TIDAL WETLAND MONITORING USING POLARIMETRIC SYNTHETIC APERTURE RADAR

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ABSTRACT:

Tidal wetlands including intertidal flats are highly productive and have dynamic and diverse ecosystems. Despite the importance of the tidal flats and associated coastal habitats, theses areas are at risk due to high development pressure, such as reclamation and marine pollution. Because of their poor accessibility, remote sensing techniques are the most effective tool for tidal flat observation. Particularly, microwave remote sensing using synthetic aperture radar (SAR) system has great potential for quantitative monitoring and mapping of coastal wetlands. This study aims to review and develop effective methods of extracting geophysical information of tidal wetlands. Fully polarimetric forward/inverse scattering models have been developed for quantitative estimation of geophysical parameters. This study aims to review and develop effective methods of extracting geophysical information of intertidal mudflats including surface geometric characteristics, such as the roughness of the scattering surface, from polarimetric SAR data. In addition, an extension of previous study to fully polarimetric space-borne SAR data sets is presented in this paper.

1. INTRODUCTION

Coastal wetlands including tidal flats are the zone of interaction between marine and terrestrial environments. They have dynamic and diverse ecosystems and provide highly productive fishery areas. Despite the importance of the tidal flats and associated coastal habitats, these areas are at risk due to high development pressure, such as reclamation and marine pollution. In addition, coastal wetlands are highly vulnerable to climate changes. Because of their poor accessibility both from sea and land, monitoring and mapping of tidal flat environments from in situ measurements in field are very difficult.

Remote sensing can provide large spatial coverage and non-intrusive measurement over the Earth's surface. Previous studies have focused on the use of optical sensors for remote sensing of tidal flats. Because of the repetitive tidal event and dynamic sedimentary process, however, integrated observation of tidal flats from multi-sourced data sets is essential for mapping and monitoring tidal flats.

Microwave remote sensing using synthetic aperture radar (SAR) system can be a complementary tool for tidal flat observation especially due to their high spatial resolution and all-weather imaging capability. Recently several studies have reported on investigation of tidal flats using single polarization SAR data [Van der Wal et al., 2005], multi-frequency approach [Gade et al., 2008], and dual or full-polarimetric approach [Park et al., 2009].

This study aims to review and develop effective methods of extracting geophysical information of intertidal mudflats including surface geometric characteristics, such as the roughness of the scattering surface, from polarimetric SAR data. Roughness of the surface sediments in intertidal flats represents both biogenic and physical depositional characteristics of sediments [Reineck and Singh, 1980]. In addition, it can also be used for describing the land-use characteristics in intertidal flats such as fishery activities. In Section II, previous researches on remote sensing of tidal wetlands are reviewed, and the inversion algorithms of surface roughness parameters are presented in Section III. Experimental results on the roughness estimation of intertidal flats are discussed in Section IV. Finally, summary and concluding remarks are presented in Section V.

2. REVIEW OF REMOTE SENSING OF TIDAL FLAT

2.1 Tidal flat monitoring from optical sensors

Remote sensing using optical sensors (e.g., Landsat TM) have been applied for mapping of surface sediment distributions of tidal flats [Yates et al., 1993; Rainey et al., 2000, Ryu et al., 2004]. The distribution of sediments of a given particle size is of great interest in the field of morpho-dynamics and sedimentary process of coastal environments.

Yates et al. (1993) tested several classification algorithms to distinguish between muddy and sandy flats using Landsat TM data. In their study, muddy and sandy flats are determined based on the sediment 'critical' grain size of 0.063 mm. Results indicated that all the classification methods showed a better performance for muddy flats than for sandy flats.

Ryu et al. (2004) claimed to use critical grain size of 0.25 mm for practical classification of fine and coarse sediments. In addition, they investigated the effect of water contents and topography which affect optical reflectance values on the classification of surface sediment distribution. Particularly,

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water content which can be remained on the intertidal flat surface for considerable times after exposure, significantly affect the spectral response of the sediment.

The classification performance can be improved by applying coarse critical grain size. Nonetheless classification of the intertidal surface sediments can still be considered to be in an experimental stage because of poor knowledge on coupled effect of the topography and the water content as well as the grain size of the sediments on the optical reflectance of intertidal sediments.

2.2 Tidal flat monitoring from microwave sensors

Improving temporal resolution is an essential issue of remote sensing of coastal environments due to the dynamic changes in morphological and sedimentary processes of tidal wetlands. Unlike optical and infrared imaging sensors SAR is an active microwave imaging system for studying Earth's environment with a high spatial resolution. Unlike optical and infrared imaging sensors which rely on reflected or radiated solar energy, imaging radars are more flexible and robust in their tidal flat observation capabilities because they are independent of sunlight and weather conditions.

Theoretical relationships between backscatter coefficients and surface geophysical parameters have been well developed over several decades. In general, radar signals backscattered from bare soil surface can be expressed by the dielectric properties of material and statistical roughness characteristics of scattering surfaces. In case of the tidal flat application, however, one can assume that surface sediments are fully saturated by sea water particularly in mud flats which dominates the tidal flats around Korean peninsular. Consequently, the effect of dielectric constants on backscattered signals can be neglected in the specific case of the intertidal mudflats [Van der Wal et al., 2005; Gade et al., 2008; Park et al., 2009]. Several studies have been proposed the inversion algorithm of remained unknown geophysical parameters, such as the rms height, *s*, and correlation length, *l*, of surface sediments, from radar measurements.

In Van der Wal et al (2005), the rms height of surface sediment was obtained by an empirical regression approach based on the C-band, VV-polarized backscattering coefficient of ERS SAR data. Due to its simplicity, it can be applied to the common SAR systems which operate in single-frequency and single-polarization. However, practical use of this approach for parameter retrieval needs time-consuming calibration work on empirical relationships for various radar configurations and surface conditions.

On the other hand, Gade et al. (2008) proposed another roughness retrieval algorithm based on multi-frequency SAR data. The rms height and the correlation length were obtained from VV-polarized backscattering coefficients of X-, C-, and L-band SAR data. In this case, the retrieval algorithm is based on the theoretical scattering model, such as Integral Equation Method (IEM) [Fung, 1992]. Since the IEM model has a broader range of validity than classical scattering models, e.g., Kirchhoff approach and the small perturbation method, it can be used for roughness retrieval of diverse surface sediments. However, it has an inherent limitation in operational use of space-borne SAR data to monitor tidal flats, because of a high temporal variety of tidal flat environment and a rare availability of multi-frequency SAR data acquired simultaneously.

Recently, Park et al. (2009) proposed an alternative roughness retrieval algorithm based on fully polarimetric SAR data. This roughness inversion technique has been validated using L-band NASA/JPL AIRSAR data sets. Roughness parameters estimated from SAR data are in reasonably good agreements with those from in-situ measurements. This study aims to present an extension of previous study to polarimetric space-borne SAR data.

3. SAR POLARIMETRY OF TIDAL FLAT

3.1 Polarimetric SAR remote sensing

The microwave transmitted by a radar system is characterized by its frequency and its polarization state. Conventional SAR systems operate with a single fixed polarization antenna for both transmission and reception of microwave frequency signals as shown in Table 1. Today, there is a rapidly increasing interest in the application of radar polarimetry for Earth observation due to increasing availability of polarimetric space-borne radar sensors, such as ALOS-PALSAR, RADARSAT-2, and Terra-SAR-X and follow-up satellite sensor systems.

The backscattered wave by the target is described in either the incident components $\vec{E}^i$ or by the scattered components $\vec{E}^s$, which are related by the complex 2×2 scattering matrix [*S*] of the target, defined according to

$$\begin{bmatrix} E_H^s \\ E_V^s \end{bmatrix} = \frac{e^{-jkr}}{r} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_H^i \\ E_V^i \end{bmatrix}, \text{ or } \vec{E}^s = \frac{e^{-jkr}}{r}[S]\vec{E}^i \quad (1)$$

where k is wave number, r is the distance between the target and the receiving antenna. The element $S_{pq} = |S_{pq}|\exp(j\varphi_{pq})$ is dependent on the characteristic of the target and on the direction of incident and scattered fields.

There is an advantage in many applications to expressing target scattering properties in terms of a complex feature vectors, comprising three elements in the monostatic backscatter case. The lexicographic feature vectors in linear and circular basis $\vec{k}_L$ and $\vec{k}_{RL}$, and Pauli feature vector $\vec{k}_P$ are defined as:

$$\vec{k}_L = [S_{HH} \;\; \sqrt{2}S_{HV} \;\; S_{VV}]^T; \; \vec{k}_{RL} = [S_{RR} \;\; \sqrt{2}S_{RL} \;\; S_{LL}]^T;$$
$$\vec{k}_P = \tfrac{1}{\sqrt{2}}[S_{HH}+S_{VV} \;\; S_{HH}-S_{VV} \;\; 2S_{HV}]^T. \quad (2)$$

One of the most important properties of radar polarimetry is the fact that once a target response is acquired in a polarization basis, the response in any basis can be obtained from a simple transformation without any additional measurements. All of theses target feature vectors are related with each others by

Satellite, Instrument	Frequency	Polarization
ERS-1, SAR (1991-2000)	C-band	VV
JERS-1, SAR (1992-1998)	L-band	HH
ERS-2, SAR (1995~)	C-band	VV
RADARSAT-1 (1995~)	C-band	HH
ENVISAT, ASAR (2002~)	C-band	Twin
ALOS, PALSAR (2006~)	L-band	Quad
RADARSAT-2 (2007~)	C-band	Quad
TerraSAR-X (2007~)	X-band	Dual
COSMO-SkyMed (2007~)	X-band	Dual
RISAT (2009)	C-band	Quad
HJ-1-C (2010)	S-band	Quad
SAOCOM (2010)	L-band	Quad
Sentinel-1 (2011)	C-band	Dual

Table 1. Current and future space-borne SAR systems

unitary transformation matrices [Boerner et al., 1998]. Consequently, the amount of information about a given scatterer can be increased, allowing a better characterization of scattering properties. An advantage of the Pauli basis equation (2) is that [*S*] is projected on to orthogonal basis matrices that represent simple scattering mechanisms. The first component $S_{HH}+S_{VV}$ dominates in single-bounce surface scatter, while the second component $S_{HH}-S_{VV}$ dominates in double-bounce scatter. The cross-pol element S_{HV} will be strong for backscatter from depolarizing media.

3.2 Roughness retrieval from polarimetric SAR

Since effect of dielectric constant on radar measurements can be neglected in tidal flats, the set of roughness parameters {*s*, *l*} can be can be obtained simultaneously from two independent polarization measurements. In particular, increased measurement sensitivity to surface roughness has been reported by using the circular-polarization coherence $|\rho_{RRLL}|$ defined as:

$$|\rho_{RRLL}| = |< S_{RR}S_{LL}^{*} >| \Big/ \sqrt{< S_{RR}S_{RR}^{*} >< S_{LL}S_{LL}^{*} >} \qquad (3)$$

Consequently, the pair of $|\rho_{RRLL}|$ and the co-pol response of the coherency matrix $|S_{HH}+S_{VV}|^2$ showed better performance in the roughness parameter retrieval than conventional co-and cross-polarized backscattered coefficients. Therefore, roughness parameters of the target surface can be estimated by the minimization procedure:

$$\min\left\{ \text{norm}\left\{ \begin{bmatrix} |\rho_{RRLL}| \\ |S_{HH}+S_{VV}|^2 \end{bmatrix} - F\left(\begin{bmatrix} s \\ l \end{bmatrix}\right) \right\} \right\}. \qquad (4)$$

The extended-Bragg model [Schuler et al., 2002; Hajnsek et al., 2003] has been used for the scattering model *F* in (4). This roughness inversion technique has been validated using L-band NASA/JPL AIRSAR data sets as shown in Figure 2. Roughness parameters relative to wavelength, *ks* and *kl*, derived from SAR data are in reasonably good agreements with those from in-situ

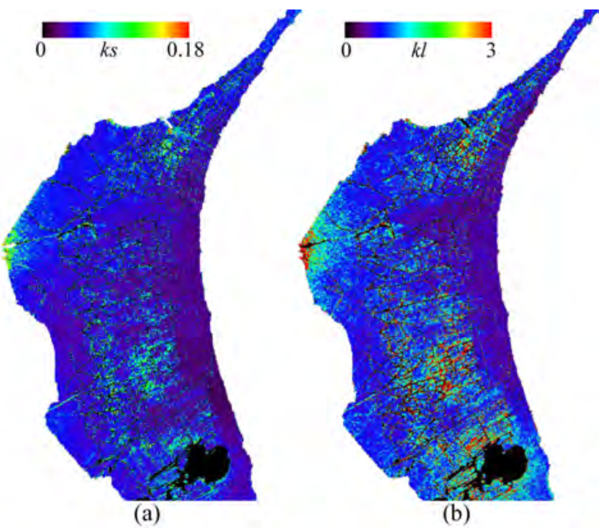

Figure 2. Radar derived (a) rms height and (b) correlation length [Park et al., 2009].

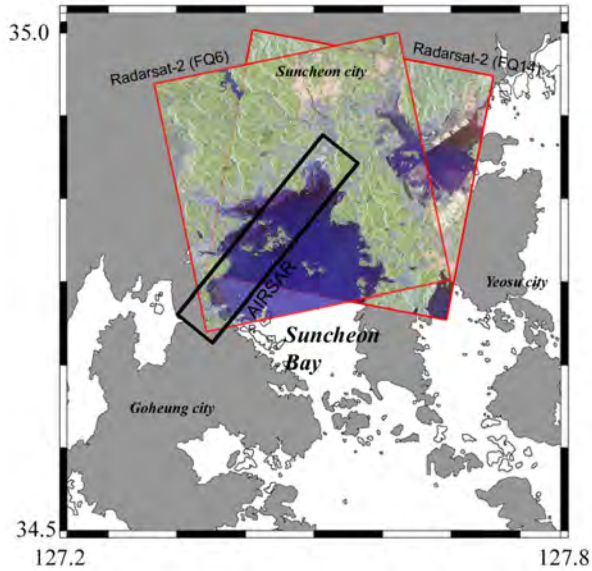

Figure 3. Suncheon Bay study area.

measurements. More details on the performance analysis of roughness retrieval algorithm can be found in [Park et al., 2009]. In case of space-borne SAR remote sensing, however, the surface of tidal flat sediment is generally very smooth in L-band frequency resulting in low backscattering signal relatively close to the radar noise floor. Therefore, higher frequencies, such as C- and X-band SAR data could be more appropriate to recognize fine details than L-band.

4. ESTIMATION OF SURFACE ROUGHNESS PARAMETERS

The south and west coastal zones of Korean peninsula are well known for their large tidal ranges and vast expanses of intertidal flats. Suncheon Bay study area in the southern coast of the Korean peninsular is one of the highly productive fishery region and provides habitat of various fish and shellfishes as well as migration birds. Recently, Suncheon Bay tidal wetland was registered as a RAMSAR Site for international convention of wetlands conservation.

Figure 3 shows available polarimetric SAR data sets over Suncheon Bay study site. The fully polarimetric NASA/JPL AIRSAR data were acquired at L-band during PACRIM-II Korea campaign on September 30th, 2000. In addition, two sets of RADARSAT-2 fully polarimetric data were obtained over the Suncheon Bay study area. The first data set was acquired on November 4, 2008 at fine beam mode (FQ14) of descending orbit. The radar incidence angles vary between 33.5° and 35.1°. The second one was acquired on December 14, 2008. In this case, the image was obtained in ascending orbit at FQ6 beam mode in which the radar incidence angles span 24.5° to 26.4°. The first data (FQ14) was acquired at an ebbing tide with the tidal elevation of 105 m, while the second one was acquired on the beginning of the flowing tide with the tidal elevation of 110 m. Figure 4 shows AIRSAR and RADARSAT-2 images for the specific test site near the mouth of the river flows into the Bay. New artificial structures can be identified in the western part of the tidal flats. Compared with AIRSAR, C-band RADARSAT-2 backscattering coefficients show higher sensitivity to vegetation and sediment structures in tidal flats.

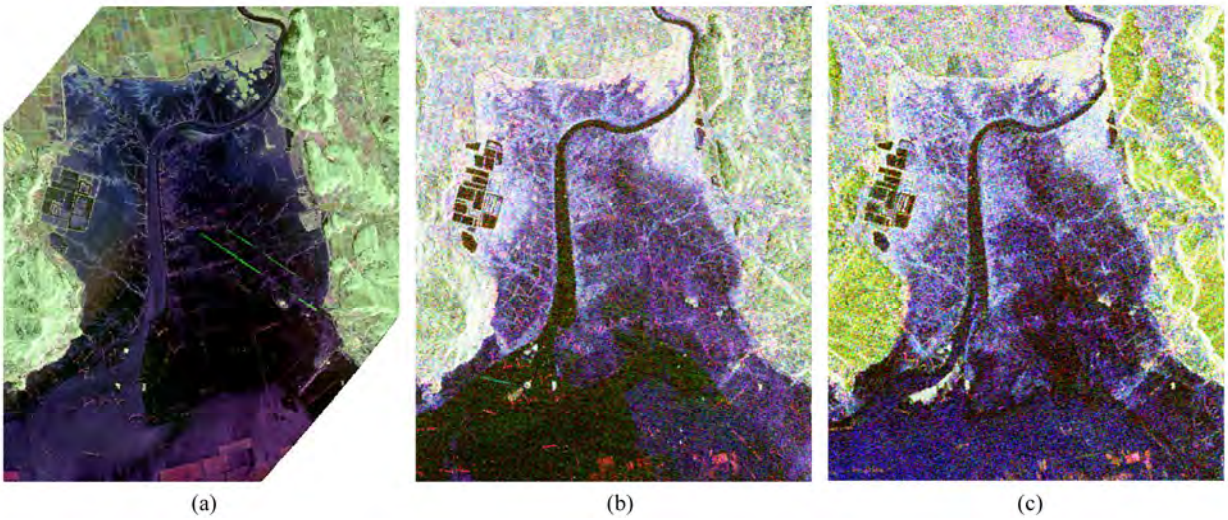

Figure 4. SAR images of Suncheon Bay study area: (a) L-band AIRSAR (Sep. 2000), (b) RADARSAT FQ14 (Nov. 2008), and (c) RADARSAT FQ6 (Dec. 2008)

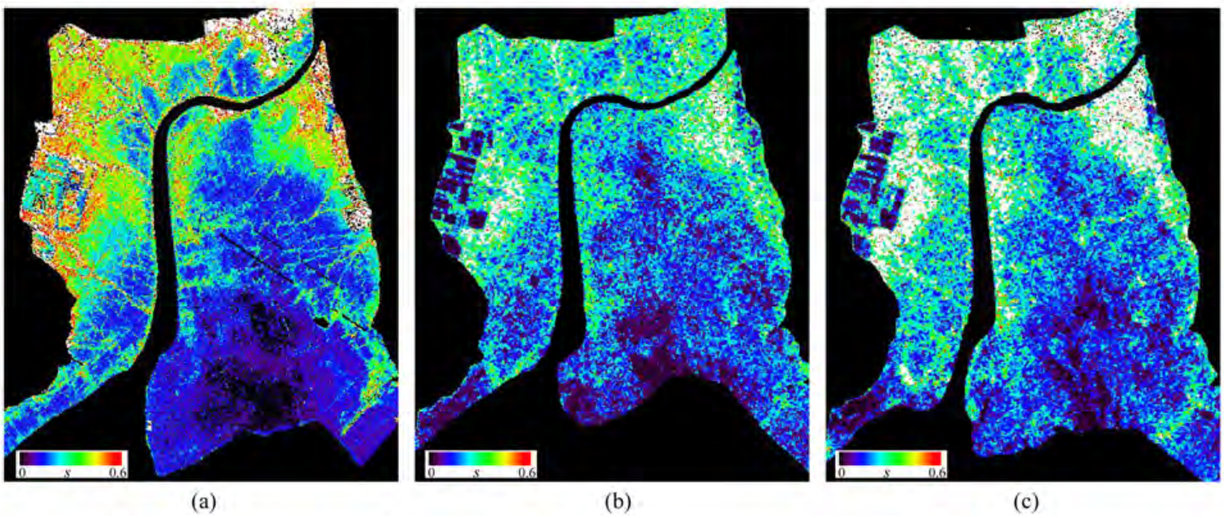

Figure 5. Radar derived rms height maps (in cm) of the tidal flats as a result of the inversion of (a) L-band AIRSAR, (b) RADARSAT-2 FQ14 beam mode, and (c) RADARSAT-2 FQ6 beam mode data sets.

Figure 5 shows the results of roughness parameter retrievals from polarimetric descriptors $|\rho_{RRLL}|$ and $|S_{HH}+S_{VV}|^2$. Pixels correspond to the land and the ocean were excluded from the inversion process. The rms height derived from NASA/JPL AIR SAR data acquired on September 30, 2000 is shown in Figure 5(a). It can infer the performance of the roughness retrieval from RADARSAT-2 data despite of eight years difference between AIRSAR and RADARSAT-2. The rms heights derived from C-band RADARSAT-2 data show good agreements with those from AIRSAR data. Consequently, the fully polarimetric approaches which have been validated originally on the basis of L-band air-borne SAR data are also applicable to the C-band space-borne RADARSAT-2 data for roughness parameter retrievals of surface sediments in tidal flats.

5. CONCLUSION

Despite of different incidence angles and looking directions of FQ14 beam mode in ascending orbit and FQ6 mode in descending orbit, roughness parameters derived from two RADARSAT-2 data are very similar to each other. Therefore, one can reduce the time gap between each observation through a combined use of different beam modes and orbits of RADARSAT-2. However, there are some areas show changes in rms heights during two acquisitions particularly in mudflat near waterline and tidal channel. They reflect the difference of tidal heights, biological activities, and texture, salinity, and moisture contents of surface sediments. Relating radar derived roughness parameters to fundamental environmental processes in tidal flats will be further investigated through time series of polarimetric SAR data sets and detailed in-site measurements.

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