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Performance Improvement of Wave Information Retrieval Algorithm Using Noise Reduction

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Abstract

This paper describes the upgrade of an existing wave information retrieval algorithm by employing noise reduction in the pixel domain. Several algorithms for collecting wave information parameters from X-band radar image sequences including the wind field and current velocity have been developed over the past three decades. Using these algorithms, a band-pass filter (BPF) is applied to remove the non-wave contribution from the image spectra after the sea surface current velocity has been computed. However, such BPF designs have been both complex and insufficient in removing undesired components in X-band radar images. For this study, to improve the performance of wave information retrieval, an efficient noise reduction algorithm is incorporated into a regular wave information retrieval process. That is, the proposed algorithm was designed for operation in a more proper manner by effectively removing the undesired components in the pixel domain. Experiment results demonstrate that the proposed algorithm produces very close estimates to the buoy data records under undesirable noise conditions.

Index Terms: Noise reduction, Ocean wave information, Radar images, 3-D FFT

I. INTRODUCTION

As marine traffic highly increases, ocean wave information parameters are becoming extremely important for the safe routing of marine transport. Conventionally, X-band radar images have been successfully employed in retrieving wave information parameters over the past three decades because X-band radar can cover a large area with a high resolution in real time. The X-band radar measurements of sea states are based on an analysis of the spatio-temporal evolution through ripples and the roughness of the sea surface. To retrieve ocean wave parameters from X-band radar, sea current velocities must first be determined. Young et al. [1] proposed a wave spectral representation algorithm by applying a 3-D fast Fourier transform (FFT) to a series of gray-scaled radar image sequences. Subsequently, several modified algorithms have been presented in improving the performance of wave extraction [2-10]. In [2], a weighted least-squares fitting technique was presented by introducing significant computational burden and additional noise reduction processing to avoid some of the error sources. In [3], a modified least squares algorithm was proposed by computing the current velocity iteratively with a fixed number of iterations based on the higher order harmonic dispersion relation. In [4], instead of using a fixed number of iterations, an iterative least squares algorithm was presented by employing an iteration-terminating criterion.

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However, the usual measurements of offshore sea states using X-band radar include undesired components such as moving vessels and the waves they create. These affect the non-wave contribution of the image spectra and lead to incorrect wave parameters. Conventionally, existing algorithms have employed a band-pass filter (BPF) in the angular frequency using the dispersion relationship to remove the noise components [2-4]. However, a complete BPF design is not only complex but also insufficient in removing undesired components. In particular, in the presence of moving vessels and their waves, the extracted wave parameters tend to be distorted. This paper presents an enhanced wave information retrieval algorithm using noise reduction. That is, the proposed algorithm is designed in such a way that it can effectively remove the undesired components in the pixel domains of X-band radar image sequences, which leads to more correct wave information extraction.

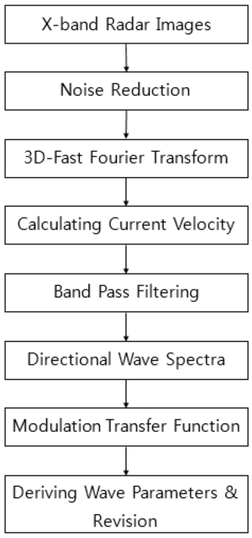


Fig. 1. Proposed control flow for wave information retrieval.

II. PROPOSED WAVE INFORMATION RETRIEVAL ALGORITHM

A. Proposed Control Flow

Fig. 1 indicates the proposed control flow for the wave information retrieval algorithm. When radar frame sequences are successively available, a noise reduction algorithm is first employed for the corresponding frame to remove non-wave contribution in pixel domain. After noises are removed, a three-dimensional (3-D) FFT is introduced. That is, in this paper, 3-D FFT analysis is applied to a sub-area region of 128×128 pixels extracted from 64 consecutive frames [1]. Fig. 2 shows an example of a radar image and its normalized wave energy in a 2-D spectral domain. In Fig. 2, the red region indicates the spectral peak locations, and the other colors indicate the magnitudes of other frequency components, relative to the spectral peak frequency.

After a 3-D FFT and wave analysis, a current estimation algorithm should be employed. In [4], four different current estimation methods are compared, and the iterative least-squares (LS) method showed very reliable results [3]. In the iterative LS method, the fundamental and higher harmonics components are both classified in samples of the image spectra, and the current velocity is then iteratively computed. In this paper, to determine the current velocity, the iterative LS method is incorporated into the proposed control flow. Subsequently, band-pass filtering removes the non-wave contribution in the spectral domain. To discriminate the fundamental wave component from the undesired components, the current-included dispersion relationship is considered. A modulation transfer function (MTF) procedure is then employed to convert the derived directional wave spectra into wave spectra, based on the Doppler shift dispersion relationship [4]. Finally, the proposed algorithm derives wave parameters including the mean wave direction, peak wave heights, mean wave period, and peak wave frequency.

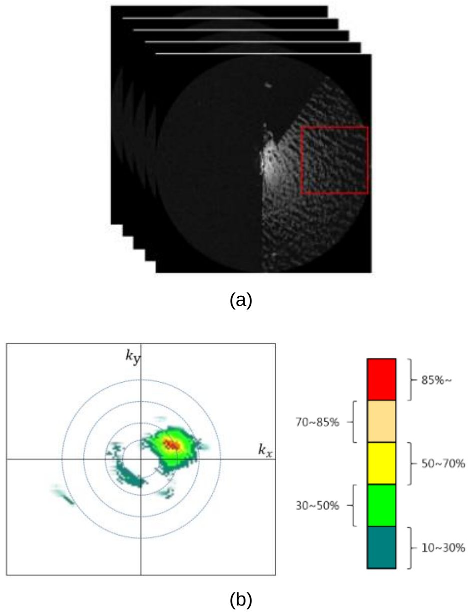


Fig. 2. Radar image and two dimensional normalized wave energy spectral representation. (a) Radar image and sub-area region for 3-D FFT and (b) spectral representation.

B. Noise Reduction Algorithm

Fig. 3 shows the proposed control flow for reducing noises in the pixel domain. Whenever a new frame is captured from

X-band radar, the frame is stored into the frame memory to obtain a moving average frame, which allows short-term noises to be decoupled by averaging the last N-frames. Then, the residual signal is obtained by subtracting it from the current frame. The residual signal may include the undesired noise components such as moving vessels and their waves. The absolute values of the residual signal instead of the signed values produce a wedge-shaped histogram. The distinct peak of the 1-D histogram is typically observed in the case of including significant noises. To separate the noise components effectively, a threshold is adaptively determined based on the following pseudo-code. Then, the residual signal is converted into a binary image where two levels are assigned to pixels that are below or above the determined threshold.

In addition, to remove the undesired noises such as from moving vessels and their waves in a binary image, a morphological operation is introduced. In this paper, an opening operation is employed to remove small objects from the foreground of an image, placing them in the background.

Input : a histogram of absolute values of residual signal

$$h = \{\, h(q) : q = 0, \ldots, 255 \,\}$$

Initialization : $j = 0;\ M = \sum_{q=0}^{255} h(q),\ T_0 = \frac{1}{M}\sum_{q=0}^{255} q h(q)$

do

$$\mu_{j,1} = \frac{\sum_{q=0}^{T_j} q h(q)}{\sum_{q=0}^{T_j} h(q)}, \quad \mu_{j,2} = \frac{\sum_{q=T_j+1}^{255} q h(q)}{\sum_{q=T_j+1}^{255} h(q)}$$

$$T_{j+1} = \frac{\mu_{j,1} + \mu_{j,2}}{2}$$

$$j = j+1$$

until $T_j \neq T_{j-1}$

Threshold $= T_j$

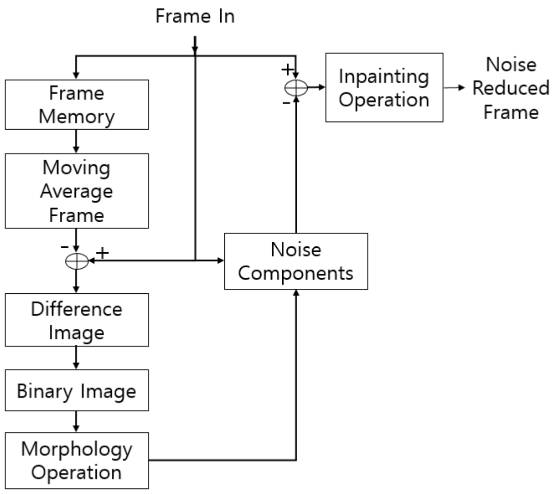
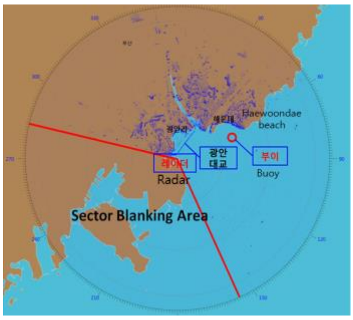
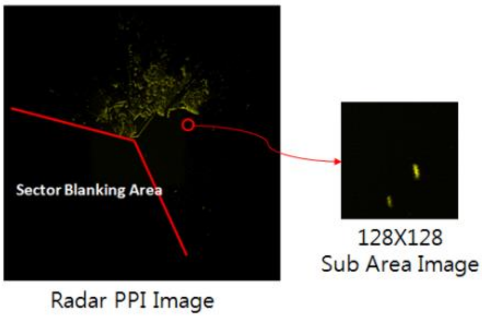


Fig. 3. Proposed control flow for noise reduction.



(a)



(b)

Fig. 4. Radar and buoy site for experimental tests. (a) Radar and buoy site (Yongho Quay near Haewoondae beach on the southeast coast of Korea). (b) Radar PPI image.

Once the morphological operation is completed, the undesired noise signals are determined by comparing the result with the input frame. However, the missing or damaged portions corresponding to the determined noise signals should be recovered to make it more legible. Because it is assumed that an understanding of the self-similarity is present in a radar image, in this paper, a non-local inpainting technique is employed [6] and therefore, a series of operations lead to a noise-reduced frame.

III. WAVE SPECTRAL MEASUREMENTS AND PERFORMANCE EVALUATIONS

Field data were collected from July 21, 2015 to September 27, 2016 at Yongho Quay near Haewoondae beach on the southeast coast of Korea, as shown in Fig. 4(a). The radar images in Fig. 4(b) were generated using the parameters listed in Table 1. In addition, to validate the results retrieved from the proposed algorithm, a wave buoy moored approximately 0.8 km offshore was employed [7].

The radar signals were measured only when a variety of noises and a local wind were present. The pixel resolution of a radar plan position indicator (PPI) image is 4096×4096. A sub-area region of 128×128 pixels utilizing 64 consecutive images is selected, and for the selected area, noise is removed and a 3-D FFT technique is applied to retrieve the wave information.

Table 1. Units for magnetic properties

	Radar system specifications
Antenna angular speed (rpm)	20
Antenna height (m)	20
Range resolution (m)	5.85, 2.9, 3.4 (for each measurement)
Image size	4096×4096
Radar location	35°07.097N, 129°07.24E
Buoy location	35°08.056N, 129°10.11E

A. Effects of Noise Reduction

As shown in Fig. 5(a), the traces of vessel movement are included in the selected sub-area images. Through a 3-D FFT analysis, a peak frequency of 0.04 Hz and a peak direction of 72° are found. These parameters correspond to waves with a period of about 25 seconds and wavelengths of a wave propagating in a NE direction. These results are slightly different from the buoy data. However, as indicated in Fig. 5(b), when the proposed algorithm is applied to the radar signal in the selected sub-area region, it is shown that noises are effectively reduced. In addition, a 3-D FFT is applied, which makes sure that the center wave number of the spectral peaks is very similar to the buoy data, indicating a peak direction of 90°.

On the other hand, Fig. 6(a) shows that the radar image includes a significant amount of noises in the sub-area region. Because of these noises, the spectral peak is estimated as a wave propagating in a westward direction, whereas the buoy data indicate a wave in a SE direction. Although a large amount of noises are present, it was observed that they can be effectively removed using the proposed algorithm, as shown in Fig. 6(b), and the radar retrieved frequency spectra with high energy agrees well with the buoy result. According to these experimental results, it is clear that the wave peaks and dominant wave directions can be refined to be close to the buoy data records.

B. Performance Comparisons of Wave Information Retrieval

Because the directional buoy data are the average values over a 5-min period, it is necessary for the radar data to be averaged over a comparable period [7]. The estimated wave directions from the radar data are shown in Fig. 7, which compares the performance between the proposed algorithm and conventional algorithms. The buoy data in Fig. 7(a) indicate that the wave direction is almost constant, and that the proposed algorithm is close to the buoy records and the estimation error is the lowest. Fig. 7(b) indicates when the

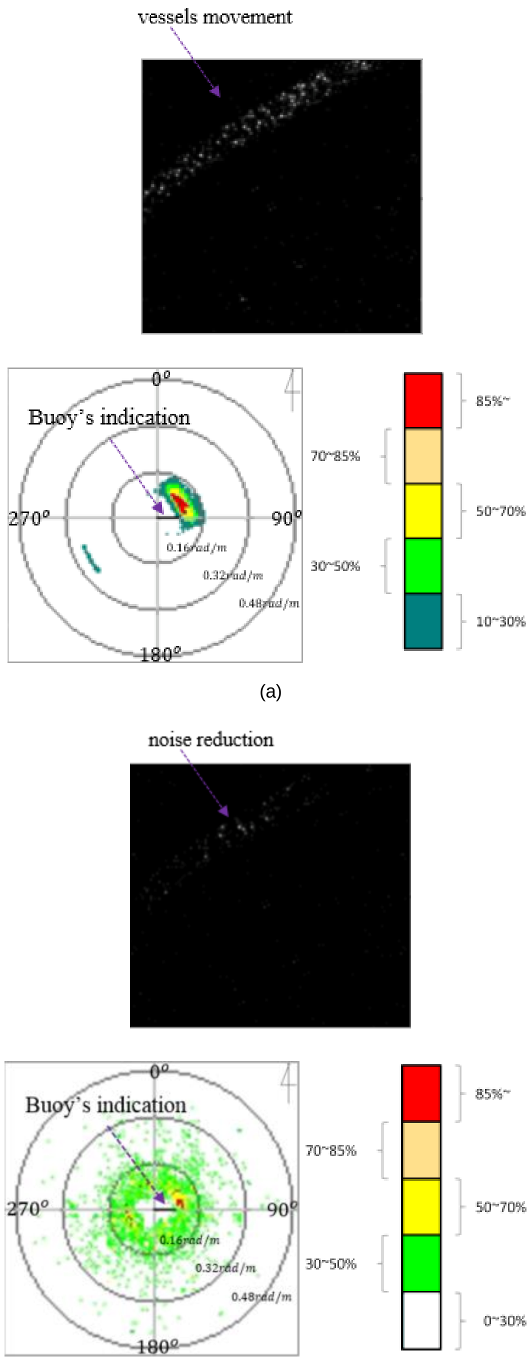
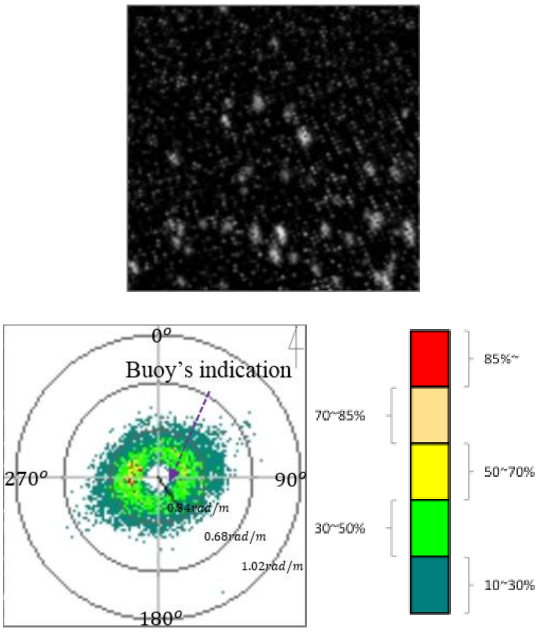


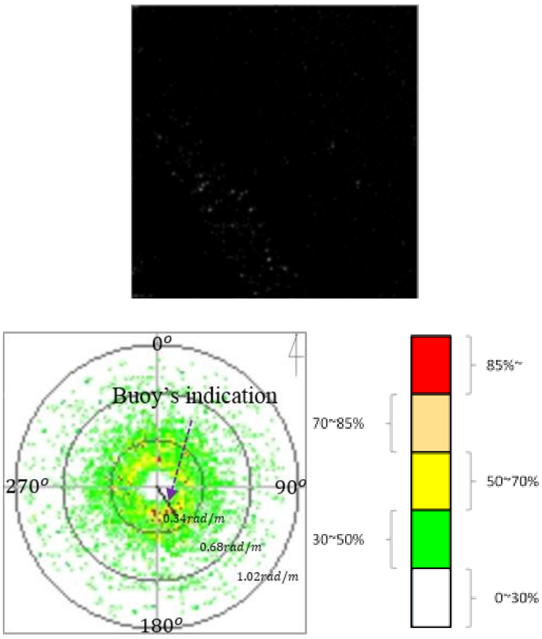
Fig. 5. Performance improvement for radar image with traces of vessel movements. (a) Before the noise reduction aid its spectral representation. (b) After the noise reduction and its spectral representation.

wave direction varies, and it is also clear that the proposed algorithm agrees well with the buoy results.

Fig. 8 compares the estimated wave heights derived by the radar data, including the buoy data. It may be observed that the estimated results by the proposed algorithm agree well with the buoy measurements. As shown in Fig. 8(b), although the wave direction varies, it was observed that the wave heights are retrieved well by the proposed algorithm.

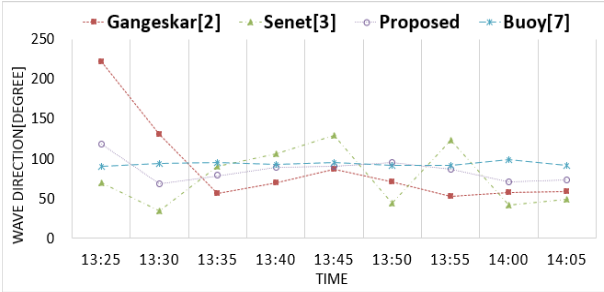


(a)

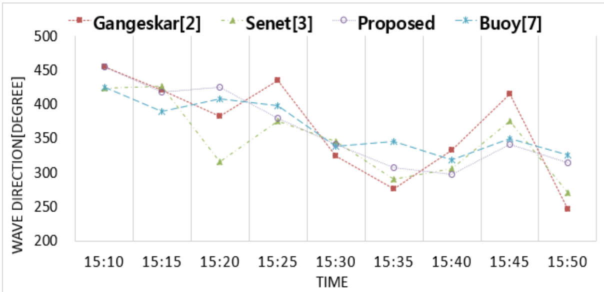


(b)

Fig. 6. Performance improvement for radar image with a significant amount of noise. (a) Before the noise reduction and its spectral representation. (b) After the noise reduction and its spectral representation.

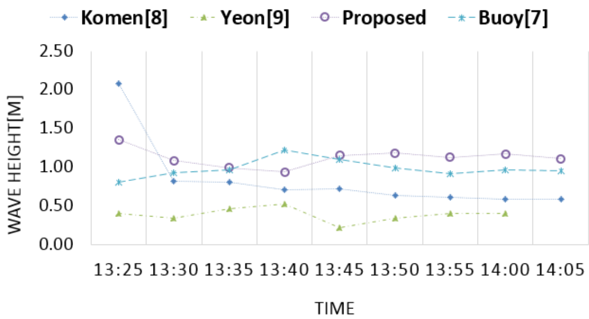


(a)

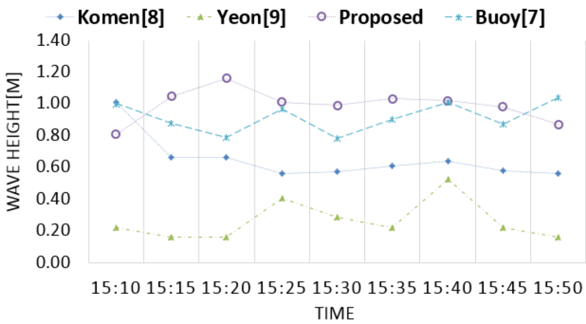


(b)

Fig. 7. Performance comparisons between the estimated wave directions and buoy data. (a) 13:25 Nov. 27, 2015 and (b) 15:10 July 10, 2016.



(a)



(b)

Fig. 8. Performance comparisons between estimated wave heights and buoy data. (a) 13:25 Nov. 27, 2015 and (b) 15:10 July 10, 2016.

IV. CONCLUSION

This paper presented an enhanced wave information retrieval algorithm that incorporates efficient noise reduction into the regular wave information retrieval process in the pixel domain. That is, when the proposed algorithm was applied to the field data, it was shown that the proposed algorithm is very effective in reducing severe noises, and furthermore, the retrieved wave parameters can be refined to be close to the actual data. Additionally, although the real wave direction was changed, the proposed algorithm can produce very reliable wave information parameters. The proposed algorithm was designed mainly for the purpose of closely observing offshore sea states where lots of vessels might be moving. As a future study, the proposed algorithm needs to be applied to data collected from systems on a moving vessel.

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