The intertidal zone, where coastal wetlands provide the first buffer to storm energy and sea level rise, has not traditionally been a focus of geodetic surveying. However, the increasing vulnerability of coastlines to environmental change, increasing population densities near the coast, and increasing reliance on coastal goods and services have all increased the need for accurate intertidal elevations.

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Geodesy on the Water's Edge

Applications of Accurate Heights in the Coastal Zone

Advances in vertical positioning now enable the application of geodetic tools to the intertidal zone, where centimetre-level changes in elevation can have dramatic consequences on coastal resources. Determining accurate elevations within coastal wetlands improves the understanding of processes affecting wetland dynamics and land loss, and the monitoring of elevation change relative to sea levels. Now more than ever, the knowledge of accurate elevations in the coastal intertidal zone is essential to informed decision making in the coastal zone.

Importance of Vertical Infrastructure

Surface elevation is a critical structural component of low-lying coastal areas, where slight changes in elevation can mean the difference between extensive wetland habitats and open water. Wetland plants, which structure the intertidal community, have very specific tolerances to flooding frequency and duration, both of which are dependent on elevation. Maintaining elevation with respect to sea level is critical to coastal wetland survival, especially where up-slope migration is constrained. Global sea level rise, local geological subsidence and human activities, including hydrological alterations, changes in sediment supply, coastal development and subsurface fluid withdrawal, are among the factors that may contribute to elevation loss in coastal wetlands. With the rapid loss of coastal wetlands worldwide, we need to carefully monitor the elevations of existing coastlines with respect to sea level, understand the processes leading to elevation change and predict the outcome of possible mitigation scenarios. The first step is to obtain accurate elevations.

Figure 1: The deep rod SET as deployed on top of a SET benchmark in a coastal salt marsh. (Photo courtesy of D.R. Cahoon, US Geological Survey).

Lack of Vertical Control

Vertical control in coastal wetlands has been problematic for several reasons. Whereas shipborne sensors provide gravimetric data offshore, and land-based measurements define gravity on stable uplands, gravity measurements in wetlands are more difficult to obtain. As a result, geoid models are not well defined in the coastal zone. The National Geodetic Survey (NGS) is currently seeking to collect new gravity measurements along coastal zones to improve geoid models and allow for more accurate (orthometric) heights from GPS observations. In addition, the national network of passive survey control marks ('benchmarks'), established by NGS over the past decades, rarely extends into the intertidal zone. The intertidal zone is often dynamic and unstable, yet its elevation is critical to sustaining its environmental value.

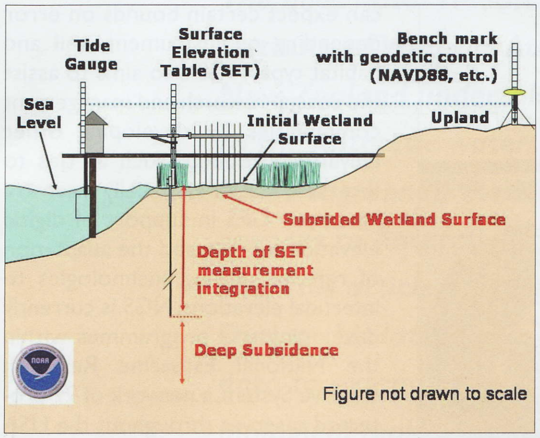

Figure 2: By tying both SET bench marks and tide stations to the National Spatial Reference System, an accurate estimate of relative sea level rise is possible.

NGS is working with partners to establish a network of intertidal benchmarks and elevation products in coastal wetlands of the Gulf and Atlantic coasts of the USA.

Height Modernisation

A height modernisation programme was developed by NGS to update the vertical (height) component of the National Spatial Reference System (NSRS) using the latest GPS-derived technologies. Without modernised heights, it is difficult to assess and manage risk in areas prone to flooding or other natural hazards. This was the case in the aftermath of Hurricane Katrina, where up-to-date heights were not available in portions of the affected states. Traditionally, NSRS benchmarks were positioned by expensive and time-consuming spirit levelling; recent advances, including high-accuracy GPS and GPS combined with laser levelling, have allowed rapid, highly accurate and precise vertical measurements, especially in non-traditional environments such as dynamic and remote coastal wetlands. Height modernisation is therefore the primary vehicle to bring vertical control to the intertidal zone. It can provide updated reference elevations for both tide stations and coastal wetlands, making it possible to relate wetland elevations to local sea level.

Louisiana Height Modernisation

The coastal zone of Louisiana is experiencing rapid land loss. NOAA, in co-operation with the US Federal Emergency Management Agency and the Louisiana Spatial Reference Center, is providing accurate heights for southern Louisiana in the areas affected by Hurricanes Katrina and Rita. Over 300 benchmarks have been re-surveyed, and their published elevations updated. New gravity measurements have generated an improved geoid model. Sixteen continuously operating reference stations have been established to enhance the GPS-derived capabilities of the NSRS. An RTK-GPS network has also been established in south-east Louisiana. As part of this project, state, local and private agencies including the coastal parishes of Louisiana have been trained in obtaining accurate heights (elevations). Accurate elevations are essential data for the rebuilding of levees and other infrastructure, flood-plain mapping and issuance of home elevation certificates.

Surface Elevation Tables

Surface Elevation Tables (SETs) are portable measuring instruments deployed atop wetland vertical benchmarks (Figure 1), allowing millimetre-level changes in surface elevation to be measured over time. SETs integrate both surface and subsurface processes affecting elevation change down to the depth of the benchmark. However, SETs do not convey information about elevation with respect to sea level. Tide gauges have traditionally been used to estimate sea level; however, since these gauges are tied to upland elevations, they do not include elevation change within coastal wetlands. Therefore, NGS is developing guidelines for surveys to be performed that will provide NSRS orthometric heights on SET benchmarks, so that wetland surface elevation measurements can be related to local sea level (Figure 2). Using these guidelines, the vertical motion of the whole SET benchmark can also be measured, providing estimates of deep subsidence.

Providing Vertical Control on SET Benchmarks

NGS has joined with federal and non-federal partners to provide accurate heights on SET benchmarks. In co-operation with the University of New Orleans, the US Geological Survey and the Louisiana Department of Natural Resources, NGS has recently provided accurate heights for over 50 SET benchmarks in south-eastern Louisiana, which will be used to understand processes of elevation dynamics in this subsiding coastline, as well as serving as sentinels for the effects of sea level rise (Figure 3). To provide these heights, NGS developed a level adapter to fit all known types of SET benchmarks. This adapter allows a SET benchmark to receive a GPS antenna, enabling it to be surveyed by a static GPS receiver, a critical step in establishing known elevations in a wetland area regardless of the proximity to upland benchmarks. This also allows elevations to be transferred to nearby SET benchmarks.

Results of Tying SET Benchmarks to NSRS

Two important results are obtained by tying SET benchmarks to NSRS. First, millimetre-level measurements of elevation change are taken out of a relative vertical frame and placed within a known ± 2cm fixed absolute elevation scale. Wetland surface elevation processes such as sediment deposition, biological production

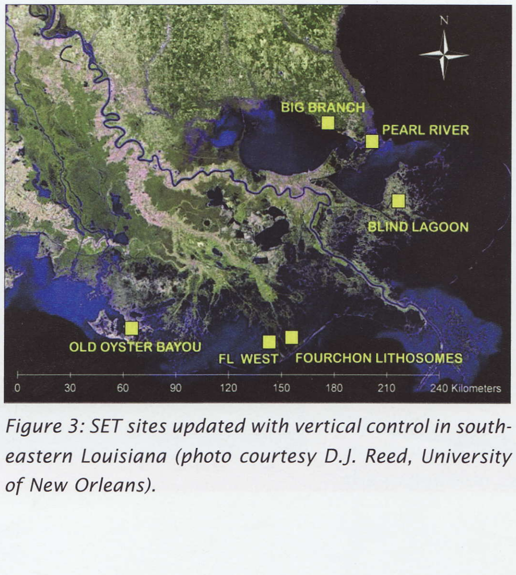

Figure 3: SET sites updated with vertical control in south-eastern Louisiana (photo courtesy D.J. Reed, University of New Orleans).

Figure 4: Protocols for tying SET benchmarks to the National Spatial Reference System. Clockwise from top: locating top of SET benchmark pipe; levelling to top of pipe; installing tribrach adapter; tribrach installed; levelling to top of tribrach; installing GPS antenna; installing RTK-GPS base station; obtaining elevation using RTK. Artwork courtesy Bob Leonard, NOAA NGS.

and peat formation are a function of hydrology, which is affected by surface elevation. Therefore, knowing where an elevation trajectory is in relation to water level is most important in its interpretation. Second, when the elevation of the SET benchmark is re-taken at a later time, a vertical velocity of the benchmark is obtained. This velocity relates to processes occurring below the benchmark, and therefore complements data from the SET, which integrates processes occurring over the depth of the benchmark (Figure 2). With these two elevation products, a complete picture of coastal sediment elevation dynamics is possible.

Expanding Vertical Control

A detailed set of guidelines will be published to enable any user to obtain vertical control on any existing or future SET benchmark according to strict NGS standards with known vertical error (Figure 4). NGS is also conducting an in-depth analysis of the vertical error of the different types of SET technology, so that users can expect certain bounds on error depending on instrument, soil and habitat type. NGS also aims to assist the coastal research and management communities by developing other elevation products, such as ties to local tide stations, spatially intensive kinematic GPS in support of digital elevation models, and the adaptation of remote sensing technologies to intertidal elevations. NGS is currently developing trial programmes within the National Estuarine Research Reserve System, a network of 27 protected reserves throughout the USA and its territories, dedicated to the research of estuarine ecosystems.■

Biographies of the Authors

Galen Scott received a master's degree in Environmental Science and Policy from Johns Hopkins University in 2003. He joined NOAA's National Geodetic Survey as a presidential management fellow, working on strategic planning and translating the science of geodesy for management purposes. Scott now heads a team that provides infrastructure, tools and training to tie together geodetic and tidal datums in support of applications at the land–water interface.

Philippe Hensel obtained a PhD in Oceanography & Coastal Science in 1998 from Louisiana State University and holds master's degrees in Statistics and Estuarine Ecology. He has worked extensively on wetland elevation dynamics and is currently helping to develop guidelines for producing coastal elevation products for NOAA's National Geodetic Survey.

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