The island of Carrie Bow Cay is home to a research station supporting small teams of scientists with housing and lab facilities. Updates to instrumentation enable the station to operate as a Sentinel Site for sea level observations.

MONITORING THE OLDEST DATUM

RISING OCEANS PRESENT CHALLENGES FOR NATURAL AND MANMADE COASTAL ENVIRONMENTS. GNSS IS HELPING TO PROVIDE A SOLID FOUNDATION FOR RESEARCH ON THE RATES AND EFFECTS OF CHANGES IN SEA LEVEL. JOHN STENMARK REPORTS

For thousands of years, sea level has served as an essential, visible physical standard that affects natural and human processes. But it's not a constant. Rapid, obvious changes in coastal water levels are caused by tides and storms. Millennial-scale, climate-induced changes are less noticeable on human timescales, but they represent a moving baseline for the local and rapid changes. Changes in sea level affect marine ecosystems, habitats, shoreline and wetland erosion and accretion processes, as well as human population centres.

In the face of rising seas and oceans, it's imperative to have accurate and reliable data about water levels in coastal areas. Measurements of sea levels using tide gauges provide scientists with quantitative evidence of local sea level ranges. The data includes seasonal (temperature and density-related) water level changes as well as major sea level excursions due to storm surges and tsunami waves. With sufficient data, scientists can derive official tidal data such as mean low water, mean sea level and mean high water – all of which carry legal implications for mapping and charting, navigation and boundary designation. Even longer datasets can provide long-term information on sea-level trends and rates of change including those associated with anthropogenic climate change.

To understand the local impacts of rising sea levels, researchers use direct measurements of water levels, tidal ranges and rates of change. They determine their spatial and functional relationships to a variety of tidal and shallow water ecosystems and coastal geomorphology closely tied to sea level. Knowledge of modern tidal datums and their relationships to sea-level tracking ecosystems such as coral reefs, mangroves and salt marshes are also essential to geologists who interpret the geo-biologic record of these environments to reconstruct paleo sea levels. The work brings together experts in coastal oceanography, geology, ecology, geodesy and marine biology.

Dr Maggie Toscano, a coastal oceanographer with the Smithsonian Environmental Research Center (SERC), has long-standing research interests in sea-level change. An expert in coastal and quaternary (glacial-interglacial cycles) geology, Toscano uses a paleo-ecological perspective in her work that involves geologic 'remote sensing' techniques including collecting and interpreting deep cores into fossil coral reefs and peat deposits. She uses geochemical dating techniques to reconstruct the development of biogenic deposits that have kept pace with varying rates of sea level rise over thousands of years.

Her most recent work has focused on mangroves, a species of trees found in tropical intertidal zones. Mangroves form thick peat deposits consisting of their own extensive root systems, leaves, wood and other plant debris. The trees grow in wet areas where anaerobic conditions allow peat to accumulate, maintaining the system's elevation in response to sea level rise.

"At one site in Belize, we have up to 12m of continuous mangrove deposition over the past 8,000 years of continuous natural, post-glacial sea level rise," Toscano says.

This work requires a thorough understanding of how these biological systems function in the modern ocean. "Because we tend to use biogenic recorders such as coral reef and intertidal mangrove deposits as paleo sea level gauges, it becomes very important to understand the modern tide regime in the places where we're working," Toscano explains.

"Understanding the modern ecosystem's relationship to tides and rates of sea level rise is essential to understanding the geologic record of sea level change."

Scientists such as Toscano are worried about whether mangroves and other shallow water ecosystems can keep pace with accelerating rates of sea level rise. The paleo rates of sea level rise reconstructed from the peat and coral record are indicators of the maximum rates of future sea level rise that will allow for the continuity of coral reefs and wetlands.

In the past few years, Toscano's focus has widened to include modern sea-level research as a means of documenting ongoing changes with actual measurements in the remote areas she studies, where instrumentation is rare and very little on-site climate change data exists

A 2007 photo of Carrie Bow Cay Field Station. The station supports small teams of scientists with housing and lab facilities. In 2015 a new instrument platform was built in the shallow water to the right of the station.

A GNSS receiver set up on a benchmark point on the new instrument platform. Long-session GNSS observations enable researchers to establish precise control and monitor any motion of the platform.

How to measure a moving target

When observing the Earth's systems, scientists seek to gather long-term measurements by going back in time as far written records allow. While tide gauges have been used for centuries to aid in navigation, physical instruments are not uniformly available. But the Caribbean region has had only limited instrumentation and little to no decadal data is available to determine rates of sea level rise and assess impacts of changing water levels on biological systems. For the past 15 years, the Smithsonian has been the only organisation collecting tidal data in Belize, which was until very recently the only western Caribbean country north of Panama (also Smithsonian) actively collecting tidal/sea level data.

Through her involvement with NOAA and the Intergovernmental Oceanographic Commission's Caribbean Tsunami Warning Network, Toscano and her Smithsonian colleagues learned how to build a modern tide station. Based on specifications defined for 'Sentinel Sea Level Sites', modern tide stations include geodetic control networks of benchmarks, regular GPS/GNSS surveying, stable instrument platforms and state-of-the-art tide gauges. They were awarded a major Smithsonian Grand Challenges grant to build four such stations from Maryland to Panama.

The study of sea level demonstrates how global changes can produce local effects. Dr Philippe Hensel, a geodesist with the US National Geodetic Survey (NGS), says that while sea levels are rising globally, local or regional effects vary widely. Rates of change of sea level are influenced by vertical land movements (uplift or subsidence) as well as thermal properties of seawater and changes in local currents. As a result, the rates can vary significantly from one location to the next. For scientists to produce accurate results, they need long-term, site-specific information.

"We all know that global sea levels are rising," Hensel explains, "but local effects of sea level change can be very different. Local ocean currents and vertical land motion will leave a much more nuanced signal on sea level change locally. So we're emphasising the fact that local coastal habitats are responding to local changes in sea level." For much of the coastal research work, consistent local data is more important than developing absolute elevations tied to a national or global datum.

According to Hensel, the key to accurate observation of any water level is confirmed stability of the gauges and sensors used to measure water depths. Researchers reduce water level observations to monthly means or datum estimates and track the data over time. But a sensor's location itself might be unstable—perhaps it's on a pier or heavy structure slowly subsiding into coastal sediments. As a result, the water level recorder will record an apparent rise in sea level, which in fact may be more related to the sinking of the pier than to actual rising of the ocean. So it's very important to conduct regular level measurements of tidal benchmarks, and to confirm the stability and calibration of the sensors.

Levelling between a benchmark and sensor does not reveal information about local, vertical land motion. That's where GNSS comes in. "If

After working through the night a Trimble R8s GNSS receiver greets the sunrise on Carrie Bow Cay. The receiver operated continuously to produce 24-hour data sets needed to connect the island to control points on the mainland.

you do routine GNSS measurements every year and take multiple, long static sessions, then you should be able to identify any local vertical land motion which can be compared to the sea level change data," Hensel says. "That comparison lets people develop conclusions on how much of the measured change in sea level is due to land movement (isostatic change) and how much is due to the combination of changes in the amount of water in the ocean (eustatic changes), offshore currents or changes in water density."

Relating tide gauges to geodetic control networks produces benefits for human and natural communities. "When we're asking questions about the resiliency of coastal communities to sea level change we need better vertical data of the water levels," Hensel says. "The geospatial infrastructure goes hand-in-hand with water level observations. Together they complete the picture of what flooding regimes local coastal communities are experiencing today while also providing information into the communities' long term resiliency to sea level change. A big part of coastal research is directed at producing reliable observations over both short and long terms."

Tidal datum at Carrie Bow Cay

One of Maggie Toscano's mangrove study sites is on Twin Cays, Belize, about 18km off the mainland coast. It's 3.5km northwest of the Smithsonian's Caribbean Coral Reef Ecosystems (CCRE) programme/MarineGEO research station on the tiny island of Carrie Bow Cay. Established in 1973, the Carrie Bow Cay Field Station (CBC) provides houses, labs and support facilities for scientists studying the area's coral reefs and mangrove and seagrass ecosystems. Over the years, the Smithsonian's CCRE programme has supported extensive research in coastal biology and the function of coastal habitats. CBC has produced more than 40 years of continuous data and dozens of important discoveries in marine biological research.

The station has had an environmental monitoring system since 1999 using a multisensor sonde, an instrument that measures parameters such as temperature, pH, salinity and depth. Installed at the end of the station's boat dock, the sonde could collect water quality data as well as functioning as a tide gauge. But after nearly 50 years of exposure to seawater the dock is showing its age.

"The concrete piers are cracking and eroding, and we don't consider it to be stable," Toscano says. "So whatever tidal data we get from the sonde, we need to factor in if the dock is moving or sinking to determine the true rate of sea level rise over time. We're working to bring ourselves up to modern tide gauge standards and to make sure our platforms are stable."

During a 2011 visit to CBC, Toscano and Dr Patricia Delgado worked with Hensel to establish a pair of deep-rod benchmarks on the island. They placed two more benchmarks in the mangrove areas at Twin Cays. Hensel then performed several simultaneous, long-observation GNSS sessions on the four benchmarks. He post-processed the data using the NGS Online Position User Service (OPUS) to produce baseline 3D data tied to geodetic control on the mainland. The team also used optical levelilng to connect the points on CBC, and tie to markers on the island's dock and water-level gauge.

As part of the MarineGEO programme, scientists want marine monitoring to be as accurate as possible to provide context for the ecological changes. In 2015, a new instrument platform was installed at CBC, roughly 75m off the island's north end. The platform pilings were driven to refusal at approximately 8m and provide a stable structure for monitoring. The new tide station instruments include a radar gauge suspended over the water on a braced beam; a below-sea level pressure gauge; a data logger; solar power equipment and a GOES (Geostationary Operational Environmental Satellite) transmitter.

To provide elevation control for the new platform, geodetic surveyor Tim Smith accompanied Toscano to CBC. Smith, the GPS program coordinator for the US National Park Service, is not new to surveying in marine settings. He conducted surveys of the Dry Tortugas and Biscayne National Parks, and used GNSS to monitor the USS Arizona Memorial in Hawaii.

For the work on CBC, Smith served as a Smithsonian-supported volunteer, using his vacation to take a 'busman's holiday' and support the scientific efforts. Smith was delighted with the opportunity to assist.

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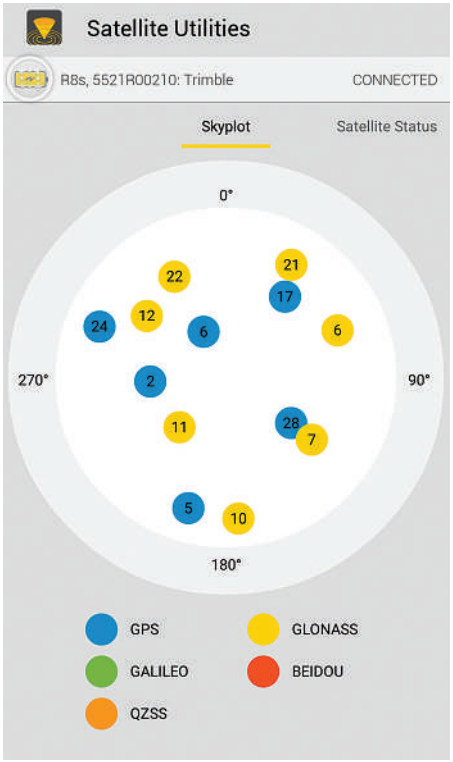
Set up at benchmark point CBC-South, Tim Smith uses an app on his smartphone to operate the Trimble R8s GNSS receiver. The receiver stored data internally for subsequent download and processing.

Tim Smith checks measurements on the CBC-South benchmark. The tiny island has served as a research station for more than 40 years.



A skyplot on Smith's smartphone depicts satellite status during observations. Smith used an Android app to control the receivers and monitor their performance.

Working for the Park Service, he has seen many unique and interesting sites. "I've mapped and surveyed many national treasures," he says. "Carrie Bow is a very special and important place."

Smith used Trimble R8s GNSS receivers to resurvey the existing CBC and Twin Cays benchmarks as well as to establish a geodetic control point on the new platform. "The points installed in 2011 were in good condition," he explained. "I wanted to collect long data sets to tie control to the mainland and update the earlier measurements." Placing one R8 on the island's primary control point, he collected six, 24-hour static data sets while using the other R8 to collect static and fast-static data. He tied in the point on the instrument platform with 12 hours of static observations. Smith sent the Trimble data to Hensel, who will conduct detailed analyses and compare it with the earlier data sets before providing results to the Smithsonian.

With the geodetic control points in place, Toscano and other scientists have a solid basis for levelling to tide gauges and other instruments. They intend to make repeated measurements to the CBC control points over the coming years. The data can add confidence to the accuracy of water levels and help determine if changes in water depth are due to changes in the land or other causes.

"We're looking at everything we can to make sure that the first 15 years of sonde data reflects the correct rate of sea level change, and to account for any rates of sinking or episodic drops of the dock," Toscano says. "We can then connect the sonde record to data from the new gauges to produce a longer trend for the region. We will monitor the benchmark on the new instrument platform periodically to ensure its stability for the new tide gauges."

Toscano and colleagues look forward to expanding their work to include monitoring wetland elevation changes and correlating them to measured water level changes. They and interested outside researchers also plan to make good use of the benchmarks on these islands as GPS base stations from which to conduct a variety of research, including hydrographic/seismic surveying of the area, mapping field sites and taking sample site elevations. "The geodetic infrastructure and the baseline GPS data we already have are major research assets at this remote location," she says. "The scientific possibilities are very exciting."

THE GEODETIC INFRASTRUCTURE AND THE BASELINE GPS DATA WE ALREADY HAVE ARE MAJOR RESEARCH ASSETS

John Stenmark is a writer and consultant in the geospatial industry