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Reconstruction of time-varying tidal flat topography using optical remote sensing imageries

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ABSTRACT

Tidal flats (TFs) occupy approximately 7% of the total coastal shelf areas worldwide. However, TFs are unavailable in most global digital elevation models (DEMs) due to water-impermeable nature of existing remote sensing approaches (e.g., radar used for WorldDEM™ and Shuttle Radar Topography Mission DEM and optical stereo-pairs used for ASTER Global Digital Elevation Map Version 2). However, this problem can be circumvented using remote sensing imageries to observe land exposure at different tidal heights during each revisit. This work exploits Landsat-4/-5/-7/-8 Thematic Mapper (TM)/Enhanced TM Plus/Operational Land Imager imageries to reconstruct topography of a TF, namely, Hsiang-Shan Wetland in Taiwan, to unveil its formation and temporal changes since the 1980s. We first classify water areas by applying modified normalized difference water index to each Landsat image and normalize chances of water exposure to create an inundation probability map. This map is then scaled by tidal amplitudes extracted from DTU10 tide model to convert the probabilities into actual elevations. After building DEM at intertidal zone, a water level-area curve is established, and accuracy of DEM is validated by sea level (SL) at the timing of each Landsat snapshot. A 22-year (1992–2013) dataset composed of 227 Landsat scenes are analyzed and compared with tide gauge data. Root-mean-square differences of SL reaches 48 cm with a correlation coefficient of 0.93, indicating that the present technique is useful for constructing accurate coastal DEMs, and that products can be utilized for estimating instant SL. This study shows the possibility of exploring evolution of intertidal zones using an archive of optical remote sensing imageries. The technique developed in the present study potentially helps in quantifying SL from the start of optical remote sensing era.

1. Introduction

Intertidal zones are technically defined by the U.S. National Oceanic and Atmospheric Administration (NOAA) as coastal zones between mean higher high water (MHHW) and mean lower low water (MLLW) lines (Dyer et al., 2000; Gill and Schultz, 2001). Tidal flats or mudflats represent major substrates in intertidal zones and are formed by soft sediment deposition. Tidal flats occupy approximately 7% of total coastal shelf areas globally (Stutz and Pilkey, 2002). However, most global digital elevation models (DEMs) do not cover these areas as a result of the water-impermeable nature of existing remote sensing approaches. For example, tidal flats (TFs) are neither covered by the German Aerospace Center's (DLR's) WorldDEM™ created by TerraSAR-X and TanDEM-X missions (Krieger et al., 2007) nor the Shuttle Radar Topography Mission (SRTM) C/X-band DEM built by Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar. Japan Aerospace Exploration Agency's (JAXA's) ALOS World 3D-30m (AW3D30) product features data gaps in these areas. The same problem appears in the Advanced Spaceborne Thermal Emission and Reflection Radiometer

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(ASTER) onboard National Aeronautics and Space Administration (NASA)'s Earth Observing System Terra, which uses stereo pair of optical images to produce the Global Digital Elevation Model (GDEM, Version 1 and 2). Another popular global DEM, the Global Multi-resolution Terrain Elevation Data (GMTED2010), also presents a similar issue; it comprises mostly of SRTM and other regional high-resolution data sources, including Ice, Cloud, and land Elevation Satellite (ICESat) laser altimeter measurements. These DEM products encounter limitations at coastal regions and reveal clear discontinuity at most sea–land interfaces (Eakins and Grothe, 2014).

Mapping of TF is laborious due to high morphological changes caused by ocean tides, currents, and river flows in estuaries. Approaches commonly used for mapping coastal bathymetry include airborne Light Detection and Ranging (LiDAR) instrument or ship-based single/multi-beam echo sounders. Accuracy levels of DEM is at several centimeters with occasional deviations at 20 cm using current methods (Athearn et al., 2010). However, these methods are unsuitable in intertidal zones owning to shallow water restriction or high water turbidity. Complete survey of TFs and regular maintenance of updated DEM is costly and time-consuming. Only a few regional DEMs integrated bathymetric/topographic data and were released for studies on storm surges (NOAA National Geophysical Data Center, 2015) and tsunami mapping (Titov et al., 2003).

One-time collection of satellite images is another cause of failure of conventional methods to retrieve coastal DEM. At low tides, swath of remote sensing images bears potential in building bottom topography of intertidal areas. However, coincidence of tidal condition and design of such mission is practically impossible from a global perspective. Revisiting remote sensing imageries may allow observation of bottom isobaths. For example, literature provided a series of developments of coastal DEM using synthetic aperture radar (SAR) images and the waterline method (Mason et al., 1995; Heygster et al., 2010; Acar et al., 2012; Wiehle et al., 2015). Feng et al. (2011) introduced a workflow to derive bottom topography of Poyang Lake, China using the Moderate-resolution Imaging Spectroradiometer (MODIS) 250 m spectral bands. Their study combined MODIS water/land boundaries and *in situ* gauge stations to reconstruct contour lines of bathymetry. Kriging interpolation was then applied to fill the rest of the elevation model. Compared with a field survey conducted fifty years ago, their model reached 0.88 m accuracy. Mean standard deviation achieved 0.49 m at relatively stable areas with less inter-annual variability. However, tide gauges may not be freely available in numerous locations around the coast. Therefore, this work mainly aims to reconstruct coastal DEM and reveal its temporal variability without ground observation. We combine an archive of Landsat imageries and a tide model to provide bottom information.

Topography of TFs and its temporal changes are eco-geomorphologically important and can be utilized as proxies for estimating instant sea level (SL) and especially aid nearshore regions. Global SL changes was studied extensively since the era of altimetry satellite two decades ago. However, monitoring coastal SL presents a challenging task in satellite altimetry as a result of land contamination in radar echoes, distracting waveform retrackers from determining water position and height (Tseng et al., 2014). Nearshore water level is isolated from open ocean scenarios because radar waveforms near shorelines must be carefully handled by sophisticated retracking algorithms (Vignudelli et al., 2011). Coastal areas are difficult to reach by current pulse-limited radar altimeters except for practical solutions using emerging SAR altimetry (conceptually similar to synthetic aperture radar that utilizes delay-Doppler) (Ray et al., 2015). Therefore, the second objective of this work is to investigate whether reconstructed coastal DEMs can sufficiently provide SL information compared with current altimetry methods.

This study aims to explore a conceptually different approach to solve problems and to address abovementioned challenges in mapping coastal topography and estimating coastal SL. A probability method is proposed using a suite of Landsat optical remote sensing imageries and a tide model to reconstruct a DEM for TFs (TF-DEM). We exploit a well-known property of TF. Water extent expands rapidly as water level increases owing to flat terrain. Thus, water level-area curves of such TF-DEM are established, and water area computed from each co-registered satellite image is used to estimate Landsat-based SL. We select a TF in the northwest of Taiwan, the Hsiang-Shan Wetland (HSW), as our study site to demonstrate possible solutions for coastal DEM reconstruction and SL estimation.

Section 2 introduces the study area. Section 3 provides data and methods used for reconstructing TF-DEM. Following that, Section 4 shows performances of Landsat-based SL, tide model, and altimetry compared with tide gauge. Section 5 discusses TF-DEM errors and its application in estimating SL. Sections 6 concludes contributions and limitations of this method.

2. Study area

HSW is a salty marsh located in northwestern Taiwan and suburban Hsinchu City. This area fully covers Keya Estuary and Yangang Estuaries at approximately 16 km^2. Width measures 2 km from east to west, with a shoreline length of 15 km from north to south. HSW was listed in the Eastern Asia-Pacific Water Bird Protection Network by the Ramsar Convention in 1996 (Taiwan's Wetland, 2016). This area serves as a major habitat for fiddler crabs and many rare/endangered species of migrant birds (Liao et al., 2008). Fig. 1(a) shows the geographic location of study area in northern Taiwan; red and yellow lines denote ground tracks of Jason-2 and Environmental Satellite (Envisat) altimetry missions, respectively. The green box that covers HSW is enlarged in Panel (b), in which Envisat pass #225 and Jason-2 pass #51 near HSW are used to examine the performance of radar altimeter in this topographic setup. The background of Panel (b) is a natural-color image composed by a low-tide scene of Landsat-8 Operational Land Imager (OLI) (LC81180432014276LGN00), with RGB from bands 4, 3, and 2. The gray part in the middle represents the mudflat of HSW, and deposition near Hsinchu Fishery Harbor at north primarily results from groin effect of the rigid structure. *In situ* data comprise an acoustic tide gauge near the harbor maintained by Taiwan's Central Weather Bureau is used as *in situ* data. However, we only validate SL in 1992–2013 for various independent observations and tide model predictions owing to limited gauge records.

3. Data and method

3.1. Workflow

Fig. 2 shows the modeling procedure for coastal DEM used for estimating SLs. We first gather less cloud-covered Landsat-family imageries and compute the modified normalized difference water index (MNDWI) (Xu, 2006) for water identification. Accumulating sequences of water appearance in time form an inundation probability map (0–100%) equivalent to a relative elevation difference between high and low tides. Thus, we select the DTU10 tide model (Cheng and Andersen, 2010) as our height reference to convert inundation probability into actual elevation by providing boundaries with a physical unit in length. A water level-area curve is formed by simulating a submerged area under stepping water