MITSUBISHI-B Project:

Title:

Novel technique to estimate wave spectra using ocean HF radar for environmental monitoring

Industrial Partner:

MITSUBISHI Electric Corp., Information Technology R&D Center.

Mitsubishi Electric is a world leader in the manufacture and sales of electrical and electronic products and systems used in a broad range of fields and applications. As a global leader among green companies, our technologies are being applied to contribute to and support society and daily life around the world. The Information Technology R&D Center is actively creating new businesses through basic research and development in the fields of information technology, media intelligence, electro-optics microwaves, and communication technologies. We are also seeking technologies that reinforce our position on the leading edge of progress, with work to renew existing businesses through the fruits of our R&D in the field of IT.

Industry Mentors

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Introduction

Since ancient times, humans have lived in close contact with the ocean through fishing and maritime trade, and this relationship has expanded further in the 20th century as human activities have increased in quantity and quality. The direct benefits we derive from the ocean include sea food, maritime transportation, water and mineral resources, and energy. Especially in recent years, various oceanographic surveys and studies have revealed the existence of unutilized energy and mineral resources in the oceans.

The observation of sea surface conditions is necessary to realize these goals. Observation results are utilized for disaster prevention and mitigation through marine warnings, as well as for providing information on sea conditions necessary to improve the efficiency and safety of the marine transportation and fishery industries. They are also used to determine the location of oil spills, floating debris, and people in distress, and to design coastal structures such as breakwaters and harbors.

Sea surface observations by ocean HF radars include ocean current velocity observations, wave height observations, and tsunami observations. In this project, we focus on wave height observation. Wave height observations capture statistical characteristics such as temporal and spatial changes of the wave height. Since the wave height characteristics are inherently inhomogeneous and change from moment to moment in each area of the sea, we divide a wide area of the sea surface into grids and observe the wave height characteristics and their temporal variation for each grid. The wave height characteristics of each grid are captured as wave spectra (also called directional spectra). The wave spectra represent the wave height values for each direction and frequency component of the waves in the sea surface grid.

Ocean HF radar is a sensor that obtains wave spectra utilizing Bragg resonance phenomena of wave components to radar signals. Ocean environmental monitoring including wave height observation by ocean HF radar has been conducted not only in Japan and the United States, but also in the Asia-Pacific region, China, and Europe[1][2][3][4][5].

Technical Background

1. Principle of Radar

The principle of object sensing by radar is to transmit radio waves toward an object and receive the reflected waves to measure the object's range, velocity, and direction. The range is determined immediately from the time difference between transmission and reception, i.e., the round-trip time of the radio wave. Velocity is radial velocity relative to the radar station, which is determined by Doppler frequency analysis of the received signal. The direction is immediately determined from the direction in which the radar antenna beam is pointed.

Fielded radars, including ocean HF radars, operate in complex radio propagation environments and are required to detect and track desired signals while suppressing unwanted signals. This requires complicated sensor processing systems that apply state-of-the-art technology, but the basic principles remain the same as described in the previous paragraphs. In this project, it is sufficient to understand what is explained in the following paragraphs in order to tackle the project theme.

Ocean HF radar is installed along the coastline. The radar transmits the radio waves to the wide area of sea surface and receives the reflected echoes from the sea surface. The received signals are measured in grids separated by direction and range, as shown in Figure 1. The width of the direction and range separations is determined by the radar's azimuth and range resolutions, which in this project are approximately 7.5 deg and 1500 m, respectively. After repeating this measurement for several seconds, a Doppler spectrum is obtained from the received signal for each grid.

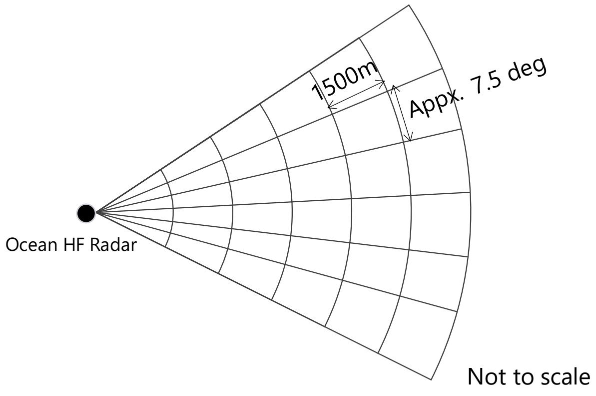


Figure 1 Radar Range-Direction Grids

2. Doppler Spectra of Sea Echoes

The random motion of the sea surface that we see can be decomposed into component waves with frequency and direction, as shown in Figure 2. Ocean HF radar uses the Bragg resonance of the component waves of sea-surface motion relative to the radio wavelength, and receives the reflected echoes of the sea surface that are scattered back to the radar, i.e., Bragg scattered waves.

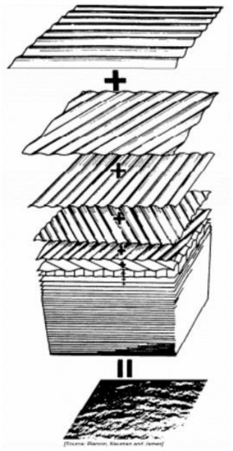


Figure 2 Decomposition of Random Sea Surface Motion[6]

Figure 3 is a schematic illustration of first-order Bragg scattering, in which reflected waves from adjacent wave peaks are in phase with each other and strengthen and resonate with each other. In other words, Bragg scattering occurs when the distance λ between the peaks is half the radio wavelength λ_0. In this figure, the sea surface is represented as if it were stationary, but in reality, the sea surface moves in the right and left directions, i.e., advancing wave and receding wave toward the radar. Therefore, the first-order Bragg scattering in the received signal is observed as two Doppler frequency components with different signs.

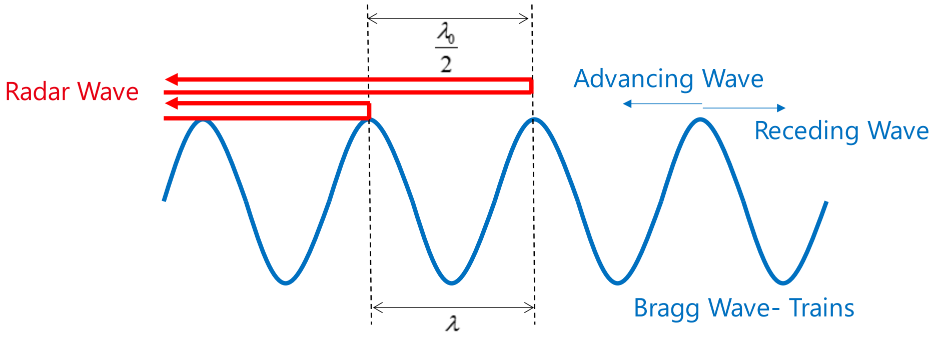


Figure 3 First-order Bragg Backscatter

Mathematically, it can be expressed by the following equations.

$$\mathbf{k}_B = \pm 2\mathbf{k}_0 \tag{1}$$

$$f_B = \pm\sqrt{\frac{g}{\pi\lambda_0}} \tag{2}$$

where $\mathbf{k}_0$ and $\mathbf{k}_B$ are the radio wavevector and the ocean wavevector corresponding to first-order Bragg scattering respectively. f_B and g are the first-order Bragg frequency and the acceleration of gravity respectively. Figure 4 is given to confirm (1).

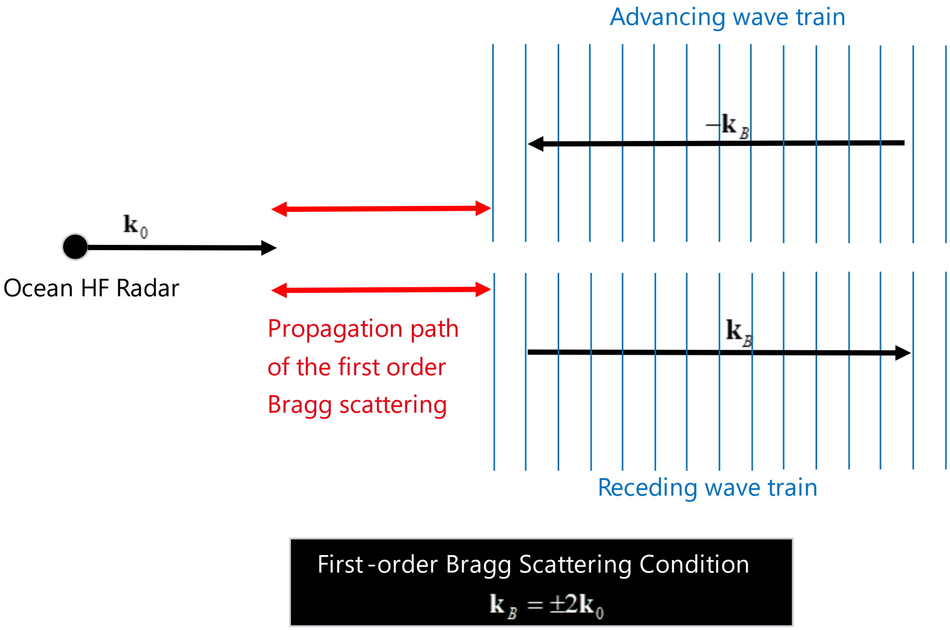


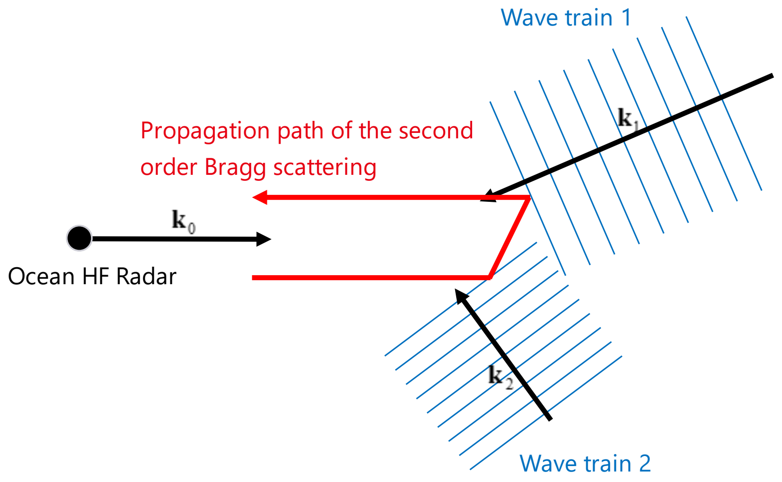
Figure 4 First-order Bragg Backscatter Condition

Second-order Bragg scattering results from a combination of electromagnetic and hydrodynamic effects. The former is the Bragg resonance due to two reflections at the sea surface, and the latter is the Bragg resonance due to the synthesis of two wave components.

Second-order Bragg scattering due to electromagnetic effects occurs via two wave components to produce an intermediate and twice scattered radio wave directed toward the radar. Figure 5 schematically illustrates the mechanism of this occurrence. Mathematically, it can be expressed by the following equation.

$$\mathbf{k}_1 + \mathbf{k}_2 = -2\mathbf{k}_0 \tag{3}$$

where $\mathbf{k}_1$ and $\mathbf{k}_2$ are the ocean wavevectors.



Condition of the Second -order Bragg Scattering

$$\mathbf{k}_1 + \mathbf{k}_2 = -2\mathbf{k}_0$$

Figure 5 Second-order Bragg Scattering due to Electromagnetic Effects

Second-order Bragg scattering due to hydrodynamic effects occurs when the wavelength of the interacted wave in the two intersecting wavenumber vectors is half the radio wavelength in the radar line-of-sight direction, similar to the mechanism that generates first-order Bragg scattering. This scattering process is expressed by (3).

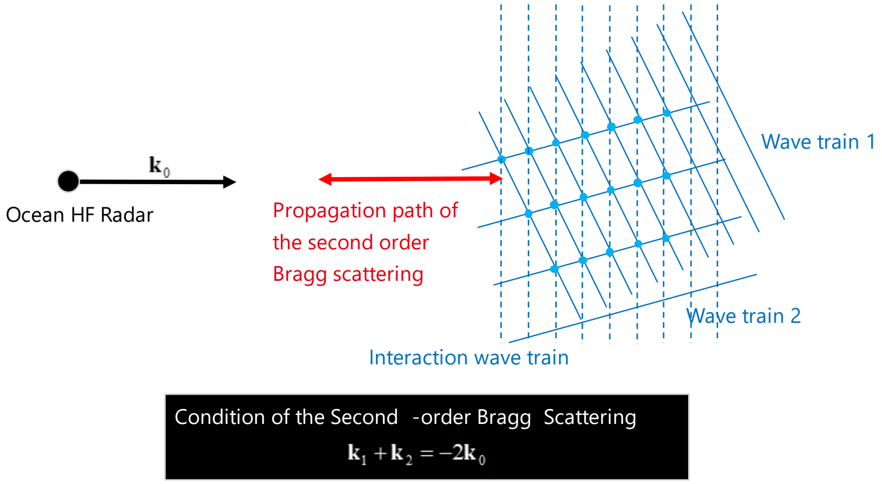


Figure 6 Second-order Bragg Scattering due to Hydrodynamic Effects

The Bragg scattering wave received over a predefined observation time, typically a few minutes, is analyzed as a Doppler spectrum using the discrete Fourier transform of the received radar signal. A typical Doppler spectrum measured at certain range and angle is shown in Figure 7. In this figure, the Bragg peak is the Doppler spectrum due to first-order Bragg scattering, and the Doppler frequency offset Δf is due to the ocean current velocity observed in the radar line-of-sight direction.

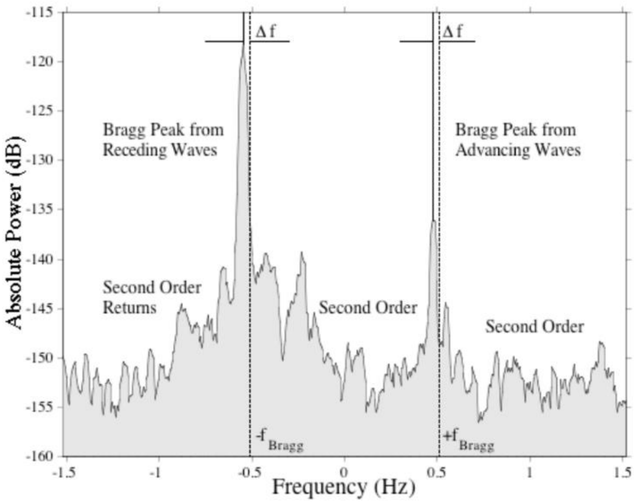


Figure 7 A typical Doppler spectrum [7]

The Doppler spectrum of Bragg scattering $\sigma(\omega)$ where $\omega(=2\pi f)$ is the Doppler frequency in radians per second is given by

$$\sigma(\omega) = \sigma_{(1)}(\omega) + \sigma_{(2)}(\omega) \tag{4}$$

where $\sigma_{(1)}(\omega)$ and $\sigma_{(2)}(\omega)$ are the Doppler spectrum of first- and second-order Bragg scattering[1].

The relationship between the Doppler spectrum of Bragg scattering and wave spectrum has been studied theoretically[8]. The Doppler spectrum of first-order Bragg scattering is given by

$$\sigma_{(1)}(\omega) = 2^6 \pi k_0^4 \sum_{m=\pm 1} S(-2m\mathbf{k}_0)\,\delta(\omega - m\omega_B) \tag{5}$$

where $k_0 = |\mathbf{k}_0| = 2\pi/\lambda$ is radio wavenumber, $S(\mathbf{k})$ is the wave spectrum for wavevector $\mathbf{k}$ and $\delta(\omega)$ is the Dirac delta function. $\omega_B = \sqrt{2gk_0}$ is known as the first-order Bragg angular frequency. Clearly (5) is a mathematical expression of the first-order Bragg scattering mechanism described above with Figure **4**. In actual ocean HF radar operations, Bragg first-order scattering is used for ocean current velocity estimation by measuring the Doppler frequency offset Δf as seen in Figure 7.

The wave spectrum on which this project focuses are estimated based on the theoretical equation for second-order Bragg scattering, which will be explained below. The Doppler spectrum of second-order Bragg scattering is given by

$$\begin{aligned}\sigma_{(2)}(\omega) = 2^6 \pi k_0^4 \sum_{m_1=\pm 1} \sum_{m_2=\pm 1} \iint_{-\infty}^{+\infty} \left|\Gamma(m_1\mathbf{k}_1, m_2\mathbf{k}_2)\right|^2 S(m_1\mathbf{k}_1)\, S(m_2\mathbf{k}_2) \\ \times \delta\left(\omega - m_1\sqrt{gk_1} - m_2\sqrt{gk_2}\right) dpdq\end{aligned} \tag{6}$$

where $k_1 = |\mathbf{k}_1| = 2\pi/\lambda_1$ and $k_2 = |\mathbf{k}_2| = 2\pi/\lambda_2$ are the ocean wavenumbers respectively and $\Gamma(m_1\mathbf{k}_1, m_2\mathbf{k}_2)$ is the coupling coefficient. The integral variable p and q is the variable associated with the radar and ocean wavenumber vectors by the following relationship

$$\mathbf{k}_0 = (k_0, 0),\ \mathbf{k}_1 = (p - k_0, q),\ \mathbf{k}_2 = (-p - k_0, -q) \tag{7}$$

The coupling coefficient $\Gamma(m_1\mathbf{k}_1, m_2\mathbf{k}_2)$ is the sum of $\Gamma_E(\mathbf{k}_1, \mathbf{k}_2)$ due to electromagnetic effects and $\Gamma_H(m_1\mathbf{k}_1, m_2\mathbf{k}_2)$ due to hydrodynamic effects, each given as in (8) and (9).

$$\Gamma(m_1\mathbf{k}_1, m_2\mathbf{k}_2) = \Gamma_E(\mathbf{k}_1, \mathbf{k}_2) + \Gamma_H(m_1\mathbf{k}_1, m_2\mathbf{k}_2) \tag{8}$$

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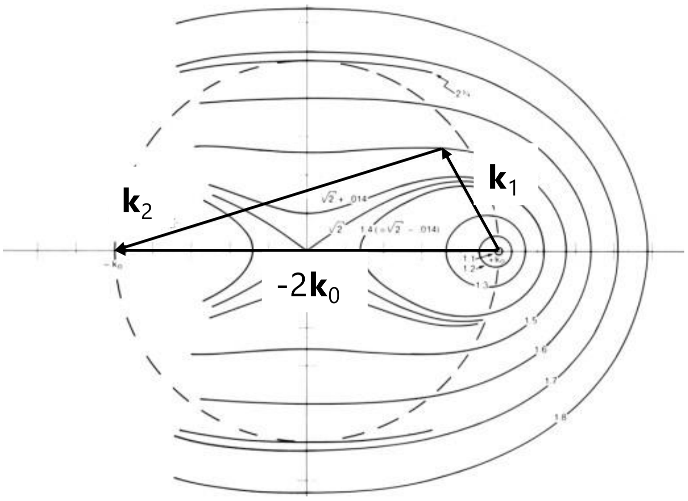
[1] In theory, the term for the Doppler spectra of higher-order Bragg scattering is added to (4), but it is typically negligible and will not considered here.

$$\begin{cases} \Gamma_E\left(\mathbf{k}_1,\mathbf{k}_2\right)=\dfrac{1}{2}\left(\dfrac{\left(\mathbf{k}_1\cdot\mathbf{k}_0\right)\left(\mathbf{k}_2\cdot\mathbf{k}_0\right)/k_0^2-2\mathbf{k}_1\cdot\mathbf{k}_2}{\sqrt{\mathbf{k}_1\cdot\mathbf{k}_2}-k_0\Delta}\right) \\ \Gamma_H\left(m_1\mathbf{k}_1,m_2\mathbf{k}_2\right)=-\dfrac{i}{2}\left(k_1+k_2-\dfrac{\left(k_1k_2-\mathbf{k}_1\cdot\mathbf{k}_2\right)}{m_1m_2\sqrt{\mathbf{k}_1\cdot\mathbf{k}_2}}\dfrac{\left(\omega^2+\omega_B^2\right)}{\left(\omega^2-\omega_B^2\right)}\right) \end{cases} \tag{9}$$

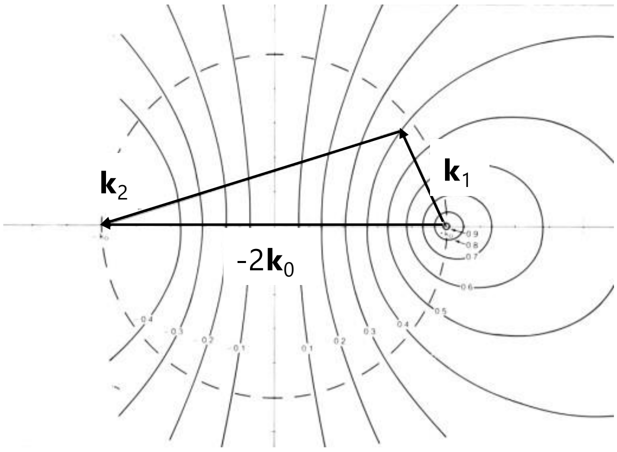
where Δ is the average normalized impedance of the seawater and typical value is $\Delta=0.011-0.012i$.

As shown in (6) through (9), two wavevectors $\mathbf{k}_1$ and $\mathbf{k}_2$ are involved in second-order Bragg scattering. There are various combinations of $\mathbf{k}_1$ and $\mathbf{k}_2$ that yield a given Doppler frequency that satisfy (3), subject to the Dirac delta function $\delta\left(\omega-m_1\sqrt{gk_1}-m_2\sqrt{gk_2}\right)=1$ in (6). Other than $S\left(m_1\mathbf{k}_1\right)S\left(m_2\mathbf{k}_2\right)$, which is determined by the combination of $\mathbf{k}_1$ and $\mathbf{k}_2$, the other elements contributing to the Doppler spectrum are the coupling coefficient $\Gamma\left(m_1\mathbf{k}_1,m_2\mathbf{k}_2\right)$.

Given a Doppler frequency ω, (6) implies that the Doppler spectrum $\sigma_{(2)}\left(\omega\right)$ is determined by the integral values of the integrating variables p and q. The integration path follows a curve on the pq plane, as shown in Figure 8, that is determined for each Doppler frequency ω of interest. Note that the Doppler frequencies in the figure are normalized by the Doppler frequency ω_B of the first-order Bragg scattering.



(a) $|\omega| > \omega_B$



(b) $|\omega| < \omega_B$

Figure 8 Normalized constant Doppler frequency contours on pq plane [8] (Note that some edits were made to the original figure)

3. Directional Wave Spectrum Estimation from the Doppler Spectrum

In this project, we work on a method to estimate the wave spectrum $S(\mathbf{k})$ contained in the right-hand side of equation (6) from the measured Doppler spectrum $\sigma_{(2)}(\omega)$ (left-hand side of equation (6)). Although many estimation methods have been proposed, such as those described in [8]-[13] , only a few of them are feasible with a single ocean HF radar, which is the premise of this project.

The Barrick method [8] is a classical method for estimating wave spectrum using a single radar. In this method, the wave spectrum is assumed to have a small directional dependence, and the frequency spectrum of the ocean wave is obtained. Specifically, based on this assumption, (6) is approximated as a linear integral, the measured Doppler spectrum is multiplied by a weight function, normalized by the first-order Bragg scattering spectrum, and integrated along the frequency axis. The Barrick method is widely known because it is a relatively simple estimation method, although the accuracy of the obtained frequency spectrum and wave height which is estimated by the frequency spectrum may not be sufficient because it ignores the directional dependence of the wave spectrum.

The Hisaki method [11][12][13] avoids the approximation to (6) as in the Barrick method and directly solves the same equation. (6) is the integral of the wave spectrum along an iso-Doppler frequency curve defined on a plane determined by the wave frequency and direction. The Hisaki method interpolates the wave spectrum at any point on this curve with the wave spectrum at surrounding grid points. This allows (6) to be rewritten with the wave spectrum at each grid point. The objective function is then given by adding the energy balance equation, foresight conditions on the wave spectrum, etc., and the wave spectrum is estimated by solving an optimization problem. Although the Hisaki method has the problem of a large number of unknowns, measurement data have shown that wave spectrum estimation is possible using the Doppler spectrum of second-order Bragg scattering, which has high receiver sensitivity.

Expectations

In this project, we expect you to propose a new estimation method for the wave spectra described above. To validate the proposed method, Industrial Mentor will provide measured Doppler spectral data and information on the significant wave height as a reference for the estimation results. The Doppler spectral data may contain signals other than Bragg scattered waves, such as ship reflection signals and radio wave interferences, which will be notified when the Doppler spectral data is provided.

Requirements

We welcome students who are motivated to contribute to industry and achieve personal growth by solving problems faced by radar systems that measure the real world. To solve the problems, students should have basic knowledge of optimization and basic programming skill (e.g. Python, MATLAB). In addition, it is desirable for the candidate to have knowledge on statistical signal processing Note that knowledge of radar technology is not necessarily required. Whatever knowledge is needed has been described above will be explained by the industrial mentors at the beginning of this project.

References

[1] Fujii, S., Heron, M.L., Kim, K. et al. “An overview of developments and applications of oceanographic radar networks in Asia and Oceania countries,” Ocean Sci. J. 48, 69–97 (2013).

[2] J. Harlan, E. Terrill, L. Hazard, C. Keen, D. Barrick, C. Whelan, S. Howden, J. Kohut, “The Integrated Ocean Observing System High-Frequency Radar Network: Status and Local, Regional, and National Applications,” Marine Technology Society Journal. 44. Pp.122-132, 2010.

[3] IOOS HF Radar (https://hfradar.ioos.us/)

[4] J. Mader, A. Rubio, J. Asensio, A. Novellino, M. Alba, L. Corgnati, C. Mantovani, A. Griffa, V. Fernandez, P. Gorringe, “The European HF Radar Inventory,” EuroGOOS HF Radar Task Team Publication, 2016.

[5] High Frequency Radar – EuroGOOS (https://eurogoos.eu/high-frequency-radar-task-team/)

[6] Journée, J.; Massie, W. Offshore Hydromechanics; Delft University of Technology: Delft, The Netherlands, 2001; p. 153.

[7] J. Paduan, H. Graber. “Introduction to High-Frequency Radar: Reality and Myth.” Oceanography 10 (1997): 36-39.

[8] B.J. Lipa, D.E. Barrick, “Extraction of sea state from HF radar sea echo: Mathematical theory and modeling,” Radio Sci., 21, 1, pp.81-100, 1986.

[9] C. de Valk, A. Reniers, J. Atanga, A. Vizinho, and J. Vogelzang, “Monitoring surface waves in coastal waters by integrating HF radar measurement and modelling,” Coastal Eng., vol.37, Aug. 1999, pp.431-453.

[10] K. -W. Gurgel, H. -H. Essen and T. Schlick, “An Empirical Method to Derive Ocean Waves From Second-order Bragg Scattering: Prospects and Limitations,” IEEE Journal of Oceanic Engineering, vol. 31, no. 4, pp. 804-811, Oct. 2006.

[11] Y. Hisaki, “Ocean Wave Directional Spectra Estimation from an HF ocean radar with a Single Antenna Array: Methodology,”J. Atomospheric and Oceanic Technology, vol.23, issue 2, 2006.

[12] Y. Hisaki, “Development of HF radar inversion algorithm, for spectrum estimation (HIAS),” J. Geophys. Res. Oceans, 120, 1725-1740, 2015.

[13] Y. Hisaki, “Ocean wave parameters and spectrum estimated from single and dual high-frequency radar systems,” Ocean Dynamics 66, 1065–1085, 2016.