TSUNAMI EARLY DETECTION: ENHANCED RESOLUTION OF HF OCEANOGRAPHIC RADAR

Yasuhiro Murata[1] , Toshiro Nagakura[1] and Takahiro Kokai [2]

HF Oceanographic radar is an equipment, for instantaneously sensing velocity distribution of sea surface current. It has a wide field of view, which extends approximately ±45° in direction and beyond 50km in distance. There are high expectations that the radar observation of Tsunami will become a new road path for preventing disasters. In this paper, we describe a method to enhance the resolutions of radar in both time and current. At first, resolutions required for tsunami observation are estimated by simulating a Tokachi-oki earthquake tsunami (2003). Here it is pointed out that traditional data processing indicates inadequate resolutions for tsunami early detection. Secondly, two techniques are proposed to achieve the necessary resolutions. Short-time Fourier transform (STFT), in place of normal FFT, enhances the time resolution of Doppler analysis. Further, zero-padding technique improves the current resolution, by interpolation of data within the frequency domain. Finally, by means of simulation, it is verified that these proposed techniques give improved resolutions in both time and current.

Keywords: Tsunami, Surface flow, HF Radar, Sea echo, Doppler shift, FFT, STFT, Zero-padding, Peak detection

1. Introduction

The HF Oceanographic radar (hereinafter referred to as the “radar”) that permits wide-ranging two-dimensional observation of the surface current and ocean waves in the coastal sea area has been widely used in the fields of ocean environment conservation and the study of ocean flow.

The radar frequency and transmission power of land-based radars allow observation of the surface current within a range from tens of kilometers to hundreds of kilometers offshore. If these radars can observe the arrival of Tsunami, the resultant damage can be reduced. There has been no report on the observation of actual Tsumani by radars, but there are some reports on the examination of the possibility of Tsunami observation(e.g.Barrick,1979; Izumiya and Imai, 2005; Izumiya and Nakajima,2006; Watanabe and Tomita,2007 etc).

Most of these preceding studies presuppose ideal detection of the change in the flow velocity of Tsumani, but the examination of specific radar observation specifications and their feasibility are insufficient.

Concerning the observation of Tsunami by radars, the authors have focused on the two problems. The first problem is the length of the observation time by radars. Conventional radars are used for approx. 8.5 minutes to observe the flow. In order to observe Tsunami according to the change in the flow velocity observed by radars, however, the velocity information must be obtained during short-time observation based on the propagation velocity of Tsunami, radar observation range, and space resolution; thereby finding the existence of the change in the flow velocity due to Tsunami.

The second problem is the flow velocity resolution. In the offshore area where the shallow-water effect is small, the change in the flow velocity caused by Tsunami is also small. Therefore, the flow velocity resolution must be enhanced to detect Tsunami in offshore areas.

This study has examined a specific signal processing technique that will permit radar observation with higher flow velocity resolution within a short period of time. As a result, it has been confirmed that the short-time Fourier transformation can solve the problem of the observation time and that the Zero-padding technique can solve the problem of the flow velocity resolution. The following is the report on a method of using radars to detect the change in the flow velocity due to Tsunami in offshore areas.

Chapter 2 of this report explains the conventional radar observation technique, and Chapter 3 examines the resolution necessary for Tsunami observation by radars. Chapter 4 proposes a signal processing technique that will materialize the required resolution. Chapter 5 simulates the proposed technique for its verification. Chapter 6 summarizes the current study and shows the problems to be solved in future.

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[1] KOKUSAI KOGYO CO.,LTD., 2-24-1, Harumicho, Fuchu city Tokyo, 183-0057, Japan
[2] Nagano Japan Radio Co.,Ltd., 381-2288, Inasato-machi,Nagano city Nagano, 381-2288, Japan

2. Conventional Oceanographic radar

This chapter explains the radar that has been used so far for observation of the flow.

Table 1 shows the basic specifications of a 24 MHz radar. The observation range of the land-based radar station (one station) is ±45°in direction from the front of the radar and from 1.5 to approx. 50 km in distance. The radar irradiates the above-mentioned range of the sea surface with radio waves for 512 seconds, the flow velocity in the direction of the line of sight is calculated based on the Doppler spectrum of radio waves that are backward-scattered by the sea surface, and the flow velocity distribution is output.

Table 1. Basic specifications of conventional radar

Basic specifications of radar	Radar frequency		24.515MHz
	Type of radar		FMICW
Antenna specifications	Directionality synthetic method		Reception DBF
	Beam width		12°
	Number of antennas		1 for transmission and 8 for reception
Space specifications	Observation range	Distance	From 1.5 to approx. 50 km
		Direction	+/- 45°from the front
	Distance resolution		1.5km
	Bearing resolution		7.5°
Time specifications	Observation time		512 s (1024 sweeps)
	Observation period		1h usually
Observation performance	Flow velocity resolution		4.8 cm/s

Signals that are backward-scattered by the sea surface and received by antennas are processed by the technique shown in Figure 1. In the DBF (Digital Beam Forming) process shown in the figure, signals received by multiple antennas with wide directionality undergo phase synthesis on a computer to form a narrow beam in an arbitrary direction.

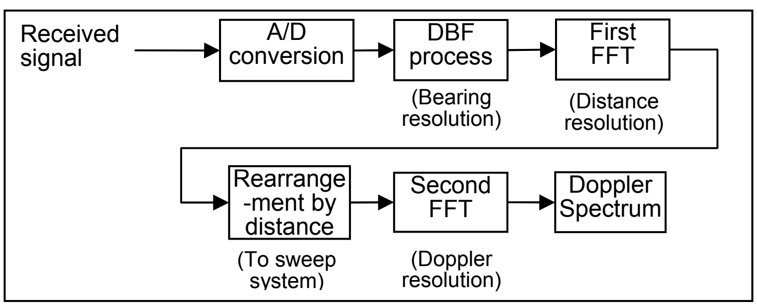


Figure 1. Method of analysis of signals received by radars

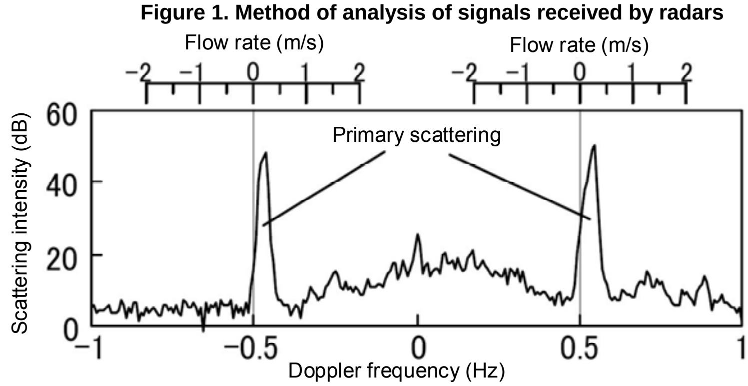


Figure 2. Example of Doppler frequency

The Doppler spectrum in Figure 2 is obtained by the processing technique in Figure 1. The flow velocity is calculated from the primary scattering peak frequency of the Doppler spectrum. The flow velocity resolution is determined by the formulae (1) and (2) in Chapter 4, which is 4.8 cm/s when the radar in Table 1 is used(5) Japan Society of Civil Engineers, 2001).

3. Radar resolution necessary for Tsunami observation – Example of Tokachi-oki Earthquake Tsunami –

This Chapter takes a case study for example to examine the resolution necessary for Tsunami observation based on the flow velocity observation by a radar and the problems that arise when the radar shown in Table 1 is used for Tsunami observation.

The change in flow velocity due to Tsunami differs of course according to the wave source, submarine topography, and observer's location. In order to examine the applicability of Tsunami observation by a radar, Tokachi-oki Earthquake Tsunami in 2003, which caused damage due to periodical seismic shaking, is taken for example. The recorded fluctuation of the water level due to Tsunami was 2-3 m, and some fishermen went missing. It was approx. 15 minutes from the time when the earthquake occurred till the time when the first wave reached the seashore.

Taking into consideration the evacuation time, this study is intended to detect Tsunami 10 minutes before the first wave arrives. If the change in flow velocity due to Tsunami is observed continuously and two- dimensionally at that stage, information that will contribute to the reduction in Tsunami damage is considered to be available for the process from evacuation guidance to rescue activities.

The change in flow velocity due to Tsunami is obtained from the Tsunami simulation shown in Table 2.

Table 2. Tsunami simulation calculation condition

Item	Calculation condition
Fundamental equation and solution	900 mm: Linear Shallow-Water wave model 300 mm: Non-linear Shallow-Water wave model Leap-Frog difference calculus
Calculation grid	From wave source to coast: 900 m and 300 m
Calculation time interval	0.1 sec
Calculation of crustal deformation	By Mansinha and Smylie (1971) method
Seismic source model	Seismic source model shown by Tanioka et al. with 1.51 times larger slip amout
Tide level condition	T.P. + 59 cm (Water level at Otsu Gauging Station when Tokachi-oki Earthquake Tsunami occurred in 2003)

Figure 3 shows the comparison of the change in the water level between the result of the above simulation and the reading of the wave meters installed off Tokachi Port. (The locations are shown in Figure 4.) As shown in this figure, the result of simulation well coincides with the change in the water label observed by wave meters.

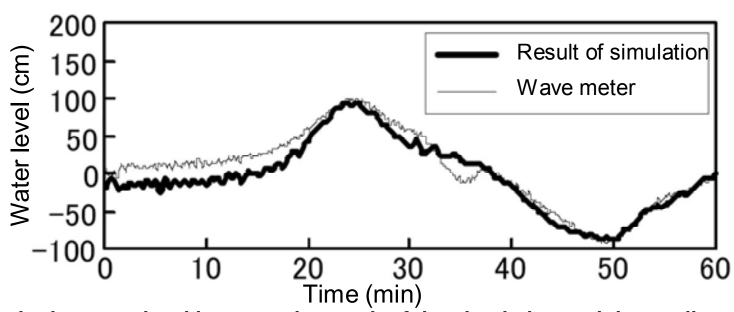


Figure 3. Change in the water level between the result of the simulation and the reading of the wave meters

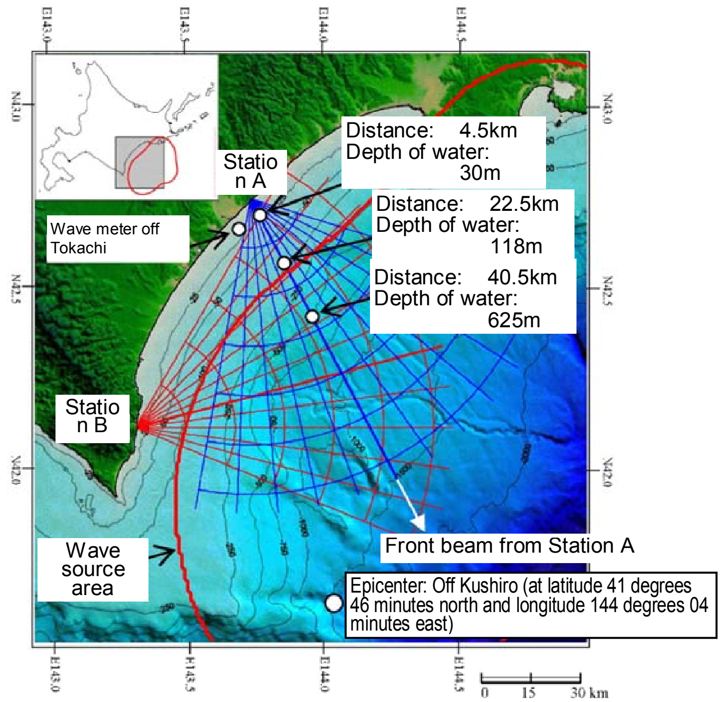


Figure 4. Locations of radar stations and observation range for simulation of flow velocity of Tokachi-oki Earthquake Tsunami

As shown in Figure 4, Station A and Station B are installed in this study and the change in flow velocity on the lines of sight of radars is examined based on the result of simulation in anticipation of Tsunami observation by radars.

The changes in flow velocity at the 4.5 km, 22.5 km, and 40.5 km points on the beam from Station A in Figure 4 are shown in Figure 5 (a)-(c). The direction of the flow toward the radar stations is positive.

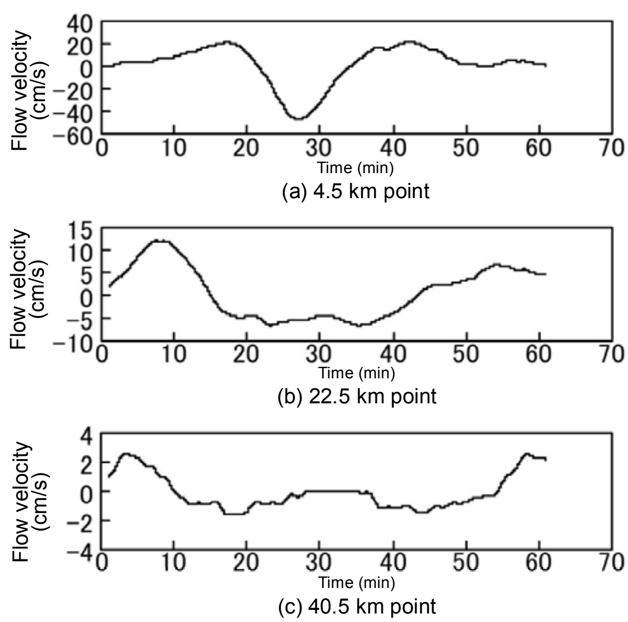


Figure 5. Result of flow velocity simulation

In Figure 5 (a) (4.5 km), the change in flow velocity is several tens of cm/s, but the change is as small as slightly more than ten cm/s in Figure 5 (b) (22.5 km) and several cm/s in Figure 5 (c) (40.5 km). In order to detect the change in flow velocity of Tsunami 10 minutes before the first wave reaches the coast, which is the target, the changes in flow velocity at locations more than 20 km offshore shown in Figure 5 (b) and (c) must be detected. Furthermore, continuous observation must be carried out to output the result at intervals of several minutes in order to ensure early detection of the time change in flow velocity.

In this case study, the following action and resolution are necessary for Tsunami observation by radars:

- Observation action — On a steady basis(continuous observation)
- Time resolution — Approx. 2 min.
- Analysis output interval — Approx. 1 min.
- Flow velocity resolution — Approx. 1 cm/s

Application of radars to Tsunami observation is discussed here. In the DBF technique, the target area is irradiated with radio waves in all directions simultaneously, and the directions are separated when received signals are processed, shortening the observation time. Since the observation distance is approx. 50 km, offshore Tsunami can be observed, and this technique is suitable for Tsunami observation in general. However, the conventional signal processing technique needs approx. 8.5-minute-long observation to output one result, and the flow velocity resolution is 4.8 cm/s. Since this resolution fails to permit the above-mentioned Tsunami observation, improvement of the time resolution and flow velocity resolution is necessary.

4. Proposal of high resolution technique

(1) Improvement of time resolution

In order to materialize the short-time observation mentioned in the previous Chapter, the authors turned the attention to the second FFT shown in Figure 1. In this FFT, the Doppler spectrum is obtained from all the time series (512 sec.; 1024 sweeps) of signals received at a specific observation point, and the time resolution of the radar is determined.

The conventional analytical technique is shown in Figure 6. In the conventional technique, the whole area is divided into seven sections (Nos.1-7) to increase the S/N ratio in order to obtain the Doppler spectra, and they are averaged. This processing technique presupposes that the flow velocity of the observed object is constant during observation (512 sec.) and the noise is random. However, the velocity of flow due to Tsunami changes substantially in several minutes, and the fluctuation due to Tsunami is also averaged by the averaging procedure, making the detection difficult.

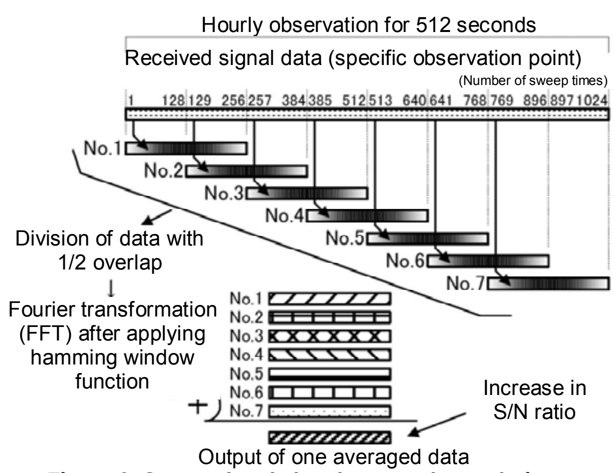


Figure 6. Conventional signal processing technique

In order to solve the problem and ensure the resolution shown in Chapter 3, the authors considered the introduction of the short-time Fourier transformation (STFT), which is a time-frequency analysis technique, as shown in Figure 7.

In this technique, the window function is temporarily overlapped with the input data and the data in the window section undergoes Fourier transformation, permitting the acquisition of the temporal change of the Doppler spectrum. The width of the window function in the STFT technique is the time resolution, and the width of the window function is set at 128 seconds (256 sweeps) in this paper in view of the required time resolution (approx. 2 seconds).

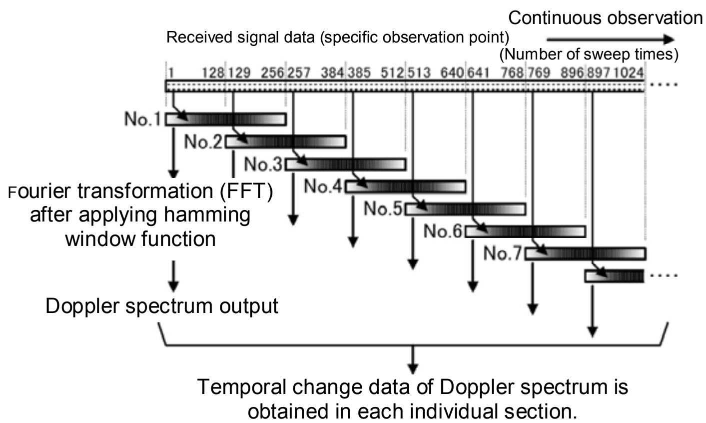


Figure 7. Proposed signal processing technique

The STFT technique shortens the time necessary for the output of one observation result from 512 seconds to 128 seconds, and the output interval is 64 seconds. Data obtained by conventional radars during one observation are processed by this technique to clarify the temporal change of the Doppler spectrum. An example is shown in Figure 8.

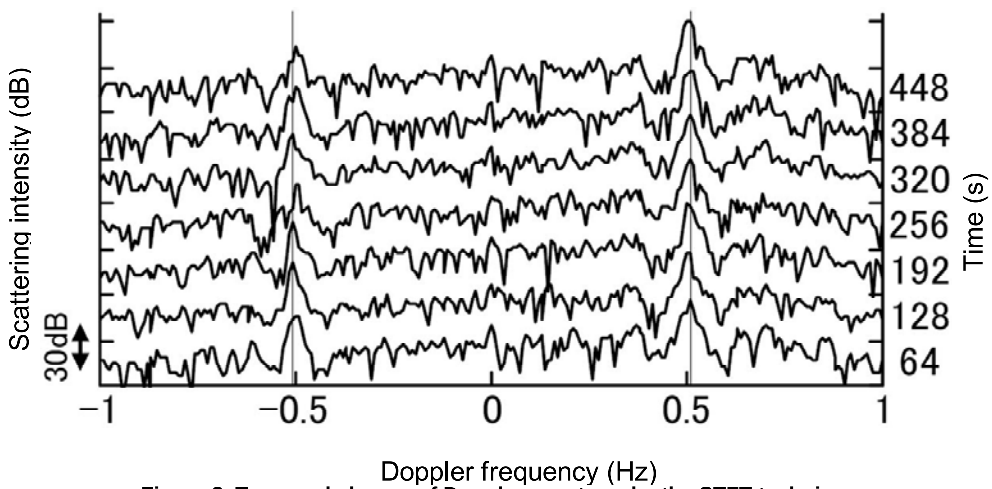


Figure 8. Temporal change of Doppler spectrum by the STFT technique
(The actual existing observation data are used.)

However, the S/N ratio of the Doppler spectrum is decreased by the STFT technique because of the absence of the averaging process. To confirm this effect, the S/N ratio obtained by this technique is compared with the S/N ratio obtained by the conventional technique using the spectrum shown in Figure 8. The result is shown in Figure 9. In the figure, the line of the conventional technique is obtained by averaging the data in Figure 8 by the conventional technique in all sections, while the line of the STFT technique is the spectrum of 64 s in Figure 8.

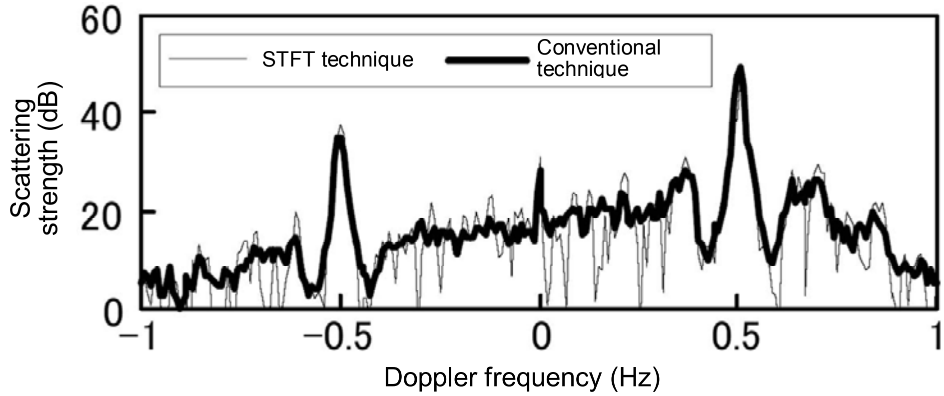


Figure 9. Doppler spectrum obtained by the STFT technique and conventional technique

Figure 9 shows that the S/N ratio obtained by the STFT technique is smaller than that in the conventional technique, but it also shows that the shape of the primary scattering peak has not been deteriorated. Tsunami observation needs the information about only the peak position of primary scattering, and the decrease in the S/N ratio is considered to cause no problem.

The above examination indicates that the STFT technique can improve the time resolution without changing the conventional flow velocity resolution.

(2) Improvement of flow velocity resolution

The flow velocity resolution (Δv) is obtained from formula (1), where f is the radar frequency (frequency of radio wave), c is the velocity of light, and δf is the Doppler frequency resolution.The above examination indicates that the STFT technique can improve the time resolution without changing the conventional flow velocity resolution.

$$\Delta v = \frac{\delta f}{2f} c \qquad (1)$$

The Doppler frequency resolution (δf) is obtained form formula (2), where TA is the observation time.

$$\delta f = \frac{1}{T_A} \qquad (2)$$

Formulae(1) and (2) show that the flow velocity resolution is in inverse proportion to the observation time and long observation time is necessary to obtain high flow velocity resolution.

In the STFT technique proposed in the preceding Section, the observation time (T_A) is equivalent to the duration of the window function. Therefore, the flow velocity resolution obtained by this technique (duration of window function = approx. 2.1 min.) is 4.8 cm/s, failing to reach the target value (approx. 1 cm/s). In addition, the observation time necessary to reach the target value is approx. 10 minutes, and such a long time cannot be spent during Tsunami observation.

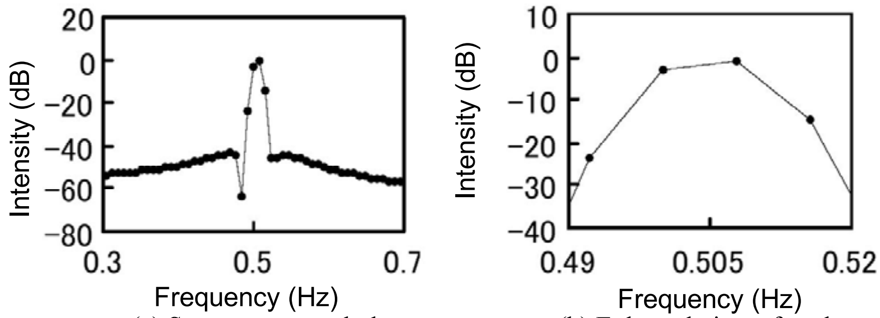
In order to improve the flow velocity resolution without extending the observation time, the authors propose the introduction of the Zero-padding technique into the STFT technique shown in Figure 7. In the Zero-padding technique, zero data are added to the observed data to increase the number of input data before FFT. When this technique is applied to the input time series data, data points are interpolated in the output frequency domain, and the peak position can be obtained more correctly.

In the case of FFT, the length of the window function is N (number of input data: 256 in Figure 7), the sampling frequency is fs, and TA is N/fs. Therefore, formula (2) can be rewritten as formula (3)

$$\delta f = \frac{f_S}{N} \qquad (3)$$

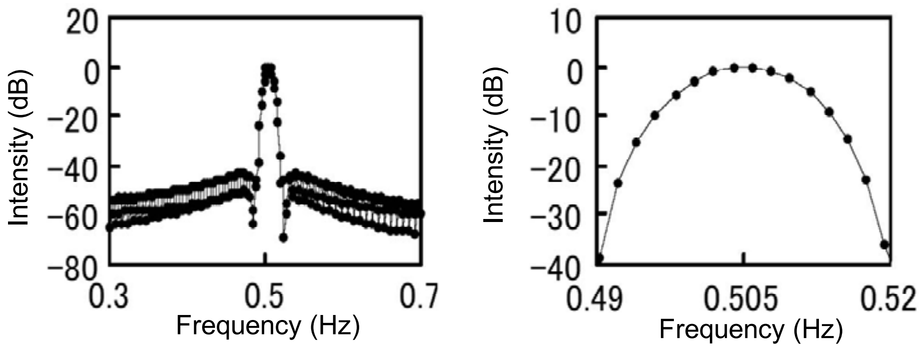
One sweep time of a 24 MHz radar shown in Table 1 is 0.5 second, and f_s is 2 Hz. The Zero-padding technique artificially increases N and makes δf smaller (improve the flow velocity resolution).

In order to confirm the effect of the Zero-padding technique using the Doppler spectrum, 256 time series data obtained by sampling sinusoidal waves at 2 Hz are made to undergo FFT. The result is shown in Figures 10 and 11. The frequency of sinusoidal waves is set at 0.505 Hz to cope with the Doppler shift at the flow velocity of 0 cm/s. The Zero-padding technique is not used in Figure 10, while the number of data is quadrupled by the Zero-padding technique in Figure 11. The points in the figure show the FFT output points.



(a) Spectrum as a whole (b) Enlarged view of peak

Figure 10. Result of FFT of sinusoidal wave (Without Zero-padding; with hamming window)



(a) Spectrum as a whole (b) Enlarged view of peak

Figure 11. Result of FFT of sinusoidal wave (With Zero-padding; quadrupled data; with hamming window)

The comparison between Figure 10 and Figure 11 shows that Figure 11 shows easier detection of the peak frequency of the spectrum because data have been interpolated by the Zero-padding technique. When the number of zero data increases further, the spectrum will become smoother, facilitating detection of the peak of the original received signal.

However, attention must be paid to the fact that the spectral band width is narrowed and a sharp peak is obtained when the observation time is extended and N is increased by actual data. However, Zero-padding is simply an act of interpolation, not producing a sharp peak.

Based on the above, the introduction of the STFT technique and the Zero-padding technique has permitted a shorter observation time and improved the flow velocity resolution simultaneously.

5. Verification by simulation of Doppler analysis

As a signal processing technique to obtain a resolution necessary for Tsunami observation, introduction of the STFT technique and the Zero-padding technique into the Doppler analysis was proposed in the previous Chapter. These techniques are applied to the observation of the flow velocity (Figures 4 and 5) of Tokachi-oki Earthquake Tsunami to simulate the Doppler analysis, and the proposed technique is verified in this Chapter. Since it is obvious that observation for approx. 8.5 minutes cannot follow the change in the flow velocity of Tsunami, the effect of the Zero-padding technique is verified, presupposing the application of the STFT technique.

(1) Verification method

The verification procedure is shown in Figure 12. First of all, an analysis signal that simulates a received signal is created. The analysis signal is created by allowing a Doppler-shift-frequency (±0.505 Hz) sinusoidal signal at the flow velocity of 0 cm/s to undergo the frequency modulation by the Doppler shift corresponding to the change in the flow velocity of Tsunami in Figure 5. Since attention has been paid to the time and frequency resolution in this study, the change in the amplitude of the analysis signal depending on the distance has not been taken into consideration, and the amplitude is fixed. The sampling frequency is set at 2 Hz in the same way as conventional radars.

Then this analysis signal is analyzed by the STFT technique to find the temporal change of the spectrum. Calculation is carried out in two cases using and not using the Zero-padding technique, respectively. Finally, the peak frequency of the primary scattering is obtained from the obtained Doppler spectrum and changed into a flow velocity to compare the result with the change in flow velocity shown in Figure 5. The details are shown in Table 3.

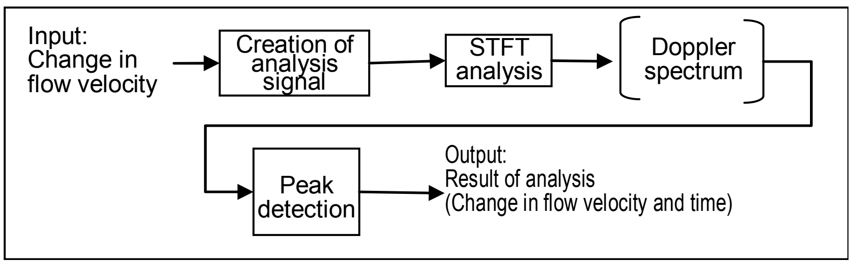


Figure 12. Verification procedure

Table 3. Details of verification method

Item		Set value
Change in flow velocity	Change in flow velocity of Tsunami	Simulation of flow velocity of Tokachi-oki Earthquake Tsunami (2003) (Fig. 5)
	Change in flow velocity in cases other than Tsunami	Not taken into consideration
Creation of analysis signal	Doppler frequency at flow velocity of 0 cm/s	±0.505 Hz (at flow velocity of 0 cm/s)
	Doppler shift equivalent to flow velocity of Tsunami	Frequency modulation by Doppler shift corresponding to flow velocity of Tsunami
	Sampling frequency	2Hz
	Amplitude of analysis signal	(Doppler frequency +/- both)
STFT analysis	Window function	Hamming window
	Length of window frequency	256 data (128 s)
	Window shift	128 data (64 s)
	Number of added zeros	• 3840 zeros (with Zero-padding) • None (without Zero-padding)
	Number of analysis data	• 4096 zeros (with Zero-padding) • 256 zeros (without Zero-padding)
Peak detection		Max. value of spectrum

(2) Result of verification

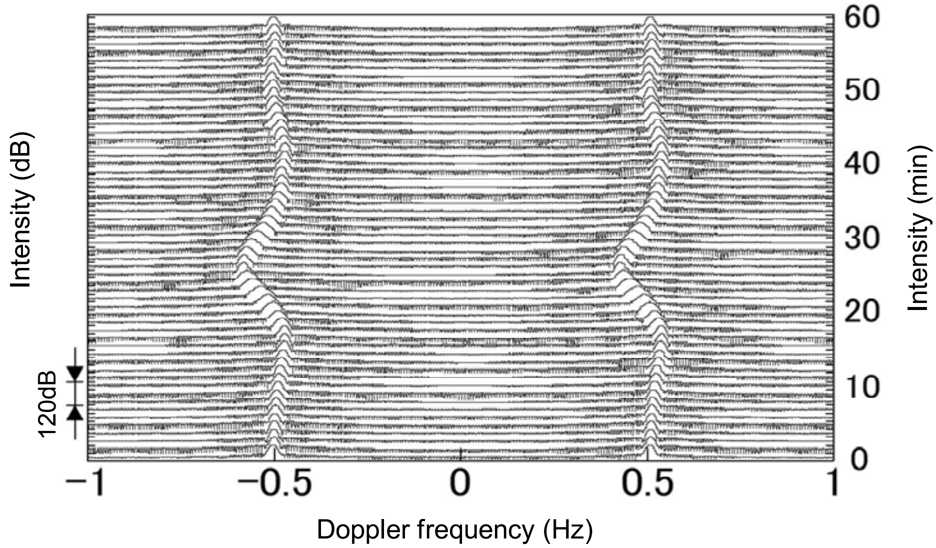


Figure 13. Temporal change of Doppler spectrum at 4.5 km point (With Zero-padding; 16 times as many data)

The temporal change of the Doppler spectrum obtained by inputting the change in flow velocity in Figure 5 (a) (4.5 km) is shown in Figure 13. It is shown that the Doppler spectrum that follows the change in input is obtained by the STFT technique.

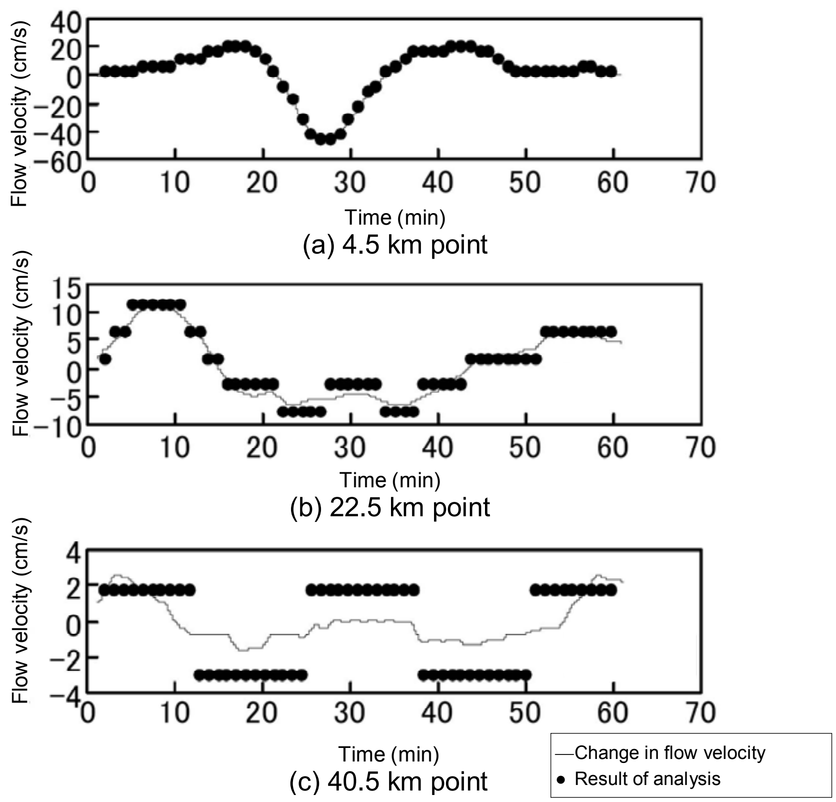


Figure 14. Result of analysis without Zero-padding

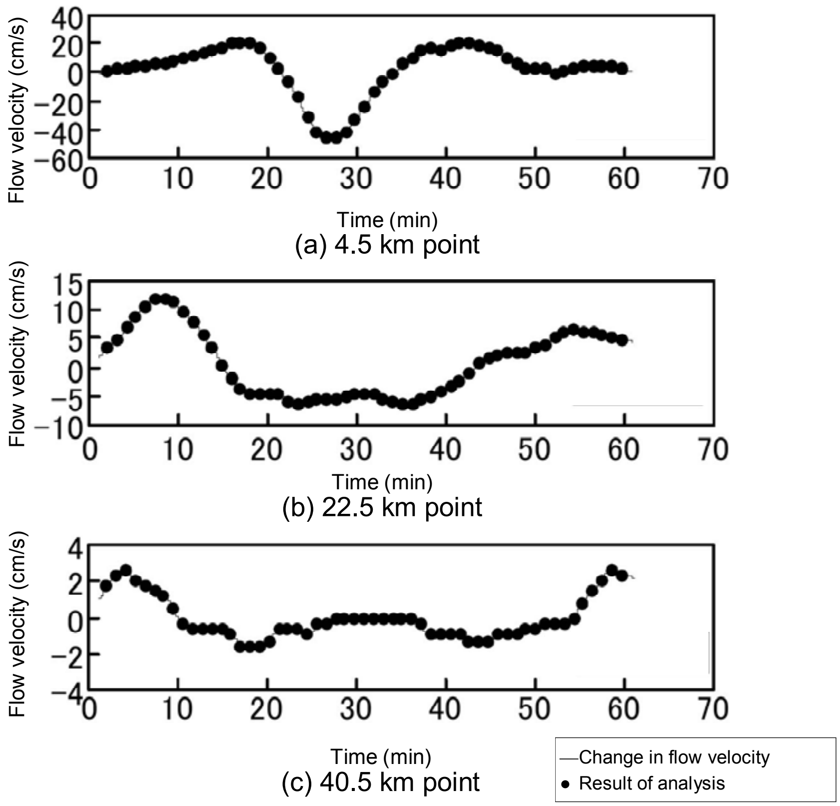


Figure 15. Result of analysis with Zero-padding

The flow velocity obtained from the maximum value of the obtained Doppler spectrum is shown in Figures 14 and 15. Figure 14 shows the cases where the Zero-padding technique is not used, while Figure 15 shows the cases where the said technique is used.

The change in flow velocity is large as compared with the flow velocity resolution of the radar in Figure 14 (a) (4.5 km), and the result of analysis almost follows the input even without Zero-padding. While in offshore areas, the resolution is insufficient because the change in the flow velocity of Tsunami is very small without Zero-padding as in the case of Figure 14 (b) (22.5 km) and (c) (40.5 km). However, the result of analysis follows even a very small change in flow velocity when the Zero-padding technique is used as shown in Figure 15 (a)-(c).

Based on the result shown above, it has been confirmed that the proposed technique permits high resolution, indicating a possibility of detection of a very small change in the flow velocity of offshore Tsunami by radars.

6. Summary

(1) Conclusions

- It is shown that the shortening of the observation time and improvement of flow velocity resolution are necessary for early detection of Tsunami.
- A signal processing technique that combines the STFT technique and Zero-padding technique is proposed for short-time observation and improvement of flow velocity resolution.
- The Doppler analysis simulation has verified that the proposed technique permits observation of the change in flow velocity due to Tsunami in a case study.

The above findings show that there is a possibility of detection of the change in flow velocity due to offshore Tsunami by radars.

(2) Future tasks

- In addition to Tsunami, tidal currents and wind currents exist in actual sea areas. Therefore, it is necessary to consider a technique to extract the two-dimensional distribution of the flow velocity of Tsunami, as well as the pattern of the change, based on flow velocity data.
- Before applying the Zero-padding technique, the Zero-padding quantity must be selected according to the desired resolution, and the selection standard must be considered.
- The Zero-padding technique artificially improves the flow velocity resolution, but the spectral band width does not change. It is necessary to consider a method to sharpen the spectrum according to the required flow velocity resolution.
- The effect of noise is conceivable during actual observation, and the decrease in the maximum observation range resulting from the decrease in the S/N ratio due to the proposed technique must be taken into consideration.

ACKNOWLEDGMENTS

The authors are grateful to Mr. Hirofumi Hinata, Head of Marine Environment Division, Coastal and Marine Department, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism, for the actual observation data collected by Oceanographic radars.

REFERENCES

Barrick, D.E. 1979. A Coastal Radar System for Tsunami Warning, *Remote Sensing of Environment*, Vol.8, 353-358.

Izumiya, T. and T. Imai. 2005. Real-Time Tsunami Prediction Using Surface Current Velocities Retrieved by HF Ocean Radar, *Annual Journal of Coastal Engineering*, Vol.52, 246-250.

Izumiya, T. and T. Nakajima. 2006. Real-Time Prediction of Tsunami Using a Time-Averaged Surface Current, *Annual Journal of Coastal Engineering*, Vol.53, 246-250.

Japan Society of Civil Engineers. 2001. *Coastal Marine Observation by Land-Based Radar,* Japan Society of Civil Engineers, 212pp.

Mansinha, L. and D.E, Smylie. 1971. The displacement fields of inclined faults, *Bulletin of the Seismological Society of America*, Vol.61, No. 5, 1433-1440.

Tanioka, Y., K. Hirata, R. Hino, and T. Kanazawa. 2004. Slip distribution of the 2003 Tokachi-oki earthquake estimated from the tsunami waveform inversion, *Earth, Planets and Space*, Vol.56, 373-376.

Watanabe, K. and T.Tomita, 2007. Study of Method to Remove Wind Current Component toward Materialization of Tsunami Observation by Ocean HF Radar, *Annual Journal of Civil Engineering in the Ocean*, Vol.23, 1129-1134.