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Retrieval of surface parameters in tidal flats using radar backscattering model and multi-frequency SAR data

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Abstract : This study proposes an inversion algorithm to extract the surface parameters, such as surface roughness and soil moisture contents, using multi-frequency SAR data. The study areas include the tidal flats of Jebu Island and the reclaimed lands of Hwaong district on the western coasts of the Korean peninsula. SAR data of three frequencies were accordingly calibrated to provide precise backscattering coefficients through absolute radiometric calibration. The root mean square (RMS) height and the correlation length, which can describe the surface roughness, were extracted from the backscattering coefficients using the inversion of the Integral Equation Method (IEM). The IEM model was appropriately modified to accommodate the environmental conditions of tidal flats. Volumetric soil moisture was also simultaneously extracted from the dielectric constant using the empirical model, which define the relations between volumetric soil moistures and dielectric constants. The results obtained from the proposed algorithm were verified with the in-situ measurements, and we confirmed that multi-frequency SAR observations combined with the surface scattering model for tidal flats can be used to quantitatively retrieve the geophysical surface parameters in tidal flats.

Key Words : Surface parameter, Synthetic aperture radar, Multi-frequency, IEM, Tidal flat

1. Introduction

In the western and southern coasts of the Korean peninsula, tidal flats are widely developed occupying approximately 3% of the South Korean territory and known as the one of the five major tidal flats in the world(Koh, 2001). As transitional zones between the ocean and the land, they conserve the biodiversity of benthos, but also perform various functional roles in the coastal ecosystem. For example, they purify the contaminants from the land and improve the quality of water. They can immediately absorb and control a large amount of water, so prevent floods and contribute to the climate control in coastal regions. In addition, owing to high levels of nutrients flowing in from seawater and freshwater, tidal flats are much more productive than any other ecosystems and have become commercially valuable for benthic products, such as small octopus species and shellfishes including oyster, clam, and crab. Therefore, in order to

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manage and conserve these coastal environments and ecosystems constantly, it needs to acquire the quantitative and statistical surface information with the regular monitoring of tidal flats. However, tidal flats are extremely limited to access because of the ebb and flow of the tide, and quite difficult to investigate and move around them which are mostly composed of mud. There have been relatively few investigations and comprehensive reports on tidal flats.

Recently, with the development of remote sensing techniques, the application of the earth observation satellite data has been widely used in monitoring and mapping for the geophysical environments of tidal flats. Synthetic aperture radar(SAR) has also become a promising tool for quantitatively estimating the physical characteristics of the earth' s surface because the radar backscattering is strongly affected by surface parameters, such as surface roughness and soil moisture. It is particularly useful for extracting the information of surface roughness in tidal flats saturated with a high moisture content. Several studies have been attempted to extract the surface parameter of tidal flats using SAR observations and surface scattering models(Van der Wal *et al.*, 2005; Gade *et al.*, 2008; Park *et al.*, 2009). However, even though tidal flats are different from the land and the ocean in terms of the microwave scattering, there have been few studies related with the microwave scattering models considering for the surface characteristics of tidal flats. In this study, we suggested the modified IEM model to accommodate to the environments of tidal flats, applying the transition coefficient and the power law spectrum to the existing IEM model. The estimated results from the modified model were verified with the measured results from a ground based scatterometer system. Using the modified model and the proposed inversion method, we extracted the surface parameters, such as the RMS height, the correlation length, and the volumetric soil moisture, from the backscattering coefficients acquired from multi-frequency polarimetric SAR data. Finally, the results derived from the proposed algorithm were verified with the in-situ measurements, and the applicability of multi-frequency polarimetric SAR observations combined with the surface scattering model for extracting the surface parameters in tidal flats has been discussed.

2. Experimental data acquisition

1) Study areas

The tidal flats of Jebu Island and the reclaimed lands around Hwaong sea dike on the western coasts of the Korean peninsula were selected for the investigation(Fig. 1). The tidal flats of Jebu Island represent a very smooth surface with a high moisture content, which is a general surface characteristic of tidal flats. The reclaimed lands of Hwaong, on the other hand, have a relatively rough and dry surface condition. The area had been tidal flats once in the past, but changed to the reclaimed lands after the construction of Hwaong sea dike in 2003. We extracted the surface parameters of the areas distinguished between before and after the reclamation, and compared the differences of surface conditions.

2) In-situ measurements and SAR data acquisition

In-situ measurements were carried out on the study site of Jebu Island, on August 2010 and May 2011. We obtained microwave backscattering coefficients using C- and X-band ground-based scatterometer systems(Fig. 2). At the same time, surface profiles and soil moisture contents were also obtained near the site, using the laser surface profiler and soil moisture sensor. These measurements were used as input

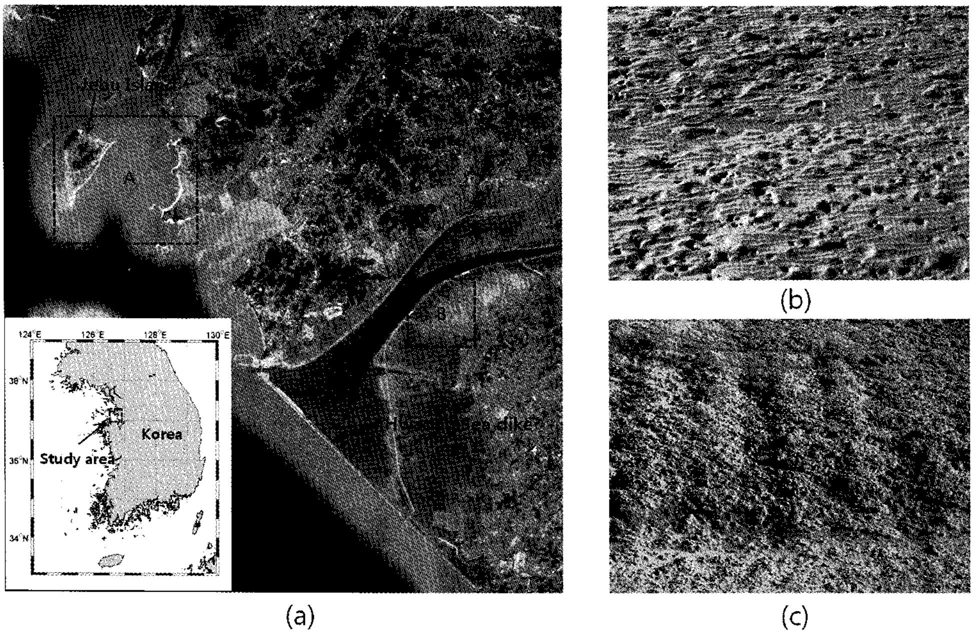

Fig. 1. (a) Aerial photograph of the study areas including the tidal flats of Jebu Island (A) and the reclaimed lands of Hwaong (B), (b) photograph of the surface condition of area A, (c) photograph of the surface condition of area B.

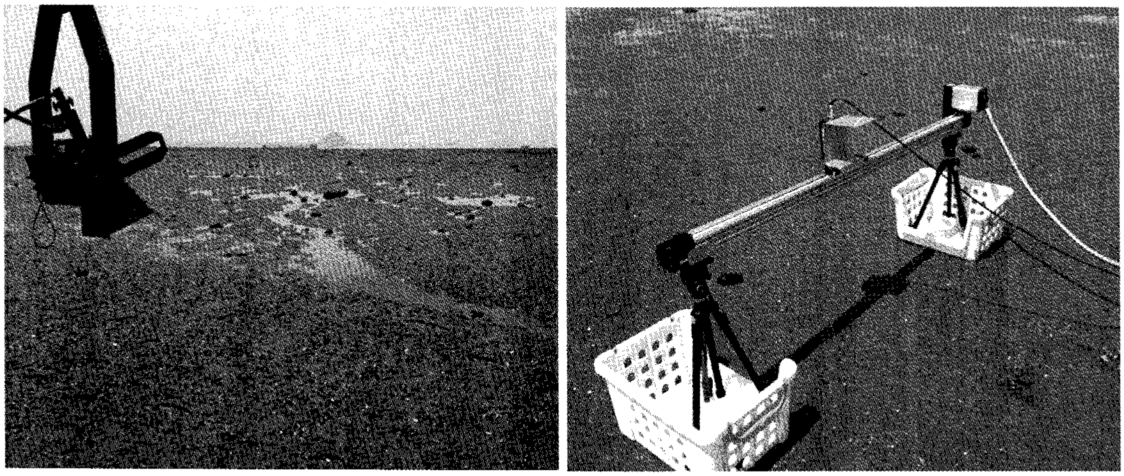

Fig. 2. Photographs of field measurements using the ground based scatterometer system (left) and the laser surface profiler (right, profile length: 1.35 m).

parameters of the modified IEM model, and the predicted results from the model were verified with the scatterometer measurements. And ten profiles including the measured surface profiles in other locations on May 2009 were verified with the estimated results from the proposed algorithm. The RMS height and the correlation length derived from the surface profiles ranged from 0.26 cm to 0.84 cm, and from 6.43 cm to 12.0 cm, respectively. The volumetric soil moistures were close to 50% in most areas.

The single look complex(SLC) data of ALOS PALSAR(L-band), RADARSAT-2(C-band), and TerraSAR-X(X-band) were acquired over the area

Table 1. Specification of SAR data used in this study

	ALOS PALSAR	RADARSAT-2	TerraSAR-X
Acquisition date /time (UTC)	2007.04.13 / 13:51	2008.11.20 / 21:37	2008.11.20 / 09:20
Frequency	1.27 GHz (L-band)	5.405 GHz (C-band)	9.65 GHz (X-band)
Polarization	VV	VV	VV
Incidence angle	22.7 ~ 24.9°	35.4 ~ 37.0°	22.4 ~ 24.2°

including Jebu Island and Hwaong district. The specification of the SAR data used in this study is listed in Table 1. We derived backscattering coefficients through absolute radiometric calibration of the SLC data. In order to obtain the backscattering coefficients of three frequencies at a same point pixel, geometric calibration was performed.

3. Methods

1) Microwave surface scattering model for tidal flats

Microwave surface scattering models have been extensively developed to estimate radar backscattering coefficients depending on the geophysical parameters of the scattering surface(such as RMS height, correlation length, and dielectric constant) and the system parameters of the incident microwave(such as frequency, incidence angle, and polarization). There have been theoretical models such as small perturbation model(SPM), Kirchhoff approximation (KA), and physical optics(PO), as well as empirical models such as Oh model. However, the valid ranges of these surface scattering models are limited only to specific conditions. The recently developed IEM model has extended the valid ranges by using the integration for the tangential surface fields and considering multiple scattering terms(Fung *et al.*, 1992). The IEM equation for the vertical polarization is given by

$$\sigma_{vv}^{0} = \frac{k^2}{2}\exp - 2k_z^2 s^2 \sum_{n=1}^{\infty} |I_{vv}^{n}| \frac{W^{(n)}(-2k_x, 0)}{n!} \quad (1)$$

where $k_z = k\cos\theta$, and $k_x = k\sin\theta$. θ is the incidence angle, k is the wave number, s is the RMS height of the surface, $W^{(n)}$ is the Fourier transform of the n th power of the surface autocorrelation function. I_{vv}^{n} is a function determined by RMS height, permittivity, and Fresnel reflection coefficient, and given by

$$I_{vv}^{n} = (2k_z^2 s)^n f_{vv} \exp(-k_z^2 s^2) + \frac{(k_z^2 s)^n [F_{vv}(-k_x, 0) + F_{vv}(k_x, 0)]}{2} \quad (2)$$

$$F_{vv}(-k_x, 0) + F_{vv}(k_x, 0) = \frac{2\sin^2\theta(1+R_v)}{\cos\theta}\left[\left(1 - \frac{1}{\varepsilon}\right) + \frac{\mu\varepsilon - \sin^2\theta - \mu\cos^2\theta}{\varepsilon^2\cos^2\theta}\right] \quad (3)$$

where R_v is the Fresnel reflection coefficient for the vertical polarization, and ε, μ are the relative dielectric constant and permeability, respectively. Here, in order to extend the applicable ranges of the existing IEM model to very smooth regions such as mud flats, particularly at high frequency domain, we replaced the Fresnel reflection coefficient with the transitional reflection coefficient R_v^T developed by Wu *et al.*(2001). It is given as follows,

$$R_v^T(\theta) = R_v(\theta) + [R_v(0) - R_v(\theta)]\Re_p \quad (4)$$

where R_p is the transition function determined by the surface roughness and the frequency. In addition, we used the generalized power law spectrum developed by Li *et al.*(2002), in the application of the surface autocorrelation function. The correlation length, which is one of the parameters related with

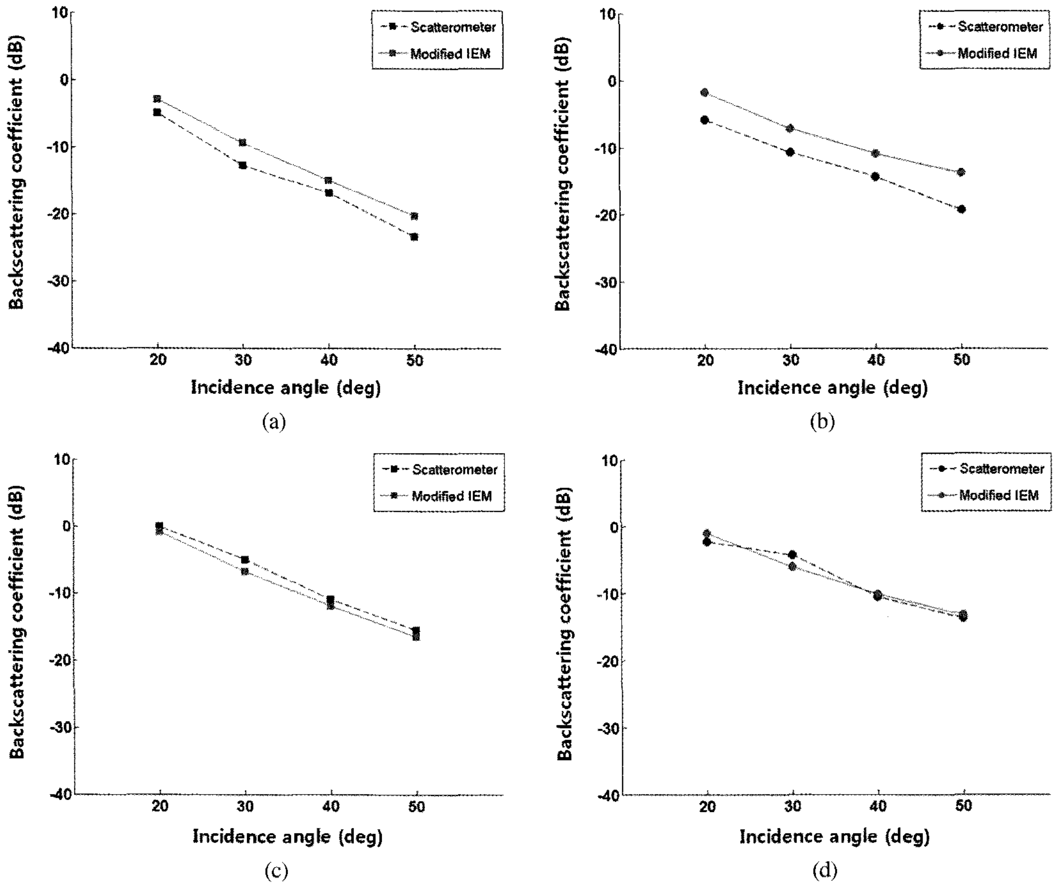

Fig. 3. Comparison between the estimated results from the modified IEM and the scatterometer measurements. (a) HH polarization mode of C-band, (b) VV polarization mode of C-band, (c) HH polarization mode of X-band, (d) HH polarization mode of X-band.

the surface roughness, is derived from the surface autocorrelation function. The generalized power law spectrum can describe the various cases between the Gaussian and the exponential functions, and the power law spectrum generated by the power index of 2.1 appeared to properly reflect the surface characteristics of tidal flats(Park *et al.*, 2009; Kim *et al.* 2011). Finally, we validated the modified IEM model. We calculated the backscattering coefficients by forwarding the input parameters obtained from in-situ measurements to the modified IEM model, and compared the results with the backscattering coefficients directly measured by the C- and X-band scatterometer systems. Fig. 3 shows the results of the verification. While the predicted X-band backscattering coefficients using the modified IEM model showed good agreements with the in-situ scatterometer measurements(Fig. 3(c) and(d)), the C-band backscattering coefficients were somewhat overestimated(Fig. 3(a) and(b)). Although there was some discrepancy in C-band prediction, the amount of discrepancy was consistent and the decline trend with respect to incidence angles was similar to the measured result from the scatterometer. Thus, the approach using transition model for the reflection coefficient appears to be most desirable in estimating

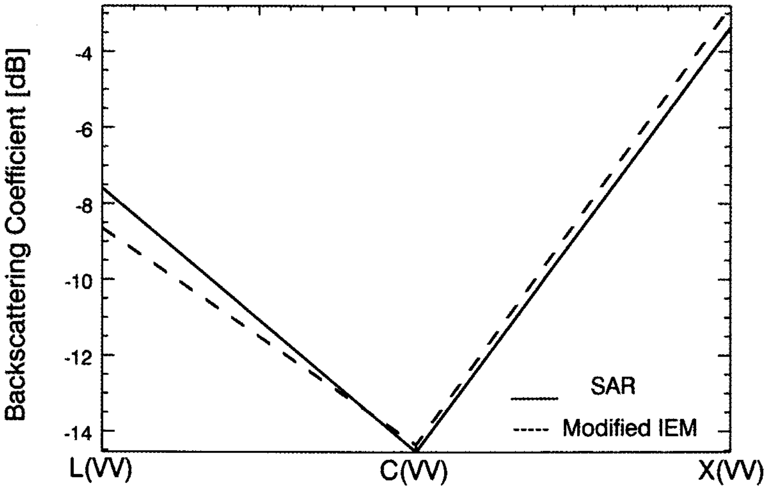

Fig. 4. Specific example of the inversion process. The values approximately equivalent to the backscattering coefficients from multi-frequency SAR data are extracted from the lookup table based on the modified IEM model.

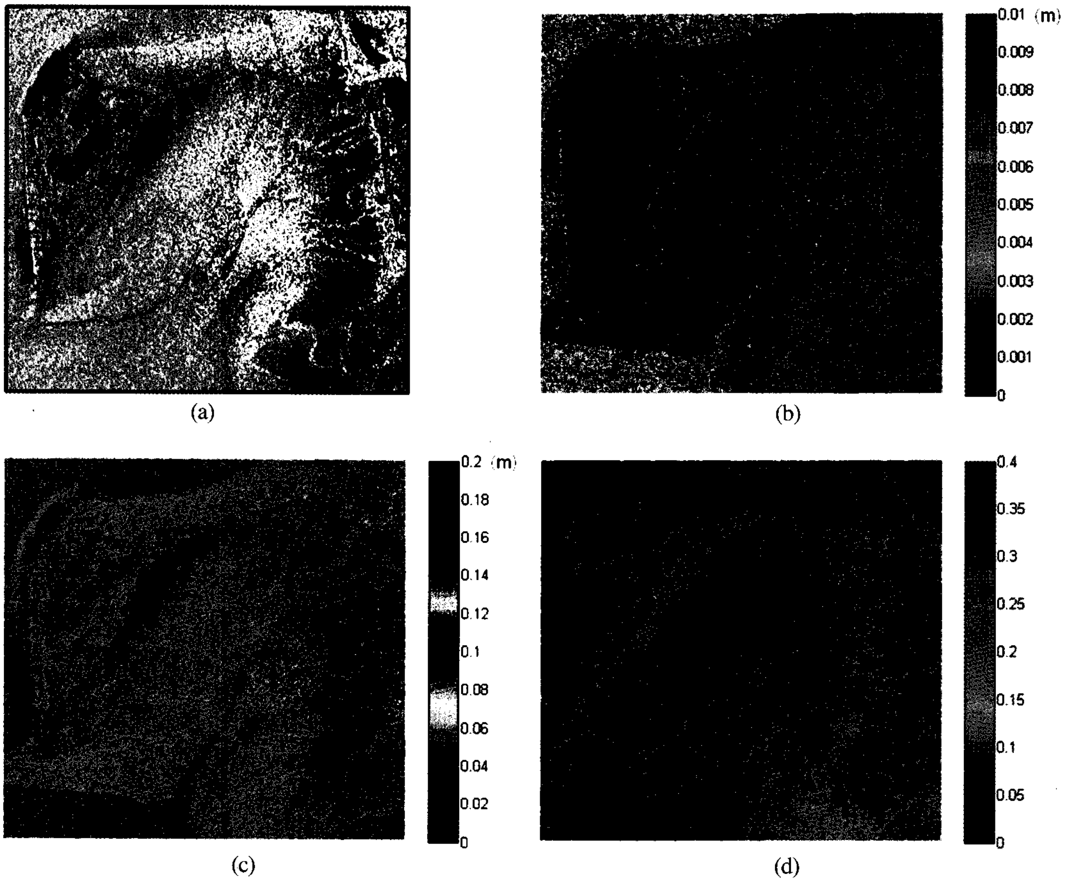

Fig. 5. Estimated surface parameters from the tidal flats of Jebu Island. (a) TerraSAR-X backscattering coefficient image, (b) RMS height (m), (c) correlation length (m), (d) volumetric soil moisture.

surface parameters of smooth surface such as mudflats. If the discrepancy is compensated with further investigation, the modified IEM model can be used for better description of the surface scattering in tidal flats.

2) Inversion algorithm

The radar backscattering coefficient calculated by the IEM model can be assumed as a function which is determined by the RMS height, the correlation length, and the dielectric constant, because the other parameters are known. Therefore we can extract the RMS height, the correlation length, and the volumetric soil moisture from the backscattering coefficients using the inversion of the IEM model. Here, the volumetric soil moisture can be extracted using the empirical model developed by Hallikainen *et al.*(1985), which empirically defines the relations between volumetric soil moistures and dielectric constants. The specific procedures for the inversion are as follows. First, we made the three dimensional lookup tables of three frequencies(L-, C-, and X-band) according to the RMS height, the correlation length, and the volumetric soil moisture, using the modified IEM model. And we obtained the backscattering coefficients of three frequencies from each point pixel of the SAR data. Then, comparing the backscattering coefficient values from the SAR data, we found the point representing the most similar values and the highest correlation in the pattern from the lookup table, as shown in Fig. 4. From the point, the RMS height, the correlation length, and the volumetric soil moisture were extracted.

4. Results and discussion

The surface parameters of the tidal flats of Jebu Island derived from the proposed algorithm are shown in Fig. 5. The RMS height ranged from 0.6 cm to 0.9 cm, and the correlation length ranged from 5 cm to 20 cm. The volumetric soil moisture denoted high values above 40% in most areas of tidal flats. The results were compared with in-situ measurements(Fig. 6). The estimated RMS height values were a little greater than the measured RMS

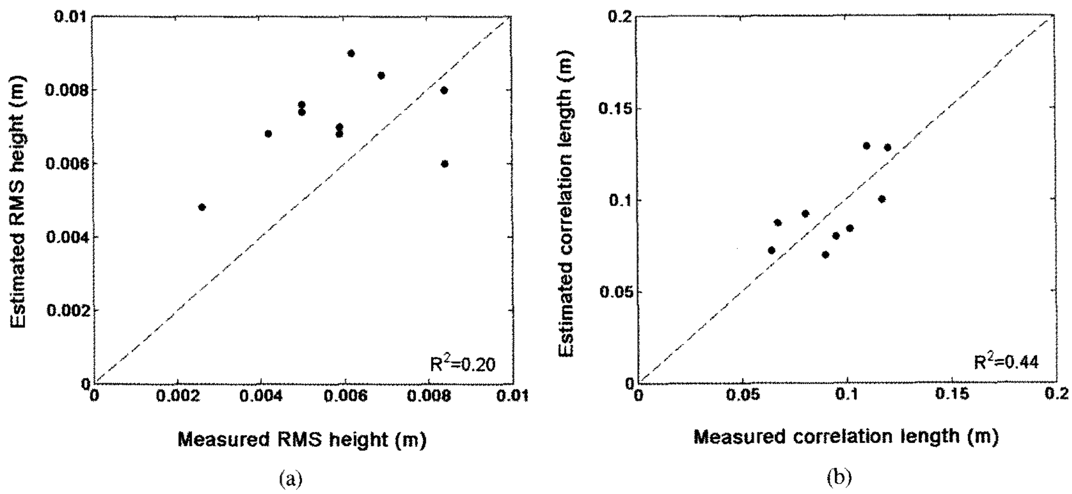

Fig. 6. Comparison between the estimated (a) RMS height and (b) correlation length from the proposed algorithm and in-situ measurements. The dotted diagonal lines indicate where the estimated value is equal to the measured value.

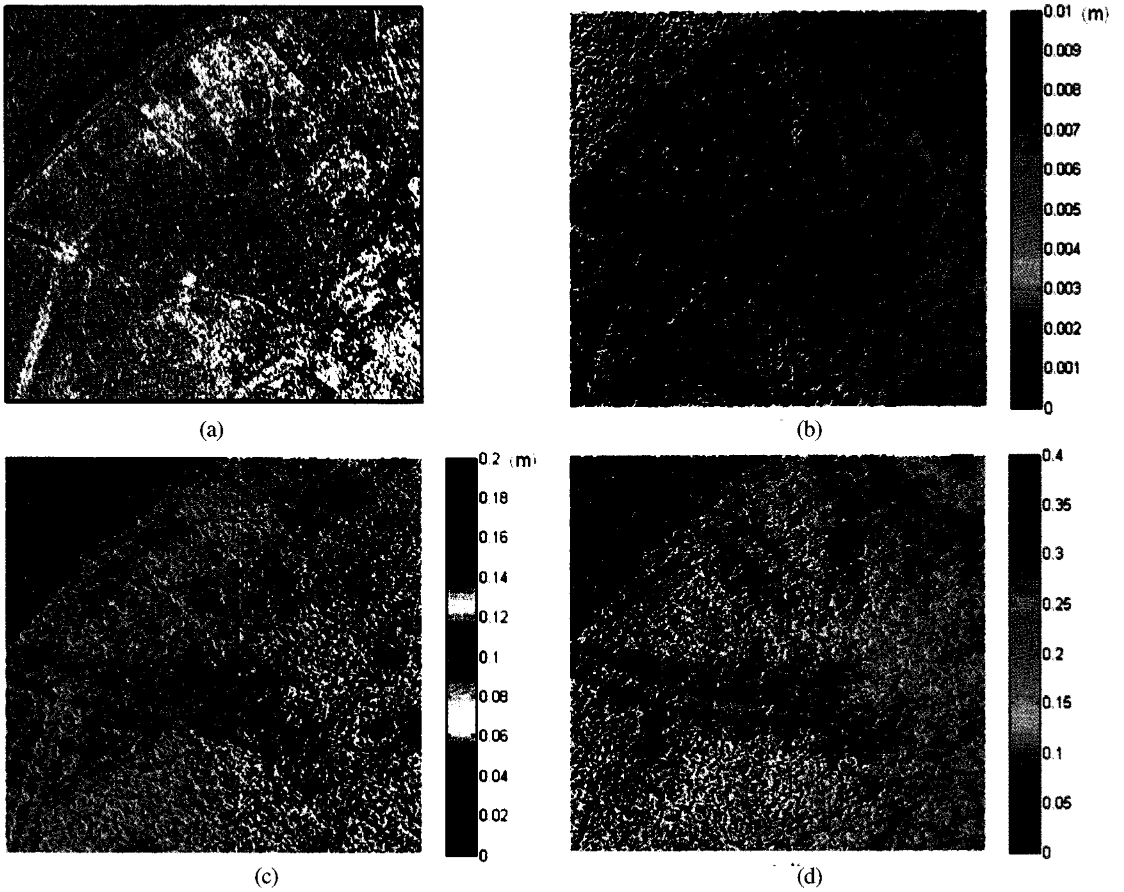

Fig. 7. Estimated surface parameters from the reclaimed lands of Hwaong. (a) TerraSAR-X backscattering coefficient image, (b) RMS height (m), (c) correlation length (m), (d) volumetric soil moisture.

height, but the difference is not considered to be significant because the range of the surface roughness in tidal flats is very small in absolute value. The correlation length was entirely in accordance with the in-situ measurements. The volumetric soil moisture also described the characteristic of tidal flats with a high moisture content. However, the estimated range of the volumetric soil moisture tended toward the high values and the spatial variations were not well distinguished. That is because the radar backscattering is not affected by the changes of the soil moisture when the volumetric moisture is larger than 30%. These results demonstrate that the radar backscattering is more sensitive to the effect of the surface roughness in the case of tidal flats.

Fig. 7 shows the results derived from the reclaimed lands of Hwaong. Compared to the tidal flats of Jebu Island, the RMS height was relatively large, and the correlation length was small. The volumetric soil moisture ranged between 10% and 20%, except for a part of the area. The difference was easily observed from the photographs of the surface condition of two areas, as shown in Fig. 1. The results indicate that the surface condition of these areas has been changed to a relatively rough and dry soil after the land reclamation. However, in the central and upper right areas of the reclaimed lands, the relatively high values in the volumetric soil moisture were observed.

And the correlation length of these areas was also much smaller than other areas. The areas are namely around where tidal channels passed in the past. The surface conditions of these areas are assumed to be wetter and smoother than the surrounding areas.

5. Conclusion

In this study, we extracted the surface parameters in tidal flats, using the backscattering coefficients derived from multi-frequency SAR data and the inversion algorithm based on the modified IEM model. Although the estimated results were slightly different from the in-situ measurements, they were enough to investigate the surface characteristics of the study areas. We could also distinguish the difference of the surface conditions between the tidal flats and the reclaimed lands. In particular, the spatial variation of the surface roughness was more clearly classified by the correlation length, compared to the RMS height. If the surface autocorrelation function related with the correlation length is improved to accurately describe the surface profile of tidal flats, we will obtain the more accurate surface roughness. Therefore, in future, the surface autocorrelation function optimized for tidal flats should be devised to the surface scattering model. In conclusion, this study suggests that multi-frequency SAR observations combined with the surface scattering model for tidal flats can be used to quantitatively retrieve the geophysical surface parameters in tidal flats.

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