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Mapping coastal morphodynamics with geospatial techniques, Cape Henry, Virginia, USA

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ABSTRACT

The advent and proliferation of digital terrain technologies have spawned concomitant advances in coastal geomorphology. Airborne topographic Light Detection and Ranging (LiDAR) has stimulated a renaissance in coastal mapping, and field-based mapping techniques have benefitted from improvements in real-time kinematic (RTK) Global Positioning System (GPS). Varied methodologies for mapping suggest a need to match geospatial products to geomorphic forms and processes, a task that should consider product and process ontologies from each perspective. Towards such synthesis, coastal morphodynamics on a cuspate foreland are reconstructed using spatial analysis. Sequential beach ridge and swale topography are mapped using photogrammetric spot heights and airborne LiDAR data and integrated with digital bathymetry and large-scale vector shoreline data. Isobaths from bathymetric charts were digitized to determine slope and toe depth of the modern shoreface and a reconstructed three-dimensional antecedent shoreface. Triangulated irregular networks were created for the subaerial cape and subaqueous shoreface models of the cape beach ridges and sets for volumetric analyses. Results provide estimates of relative age and progradation rate and corroborate other paleogeologic sea-level rise data from the region. Swale height elevations and other measurements quantifiable in these data provide several parameters suitable for studying coastal geomorphic evolution. Mapped paleoshorelines and volumes suggest the Virginia Beach coastal compartment is related to embryonic spit development from a late Holocene shoreline located some 5 km east of the current beach.

1. Introduction

A fundamental aim of geomorphology is to understand how landscapes change through time. A landscape in its broadest sense can be envisaged as a composite of landforms. For example, a watershed consists of hillslopes, rills, gullies, and channels; a barrier island comprises a beach, dunes, overwash fans, and a backshore flat or marsh. Recognizing rapidly evolving technology and diverse needs for coastal geodata, the National Research Council (2004) conducted an assessment and developed a vision for the future of geospatial information in the coastal zone. In the intervening period since the NRC's, 2004 report, much progress has been made. Nonetheless, the geomorphology research community has to be focused on problem-centered research (shoreline erosion or process geomorphology studies) while the geospatial research community has tended to emphasize technological research (e.g., terrain modeling, topobathymetric light detection and ranging (LiDAR), and developing remote sensing techniques). In this case, it may well be that the science is playing catchup to the technology, and so periodic review and case studies are complementary.

Coastal geomorphology emphasizes *problem ontology*, centered on the characterization of landforms as entities derived from complex coastal processes. By comparison, Geographic Information Systems (GIS) and remote sensing most often apply *product ontology*, focused on landforms as objects of mapping techniques, advancing methodology, and developing new algorithms for accurate identification, delineation, and classification (c.f. Van de Vlag et al., 2005). High precision and accuracy achievable with 3D GIS techniques and digital LiDAR coastal change products are possible (Zhou and Xie, 2009), yet quantitative description must be alert to process and scale in order to identify and delineate landforms. Coastal geomorphology has been recognized for being on the forefront of geomorphology in exploitation of new instrumentation and remote sensing (French and Burningham, 2009). Studies that critically advance GIS methodology while also investigating scientific problems inherently invoke both ontologies. A principal contribution to the GIScience community from this research could be the need to identify scale thresholds for various products derived from LiDAR and other 3D geophysical data sources. In addition, the work presented identifies scale limitations and potential geophysical spatio-temporal processes that GIScience can further address (erosion, non-linear morphodynamics, and representing uncertainty in low-relief

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terrain data). A case study of coastal morphodynamics and sea-level rise is presented which explores these issues and identifies implications for product and process ontologies.

2. Mapping coastal geomorphology

Advances in mapping have developed along a technological continuum from replication of traditional techniques (e.g., shoreline surveys and profiles with transits, theodolites, and leveling to GPS, Real-time Kinematic GPS, and remote sensing photo- and image analysis) to maturation (e.g., widespread orthophotography and Light Detection and Ranging LiDAR analysis), and eventually pioneering techniques and new sensing instruments and capabilities (e.g., laser scanning systems, radar and synthetic aperture radar, and geophysical techniques). These techniques exhibit unique characteristics but also share common constraints arising from scale of observation, computational limitations, uncertainty, and error propagation.

2.1. Transects

Field studies have relied on surveying along sample transects to capture and represent landforms (Faustini and Jones, 2003), often using total stations to obtain X, Y and Z values for points distributed relative to the landscape (Andrews et al., 2002); or using RTK-GPS to obtain X, Y, Z values tied to an earth coordinate system (McLeod et al., 2007). An alternative approach involves using remotely sensed data, either in the form of aerial photography, satellite imagery, or airborne LIDAR (e.g., Brock et al., 2002; Stockdon et al., 2007).The problem with either approach is that scaling issues can miss obvious features of landform, such as a crest or a valley, that are integral components of the profile. This deficiency can be overcome by adding survey points at those features, using higher resolution data, or conducting spatial analysis to explicitly extract features.

A critical issue with the survey approach to landform representation is the lateral spacing of transects in cases when some measure of the spatial variability of the landform is desired. Transects are often separated by long distances from one another, and it is assumed that the spatial distribution thus established provides an accurate representation of the variability of the feature. This largely depends on the level of spatial variability that is inherent in the landscape being monitored. Beaches are regarded as fairly linear features that have a high degree of consistency in the alongshore direction, and thus transects used to represent beach changes are often spaced at considerable distances apart. For instance, at the U.S. Army Corps of Engineers Field Research Facility (FRF) at Duck, North Carolina, where coastal processes have been monitored using a dense array of ocean process sensors for decades, beach profiles are distributed at 90 m intervals along the approximately 1 km of beach. In broader studies of North Carolina shoreline changes, transects further apart have been used to depict spatial and temporal variations in both beach and dune systems (Dolan et al., 1991). These relationships have analogous considerations with respect to LiDAR remote sensing. More complex shorelines and landforms require a denser distribution of survey points in both the X and Y directions (or finer post-spacing of LiDAR). The density used should be a function of the dimensions of the features being captured. Woolard and Colby (2002) established that a 2–2.5 m density was optimal for coastal dune landscapes. This survey approach has been used in numerous coastal studies, but it is time-consuming due to the necessity of laying out the grid each time a survey is conducted.

In the mid-1990s survey technology improved with the development of total station survey instruments that project a laser toward a prism that returns the beam to the instrument. Using a base station and successive traverses with a range pole improves mapping efficiency. This allows measuring landform features such as dune crests and troughs as well as points in between and provides the X, Y and Z (elevation) data needed to map the survey area. Andrews et al. (2002) successfully used this approach to monitor landscape change at an Outer Banks (NC) site by conducting monthly surveys over a one-year period. Digital elevation models (DEMs) derived from multitemporal beach LiDAR have also been used to analyze morphologic change (White and Wang, 2003). Similarly, McLeod et al. (2007) demonstrated the practical application of RTK-GPS to map dunes at very high-resolution (<1 m post-spacing) without the use of LiDAR, including purposive sampling of landform features, such as dune crests, toe, and swales.

2.2. Remote sensing

Data obtained from sensors deployed above the earth's surface have long been used to monitor coastal landscapes from balloons, to airplanes, to satellite platforms. Extraction of features such as shorelines have further advanced with the use of higher resolution sensors, the use of algorithms and filters, and time series satellite Synthetic Aperture Radar (SAR) imagery (Wang and Allen, 2008). The NOAA Coast and Geodetic Survey pioneered the mapping of shorelines and coastal resources and more recently the National Geodetic Survey's Remote Sensing Division has undertaken coastal missions developing co-registered orthophotography and airborne topographic LiDAR for interoperable mapping applications (NOAA Interagency Operational Coastal Mapping (IOCM) product, 2008; NOAA Coastal Services Center (CSC)). These data have also been provided in a centralized repository of the CSC's "Digital Coast" (http://www.csc.noaa.gov/digitalcoast/) in standard spatial data formats, yet the production of ubiquitous LiDAR-derived bare earth elevation data and digital elevation models (DEMs) remains an incomplete and intensive production task.

Barber and Shortridge (2004) describe the core tasks in producing DEMs from georectified airborne topographic LiDAR. They note that LiDAR seldom provides the "silver bullet" for broad area terrain mapping, and the primary challenges of data reduction from the point cloud (for bare earth points) and appropriate selection of interpolation method are paramount. These procedures computationally intensive, and mostly proprietary commercial software is used owing to the voluminous data involved and the limited memory constraints of typical desktop GIS software (Shortridge, 2001). Exceptions to these generalities for workstation or small cluster processing of large datasets are few, for example GRASS GIS (Mitasova et al., 2009); TERRAStream (Mølhave et al., 2010), or the public domain Airborne Lidar Data Processing Tool (ALDPAT; Zhang and Cui, 2007). In combination with GIS techniques, LiDAR data for coastal dunes has provided new, three-dimension capabilities for measuring volumes, extracting features, and detecting morphological changes (c.f., Mitasova et al., 2005).

Three-dimensional mapping and spatial analysis in coastal geomorphology have rapidly advanced with the increasing availability of high-resolution digital topographic data. For example, Ventura and Irvin (2000) combined coastal DEMs and soils data for automated landform classification by ISODATA cluster analysis of characteristics. Further, Buonaito et al. (2008) used morphological variables and Principal Components Analysis (PCA) to identify dominant patterns of change in morphology of a tidal inlet (channels, bars, shoals, and bypass bars). Kim and Yu (2009) have illustrated the additional utility of vegetation and soils along with DEMs for mapping coastal dune ecological features. These approaches demonstrate new methods for landform characterization using composite measures rather than individual metrics (Furbish, 2003). In their study of Jockey's Ridge, a coastal dune on the Outer Banks of North Carolina, Mitasova et al. (2005) used terrain analysis techniques to map the peaks, slip faces, windward/leeward slopes and slacks and to quantify change in active and inactive areas of the dune. More recently, time series LiDAR