# 3d Acoustic Mapping of the Kuroshio (Taiwan Current) off the Southeast Coast of Taiwan

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## INTRODUCTION

The long-term monitoring of the western boundary current (WBC) is still a challenging issue in the operational oceanography. The surface current of the WBC can well be measured by a pair of advanced high frequency ocean radars, located at the shore washed out by the WBC. However the radar has little capability of measuring the subsurface structures of WBC. The Argo floats might not be suitable to monitor the WBC at a fixed point because deployed floats quickly run away from the observation site. The travel-time ocean acoustic tomography (OAT) from the axis of the underwater sound channel (USC) is an unique, cost-effective technology for measuring the temporal variations and 3D structures of WBC.

The OAT from the USC axis is here applied to the long-term measurement of the Kuroshio (Taiwan Current), flowing northward off the southeast coast of Taiwan. The Kuroshio takes a relatively stable stream path in this region after entering into the Pacific from the northern part of the Luzon Strait. The Kuroshio transport data obtained here provide critical information to understand the change of ocean climate and fisheries environment which occurs in the northern part of Taiwan and the east Asian countries (Japan, China and Korea) on the downstream side.

## DEPLOYMENT CRUISE

The R. V. Ocean Researcher No 3 of the National Sun Yat-sen University left the Kaohsiung Port for the sea off the southeast coast of Taiwan at 9:00 of April 27, 2011 (LT). Notice that the local time (LT) goes 8-hour ahead of UTC. Four 800Hz CATSs (coastal acoustic tomography systems) attached on the near-bottom mooring line were deployed at the stations T1, T2, T3 and T4 (Fig.1). The station-to-station distances range from 16 km for T1-T2 to 70 km for T1-T4. Notice that all the stations are located on both sides of the deep channel (trough) with the maximum depth of about 3000m, running in the north-to-south. This experiment may, thus, be called the deep-channel tomography. The deployment works were performed onboard the ship (Fig.2, Fig.3). The date, position and depth of deployment are presented in Table 1. After the finish of deployment work, the hourly CTD casts were done at T1 during 12:00 April 28 to 0:00 April 29. This position of repeat CTDs was accidentally determined by considering that strong current (2.5 knots with ship drift) occurred at T1 rather than T2. After that the 25-hour ship-mounted ADCP survey was done at a 8.3-hour interval along the T1→T4'(middle between T1 and T4)→T3'(middle of T3 and T4)→T2→T1 during 0:00 April 29 to 01:00 April 30. Finally she went back to the Kaohsiung Port at 15:30 of April 30.

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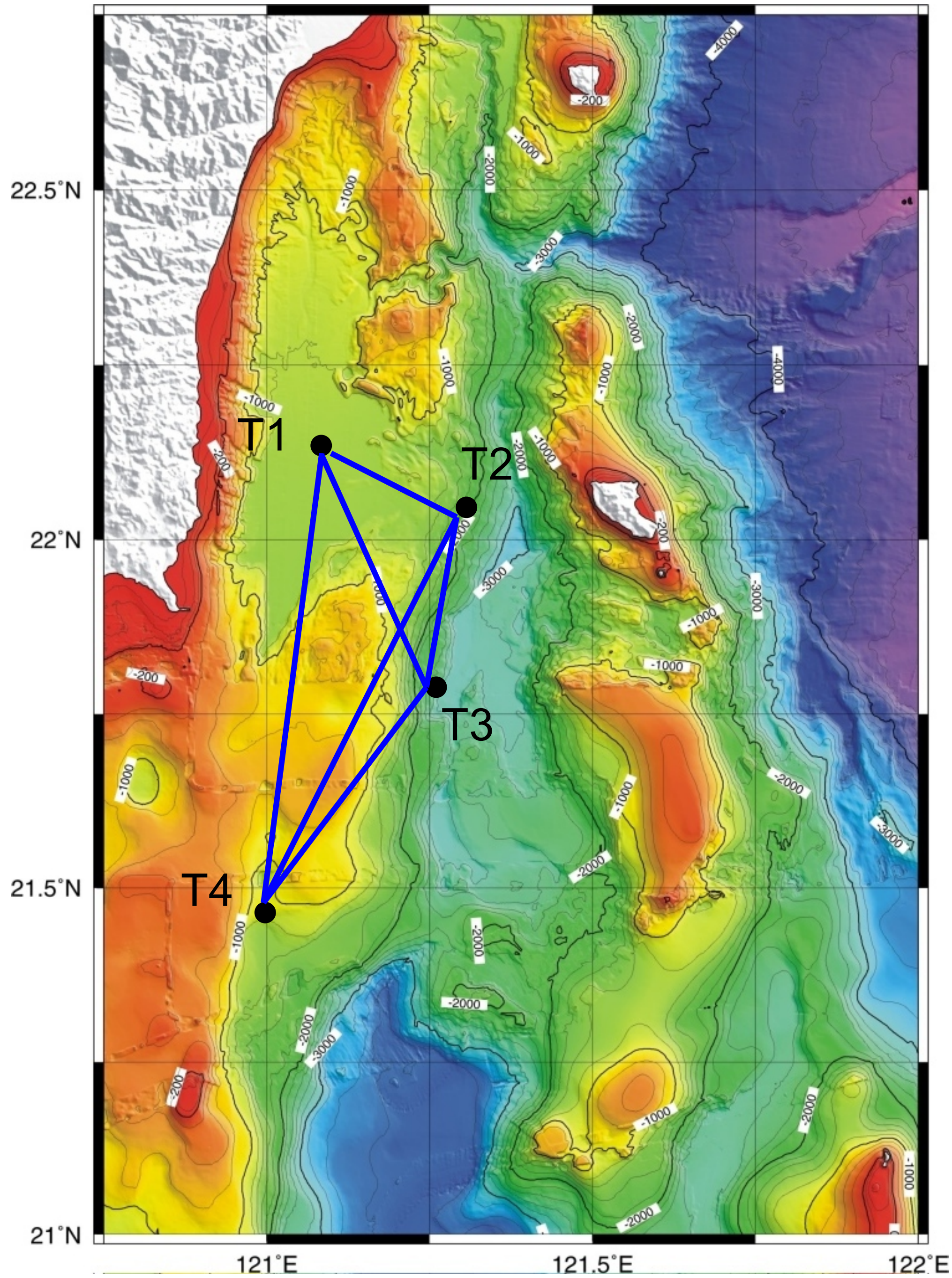



*Fig. 1  Location map of the mooring sites superimposed on the bathymetric chart.*


***Fig. 2 The R. V. Ocean Researcher No 3, anchored at Kaohsuing Port***

***Fig. 3 The EAI 800Hz transducer and the pressure housings for the system and battery packages.***

***Table 1 Deployment date, position and depth of the mooring lines***

| ST. NO | Date (local time) *8 hour ahead of UTC | Position | | Depth (m) |
|---|---|---|---|---|
| | | Latitude (N) | Longitude (E) | |
| T1 | 10:30 April 28, 2011 | 22° 10.420’ | 121° 15.040’ | 1050 |
| T2 | 06:42 April 28, 2011 | 22° 04.999’ | 121° 26.460’ | 1250 |
| T3 | 01:51 April 28, 2011 | 21° 48.581’ | 121° 26.158’ | 1250 |
| T4 | 20:32 April 27, 2011 | 21° 32.495’ | 121° 10.167’ | 1250 |

## MOORING DESIGN AND EXPERIMENTAL PARAMETERS

The mooring design is shown in Fig.4. The length of the mooring lines range from 230 m for T1, T2 and T4 to 330 m for T3. The coastal acoustic tomography system (CATS) is attached to the mooring line at 220m (T1, T2 and T4) and 320m (T3) from the bottom. The 800Hz transducer is put at 2m above the CATS. The current meter (CM) at T1 and T2 and acoustic Doppler current profiler (ADCP) at T3 are located at 5m below the top buoys. For T4, the mooring line is not equipped with CM. All the mooring lines are anchored with the 220kg weight. After the finish of experiment, all the mooring lines will be released toward the surface by operating the acoustic release (AR) from the ship.

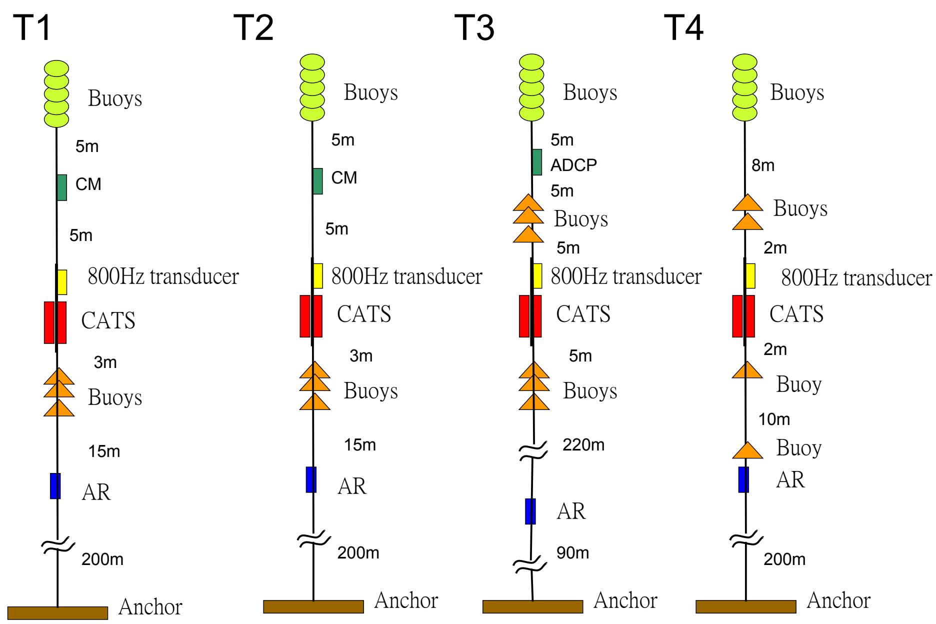



***Fig. 4 Design of the Mooring lines (T1, T2, T3 and T4)***

The 800 Hz sound phase-modulated by three cycles of the 9$^{th}$ order M sequence (19.16 s) is released ultimately from T1, T2, T3 and T4 in the strategy that the 20-min interval is taken for the first day of four-day duration and no transmission for the remaining three days. This four-day cycle is repeated until the end of experiment. This sampling strategy is taken to resolve not only the low-frequency Kuroshio variability, but also the high-frequency variations due to internal tides and waves. The 800 Hz transducer is of the narrow-band type with the frequency band of 25 Hz. Then the larger Q-value (10 cycles per digit) is required to transmit the broad-band sound from the narrow-band transducer. For f= 800 Hz and Q=10, the time resolution of M sequence for multi arrivals (cycle per digit) is 10/800= 12.5 ms.

The long-term accuracy of clock is maintained by the clock system in which the continuously operated quartz clock is supplemented by the Rubidium clock, waken up at a scheduled interval. The quartz clock accuracy of about 1ms/day is insufficient for the 4-month experiment in spite of the quite small power consumption of 5 mW. In contrast, the Rubidium clock cannot be operated continuously because of heavy power consumption (8 W) although it possesses enough accuracy (1ms/year in accuracy) even in one-year continuous operation. The sound transmission and reception are performed with the quartz clock during the entire period of experiment. The drift of the quartz clock is measured by comparing the one-hour oscillation number of quartz and Rubidium and the drift rates per second are memorized in the system. The correction of the drifted quartz clock will be done, using all the drift rates acquired after the finish of the experiment.

Another validation of quartz clock is provided by the GPS clock. Before the deployment of the system in the sea, the quartz clock is synchronized onboard the ship with the GPS clock. The total drift value of the quartz clock during the whole experimental period is measured with GPS onboard the ship immediately after the recovery of the system from the sea.

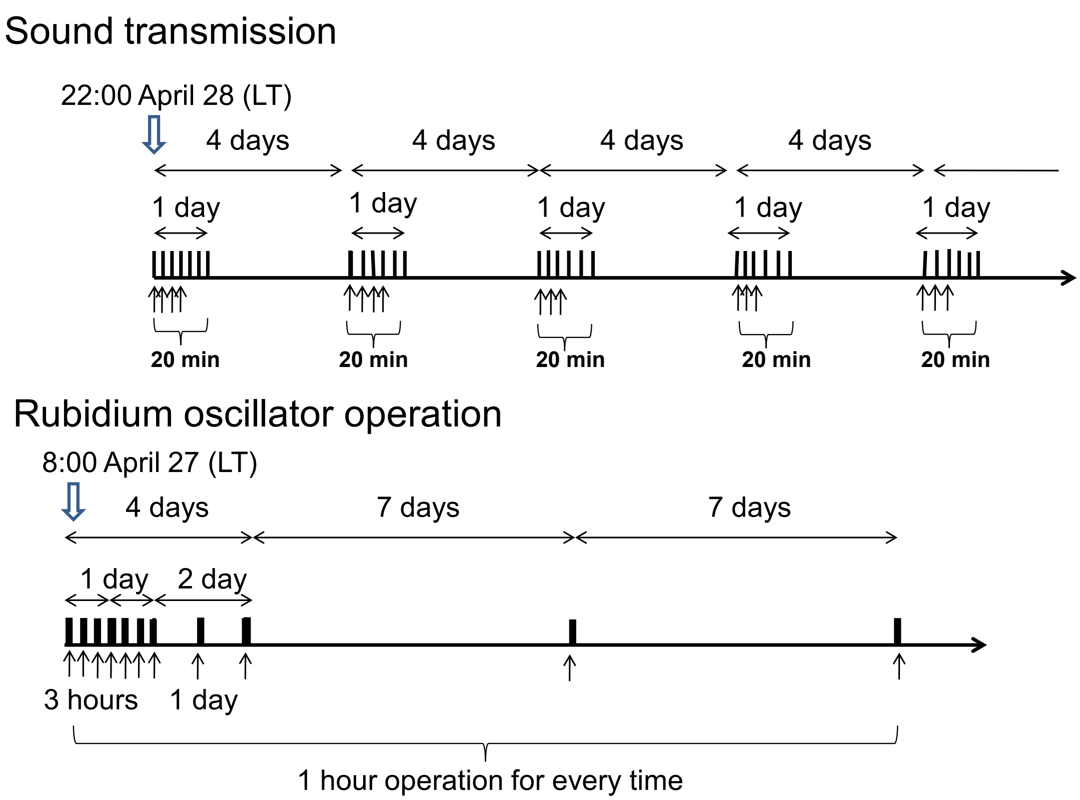
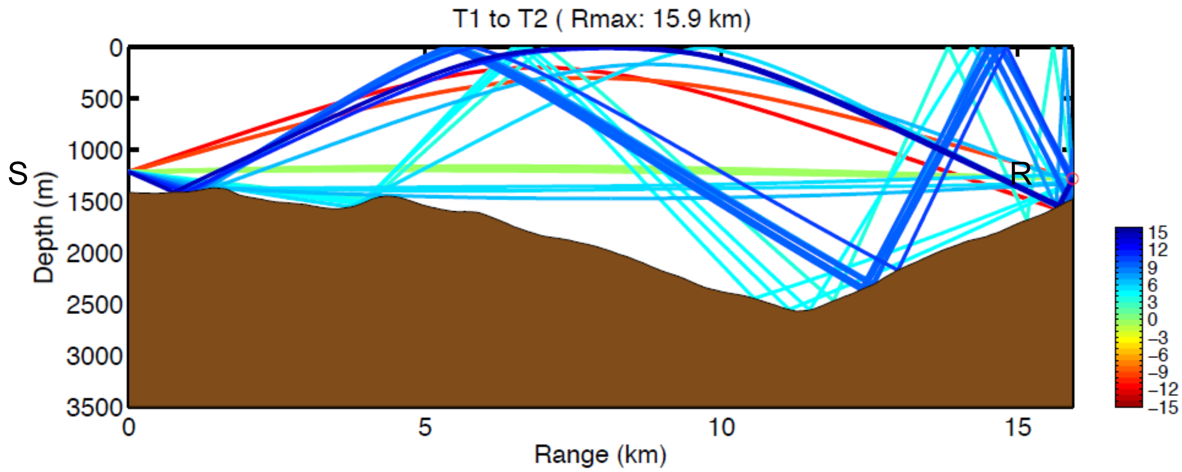



*Fig. 5 Strategy for sound transmission and Rubidium oscillator operation*

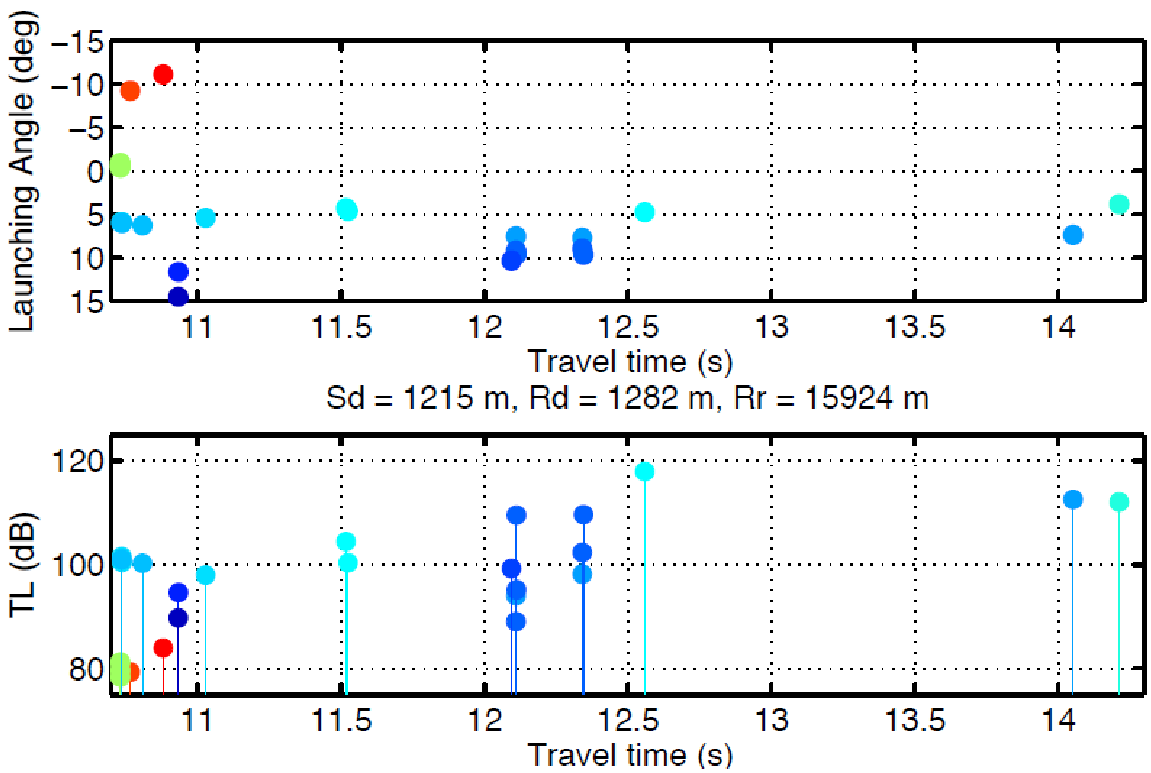
## RAY SIMULATION

Transmission processes of 800Hz sound between the station pairs T1-T2 (Fig.6), T1T3 (Fig.7), T1-T4 (Fig.8), T2-T3 (Fig.9), T2-T4 (Fig.10) and T3T4 (Fig.11) are simulated with the ray-tracing method, using the past CTD data obtained in the tomography site. The source (S) and receiver (R) are placed at depth 1200 m. The rays, launched from S at angles of ± 15 from the horizontal and received at R, are drawn in the figures.

For all the station pairs, there are ray paths which travel near the axis of the underwater sound channel (USC), existing in depth about 1200 m. These near-axis rays make the first arrival among all rays traveling in the depth layer extended from the surface to bottom. The shortest station-to-station distance between T1 and T2 forms three kinds of ray groups (Fig. 6). The first ray group travels near the USC axis, the second one reaches the depths 400-500 m and the third one is reflected by the surface. The travel times are distributed in the range of 10.8- 11.5 s. Thus the three ray groups are resolvable because the time resolution of M sequence for multi arrivals (cycle per digit) is 12.5 ms. The rays traveling between T1 and T3 are well distributed over depth in the northern half of the transmission line, but reflected between the surface and bottom in the southern half of the line (Fig.7). This ray pattern provides a crowded travel time in the narrow range of 26.7- 27.3 s so that the ray resolvability is worse for this station pair. The rays which travel between T1 and T4 without crossing the deep channel (trough) make a crowded arrival in the range of 47.5 s to 48.5 s (Fig.8). Some of the crowded arrivals within the time width of 100 ms are resolvable because of the M-sequence time resolution of 12.5 ms. The best ray distribution is obtained between the station pairT2-T4 (Fig. 10). A few rays arrive at the receiver, traveling the different depths of the upper 1000m. The travel times for these rays also scatter in the wide range of 49.5-52.0 s. The multi reflected rays at the surface and bottom with later arrivals may be not received due to increased transmission losses greater than 120 dB.

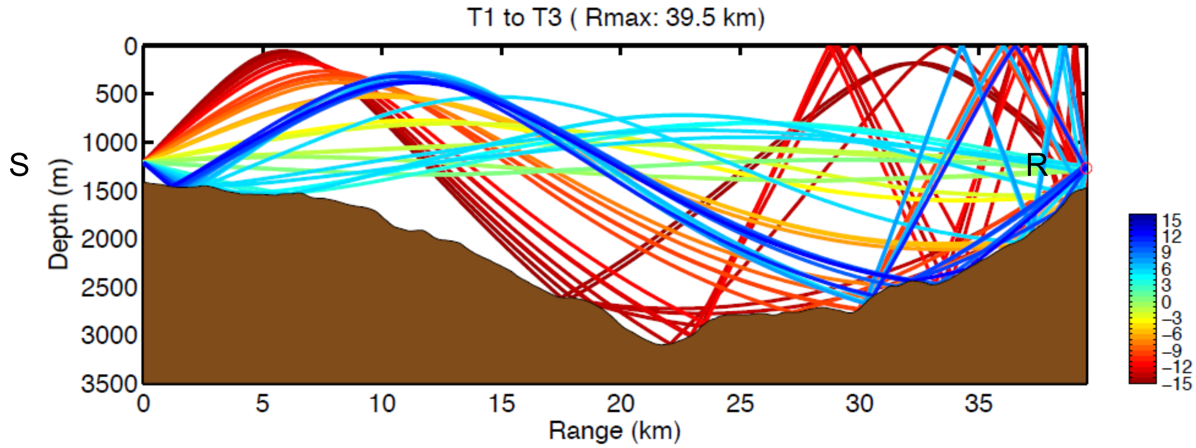



***(a) Ray pattern***

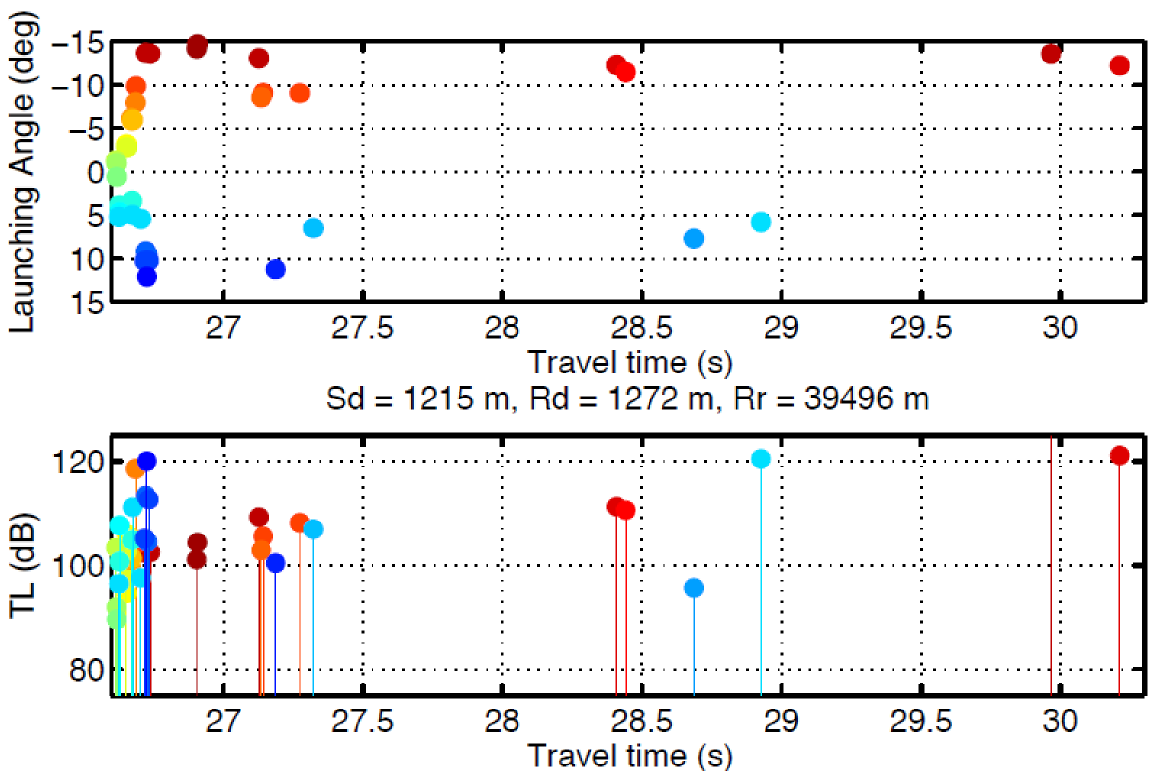



***(b) Launch angle and transmission loss (TL)***

***Fig.6 Ray simulation of sound transmission between T1 and T2***

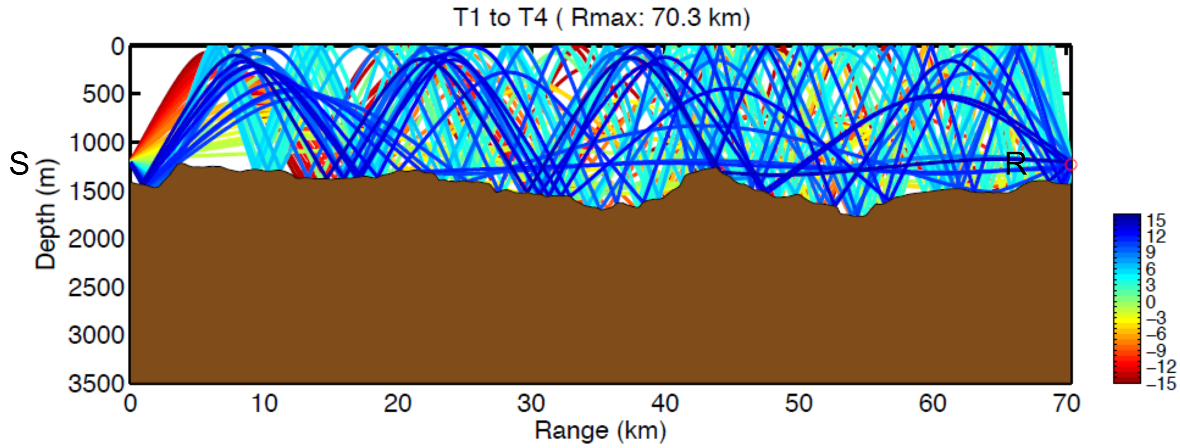



*(a) Ray pattern*

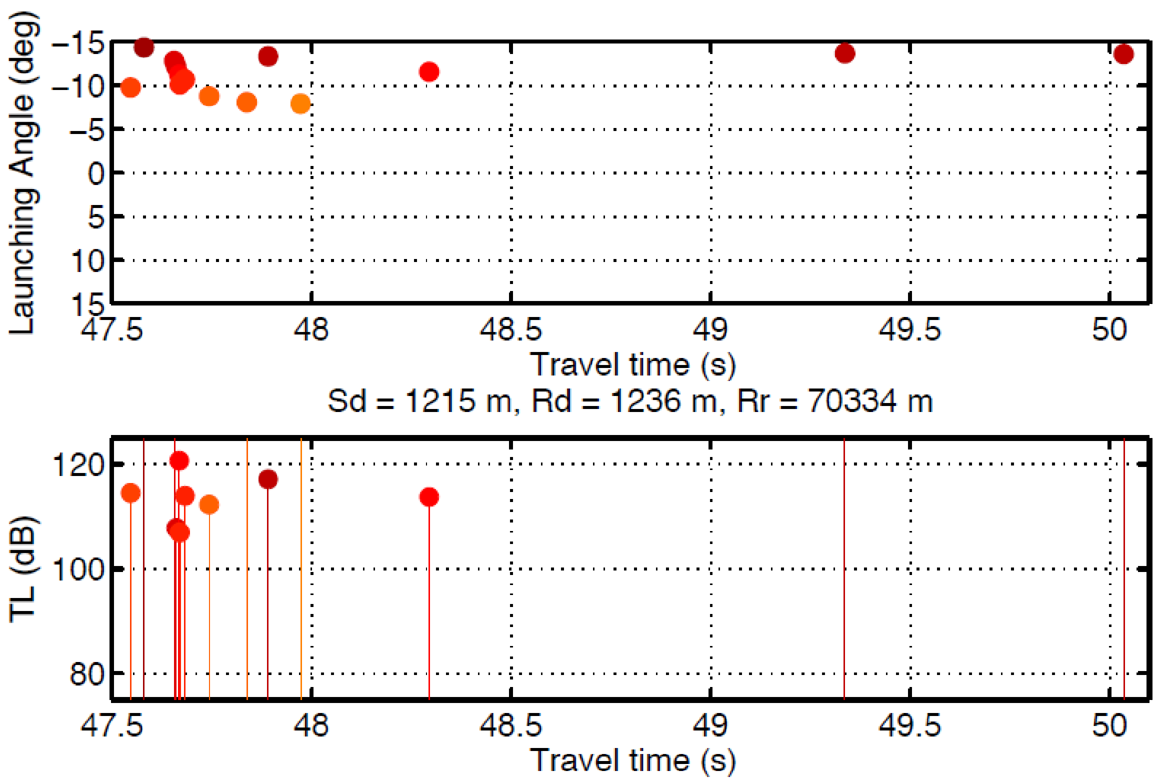



*(b) Launch angle and transmission loss (TL)*

***Fig.7 Ray simulation of sound transmission between T1 and T3***

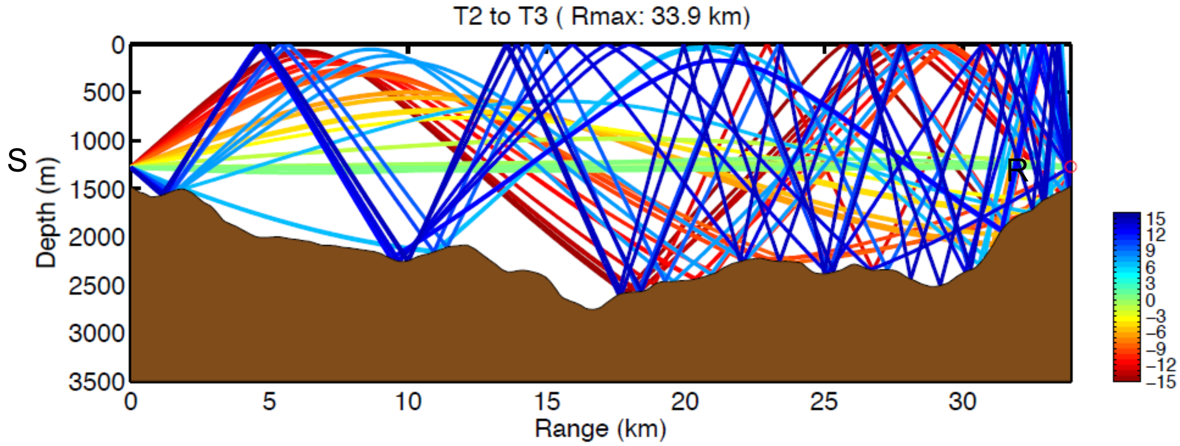



***(a) Ray pattern***

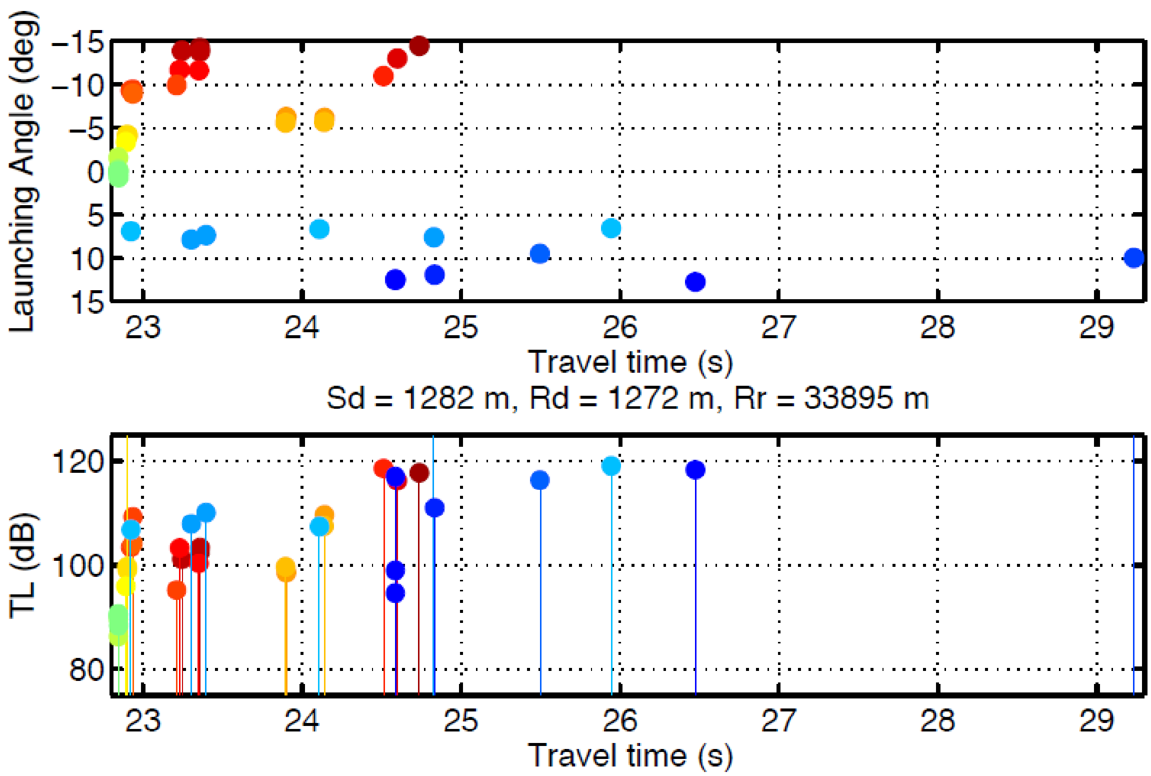



***(b) Launch angle and transmission loss (TL)***

***Fig.8 Ray simulation of sound transmission between T1 and T4***

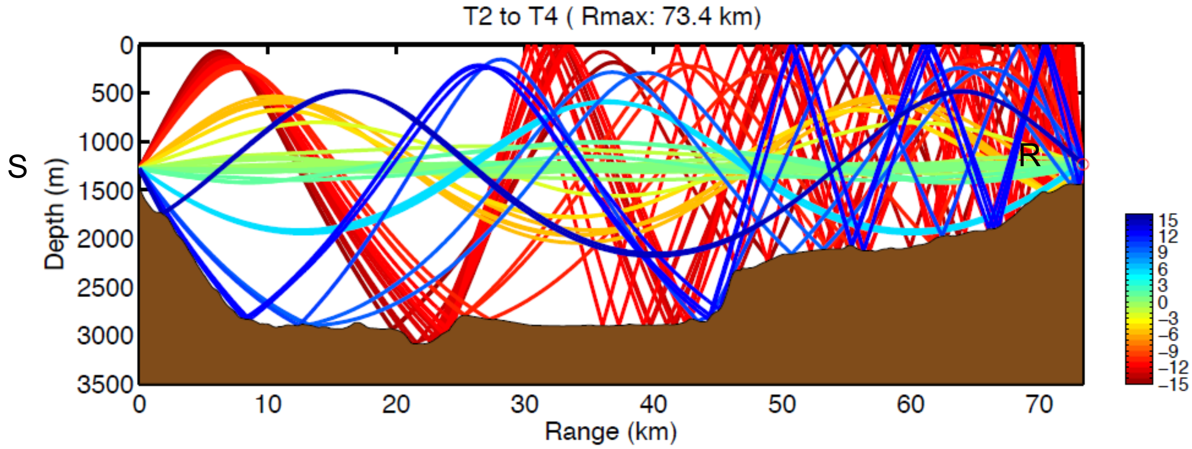



***(a) Ray pattern***

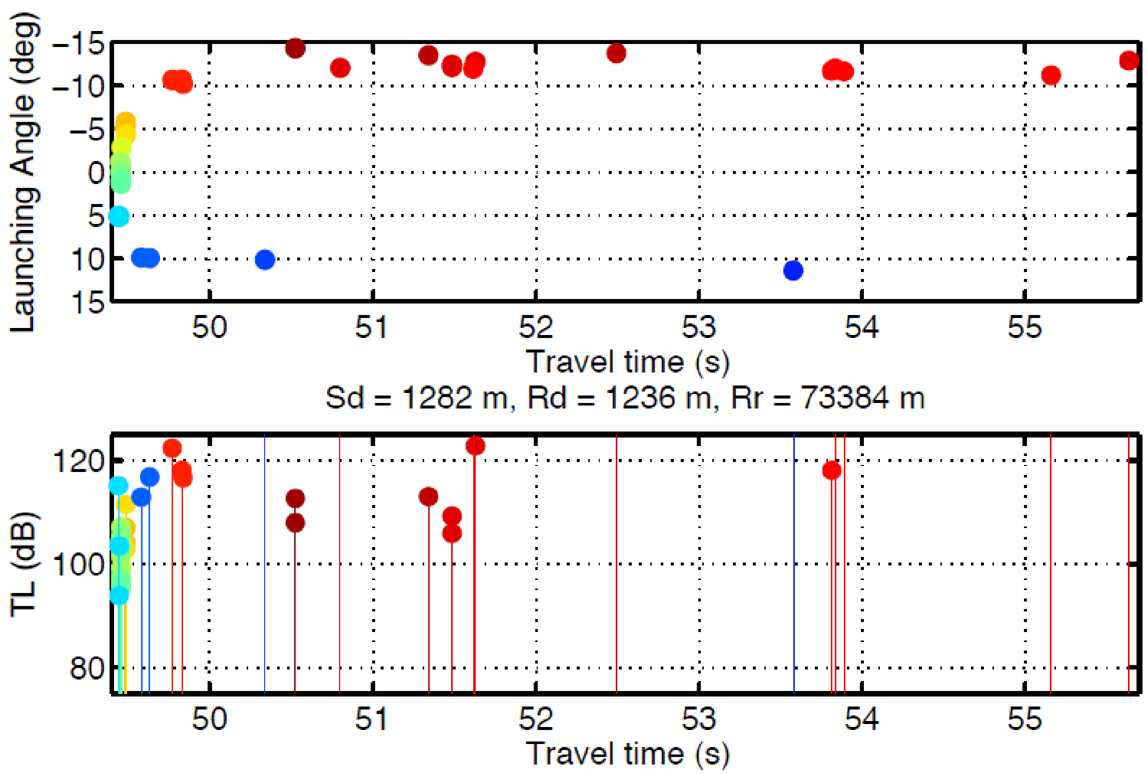



***(b) Launch angle and transmission loss (TL)***

***Fig.9 Ray simulation of sound transmission between T2 and T3***

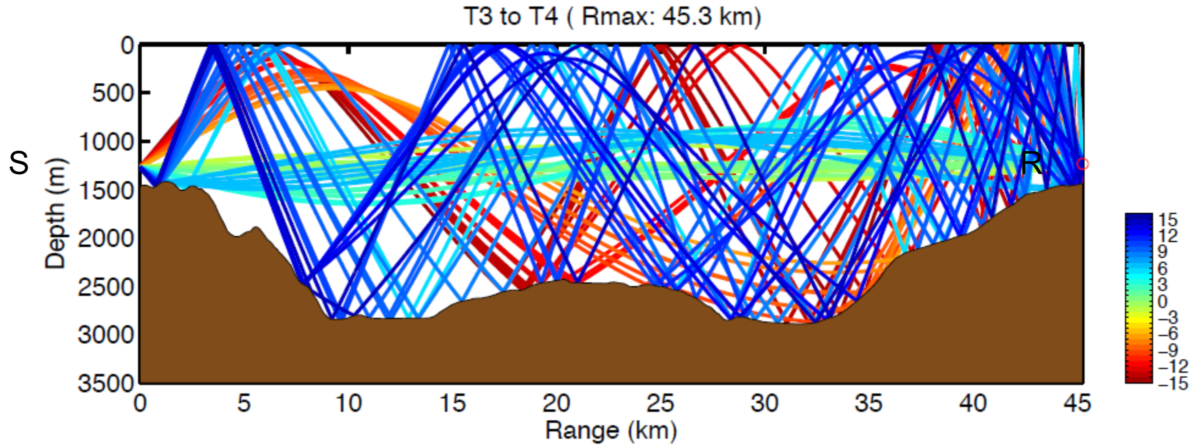



*(a) Ray pattern*

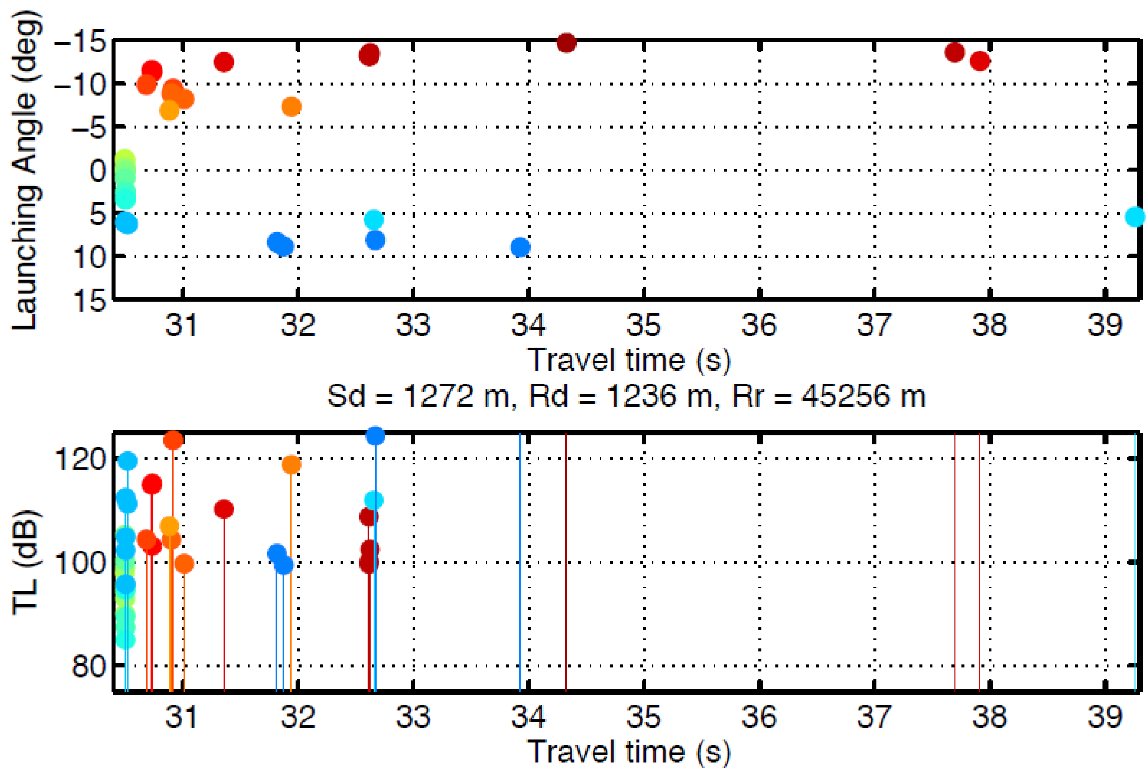



*(b) Launch angle and transmission loss (TL)*

***Fig.10 Ray simulation of sound transmission between T2 and T4***




*(a) Ray pattern*




*(b) Launch angle and transmission loss (TL)*

*Fig.11 Ray simulation of sound transmission between T3 and T4*

**FORTHCOMING ISSUES**

The recovery cruise of the mooring lines is scheduled at the beginning of September 2011. The R. V. Ocean Researcher No 3 will also be operated as in the deployment cruise. The data analysis is a prompt issue to be tackled as the next step. Through the data analysis, we do expect to elucidate the four-month variations of the Kuroshio and its associated frontal wave/eddy activity. The interaction between the Kuroshio and the internal tides and waves is also a target to be clarified in this study.

The layered structures of current velocity is first reconstructed by the inverse analysis which uses as data the travel time differences, acquired for rays traveling different depths in each vertical section between all the station pairs. The inverse analysis for the horizontal section is secondly performed by using as data the range-averaged currents for all the station pairs at a fixed depth. The 3D structures of current are reconstructed by gathering the results of horizontal inversion for various depth layers.

The major results will be submitted to the international journals such as Journal of Geophysical Research and the IEEE Journal of Oceanic Engineering at the earliest timing.