Using tsunami interferometry to measure ocean currents

Suvan Agarwal

October 10, 2023

Abstract

Cross correlation of three months of ambient seismic noise recorded by the Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) sensor array yielded many phase speed measurements on interstation paths. We used a tsunami interferometry technique involving taking the cross correlation of data from two sensors located on the ocean floor. We measured a current with a reasonable velocity using this method. However, there was not time to conduct proper error analysis, so we cannot conclusively say that we demonstrated the viability of using ambient seismic noise to measure ocean currents. The results were promising and encourage further research into this interferometry technique.

1 Introduction

Figure 1: Wreckage caused by the 2004 Indian Ocean Tsunami in Indonesia[1]

A tsunami is a series of oceanic gravity waves generated by submarine or coastal geologic processes such as earthquakes, landslides, or volcanic eruptions. Tsunamis are usually small and hardly noticeable when forming in the deep ocean but become large and can cause major damage when they approach coasts or harbors.[2]

The most major example from this century is the 2004 Indian Ocean tsunami, damage depicted here. This tsunami claimed the lives of 300,000 people.

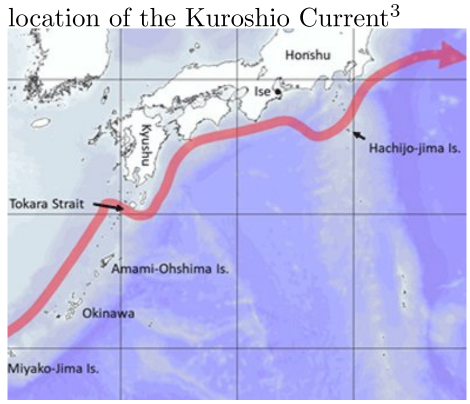
The Kuroshio Current also known as the Black or Japan Current or the Black Stream, is a north-flowing, warm ocean current on the west side of the North Pacific Ocean basin. It was named for the deep blue appearance of its waters. Similar to the Gulf Stream in the North Atlantic, the Kuroshio is a powerful western boundary current that transports warm equatorial water. Off the East Coast of Japan, it merges with the Oyashio Current to form the North Pacific Current.

The Kuroshio Current is useful as a shipping lane as the current saves time and fuel usage when underway with the current. However, ships that travel against the current will spend more time and fuel to compensate for the water flowing against the shipping vessel.

The Kuroshio supports many important fisheries. As the Kuroshio flows northeastward from northeast of Taiwan along the shelf slope of the Eastern China Sea, it carries fish eggs and larvae to southern Japan and Honshu Island. These larvae are caught and then raised in aquaculture through adulthood and harvested.

The variations in the Kuroshio current, in both short and long time scales are of great economic and climatic importance. The objective of this project was to use cross-correlations, a commonly used mathematical tool, to detect the Kuroshio current.

Figure 2: A map displaying the general location of the Kuroshio Current[3]



2 Methods

Coastal sea-level heights have been measured for more than a century by tide gauges at ports and harbors throughout the world. Tsunami sensors must be located in deep ocean, so the use of sensors to monitor tsunamis is more recent.

Figure 3: A map displaying the location of NIED deep ocean sensors[4]

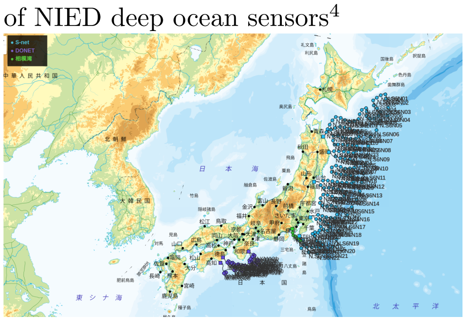


Figure (3) is a map of the deep ocean sensors belonging to the National Research Institute for Earth Science and Disaster Resilience (NIED). The network runs along the Nankai Trough to the east of Shikoku and to the south of Shizuoka. These sensors are pressure gauges located on the ocean floor that measure water pressure which is then converted to sea level height.

We followed the process displayed in Figure (4) with minor changes. We used Seismic Analysis Code (SAC) to execute all preprocessing steps before phase 2.

Figure 4: The method used to process data[5]

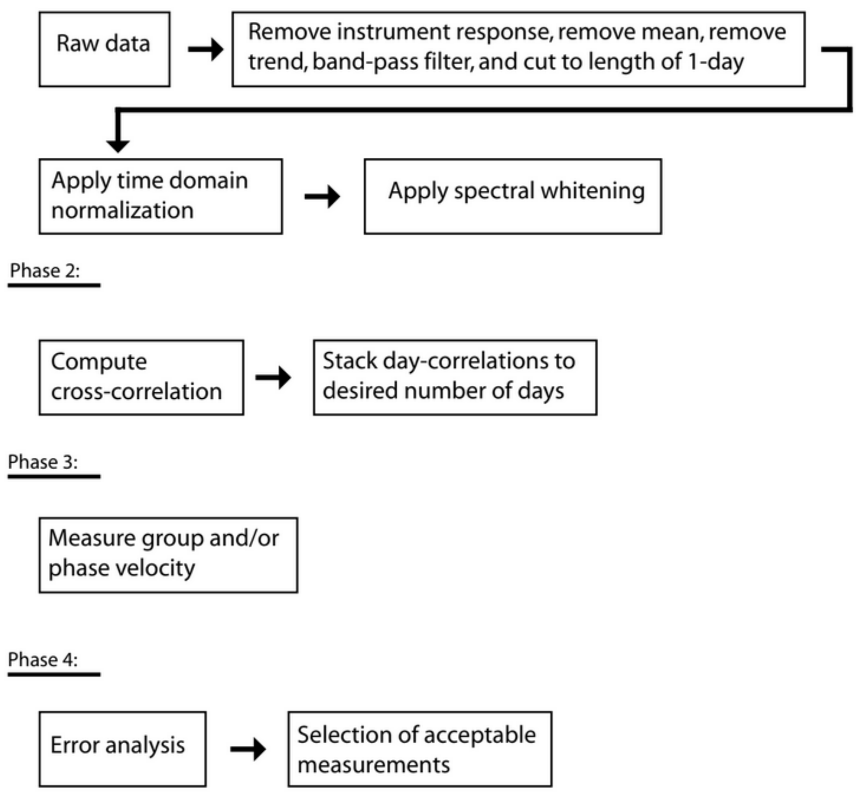
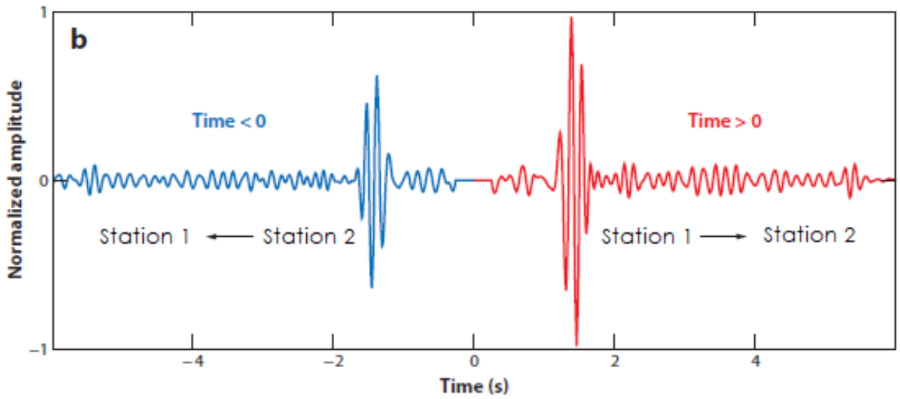


Figure 5: Meaning of the positive time domain and negative time domain of the cross-correlation when the seismic data from two stations are used[6]



Phase 2 involved using the cross-correlation. Cross correlations have been used extensively in seismology in the last decade for ambient noise surface wave tomography, where diffused ambient noise waves recorded by seismometers are used to measure phase speeds and determine the depth and map internal structure of the Earth.

The cross-correlation is a measure of similarity of two series as a function of the displacement of one relative to the other. In its' most basic form it can be represented by the following equation:

$$(2N+1)\Phi_{pg}(\tau) = \sum_{k=-N}^{N} p(k)g(k+\tau) \tag{1}$$

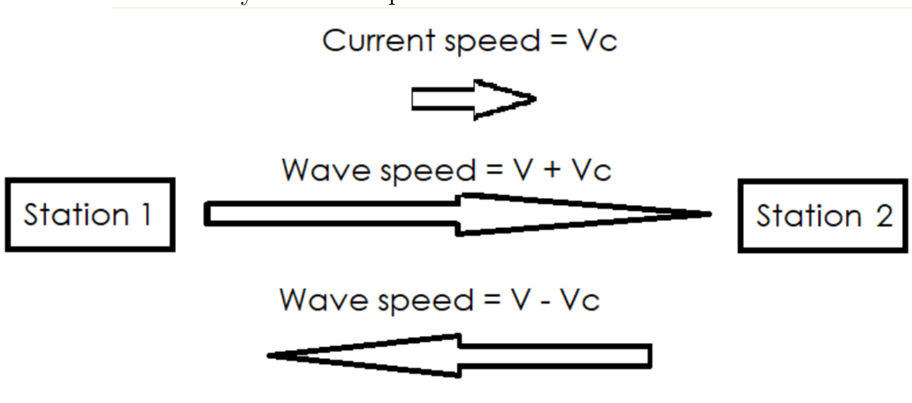
where p(k) and g(k) with k integer, are two sampled sequences of signals. 2N+1 is the window length for the cross-correlation. τ is the time lag of the two signals.

Previously, data from real earthquakes were the main seismic information that could be used to map the internal structure of the Earth. However, the cross-correlations formed using ambient seismic noise behave like virtual seismic sources. The positive time domain represents a seismic wave traveling from the first station to the second and the negative domain represents the opposite (Figure (5))

Our work aims to use the data from the Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) pressure gauges to compute cross correlations between the DONET stations. Thus, creating virtual tsunamis sources.

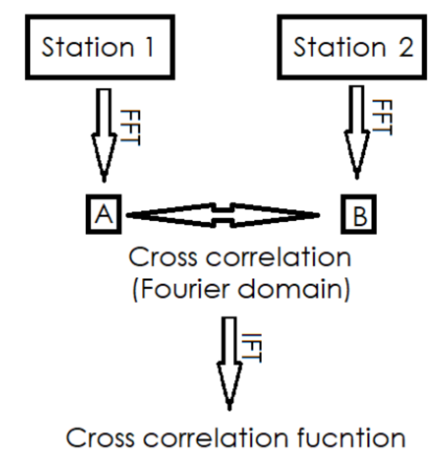
The dispersed waveforms of the cross correlations are then used to measure phase velocities. If the two stations chosen lie along the Kuroshio current, the difference in the phase velocity from station 1 to station 2 and the opposite direction the will differ by twice the speed of the current (Figure (6))

Figure 6: The phase velocities from station 1 to station 2 and in the opposite direction will differ by twice the speed of the medium



To compute cross-correlations between station data, we first used the Fast Fourier Transform on the original time series to generate the Fourier coefficients. We then multiply the coefficients in the Fourier domain (Equation (2)). See Figure (7). See Figure (13) at the end of the report for an example of a cross-correlation function.

Figure 7: Using Fast Fourier Transform (FFT) to reduce computational time of cross-correlation



The Inverse Fourier Transform of

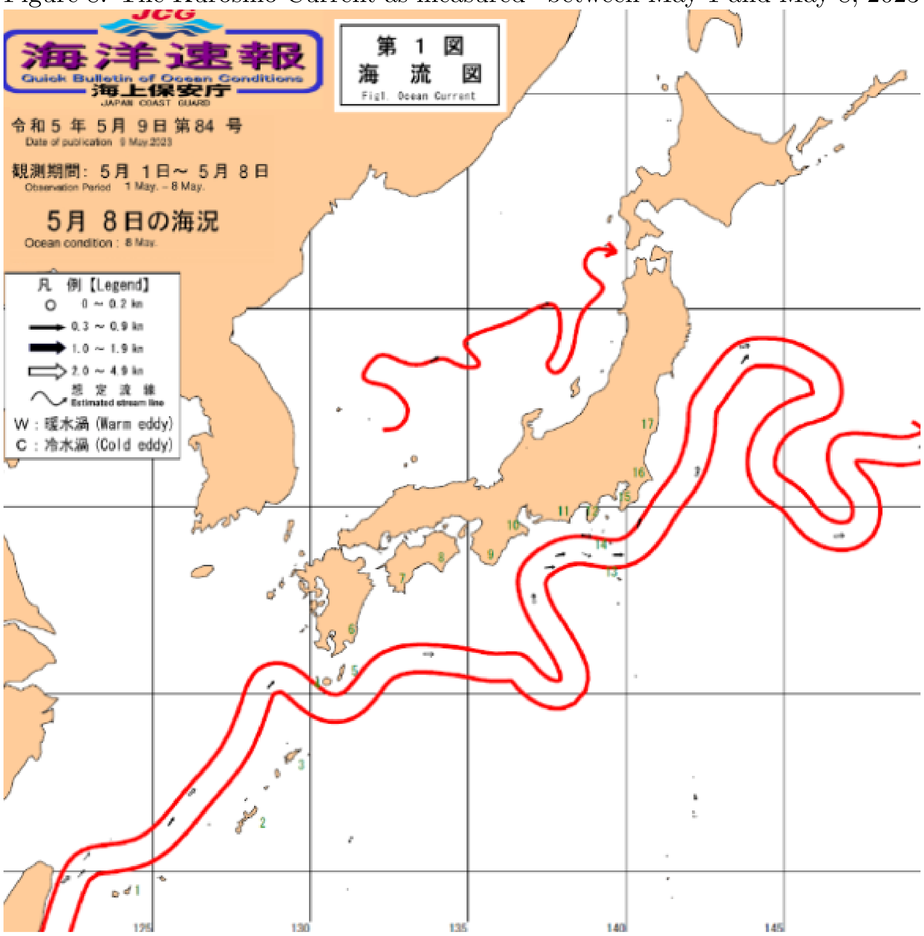
$$C = AB^* \tag{2}$$

where B and A are coefficients in the Fourier domain and the asterisk denotes the complex conjugate, gives us the cross-correlation function. Calculations are done in the Fourier domain because it significantly reduces the computational time needed.

The second part of phase 2 as seen in Figure (4) involves adding the cross-correlation functions over a long period of time (days) in order to improve the signal-to-noise ratio. In our case, the data was stacked over a period of about 60 days using scripts written in SAC and Bash.

Phase 3 involves measuring the phase velocity of the virtual tsunami. We measured the phase velocity by manually selecting the phases from the cross correlation in the frequency domain that corresponded to the estimated velocity of a tsunami between the two stations. The estimated velocity of a tsunami is determined by

Figure 8: The Kuroshio Current as measured[7] between May 1 and May 8, 2023



$$\sqrt{gd}, \tag{3}$$

where g is gravity acceleration and d is the averaged depth of the two stations of interest.

Finally, we compared the two phase velocities from each side of the cross-correlation. The difference in phase velocities allows us to measure the movement of the medium through which the virtual wave is traveling.

3 Results

First we present a map that displays the Kuroshio current at the time period during which our data was sourced. (Figure (8))

Now we present an example of a cross-correlation that demonstrated a viable current. The stations selected were DONET stations KC21 and KD16, two stations that lay along the path of the current as measured. Here we can see the location of the stations (Figure (9)) as well as the phase velocities obtained from the cross correlations (Figure (10)). The measured velocity of 2.5 meters per second is both viable and the direction follows that of the Kuroshio current.

Figure 9: KD16 and KC21 are located along the path of the Kuroshio Current (green arrows)

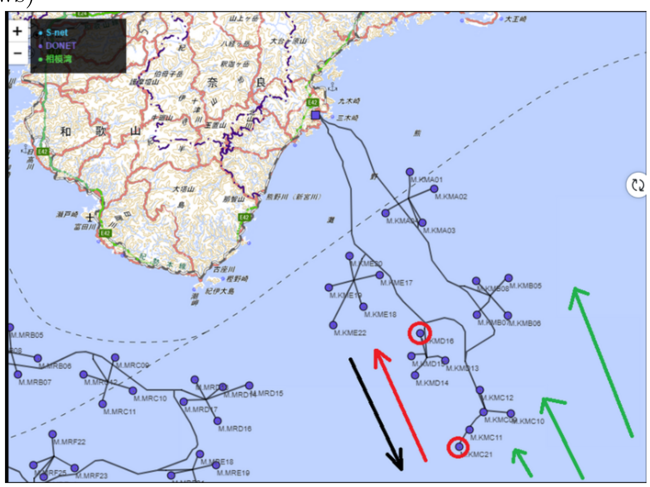


Figure 10: The phase velocity is faster from KC21 to KD16 than vice versa. The red line corresponds with the red arrow in Figure (9), indicating that the medium moves in the same direction as the flow of the Kuroshio Current.

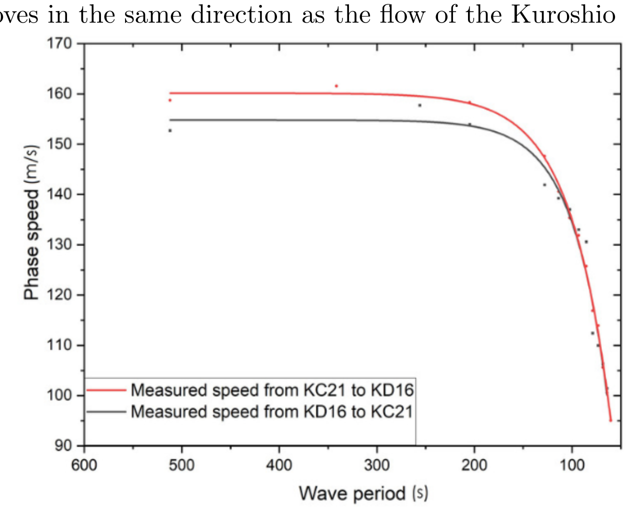


Figure 11: KD16 and KB08 are located normal to the path of the Kuroshio Current (green arrows)

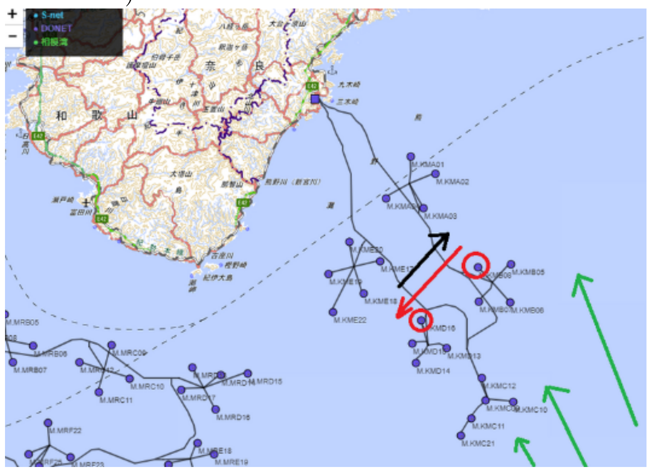
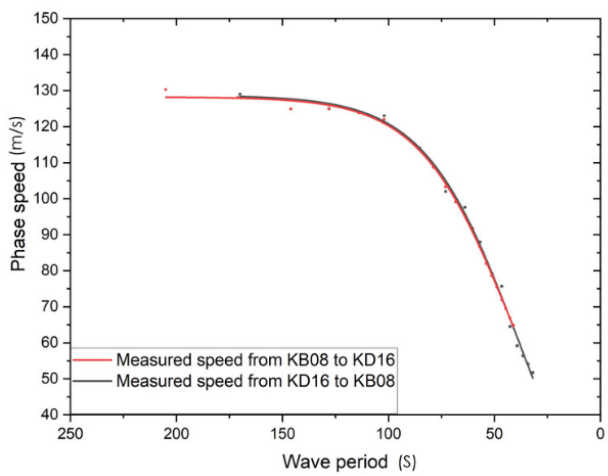
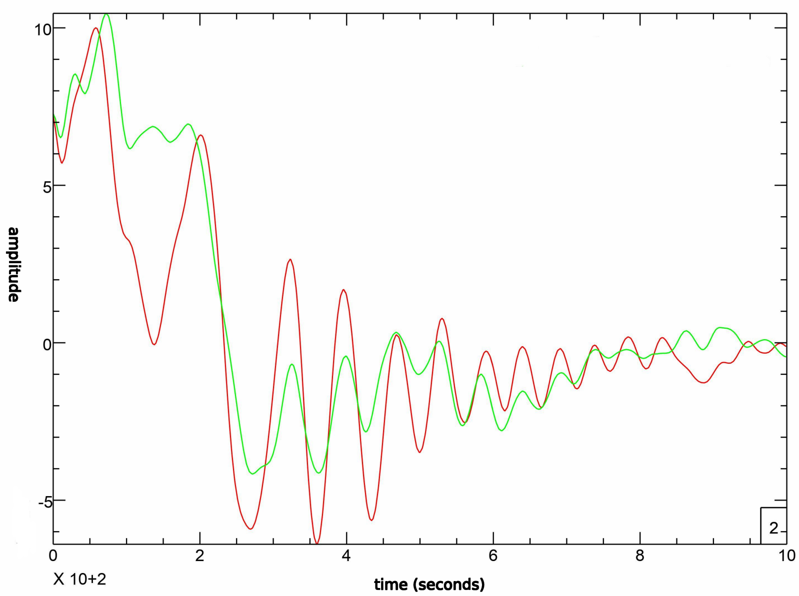


Figure 12: The phase velocity is approximately zero, which is expected given that we are measuring the movement of the medium normal to the direction of the Kuroshio current.



Next we present an example of a cross-correlation that did not demonstrate a current, as expected. The stations selected were DONET stations KB08 and KD16, two stations that lay normal to the path of the current as measured. Here we can see the location of the stations (Figure (11)) as well as the phase velocities obtained from the cross correlations (Figure (12)). The measured velocity of approximately 0 meters per second is expected because the wave path is normal to the measured flow.

Figure 13: Here we present an example of a computed cross-correlation function displayed in the time domain. This specific function is that of the KB08-KD16 station pair, added up over a length of 20 days. The function has been mirrored over the y-axis to display both propagation directions overlaid. The green curve is the virtual wave that runs from KB08 to KD16, while the red curve is the wave running from KD16 to KB08. From the arrival times of the peaks and troughs of this graph, we can find that the phase speeds of the two waves are close to each other.



4 Conclusion

We can see from these results that this interferometry technique using ambient seismic noise is potentially viable and worth exploring further. Though we cannot come to any conclusions because of the shallow nature of the research conducted (due to the limits of a short research time period), there are abundant opportunities for further research. The clear next step is to analyze the phase velocities of the cross-correlations of more station combinations. Proper error analysis also needs to be conducted to determine the accuracy and precision of the phase velocity differences.

5 Acknowledgements

I would like to thank Professors Shingo Watada and Osamu Sandanbata for their generous support in this project. The time and effort they put into this internship has helped me grow as a scientist and encourage me to apply to graduate school in Japan. I would also like to thank Soham Bhattacharya, who I conducted this research alongside, as well as mentors Kazuki Ohtake and Teppei Enari for making me feel welcome at ERI! I would like to thank the ERI and UTRIP team for organizing this internship. And of course, none of this would have been possible without financial support from the Friends of UTokyo organization.

6 References

1] U.S. Navy photo by Photographer's Mate 2nd Class Philip A. McDaniel - This image was released by the United States Navy with the ID 050102-N-9593M-040
2] Satake, K. (2015) Treatise on Geophysics, Second Edition, Vol. 4, pp. 477-504.
Japan Coast Guard Hydrographic and Oceanographic Department Website. https://www1.kaiho.mlit.go.jp/KANKYO/KAIYO/qboc/.
3] Nagai, T. (2019), The Kuroshio current: Artery of life, Eos, 100, https://doi.org/10.1029/2019EO131369. Published on 27 August 2019.
4] Screenshot taken of https://www.seafloor.bosai.go.jp/st_info_map/ on 22 September 2023.
5] Bensen, G. D. et al (2007). Geophysics J. Int. Vol 169, 1239-1260. Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements.
6] Snieder, et al (2013). Annual Revier of Earth and Planetary Sciences. Vol 41, 183-206. Extracting Earth's Elastic Wave Response from Noise Measurements.
7] Japan Coast Guard Hydrographic and Oceanographic Department Website. https://www1.kaiho.mlit.go.jp/KANKYO/KAIYO/qboc/.