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Potential uses of TerraSAR-X for mapping herbaceous halophytes over salt marsh and tidal flats

Yoon-Kyung Lee [a,b], Jeong-Won Park [a], Jong-Kuk Choi [b], Yisok Oh [c], Joong-Sun Won [a,*]

[a] Department of Earth System Sciences, Yonsei University, 134 Shinchon-dong, Seodaemun-gu, Seoul 120-749, Republic of Korea
[b] Korea Ocean Satellite Center, Korea Institute of Ocean Science & Technology, 787 Haean-ro, Sangrok-gu, Ansan, Gyeonggi-do 426-744, Republic of Korea
[c] Department of Electronic Information and Communication Engineering, Hongik University, 94 Wausan-ro, Seoul 121-791, Republic of Korea

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This study presents a method and application results of mapping different halophytes over tidal flats and salt marshes using high resolution space-borne X-band synthetic aperture radar (SAR) that has been rarely used for salt marsh mapping. Halophytes in a salt marshes are sensitive to sea-level changes, sedimentation, and anthropogenic modifications. The alteration of the demarcations among halophyte species is an indicator of sea level and environmental changes within a salt marsh. The boundary of an herbaceous halophyte patch is, however, difficult to determine using remotely sensed data because of its sparseness. We examined the ecological status of the halophytes and their distribution changes using TerraSAR-X and optical data. We also determined the optimum season for halophyte mapping. An annual plant, *Suaeda japonica* (*S. japonica*), and a typical perennial salt marsh grass, *Phragmites australis* (*P. australis*), were selected for halophyte analysis. *S. japonica* is particularly sensitive to sea level fluctuation. Seasonal variation for the annual plant was more significant (1.47 dB standard deviation) than that for the perennial grass, with a pattern of lower backscattering in winter and a peak in the summer. The border between *S. japonica* and *P. australis* was successfully determined based on the distinctive X-band radar backscattering features. Winter is the best season to distinguish between the two different species, while summer is ideal for analyzing the distribution changes of annual plants in salt marshes. For a single polarization, we recommend using HH polarization, because it produces maximum backscattering on tidal flats and salt marshes. Our results show that high resolution SAR, such as TerraSAR-X and Cosmo-SkyMed, is an effective tool for mapping halophyte species in tidal flats and monitoring their seasonal variations.

1. Introduction

Salt marshes develop in the upper intertidal zone when dominated by halophytic herbaceous plants under favorable conditions and influenced by tides and salinity at the transition point between tidal flats and inland (Adam, 1990). A salt marsh plays several important roles: 1) it acts as a buffer zone from storms and contamination (or heavy metals), 2) it exchanges materials between tidal flats and open water, and 3) it removes a large amount of carbon from the atmosphere (Kirwan and Murray, 2007; Mitsch and Gosselink, 2007). Communities of salt marsh vegetation called halophytes play a fundamental role in the stability and topography of coastal wetlands. Halophyte communities in salt marshes have vertical zonation, a spatial segregation based on plant competition and physical gradient characteristics of the habitat such as salinity, water level, and exposure time (Bertness et al., 2002). Halophytes are particularly sensitive to sea level changes, the rate of marsh accretion, sediment supply, and anthropogenic modifications (Gardner and Porter, 2001). Halophyte zonation is closely related to salinity and exposure time (Lee et al., 2006). The imbalance between sea level rise and sediment accretion is one of the major factors driving the loss of salt marshes (Warren and Niering, 1993). Rizzetto and Tosi (2011, 2012) demonstrated the aptitude of modern salt marshes to counteract relative sea-level rise, as well as the rapid response of tidal channel networks to sea-level variations. Halophyte species alteration and demarcation is one of the environmental indicators of sea level changes in a salt marsh (Gardner and Porter, 2001). Therefore, accurate mapping of salt marshes is useful in understanding wetland functions and monitoring their responses to natural and anthropogenic actions (Baker et al., 2006).

* Corresponding author.
E-mail address: jswon@yonsei.ac.kr (J.-S. Won).

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Spaceborne synthetic aperture radar (SAR) has been used to monitor coastal regions and wetlands. Recently, high-resolution space-borne X-band SAR systems such as TerraSAR-X and Cosmo-SkyMed have been made available to the public, but they have rarely been used for salt marsh mapping. X-band SAR applications have gradually increased since the launch of the TerraSAR-X in 2007 (Strozzi et al., 2009). This study is to examine the potential of the high resolution X-band SAR system as a tool for salt marsh mapping. While optical satellite images are very useful for land vegetation studies, it is often difficult to acquire data from tidal flats due to the lack of optimal water and cloud conditions. In addition, optical data are insufficient for identifying salt marsh vegetation because of limitations in the spectral resolution and the lack of spatial resolution for detecting vegetation types (Adam et al., 2010). Radar reflection provides different information than optical sensors (Ozemi and Bauer, 2002). While free from weather condition limitations, radar backscatter is sensitive to dielectric properties (inundation level, soil moisture, soil salinity) and surface roughness (Henderson and Lewis, 2008). Various vegetation communities can be distinguished based on canopy structure, soil moisture, and the presence or absence of flooding (Kasischke and Bourgeau-Chavez, 1997). Hong et al. (2010) reported a strong dependence of scattering mechanisms on vegetation type over wetlands and demonstrated the effectiveness of using TerraSAR-X radar interferometry for monitoring water-level change. A strong correlation of double bounce between the water surface and vertical pole structures in coastal areas was also reported (Lee et al., 2006). Ramsey (1998) recommended shorter wavelength imagery at low incidence angles for herbaceous areas. X-band (3.1 cm) SAR exhibits more sensitivity to leaves and small branches because it has a shorter wavelength and light penetration depth (Huang et al., 2010). Wet troposphere (atmospheric water vapor) can, however, cause artifacts in SAR interferograms, and these artifacts are larger for shorter wavelengths (Zebker et al., 1997). L-band and C-band SAR data have also been used for coastal wetlands mapping (Townsend, 2002; Lang et al., 2008; Slatton et al., 2008; Kwoun and Lu, 2009). Lucas et al. (2007) effectively mapped mangroves using ALOS PALSAR data. Crevier et al. (1996) reported that late autumn is the best season for detecting wetlands when using ERS-1 C-band. Polarimetric analysis is generally considered effective for vegetation monitoring. Like-polarized radars are well suited for detecting flooded vegetation, and L-HH is preferred for wooded vegetation and C-HH for herbaceous wetlands (Kasischke et al., 1997). Cross-polarization is necessary for differentiating herbaceous vegetation from forested areas (Bourgeau-Chavez et al., 2001). Quad-polarization is another benefit of estimating biomass using TerraSAR-X (Englhart et al., 2011).

The potential for using high resolution space-borne X-band SAR in salt marsh mapping has not been thoroughly explored. The primary objective of this study was to investigate the potential of space-borne X-band SAR as a tool for salt marsh mapping. Multi-temporal TerraSAR-X data were acquired under flood/ebb conditions to differentiate halophyte species over tidal flats and to determine their temporal variations. The characteristics of X-band radar backscattering from different halophyte species and their seasonal variations were examined. We also studied the relationship between radar backscattering and a vegetation index derived from Landsat ETM+ to better understand how radar signal is related to vegetation information for different seasons. We aimed to determine the optimal season and tidal flat conditions for satellite observation. Major halophyte species around the west coast of the Korean peninsula include *Suaeda japonica* (*S. japonica*) and *Phragmites australis* (*P. australis*), among others. We determined the distribution of different species and the border between *S. japonica* and *P. australis*. We focused on *S. japonica*, which is an annual, because it changes dynamically according to sea level fluctuation. To differentiate halophyte species and determine the optimal season for salt marsh mapping, a multiple regression analysis and an independent *t*-test were performed for different polarizations. A final salt marsh map was constructed using a decision tree based on a statistical analysis of the backscattering coefficient to validate our approach.

2. Halophytes in the study area

The Ganghwa tidal flat is located on the mid-west of the Korean Peninsula near the estuaries of the Hang-gang (or Han River), as shown in Fig. 1. Tides are semi-diurnal with a mean tidal range of 6.5 m (spring tide = approximately 8 m, neap tide = approximately 4 m) (Choi et al., 2011). The surface sedimentary facies are primarily mud flats in the eastern part of the tidal flat, sand flats in the western part, and mixed flats in-between, as shown in Fig. 1 (Woo and Je, 2002).

The dominant area of *Phragmites australis* is the already stabilized salt marsh, which is affected by seawater only a few times each month. Conversely, the seaward or landward migration of *Suaeda japonica* is an indicator of sea level change, because of the species' sensitivity to sea level. *S. japonica* is an annual plant belonging to the Chenopodiaceae family. It has a stem that grows up to 50 cm high, and it emerges primarily in the spring (March to May). The rapid growth of the underground portion of *S. japonica* during its beginning stage allows it to adapt to the ebb and flood tidal environment. After the roots are firmly fixed in the ground (typically by May), the plant's above-ground portion grows quickly (Lee and Ihm, 2004). Abrupt changes in *S. japonica* distribution represent environmental changes in the local area, as *S. japonica* is particularly sensitive to local sea level changes (Min, 2005). As the frequency of seawater inundation decreases, *S. japonica* appears and migrates seaward. Due to the sparseness of the population at the seaward front, it is, however, difficult to determine the precise boundary for annual observation. Migration of the rear boundary between *S. japonica* and *P. australis* is also an indirect indicator of sea level change.

Phragmites australis, otherwise known as the common reed, has been found at the edges of high marshes and is a perennial grass with annual shoots emerging from underground rhizomes (Orson et al., 1997). This plant grows to 3–4 m in height in optimal conditions (Poulin et al., 2010). The stem dies in the early winter but remains standing as a rigid cane until the plant is reborn the next spring (Burgess and Evans, 1989). *P. australis* spreads primarily through the growth of surface runners and underground rhizomes at the edges of salt marshes (Philipp and Field, 2005).

3. Data and processing

3.1. TerraSAR-X data processing

In this study, a total of 16 TerraSAR-X data sets acquired between 2008 and 2010 were used for analyses of backscattering, polarization, incidence angle, and other characteristics, as summarized in Table 1. Due to the restrictions on quad-polarization data in the study area, only single- and dual-polarization data were used in this study. Halophyte characteristics were initially examined using TerraSAR-X HH single polarization data, which is generally better for discriminating between water-free and partially water-covered surfaces in tidal flats. Single HH-polarization data were the most abundant in this study and were thus utilized as the primary source in the analysis. Dual-polarization of VV and VH TerraSAR-X data was used to examine their effectiveness in distinguishing different species. One data set of 13 single-look slant range complex (SSC)