Applications and Analyses of Satellite-borne L-band Synthetic Aperture Radar Data in Coastal Environments

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Abstract
There is rapid population growth in coastal environments. Development and competing demands for resources and natural hazards offer an additional threat to coastal communities. Remote sensing provides a means of monitoring the intra- and inter-annual variability both natural and human impacts cause. In this article, we review the application of satellite-borne Synthetic Aperture Radar (SAR) to the coastal zone and provide two examples, seasonal inundation mapping on coastal floodplains at the regional scale in eastern North Carolina, USA, and shoreline delineation and change in estuary of Pamlico Peninsula, Dare County, North Carolina. The results SAR data provide are reliable and repeatable, and can potentially be used to identify critical areas in coastal environments where there is a need to respond to the pressures caused by population growth, land use and land cover change, natural hazards and sea level rise that may be brought about by global climate change.

Introduction
Since the successful launch of SeaSat L-band (with a wavelength of 23.5 cm) HH (horizontally transmitted and horizontally received) Synthetic Aperture Radar (SAR) of USA into space in 1978 (Born et al. 1979; Evans et al. 2005), a new era of acquiring and analyzing spaceborne imaging SAR data has begun. Then there were/are other successful spaceborne missions of L-band SARs including the USA Shuttle Imaging Radar Mission–A (SIR–A) in 1981, USA SIR–B in 1984, USA/German/Italy SIR–C/X-SAR in 1994, Japanese Earth Resources Satellite-1 (JERS-1) between 1992 and 1998, and Phased Array type L-band Synthetic Aperture Radar (PALSAR) of Advanced Land Observation Satellite (ALOS) of Japan since December 2006. As compared to a passive optical sensor (such as USA Landsat TM sensor) that relies on solar radiation for its energy source, SAR is an active sensor that transmits its own microwave energy, and detects the energy backscattered by objects or backscatter. Thus, SAR can operate in day and night. SAR’s wavelength is within microwave range, between 1 mm and 1 m. Thus its
energy can penetrate cloud, fog or rain; it can be independent of weather conditions, especially for SARs of long wavelengths (centimeters or longer). SAR energy can also penetrate vegetation canopy in forested environments. The penetration depth depends on types of forests or total above ground biomass that is linked to tree size and density of a forest stand, and wavelength of the radar system. In general, the longer the wavelength is, the deeper the penetration depth. Also, in comparison with a side-looking radar (SLR) of real aperture, SAR achieves a fine azimuth or along-track resolution by storing and processing data on the Doppler frequency shift of multiple returns and a fine cross-track or range resolution by frequency modulation technique.

To show SAR imagery to a reader, we present a mosaic of near 20 scenes of JERS-1 L-band SAR data covering eastern North Carolina, USA (Figure 1). JERS-1 was operated by then the National Space Development Agency of Japan (NASDA), now the Japan Aerospace Exploration Agency (JAXA). It collected global SAR data from 1992 to 1998. The SAR is a single polarization HH sensor with a nominal incidence angle of 35°. The re-sampled backscatter data can have a spatial resolution or pixel size of 12.5 × 12.5 m. Each scene covers an area of ~75 × 75 km. Individual scenes in Figure 1 were collected between 1993 and 1995. The imagery is shown in grey scale, i.e., the brighter the tone is, the stronger the backscatter. In the figure, the bright signatures along river banks were flooded forests. Scattered bright spots were houses and buildings in towns and cities. Upland forest areas were in light-to-middle gray. Agriculture fields, and herbaceous and shrub lands were middle-to-dark gray. Dark signatures showed flat surfaces such as airport, road, pond, lake, river, sound, and ocean.

Today, there are many successful studies in which SAR data are used as the primary data sources. The studies include the global/national land use and land cover (LULC), national land survey, agriculture, forestry, fishery, resource exploitation, environmental protection and monitoring, disaster prevention and mitigation, and national security. Therefore, the objective to write this compass article is to add additional analyses and datasets of two types of recent published studies in coastal zones. The topics are the seasonal inundation mapping on coastal plains using a single delineation algorithm of multi-temporal datasets at the regional scale in thousands of squared kilometers, and shoreline delineation and study of shoreline change in estuary. Thus, one can foster and promote new researches and studies of using SAR data in coastal environments and communities in the arena and readerships of the geography compass.

Seasonal Inundation Mapping on a Coastal Plain Using JERS-1 SAR Data

NEED FOR UPDATED AND ACCURATE FLOOD MAPS

Mapping the seasonal inundation extent and monitoring its intra- and inter-annual variations on coastal and flood plains are major challenges to
natural resource managers, planners, property owners, and scientists. On the plains, flooded areas can be large in extent due to its flat topography, sometimes in remote regions where ground access can be difficult, and under forest canopies where the usage of optical remotely sensed data may not be able to delineate the flooded versus non-flooded areas. The delineation of the extent is further complicated by the dynamic nature of the streams/rivers on the plains that display great annual variability in
water flow. Also, boundaries of a 100-year or a 500-year flood insurance rate map (a.k.a. the flood map) vary slightly due to the change of annual precipitation. It will take decades for Federal Emergency Management Agency to update the flood maps county-by-county in the USA once, (and then the previously and early ‘updated flood maps’ may be due for updating again). This is problematic for governmental agencies and personnel that manage and enforce flood regulations and provide assistances during a flood event. Finally, updated and accurate flood maps and inundation extent of a particular flood event provide essential information to perform risk assessment of flood hazards, prepare and response to a future flood event, identify short- and long-term flood prevention and mitigation activities, and disseminate the information of flood/inundation hazards to stakeholders and citizens. Thus, a method that can update this information easily and reliably for an area of a large spatial extent is needed; remote sensing, especially SAR, remote sensing can help.

**UNIQUENESS OF USING SAR DATA IN FLOOD MAPPING ON PLAINS**

In mapping an inundation extent using satellite data, a key is to delineate the flooded/non-flooded boundary on the plains. Once the boundary is determined, calculation of the aquatic or upland extent is straightforward. There are mainly two types of boundaries: the boundary between open water bodies or rivers/streams and adjacent non-flooded uplands, and the wet/dry boundary under tree canopies in forested environments. In the first case of boundary identification SAR as well as optical data can be readily used because the open water and adjacent uplands have distinct characteristics on the SAR and optical imagery. In the second identification situation, if forest canopy is not continuous or trees are leaf-off, both SAR and optical data can well identify the flooded/non-flooded boundary. When the forest is of continuous canopy coverage, and trees are in a leaf-on stage or trees are evergreen; however, optical sensor may not be applicable because of the lack of canopy penetration. Radar energy can potentially penetrate through the canopy layer, reach the ground surface, and then bounced back to the radar sensor, which offers radar data unique opportunity in mapping inundation in forested areas. Due to the double-bounced trunk–ground interactions caused by penetrated radar signals and water or saturated/wet ground surface, strong radar returns from flooded forested areas have been created and observed by a SAR sensor, which provides bright or enhanced signatures on a radar image. The bright signatures along river banks of Figure 1 are examples of the strengthened returns. The observation of enhanced returns on the SAR image is especially easy to notice for a radar system with a long wavelength such as the JERS–1 L-HH SAR and current PALSAR in comparison with a radar system of short wavelength such as the spaceborne C-band (5.6 cm wavelength) SARs of the ESA’s ERS-1/2 and ASAR, and Radarsat-1/2 of Canada.
Even though C-band data have been successfully used in the monitoring of the variations of tidal-driven inundation in coastal marshes and wetlands (Ramsey 1995), inundation mapping of wetlands (Kasischke and Bourgeau-Chavez 1997; Rao et al. 1999), study of the temporal and spatial hydro-patterns of wetlands (Bourgeau-Chavez et al. 2005; Lang et al. 2008a,b, Lang and Kasischke 2008), the consensus and recommendation from data analysis and backscatter modeling is, in the inundation mapping of forested environments especially with high volume of biomass, to use the long wavelength SAR data if possible (Henderson and Lewis 2008; Hess et al. 1990, 1995; Hess and Melack 1994; Townsend and Walsh 1998; Wang et al. 1995). Thus, numerous studies using JERS-1 L-HH data have been available in the mapping of the inundation, e.g., the rainforests on Amazonian floodplains, Brazil (Frappart et al. 2005; Melack and Wang 1998; Miranda et al. 1998; Podest and Saatchi 2002; Rosenqvist et al. 2002; Siqueira et al. 2000), coastal plain of North Carolina, USA (Wang 2004), and Mekong Delta, Southeast Asia (Hariyama and Shida 2008). Recently, Rosenqvist et al. (2007) proposed a framework using the operational satellite-borne PALSAR to support the implementation and assessment of the progresses of the Ramsar Wetlands Convention, an international treaty, agreed in Ramsar, Iran, in 1971 (http://www.ramsar.org/).

INUNDATION MAPPING ON THE COASTAL PLAIN OF EASTERN NORTH CAROLINA

In this section, a study using a previously developed algorithm to delineate inundation extent in one location (a rectangle outlined by solid lines, Figure 1) to another location (a rectangle outlined by dashed lines, Figure 1) at regional scale is presented. In particular, the algorithm based on overlapped SAR datasets on January 14, 1993 and August 9, 1994 of Wang (2004) is directly applied to the datasets of March 29, 1994 and August 8, 1994. Can the same algorithm be useable and repeatable in another region?

Based on NC LULC data layer and for the area within the rectangle outlined by dashed lines, southern yellow pines (5470 km²), cultivated areas (5222 km²), and bottomland forests/hardwood swamps (3311 km²) are dominant top three cover types. Together, they make up ~3/4 of the total study area (18,673 km²). The southern yellow pine stands are areas where stocking of trees is at least 75% evergreen needle leaf species, including longleaf pine (Pinus palustris), loblolly pine (Pinus taeda L.), slash pine (Pinus elliottii), and pond pine (Pinus serotina). A mature pine stand (age 50+ years) could have an above-ground dry biomass up to 20 kg/m². Cultivated lands are areas farmed in distinguishable rows and patterns. Typical crops include winter–spring wheat, and sprint–summer–fall corn, cotton, soybean, or tobacco. Bottomland forests/hardwood swamps are areas where deciduous and woody vegetation is above 3 m tall and occur mostly in lowland and wet areas. Crown density is greater than 25%.
predominant species are Tupelo (*Nyssa aquatica*) and cypress (*Cupressus*). The biomass can also be up to $20 \text{ kg/m}^2$ or higher for a mature stand of dense trees. There are other 15 LULC categories whose areas are $\geq 1 \text{ km}^2$, including the high- and low-intensely developed areas. Since the developed areas are less than 2% of the entire study area, and the focus here is inundation delineation on the coastal plains, no effort or attention has been given to separate the developed areas from the five categories. In other words, pixels in the developed areas could be classified as one of the five selected categories depending on the strength of the backscatter from the pixels.

Nineteen river gauge stations operated by the US Geological Survey exist within the area (marked as Xs in Figure 2a), where surface water height, discharge, and other parameters are measured (http://waterdata.usgs.gov/nc/nwis_measurements). From March to August of 1994 the water flow of the rivers and tributaries decreased (Table 1).

Using Wang’s algorithm (2004), we derived five categories, water, marsh, field, non-flooded forest, and flooded forest in the study area. Table 2 lists the coverage of each category. From March to August, the

### Table 1. Descriptive statistics of the decreases in surface water height and discharge measured at 19 river gauge stations within the study area from March 29 to August 8 of 1994.

<table>
<thead>
<tr>
<th>Surface water height (m)</th>
<th>Discharge (m$^3$/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.4</td>
</tr>
<tr>
<td>Median</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.7</td>
</tr>
<tr>
<td>Mean</td>
<td>1.7</td>
</tr>
<tr>
<td>One standard deviation</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Table 2. Classification results of the Japanese Earth Resources Satellite-1 Synthetic Aperture Radar SAR data on March 29 and August 8, 1994. The total study area is 18,673 km$^2$.

<table>
<thead>
<tr>
<th>March 29</th>
<th>August 8</th>
<th>Changes from March to August (km$^2$)</th>
<th>Changes based on March results (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>869.9</td>
<td>648.1</td>
<td>-221.8</td>
</tr>
<tr>
<td>Marsh</td>
<td>1477.3</td>
<td>1345.4</td>
<td>-132.0</td>
</tr>
<tr>
<td>Field</td>
<td>7135.2</td>
<td>8021.4</td>
<td>886.1</td>
</tr>
<tr>
<td>Non-flooded forest</td>
<td>8282.9</td>
<td>8316.1</td>
<td>33.2</td>
</tr>
<tr>
<td>Flooded forest</td>
<td>907.6</td>
<td>342.0</td>
<td>-565.6</td>
</tr>
</tbody>
</table>

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areas covered by water, marsh, and flooded forest categories decreased, but fields and non-flooded forested areas increased. The smallest percentage of absolute change occurred at non-flooded forest category (0.4%), and the largest one at flooded forest category (–62.3%). Three factors are attributed for the changes/decreases. First, the area is fairly flat. Drops of surface water height and discharge mean that there were more inundated areas in March than in August of 1994. Second, there might be more wet or even saturated ground surface, as well as more standing still water surface on the ground in March than August because of no or low
evapotranspiration from deciduous vegetation. A deciduous tree is at a stage of almost no-leaf in March as compared to a full leaf-on stage in August in eastern North Carolina. If these surfaces exist in forested areas, they are likely classified as flooded forest category due to its high backscatter. Additionally, the standing water surface could be in an open place; it was identified and classified as water surface. Third, because deciduous trees were full leaf-on in August, it was possible that even L-band SAR might not penetrate some forested areas with very dense canopies and stems; there would be no enhanced backscatter from these areas even if the ground was flooded or saturated. Thus, the classification method did not treat the areas as flooded forest areas. Intuitively, to resolve the doubt of the penetration one could want to use SAR data of (even longer) wavelength such as the Jet Propulsion Laboratory P-band (wavelength of 68 cm) airborne SAR (AIRSAR). Unfortunately, there are other issues. First, there has not been or is not a spaceborne P-band SAR (even in the planning stage). Second, the massive mass of a P-band SAR system based on current technology, and severe (and random) effects of the Faraday rotation on P-band signal in upper atmosphere make it impossible to have an operational satellite-borne P-band SAR.

With ground visits and analyzing the ancillary data at test sites, there is high certainty (80% or higher, Table 3) about producer’s accuracies of flooded forest, field, and non-flooded forest, user’s accuracies of water, flooded forest, field and non-flooded forest, and overall classification accuracy. For the transition zones between flooded and non-flooded marsh, field, and forest categories, there is some uncertainty. For example, because of the long wavelength and single polarization of JERS-1 SAR, it is difficult for the sensor to distinguish water surface with waves, marsh with dry or wet ground, and fields with dry or wet surface from each other. This leads to low producer’s accuracy for water (49%) and marsh (41%) and very low user’s accuracy for marsh (21%). Thus, additional studies using radar

<table>
<thead>
<tr>
<th>Table 3. Classification accuracy at test sites of March and August 1994 Synthetic Aperture Radar datasets. Overall classification accuracy: 80% of March 1994 data or 83% of August 1994 data.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Producer’s accuracy (%)</strong></td>
</tr>
<tr>
<td>March</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Marsh</td>
</tr>
<tr>
<td>Flooded forest</td>
</tr>
<tr>
<td>Field</td>
</tr>
<tr>
<td>Non-flooded forest</td>
</tr>
</tbody>
</table>
data at short wavelength (e.g., a C-band SAR) and multi-polarization (e.g., PALSAR) or combination of radar and optical data are needed to improve the accuracy.

SIGNIFICANCE IN ACTIVITIES OF LULC MANAGEMENT AND MITIGATION

Overlaying the LULC data layer on the inundation layers, one found that 908 km² flooded forests in March (Figure 2a) consist mainly of bottomland forest/hardwood swamps, 441 km², southern yellow pines, 134 km², and mixed hardwoods/conifers, 76 km². The flooded forests in August (Figure 2b) of 342 km² are dominated by bottomland forest/hardwood swamps, and southern yellow pines. From March to August 1994, the most reduction of flooded forest category occurred in bottomland forest/hardwood swamps (337 km²), mixed hardwoods/conifers (67 km²), and southern yellow pines (45 km²). The seasonal variation between dry and flooded ground in mixed hardwood/conifer and southern yellow pine areas provides interesting thoughts. It is known that the bottomland forest/hardwood swamps are wetlands and are protected by laws. Flood hazards posed by seasonal inundation in these areas can be zoned to exclude certain landuse such as residential housing or commercial development but not necessarily agriculture. Thus, seasonal inundation extents and flooded forest types can be translated into information that is useful for policy and decision makers with the responsibility of LULC management and associated natural resources. Also, in southeastern USA, southern yellow pine stands are typically harvested for papermaking because of the tree’s fast growth pace. On the other hand, the laws preserve wetlands. Therefore, the ability to identify and quantify the seasonally flooded forest areas is of great interest to governmental agencies, papermaking industry, landowners, and the general public.

Shoreline and Shoreline Change in North Carolina Estuary

ESTUARINE AND COASTAL ENVIRONMENTS, AND CHALLENGES TO COASTAL COMMUNITIES

Climate Change 2007 Report of Working Group II from Intergovernmental Panel on Climate Change (http://www.ipcc-wg2.org/) highlights the potential impacts and management options for policy on climate change. In light of global warming and sea level rise, the impacts on coast will accelerate, and environmental, economic, and social vulnerabilities of the coastal zones increase. In USA, the situation is further compounded by the rapid increase of coastal population growth (US Commission on Ocean Policy 2004). The value of the coastal zone for fisheries, recreation, housing, coastal ecosystem integrity, water quality, and storm damage protection is extremely high. However, some coastal areas are eroding.
faster than others, yet extensive shorelines such as found in major estuaries are not readily available or very difficult to map and monitor routinely. Furthermore, the study of shoreline landward migration has important implications because salt marshes and upland vegetation are important components to help understand the global carbon cycle (Nyman et al. 1995). Marsh and estuarine ecosystems also figure important record of past climate changes (Mendelssohn and Kuhn 2004). In North Carolina estuary, Riggs and Ames (2003) documented estuarine shoreline erosions. Their observations were sample sites with limited spatial extent and some outcomes were visual interpretation of historical airphotos that could lack fidelity in spectrum and geo-referencing. Also, landward migration rates of estuarine shorelines especially for North Carolina estuary of a large extent are generally unavailable except where long-term research has been undertaken. The lack of an accurate baseline for systematic monitoring of its estuarine shorelines causes a great deal of uncertainty in the rates of estuarine shoreline erosion in the recent past, let alone indentifying hot spots where erosion rates are high and critical infrastructure such as bridges and evacuation routes are nearby or forecasting the rates in near- or long-term future. Therefore, remote sensing methods that can identify shoreline locations through time, create shoreline database, and improve the understanding and estimation of landward retreat rate or erosion of the shorelines can be quite beneficial. Figure 3 is an example of using aerial photos to delineate shorelines and assess their changes in the estuary in cloud-free dates at the location where there is no vegetation. Two solid lines indicate the distances to the shorelines starting from the same reference point. The length of two dashed lines is the same. A near 30 m and 50 m inland migration occurred from 1993 to 2006 along the solid and dashed lines, respectively.

Aerial photos or optical data can be used to derive shoreline lines. However, following concerns exist. First, they can not delineate shorelines in vegetated areas with high confidence although the weather condition is fine or free of cloud cover. There are mis-geo-referencing among individual quad or quarter–quad of orthorectified digital airphotos, and
inconsistency in reflectance value of adjacent photos (Figure 4). Temporal resolution of aerial data acquisition is low and the cost for the acquisition can be high. Finally, there are available commercial optical sensors (e.g., GeoEye, http://www.geoeye.com/CorpSite/) of high-temporal and high-spatial resolutions. With a typical price of ground coverage, $10–15 per km² the cost can be prohibitive for one to use the data in regional shoreline delineation and change study routinely. Contrarily, these concerns can be eased or removed using SAR data for the mapping. Thus, the use of L–HH SAR data to map North Carolina estuarine shorelines is presented next.

STUDY SHORELINES AND SHORELINE CHANGES

To demonstrate the usage of multi-temporal L–HH SAR datasets in shoreline study, Wang and Allen (2008) developed an edge extraction model to delineate shorelines. Using JERS-1 L–HH SAR data acquired in December 1994 and PALSAR HH data (with the data acquisition mode of the fine beam and single polarization) in December 2006 for Pamlico Peninsula, Dare County, North Carolina (identified in Figure 1) they delineated and verified two sets of shorelines. Then, shoreline changes between 1994 and 2006 of the Peninsula were quantified. They found no noticeable changes on the north and south sides of the Peninsula. However, there was significant landward retreat in the middle to southern portion on the east shore. Inland migration of shorelines varied greatly, with the maximum rate exceeding 11 m per year. They attributed the erosion mainly to several tropical storms hitting the area between 1994

Fig. 4. Mosaic of two rectified airphoto quads showing variable radiometric characteristics and mis-geo-referencing of the quads, Kill Devil Hills, Outer Banks, North Carolina. The road is off ~15 m indicated by a black segment.
and 2006. Since the publication, two additional PALSAR datasets were available in December 2007 and June 2008. There were no major storms impacting the area between December of 2006 and June 2008. Therefore, the shoreline should be stable. Using the same model and analyzing the shorelines of 2006, 2007, and 2008, we found that they were almost identical, even in the middle to southern part of the east shore. Figure 5 shows area near Stumpy Point, Dare County with PALSAR image on December 8, 2007 (a), and derived shorelines using the data acquired on December 5, 2006 (b), December 8, 2007 (c), and June 26, 2008 (d). The
solid dark lines indicate the distances to the shorelines starting from the same reference point. The cross of thin–white lines shows the same geographic location. Shorelines observed between December 2006 and June 2008 are indeed almost identical. Finally, Figure 6 shows the delineated shoreline of entire Pamlico Peninsula in June of 2008. In summary, the results further support the applicability, reliability, and repeatability in shoreline delineation using the model previously developed, and quantification of shoreline variations in estuary.

SIGNIFICANCE

Rapid coastal population growth, and possible acceleration of sea level rise due to the climate change require the public, researchers, and government officials to understand the impacts on shoreline erosion, identify hot spots, implement appropriate mitigation polices in coastal zones, and inform the general public about the hazards and risks to coastal communities and economies. Rapidly advancing technologies in remote sensing, particularly high spatial and temporal resolution datasets of SAR allow improved research on shore erosion processes and patterns. On-going and future studies will reveal the potential to use the techniques and latest spaceborne SAR data coupled with optical datasets and comprehensive and historical records (a) to map and quantify trends of estuarine shorelines, (b) to discover how shoreline changes and erosion rates may affect infrastructure and security, and social and economic vulnerabilities, (c) to model shoreline changes at hot spots, and (d) to disseminate the geospatial data and shore information to stakeholders in support of improved coastal policy and community planning that are resilient to natural hazards.

Concluding Remarks

Advantages of synthetic aperture radar (SAR) include the ability of radar's microwave energy to penetrate cloud cover and forest canopies, and the sensor's independence of solar radiation. Thus, SAR offers unique opportunities in data acquisitions, analyses, and interpretations in the studies of scientific, environmental, natural hazard, and national security problems and issues that greatly impact on humans and societies. The inundation mapping and shoreline delineation using L–HH SAR data are just a tip of iceberg in the applications of imaging radar datasets in coastal areas. The methods are simple, reliable, and repeatable, and take fully the advantage of the available spaceborne SAR data.

Before the end, we would make three remarks. First, there is the limitation of spatial resolution of JERS–1 and PALSAR sensors. As stated previously, the pixel size of the re-sampled JERS–1 data is 12.5 × 12.5 m. Thus, it is impossible for the identification of flood or non-flood areas about or less than a pixel size (156 m²) using a single image. Also, in
Fig. 6. Delineated shoreline of Pamlico Peninsula, Dare County, North Carolina, using PALSAR HH data on June 26, 2008. The peninsula shown is \( \sim 22 \times 46 \) km.
shoreline delineation and change detection, lateral change near or less than 12.5 m cannot and should not be assessed. There has been an improvement of the spatial resolution for the PALSAR. For instance, in the data acquisition mode of the fine beam and single polarization, the pixel size of re-sampled L-HH data is 6.25 × 6.25 m. However, one still facing the difficulty to identity areas less than one pixel (39 m²), and delineate horizontal change less than 6.25 m. One could not unfortunately afford to wait for the next generation of sensor; alternative should be sought. One possible candidate is the interferometric SAR (InSAR) technique because it allows us to identify small and sub-pixel changes between a pair of repeating paths of data acquisitions. As the analysis method of InSAR data becomes mature, and the availability of repeating-path data increases, one should and can explore the InSAR techniques in the studies of the delineation of inundation and shoreline lines, and their variations through time.

Second, improvements of accuracy in inundation mapping could be further made should we incorporated (a) C-band or L-HV data to locations where L-HH may not so sensitive to variations or unable to delineate the changes. The places include marsh areas with dry or wet ground and fields with different moisture contents; (b) airborne P-band data to areas where there is doubt whether L-HH radar energy penetrates through the dense canopies, reaches the ground, reflects from the surface and hits tree trunks, penetrates the canopies again, and finally is received by the radar. The incorporation of C-band and L-HV data should also help the delineation of shoreline and improve the delineation accuracy near mudflats, and areas dominated by herbaceous plants, as well as in the winter or early spring when wetland and upland herbaceous plants are dormant or semi-dormant. In these places and conditions, L-HH data may not be sensitive to the changes of water/non-water boundaries. As mentioned above, the InSAR technique should be explored too.

Third, a reader or user can be overwhelmed by the cost to obtain SAR data, large data volume with complex data formats, and complexity in data analyses. The cost concern reduces greatly because one can apply for data grants. For example, a user can visit http://www.asf.alaska.edu/sardatacenter/ of NASA/Alaska Satellite Facility (ASF) and http://earth.esa.int/dataproducts/accessingeodata/ of European Space Agency (ESA) to apply for the grants of JERS-1, RadarSat-1, and ESA’s SARs. Information to request PALSAR data can be found at http://www.eorc.jaxa.jp/en/index.html of JAXA, and https://ursa.aadn.alaska.edu/cgi-bin/login/guest/ of ASF. With previously completed spaceborne as well as airborne radar flights, and ongoing and planned future data acquisition missions, one is readily provided with SAR data of multiple sensors, wavelengths, polarizations, incidences, spatial resolutions, and temporal observations.

Also, with progresses made in computer hardware/software, and available analytical tools/software specially designed for radar data analysis, the data
volume and formats, and analyses should be no longer issues. In addition to commercial software packages, we recommend links http://earth.esa.int/best/ of Basic Envisat SAR Toolbox, BEST, http://earth.esa.int/polsarpro/ of the Polarimetric SAR Data Processing and Educational Tool, PolSARPro, and http://mac.softpedia.com/get/Math-Scientific/Radar-Tools.shtml of Radar Tools, RAT. All contain necessary and downloadable no-cost software with open source codes to analyze the radar data. With the available datasets and software, a user’s exploration of the use of SAR data in studying and solving his/her problems is ready to begin.

Acknowledgments

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Short Biographies

Yong Wang obtained his PhD degree from University of California at Santa Barbara in 1992. Since 1994, he has been with East Carolina University (ECU). He has published over 30 peer-reviewed journal articles. His current research interests include the studies of responses and variations of shorelines and coastal wetlands to changes of environments and climate, and to sea level rise, landcover types, and landuse changes caused by nature and human disturbance, microwave canopy backscatter numerical modeling, retrieving forest physical parameters by model inversion, and geographic information sciences and analyses, and image processing and analysis. Employment: Department of Geography, ECU; email: wangy@ecu.edu.

Mingsheng Liao is a professor of Wuhan University and State Key Laboratory for Information Engineering in Surveying, Mapping and Remote Sensing (LIESMARS). He leads a SAR data processing and analysis group at the laboratory. His main research interests include the studies of interferometric and polarimetric SAR data processing and analyses, differential SAR interferometry, multi-temporal SAR image analyses, and their applications in geosciences. His studies have appeared in IEEE Transactions on Geoscience and Remote Sensing, Photogrammetric Engineering and Remote Sensing, International Journal of Remote Sensing, etc. Employment: Wuhan University, China; and email: liao@whu.edu.cn.

Changcheng Wang obtained his PhD degree in 2009 from the State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing (LIESMARS) at Wuhan University, China. His research interests include the studies of synthetic aperture radar (SAR) image processing and analysis, landcover types and landuse change, automatic target detection and recognition, and polarimetric SAR image processing and analysis.
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