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Article

A Review on Monitoring the Everglades Wetlands in the Southern Florida Using Space-based Synthetic Aperture Radar (SAR) Observations

Sang-Hoon Hong*† and Shimon Wdowinski**

*Department of Geological Sciences, Pusan National University
**Department of Earth & Environment, Florida International University

Abstract : Space-based Synthetic Aperture Radar (SAR) observations have been widely and successfully applied to acquire invaluable temporal and spatial information on wetlands, which are unique environments and regarded as important ecosystems. One of the best studied wetland area is Everglades, which is located in southern Florida, USA. As a World Heritage Site, the Everglades is the largest natural and subtropical wilderness in the United States. The Everglades wetlands have been threatened by anthropogenic activities such as urban expansion and agricultural development, as well as by natural processes, as sea level changes due to climate change. In order to conserve this unique wetland environment, various restoration plans have been implemented. In this review paper, we summarize the main studies using space-based SAR observations for monitoring the Everglades. The paper is composed of the following two sections: (1) review of backscattered amplitude analysis and observations, and (2) review of interferometric SAR (InSAR) analysis and applications. This study also provides an overview of a wetland InSAR technique and space-based SAR sensors. The goal of this review paper is to provide a comprehensive summary of space-based SAR monitoring of wetlands, using the Everglades wetlands as a case study.

Key Words : Wetland, Everglades, Synthetic Aperture Radar, SAR, Interferometric SAR, InSAR

1. Introduction

Wetlands are defined as areas saturated with low water levels permanently or seasonally, covered by aquatic herbaceous or woody plants. Wetlands are distinguished from other land or water covered areas by these characteristic aquatic vegetation. They are highly productive ecosystems providing unique habitats for various kinds of wildlife. Wetlands also provide invaluable ecosystem services, including water resources, food, filtering of contaminants, flood control, carbon sequestration, shoreline protection, outdoor recreation and other functions. Despite these important benefits, wetland environments have been severely

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† Corresponding Author: Sang-Hoon Hong (geoshong@pusan.ac.kr)

threatened and polluted by natural causes, such as sea level rise, and anthropogenic changes including agricultural and urban development. Recently, various restoration and mitigation projects have begun over some wetlands area. Typically in-situ observations of water level using stage station are essential for hydrological monitoring.

The Everglades wetlands, which are located in southern Florida, USA, are subtropical wetlands consisting of vast, shallow, and slow sheet-flow environment. The sheet flow begins in Lake Okeechobee and flows southward to the Everglades wetlands as shown in Fig. 1(a). In the past 50 years, a significant part of the vegetation in the Everglades wetlands has altered or deteriorated by anthropogenic activities owing to the construct of canals and levees. The current Everglades wetlands are divided into managed and natural wetland environment. The northern and central Everglades are grouped into several Water Conservation Areas (WCAs). Only a small part (~30%) of original wetland area, which is located in the southern part of the original Everglades has remained in its natural conditions maintaining sheet flow characteristics. A significant amount of water level stage stations were constructed for monitoring the hydraulic and ecology conditions of the Everglades wetlands.

Remote sensing observations have been extensively deployed as tools to acquire spatial and temporal information on the Earth surface's characteristics and

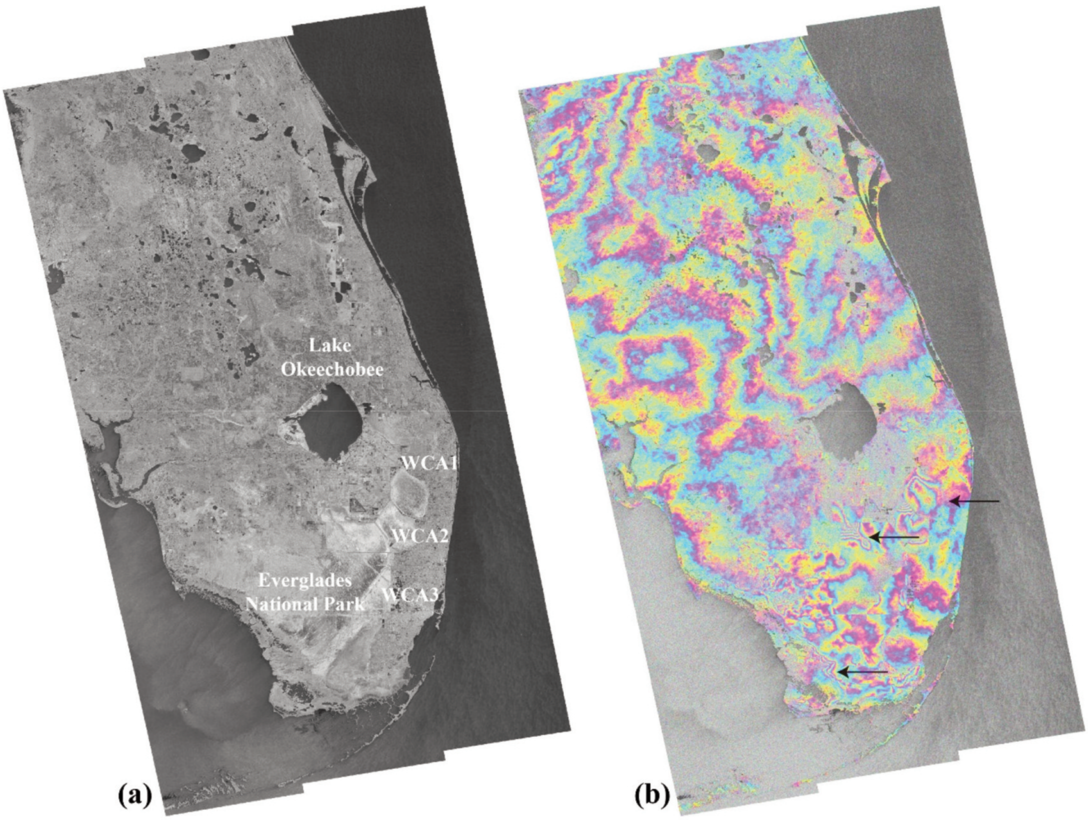

Fig. 1. (a) Sentinel-1 Interferometric Wide amplitude image of the study area (image courtesy of European Space Agency): acquisition date – Oct-09-2016, and (b) interferogram using Sentinel-1 IW mode (Oct-09-2016/Oct-21-2016) showing short wavelength fringe patterns related to water level change (black arrows) over the Everglades wetland. Longer wavelength fringes in entire interferogram are related to atmospheric noise.

their changes. Although in-situ ground observations provide information with very high temporal resolution, their spatial coverage are often too coarse for understanding the larger scale processes due to the limited number of observation points. Thus, remote sensing techniques can serve as excellent complementary tools for better understanding and monitoring wide areas with high spatial resolution. In the past four decades, several remote sensing studies using synthetic aperture radar (SAR) observations have been applied to the Everglades wetlands including (1) change detection of wetland (Bryan, 1981; Bryan and Clark, 1984); (2) monitoring of flood or inundation (Bourgeau-Chavez *et al*., 1996; Kasischke and Bourgeau-Chavez, 1997; Kasischke *et al*., 2003; Bourgeau-Chavez *et al*., 2005); (3) estimation of biological parameters on biomass (Simard *et al*., 2006; Feliciano *et al*., 2011; Feliciano, 2015; Feliciano *et al*., 2017); (4) wetland classification (Brisco *et al*., 2015; Hong *et al*., 2015) and (5) observation of water level change (Wdowinski *et al*., 2004; Wdowinski *et al*., 2008; Hong *et al*., 2010a; Hong *et al*., 2010b; Hong and Wdowinski, 2012; John *et al*., 2013; Kim, 2013; Kim *et al*., 2013; Wdowinski *et al*., 2013; Hong and Wdowinski, 2014a; Hong and Wdowinski, 2014b; Kim *et al*., 2014; Brisco *et al*., 2015). In this paper, we provide a comprehensive review of selected publications of environmental monitoring of the Everglades wetlands using SAR observations. Even though we review only the Everglades wetland in this paper, we can apply these remote sensing techniques for other wetland hydrology around the world like Louisiana in U.S.A., Sian Ka'an in Mexico, Danube delta in Romania, and The Ciénaga Grande de Santa Marta (CGSM) in Colombia, etc.

2. SAR Remote Sensing Techniques

In this section, we will examine remote sensing techniques using SAR observations, which consist of two observables, backscatter amplitude and phase. First, we explain the use of amplitude information over wetlands for monitoring hydrologic conditions and, second, we introduce wetland interferometric SAR (InSAR) technique, which utilizes phase information to retrieve water level change between two consecutive SAR observations.

1) Space-based SAR observations

Since the late 1970s, satellites including space shuttle equipped with SAR sensor have been in orbit monitoring the Earth's surface with various system parameters. Some of the important system parameters include radar wavelength, polarization, and revisit time; these parameters are critical when considering SAR applications for monitoring the Earth's surface (Table 1). More than twenty SAR satellites have been operated in the past four decades, and a series of new SAR satellites are being developed to be launched to monitor the Earth.

Airborne and ground-based SAR systems utilize a variety radar wavelengths, including K- (1.10~1.67 cm), X- (2.40~3.75 cm), C- (3.75~7.50 cm), S- (7.50~15.0 cm), L- (15.0~30.0 cm) and P- (30.0~130 cm) bands. However, most space-borne SAR system have used, so far, only three wavelengths X-, C-, and L-bands. According to a common radar theory, penetration depth increases with wavelength. The longer wavelength of the L-band can penetrate deeper than shorter wavelength of the X- or C-bands. Thus, in vegetated areas X-band radar signal is typically backscattered from the canopies, C-band signal can penetrate the canopies and interacts with mid-level brunches, and the L-band signal can penetrate deeper and even reach the ground beneath the vegetation.

Radar signals can be decomposed into two orthogonal components, or polarizations. The most common polarizations are horizontal linear (H) or vertical linear (V), which were used in the first

Table 1. Space-based SAR Satellites (modified from (Wdowinski and Eriksson, 2009, UNAVCO, 2017))

Satellite	Launch Date	Wavelength	Polarization	Revisit Cycle (days)	Agency
SeaSAT	1978	L-band	HH-pol	17	Department of Defense (DoD), USA
ERS-1	1992-1996	C-band	VV-pol	35	European Space Agency (ESA)
JERS-1	1992-1998	L-band	HH-pol	44	Japan Aerospace Exploration Agency (JAXA)
Radarsat-1	1995-2013	C-band	HH-pol	24	Canadian Space Agency (CSA)
ERS-2	1996-2011	C-band	VV-pol	35	European Space Agency (ESA)
SRTM	2000	X-, C-, and L-band	Dual-pol	–	National Aeronautics and Space Administration (NASA)
Envisat	2002-2012	C-band	Dual-pol	35	European Space Agency (ESA)
ALOS-1	2006-2011	L-band	Quad-pol	46	Japan Aerospace Exploration Agency (JAXA)
Comso-SkyMed	2007-present	X-band	Quad-pol	16	Italian Space Agency (ASI)
Radarsat-2	2007-present	C-band	Quad-pol	24	Canadian Space Agency (CSA)
TerraSAR-X	2007-present	X-band	Quad-pol	11	German Aerospace Center (DLR)
TanDEM-X	2010-present	X-band	Quad-pol	11	German Aerospace Center (DLR)
RISAT-1	2012-2016	C-band	Dual-pol	25	Indian Space Research Organization (ISRO)
KOMPSAT-5	2013-present	X-band	Single-pol	28	Korea Areospace Research Institute (KARI)
ALOS-2	2014-present	L-band	Quad-pol	14	Japan Aerospace Exploration Agency (JAXA)
Sentinel-1	2014-present	C-band	Dual-pol	12	European Space Agency (ESA)
PAZ	2017 (planned)	X-band	Quad-pol	11	Instituto National de Técnica Aeroespacial (INTA)
SAOCOM	2017 (planned)	L-band	Quad-pol	16	Comision Nacional de Actividades Espaciales
Radar Constellation	2018 (planned)	C-band	Quad-pol	12	Canadian Space Agency (CSA)
NISAR	2020 (planned)	L-band	Quad-pol	12	National Aeronautics and Space Administration (NASA) & Indian Space Research Organization (ISRO)

generation satellites, in the form of HH (transmit horizontally and receive horizontally) or VV (transmit vertically and receive vertically) polarizations. As the more advanced and complex radar system have developed, their antennas can transmit and receive the radar signals in more than a single polarization. Because the radar system is often designed to receive the orthogonal polarization to one another, cross polarization signal were acquired, including HV (transmit horizontally and receive vertically) or VH (transmit vertically and receive horizontally). Therefore, three kinds of polarization system can be implemented at the linear polarization basis. These polarizations are (1) single polarized (HH or VV or HV or VH), (2) dual polarized (HH and HV, VV and VH, or HH and VV) and (3) quadruple polarized (HH, VV, HV and VH). The polarimetric properties varied by characteristics and structures of the Earth's surfaces can contain different information of the surface according to polarizations. Oriented structures lead to oriented polarizations and tend to preserve polarimetric coherence, whereas randomly oriented structures like vegetation show depolarization from the backscattered signals (JPL, 2017).

The revisit orbit time is the elapsed time between repeated observations from the same points in space and is a critical parameter for determining a temporal baseline in InSAR application. Since the Earth's surfaces keeps changing over time, the coherence, which is a quantitative indicator of how well the phases of two consecutive SAR observations agree in InSAR application, is severely affected by the Earth's surface's changes. Most especially some Earth's surfaces, such as wetlands and glaciers, change faster compared with other dry land areas such as desert or urban environment (Hong *et al*., 2010a). Temporal baseline, which is time span between two SAR observations, significantly degrades the coherence. Thus, the revisit orbit time, which corresponds very closely with the temporal baseline, is a critical factor in wetland InSAR application.

2) Amplitude Analysis in Wetland

Backscattered amplitude is one of two basic measurements acquired by SAR sensors. It can be converted from its original complex presentation to a real number presentation, using the following relations:

$$A = \sqrt{I^2 + Q^2} \qquad (1)$$

where A is amplitude, I is the real part and Q is the imaginary unit. The amplitude is highly sensitive to the Earth surface characteristics, acquisition geometry, and their changes over time. The two dominant Earth surface characteristics parameters that affect the amplitude are the dielectric constant and surface roughness. The dielectric constant is a quantity measuring a substance ability to store electrical energy. It is defined as the ratio of the permittivity of a material of that of a vacuum. The dielectric constant is 1.00 for a vacuum and higher in non-vacuum environments. The radar signal reflects more from materials with the high dielectric constants, whereas it penetrates deeper in materials with low dielectric constant. For example, the dielectric constant of water is relatively high (about 80) in the natural environment (Short, 2017). Thus, the backscattered amplitude is strongly affected by the dielectric constant and, hence, can be used to classify water covered regions or contents like an ocean, river channel, soil moisture, etc. on the Earth's surface.

The other dominant factor contributing to the backscattered amplitude is the surface roughness, which is related to the irregularities of surfaces and affects the surface's texture. The roughness differs from one place to another, whether in a man-made or natural environments. Strength of the backscattered amplitude of returned radar signal can be varied by the height of surface's roughness. Higher backscattered radar signals are acquired over high roughness surfaces, whereas the lower signals acquired over smooth surfaces such as water surfaces.

Scattering behavior of the radar signal also depends on the radar system wavelength. A surface roughness with a height of 2 cm will have rough, intermediate, or smooth surface characteristics when sensed with X- (3 cm), C- (5.6 cm) and L-band (23 cm), respectively. Surface roughness is often closely related to the incidence angle of satellites. According to the common scattering behavior theory, the dominant scattering mechanisms over land are: surface (single bounce), double bounce, and volume scattering (Cloude, 2009). Single bounce scattering can have characteristics of rough scattering, because it results from slightly rough surfaces, as rough water or small shrubs. Double bounce scattering or dihedral scattering occurs when two smooth surfaces comprising of an orthogonal angle like building or vegetated wetland. The volume scattering arises from dense vegetated areas with multiple scattering in their medium. Besides the above three scattering behaviors, there is also the specular scattering which can be defined. There is no returned power from the Earth's surfaces in specular scattering because the transmitted signal is entirely reflected in the other direction on the very smoother surface such as calm water or bare soil (White *et al*., 2015). The

Bragg scattering was also introduced to explain the effects of the reflection of electromagnetic waves on periodic structures like ocean waves.

Backscattered amplitude analyses have been used for characterizing wetland environments based on radar signal properties mentioned above. First, SAR observations are useful resource for detecting flooded or inundated areas. Because water has a high dielectric constant and behaves as a specular reflector, very little signal is backscattered to the sensor (Di Baldassarre *et al*., 2011). Generally, SAR observations can be displayed as grey-scale images; thus, it is difficult to discriminate or classify vegetation types using a single SAR observation. Multi-temporal or multi-frequency SAR observations provide better sets of observations for generating classified map over vegetated areas. More advanced SAR systems equipped with multi-polarization such as dual or quadruple polarized SAR observations are beneficial in decomposing scattering behaviors depending on surface land covers. Decomposed scattering components provide a new scheme to map vegetation in natural environments. By using a series of SAR observations, we can efficiently classify vegetation in wetland environments.

2) Wetland InSAR

Phase information is the second observable acquired by SAR sensors. It is the fraction of the wavelength of the radar signal that travels from the satellite to the surface and back to the satellite. InSAR techniques have been widely applied to detect centimeter- or even millimeter-level displacements of the Earth's surface (Hanssen, 2001). The technique calculates the phase difference between at least two SAR observations over the same area, acquired from roughly the same location in space. Maps of phase differences, termed interferograms, indicates the extent of how the displacement from earthquakes, volcano, land subsidence, glacier movement, and other kinds of surface's displacement (Wdowinski and Eriksson, 2009). Surface displacements are measured in line-of-sight (LOS) geometry, because SAR signals are captured in slant range geometry. The displacement in LOS direction contains both horizontal and vertical movements. If horizontal displacements are negligible, LOS displacements can be converted into vertical surface displacement using the wavelength of the radar signals and the incidence angle of sensors, as follows:

$$ø_{vertical} = \frac{\lambda}{2\cos(\theta)} ø_{LOS} \qquad (2)$$

where ϕ is the measured phase change, λ is the radar wavelength, and is θ the incidence angle. We use the half-wavelength because SAR systems measure two-way travel time between the satellite and the surface. An increase in LOS direction indicates surface subsidence, whereas a decrease in LOS reflects surface uplift.

While most InSAR applications observe displacements of solid surfaces, the wetland InSAR technique measures changes of aquatic vegetated surfaces. The wetland InSAR technique was first introduced by Alsdorf *et al*. (2001), who detected water level variations in the Amazon basin using interferometric SIR-C radar data. The technique works where vegetation exists above the aquatic surfaces due to the "double bounce" effect, in which the radar pulse is backscattered twice from the water surfaces and the vegetation (Richards *et al*., 1987) as shown in Fig. 2. Wetland InSAR applications were successfully used to study hydrological variations in various wetland environments, including the Everglades (Wdowinski *et al*., 2004; Wdowinski *et al*., 2008; Hong *et al*., 2010a), Louisiana (Lu *et al*., 2005; Lu and Kwoun, 2008; Talib and Wdowinski, 2016), and the Sian Ka'an in Yucatan (Gondwe *et al*., 2010). Fringe density in wetland InSAR interferograms vary depending on the radar signal's wavelength. One fringe cycle corresponds to 2 π shows 2 cm of vertical water level change in X-band (3 cm), 4 cm in C-band (5.6 cm), and 15 cm in L-band radar signal (23 cm) (Tiner *et al*., 2015).

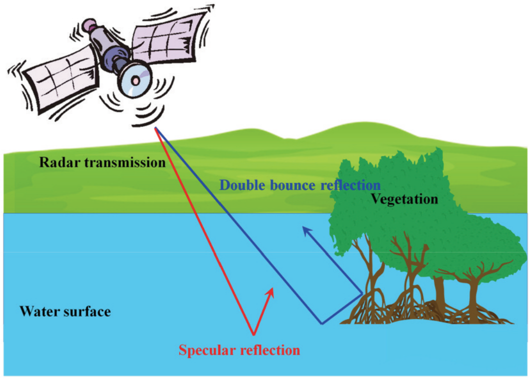

Fig. 2. An illustration showing the double bounce radar signal (blue line) reflected from water surfaces and which then bounced from the vegetation. However a specular reflectance (red line) can be occurred where the vegetation does not exist.

For calibration and validation of observed interferometric phase changes measured over wetland areas, independent observations of water levels are required. Such observations are provided by water level stage stations, which are available in the Everglades, but not in all wetland environments (Wdowinski *et al*., 2004; Wdowinski *et al*., 2008). In areas where ground-based stage stations are not available, space-based altimetry data can be utilized for calibration (Kim *et al*., 2009). The first stage of calibration is extracting water level differences between the interferogram's acquisition dates using either stage station or altimetry data. In the second stage, interferometric phase changes are fitted using a straight line with a slope of one (y = x + b) in order to determine the constant offset value of "b." Finally, the intercept value of "b" should be subtracted from the InSAR water level change observations. The accuracy of relative water level change is about 3~5 cm regarding the L-band SAR observations (Wdowinski *et al*., 2008; Hong and Wdowinski, 2014b), and is 6~7 cm in the C-band data (Hong *et al*., 2010b). The difference in accuracy in the C- and L-band wetland InSAR is likely dependent on the coherence of interferogram. More details can be found in Tiner *et al*. (2015).

3. Review Results

1) SAR amplitude observations

(1) Change detection of wetland

Bryan and Clark conducted the first experiment using space-based SAR observation over south Florida with Seasat satellite, which was operated in 1978 in 106 days (Bryan, 1981; Bryan and Clark, 1984). They used SAR images for change detection of the Earth's surface, which relies on target orientation, azimuth angle, and depression angle of sensors. They first searched for consistency of system parameters, including wavelength, polarization, incidence angle, and azimuth direction is maintained during the SAR image acquisition. Once the consistency achieved, the multi-temporal SAR images were utilized efficiently to detect changes on the Earth's surface. They also proposed guidelines for change detection using the SAR images such as (1) radar system consistency (2) radar look direction consistency, and (3) the interpreters should have background information and basic understanding about area of interest.

(2) Monitoring of flood or inundation

Borgeau-Chavez *et al*. (1996) reported an evaluation study of the ERS-1 C-band VV-pol SAR observation to monitor the spatial and temporal variation of flooding patterns in the Everglades wetland. They demonstrated that backscattered amplitude of the ERS-1 SAR observations could be utilized for monitoring water surfaces in sparse canopy forest and herbaceous vegetation. The SAR observations showed that an increase of inundated surface water from May to November (the wet season in Everglades) of 1995 (Bourgeau-Chavez *et al*., 1996). Kasischke and Bourgeau-Chavez (1997) conducted another study for monitoring changes in soil moisture, flooding and biomass in the Everglades wetland using ERS-1 SAR images, by analyzing two SAR images collected at the end of the dry season (April) and at the end of the wet season (October). They showed that the SAR observations could discriminate between different vegetation communities depending on canopy structure, soil moisture, the presence or absence of excessive water and vegetation growth. Kasischke *et al*. (2003) also presented a multi-year study using ERS SAR imagery to monitor surface hydrologic condition in the Everglades wetland. The multi-temporal backscattered SAR amplitude images showed wide variation of flood conditions. Their results revealed that the inter- and intra-annual variations of backscattered amplitude were reflected by changes in soil moisture and the degree of inundation in the wetland. They suggested that mapping the extent of the flood or inundation is required to better understand and manage wetland regions. Bourgeau-Chavez *et al*. (2005) also used ERS SAR imagery, which were collected from 1997 to 1999, to create inundation maps of relative soil moisture and flooding in the Greater Everglades wetland area. They also developed a method for deriving spatial and temporal changes in the degree of flooding. Unsupervised classification based on principal component analysis was applied to create hydro period maps using a temporal series of 14 months of SAR imagery.

(3) Estimation of biological parameters on biomass

Estimation of tree height is regarded as a good indicator of biomass in forests. Simard *et al*. used the digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) to calculate the mean mangrove tree height in Everglades National Park (ENP) (Simard *et al*., 2006). They also adopted airborne LiDAR data to calibrate the SRTM data and conducted a field survey to derive a relationship between biomass and the mean height of forest stand height from SRTM. The result showed that the total mangrove standing biomass in ENP was estimated to be 5.6×10^9 kg. Feliciano *et al*. (2017) repeated the same study using airborne LiDAR and space-borne TanDEM-X data which were acquired between 2012 and 2015. They detected 10-15% increase in tree height and Above Ground Biomass, compared to the study of Simard *et al*. (2006).

Feliciano *et al*. (2011) presented a study of multi-frequency and multi-polarization (quadruple) SAR observations and terrestrial LiDAR for measuring above ground biomass and analyze vegetation structure over the ENP area. They utilized different scattering mechanisms, which are related to determining that radar interaction can be reflected from various sections of the vegetation and they depend on different polarizations. A comparative analysis using space-based SAR observations and ground-based laser measurements were conducted to estimate biomass over three vegetation types: hammock, pine, and cypress. They also found that space-based SAR observations can be handy tools for wetland forestry studies as a result of their successive studies by using TanDEM-X and airborne LiDAR (Feliciano, 2015). The results showed that canopy height in the mangrove forests was successfully estimated with a coefficient of determination (R^2) = 0.85 and root mean square error (RMSE) = 1.96 m.

(4) Wetland classification

Brisco *et al*. (2015) reported anomalous polarimetric scattering characteristics by using Radarsat-2 SAR observations. According to common scattering theories, wetlands are predominantly double bounce scattering environments due to emergent vegetation over the open water surface. However, Brisco *et al*. found that dominant observed scattering component in wetland environments is odd bounce scattering, as found by several SAR decomposition. SAR decomposition is used to express scattering responses of simple objects from measured polarimetric scattering matrix (Cloude, 2009). This anomalous result might be caused by a combined effect of changes in vegetation double bounce scattering and the incidence angle. The study also suggested that the SAR community should re-interpret the common scattering mechanisms to appreciate this new result from the wetland environment. Hong *et al*. (2015) used TerraSAR-X quadruple polarimetric observations for classifying wetland vegetation in the Everglades. They used the Hong and Wdowinski decomposition (2014a) with TerraSAR-X quad-pol data to obtain four scattering mechanism components (single, co- and cross-pol double, and volume scattering). Optical RapidEye image was also used to compare statistics and results with the SAR observations. The classification was conducted using object-based classifier with model-based SAR decomposition. The accuracy of classification was higher than 85 % which showed that the space-based quad-pol SAR observations could be useful tools for classifications of vegetation over wetland environment.

2) Wetland InSAR observations

(1) Observation of water level changes

Most recent SAR studies of the Everglades wetland have focused on the wetland InSAR application for measuring water level changes. Wdowinski *et al*. (2004) presented the first InSAR measurement of water level changes in the WCAs of the Everglades wetlands. The JERS-1 L-band SAR observations were used for the calculation of water level changes, which varied in the range of 0-105 cm, obtained with 100 × 300 m^2 spatial resolutions. They also showed quantitative estimates of flow diffusivity using a linear diffusive flow model, which are the first space-based estimates of the hydrologic parameter for the Everglades. Wdowinski *et al*. (2008) presented various interesting wetland InSAR results for extended wetland regions including the ENP area using a multi-temporal JERS-1 L-band SAR images for detection of water level changes for both managed and natural flow environments. They found that interferometric coherence is very sensitive to wetland vegetation and are significantly degraded by temporal decorrelation. The L-band SAR observations showed that temporal baselines of less than six months maintained sufficient coherent interferometric phases for estimating water level changes. The results showed that the fringe patterns were organized in the managed wetlands, whereas irregular fringe patterns with low-frequency were detected in the natural environments. Most of the interferograms in the natural wetlands presented an elongated fringe in the transition zone between salt- and freshwater wetlands.

It is well known that the longer wavelength radar signal such as L-band SAR images can maintain a better interferometric coherence over natural vegetated environment like wetland than shorter wavelength C- and X-band data. Thus, most scientists believe that the space-based X-band SAR observations may not be suitable for wetland InSAR application. Hong *et al*. (2010a) presented the first X-band InSAR result over the Everglades using TerraSAR-X observations acquired during an eight-month period in 2008. The interferometric phases were surprisingly maintained in short temporal baseline pairs of 11 days and even 33-days. They also evaluated the multi-polarized SAR observations and noted that it could be utilized for wetland InSAR application. The results showed that multi-polarization interferograms have very similar fringe patterns regardless of the polarization type. Through this result, they implied that volume scattering mechanisms at vegetation in the wetland environment might be less important than commonly believed. Hong *et al*. (2010b) also published a paper related to algorithm development for deriving absolute water level changes. Basically the wetland InSAR technique provides only information on relative water level changes instead of an absolute one. They presented an advanced InSAR time-series analysis technique called Small Temporal Baseline Subset (STBAS) for monitoring absolute water levels, using C-band

Radarsat-1 SAR observations. Their dataset generated 28 successive high spatial absolute water level maps with 50 m pixel resolution and 6.6 cm of RMSE. Hong and Wdowinski (2012) presented another study using multi-polarized (quad-pol) C-band Radarsat-2 SAR observations confirming that the quad-pol SAR observations yield very similar fringe patterns regardless of polarization modes. The results also showed that the highest coherence was observed in HH and VV and lowest in HV or VH suggesting that the double bounce is the dominant scattering behavior in wetland InSAR technique even in cross polarization.

Kim *et al*. (2013) presented interferometric coherence analysis study using various space-based SAR observations of JERS-1, ERS-1/2, ENVISAT, and Radarsat-1. They analyzed coherence variation in various wetland vegetation types, including sawgrass, graminoid, cypress, mixed shrubs, and mangrove marsh. Through this study, they found that woody wetlands have a higher coherence than herbaceous wetlands of sawgrass and graminoid. Unlike the L-band data, the coherence of C-band data was strongly dependent on a temporal baseline. Also, backscattered amplitude from JERS-1 and Radarsat-1 were correlated with coherence in vegetation covered sawgrass, cypress, mixed shrubs, and mangrove. However, ERS backscatter had no relation to coherence except over sawgrass marsh. Finally, they suggested that high resolution, HH-pol and small incidence angle SAR observations are most suitable for wetland InSAR applications. Wdowinski *et al*. (2013) expanded the use of wetland InSAR for monitoring tide propagation over coastal wetlands. Highest water level changes were occurred along tidal channels which reflect a high-velocity gradient between horizontal flow in the channel and the slow propagation in vegetation. They suggested that InSAR observations can provide useful quantitative constraints for coastal wetland flow model generation. John *et al*. (2013) suggested an approach using additive models with single SAR polarimetric SAR observations. They suggested that the radar backscatter models using C-band Radarsat-2 SAR images with lower incidence angle can provide a more accurate estimation of standing water. They also compared the correlation between the radar backscatter and vegetation types and Normalized Difference Vegetation Index (NDVI) result from optical WorldView-2 images.

Kim *et al*. (2013) showed that the L-band ALOS SAR backscatter coefficient in freshwater marsh is inversely proportional to water levels calculated by an InSAR technique. However, another study concluded that the C-band SAR backscatter coefficient has no close relationship with the water level (Kim *et al*., 2014).

By improving the wetland InSAR technique, multi-track and multi-temporal SAR observations were used for calculating a time series of high spatial resolution water level maps. Hong and Wdowinski (2014b) used a four-year-long L-band ALOS SAR images to retrieve the water level. They showed the temporal resolution, which is entirely dependent on revisit cycle of satellites (46-day in the case of L-band ALOS SAR), could be improved by combining the result from different tracks. The observation frequency was improved to seven days in the shortest case.

Hong and Wdowinski (2014b) proposed a new scattering decomposition model which explains the coherence interferogram in the cross-pol SAR observations. In common vegetation scattering theories, the cross-pol is solely attributed to volume scattering. However, they found that cross-pol observations include both double bounce and volume scattering components. They also explained that cross-pol double bounce scattering component by developing a new model-based four-scattering decomposition algorithm. They assumed that the simplest multi-bounce scattering behavior was generated by the cross-pol signals due to rotated dihedrals. They decomposed Radarsat-2 quad-pol data into single-bounce, co-pol double-bounce, cross-pol double-bounce, and volume scattering components. Brisco *et al*. (2015) suggested another wetland InSAR study using Radarsat-2 to evaluate various Radarsat-2 acquisition modes followed by block adaptive quantization (BAQ) coding for wetland InSAR applications. Their results show that wide-swath high-resolution modes are suitable for InSAR applications from the analyses of coherence and backscattered amplitude.

4. Literature survey

We used the Google scholar and the Science Citation Index Extended (SCIE) database from the Web of Science, which are very comprehensive tools for search and review of publications using keywords. The selected keywords are "Wetland," "Synthetic Aperture Radar," and "Everglades." Using these keywords, we found 21 papers from the Web of Science and quite a lot of papers from the Google Scholar (Search date is 20 June 2017). Manual refinement was conducted in order to remove non-relevant wetland research with SAR observations. Finally, 25 papers were selected for the review of wetland SAR studies over the Everglades. The number of publications on wetland SAR is shown in Fig. 3. The figure indicates that more than a half of the entire were papers published after 2010.

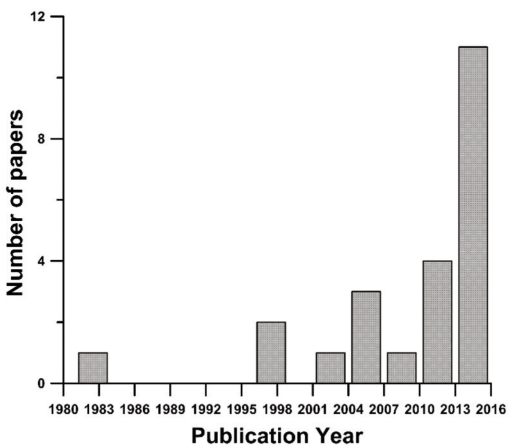

Fig. 3. Number of wetland SAR publications over the Everglades.

5. Conclusion and discussion

Wetland environment is a unique and important ecosystem, which need to be monitored carefully and continuously. This paper provides an overview of wetland remote sensing using space-based SAR observations of the Everglades wetland located in south Florida, U.S.A. A total of 25 articles have been published in the past four decades. The studies can be categorized into (1) change detection of wetland, (2) monitoring flood or inundation conditions, (3) estimation of biological parameters, such as biomass, (4) wetland classification, and (5) observation of water level changes. The overview on backscattered amplitude analysis and wetland InSAR techniques for investigating wetland environment was also carried out. All reviewed papers suggest that the space-based SAR observations are very promising for monitoring hydrologic conditions in wetland environment.

The wetland monitoring with space-based SAR observations as reviewed in this paper can provide high spatial resolution of hydrological parameters which cannot be obtained by any in-situ observations. However, the space-based SAR observations have limitations such as revisit time or spectral resolution, etc. We already pointed out the revisit time is one of critical parameters when applying InSAR technique for wetland area at the second section, and fully polarimetric SAR images have more benefits to discriminate the vegetation compared with a single polarization image. In order to overcome coarse temporal resolution from revisit cycle, it is important to utilize ground measurement to complement the SAR observations. Data fusion technique with optical remote sensed observations to enhance the spectral resolution can be useful to classify and map the wetlands more efficiently.

Though we reviewed selected articles dealing with only SAR observations for Everglades wetland environment, we believe that optical remote sensing can be also invaluable resources for monitoring wetlands. Generally, hyper-spectral or multi-spectral remote sensing images can be used for wetland classification, identification of vegetation species because of high spectral resolution. High spatial resolution optical images can also be utilized for classification of vegetation and detection of boundaries of wetland. Medium and coarse resolution images can be applied to map flooding area and classify wetlands over vast wetland environment. As new methodologies and more advanced satellite system in both SAR and optical sensors will be developed and launched in the future, the wetland study would be greatly improved.

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