

GPS Buoys Nautical Measurement

Knowing exact sea depths along the shoreline is critical to the U.S. Navy and other maritime efforts, but traditional measurement methods aren't always feasible. A new positioning and telemetry buoy equipped with GPS monitors critical water-level measurements far from shore in real time.

By Elliot N. Arroyo-Suarez, Deborah L. Mabey, Vic Hsiao, and Reo Phillips

Global Satellite Based Augmentation Systems (GSBAS) technology has presented us with an opportunity to greatly simplify the gathering of shore data used by the U.S. Navy and other mariners. These critical measurements have traditionally been made using land-based tidewater gauges, dependable only within 12 nautical miles, or hydrodynamic models.

With GSBAS, the same measurements can be made using an offshore buoy specially outfitted with GPS and supporting equipment. The positioning and telemetry buoy is a combined effort of the Naval Oceanographic Office (NAVOCEANO) and the U.S. Navy's Fleet Survey Team. Together, these organizations conduct worldwide hydrographic surveys, measuring the depth and flow of oceans in accordance with International Hydrographic Organization S-44 standards.

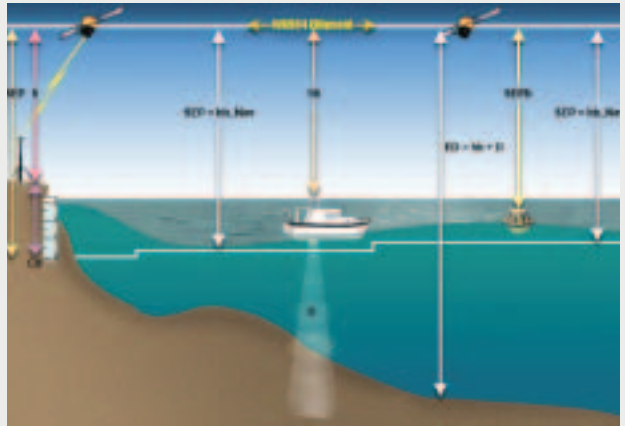
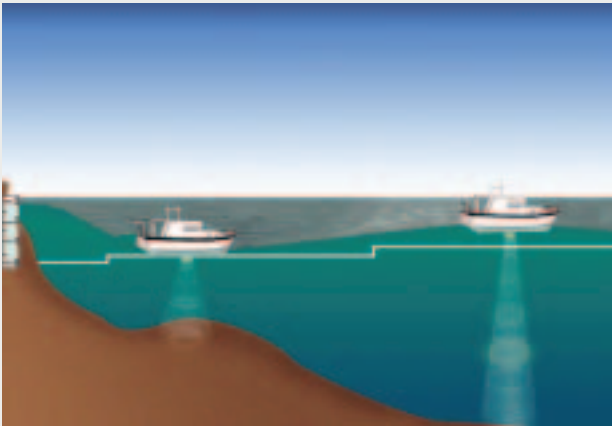
The specialized buoy NAVOCEANO has developed eliminates the need for land-based tide gauge installation, the need for the hydrodynamic models, and the 12-nautical-mile constraint on land-based measurements (see sidebar).

Current Methods Fall Short

To gather water-height data, the Navy primarily uses onshore tide gauges. Installing shore-based tide gauges takes time and resources, adding to the cost of Navy operations. To establish and access these shore stations, the Navy must get clearances and permissions from national and local authorities as well as landowners. Navy personnel must also put forth substantial effort to establish and maintain security for shore parties and equipment left behind.

Furthermore, the Navy doesn't always have convenient access to the shore to set up tide gauges in the first place. Harsh terrain or armed resistance could make it impossible for the Navy to gather the data necessary to let them know the full contours and depths of the seabed. When armed forces are required due to resistance for such installation operations, the installation cost increases exponentially.

As a secondary solution, the Navy has had to rely on hydrodynamic modeling for information on the tidewater level. To make



▲ FIGURES 1 AND 2 Top: A tide gauge at left measures low-low tidewater. Bottom: The measurement, or separation (SEP), from the WGS 84 ellipsoid enabled direct comparisons between the buoy data and the tide gauge data.

The 12-mile limit

One of the key concerns a navigator has regarding nautical charts is the depth of the seabed relative to the low-low water level of the tide cycles. FIGURES 1 AND 2 show a transition from using traditional techniques to using buoy techniques. A GPS receiver is used onboard a boat to measure the h_{Nav} and a depth sounder is used to measure the depth wherever the water level is at the time of measure.

To convert the measured depth to a charted depth, the low-low tidewater level is measured using an onshore tide gauge (see the left-hand side of Figure 1.) Figure 2 illustrates how, as a boat heads out to sea, the tidewater level varies because of changing sea-floor depth. Because the water dynamics become unpredictable beyond 12 nautical miles offshore, the land-based tide gauge technique is often only applicable within 12 nautical miles.

such a model, scientists rely on accurate measurements of the seabed, the coastlines, inlets and channels, and tide data. But these models are only estimates. In reality, the information on conditions is often incomplete or inaccurate, and often are not even available.

Because of the uncertainty of the model input, the current water level error is 40 to 60 percent of the total depth solution.

Occasionally, the sea-depth error can be as high as the total tide amplitude.

The GPS Buoy

NAVOCEANO's positioning and telemetry buoy (Figure 1) uses the NavCom SF-2050G StarFire GPS receiver to provide real-time accurate three-dimensional positions.

GSBAS operates on a globally distributed reference station network, meaning there is no regional boundary for operation and no need to set up a reference station. StarFire, a GSBAS system, will enable the depth and contours of the seabed to be measured on the absolute three-dimensional International Terrestrial Reference Frame (ITRF2000), an earth-centered, earth-fixed (ECEF) reference frame, at the decimeter level globally and, when required, at the centimeter level on baselines of less than 20 kilometers using GPS real-time kinematic (RTK) or post-processed kinematic (PPK) techniques. Using GSBAS eliminates the uncertainty introduced by changes in water level due to tides and vessel dynamics. If land access from the survey vessel isn't feasible, a parallel effort will be conducted to gather reference station data for post-pro-

cessing purposes.

The StarFire GSBAS receiver provides solid-earth-tide corrections. These compensate for three-dimensional position offset relative to the ECEF reference frame from contraction or expansion of the earth caused by the sun and orbit cycles, which repeat every 19.8 years. The magnitude of the solid-earth-tide effect varies depending on the location on the earth and the time of measurement relative to the 19.8-year cycle. NavCom has implemented correctors in their GPS receivers as a user option. When the option is turned on, the GPS receiver will provide solid-earth-tide correctors at the position and time measured by the GPS receiver.

The measurement of water levels tied to an ECEF coordinate system and the derivation of chart data from a GPS-equipped buoy are possible, as proved by a number of studies. Research has shown that the use of high-accuracy GPS buoys to derive chart data increases the accuracy of depths on nautical charts. Our positioning and telemetry buoy is designed to make enough water level observations to derive a localized measurement within each survey zone.

Motion Sensor. Along with this position



▲ REO PHILLIPS of AXYS (left) and Elliot Arroyo-Suarez of NavO prepare the buoy.

One World Four Ways to Stay on Top

- *GPS World Magazine*
- *GPS World Digital Edition*
- *GPS World Website*
- *GPS World E-newsletters*

www.gpsworld.com

Faster access to focused news and analysis about the Global Positioning System, Galileo and other positioning- and navigation-related technologies.

GPS World

The Business and Technology of Global Navigation and Positioning

measurement, a motion sensor on the buoy measures the pitch, roll, and heading of the buoy in real time. Along with the position of the GPS antenna, the pitch, roll, and heading are used to calculate the precise position of the center of gravity of the buoy. The earth tide corrections, pitch, roll, and heading data are all supplied to the buoy's processors, which perform the necessary tilt corrections.

An Iridium satellite link provides the user with processed data. Data is also logged internally for the duration of any data-collection period, allowing the GPS and motion data to be further analyzed in post processing and to increase position accuracy.

The user can configure the buoy's onboard processors, including GPS data observation, logging, filtering, and averaging, making for the most optimum water-level position solution in real time. We also installed a power-saving scheme into the buoy, so that each deployment could last as long as possible.

NAVOCEANO's positioning and telemetry buoy enables the user to measure water elevation over 240 continuous hours, and over a five-year lifetime. It can operate in any climate or location in the world where a measurement buoy can be moored. The buoy is powered with rechargeable lead acid batteries and solar cells, so no additional or environmentally harmful waste is created during the operation and life of the buoy.

The buoy is fitted with a navigation obstruction light programmed with the Ocean Data Acquisition System flash sequence for U.S. Coast Guard compliance and navigation and operational safety. A power switch allows the light to be disabled, which might be necessary for covert operations.

The system is completely configurable and controlled using a wireless interface via a secure Bluetooth link, allowing setup and configuration of the system without hands-on contact, such as from a boat alongside the buoy. We can configure both the operational parameters for the buoy's processors and for the SF-2050G GPS receiver. The buoy's watch circle — the range within which it can move on the water — can be enabled or disabled, the buoy centered within it, or the radius changed. If the buoy drifts out of the watch circle, an alert is transmitted.



▲ THE BUOY is deployed at Patricia Bay in British Columbia.

TABLE 1 Ellipsoid-chart datum separation

	Benchmark 78C9501 (in meters)	Benchmark 867001 (in meters)
Elevation above chart datum	5.431	22.701
Ellipsoidal height	-15.645	1.625
Separation	-21.076	-21.076

TABLE 2 NAVOTAS tide-record analyses for both tide gauge and buoy data

	Tide Gauge Data in meters	Buoy Data	Difference
Mean Higher High Water	-17.64 meters	-17.57	-0.07
Mean Lower Low Water	-20.55 meters	-20.59	0.04
Mean Tide Range	2.91 meters	3.02	-0.11
Mean Sea Level	-18.78 meters	-18.79	0.01

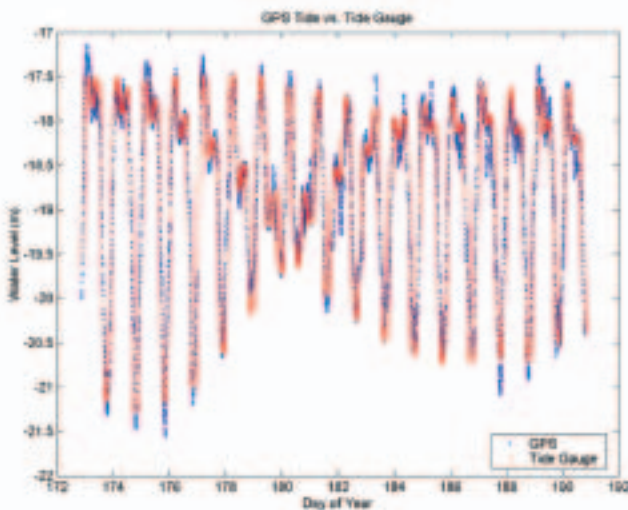
The complete buoy system is 0.9 meter in diameter, weighs less than 216 kilograms, and is able to withstand the impact, shock, and spinning of the ocean environment. The buoy doesn't require any special tools or equipment to be serviced. It can be maintained by general technically trained staff.

Data Comparison

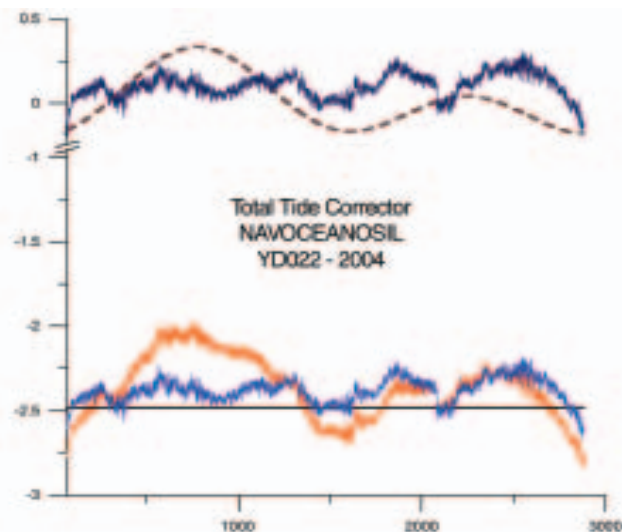
NAVOCEANO's positioning and telemetry buoy was deployed in Patricia Bay, off of Sydney in British Columbia, Canada, from June 21 to July 10, 2005. For comparison, the buoy was anchored within 500 meters of a permanent tide gauge owned and maintained by the Canadian Hydrographic Service.

So that we could make direct comparisons between the buoy data and the tide gauge data, we needed to establish the separation between chart data and the World Geodetic System 1984 (WGS 84) ellipsoid (see Figure 2). The Canadian Hydrographic Service provided elevations of tidal benchmarks above chart data. National Resources Canada, Geodetic Survey Division, provided geodetic positions for these same benchmarks. The separation between chart data and the WGS 84 ellipsoid was calculated for two benchmarks, 78C9501 and 867001 (TABLE 1).

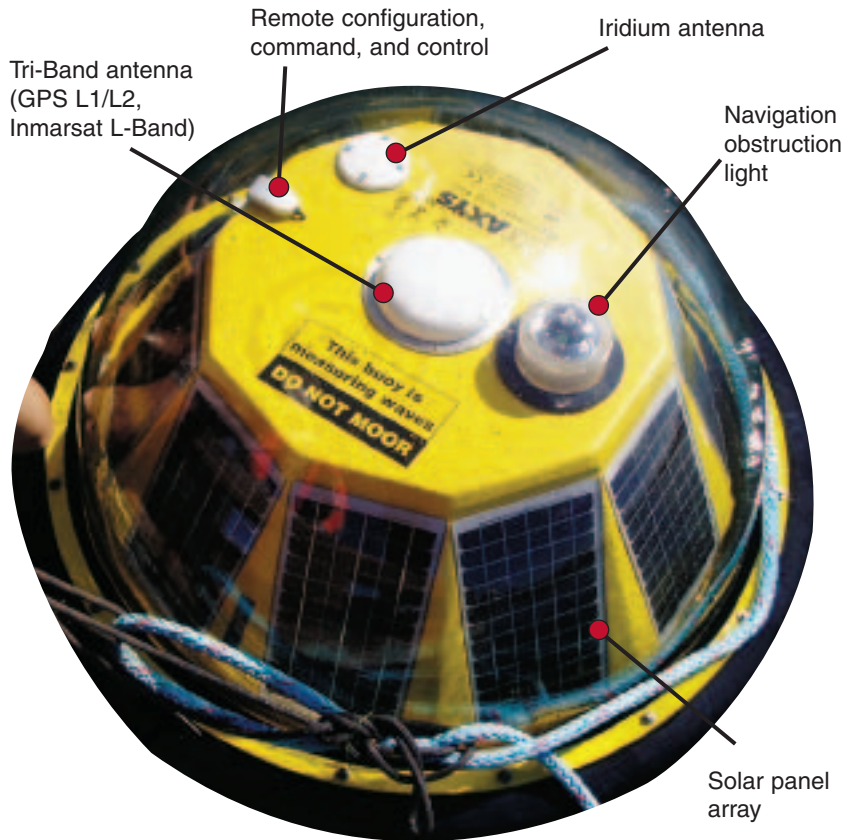
Height data recorded by the buoy was compared to tide gauge data obtained from the Canadian Hydrographic Service. The tide



▲ **FIGURE 3** The mean water level as measured by the tide gauge (red) and NAVOCEANO's buoy (blue).



▲ **FIGURE 4** The buoy's observed accuracy over its known position



▲ **BUOY ARCHITECTURE**

gauge data was converted to height from the WGS 84 ellipsoid by adding the separation to the tidal time series. We manually selected daily high and low values, and used NAVOCEANO's NAVOTAS software to calculate mean higher high water, mean lower low water, mean tide range, and mean sea level for the observation period (TABLE 2).

The data show how accurate the buoy is compared to measuring with a tide gauge, giving us confidence in the buoy's capabilities on the open ocean. Mean lower low water measurement varies by only 4 centimeters; mean sea level difference is only 1 centimeter. Tide gauge and GSBAS height records are shown together in FIGURE 3.

Future Plans

Testing. Two additional tests of NAVOCEANO's positioning and telemetry buoy are planned. The first involves simultaneous collection of raw GPS data for post-processing, real-time GSBAS data, and tide gauge data for comparison. The second is an operational scenario in which the seabed will be mapped from a seamless reference, the WGS 84 ellipsoid. Depths measured

from the ellipsoid will be reduced to chart data by subtracting the buoy-produced separation. The separation-reduced depths will then be compared with depths reduced using traditional tidal methods. Further data collection is scheduled for early April in Chile for about three weeks.

Processing Methods. Traditional tide gauges use a combination of mechanical and numerical filters to remove the unwanted effects of high frequency wind waves and currents. These filters are part of the physical design of the sensor and the data-collection algorithm in the data collection platform. We still need to determine an optimal filter to extract the water levels due to astronomic, hydrodynamic, and atmospheric effects, thus eliminating the noise from the GSBAS height solution.

We are continuing to collect and analyze data to develop improvements and enhancements. For instance, signal processing and harmonic analysis techniques will be applied to the buoy-produced water level data with the goal of consistently producing separation values within 10 cm of those calculated using established land-based gauges.

Next Generation. We expect the next generation of the positioning and telemetry buoy to be smaller and lighter, to incorporate new battery technologies as well as use less power, and to replace the current Bluetooth communication link with WiFi capability. We are also aiming for more than 30 days of continuous operation, an improvement over the current 17 days.

Other improvements on the horizon include implementation of ocean loading corrections, and the broadcast of raw GPS data.

Acknowledgments

Deborah L. Mabej thanks Lieutenant James Coleman and Lieutenant Commander Christopher Sterbis of the U. S. Navy's Fleet Survey Team for their willingness to investigate and operationalize new technologies. Elliot N. Arroyo-Suarez thanks his wife, Maria de Lourdes, for her support. The authors also thank Neil Sutherland of the Canadian Hydrographic Service, Tidal Survey Division, for providing tidal and geodetic data; Jeannette Bedard of AXYS Technologies for providing buoy data; and Jim Mattock for his contribution to the design and for implementing the algorithms. 🌐

Manufacturers

AXYS Technologies provided the *Tri-AXYS* buoy with motion sensor, data logger, and telematics sensors (www.axystechnologies.com). **NavCom** provided the *SF-2050G* GPS receiver, *StarFire* GSBAS correction service, telemetry architecture, and buoy system integration (www.navcomtech.com). **NAVOCEANO** provides oceanographic products and services to all elements within the Department of Defense (www.navo.navy.mil).

VIC HSIAO is Director of Mobile Communications for NavCom Technology, Inc., Torrance, California.

ELLIOT N. ARROYO-SUAREZ is an advanced researcher with the Naval Oceanographic Office, Stennis Space Center, Mississippi.

DEBORAH L. MABEY is a lieutenant with the U.S. Navy Fleet Survey Team based out of Stennis Space Center, Mississippi.

REO PHILLIPS is engineering manager of AXYS Technologies Inc., of Sidney, British Columbia, Canada.