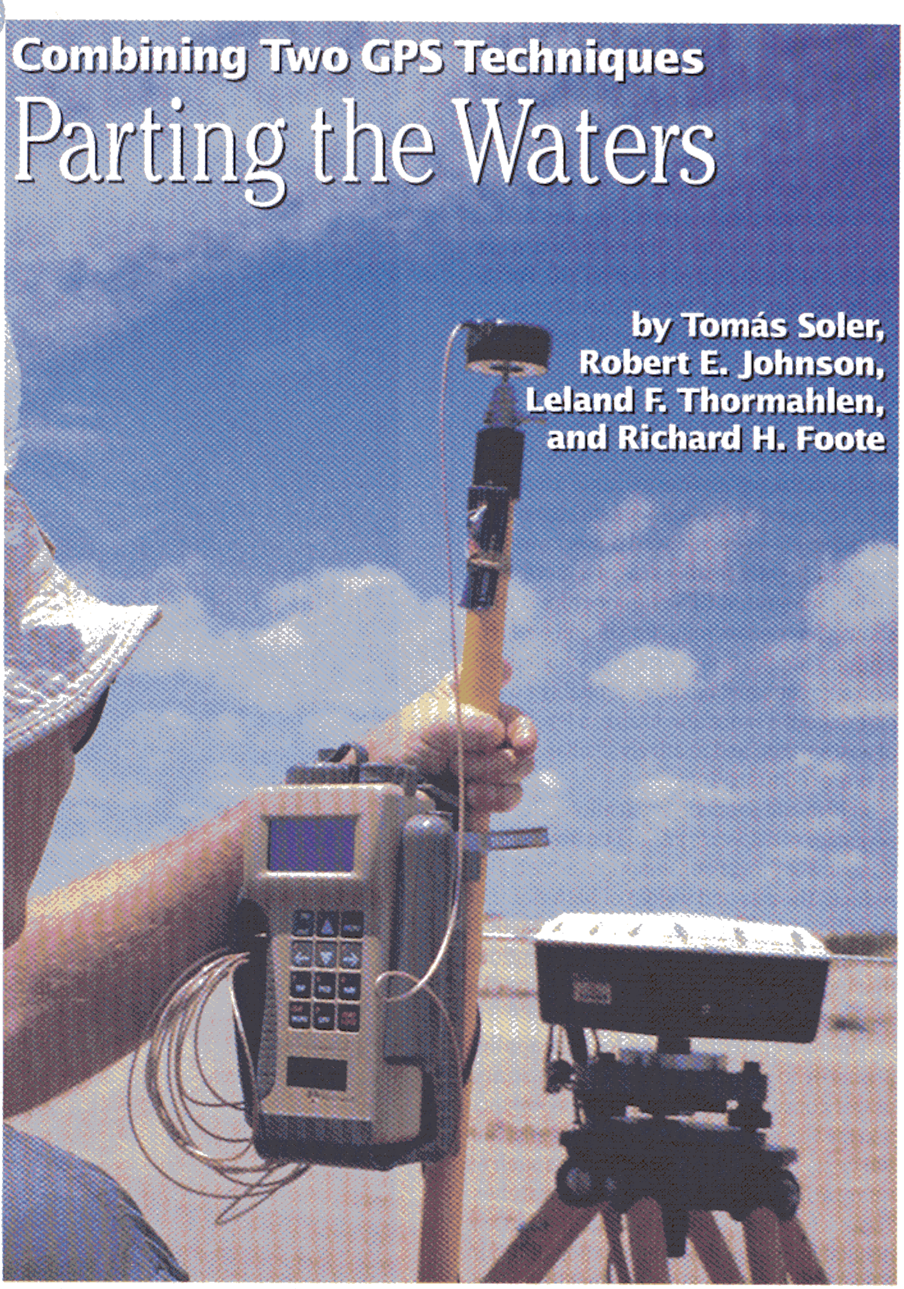

Combining Two GPS Techniques

Parting the Waters

by Tomás Soler, Robert E. Johnson, Leland F. Thormahlen, and Richard H. Foote

This article shows . . .

- how an international survey team calculated the position of the economically important U.S./Mexican boundary in the Gulf of Mexico
- how the U.S. and Mexican governments accepted a combination of real-time and static differential GPS data as a basis for mapping marine boundaries

On October 22, 1997, the U.S. Congress ratified the 1978 Bilateral Agreement establishing the U.S./Mexican boundary in the Gulf of Mexico. Two gaps — named the Western and Eastern Gaps — remained in this boundary. The gaps were areas beyond the 200-nautical-mile (370-kilometer) Exclusive Economic Zone (EEZ) that surrounds both countries. In areas with thick continental shelf deposits, such as those that exist in the Gulf of Mexico, the United Nations Convention on the Law of the Sea (UNCLOS) allows nations to claim territory beyond the EEZ out to a maximum of 350 nautical miles (648 km). Because rich oil and gas deposits underlie the area, petroleum companies were eager to undertake preliminary exploratory surveys as soon as the governments finished delineating the boundary, so both governments were interested in dividing the Western Gap quickly and fairly.

During negotiations with Mexico, the United States, in conformity with UNCLOS guidelines, proposed that the Western Gap (**Figure 1**) be divided by a line equidistant from the low-water marks of both countries' coastlines. However, questions arose regarding the accuracy of the nautical charts that would be used to depict the coastal baselines from which to calculate such an equidistant line. To check the accuracy and currency of the coastline charts, Mexico and the United States agreed to conduct a joint survey. The agencies involved were the U.S. Department of State, the Mineral Management Service (MMS) of the U.S. Department of the Interior, the National Geodetic Survey (NGS) and the National Ocean Survey (NOS) of the National Oceanic and Atmospheric Administration (NOAA), and Mexico's Instituto Nacional de Estadística, Geografía y Informática (INEGI).

During the early stages of the survey planning, representatives of the agencies evaluated Mexican and U.S. sources of information to determine which portions of the coastline might need to be resurveyed. The two countries agreed on surveying procedures and techniques to be used. Together, in 1998, teams representing both countries surveyed various locations along the coastline which, as we will see later, were found to have changed considerably from locations shown on current nautical charts. The survey unequivocally determined the location of the low-water line along the coasts of both countries, providing the baseline coordinates to compute the required equidistant line to be used in the delimitation.

Survey Methods

The parties agreed to use identical survey procedures in both countries. Originally, Mexico wanted the most accurate survey possible, exclusively dependent on tripod-mounted static relative (differential) procedures, the use of dual-frequency geodetic receivers, a minimum of two-hour observing periods, and rigorous office postprocessing of carrier-phase observables to obtain centimeter accuracies. In contrast, the United States proposed a real-

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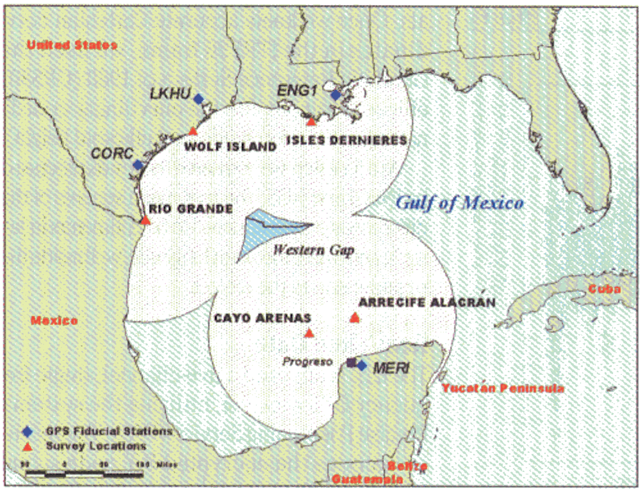

FIGURE 1 The Western Gap in the U.S./Mexican boundary surrounded by the 200-mile EEZ plotted from our survey locations. The gap covers 5,092 square nautical miles (17,487 square kilometers), an area slightly smaller than the state of New Jersey. The line shows how the gap was divided as a result of our survey.

TABLE 1 Survey dates and locations

Survey	Date	Country	Location
A1	6/30/98	U.S.	Isles Dernieres (Raccoon Island), south of New Orleans, Louisiana
B1	7/20/98	Mexico	Arrecife Alacrán (Scorpion Reef)
B2	7/21/98	Mexico	Cayo Arenas (Sandy Cay)
C1	8/24/98	Mexico	Mouth of the Rio Grande
C2	8/25/98	U.S.	Wolf Island, south of Freeport, Texas

time point positioning approach using a handheld P-Y code GPS receiver. Users from federal civilian agencies have found that this receiver's Wide Area GPS Enhancement (WAGE) feature can improve accuracies from an average of 8 meters (without WAGE), to an average of 4 meters (with WAGE). It was felt that 4-meter accuracy would be sufficient, given the United States' practice in earlier maritime boundary agreements of rounding boundary turning point coordinates to the nearest second of a degree (30 meters). Finally, it was estimated that the expected 4-meter error would yield more precise results than digitizing points from a paper chart (MMS' standard procedure for this type of work). MMS preferred the handheld receiver because it would allow the surveyors to collect more points along the shoreline and outlying rocks and because it would be within the acceptable range of accuracy.

After negotiating, the U.S. and Mexican teams agreed to use both methodologies. During a typical field survey on this joint project, at least one fixed geodetic receiver continuously collected data for the entire span of time (three to six hours) at each visited location. Wherever possible, base stations were set up at prominent landmarks such as lighthouses. Other static stations, observing a minimum of two hours, were established along the beaches. Simultaneously, surveyors ran a traverse with the handheld between the static points, collecting additional information along the water's edge, including rocky formations that emerged offshore during low tides. This traverse produced a detailed inventory of the coastline and its outlying rocks, while the static receivers provided the necessary accurate geodetic control for confidence checks.

We made five days of observations at several geographical locations on three campaigns named A, B, and C. **Table 1** shows the specific days and areas selected for the survey.

Survey Campaigns

Isles Dernieres. The Isles Dernieres, Louisiana (like Wolf Island, Texas, discussed later), are barrier islands, an ensemble of long, narrow, flat bodies of sand running parallel to the Gulf of Mexico's U.S. shoreline, separated from one another by inlets and from the mainland by marshes or shallow lagoons. The term "barrier" is apt, because they shield the mainland from the force of big storms. Periodically, they suffer extensive erosion and sand relocation caused by the energy of the waves. These isolated islands are most conveniently reached by helicopter. We collected GPS static data for more than three hours at two points located at the extreme east and west ends of Raccoon Island and marked the points with iron pegs. Because of the high mobility of the sand at these islands, the marks can be easily recovered with metal detectors if the need arises. We deployed two dual-frequency GPS receivers provided by the Louisiana Department of Transportation and Development. Simultaneously, we used two handheld receivers to map as closely as possible the southern (seaward) shoreline spanning the two static points.

Mexican coral reef islets. Two small islands and reefs located about 100 nautical miles north of the Yucatán Peninsula are the closest Mexican territory to the U.S. across the expanse of the Gulf of Mexico. Determining the accurate location of these islands was an important objective for Mexico.

These islands are different from the barrier islands described previously. They consist of sandy outcrops with shrub vegetation that helps to anchor the dunes, which are bounded by small rocky islets encrusted with coral. Arrecife Alacrán, the first island we visited, is uninhabited, while Cayo Arenas, about 100 nautical miles west, has a permanent two-person settlement, staffed by the Mexican Navy.

Both parties boarded the Mexican Navy's oceanographic ship Antares at the seaport of Progreso. After an overnight cruise of about six hours, the ship moored early in the morning near Arrecife Alacrán. A motor launch and a Zodiac brought the survey crew to the island.

We collected readings from the island and by boat along the reef. At sunset we departed for Cayo Arenas, where we arrived at dawn of the next day. At both islands we had the support of a helicopter from the Mexican Naval Base at Veracruz for aerial reconnaissance. For the reefs campaign, INEGI provided four dual-frequency receivers. We established static points called BALIZA, MEX6, MEX7, and MEX8 (Arrecife Alacrán) and MEX4 and MEX5 (Cayo Arenas). We then selected two man-made structures, a metallic tower with a solar-powered light beacon at Alacrán and a lighthouse at Arenas, as reference points for the static observations. As before at Isles Dernieres, we took real-time absolute observations at the northern (seaward) fringe of the two reefs.

Mouth of the Rio Grande. On the first day of this final trip, we collected observations at the mouth of the Rio Grande in Mexico. INEGI provided four dual-frequency receivers. We observed four points (MEX1, MEX2, MEX3, and FARO) for four hours each. Three points were positioned along the beach, and FARO was the reference station at the base of an inoperable lighthouse shown on topographic maps.

Deep Water, High Stakes

The U.S. Department of the Interior's Mineral Management Service (MMS) collects royalties for minerals extracted from federal and Indian lands and oversees leasing and the regulation of mineral production (primarily oil and gas) on the nation's outer continental shelf. Offshore mineral leases, located largely in the Gulf of Mexico, generate nearly $4.7 billion in annual revenue and are one of the federal government's greatest sources of nontax revenue.

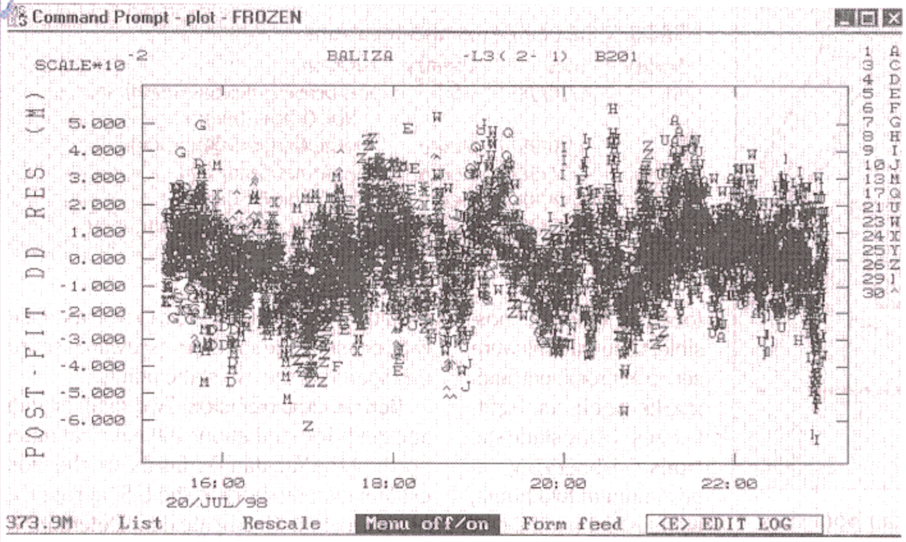

FIGURE 2 Post-fitted double-difference residuals at base station BALIZA (Arrecife Alacrán, Mexico). The dispersion of the residuals is within 5 centimeters, although their root mean square is only 1.5 centimeters. The satellites above the local horizon during the observing period are listed at the top right.

Wolf Island, Texas. The next day, we went to Wolf Island, adjacent to the mouth of the Brazos River, south of Freeport, Texas. In this case, the Harris-Galveston Coastal Subsidence District made available two dual-frequency receivers, which we used during a three-hour static survey to position stations on Wolf Island. As previously, we also collected real-time observations.

Static Data

We processed all static observations at NOAA's NGS headquarters in Silver Spring, Maryland, using NGS's own software, PAGE4. Independently, the Mexican team processed the static data using its own software and methodology. However, the discussion that follows is restricted to the procedures and results of NGS.

Users familiar with GPS are well aware that the three-dimensional coordinate system to which all reduced vector components refer is determined by the inherent characteristics (coordinate frame and accuracies) of the satellite ephemerides employed while processing the observations. Generally, the position of the satellites in their orbits is assumed known and fixed (internally) by the reduction software. This technique automatically designates the ephemeris frame as the three-dimensional Cartesian frame in which all resulting coordinates and vector components will be expressed. Geodetic applications requiring maximum accuracies rely on static relative (differential) positioning methods. Then, it is imperative to start with known coordinates of at least one reference (base) station. In order to produce accurate vectors, the quantities to be fixed — the coordinates of the base station(s) and the orbits of the satellites — should refer to identical coordinate frames. Obviously, vectors can be accurately reduced only if consistency in all pertinent coordinate frames is enforced.

In today's environment, this requirement should be easy to fulfill for North American users. With the recent densification of NGS's Continuously Operating Reference Station (CORS) network, mixing of coordinate frames during processing can be completely avoided. The precise ephemeris determined by the International GPS Service (IGS) at the time the data for this project were collected was expressed in the ITRF96 coordinate frame. The adopted coordinates for the sites used in the reductions are also available on the same coordinate frame.

Three CORS stations in the United States (CORC, Corpus Christi, Texas; ENG1, English Turn, Louisiana; and LKHU, Lake Houston, Texas) and one in Mexico (MERI, Mérida) belonging to the Mexican Red Geodésica Nacional Activa (RGNA), which are the closest to the static points observed on each individual campaign, were selected as fiducial stations. The term fiducial station is loosely applied to describe continuously operating sites whose data are electronically made available to the geodetic/surveying community. The stations are represented by blue diamonds in Figure 1.

We determined final solutions using double-difference carrier-phase measurements, and the ionosphere-free linear combination of the L1 and L2 frequencies. When the length of the vectors between the base and remote stations was shorter than 2 kilometers we used single L1 frequency reductions. **Figure 2** is a typical plot of the double-difference residuals. Once we knew accurate Cartesian coordinates in the ITRF96 frame, we used the Geodetic Reference System of 1980 (GRS80) ellipsoid to compute the curvilinear coordinates (latitude, longitude, and ellipsoid height).

As a final step, we compared the results processed by INEGI and NGS. The root mean squares of the differences only amounted to 5 centimeters in latitude and 8 centimeters in longitude, well inside the requirements of the project.

Real-Time Data

The U.S. team used a five-channel, single-frequency GPS receiver, utilizing the system's Precise Positioning Service (PPS). The receiver decodes the encrypted P-Y code signal included in the broadcast message. Because of DoD restrictions, only selected federal civilian agencies are authorized to use this type of P-Y code receiver. Such a receiver internally corrects the pseudorange observables for degradation imposed by selective availability (SA) and antispoofing (AS), if any. (SA was in effect during our survey campaigns.)

Position solutions can be displayed in three-dimensional curvilinear coordinates: latitude, longitude, and ellipsoid height referred to the WGS 84 datum. The receiver also has the option of computing instantaneous range and bearing from a known control point.

Handheld receivers are often used for fast and accurate augmentation of terrain databases used in conjunction with mapping. This was why a complementary real-time survey was deemed appropriate for this specific project. Because the results are based on broadcast orbits, the determined coordinates are referred to the WGS 84 (G873) frame. The letter G stands for GPS, and 873 denotes the week number (starting at 0h UTC, September 29, 1996) when the National Imagery and Mapping Agency introduced this terrestrial frame. The Operational Control Segment responsible for predicting orbits started to express broadcast ephemeris on this reference frame on January 29, 1997. In contrast, the results of the static, relative, carrier-phase survey are referred to the ITRF96 frame. The maximum difference between the two coordinate frames only amounts to one decimeter and could be neglected when interpreting measurements.

Results

The handheld receiver allowed us to obtain more points than was possible with the static survey, providing a better definition of the shoreline and outlying rocks. Using mapping software on a laptop, we could immediately plot points on our previously scanned and registered nautical charts. The navigation feature was a great help in positioning points along the beaches,

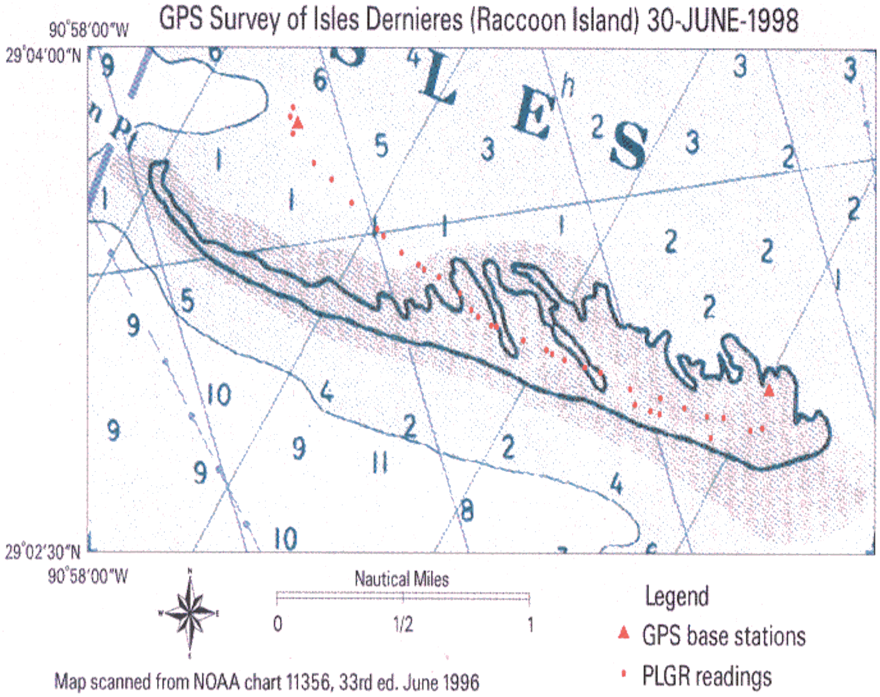

FIGURE 3 Measured points at Raccoon Island (Isles Dernieres, Louisiana), plotted on a current nautical chart. The figure shows significant displacements, possibly caused by the shifting of sand due to large storms. The horizontal reference datum of this chart is North American Datum of 1983 (NAD 83) which for charting purposes is considered equivalent to WGS 84.

but we could not display locations on a computerized map in real time.

Floating island. We were often surprised by how far the shoreline had moved since the charts were published. After postsurvey analysis, we discovered that the sandy shorelines at the barrier islands had indeed migrated northward, often over 100 meters, from the locations shown on the most recent NOAA nautical charts. **Figure 3** shows the case at Isles Dernieres.

Comparing readings wiyh the static points was an interesting exercise. INEGI representatives who were not familiar with real-time GPS technology gained confidence in it from this experience.

A mysterious bias. Figure 4 depicts the differences between the real-time measurements and the post-processed static results. Apparent from the plotted values is an as-yet-unexplained bias of about 2 meters in latitude attributed to the handheld measurements. However, except for one instance, all differences were within ±5 meters, as expected.

Although the sample and the bias are both small, the fact that these points were collected over a wide geographic area, and over a three-month period, strengthens our suspicion that the bias may be real. We would be interested in hearing from any readers who have experienced similar results or have a possible explanation.

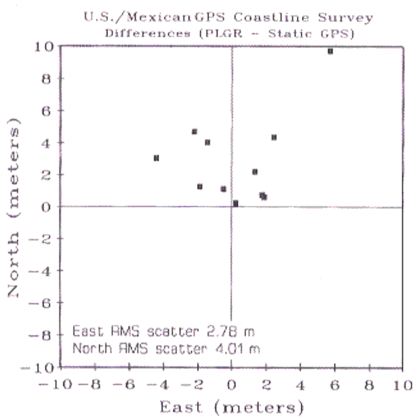

FIGURE 4 Differences plotted on a horizon plane between coordinates determined by PLGR and static GPS at eleven control points observed during the three campaigns.

Despite the bias, INEGI's experts accepted real-time results as an important contribution to the final baseline determination along the shores of Mexico and the United States.

The treaty. The four survey campaigns resolved the questions pertaining to coastline location and provided the baseline coordinates required for defining the equidistant line in the Western Gap. On June 9, 2000, U.S. Secretary of State Madeleine Albright and Mexican Secretary of Foreign Relations Rosario Green signed the treaty based on this boundary. The boundary divides the Western Gap, giving 38% of the area to the United States and 62% of it to Mexico, and establishes a buffer zone 1.4 nautical miles wide on either side of the boundary. Mexico and the United States have agreed to a 10-year moratorium on oil and gas exploitation in this zone. This will provide time to learn more about the geology and geophysical characteristics of this area. After the moratorium expires, each nation will be allowed to authorize drilling on its side of the buffer zone.

The Eastern Gap still remains unsurveyed, and it will have to stay that way until the United States establishes diplomatic relations with Cuba.

Acknowledgements

Many people contributed to the success of this project and were directly involved in many of the different aspects that a complex endeavor of this kind requires. In particular, we thank R.W. Smith and R.V. Ainger, who directed the U.S. side from the U.S. Department of State's Office of Oceans Affairs, and from MMS headquarters in Herndon, Virginia, respectively. They were instrumental in coordinating the planning and observational schedule with their Mexican counterparts and taking to completion this phase of the project. On the Mexican side, we thank Captain Miguel Pascual, Mareografía y Cartografía, Armada de México, and to the staff of INEGI for their dedicated work, especially engineers F.J. Rodriguez, M.A. Bustamante, and J.M. Rosales. Finally, we thank Robert Zurfluh, NGS State Geodetic Advisor to Louisiana, for arranging the static GPS observations with the Louisiana Department of Transportation and Development and the Harris-Galveston Coastal Subsidence District in Friendswood, Texas. We extend our appreciation to these two organizations for their generous cooperation.

Use of trade, product, or firm names in this article is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Manufacturers

For real-time measurements, we used the **Rockwell Collins** Precision Lightweight GPS Receiver (PLGR) (Cedar Rapids, Iowa). For the reefs static survey campaign, INEGI supplied four Ashtech XII dual-frequency receivers from **Magellan Corporation** (Santa Clara, California). At the mouth of the Rio Grande, INEGI provided one Ashtech XII receiver and three 4000SSE receivers from **Trimble** (Sunnyvale, California). At Wolf Island, the Louisiana department of Transportation and Development and the Harris-Galveston Coastal Subsidence District each lent us two Trimble 4000SSE receivers.