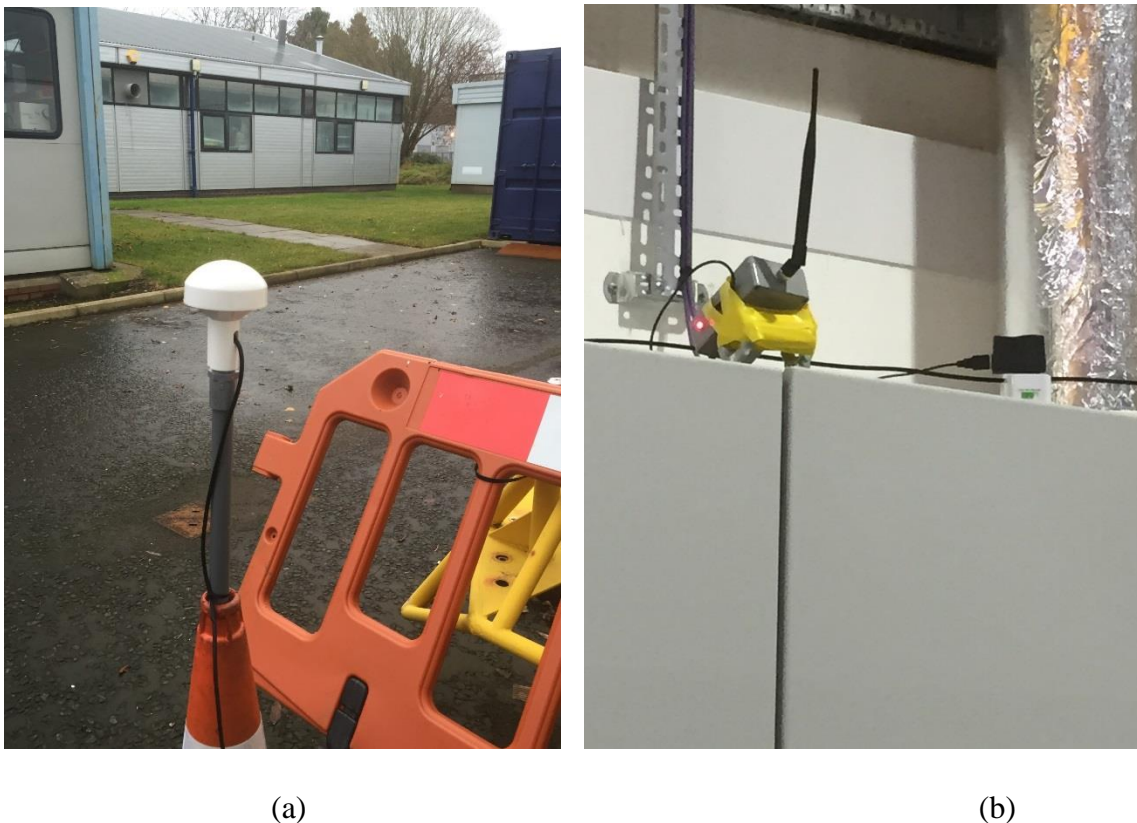


**Figure 6. 3:** Uniform flow generated in the circular basin. The velocity of the flow is  $0.8\text{ms}^{-1}$  and the direction is changed by combined controlling of impellers as shows in chapter 2.

The sound transmission experiment in the circular basin shows in chapter 5 demonstrates that aacoustic tomography research in the experimental tank is realisable with high frequency sound waves. The central frequency of the transmitted signal was set to 50 kHz in this acoustic tomography experiment. 2 cycles of sine wave per digit (Q2) was selected for phase modulated sound wave transmitting from the broadband transceivers. The bandwidth of the transmitted signal is 25 kHz. The working range of this broadband transceiver is 10Hz-150 kHz. As shows in chapter 2 autocorrelation of the M-sequence is very sharp, no correlation peak appears between different M-sequence even if they has the same order. The 12-order M sequence modulated broadband sound pulses were transmitted in turns every 1min from both acoustic stations. The time resolution is defined as one-digit width of the M sequence, 0.04ms. Generally, application of the 50-kHz acoustic tomography system to the 25m scale circular tank is hopeless to attain the sufficient accuracy of velocity measurement. Without the proposed data processing, acoustic tomography application to the 25 m circular tank is unrealistic. 20 repeat of signal was transmitted at one time and summed at the receiving site to improve SNR. The summation of 20-repeat signals is taken every minute, using the CPU memory inside the system and the 20-repeat received data are compressed in the one-period

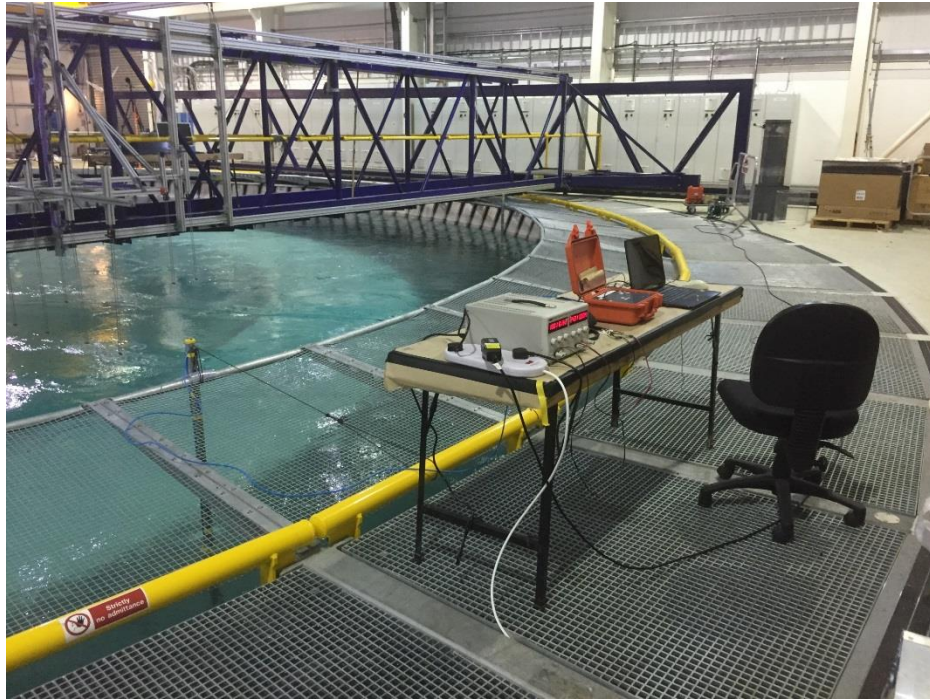
(repeat) size of M sequence. The SNR is further increased by the 5-min ensemble average. Finally, the ensemble of 100 data decreases error velocity by 1/10. GPS clock signals was used for system synchronize. GPS repeater is also used in the FloWave facility to strength the GPS signal for better time accuracy (figure 6.4).

Figure 6.5 shows the underwater acoustic tomography system used in this flow current mapping experiment. The power system used in this testing is power source, which can offer two channel power supply for the acoustic tomography system. Voltage for control system is 12V and the power supply for sound transmitting is 24V. A power transformer is used in the control system, which can change the voltage from 24v to up to 500V during the sound transmitting. The current of sound transmission channel is between 0.2-0.4A. As the attenuation of sound waves increase rapidly with frequency, strong sound waves need to be transmitted. Strong power supply for the sound transmission system assure high SNR acoustic signal received in the other station.



**Figure 6.4:** GPS repeater (receiver (a) and strengthened signal transmitter (b)) is used in this experiment. Indoor GPS signal is relatively weak, GPS repeater is applied here to strengthen the GPS signal.

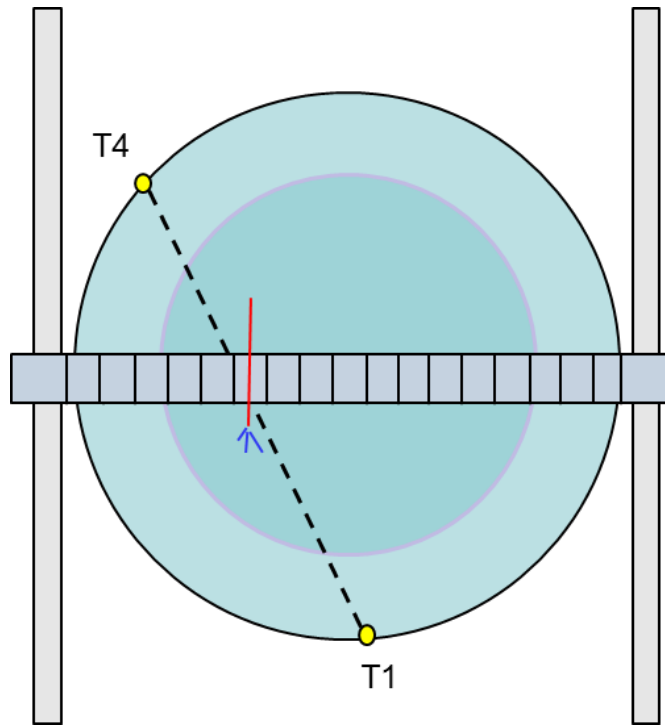




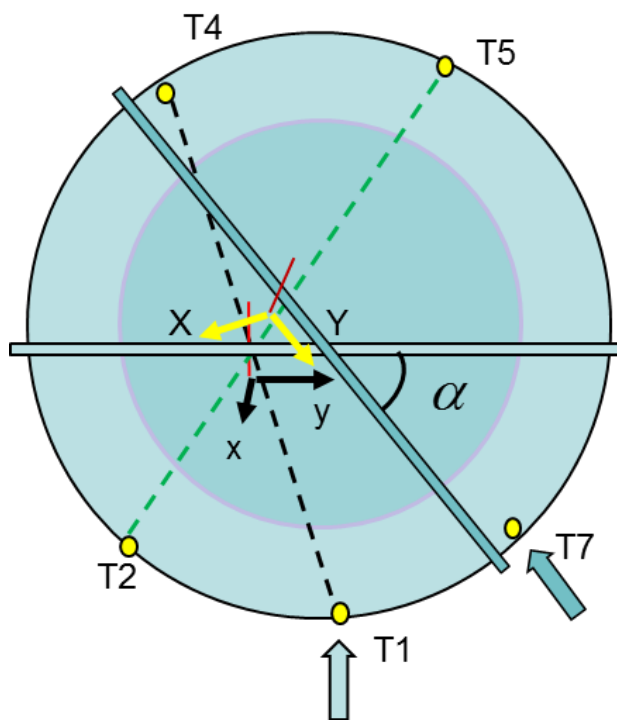
**Figure 6.5:** underwater acoustic tomography station used in the small-scale flow detail mapping. The battery of this system is replaced with power source, which offer power supply to transceiver and control system. Sonar transceiver is controlled with the underwater acoustic tomography system for high frequency sound wave transmission and acoustic signal receiving.

### **6.2.2 ADV measurement of flow velocity**

During the sound transmission in the circular basin fixed-point measurement of flow velocity is also conducted with ADV in the central testing area. A Vectrino was used here for fixed point measurement of the flow current. As shows in chapter 2, there has a working bridge across the circular basin. Two railways are installed at both side of the experimental basin, the working bridge can move above surface of water. Testing devices can be installed at the risible floor easily using the moving bridge. One can install device at any position of the bridge. All the area in the circular basin is accessible by combined using of the bridge and the risible working floor. The floor can rise up and lower down quickly. It is designed to install and remove testing device in the basin easily, no need to get into water for device installing. As shows in figure 6.6, the Vectrino is installed at the middle point of the sound transmission path. The depth of Vectrino is 0.5m below water surface in the 2m testing area. The flow velocity around middle point of the sound transmission is measured continuously with the Vectrino. All the flow velocity in 7 middle-point can be acquired by changing the flow direction in the circular basin.

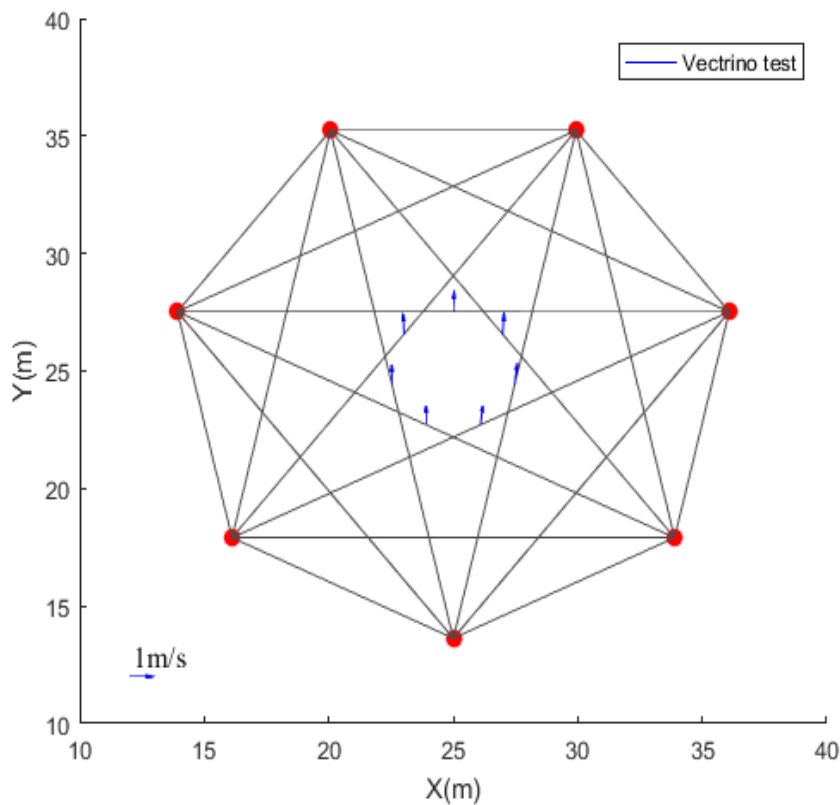


**Figure 6.6:** fixed point measurement of flow velocity with ADV. The vectrino is installed in the middle of sound transmission path in the bridge across the FloWave basin.



**Figure 6.7:** coordinate rotation with flow direction changing in the basin. When the flow inlet changes from T1 to T7. It works like the sound transmission is between T2 and T5 (green dash line). The coordinate of Vectrino also rotate with the bridge.

The acoustic tomography stations are originally installed at station T1 and T4. The first ADV measurement of flow velocity is in the middle of sound transmission path. When the flow inlet changes from T1 to T7. It works like the sound transmission is between T2 and T5. The coordinate of Vectrino rotated as flow direction changing. The flow velocity that measured with Vectrino is broke down to original coordinate. The flow velocity is measured with Vectrino in the middle point of each sound transmission path. The discrete measurements are plotted in figure 6.8. To better show flow velocity measurement result in the figure the central point of the circular basin is moved to (25, 25). All the flow area is presented in the first quadrant of this coordinate. Acoustic stations is represented by red dot in the figure. Multi-station network is also showing in the figure. As all measurement is conducted in the middle point of sound transmission path all the ADV measurements are locate in the central area of the testing area, where uniform flow is more ideal than boundary area. The point discrete measurement could be used for the acoustic tomography result verify.

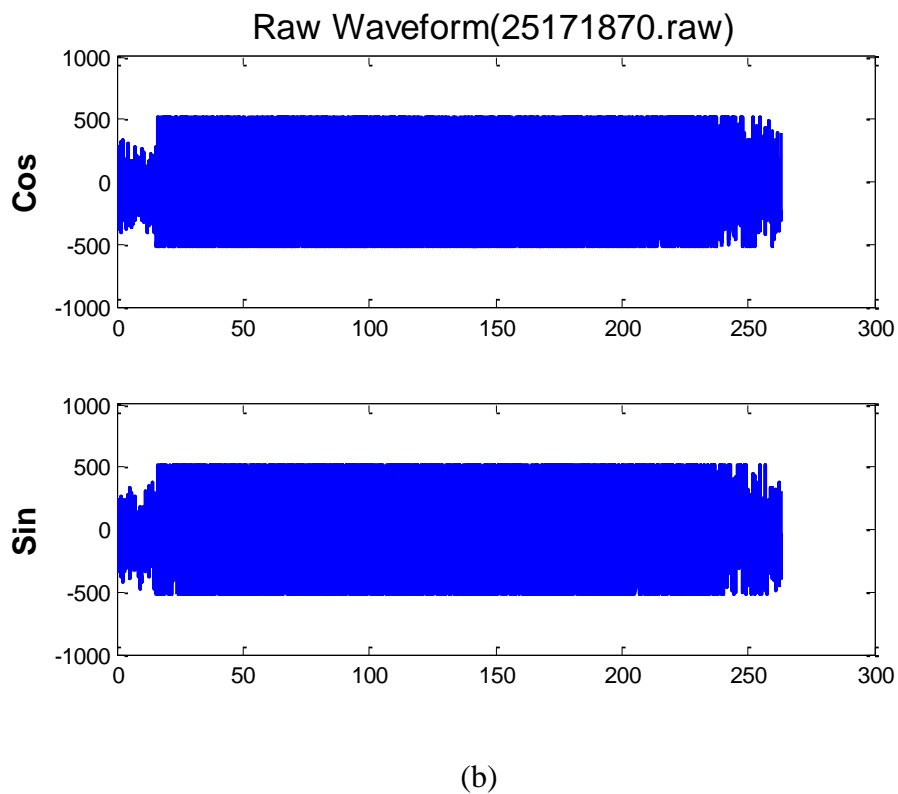
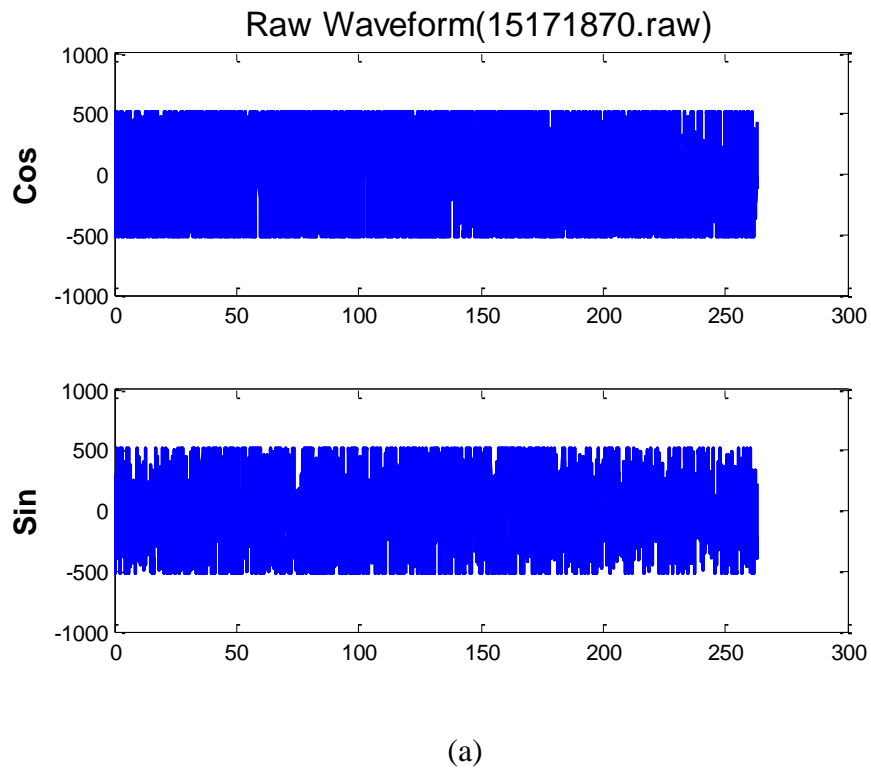


**Figure 6.8:** discrete measurement of flow velocity in the circular basin using Vectrino. The ADV is installed in the middle of each sound transmission line. Red circular point is acoustic stations that installed in the circular basin. The velocity of uniform flow during ADV measurement is  $0.8\text{ms}^{-1}$ .

### 6.3 Received data analysis

Sound transmission in the circular basin is conducted with two acoustic tomography systems. The transmitted sound waves are received with transceivers after a short distance propagation in the basin. The sound waves are transmitted in all directions, which results in multi-path propagation in the circulation basin. The sonar sensors used in this experiment are transceivers that can transmit broadband sound wave and receive arrival signal as well. The transceivers are adjusted to transmit sound wave in turns, the time gap between two transmissions is 30 s. Every transceiver switch to receiving mode after its sound transmission. The sine wave is modulated with M sequence for high SNR at the transmission station. The received signal is stored in the control system for post-processing, it is correlated with transmitted signal for peak identification. For self-contained system, however, the received data can be pre-processed with control system and get the travel time of each transmission. As shows in chapter 2, the arriving signal is divided into two channels. They are multiplied with sine wave and cos wave that of same frequency with transmitted acoustic signal. The multiplied signal is processed by low pass filter to get low frequency component. The processed signal is used for correlation with transmitted signal to identify arrival time of each boundary reflected sound wave.

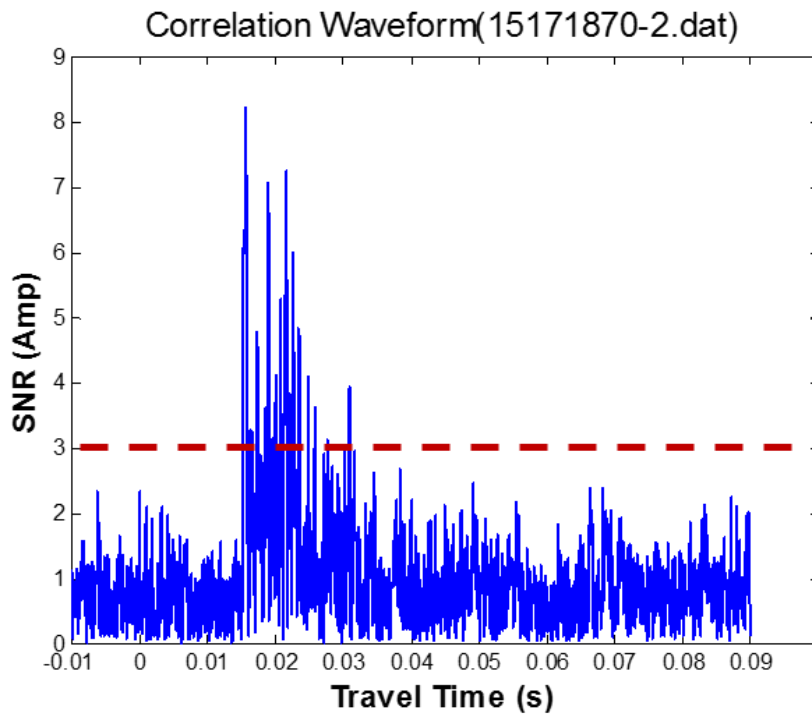
Figure 6.9 shows received raw data with underwater acoustic tomography systems. As discussed in chapter 2, the received data is multiplied with sine wave and cos wave and stored separately. The frequency of sine and cosine signal used here is same as carrier signal of transmitted sound wave. These two channels of data are combined together for correlation with the transmitted sound waves at the sound transmitting station. Both of these two signals are received when no flow current is created in the circular basin. The upper figure (figure 6.9 (a)) shows raw data received at station one (T1), this sound wave is transmitted by the other station (T2). The control system has fast response when raw data arrives, amp of received signal rise to average level immediately. This shows the transceiver used in station one is of high sensitivity when receiving signal. Sine channel is worse than the sine channel for this station. The lower panel shows the raw data received with the station T2. The transceiver in station T2 has slow response to arriving signal, the amp of the signal increase to peak after short time receiving. Meanwhile, the latter part of received signal also has small distortion as shows in figure 6.9 (b). The received signal in station T2 shows that the sonar sensor used in this station need time to response to the arriving acoustic signal. The consistency of sonar sensors used in network sensing system is of great importance, which can assure same performance of each station.



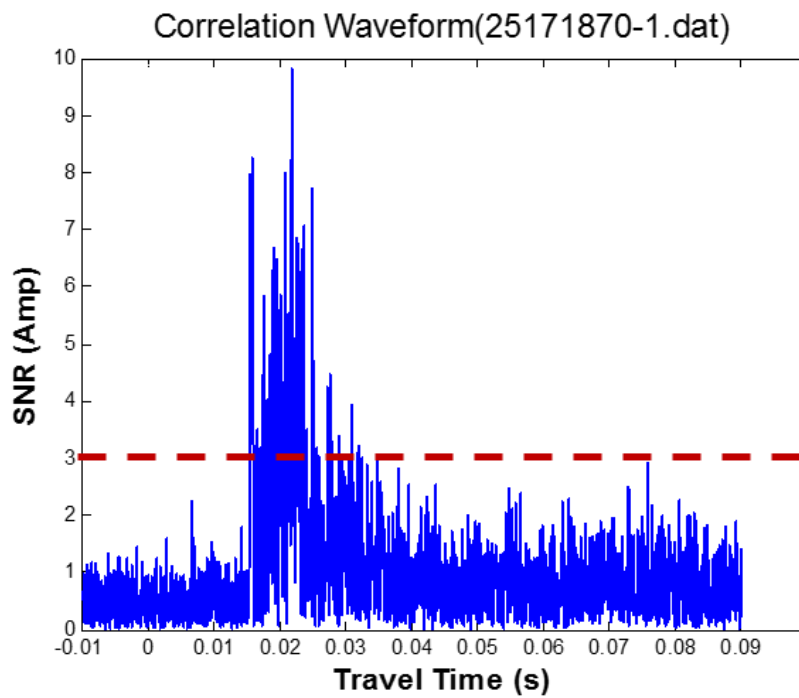
**Figure 6.9:** Raw data at two channel of station T1 (a) and T4 (b), no flow is generated when the arrival data is received. X and Y coordinate is time log and magnitude of received signal. Strong signal is received at two acoustic station and the data has small distortion after short distance propagation in the circular basin.

As shown in chapter 2 the M sequence modulated signal can be used for multi-station network sensing as it has no cross-correlation between different M sequence signals. The auto-correlation of this signal appears like a pulse, which can be identified easily in the sound transmission experiment. Meanwhile the M sequence has no correlation with ocean ambient, it has high ability of noise suppressing. The received raw data is correlated with transmitted signal for arrival signal identifying in this study. The underwater acoustic tomography system starts to record 0.01s before sound transmission by the other station and the recording ends 0.09s after the sound transmission. The length of each signal receiving is 0.1s in total, direct propagation of sound wave takes less than 0.016s. The recording length is set to 0.1s to assure all acoustic signals can be obtained. The processed result shows that the first signal comes at about 0.016s and efficient arrivals come after the first arrival. As shown in figure 6.10, plenty of peaks appear at the time range 0.015-0.03s. The average SNR of ambient is 2 dB in this experiment, the threshold is set to 3 dB for this analysis. The correlation result of raw data received at two sound stations both has low ambient and the SNR of received sound waves is much higher than ambient noise. The travel time of multiple arrival sound wave can be identified easily in this way. The correlation result shows that the M sequence modulated sound wave has good performance for short distance transmission in the experimental basin. Meanwhile this data also shows the flow basin, FloWave facility, can offer ideal testing bed for sound transmission. High SNR boundary reflected signals demonstrate the bottom concrete floor and wave maker paddles have strong reflection of high frequency sound wave.

The correlation results are zoomed in to explore first few arrival peaks, which correspond to the direct arrival signal and boundary reflected ones. As shown in figure 6.11 the SNR of first arrival signal is 7-8 dB for each sound station. The surface and bottom reflected sound waves reach receiving station followed the direct arrival. The SNR for each ray path is different due to boundary reflection and water attenuation in the circular basin. Multi-path propagation signals can be identified with ray tracing programming. Mirror reflection theory can also be used in this experiment as the surface and bottom floor are both treated as a plane. The transmitted sound waves are reflected with boundary (water surface, bottom floor and wave maker paddles) in the circular basin. Only the first arrival (direct propagation sound wave) signal is used in this study for flow detail reconstruction in the horizontal plane. Surface and bottom reflections follow the first arrival signal and all of these signals have high SNR. The arrival signals following the first peak can be used for vertical layered analysis as analysed in chapter 5.

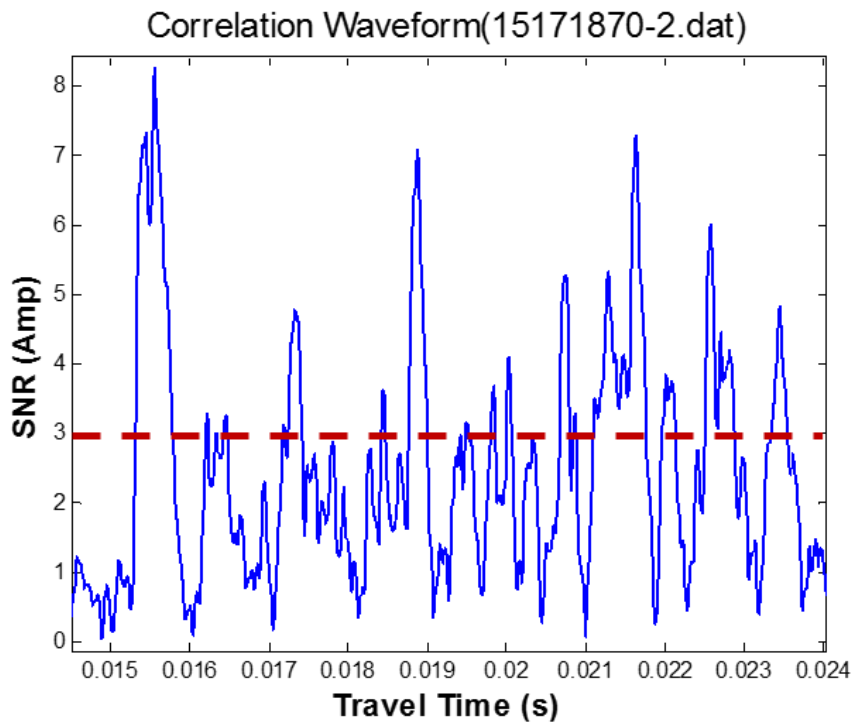


(a)

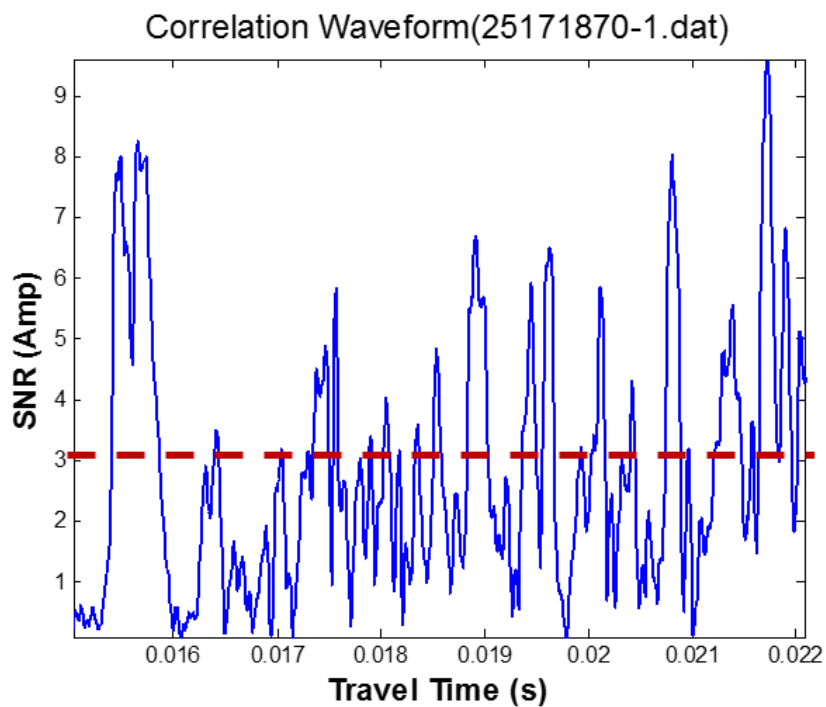


(b)

**Figure 6.10:** correlation of received data and transmitted M sequence signal at station T1 (a) and T4 (b). The noise level is about 2 dB. Plenty of peaks are picked out when the threshold is set to 3 dB.



(a)



(b)

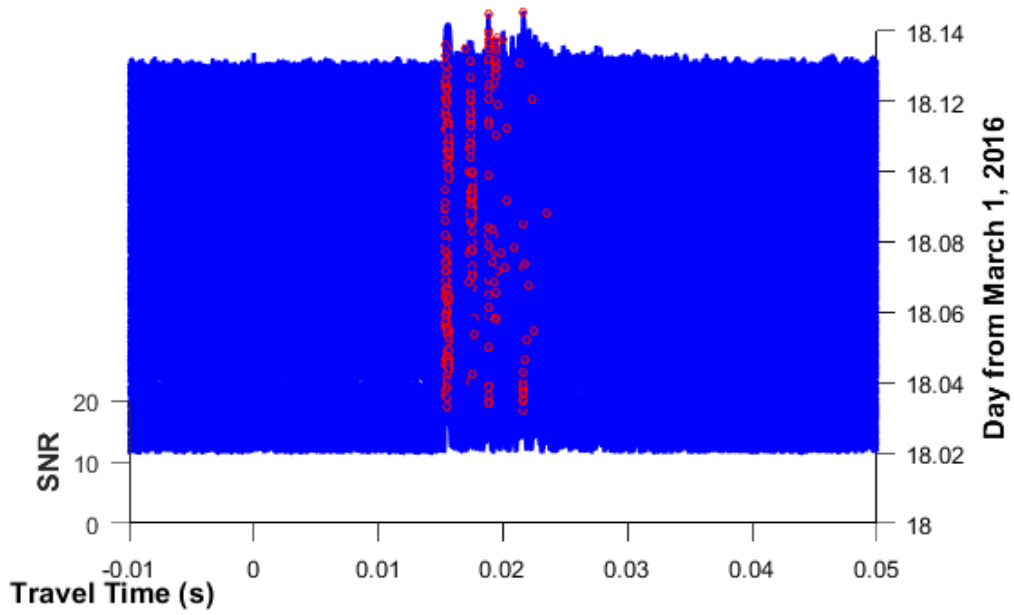
**Figure 6. 11:** Zoom in of correlation data received at two acoustic stations. First arrival signal is between 0.015s and 0.016s. Strong water surface and bottom floor reflected sound waves can be identified.



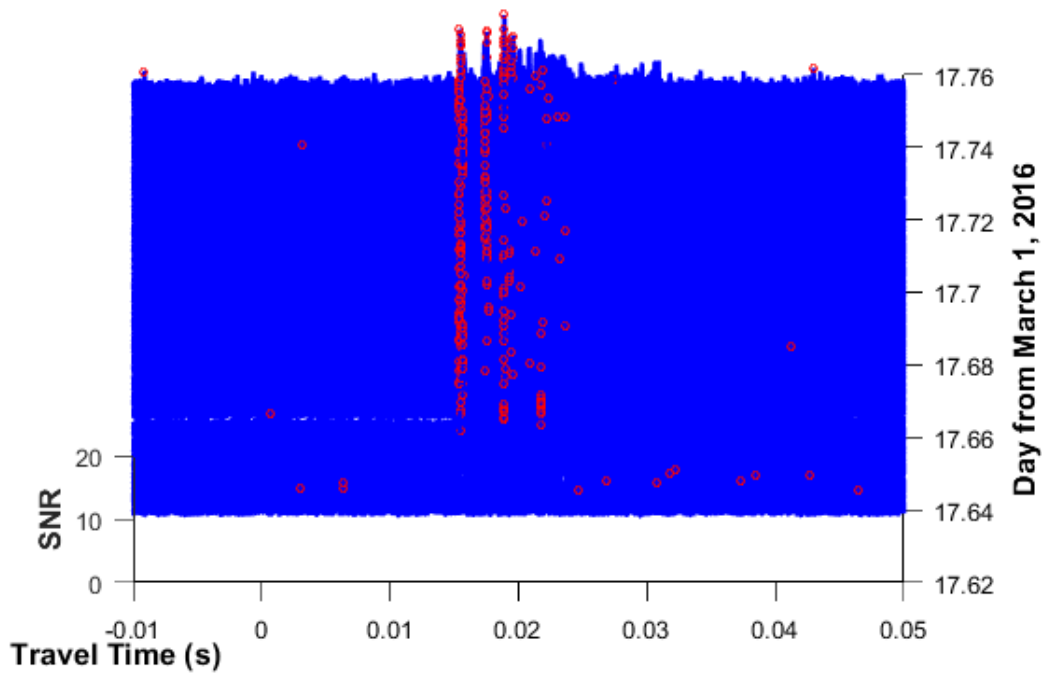
## 6.4 Signal processing

A pair of acoustic tomography stations are installed in the circular basin for sound transmission, these sound stations are named as S1 (T1) and S2 (T4). Flow direction is changed to seven directions to construct a 7-station sensing network with only two set acoustic tomography systems. Steady testing is conducted firstly with no flow current is generated in the basin. The signals acquired with steady test is used for system calibration. This method cannot be used in open water survey as complicate flow always exist and still water condition is impossible in ocean and flowing river. The flow current is changed continually after the steady testing to assimilate sound transmission along other ray paths in the sensing network. The travel time of sound waves along each transmission path can be identified using ray tracing programming. The sensing network is complete when all transmission is conducted along the sound transmission paths. Only the first arrival signal is used for flow detail reconstruction in a horizontal plane. The latter arrival signals can also be analysed for more detailed mapping of current velocity in the circular experimental basin. It is out of the range of this study and can be discussed in future research.

The underwater acoustic tomography acquires arriving signal during steady testing and all other sound transmissions with flow current of different direction. The correlated data are stacked together (figure 6.12) to get flow information in the basin. The highest peak is picked out for each transmission marked with red circle (figure 6.12). As shows in figure 6.10, the transmitted sound waves reach receiving station at about 0.015s and it last about 0.02s. The received data shows here focus on efficiency acoustic signals. All transmission data is shown at a time range from 0.01s before sound transmission to 0.05s after its transmission by the other station. It assures enough sound waves to be received with receivers as sound waves can be reflected by boundaries. First few receiving data is conducted without sound transmission, the highest peaks distribute in all time zone. These data are not considered in this study. Most of the highest peaks are at the range of 0.015-0.025s, gathering together to four groups. The first group of peaks are mainly contains direct arrival signal, surface or bottom reflected sound wave. The travel time of these peaks are mainly used in the underwater acoustic tomography research for this study. The latter three groups of peaks correspond to more complicated boundary reflected sound waves. Though not used in this study these peaks can also be identified with ray tracing for flow detail mapping in the experimental basin. The flow velocity can be mapped in detail when more sound transmission information is added in the acoustic tomography research.

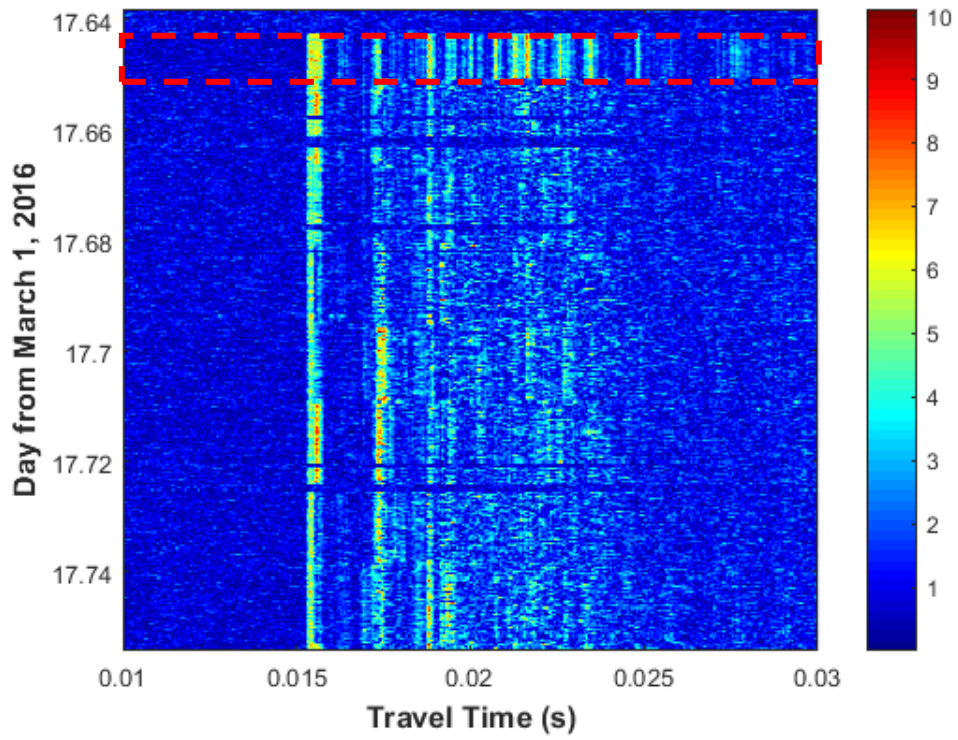


(a)

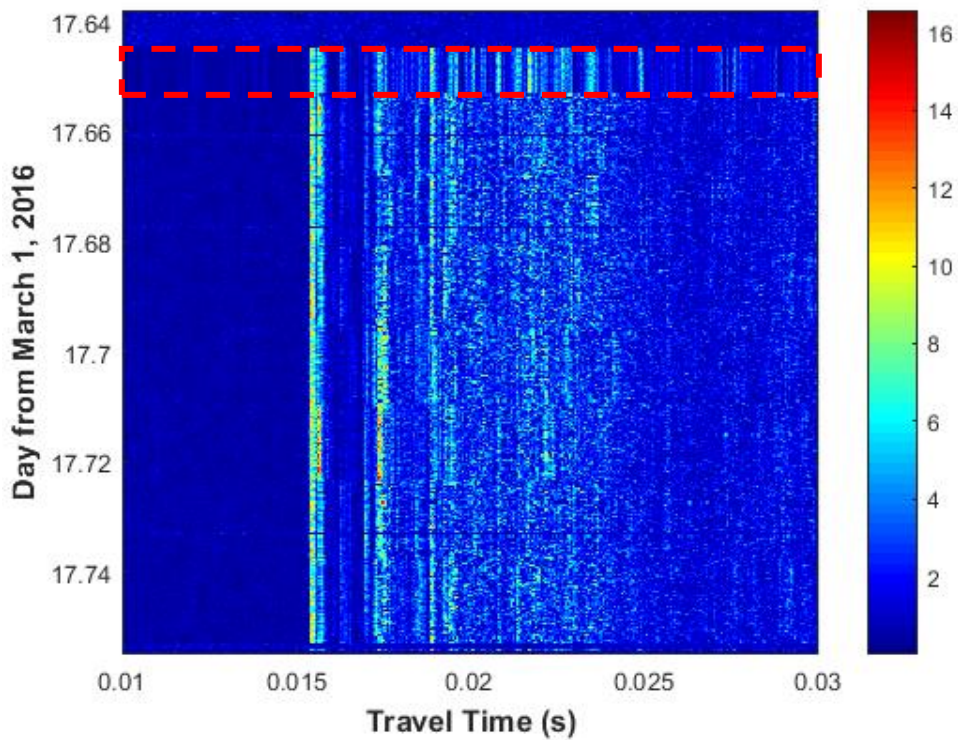


(b)

**Figure 6.12:** Correlation result of the received data at station S1 (a) and S2 (b) during the whole experiment.



(a)

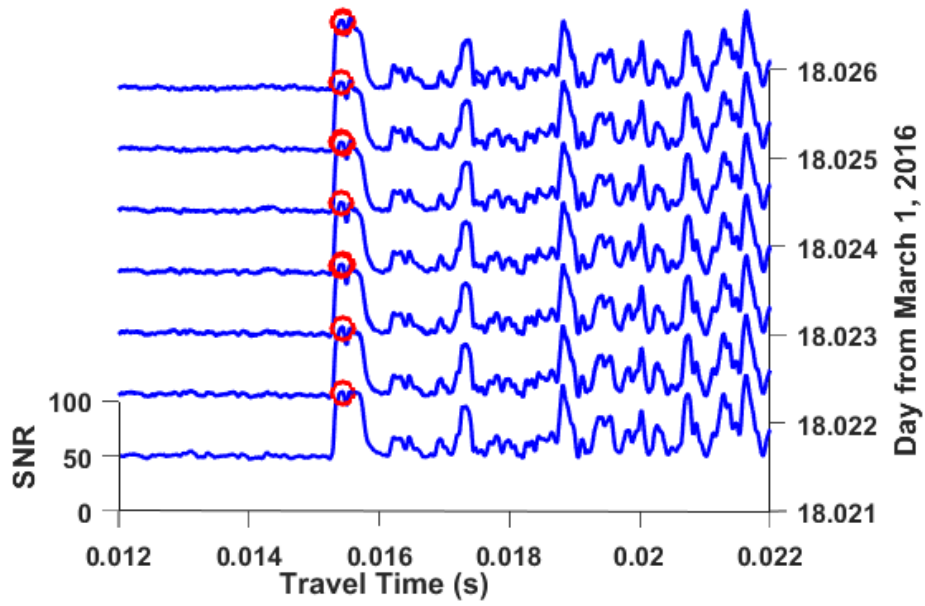


(b)

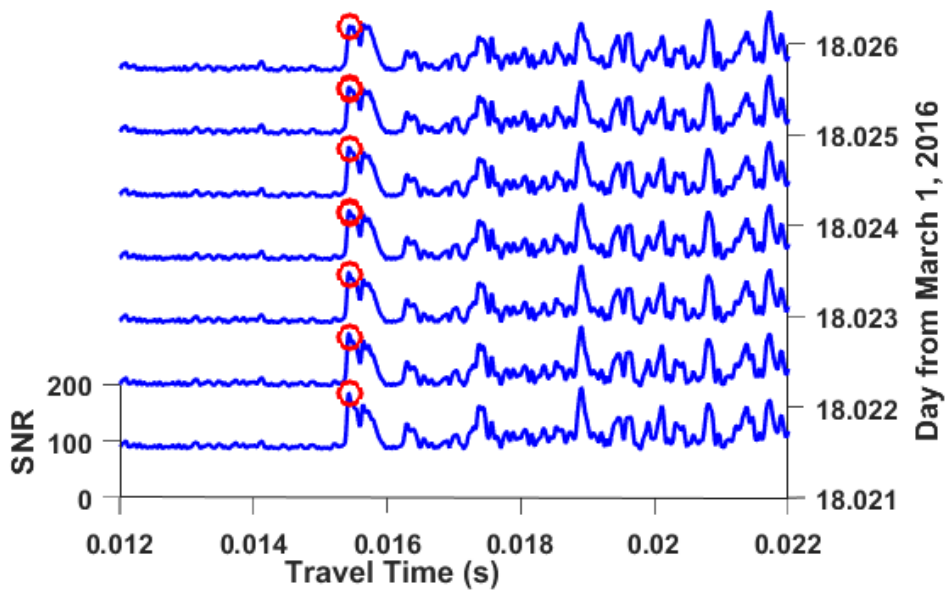
**Figure 6.13:** The signal strength mapping of all received data at station S1 (a) and S2 (b). Plenty groups of peaks appear after 0.015s.

All of the sound transmissions along ray paths are conducted continually, with different flow directions. To better explore the travel time of different sound waves the correlated data is plotted in figure 6.13. As the received data is correlated with transmitted M sequence modulated acoustic signal high pulse peak will appear when sound wave is received. The travel time of multi-path propagated sound wave can be determined with this method. The SNR of received data is clearly shown in this figure, it also shows the transmitting and receiving performance of sonar sensors used in underwater acoustic tomography system. Sound waves received at station S2 has higher SNR than that of station S1, it shows that the transmit sensitivity of the sonar sensor used in S1 is higher. Meanwhile, the SNR of ambient noise of two stations are both below 2dB. The M sequence used in this sound transmission experiment has good performance of noise suppressing. The received data in the red dash box is received when steady testing is conducted. High SNR signal is received for the steady testing for both stations, which shows the ambient noise level is lower compared with flow testing. Multi-path propagated sound waves are receiving with higher SNR and can be clearly identified. Meanwhile, the received data shows above the red box in figure 6.13 are received data without sound transmission. It is the ambient noise of the circular basin, without any flow current in the tank. Ambient noise level is much higher when sound transmission is conducted with flow current in the basin. The uniform flow is pushed with 28 turbines installed underneath the testing floor, which will also bring ambient noise to the received data. The SNR level of ambient noise is much lower than received sound waves, which makes sound propagation path identifying possible for this sound transmission experiment in the circular basin.

Generally, application of the 50-kHz CAT system to the 25m scale circular tank is hopeless to attain the sufficient accuracy of velocity measurement. In collaboration with Hiroshima University, the multi-repeat transmission program and the ring-buffer summation program for received data are newly constructed to increase largely the signal-to-noise ratio (SNR) of received data. The summation of 10-repeat signals is taken every transmission, using the CPU memory inside the system and the 10-repeat received data are compressed in the one-period (repeat) size of M sequence. Without the proposed data processing, application of acoustic tomography system to the 25m circular tank is unrealistic. The received data was correlated with the M-sequence, used in the transmission. Arrival peaks appear for the direct and wall-reflected signals. To filter out the high frequency variation and increase the signal-to-noise ratio (SNR), 10 data moving average was applied. The moving-averaged signal has higher SNR (peak), which makes peak searching possible.

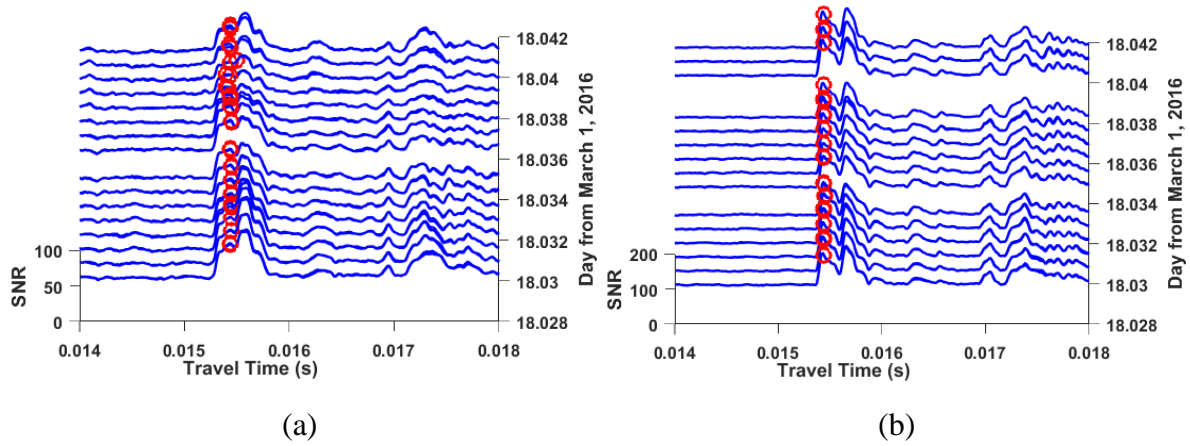


(a)

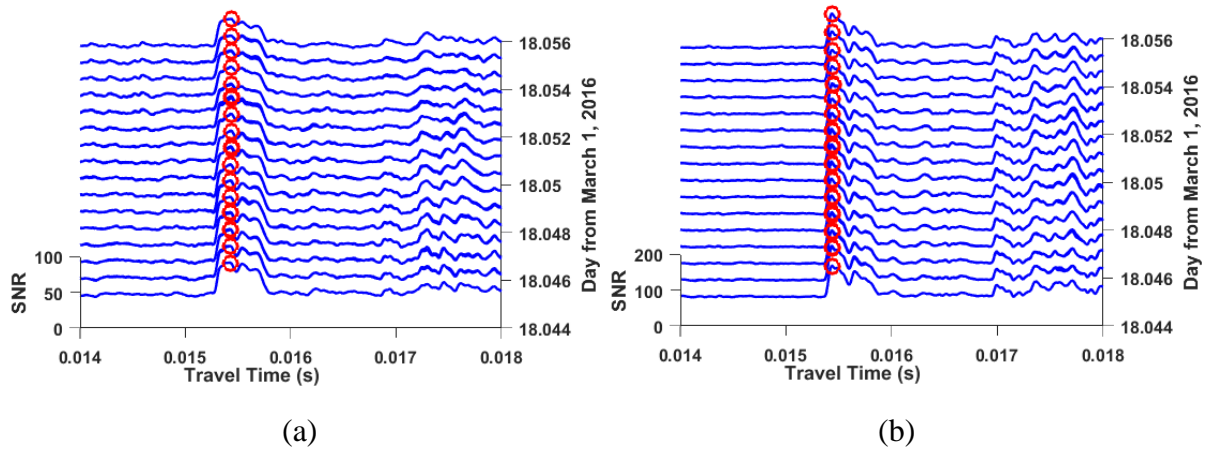


(b)

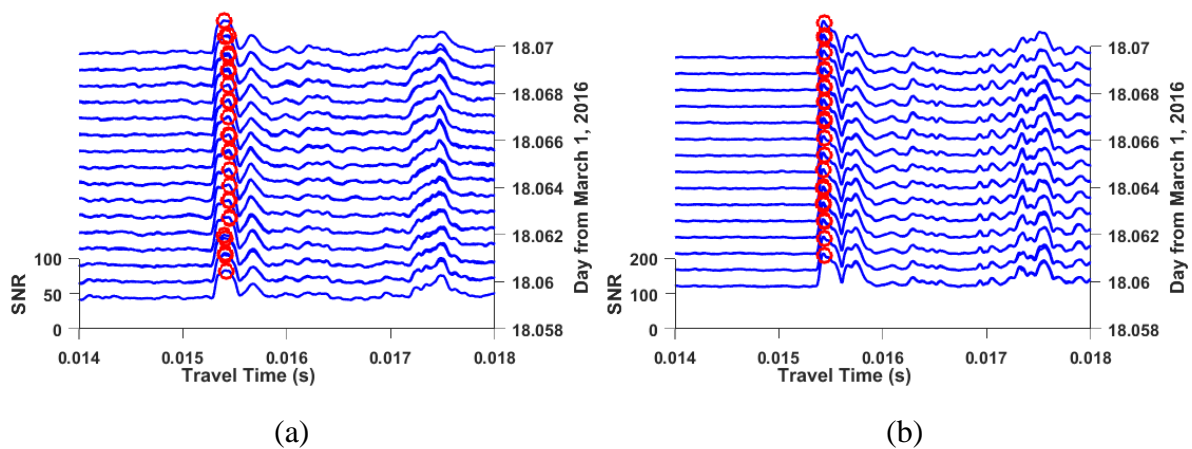
**Figure 6.14:** Stack of the received data at station S1 (a) and S2 (b) with no current in the basin. This is a steady testing; the direct arrival signal corresponds to first peak marked with red circle.



**Figure 6.15:** Stack of correlation result received at station T1 (a) and T4 (b) for path T1-T4.

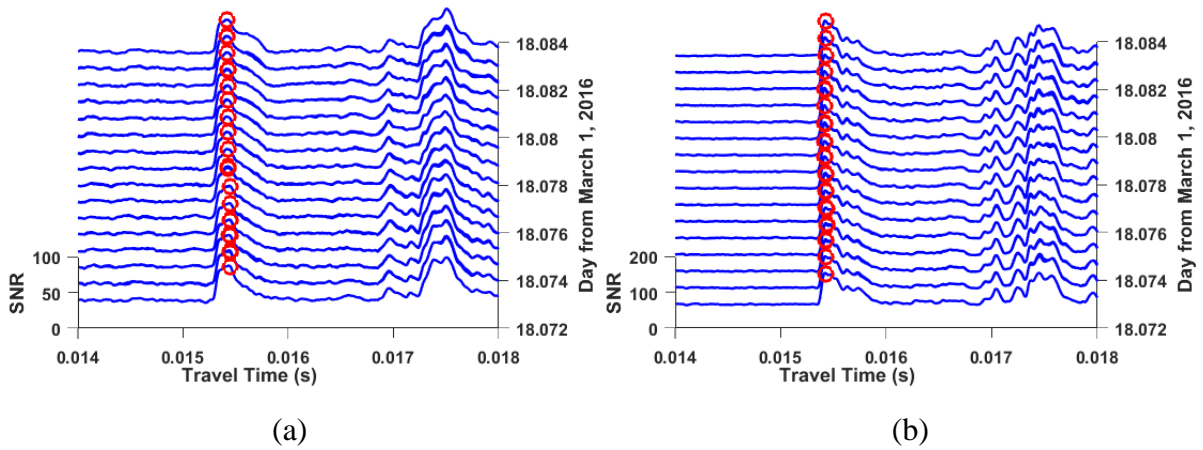


**Figure 6.16:** Stack of correlation result received at station T2 (a) and T5 (b) for path T2-T5.

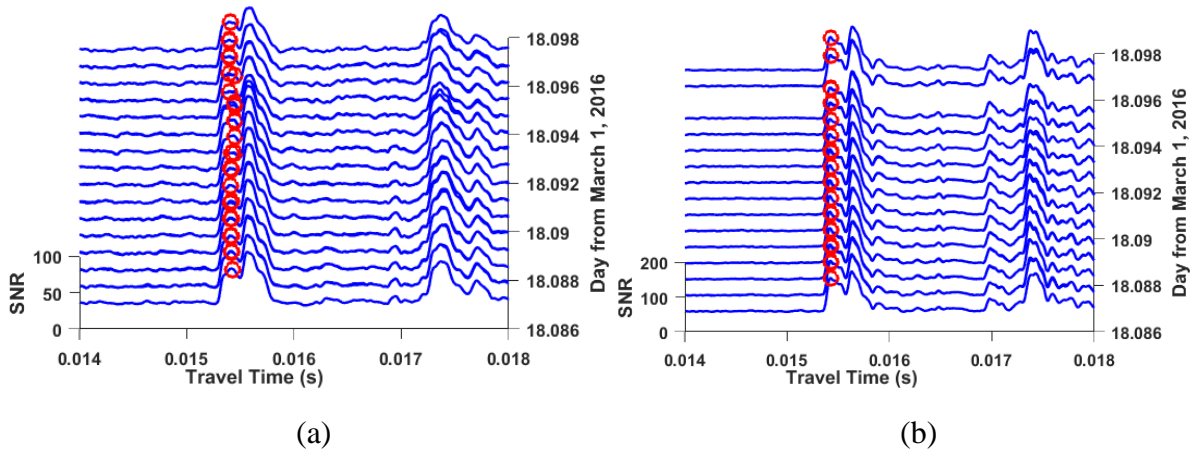


**Figure 6.17:** Stack of correlation result received at station T3 (a) and T6 (b) for path T3-T6.

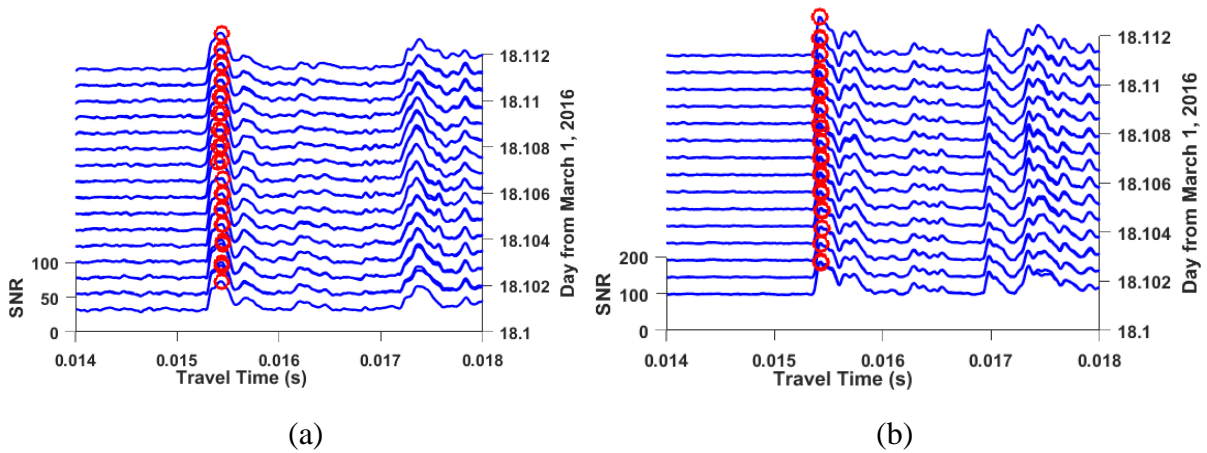




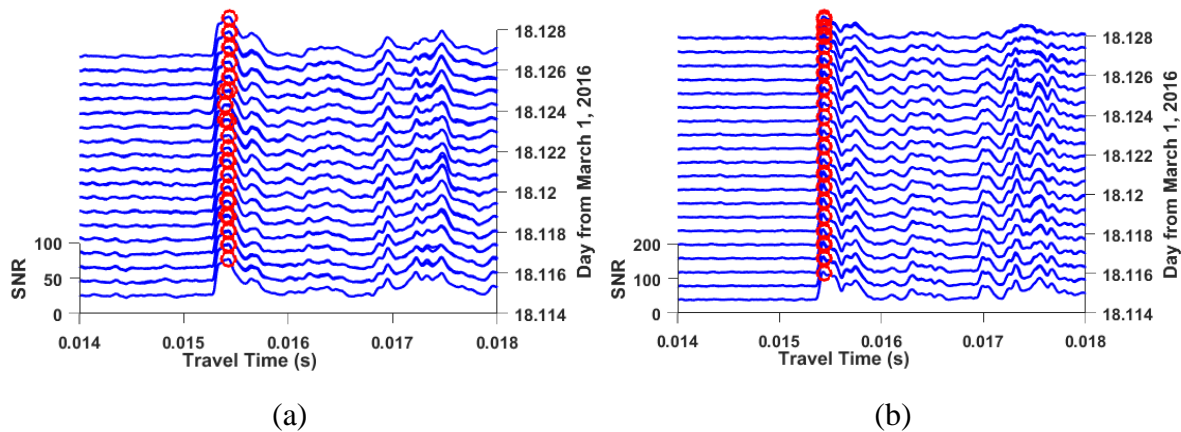
**Figure 6.18:** Stack of correlation result received at station T4 (a) and T7 (b) for path T4-T7.



**Figure 6.19:** Stack of correlation result received at station T5 (a) and T1 (b) for path T5-T1.



**Figure 6.20:** Stack of correlation result received at station T6 (a) and T2 (b) for path T6-T2.



**Figure 6.21:** Stack of correlation result received at station T7 (a) and T3 (b) for path T7-T3.

The steady testing (no current is generated) is conducted in the circular tank for system calibration. The Figure 6.14 shows correlated result of received data with transmitted M sequence modulated signal. Multi-path propagations can be identified in this figure for two stations. First arrival signal (first peak) is identified with red circles for reciprocal sound transmission. The SNR of signal received at station S2 is higher than that of station S1, which shows the receiving sensitivity at S2 is a little better. The travel time of direct arrival sound wave is consistent in still water as no current is generated.

This flow velocity testing experiment is conducted in the circular basin with a uniform flow current. As presented in former section, the flow direction is changed to generate a multi-station network with only two acoustic stations. The flow details is assume same for each direction's steady flow. Plenty of transmissions are conducted for each direction in the steady flow with same flow velocity. The correlation result of received data at two stations along each sound transmission path is shown in figure 6.15 to figure 6.21. Sound transmission is conducted in the circular basin with seven different directions. Travel time of sound waves in the circular basin is affected with flow current, which is used in the flow velocity reconstruction. Meanwhile, multi-path sound propagation is affected by flow current with different direction. As the steady testing in the circular basin the received data for sound transmission along other ray path is different for two stations. The highest SNR for first arrival signal at station S2 is about 200 dB, which of station S1 is below 100dB. Only the travel time of sound waves propagated in the basin is used in this research for flow velocity profiling. The travel time of first arrival for all the received data at two stations is used as input in the inverse problem-solving progress.

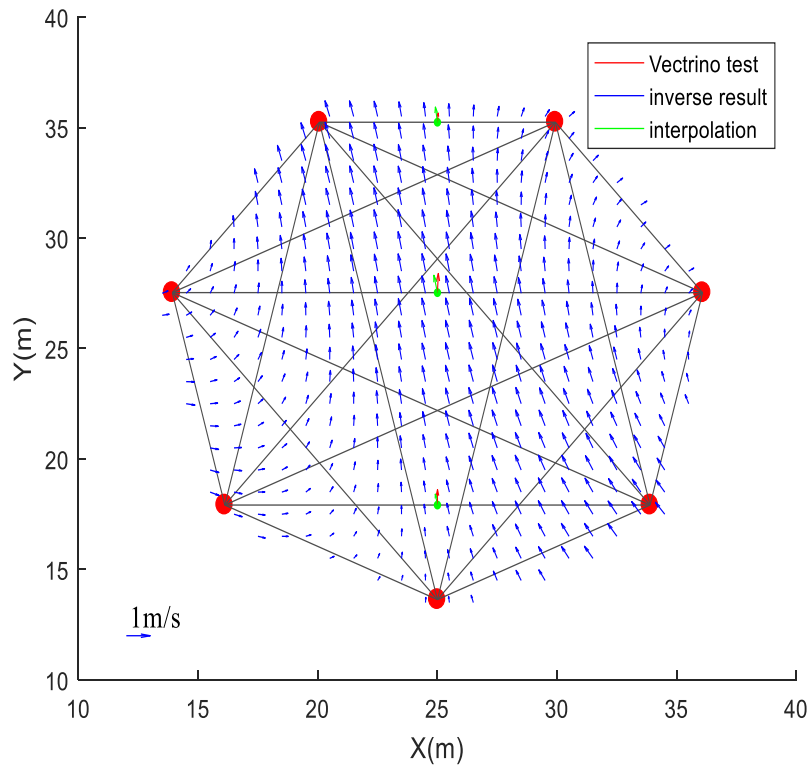


All of the acoustic signal received with two set of underwater acoustic tomography systems demonstrates that steady sound transmission can be conducted in the circular basin. This flow experimental tank offers a good testing bed for sound transmission, it can be used for sound channel analysing with sonar arrays. The received acoustic signals are of high SNR, they can be used in the flow velocity reconstruction work. The effect of flow current on the travel time of acoustic signal is relatively small compared to the transmission length difference of the multi-path propagating sound waves. At the same time the arrival peaks for all sound transmissions are steady, with almost same travel time. The sound strength of each transmission is similar when flow direction is fixed. The SNR varies when the flow direction changes even for the same sound propagation ray path. It shows the flow current has effect on the SNR of the received data. More detailed analysed of the received signal need to be completed to get the precise travel time of the sound waves propagated along different ray paths.

## **6.5 Flow velocity mapping**

As shows in former section a uniform flow was generated in the basin by the combined control of inflow velocity of different vanes. Uniform flow was pushed in the circular tank with a velocity of 0.8m/s. Flow direction is changed during testing to construct multi-station sensing network using only two underwater acoustic tomography stations. A flow detail testing experiment with underwater acoustic tomography method was conducted in the circular tank to monitor the flow conditions. The circumference of the tank is divided into 7 segments equally. By changing the flow directions in turns the equidistant 7 station network is formed with only two underwater acoustic tomography systems. The travel time of the acoustic signal along 7 lines are obtained as the flow direction changes, it is used as input information in the inverse problem.

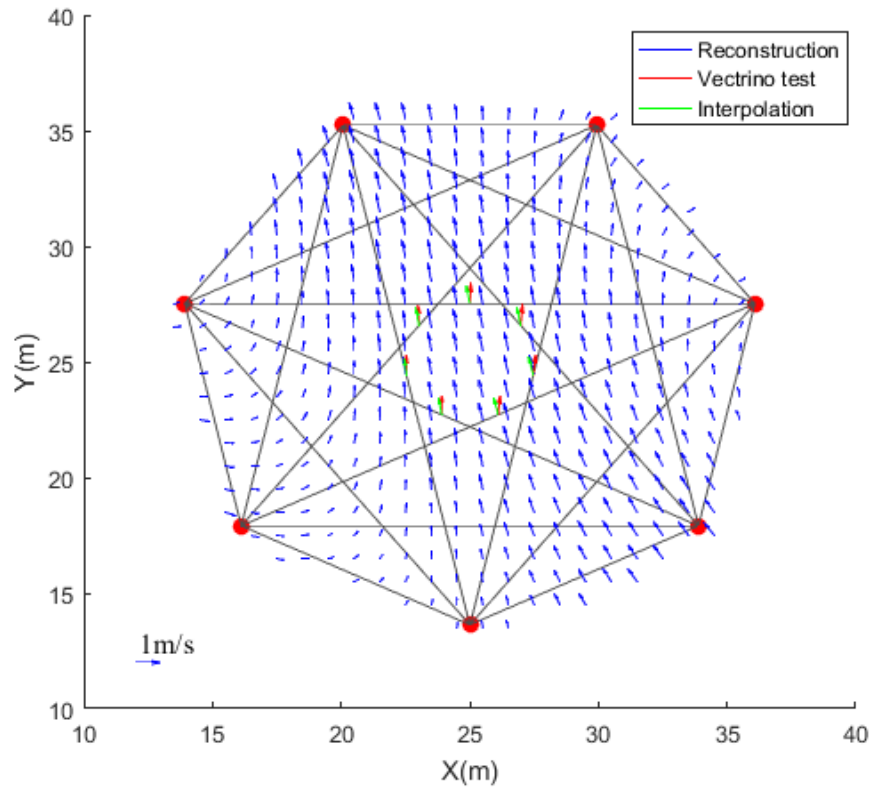
Uniform flow condition is tested in this research, the flow condition in testing area is in some extend like a linear flow. To simply the central point is moved to (25, 25) in this coordinate system as the diameter of this circular basin is 25m. Grid width is set to 1m in this research, flow velocity at each grid is calculated by stream function. The number of all grids used in this research is 676, only the grids that located in the basin are taken into consideration as this tank is of circular shape. Second order of truncated Fourier series is used to calculate flow velocity in the experiment area. Flow velocity in the horizontal plane is reconstructed in the circular basin as only first arrival sound wave (no surface or bottom reflection) is used in the inverse problem-solving progress.



**Figure 6.22:** Reconstructed result of the flow current in the circular tank by acoustic tomography. Fixed point measurement of the flow current velocity was taken along the central line. The reconstructed velocity at the discrete point was interpolated from neighbour points.

By solving the inverse problem with least squares method, the 2D flow on a horizontal slice is mapped in figure 6.22. Sound stations are presented as red circles, black solid lines show sound transmission paths in the network. The round way travel time of the sound wave was used to reconstruct flow current details in the tank. From the flow detail result shown in figure 6.22 we can see the nominal flow current was reconstructed with the acoustic tomography method. Uniform flow condition is assured in the central testing area, which is the main target of this research.

This study also conducts fixed-point measurement of flow velocity with ADV in the central testing area. During the experiment fixed point direct measurement was taken in the middle of lines T4-T5, T3-T6 and T2-T7 with Vectrino (ADV). The current velocity measured by Vectrino (red vector) consistent with the acoustic tomography reconstructed result (green vector). This study shows that the acoustic tomography method could be used for small scale flow detail reconstruction particularly in the experimental tank. The inverted flow at middle of T2-T7, T3-T6 and T4-T5 was in good agreement with the ADV measurement data. The root mean square deviation at X axis is 0.1538, it is 0.199 along Y axis. It means this measurement has small error compared with the discrete measurement using ADV.



**Figure 6.23:** Experimental design for the multi-station acoustic tomography network. Two CAT stations were deployed at T1 and T4. The flow direction changes at.

As central testing area of this circular basin is of great importance to this flow testing facility the flow profile in this area is analysed in detail. Vectrino is installed in the middle of two sound stations during flow detail testing experiment as shows in figure 6.8. Flow velocity is also measured with Vectrino in those discrete positions, it is plotted in figure 6.23 with red arrows. The reconstructed flow details in the circular is interpolated in the discrete measurement positions, they are represented with green arrows. The root mean square deviation between Vectrino measurement and interpolated result along X axis is 0.25, it is 0.367 along Y axis. This figure shows that flow details in the basin is reconstructed with underwater acoustic tomography technique with sound transmission. The error of this reconstructed result can be decreased by installing more stations in the tank. The resolution of result in the inverse problem-solving progress is determined with number of stations used in the network.

The flow-field mapping results shows that the FloWave facility is an ideal test facility for offshore renewable energy platforms which can generate a steady uniform flow. The underwater acoustic tomography systems can enable quick mapping of flow progress in

comparison with the fixed- point measurement. The mapping of flow fields is performed every minute when the 7 underwater acoustic tomography stations are installed at the periphery of the tank for further research. The acoustic tomography is an innovative method for mapping flow fields that grow rapidly in the experimental tank. This experiment used two underwater acoustic tomography stations, composed of the system controller and the acoustic transceiver, to simulate a 7-station network by changing flow directions rather than the underwater acoustic tomography stations. As stated in chapter 2, the circular basin could generate flow in all directions and change the flow direction quickly. Changing flow is a time saving method with comparison of moving station as only 7min is needed to change the flow direction. The frequency of sound waves is of great importance in underwater acoustic tomography research. Sound frequency used in this system is 50 kHz, which can be improved to a higher level (200-500k Hz) to get finer reconstructed result of the flow details.

## **6.6 Conclusion and discussion**

This chapter explore flow details in the circular basin using acoustic tomography method. As discussed in chapter 2 the state-of-art wave/current experiment basin was designed for offshore renewable energy system model testing. To monitor flow condition in the basin a steady uniform flow field that generated in the circular experimental basin was studied with acoustic method in this study. Underwater acoustic tomography technique was at the first time applied for small scale flow velocity reconstruction in a horizontal plane within the experimental tank. The sophisticated design of this all-direction flow tank makes multi-station networking possible with only 2 sets of underwater acoustic tomography systems for the horizontal flow detail mapping. Multi-station sensing network is constructed in the circular basin using two sets of underwater acoustic tomography systems. Besides, fixed-point measurement was carried out in the central test area of the basin. The flow velocity is measured with ADV monitored fixed point flow condition continuously. Time resolution is determined by sound frequency, high frequency acoustic signal is transmitted in the basin and received by the other stations after short distance propagation. 20 period of signal is transmitted together and added up in the receiving side for higher SNR. GPS repeater is used to strengthen GPS signal during the flow experiment. Like sound transmission in chapter 5 multi-path propagation sound wave characteristic is also observed in the experiment using 50 kHz acoustic signal, which shows strong reflection of water surface and bottom floor. Only first arrival signal (direct propagate sound wave) is used in this study for flow details profiling in a horizontal plane. Other than moving stations in the circular basin by changing the flow current direction, a 7-station network

was constructed with two underwater acoustic tomography stations in the experiment. This experiment scheme is achieved due to repeatable is generated in the circular flow basin flowing with different direction. The 2D horizontal flow details was reconstructed by acoustic tomography method using travel time of sound waves reciprocal transmission. Reconstructed flow velocity is compared with the Vectrino measurement of flow velocity in the basin. The result was consistent with fixed point direct measurement with Vectrino, which shows acoustic tomography technique is a powerful method for flow detail monitoring in the whole tank.

Flow details in the circular test basin is well analysed with sound wave transmission in this chapter. The FloWave facility can generate variety of actual ocean conditions for device development in ocean engineering. More detailed comparison of the results from these methods can be attempted. Considering the time resolution, more attention should be paid on higher frequency sound wave transmission for the flow condition monitoring in the experimental tank or other small-scale cases. By combining the horizontal and vertical slice inversions, three-dimensional flow fields in the tank can be mapped by underwater acoustic tomography. Further effort is required for the velocity mapping of flow fields with acoustic tomography in the tank. This research also shows the large circular tank, FloWave is an ideal testing basin for offshore renewable energy facilities, which can generate repeatable steady flow. It can also be used for wave and flow current interaction analyse in the ocean flow dynamic research. Beside the flow velocity reconstruction in the circular basin, this method can also be used in other experimental tank and basin. Multi-station sensing network is constructed using only two acoustic stations in this research by changing flow direction in the circular basin. This research can be conducted is based on the particular design of the flow basin. More acoustic tomography stations can be used in the small-scale flow detail monitoring, especially for real time presenting of flow progress.

## Chapter 7

# Summary and discussion

In the past few years acoustic tomography research mainly focuses on field work in the open water area [147]. Acoustic tomography research is developed to small scale flow detail profiling in the experimental tank here. This research, for the first time, explores flow details in experimental tank using underwater acoustic tomography system. This research using acoustic tomography method for small scale flow detail profiling, especially for flow velocity sensing. The experiments are mainly conducted in a circular experimental basin. The three-dimensional model of the circular tank, FloWave facility is constructed, uniform flow is simulated in the basin. To monitor flow progress in the tank when, network sensing is conducted with acoustic tomography systems. Meanwhile, a new underwater acoustic tomography system is developed based on the coastal acoustic tomography system with corporation with Hiroshima University.

To get the performance of coastal acoustic tomography system, a field work is conducted in open water. Meanwhile, the acoustic tomography method can also develop to flow details mapping in a region by combining horizontal mapping and vertical layer analyse of flow velocity. Tide detail in the Bali strait is also reconstructed with coastal acoustic tomography system. The multi-station sensing network is used to reconstruct the flow velocity mapping in the strait with acoustic tomography method.

The coastal acoustic tomography system is modified for high frequency sound wave transmission in short distance. New broadband sonar sensor is choosing in this new system, which is suitable to high frequency sound wave transmitting and receiving. Horizontal flow velocity in the circular experimental tank is reconstructed with underwater acoustic tomography method using only two acoustic stations. The multi-station network is acquired with two acoustic tomography station by changing flow direction in the circular basin. The underwater acoustic tomography experiment conducted in this research shows that flow detail can be mapped with sound transmission method. This study also demonstrates that acoustic tomography is a powerful tool for the continuously mapping of flow progress in the experimental tank.

## 7.1 Summary and conclusion

The circular basin and underwater acoustic tomography are introduced in chapter 2. Flow velocity in open waters and experimental tank can be obtained with discrete measurement and network sensing. ADV, ADCP and PIV are all normal kind of discrete measurement. Compared with discrete measurement of water parameter, acoustic tomography can take more detailed mapping continuously.

A model of the FloWave facility is built and the flow condition is simulated. The circular experimental basin, FloWave facility is also introduced. It is designed to simulate various kinds of ocean conditions in laboratory. The three-dimensional model of this basin is constructed and uniform flow in the basin is simulated. This simulation shows the potential to generate complicate flow conditions of this experimental basin. A flume is simulated in this research to explore the performance of sub-vane, which is used in the FloWave facility. The vanes has different inlet angle to restrict input flow direction. Meanwhile, the outlet also has vanes to led water flow in particular direction. The circular basin works like a combination of some flume. By combined controlling of the inlet velocity complicate flow condition can be generated in the basin for ocean device testing.

The tomography technique is widely used in medical imaging and engineering progress monitoring. Sound waves is used as media in tomography technique for resource surveying earthquake monitoring and weather forecasting. The acoustic tomography method is also proposed in sea water parameter sensing, which is a result of global climate's changing. Acoustic tomography research in coastal area is developed by researchers in Hiroshima University. It is developed to strait, lake and river for flow detail profiling and water temperature mapping. Meanwhile, coastal acoustic tomography is also used to reconstruct sound speed distribution in certain area. Small scale underwater acoustic tomography is firstly developed here in an experimental tank. The underwater acoustic tomography technique is introduced in this chapter. Moreover, the new underwater acoustic tomography system that developed based on coastal acoustic tomography is presented here. This system is suitable to short distance sound transmission, which can be used in small scale acoustic tomography research. The sound frequency is modified to a much higher range for better time resolution. New broadband high frequency sonar sensor is choosing for this underwater acoustic

tomography. The test in FloWave facility of acoustic tomography shows that the circular basin has strong reflection of sound wave and it can be used for sound transmission.

Sound wave propagation theory is introduced in the chapter 3. Sound propagation in water is in large extent affected by sound speed profile (SSP). The sound speed in water is mainly determined by water temperature, salinity and water depth. The ray tracing programming is also introduced in this chapter. The propagation path of sound waves can be tracked with ray tracing programming based on the sound transmission theory in water. The reciprocal travel time of acoustic signal is different when it transmits along and opposite the flow current. Steady flow velocity can be measured by the acoustic signal travel time difference when the distance is fixed. The horizontal flow details can be reconstructed with acoustic tomography method by constructing sensing network. The flow velocity is obtained by solving the inverse problems in the target area. The truncated Fourier series is used in this study for the flow velocity reconstruction. The vertical layered flow current velocity can be reconstructed if the multi-path propagation signals that transmitted along the vertical slice between two stations are picked out. The horizontal flow details however could be mapped with multiple station networking in the interested area by acoustic tomography method. The three-dimensional mapping of flow details can be achieved with combining the horizontal acoustic tomography research and vertical layered analysing of flow velocity. This method is used in the following chapters, where the flow details is reconstructed with acoustic tomography systems.

Acoustic tomography research method is developed for water parameter sensing. It is applied in the field survey for flow detail sensing in the chapter 4. The tidal flow progress is reconstructed in the Bali strait with coastal acoustic tomography method. Indonesia is a country that laying in the middle of India Ocean and Pacific Ocean. It is an important channel for water and heat exchanging, which is a result of global climate changing. Air temperature variation of two zones causes water level difference, which leads to salinity and heat exchange in waters around Indonesia. The tide in Bali strait is quite strong as the inlet and outlet are both like a loud speaker mouth. To explore tide progress in the Bali strait four coastal acoustic tomography stations are installed at two sides of shore. Another 3 virtual station is introduced in this research, the boundary condition along shore is restricted with this method. Multi-path propagation sound waves are received at all four stations. The flow details in the Bali strait is reconstructed in a horizontal plane with acoustic tomography method by solving inverse problems. The tidal flow details are reconstructed with acoustic tomography in the Bali strait,



which also shows its potential of small-scale flow detail mapping in experimental tank and basin.

Sound receiving hydrophone array can be used in the field work to assure multi-path arrival signal to be acquired. It a good method for flow progress remote sensing with acoustic tomography in open waters. Meanwhile, GPS position system is used in this study like ocean acoustic tomography research. This method can also be used in moving station acoustic tomography, where some acoustic tomography station is installed on moving vehicles (UUV, USV and boat). The moving station acoustic tomography is particularly making sense when limited station can be used. The position of moving station can be acquired with GPS positioning system when it constructing network with fixed station. This research explores tide progress in the Bali strait, where complicate flow style is generated due to its shape. It shows the acoustic tomography can be used in coastal area for flow detail monitoring. Ocean renewable research is developing quickly around coastal area. The acoustic tomography technique can be used in ocean flow resource searching and monitor flow progress in the interested area. Further research can be also be focused on offshore renewable energy farm monitoring. The interaction of ocean turbine and flowing sea water can be monitored continuously with help of telecommunication.

A small scale underwater acoustic tomography experiment is presented in the chapter 5. The acoustic tomography technique is developed to a much smaller scale in a circular experimental flow detail charactering in a vertical slice. Two underwater acoustic tomography are installed in the circular basin for sound waves transmission. This experiment is the first test to conduct short distance sound transmission in the experimental basin. High frequency M sequence modulated sound waves are used in the experiment for high SNR. The sound transmission experiment that conducted in the circular basin demonstrates the sound propagation is steady. Multi-path propagation sound waves are received with the underwater acoustic tomography system, which demonstrate strong reflection of sound waves by bottom floor and surface. The water surface and bottom floor are treated as a plane, which can reflect sound wave as mirror. The mirror reflection theory and ray tracing programming can be used for sound path identifying. The ray tracing programming, TRACEO, is used here to identify the sound propagation path for each sound ray.

Uniform flow is generated during the experiment with a same direction with the sound propagation path. The multi-path propagation sound waves are used in the inverse problem

solving. Layer averaged flow velocity is reconstructed along a sound transmission line in the circular basin. A Vectrino is used to measure the velocity distribution in the testing area with the same flow condition as this acoustic tomography experiment. The reconstructed flow velocity along sound transmission path consistent with the ADV measurements. This experiment shows that high frequency sound transmission can be conducted in the circular experimental basin. Steady sound channel exists in the flow basin, it can be used as sound transmission bed. Multi-path sound transmission assures enough sound information to be used in the acoustic tomography research. 2D horizontal acoustic tomography can use wall reflection for more information in the inverse problem.

Underwater acoustic tomography method is used in a 2D horizontal plane in chapter 6. Flow velocity is reconstructed in the circular experimental basin with underwater acoustic tomography method. Two acoustic stations are used to construct a 7-station sensing network by changing the flow inlet direction, which is based on the ideal design of this circular tank. As shows in chapter 2 the flow basin can generate steady from all combined directions by controlling the speed of turbines that installed underneath testing floor. Uniform flow with a velocity of  $0.8\text{ms}^{-1}$  is pushed from 7 different direction in this study. Besides flow detail mapping with sound waves, discrete point measurement of flow velocity in the basin is also conducted with a Vectrino. The Vectrino is installed in the middle of each sound transmission line. The flow velocity in the experimental basin is reconstructed by solving inverse problems using travel time difference of each sound reciprocal transmission. The inverse result has good agreement with the ADV measurement. This research demonstrates that the small scale underwater acoustic tomography can be used in testing tank or other experimental conditions for flow progress monitoring.

As discussed in former section this project is the first trail to use underwater acoustic tomography method for flow detail profiling in the experiment tank. The small-scale acoustic tomography research is developed based on the technique applied in open waters (ocean, strait, lake and river). The biggest difference is the sound frequency of small-scale acoustic tomography is much higher. New underwater acoustic tomography is specially developed in this project for sound transmission in short distance. A pair of high frequency transceivers (up to 125 kHz) is used in this underwater acoustic tomography system for sound wave transmission and signal receiving. The frequency of sound wave used in this study is 50 kHz. Only two set of underwater acoustic tomography system and high frequency broadband sonar sensors are developed in this study due to the restrict of fund. The multi-station network sensing

system is achieved successfully by using the circular experimental basin cleverly. Further effort can be focus on constructing more underwater acoustic tomography system and acquire real time presenting of flow details in experimental tank. Meanwhile, higher frequency sonar sensor can be used in short distance sound waves transmission for higher time resolution, which is a key factor affecting inverse result. The flow type used in this research is uniform flow, which is normal and relatively simple in real ocean condition. More complicated flow condition can also be tested with this method to better monitor flow details in the experimental tank. This underwater acoustic tomography system can be used in flow progress monitoring when ocean structure is being tested in the testing bed in further research.

## **7.2 Contributions**

This study explores the use of underwater acoustic tomography method for flow details mapping in the experimental tank FloWave TT. By overcoming some technique challenges and difficulties, this research is completed with efforts. The major contributions to knowledge are as follows:

1. For the first time, acoustic tomography techniques have been used in an experimental tank to map the current.

Model testing in the experimental tank is a critical progress for the ocean engineering system designing. To get flow details in the tank fixed point direct measurement equipment is always used, which is relativity slow and difficult to avoid disturbing the original interest field. By using tomography, one could get internal details of interest area with the non-contact method. The acoustic tomography technique is developed for water parameter variation monitoring in the deep sea, coastal area, inland lake and river [20,25-26,114,116,157-164]. The small scale underwater acoustic tomography method is for the first time used for flow current mapping in the experimental basin. It offers an efficiency choice for the real-time flow progress monitoring.

2. High frequency acoustic tomography research for small scale flow detail profiling.

High frequency sound waves are absorbed more rapidly than low frequency signals in the water. A low frequency acoustic signal, therefore, travels longer distance with smaller attenuation. In the mid-scale ocean acoustic tomography research, oceanographers use low frequency acoustic signal for long distance propagation. The use of low frequency sound wave also restricts the time resolution, which is a key factor

for acoustic tomography research. High frequency underwater acoustic tomography is used for flow detail reconstruction in this research. Steady signals and multi-path arrivals are identified with high time resolution.

### 3. Improvement of acoustic tomography system

The acoustic tomography system is mainly composed with central control system and transceiver (sonar sensor). The control system and the sonar sensor are combined together and deployed in the water for the self-contained system. These two parts are separated for land based coastal acoustic tomography and river acoustic tomography research. To conduct high frequency acoustic tomography experiment in the tank, the system is adapted to fulfil the requirement of small-scale research. Ring buffer is used for raw data storing and the filter is also modified. High frequency broadband sonar sensor is used for high frequency acoustic signal transmitting and receiving. This underwater acoustic tomography system could also be used in the short distance sound propagation research.

### 4. Multi-station acoustic tomography simulation experiment using 2 stations.

The FloWave facility is a specially designed circular basin that generates steadily flowing current in any relative directions. 28 impellers are installed along circumference underneath the testing floor. It could simulate steady flow from different direction by combined control of pumps. 2 acoustic tomography stations are deployed in the basin for reciprocal sound transmission. It works as other pairs of stations round-way transmitting sound wave in the basin when changes the flow direction. In this way multi-station network is constructed. The flow details are reconstructed by acoustic tomography method in the experimental basin with network sensing. It demonstrates that small scale multi-station acoustic tomography network could be used in the experimental tank for real-time flow detail profiling, which is a research topic for the small scale underwater acoustic tomography.

### 5. Ray tracing in the experimental tank for acoustic signal peak tracking

In the oceanography research, low frequency sound wave is used for long range propagation and it could be detected by hydrophone. Unlike light propagating in the air, sound wave always travel along arc path as the sound speed changes in different depth. Ray tracing programming is used to study how sound wave propagate in the water. The expected attenuation, launch angle, arrival angle and travel time of signals could be

simulated with ray tracing. The underwater acoustic tomography research mainly uses travel time of sound wave for water parameter variation sensing. The ray tracing programming TRACO is used here for peak tracking in the circular basin. Steady signals are detected in the experimental tank. Different arrival peaks are identified according to the expected travel time. The ray tracing of signals propagating along different paths in the basin makes it possible for the flow velocity vertical layered analysis.

6. Use acoustic tomography method for flow details reconstruction in a 2D horizontal plane and vertical slice in shallow water.

After long range propagation multi-path arrival signal is detected with vertical hydrophone array in the deep sea. For the coastal acoustic tomography research, it's normally difficult to get steady multi-path arrival signal due to restriction of surface and bottom. The steady arrival peaks that transmit along different paths are identified by ray tracing in the experimental tank. Two single acoustic transceivers are used in this study for vertical layered analysis of flow current. By changing the flow direction, a multi-station acoustic tomography network is constructed, 2D horizontal detail of the flow current is mapped in the tank. The flow details in the whole circular basin is reconstructed with underwater acoustic tomography method by combining vertical layered analysis and horizontal mapping of flow current velocity. It's a big progress for the underwater acoustic tomography research, flow velocity measuring and experimental tank developing.

### **7.3 Future work**

This project not only develops a new underwater acoustic tomography system, this method is also applied in a new condition for flow detail sensing. The outcome and breakthroughs have been discussed in former chapters. By the restriction of time, there still has some work to do, such as more detailed flow testing, system design and signal analysis. To further develop the acoustic tomography in small scales and use it in the experimental tank testing, more work should be conducted. Considering the research in this thesis, further stages of work can be focused on following aspects:

1. New self-contained flow progress monitoring system

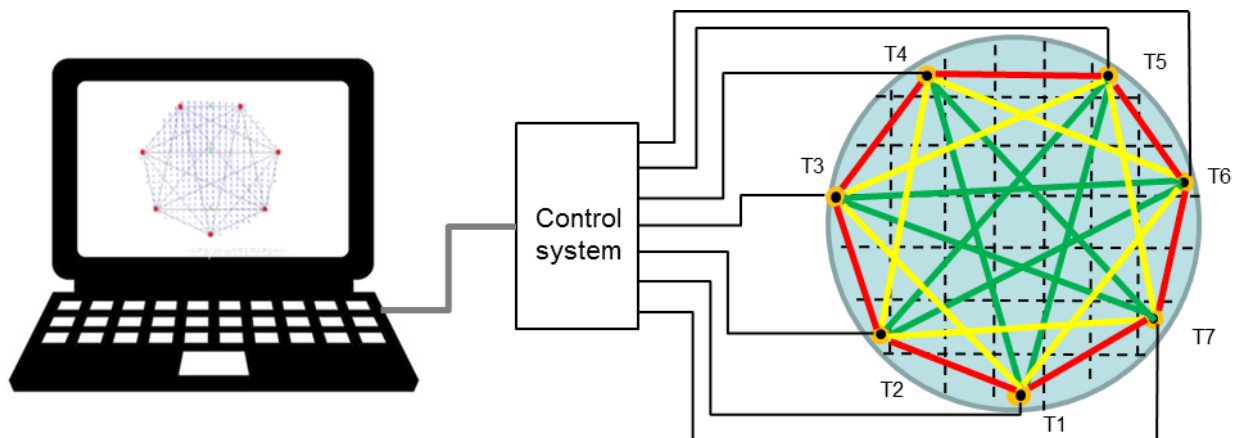
Ocean acoustic tomography method is firstly proposed for remote sensing of sea water temperature with certain number of sound stations. The large scale and long distance in the ocean determine discrete sound station is used and construct a network with telecommunication

technique. The position of sound station is acquired with GPS system and all sound stations are synchronised by GPS timing. In short distance transmission or laboratory testing integrated system can be used for real time showing of inverse result. Figure 8.1 shows a self-contained flow detail online monitoring system with underwater acoustic tomography that to be used in the FloWave facility. High frequency sonar sensors are installed in the experimental tank and construct a multi-station sensing network. The acoustic station is controlled by the central system for sound wave transmitting and receiving. All the sound stations can be synchronized easily with the control system. The acquired data is transported to computer for inverse problem solving, inversed flow detail can be presented continuously with screen. The online f system offers a new method for low progress monitoring in experimental tank and basin. This system can also be used in other experimental tank and small-scale flow testing condition, especially in Flume testing. New system can be developed for particular application in other small-scale acoustic tomography research.

In the ocean acoustic tomography, sound station will include a low frequency sound source and a hydrophone array. The sound source transmit low frequency sound waves with high strength and the hydrophone array can increase the SNR with array signal processing. By install vertical sensor array the weak signal that propagate along a long distance can be picked out with beamforming. For slow variation progress in ocean, this system can work well as after sound transmission the control system can change to receive model. The long-distance transmission allows enough time for the model changing. The sound sensor used in this research however is high frequency broadband transceiver, this means it can not only transmit sound waves and also can receive arrived signal. The transceiver can only transmit or receive sound wave at one time, it cannot acquire acoustic signal while transmitting. In the short distance sound wave transmission, travel time of acoustic signal is quite short. Meanwhile, fast varying flow progress need high speed acquiring of flow velocity mapping. Especially for ocean structure testing, small scale flow detail will change rapidly, which has high requirement of data acquiring speed. Therefore, sound source and hydrophone can be used together at one sound station. Sound source only transmit sound source continuously and received signal is acquired with hydrophone. The sound travel time of every transmission can be used in flow detail mapping with acoustic tomography method. Furthermore, vertical sonar array can be applied at each sound station to get more multipath propagation signal along different ray paths. The three-dimensional flow details in the experimental tank can be better mapped with adequate sound information.

Like discrete measurement spatial resolution of network sensing is determined by number of measurements, this means more information acquiring will lead to higher resolution result. The tide flow reconstruction experiment In the Bali strait uses four station and put in three virtual station. The virtual station brings restrict around the boundary condition along shore. Meanwhile, fast varying flow progress within small area require high spatial resolution in the small scale underwater acoustic tomography research. The number of acoustic stations will restrict the inverse result when it is used in the fast-changing flow condition. More acoustic station can be installed in the flow current profiling system to get more detailed inverse result of velocity mapping.

As shows, the attenuation of sound wave increases with frequency when transmit in a same distance. Low frequency sound source is used in ocean acoustic tomography research, where SNR should be assured to get enough sound information. The accuracy of inversed result is determined by time accuracy of transmitted acoustic signal. In short distance sound transmission experiment however high frequency sonar sensor can be used for higher time resolution. The sound wave frequency used in this research is 50 kHz, which is restricted by hardware system. Higher frequency (200 kHz-500 kHz) can be used in short distance (within 100m) sound transmission experiment, which is in the range of most experimental tank and basin. Meanwhile, the high frequency sonar sensor also requires some modification of the underwater acoustic tomography system. It mainly contains the transmit power transfer, filter and data acquiring speed.



**Figure 7.1:** Real-time flow progress monitor system. This system uses multi-station underwater acoustic tomography system for flow detail sensing. Control system can transmit and receive acoustic signal with sonar sensor. Inversed flow velocity is showed continuously with screen.

## 2. New function used for inverse problem solving

The truncated Fourier series is used for the stream function calculation, the flow velocity in interest area can be obtained if stream function is determined. More complicate function can be used in the flow velocity reconstruction, Chebyshev and Bessel function for example. Those function can be used in the velocity calculation when the boundary condition have strong effect on the flow condition. Some function is used in inverse problem for other type of tomography research. The radial basis function is used for the inverse problem solving in acoustic tomography research [165-168]. The air temperature is monitored with acoustic tomography systems using this method. The radial basis function can also be used in flow detail profiling in the underwater acoustic tomography research. This research focus on flow details in a horizontal plane with stream function, this method can also be used in the vertical slice. The flow details in a water column can be monitored by combining horizontal and vertical slice. More complicated stream function and function can be applied in the inverse problem for acoustic tomography research. Moreover, as those functions is suitable to flow detail charactering, they will have good performance when they are used in three-dimensional flow details reconstruction.

## 3. More detailed mapping of the flow current.

Flow details in the circular basin is explored with sound transmission method. To map the current velocity distribution in the flow basin underwater acoustic tomography technique is used in the experimental tank. A steady uniform is generated, the flow condition in the flow basin is controllable. The uniform flow can simulate tide current in open water, which is of great importance to offshore renewable energy research. The testing area of this circular basin is in the central area, where steady flow condition is assured around. The flow condition in the FloWave facility is quite complicate around the vertical wall as it has interaction with boundary. The sound transmission across central area brings much information about flow in the basin and can be used in the inverse problem-solving progress. This circular experimental basin can generate kinds of flow states in ocean. More complicate flow condition can be analysed using underwater acoustic tomography technique. This technique can be used in the experimental basin for flow condition monitoring.

This research focus on the flow conditions in the circular basin, FloWave facility. The exquisite design of this flow basin makes multi-station network possible with only two underwater acoustic tomography systems. This experiment scheme is designed base on the excellent

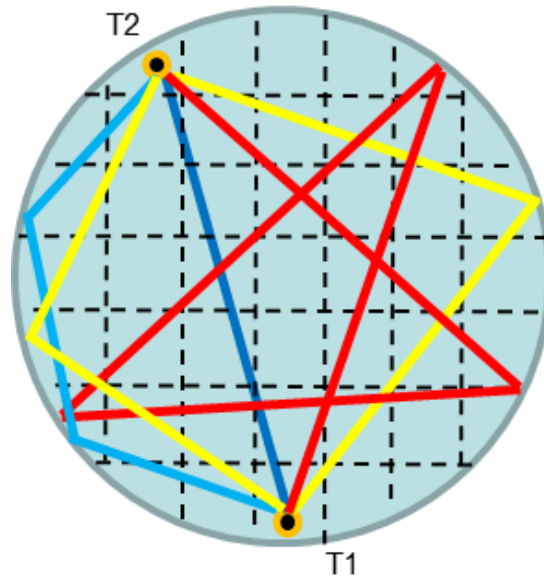


performance of the circular basin. Repeatable steady flow condition can be generated in all directions. Real multi-station network sensing of flow details can be achieved using more acoustic tomography stations in the testing tank. Meanwhile, there has many experimental tanks and basins that with other shape other than circular, rectangle tank and flume for example. This small scale underwater acoustic tomography technique introduced in this study can also be used in other experimental basins and tanks. The flow condition will have strong interaction around boundary of flow tanks, more acoustic stations will be needed to profile the complicate flow velocity.

#### 4. Ray tracing in the horizontal plane to get more information from arrival signals.

As shows in figure 8.2 two sound station are installed in the experimental tank. The FloWave has strong reflection of sound waves in the boundary, including vertical wall (paddles). When wall reflected sound, wave propagate in the circular basin its travel time is affected by flow current, which is the principle of acoustic tomography. In this way, the wall reflection sound wave can be used to inverse problem solving in the underwater acoustic tomography research. As discussed in former chapter, different arrival peaks can be identified with ray tracing programming. By ray tracing in the horizontal plane arrival signals propagate along different ray path can be identified and the travel time difference in the reciprocal sound transmission along this ray path can be used in the horizontal flow detail reconstruction [136].

Meanwhile, the wall reflected sound waves can also be used together with direct arrival acoustic signal in the multi-station sensing network. It works as more sound stations are installed in the sensing network. In this case, it will bring much more information in the acoustic tomography research for better inverse result of flow details. It can improve the spatial resolution of the network without adding extra acoustic stations. The resolution of inverse result will be largely improved in this method. Similarly, horizontal wall reflection signal can also be used in the acoustic tomography research in another experimental tank or basin. More complicated ray tracing should be conducted in rectangle to identify the multipath propagation sound waves.



**Figure 7.2:** Horizontal ray tracing in the circular experimental basin. Besides water surface and bottom floor reflection sound wave is also reflected by wall (paddles) of the circular basin. Multi-path propagation signal that reflected by wall of different contact number is plotted with different colour. The dark blue line indicates direct propagate sound wave. Flow detail in the horizontal plane can be reconstructed with only few acoustic tomography stations.

##### 5. Wave and flow current reconstruction

Wave is normally measured with remote sensing system; it can also be detected using acoustic tomography system. Meanwhile, the FloWave facility is designed to generate wave and flow current in all directions. Complicate type of flow current and surface wave can be generated simultaneously, which offers an ideal testing bed for flow current and wave interaction charactering. The wave and current interaction can be explored in the circular experimental flow basin with sound transmission. This underwater acoustic tomography system can be used in small scale flow wave and current profiling.

Coastal acoustic tomography technique can also be applied to characterise the flow detail around offshore renewable energy farms. Before installing offshore renewable energy devices in ocean the flow condition around interest area needs to be surveyed. The acoustic tomography system can be installed around interest zone to monitor flow details. Meanwhile, the working progress can also be sensed with sound transmission method. The moving station can be used in open water acoustic tomography survey to get more detailed mapping of water parameter distribution. For slow changing field the moving station network can be constructed with limited number of acoustic tomography systems. In recent years the moving station has been

used in ocean parameter charactering using moving vehicle [167-169]. This method can also be considered in coastal acoustic tomography research and small scale underwater acoustic tomography for flow detail profiling.

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