# Increasing the Accuracy and Resolution of Coastal Bathymetric Surveys

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## ABSTRACT

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The development of coastal sediment budgets and models for sediment transport and shoreline change require bathymetric surveys with vertical resolution and accuracy of 5 cm or better. Horizontal resolution and accuracy need to be at least 10 cm to quantify bedforms and bars. Sleds are probably the most accurate, widely used system for nearshore surveys, but their contact with the bottom limits their speed, spatial resolution, and ability to operate in many situations. Boat-based echo sounder surveys can achieve a higher spatial resolution and can operate where sleds cannot, but waves, tides, and other water-level fluctuations as well as boat dynamics and variations in the speed of sound in water can greatly limit their accuracy. Problems related to a survey sled's contact with the bottom cannot be overcome; therefore, echo sounder surveys must be improved.

The newly developed high-accuracy, high-resolution bathymetric surveying system (HARBSS) is designed to overcome the confounding effects of changing vessel draft, waves, and tides on depth soundings and to eliminate the need for measuring and modeling water level for a particular survey. The system combines Global Positioning System (GPS) receivers, an electronic motion sensor, a digital-gyro compass, a digital-analog echo sounder, a conductivity-temperature-depth probe (CTD), a computer, and custom software. The GPS antenna, compass, and motion sensor are aligned with the echo sounder's transducer. Using a bias-free phase solution from the GPS data (X,Y,Z accuracy of better than 1 cm), attitude information from the motion sensor, and heading information from the compass, the position and aim of the transducer is determined for each sounding. The CTD provides data to calculate the speed of sound. Using the above data, the sounding depths and horizontal locations of sounding points are corrected in X,Y, and Z with respect to an Earth-centered ellipsoid.

In constant and uniform speed-of-sound conditions, HARBSS can provide soundings that are within 5.2 cm (mean error of 3.7 cm) of their true elevations. Horizontal accuracy is estimated to be within 10 cm. This accuracy can be achieved from a small, open boat that is rolling, pitching, heaving, or listing. Error analysis indicates that we may be able to decrease the error by one half with better synchronization and interpolation of the various data streams.

**ADDITIONAL INDEX WORDS:** *Bathymetry, surveying, nearshore, echo sounder, GPS.*

## INTRODUCTION

Detailed comparisons of repeated bathymetric surveys are commonly inconclusive because the magnitudes of potential errors are equal to or greater than the actual changes of the seafloor morphology. This paper describes our progress in the development of a bathymetric surveying system that is designed to increase the accuracy and decrease the limitations of current systems used for coastal research. Specifically, we have set out to develop a system that can survey in water depths of 0.5 to 5 m with a horizontal and vertical accuracy of at least 5 cm. In addition, the system is designed to be (1) transportable and deployable with only minor modifications on boats as small as 6 m in length, (2) capable of obtaining accurate data in sea conditions as rough as the boat may safely operate, (3) able to resolve bottom features under calm sea conditions, including bedforms as small as 1 m in horizontal extent and having a vertical relief of less than 3 cm,

and (4) capable of operating across a variety of bottom types and slopes.

### The Need for Accuracy and Resolution

The development and testing of beach profile change and shoreline recession models (*e.g.,* AUBREY *et al.* 1980; BRUUN, 1962; 1988; DEAN and MAURMEYER, 1983; EDELMAN, 1970; KRIEBEL and DEAN, 1985) require more precise and spatially continuous, shallow-water (from less than 1 m to 10 m water depth) bathymetric surveys than are currently available. Bruun's rule (1962) regarding shoreline erosion caused by sea-level rise predicts vertical nearshore sediment accretion equivalent to the amount of sea-level rise. Considering a typical sea-level rise rate of 3 mm/yr for the United States east coast, the Bruun rule predicts average vertical sediment accretion of 3 mm/yr or 6 cm over 20 years. KEEN and SLINGERLAND (1993) used a numerical model to hindcast storm erosion and deposition of a few tens of centimeters or less on the inner shelf of the western Gulf of Mexico. Their model complements previous studies using cores from the inner

shelf (e.g., HAYES, 1967) that show that a single storm can form deposits on the order of 10 cm thickness across hundreds of square kilometers. Other studies have illustrated the importance of sediment exchange between the inner shelf, nearshore, and beach in understanding sedimentation cycles and patterns (e.g., AUBREY, 1979). The vertical changes of the outer nearshore and inner shelf may only be on the order of 10 cm or less over several years or for particular events, but they occur over large areas, and hence these small vertical changes constitute large volumes of sand. In addition, bedforms that are sediment transport indicators and diagnostic of the hydraulic regime occur in the nearshore and on the inner shelf (e.g., CLIFTON et al., 1971). The ability to obtain quantitative measurements of these bedforms, which have vertical and horizontal scales as small as a few centimeters, will add important information to coastal surveys.

Monitoring of beach nourishment projects and the development of coastal sediment budgets also require precise surveys. In a survey covering 2,500 m of shoreline across a nearshore width of 400 m, a systematic elevation error of just 5 cm would translate into an error in sand volume of 50,000 m³. This amount of sand is about 12% of the volume for a beach nourishment project along 2,500 m of the west coast of Florida, and it is more than the amount lost from the beach over the first two years of that project (DAVIS, 1991). An enhanced ability to account for the distribution of beach nourishment sediment in the nearshore zone will greatly improve our ability to predict project performance and future renourishment needs.

Imprecision in bathymetric surveys in the vicinity of tidal inlets can render sediment budget calculations invalid. MANN (1993) described how a systematic vertical survey error of 9 cm of the ebb-tidal delta at Jupiter Inlet, Florida, would create an error in the volume calculation that would be on the same order of magnitude as the volume of the entire ebb-tidal delta. DALLY (1993) also pointed out that better surveys include the need for precise horizontal positioning. In a simple example, he calculated that a 1 m error in the measured horizontal position of a bar of 1 m relief creates 1,000 m³ of apparent sediment transport per kilometer of bar.

International Hydrographic Office (IHO) standards are applied to navigation charts in the United States and around the world. For shallow-water surveys (<30 m water depth), errors in depth measurements should not exceed 30 cm, with a 90% probability (IHO, 1987). IHO standards for horizontal accuracy depend on the scale of the survey. Positions of soundings should have a 95% probability that the true position lies within a circle of radius 1.5 mm, at the scale of the survey (IHO, 1987). For a survey scale of 1:10,000, the radius is 15 m. Most modern surveys probably surpass the IHO standards, but CLAUSNER et al. (1986) showed that vertical error in a typical echo sounder survey was ±22.6 cm (mean error), and that repeatability was only as good as ±9.1 cm (mean error). Thus, typical echo sounder surveys have severe precision and accuracy limitations for use in studies of vertically small-scale but important sedimentation and erosion patterns.
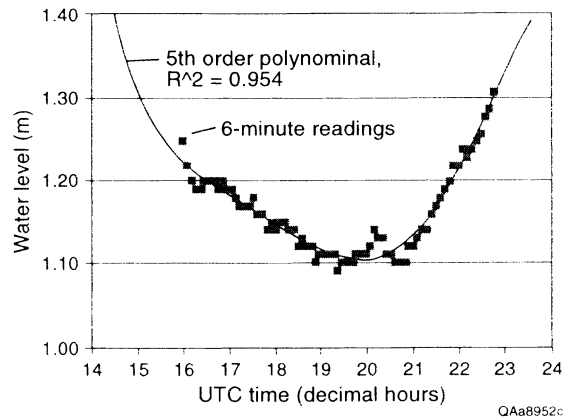


Figure 1. Water level recorded on December 8, 1994, by open-ocean tide gage on Galveston Island, Texas (Pleasure Pier gage). Readings are 6 minutes apart and are smoothed (see text). Note excursions of individual readings from fitted polynomial. These excursions would be difficult to model at short distances from the gauge and would likely cause errors in water-level corrections for bathymetric surveys.

## DIFFICULTIES IN OBTAINING ACCURATE BATHYMETRIC SURVEYS

### Boat-Based Echo Sounder Surveys

Conventional echo sounder surveys attempt to measure the vertical position of the bottom relative to the still-water level. Therefore, the temporal and spatial variation of the vertical position of the still-water level must be determined relative to a reference datum such as mean sea level. Depth soundings and water-level determinations can then be combined to determine the vertical position of the bottom relative to the datum. Measuring depths relative to the still-water level is difficult from small boats because waves, course and speed changes, and variations in load distribution cause boat motions that affect the vertical position and tilt of the transducer. Determining the still-water level is also difficult because astronomical tides, meteorological conditions, and wave conditions cause long-period (relative to individual waves) and local changes in water levels that are difficult to measure or model (BLAIR, 1983).

Tide-gauge data combined with a hydrodynamic model are typically used to determine the still-water level for a survey, but this approach generally cannot obtain the subdecimeter accuracy needed for coastal research surveys as described previously. Figure 1 shows an open-coast, tide-gauge record from Galveston Island, Texas, obtained during a nearby bathymetric survey. Water levels are recorded every 6 minutes and are determined by taking the mean and standard deviation of 181, 1 s readings, discarding those readings greater than 3 standard deviations from the mean, and then recomputing the mean. The primary variation in the water level that occurs over the 7 hour record is caused by the astronomical tide. Excursions in the water level of several centimeters over periods of less than an hour also occur in the data. It is probable that the timing and amplitude of these smaller variations were quite different short distances (1 km

away from the tide gauge. Furthermore, the smoothing of the water-level data probably masks even higher frequency and greater amplitude variations. Unless these water-level excursions are accurately modeled at the survey site, they may cause biased errors in the survey.

Wave set-down, which is the difference between the still-water level and the mean water level in the presence of waves, can also cause a biased error in nearshore bathymetric measurements (DEAN, 1989). LONGUET-HIGGINS and STEWART (1963) showed that the set-down caused by waves seaward of the breakers is described by the following:

$$\eta = -0.125 \left( \frac{\dfrac{H^2 2\pi}{L}}{\sinh\left(\dfrac{4\pi h}{L}\right)} \right) \qquad (1)$$

where $\overline{\eta}$ is the set-down or set-up, $H$ is the wave height, $L$ is the wave length, and $h$ is the water depth. For 1 m high shallow-water waves with a 6 s period, the set-down seaward of the breaker zone in 2 m depth is calculated to be 2.7 cm; in 3 m depth it is 1.7 cm. This error is potentially important for some surveys conducted for scientific research especially when added to other sources of error. To our knowledge, however, this effect is ignored by surveyors.

Measuring the distance from the still-water level to the bottom using a boat-based echo sounder is affected by (1) heave of the transducer, (2) "dynamic draft" of the transducer, (3) tilt of the transducer, and (4) speed of sound in water (SOS). Heave of the transducer caused by waves creates an unbiased error. The root mean square heave displacement is about 0.354 times the wave height (DEAN, 1989). Because this error is unbiased, its affect on volume calculations may be small. Heave caused by waves just 0.5 m high, however, would mask bedforms and obscure bars of similar or smaller amplitude.

The draft of the transducer is its distance below the still-water level. The draft will change, especially for a small boat, depending on speed, heading, currents, water density, and the amount and distribution of load onboard, thus the term "dynamic draft." In practice, dynamic draft tables are created for particular boats going various speeds. Dynamic draft corrections are imperfect, however, particularly in shallow-water conditions where tight maneuvering is required. Errors in dynamic draft corrections are generally biased errors.

The tilt of the transducer from vertical causes the echo sounder to record slant distances to the bottom and thus imparts a biased error by measuring the bottom to be deeper than it is. To a first approximation, vertical error caused by tilt is

$$E_{vt} = h_t - \frac{h_t}{\cos(T)} \qquad (2)$$

where $E_{vt}$ is the vertical error caused by tilt, $h_t$ is the depth measured vertically below the transducer, and $T$ is the angular tilt from vertical of the transducer. Figure 2a is a plot of vertical error versus tilt for 3, 5, and 10 m water depths. For a 5 degree tilt (a moderate roll for a small boat) in 5 m
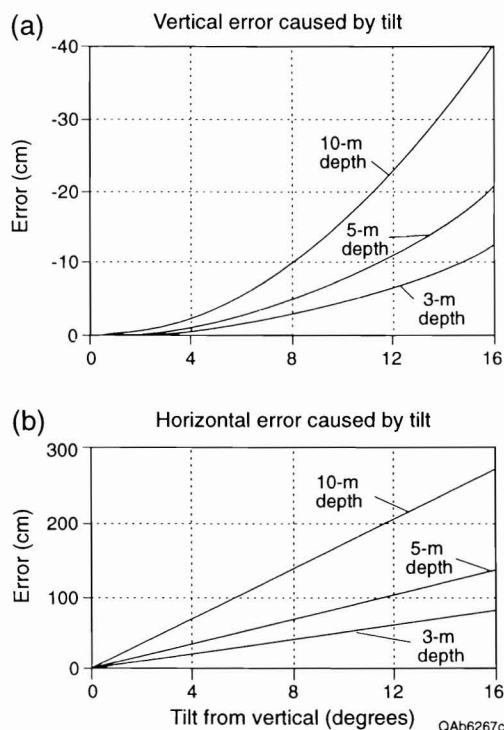


Figure 2. Calculated error versus a transducer's tilt from vertical for various depths. Vertical error caused by tilt is biased toward deeper (lower elevation) measurements of the bottom, hence the negative error values.

water depth the error is 1.9 cm. Tilt also causes a horizontal displacement (error) of the sounding point as follows:

$$E_{ht} = (h_t)(\sin(T)) \qquad (3)$$

where $E_{ht}$ is the horizontal displacement of the sounding point away from the transducer. Figure 2b is a plot of horizontal error versus tilt. For a 5 degree tilt in 5 m of water, the displacement is 44 cm.

The above calculations of vertical and horizontal errors are upper limits. The calculation assumes the sonar energy from the transducer travels along a line at the center of the energy pulse and is reflected back along the same line. In reality, a sonar pulse emanates in the shape of a cone, and when reaching the bottom at an angle, the energy is distributed spatially so that the backscattered echo is distributed in time. An echo sounder cannot resolve this type of return as well as a crisper return from a vertical sounding, and the receiver may detect the bottom at a point closer to the boat than where the transducer is actually pointing. Shallow-water conditions and narrow-beam transducers lessen this effect.

The SOS must be provided to the echo sounder so that the travel time of the sonar pulse may be converted to distance. Wrong SOS corrections cause biased errors in depth soundings. In shallow water, the SOS is primarily dependent on temperature and salinity (CHEN and MILLERO, 1977). SOS increases with increasing temperature and salinity as shown in Figure 3. Surveyors can determine the depth-integrated
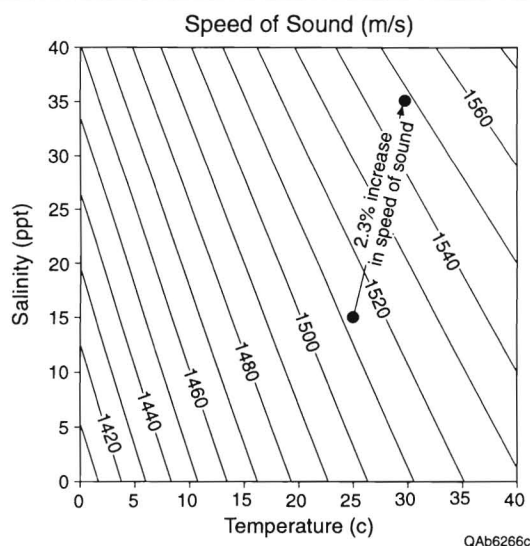
## Speed of Sound (m/s)



Figure 3. Speed of sound in water (SOS) as a function of salinity and temperature. The equation of CHEN and MILLERO (1977) is used. Arrow shows a typical spatial or temporal gradient in salinity and temperature that may be experienced during surveys in estuaries. If echo sounder surveys are not corrected for the consequent variation in SOS, significant errors may result depending on the height of the transducer above the bottom.

SOS during a survey by measuring the salinity, temperature, and pressure and converting to SOS using a formula (CHEN and MILLERO, 1977) or by measuring directly by lowering a sonar reflector a known distance below the transducer (bar check). In nearshore and estuarine conditions, however, the SOS may vary significantly in time and space. Consider a survey line beginning in water with a temperature of 25° C and a salinity of 15 ppt and ending in water with a temperature of 30° C and a salinity of 35 ppt. The SOS would increase by 2.3% (Figure 3), and for a water depth of 5 m, the maximum error would be 11.5 cm if the SOS were not updated at the end of the line. Therefore, typical temporal and spatial variations in salinity and temperature may impart a significant error to coastal bathymetric surveys.

In a comparison of 4 nearshore surveying techniques, CLAUSNER et al. (1986) determined that a boat-based echo sounder survey had a vertical repeatability, as defined by the average difference from the mean of repeated surveys, of ±9.1 cm. They also compared the echo sounder survey to a survey obtained by the Coastal Research Amphibious Buggy (CRAB) (BIRKEMEIER and MASON, 1984). The CRAB is a 10.6-m high motorized tripod that traverses the nearshore in contact with the bottom while an electronic total station on the beach shoots a reflecting prism mounted on it. This method of surveying eliminates the errors associated with boat-based surveys discussed previously. The vertical repeatability of the CRAB was 1.8 cm. Assuming that the CRAB measured the true profile, the accuracy of the echo sounder survey was only ±22.6 cm (mean error). Much of the error in accuracy was attributed to a possible SOS gradient across the nearshore zone.

### Sled Surveys

Using a vehicle in contact with the bottom, such as the CRAB, can greatly improve the accuracy of nearshore surveys over conventional boat-based echo sounder surveys. However, the CRAB is not very portable, and it is expensive. Survey sleds (e.g., SALLENGER et al., 1983), on the other hand, are easily portable and inexpensive, and CLAUSNER et al. (1986) determined that vertical accuracy of a sled is equal to the CRAB. Currently, sleds are probably the system most widely used to obtain nearshore surveys with vertical accuracy of at least 5 cm. A survey sled has runners and a mast on which reflecting prisms are mounted (Figure 4). A boat or onshore winch tows the sled along a transect while a conventional electronic total station takes readings of the prism. Two prisms may be mounted at different heights on the mast and a measurement taken of each to correct for tilt. No water-level, wave, draft, or SOS corrections are required. The nearshore surveys can be highly accurate if the instrument station is surveyed relative to a reference datum.

Contact with the bottom makes sled surveys more accurate than conventional boat-based echo sounder surveys, but this contact also limits their use. Sleds cannot be effectively used where many obstructions occur, because they get stuck. Obstructions may be rock ledges or debris deposited offshore
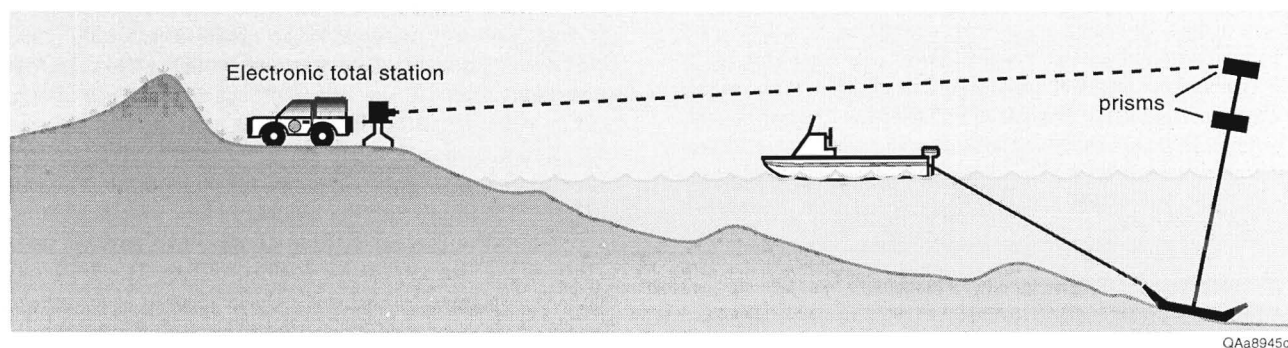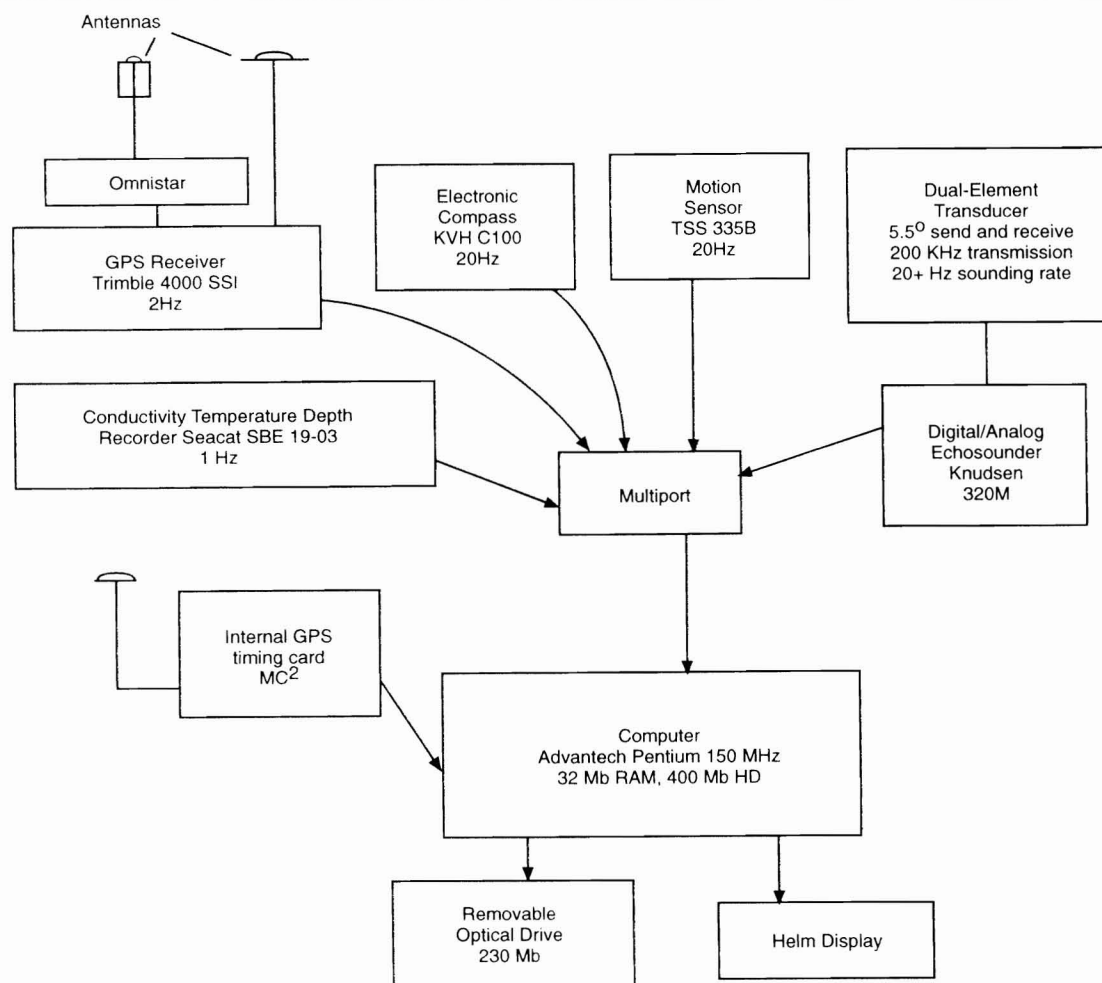


Figure 4. Nearshore bathymetric surveying using a sled.

Figure 5. Schematic of instruments that make up HARBSS.

after a storm. Obviously, sleds should not be dragged across sensitive bottom communities and cannot be used on muddy bottoms. Steep slopes or swift currents, such as occur in tidal channels, are a problem because sleds will tip over. Sled surveys are slower than echo sounder surveys, and this limits the line spacing that can be achieved during a single survey. Sleds also average the bathymetry over the length of their runners (typically about 4 m), thus obscuring bedforms and the exact positions of bar crests. Sleds are also limited to about 10-m water depth depending on the height of the mast. The distance that they can survey offshore is limited also by the electronic total station used and atmospheric conditions such as haze and rain. All these limitations makes sleds useful only for surveying sandy, obstruction-free nearshore zones.

## HIGH-ACCURACY AND RESOLUTION BATHYMETRIC SURVEYING SYSTEM (HARBSS)

Although sleds are accurate (±5 cm), their restricted use limits their overall effectiveness. Conventional boat-based echo sounder surveys are faster and can be performed in a variety of bottom and current conditions, but they are limited to activities where accuracy of ±20 cm is acceptable. Because little can be done to overcome the problems associated with sled surveys, the best approach is to improve the accuracy of echo sounder surveys. The HARBSS is a boat-based echo sounder system that we have developed to obtain bathymetric data that are as accurate as sled surveys but have the resolution, versatility, and speed of conventional echo sounder surveys.

### System Approach

The key to improving the accuracy of echo sounder surveys is to determine the exact three-dimensional position and attitude of the transducer for each sounding. In addition, one needs to continually determine the SOS or at least minimize the effect of varying SOS during a survey. To achieve this, HARBSS combines several available technologies in a custom configuration (Figures 5 and 6). HARBSS is also designed to
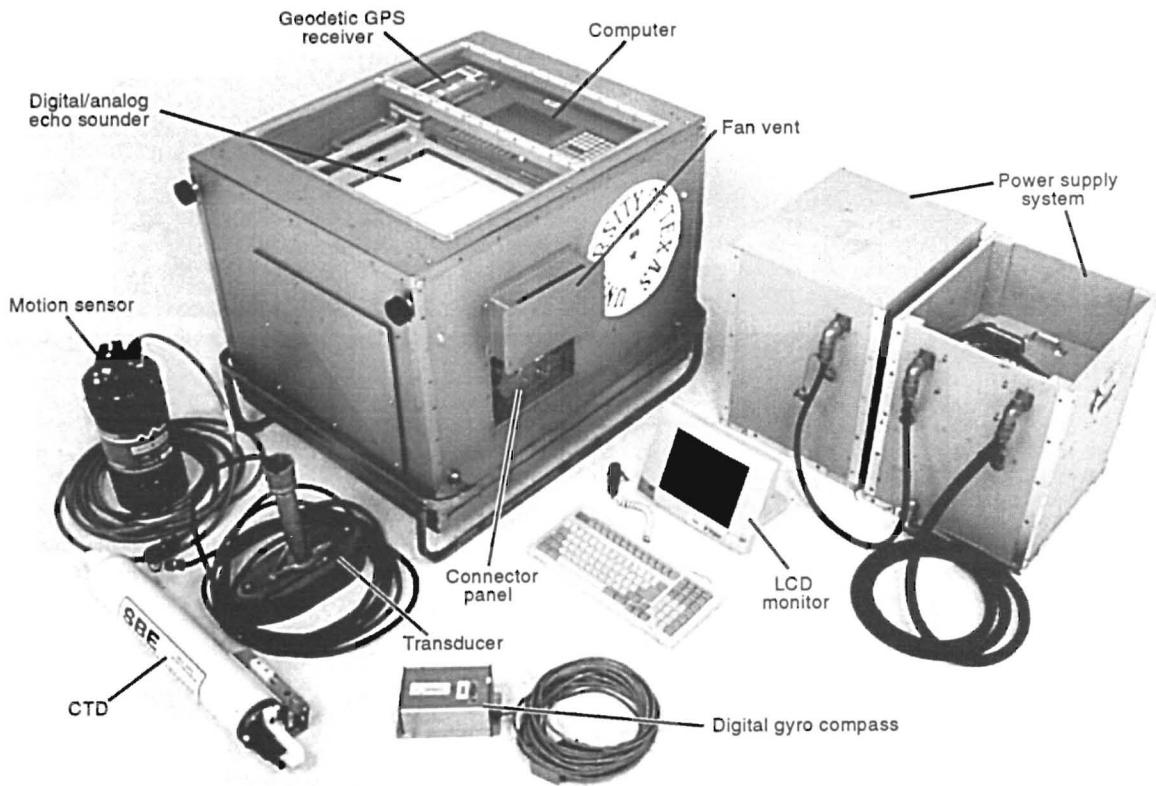
Figure 6. Photograph of instruments, power supply, and enclosures of HARBSS.

be weatherproof and can be transported and set up in small, open boats.

Vertical and horizontal positions of the echo sounder transducer and the insonified point on the bottom relative to an Earth-centered ellipsoid are determined by combining data from a geodetic-quality GPS receiver, a digital echo sounder, an electronic motion sensor, and a digital gyro compass. The GPS antenna is mounted on one end of a mast and the echo sounder transducer on the other end (Figure 7). The three-dimensional position of the GPS antenna is determined using a bias-free phase solution obtained 2 times per second. The motion sensor provides roll, pitch, and heave (dynamic vertical motion associated with waves and other motions with periods of less than about 20 s) data at a rate of up to 20 times per second. The compass provides headings relative to magnetic north at about 20 times per second. The motion sensor is mounted on a platform welded to the mast so that its vertical axis is parallel to the mast (Figures 7 and 8). The compass is mounted on the same platform as the motion sensor so that its heading is parallel to the roll axis of the motion sensor (Figures 7 and 9).

To solve for the position of the transducer and the sounding point on the bottom, an Earth-fixed coordinate system is defined at the phase center of the GPS antenna. The $X$-axis is positive eastward, the $Y$-axis is positive northward (true north), and the $Z$-axis is positive upward. A second coordinate

system is defined to correspond with the instrument mast. In this boat-fixed coordinate system, which also has its origin at the antenna phase center, the $x$-axis is positive forward, the $y$-axis is positive leftward, and the $z$-axis is parallel to the mast and positive upward.

The angular motions must also be assigned positive and negative directions. Pitch is the angle made by the boat's $x$-axis and Earth's horizontal $(X,Y)$ plane and is positive when the bow ($x$-axis) is above the plane. Roll is the angle made by the boat's $y$-axis and Earth's horizontal plane and is positive when the port side ($y$-axis) is above the plane. Heading is defined in a clockwise direction relative to Earth's $Y$-axis, therefore, magnetic compass headings must be converted to true north headings. A new variable for the travel direction is defined by

$$D = 90° - heading \qquad (4)$$

where $D$ = direction of travel in the $X,Y$ plane defined counterclockwise from Earth's $X$-axis.

The first step in the calculation is to determine the position of the insonified point relative to the boat's coordinate frame. In the $x,y$ plane, the distance of the point forward of the origin is

$$\Delta x = (L_m + L_s)\sin(P) \qquad (5)$$

where $L_m$ is the length of the mast from the GPS antenna phase center to the bottom of the transducer, $L_s$ is the sonar
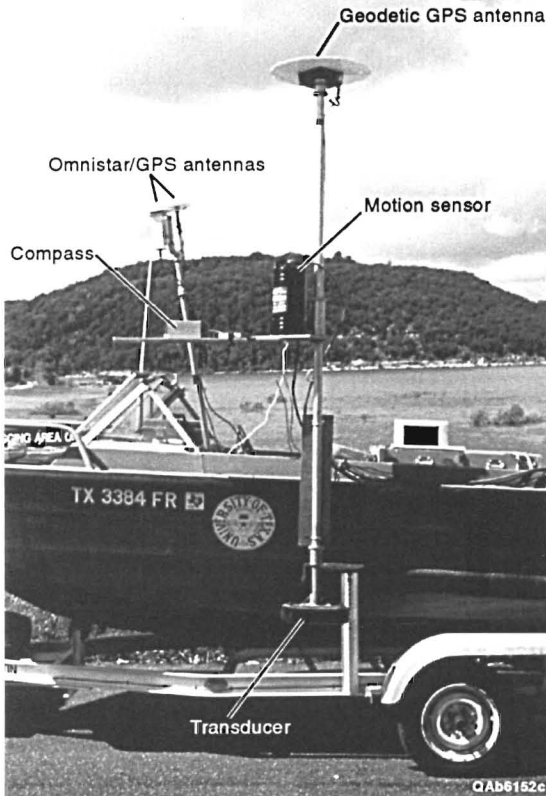
Figure 7. HARBSS instrument mast mounted on 6 m aluminum tri-hull boat used for test survey in a lake. Mast is in a raised position for launching of the boat. During the test survey, the transducer was about 0.5 m below the water line.

path length (raw depth recorded by the echo sounder) (Figure 8), and $P$ is the pitch. $L_m$ and $L_s$ are given as negative numbers because they are measured downward from the GPS antenna. Similarly, the position of the point leftward of the origin is

$$\Delta y = (L_m + L_s)\sin(R) \qquad (6)$$

where $R$ is the roll. In the $x,y$ plane, the distance of the point from the origin is

$$\Delta x, y = \sqrt{\Delta x^2 + \Delta y^2} \qquad (7)$$

which is the same as the distance in the $X,Y$ plane because the two coordinate systems share the same origin. The $z$-position of the insonified point in the boat's reference frame is simply

$$\Delta z = L_m + L_s. \qquad (8)$$

These expressions define a vector that may be projected into the $X,Y$ plane to determine the insonified point's position in terms of Earth-fixed coordinates. The direction of the sounding vector in the $X,Y$ plane ($V_{x,y}$) is found by

$$V_{X,Y} = \left(\frac{\Delta y}{|\Delta y|}\right)90° + D \quad \text{for } \Delta x = 0 \quad \text{and} \quad \Delta y \neq 0 \qquad (9)$$

$$V_{X,Y} = \left|\arctan\left(\frac{\Delta y}{\Delta x}\right)\right| + D \quad \text{for } \Delta x > 0 \quad \text{and} \quad \Delta y \geq 0 \qquad (10)$$

$$V_{X,Y} = -\left|\arctan\left(\frac{\Delta y}{\Delta x}\right)\right| + D \quad \text{for } \Delta x > 0$$
$$\text{and} \quad \Delta y < 0 \qquad (11)$$

$$V_{X,Y} = -\left|\arctan\left(\frac{\Delta y}{\Delta x}\right)\right| + 180° + D \quad \text{for } \Delta x < 0$$
$$\text{and} \quad \Delta y \geq 0 \qquad (12)$$

$$V_{X,Y} = \left|\arctan\left(\frac{\Delta y}{\Delta x}\right)\right| - 180° + D \quad \text{for } \Delta x < 0$$
$$\text{and} \quad \Delta y < 0 \qquad (13)$$

$$V_{X,Y} = 0 \quad \text{for } \Delta x = 0 \quad \text{and} \quad \Delta y = 0. \qquad (14)$$

The $X$- and $Y$-coordinates (earth-fixed coordinate system) of the insonified point relative to the origin (GPS antenna phase center), can now be found by

$$\Delta X = (\Delta x, y)\cos(V_{X,Y}) \qquad (15)$$

$$\Delta Y = (\Delta x, y)\sin(V_{X,Y}). \qquad (16)$$

The $Z$-coordinate is

$$\Delta Z = (L_m + L_s)\cos(T) \qquad (17)$$

where $T$ is the tilt from Earth's vertical determined by combining the roll and pitch. $T$ is determined by using the identity:

$$\cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1 \qquad (18)$$

where $\alpha$, $\beta$, and $\gamma$ are the direction angles that a vector makes with the respective coordinate vectors (axes). For the situation of a boat:

$$\alpha = 90° - P \qquad (19)$$

$$\beta = 90° - R \qquad (20)$$

$$\gamma = T. \qquad (21)$$

Solving (18) for $\gamma$ and substituting for $\alpha$, $\beta$, and $\gamma$.

$$T = \arccos(\sqrt{1 - \cos^2(90° - P) - \cos^2(90° - R)}). \qquad (22)$$

The position of the insonified point in terms of absolute Earth coordinates, or coordinates relative to any desired origin, can be found by using the GPS position together with the above calculations. If the position of the GPS antenna in the desired reference frame is $(X_0, Y_0, Z_0)$, then the position of the bottom point is

$$X = X_0 + \Delta X \qquad (23)$$

$$Y = Y_0 + \Delta Y \qquad (24)$$

$$Z = Z_0 + \Delta Z. \qquad (25)$$

GPS positions are obtained every 0.5 s. A boat in 0.6 m high, 6 s waves will move vertically more than 10 cm in 0.5 s. Therefore, the heave data from the motion sensor, which is
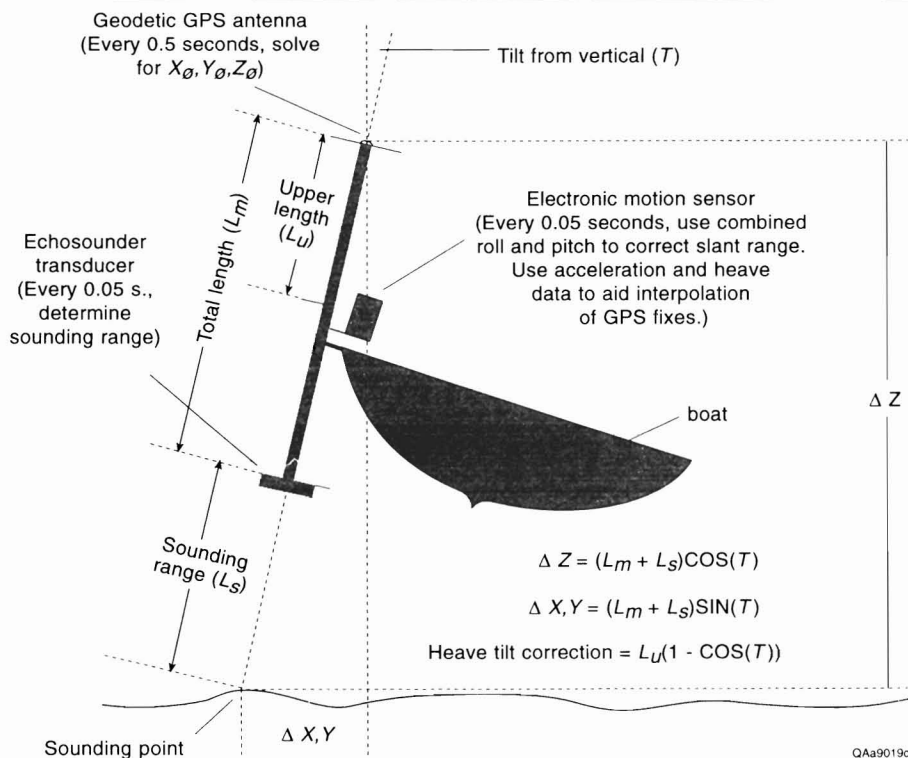
Figure 8. Cross section of boat and instrument mast assembly. Variables involved in the solution of the vertical position of the sounding point (bottom) are shown. If heave data are used to interpolate vertical GPS positions of the antenna and if the electronic motion sensor and GPS antenna are not at the same height, then a correction for tilt must be applied to the heave data.

output about 20 times per second, may be used to interpolate heights of the GPS antenna between position fixes. The use of horizontal acceleration data provided by the motion sensor is also being considered to aid in the interpolation of horizontal GPS positions.

The SOS affects the measurement of $L_s$. To determine the integrated SOS between the transducer and the bottom, a conductivity, temperature, and depth probe (CTD) is incorporated into the system. SOS is determined from data provided by the CTD. Surveyors can lower the CTD to measure the depth-integrated SOS. In areas with horizontal gradients in the SOS, several SOS depth profiles must be horizontally integrated to develop an SOS correction grid. The CTD can be attached to the instrument mast for continuous recording of SOS data during a survey. The probe is easily detachable to collect SOS depth profiles.

Another approach to lessen errors related to SOS, tilt, and the spreading of the sonar beam involves keeping the transducer as close to the bottom as possible. We have experimented with a telescoping mast that lowers the transducer 2.5 m below the surface. We have been able to control the 6 m boat without vibration or flexing of the mast in this configuration, and we think it is a viable way to reduce error at least in low-wave conditions.

## System Components

The mast on which the GPS antenna, motion sensor, compass, transducer, and eventually the CTD are mounted may

be attached to the side of various vessels (Figure 7). Other components, including the computer, optical drive for data storage, echo sounder, and GPS receivers, are housed in a portable, weatherproof box (Figure 6). The entire system is powered by 4 12-volt batteries arranged in 2 separate boxes. The system can run for about 8 hours before the batteries need to be recharged. These features allow surveying to be conducted from various small and open boats.

## Echo Sounder

The digital echo sounder we use is made by Knudsen Engineering, Ltd. It emits a 200 kHz pulse from a dual-element transducer. One element sends the sonar pulse and the other receives the echo. This configuration overcomes the critical problem of "ringing," which occurs in shallow water when the generating pulse and echo interfere. A selectable power output and pulse length further enhance the ability of the echo sounder to obtain reliable, high-resolution data in shallow water. Low-power and short-pulse lengths are desirable for shallow-water conditions and high resolution. A frequency of 200 kHz is a compromise that allows fine resolution of the bottom with little water column interference. A different frequency, however, may be suitable for some situations. The digital output rate is about 20 Hz, and the digital resolution is 1 cm.

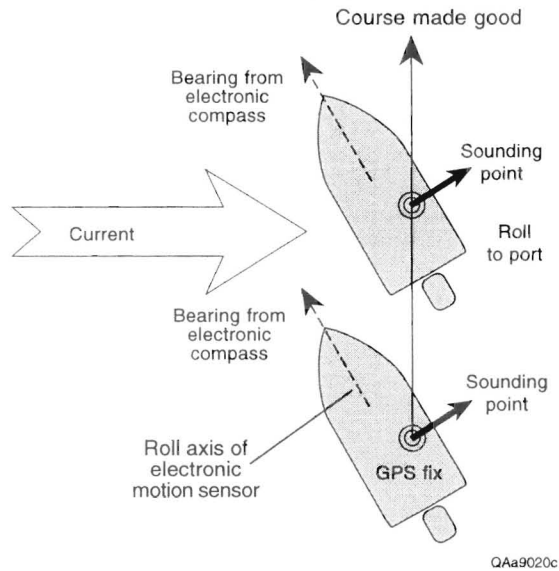During laboratory tests, the echo sounder reliably mea-

Figure 9. Effect of roll on horizontal position of the sounding point on the bottom. In HARBSS, the digital gyro compass is aligned with the roll axis of the electronic motion sensor. This allows the calculation of the direction of offset of the sounding point from the GPS antenna position. The motion sensor and compass must be aligned, but alignment with the boat's roll axis is not critical. In currents and waves, the orientation of a boat is often oblique to the direction of travel, but using the compass and motion sensor to determine the sounding point position overcomes this effect.
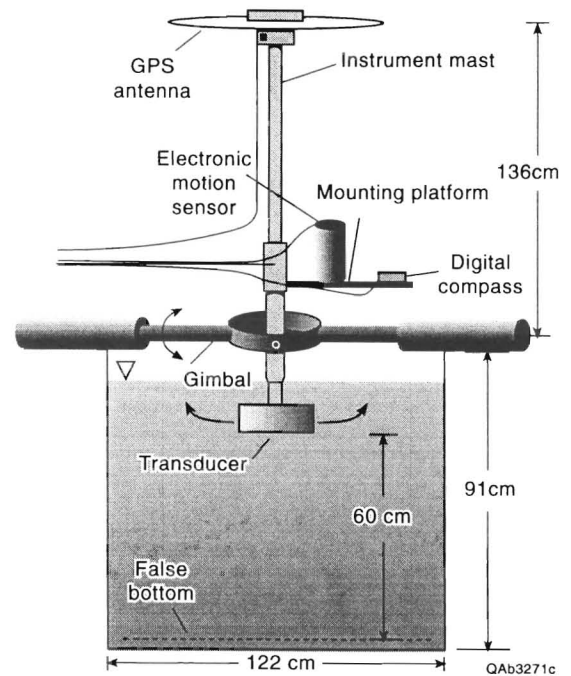


Figure 10. Setup of small-tank test. The tank is too small for analysis of the echo sounder data, but data from the GPS and electronic motion sensor were analyzed. Results from the test are discussed in the text and shown in Figure 11.

sured depths as shallow as 20 cm. In a calibration tank at the Applied Research Laboratory of The University of Texas at Austin, we measured the beam widths of the transducer elements to be $5.5°$. Also in the calibration tank, we determined that the echo sounder could resolve sandy bottom features with vertical relief of less than 5 cm and horizontal extents of less than 10 cm in about 3-m water depth (KYSER, 1996). The noise in the echo sounder under these ideal test conditions appeared to be about $\pm 1$ cm (KYSER, 1996). Accuracy, as stated by the manufacturer, is better than 0.25% of range or 1.25 cm for a range of 5 m.

### Motion Sensor

Obtaining accurate heave, roll, and pitch data in a highly dynamic environment, such as a small boat, requires a sophisticated instrument. HARBSS uses a TSS, Ltd., 335b electronic motion sensor. This instrument combines linear accelerometers and angular rate sensors to provide dynamic heave displacement, roll, pitch, and vertical and horizontal acceleration at a rate of about 20 Hz. TSS states the accuracy of heave measurements to be $\pm 5$ cm or 5%, whichever is greater, and roll and pitch accuracy to be better than $\pm 0.1°$ under dynamic conditions. In field tests conducted on the Gulf of Mexico in a 6-m, tri-hull boat, we found that we could cause errors of 10's of centimeters in the heave and a few degrees in the roll and pitch by making sharp turns. The sharp turns caused high horizontal accelerations, and when these accelerations exceeded 0.275 m/s$^2$, errors occurred in the data for

several minutes. The tests were conducted in 1 to 1.5 m waves, but the waves did not cause excessive accelerations. It is not difficult to keep the horizontal accelerations below 0.275 m/s$^2$, but surveyors need to monitor the data.

### Geodetic GPS Receivers

The GPS instruments used for precise survey positioning are Trimble 4000SSE geodetic receivers. These are dual frequency, 18 channel receivers capable of tracking 9 GPS satellites simultaneously on both the L1 and L2 frequencies. They record C/A and P-code pseudorange and L1 and L2 carrier phase observations at a rate of up to 2Hz. Both receivers, the base station instrument onshore and the mobile receiver onboard, are equipped with Trimble ST L1/L2 geodetic antennas with ground planes to minimize the effects of multipathing. GPS data are post processed to yield precise three-dimensional positions.

To estimate the vertical precision of the kinematic GPS surveying technique using Trimble 4000SSE receivers, we conducted a test in an outdoor tank. Figure 10 shows the setup for the test. The test tank is steel and measures 1.22 m by 2.44 m by 1.88 m deep. A short version of the instrument mast was attached to a gimbal, which allowed angular motion of the mast to simulate boat motion. Heave motion was not simulated. We originally intended the test to include the calculation of the height of the flat, false bottom, but the small size of the tank caused excessive multipathing of the

sonar signal. The tests, however, show the level of agreement between the GPS and motion sensor devices.

Figure 11a is a time series plot of kinematic GPS positions showing the height of the GPS antenna relative to the GPS reference station and the tilt of the mast as measured by the electronic motion sensor. GPS positions were computed 2 times per second and tilts 5 times per second. GPS positions were linearly interpolated to coincide with tilt measurements. We manually swung the mast back and forth with a period of about 8 s, which caused an absolute tilt period of about 4 s. Tilts ranged from 4° to 17°, and as the tilt increased the height of the GPS antenna lowered. Figure 11a shows the expected relationship between large tilts and lower antenna positions during the 70 s test even though the antenna height is varying only 2 to 4 cm. Figure 11b is a plot of antenna height versus tilt. By knowing the height of the antenna when vertical and the distance from the mast pivot point (gimbal) to the antenna, we can calculate the expected antenna height as a function of tilt. The line labeled "calculated" in Figure 11b is a plot of this function. The 353 measured points in Figure 11b follow the calculated line well, but are offset slightly higher. The mean difference between the calculated and measured heights, found by subtracting the calculated heights from the measured heights, is 0.35 cm. This difference is most likely caused by inaccurately measuring the distance between the pivot point and antenna. The standard deviation of the difference is 0.46 cm, and the maximum difference is 2.54 cm.

If we consider the tilt measurements provided by the motion sensor to be perfectly precise, the synchronization between the GPS and motion sensor data to be perfect, and the interpolation of the GPS positions to perfectly represent the antenna positions, then the above standard deviation would be a measure of the precision of the GPS positions during the dynamic conditions of the test. Of course none of these conditions were completely met. We think the result of the test, however, does show that we can expect subcentimeter-scale precision when combining the two devices during a bathymetric survey. Furthermore, we think that a significant amount of the scatter in Figure 11b is caused by poor interpolation and synchronization, both of which can be improved.

In another approach to estimating the vertical precision of the kinematic GPS surveying technique, we examined the results of kinematic vehicle surveys conducted on the beach at Galveston Island State Park in Texas (MORTON et al., 1993). These surveys involved mounting a GPS antenna on the roof of a vehicle and driving over the beach collecting GPS data at a 2-Hz rate. As the vehicle drove back and forth over the beach, the vehicle's path frequently crossed itself, and therefore it collected GPS data over the same point more than once. Because the rover antenna is mounted atop a 4 × 4 vehicle, the point elevations we obtained are actually average elevations over the footprint of the vehicle. In this context, we define crossover points as points surveyed during different passes over the beach, but with horizontal positions separated by less than 50 cm. By sorting through the GPS data, we identified 65 crossover points (out of 6,100 survey points) in a kinematic GPS survey conducted over a 2-km long section of beach on May 1, 1995. The average vertical difference

between these crossover points is 1.2 cm with a standard deviation of 0.79 cm. This and the previously described estimate of precision compares well with an estimate of 0.4 cm as the standard deviation for kinematic relative height accuracy for baselines under 1 km presented by REMONDI et al. (1990).

## GPS System for Real Time Navigation

The previously described geodetic quality GPS receivers only provide real time positions accurate to about 100 m (geodetic-quality positions are determined during post processing). This accuracy is not adequate for scientific surveys that require the reoccupation of specific transects. To provide navigation accuracy of a few meters, HARBSS uses a real time differential GPS system. The OMNISTAR system (John E. Chance & Associates, Inc.) consists of an array of GPS base stations and a network control center that combines base station corrections. The corrections are transmitted to a communications satellite. With OMNISTAR hardware, a user can receive the corrections from the satellite for input to a GPS receiver. The corrections are optimized for the user's specific location. HARBSS uses a Trimble Path Finder Basic Plus GPS receiver. Field tests conducted in the Galveston Island area of the Gulf of Mexico indicate horizontal accuracy of 2 m or better.

## GPS Timing Card

HARBSS uses a GPS time-base generator to time tag the various sensor inputs as they arrive at the data logging computer. This device, manufactured by MC² GPSystems, incorporates a GPS receiver on a personal computer (PC) card. It provides GPS-derived time with a 50-msec resolution over the serial communications port or, with either a 10-msec or 15 μsec resolution, over the PC bus. The HARBSS software currently uses the 10 msec timing information. This GPS timing card is a recent modification to HARBSS. Limitations of the PC clock for data time tagging were apparent during initial HARBSS development and prompted the addition of the GPS timing card. Test results shown in this paper do not reflect improvements to HARBSS from the GPS time-base generator.

## Compass

The digital gyro compass, manufactured by KVH Industries, Inc., consists of a two-axis rate gyro device and a digital fluxgate electronic compass. The gyroscopic rate sensor provides information to correct headings during times of acceleration. Heading is output at a rate of 20 Hz with a digital resolution of 0.1°. Accuracy, as stated by the manufacturer, is ±0.5° RMS for tilt angles (tilt from vertical) of ±20°.

## Computer

The computer runs custom software that logs and time tags data from the various sensors. It also runs custom navigation and survey planning routines. Heat, vibration, shock, and humidity encountered in open boats necessitate the use of an industrial-grade computer. HARBSS uses an Advantech PC with an Intel processor. We recently upgraded the computer
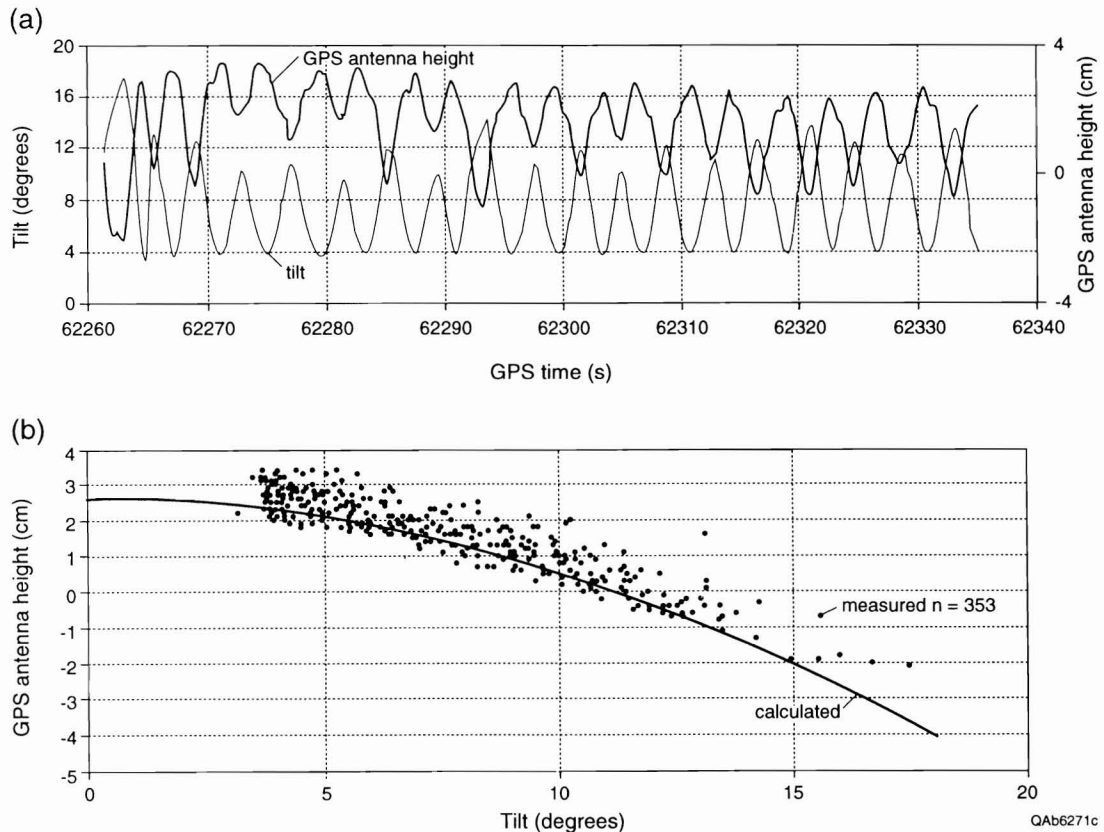
Figure 11. Plots of kinematic GPS antenna positions determined from GPS data and tilts from vertical of the antenna mast determined by the electronic motion sensor. Test is described in the text, and the setup is shown in Figure 10. (a) Time series of relative height of GPS antenna and tilt from vertical of the antenna mast. As expected, large tilts correspond with low antenna heights. Note that the height ranges only about 5 cm indicating the sensitivity of the GPS positions to small changes. Also, there was a minimum tilt of about 4° because of the way the mast was manually held during the test. (b) Scatter plot of GPS antenna height versus tilt. The 353 points show the expected relationship of lower heights with greater tilts. The solid line is a calculated relationship based on the known geometry of the test. The data points follow well the calculated line but are offset higher by about 0.5 cm. A slight mismeasure of the distance from the gimbal pivot point to the antenna phase center (used to determine the calculated line) may be responsible for the offset.

to a Pentium 150 mHz system, but the tests presented here were conducted with a 486DX2 66 mHz processor. To provide efficient logging of digital data, the computer is equipped with an 8-port, intelligent serial communications card. A magneto-optical drive is connected through a SCSII port for data storage. This drive uses 230MB, 3.5 inch removable diskettes and thus provides a means for safely storing large survey files. During a survey, the system collects about 10MB of data per hour. The computer has a 9 inch CRT screen, but a stand-alone LCD monitor is used to provide a helmsman display to the boat operator.

## CTD Profiler

The CTD device is a recent addition to HARBSS, and the tests presented in this paper did not use it. The CTD profiler measures conductivity, temperature, and depth. These measurements are converted to SOS using the equation developed by CHEN and MILLERO (1977). The manufacturer, Sea-

Bird Electronics, Inc., states that the CTD can predict SOS to within 0.5 m/s, which is about 0.03% of the SOS in sea water. Data are digitally output in real time at a rate of up to 2 Hz.

## Software

Mission planning, real-time navigation, data logging, and post processing software have been developed. Mission planning routines automate the construction of survey grids or single transects. Real-time navigation routines provide a helmsman display with indicators for right and left of intended track line and a map showing position within the survey area. Data logging routines collect data from the various devices, check for errors, and time tag each data string. These routines also provide real time graphical displays of the incoming data. Post processing routines merge and interpolate data, solve for the position of the bottom, and remove anomalous data points.
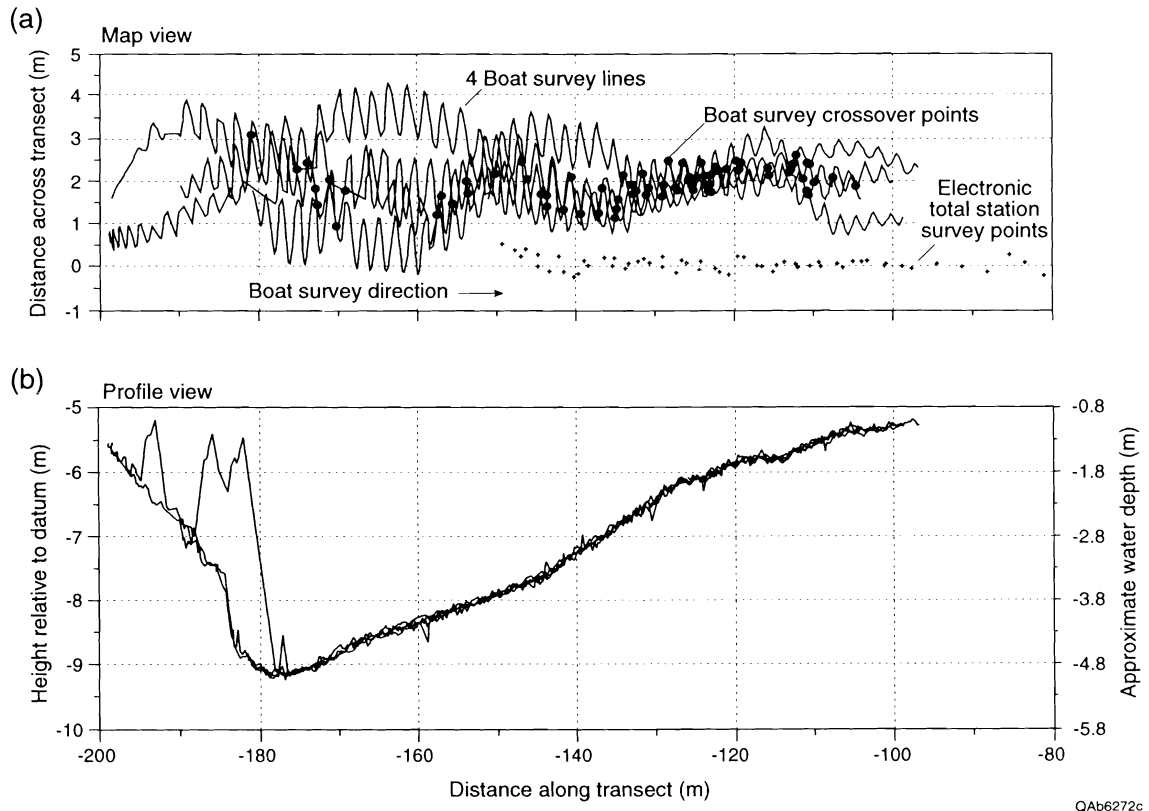
Figure 12. Data from the test survey at Lake Travis, Texas conducted on August 30, 1995. The transect obliquely crosses a drowned tributary creek valley and was surveyed five times. See text for explanation of the test and analysis (a) Map view of track lines of the boat survey using HARBSS and wading survey using an electronic total station. Map view is highly exaggerated in the across-transect direction. Track lines are actually the positions of the sounding points on the bottom. Points used in the crossover analysis are also shown. (b) Profile view of transects. All profiles are corrected using HARBSS. Spikes in one survey to the left of −170 m are likely caused by water column returns, presumed to be fish. The survey traverses were not perfectly aligned; therefore, the profiles are not of precisely the same transect (see text for details).

## ERROR ANALYSIS

The precision and accuracy of the total system is not only a function of the independent components but also of how well the various data streams are synchronized and interpolated. Errors experienced during a particular survey also depend on the depth of the survey, the dynamics of the survey (how much roll, pitch, and heave), and the length of the HARBSS instrument mast. To estimate the precision and accuracy of HARBSS, we conducted a test survey on a lake.

### Test Survey

The test survey was conducted on August 30, 1995, on Lake Travis near Austin, Texas. Lake Travis is a reservoir, and the 100-m long transect for the test survey crossed a drowned tributary creek valley about 5-m deep (Figure 12b). The shallowest portion of the transect was less than 1-m deep. Using a 6-m, tri-hull aluminum boat (Figure 7), we measured the same transect line 5 times. For this test, the transect was marked by range markers placed on shore, and all surveys were conducted with the boat heading toward the range markers at a speed of about 1 m/s. During each survey, the

boat was intentionally rolled by persons shifting their weight. Roll was 5 to 10° to each side and had a period of a little more than 2 s. The pitch was relatively steady at about 2.7°. Soundings, bearings, and attitude data were recorded at approximately a 5 Hz rate, and GPS observations were logged at a 2 Hz rate. The CTD was not available for the test survey, and the SOS was set at a constant value of 1500 m/s, which approximated the calculated values of SOS for the temperature and salinity conditions. It is improbable that the speed of sound varied spatially or temporally during the 30 minute survey.

For comparison, we conducted a conventional survey along the same transect line using a Zeiss ELTA-4 electronic total station (ETS) setup on the transect datum mark, and a rod person who waded as deep as possible into the lake. This survey was conducted on January 26, 1996, when the level of the lake was about 2 m lower than during the earlier HARBSS survey. The lower lake level allowed 50 m of overlap with the HARBSS survey. The very low-energy conditions at the transect location and the gravely, muddy sand sediment allow us to infer that no significant changes occurred in the lake bottom sediments between surveys.
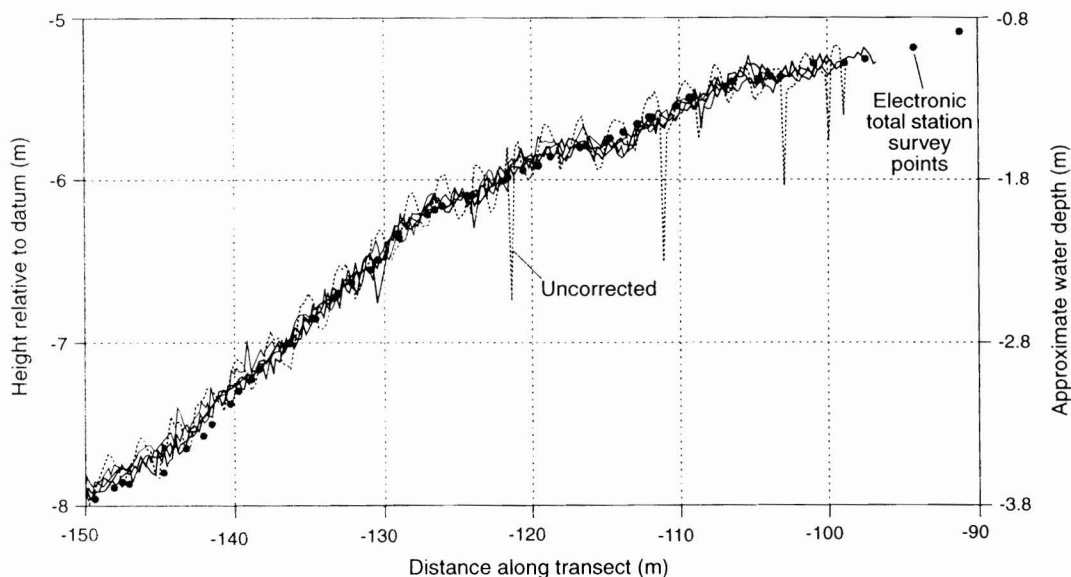
Figure 13. Expanded view of profile data shown in Figure 12b. Five corrected HARBSS profiles and one uncorrected profile (dashed line) are shown. The uncorrected profile, which consists of raw depth measurements recorded by the echo sounder, was adjusted vertically to overlay the corrected profiles. Also shown are points measured using a conventional electronic total station (ETS) and a rod person who waded into the lake. The ETS survey was conducted on January 26, 1996, when the lake level was lower than during the earlier HARBSS survey.

Post processing of GPS observations provided the precise positioning for the HARBSS survey. Prior to the survey, a static GPS receiver was set up on shore and the mobile GPS receiver and antenna were installed on the instrument mast of the survey boat. To assist the initialization of the fully kinematic GPS survey, a small amount (15–20 min) of GPS data were collected in the static mode prior to the launch of the survey boat. Once launched, the survey boat traversed the survey area maintaining lock on at least four GPS satellites at all times. The maximum distance of the survey boat from the static GPS reference receiver on shore was about 300 m. After the survey, the GPS data were processed using the National Geodetic Survey's OMNI software, and the GPS positions were then merged with the other data. GPS antenna positions for the time of each sounding were determined by linear interpolation between GPS positions.

Figure 12a is a map of the track lines of the five boat surveys along the transect. The track lines shown are actually the calculated location of the sounding point on the bottom. The sinusoidal track lines are caused by the rolling of the boat. The amplitudes of the across-track offsets are greatest in deep water and decrease toward shallow water. This is expected because the roll during the survey caused greater horizontal offsets of the sounding points in the deeper water. Along the transect, all survey lines are within 4 m of each other and within 2 m of each other closer to shore. Also shown in Figure 12a are the locations of the ETS survey points. The boat transect lines are parallel to the ETS points but they are offset about 2 m. This offset occurred because the driver was on the opposite side of the boat from the instrument

mast, and because the driver was lining up the boat using the range markers set along the transect.

Figure 12b shows the bottom profile measured by all five boat surveys. One profile has large spikes in the data at a distance greater than 180 m from the onshore reference point. Inspection of the paper analog record from the echo sounder revealed that these spikes are caused by water column reflections, possibly fish. Figure 13 is an enlarged view of the profiles that also includes one uncorrected boat profile and the ETS survey points. The uncorrected profile simply consists of the raw depths recorded by the echo sounder. This profile was adjusted vertically to overlay the corrected profiles. There are oscillations in the uncorrected profile of 30 to 40 cm caused by the tilt and heave of the transducer. The corrected profiles, on the other hand, do not show these oscillations and have a vertical envelope of 10 to 15 cm. The slope of the profile is about 1:20, and the transect was not oriented normal to the contours. This causes the profiles plotted in Figures 12b and 13 to have more vertical spread than they would if the transect were normal to contours or if the track lines perfectly overlaid each other. This is why we performed a crossover analysis of the data to estimate precision rather than a simple profile comparison.

## Experimental Error Derived from Crossover Analysis

We conducted a crossover analysis of the multiple transect data to determine the system's repeatability (Table 1). For this analysis, we avoided the spikes in the data by only considering data less than 170 m from the datum stake (to the right of −170 m in Figure 12b). We extracted pairs of points

Table 1. *Crossover analysis between 5 HARBSS transect surveys shown in Figures 12 and 13 and between the HARBSS and electronic total station (ETS) surveys.*

| | HARBSS vs. HARBSS (cm) | | | HARBSS vs. ETS (cm) | |
| | | | | Absolute Difference | ETS-HARBSS |
|---|---|---|---|---|---|
| Horizontal separation between points | < 10.0 | ≤ 50.0 | ≤ 100.0 | ≤ 100.0 | ≤ 100.0 |
| Mean horizontal separation | 6.6 | 37.6 | 82.5 | 87.7 | 87.7 |
| Mean vertical difference | 5.2 | 5.3 | 6.5 | 4.9 | 1.2 |
| Standard deviation vertical difference | 3.7 | 4.7 | 5.7 | 3.7 | 6.0 |
| Number of crossover pairs | 72 | 534 | 767 | 50 | 50 |

obtained during separate passes along the transect that were closer than 10 cm, horizontally. Seventy-two pairs of points had a mean vertical difference of 5.2 cm, and the standard deviation of the vertical difference was 3.7 cm. If we include points within 50 cm of each other, our vertical standard deviation increases to 4.7 cm, and for pairs of points within 100 cm, vertical standard deviation increases to 5.7 cm. F-tests for all three combinations of the horizontal separation categories (≤100 cm and ≤50 cm, ≤50 cm and ≤10 cm, ≤100 cm and ≤10 cm) show that the variances are different at the 1% confidence level. The improvement in vertical repeatability with decreasing horizontal separation of points indicates that our horizontal repeatability is better than 10 cm.

To estimate accuracy, we conducted a crossover analysis between the multiple transects and the conventional ETS survey. Because the ETS transect is offset from the HARBSS transect, a horizontal limit for the crossover points had to be set at 100 cm. Subtracting the heights of the HARBSS points from the ETS points yields a mean height error of −1.2 cm. This is a measure of the bias of the HARBBS survey relative to the ETS survey. Inspection of the data and Figure 13 shows that the ETS points are below the HARBSS points between −140 m and −150 m range. At this range, the rod person during the ETS survey was in deep water and had trouble keeping the survey rod vertical. Any tilt of the survey rod would cause a biased error that lowers the height. The survey rod was 2.71-m long and a tilt of 5° would cause a vertical error of 1 cm. This may be the cause of the bias, but an error of just 0.4% in the SOS setting could also be the cause. The vertical differences between the HARBSS and ETS crossover points have mean of 4.9 cm and a standard deviation of 3.7 cm. If we assume that the ETS survey represents the 'true' profile, then the accuracy obtained during this survey is nearly the same as our precision (repeatability) determined above.

## Expected Error of the Test Survey

Combining the errors expected from the echo sounder, motion sensor, compass, and GPS positions indicates a theoretical precision limit of HARBSS. Using average conditions experienced during the lake survey provides an expected limit

to the precision of this particular survey. Combining (17) and (25) the vertical position of the sounding point is

$$Z = Z_0 + (L_m + L_s)\cos(T). \qquad (26)$$

The error in $Z$ is defined as

$$\delta Z = \delta Z_0 \left(\frac{\partial Z}{\partial Z_0}\right) + \delta L_m \left(\frac{\partial Z}{\partial L_m}\right) + \delta L_s \left(\frac{\partial Z}{\partial L_s}\right) + \delta T \left(\frac{\partial Z}{\partial T}\right) \qquad (27)$$

$$= \delta Z_0 + \delta L_m \cos(T) + \delta L_s \cos(T) - \delta T L_m \sin(T)$$
$$- \delta T L_s \sin(T) \qquad (28)$$

where $T$ is given in radians. $\delta T$ is a function of the errors in roll ($\delta R$) and pitch ($\delta P$). Let

$$u_1 = 1 - \cos(90° - P) - \cos(90° - R) \qquad (29)$$

then (22) becomes

$$T = \arccos(\sqrt{u_1}). \qquad (30)$$

$\delta T$ is defined as

$$\delta T = \delta P \left(\frac{\partial T}{\partial P}\right) + \delta R \left(\frac{\partial T}{\partial R}\right) \qquad (31)$$

$$= \left(\frac{1}{\sqrt{1 - u_1^2}}\right)\left(\frac{1}{\sqrt{u_1}}\right)(\delta P \cos(90° - P)\sin(90° - P)$$
$$+ \delta R \cos(90° - R)\sin(90° - R)). \qquad (32)$$

Substituting into (32) 0.10° for $\delta P$ and $\delta R$, as provided by the manufacturer of the motion sensor, and 4.88° for the average absolute $R$ and 2.71° for the average absolute $P$ experienced during the survey yields a $\delta T$ of 0.14° (2.44 × 10$^{-3}$ radians).

For this error analysis, we used the high value of 1.2 cm for $\delta Z_0$, which was derived from the crossover analysis of the kinematic beach survey. We also used 0.10 cm for $\delta L_m$, which is an estimate of error caused by flexing of the mast and measurement error. As stated by the manufacturer, $\delta L_s$ is 0.25% of the range, and the average range ($L_s$) for the survey was −206.00 cm. Therefore, $\delta L_s$ is 0.52 cm for this survey. We think a more reasonable value for $\delta L_s$, however, is the noise we observed in the calibration tank tests described previously. Therefore this error analysis uses ±1.00 cm for $\delta L_s$. $L_m$ for the Lake Travis test was −265.00 cm. The average $T$ during the survey was 5.59°. Substituting these values and $\delta T$ into (28) gives the expected error in vertical positioning of the bottom for the Lake Travis survey

$$\delta Z = 1.2 + 0.10 + 1.00 + 0.06 + 0.05 = ±2.4 \text{ cm.} \qquad (33)$$

Horizontal error is a function of the errors in determining $X$ and $Y$. Taking (23) and (24) and substituting (15) and (16), respectively, gives

$$X = X_0 + (\Delta x, y)\cos(V_{X,Y}) \qquad (34)$$

$$Y = Y_0 + (\Delta x, y)\sin(V_{X,Y}). \qquad (35)$$

The error in $X$ ($\delta X$) is defined as

$$\delta X = \delta X_0 \left(\frac{\partial X}{\partial X_0}\right) + \delta \Delta x, y \left(\frac{\partial X}{\partial \Delta x, y}\right) + \delta V_{X,Y} \left(\frac{\partial X}{\partial V_{X,Y}}\right) \qquad (36)$$

$$= \delta X_0 + (\delta \Delta x, y)\cos(V_{X,Y}) - (\delta V_{X,Y})(\Delta x, y)\sin(V_{X,Y}) \qquad (37)$$

and similarly for the error in $Y$ ($\delta Y$)

$$\delta Y = \delta Y_0\left(\frac{\partial Y}{\partial Y_0}\right) + \delta \Delta x, y\left(\frac{\partial Y}{\partial \Delta x, y}\right) + \delta V_{X,Y}\left(\frac{\partial Y}{\partial V_{X,Y}}\right) \quad (38)$$

$$= \delta Y_0 + (\delta \Delta x, y)\sin(V_{X,Y}) + (\delta V_{X,Y})(\Delta x, y)\cos(V_{X,Y}). \quad (39)$$

To find $\delta X$ and $\delta Y$, first determine $\delta \Delta x, y$. Substituting (5) and (6) into (7) yields

$$\Delta x, y = \sqrt{((L_m + L_s)\sin(P))^2 + ((L_m + L_s)\sin(R))^2}. \quad (40)$$

Let

$$u_2 = ((L_m + L_s)\sin(P))^2 + ((L_m + L_s)\sin(R))^2 \quad (41)$$

then $\delta \Delta x, y$ is defined as

$$\delta \Delta x, y = \delta L_m\left(\frac{\partial \Delta x, y}{\partial L_m}\right) + \delta L_s\left(\frac{\partial \Delta x, y}{\partial L_s}\right) + \delta P\left(\frac{\partial \Delta x, y}{\partial P}\right)$$
$$+ \delta R\left(\frac{\partial \Delta x, y}{\partial R}\right) \quad (42)$$

$$= \frac{1}{\sqrt{u_2}}((\delta L_m + \delta L_s)(L_m + L_s)(\sin^2(P) + \sin^2(R))$$
$$+ (L_m + L_s)^2(\delta P \sin(P)\cos(P) + \delta R \sin(R)\cos(R))). \quad (43)$$

Using the average $R$, $P$, and $L_s$ values and the constant $L_m$ for the lake survey, $\delta \Delta x, y = 1.10$ cm.

Now determine the error in $V_{x,y}$ ($\delta V_{x,y}$) by first substituting (5) and (6) into (10) to give

$$V_{X,Y} = \left|\arctan\left(\frac{\sin(R)}{\sin(P)}\right)\right| + D. \quad (44)$$

$\delta V_{x,y}$ is defined as

$$\delta V_{X,Y} = \delta R\left(\frac{\partial V_{X,Y}}{\partial R}\right) + \delta P\left(\frac{\partial V_{X,Y}}{\partial P}\right) + \delta D\left(\frac{\partial V_{X,Y}}{\partial D}\right) \quad (45)$$

$$= \delta R\left|\left(\frac{1}{1 + \frac{\sin^2(R)}{\sin^2(P)}}\right)\left(\frac{\cos(R)}{\sin(P)}\right)\right|$$
$$+ \delta P\left|\left(\frac{-1}{1 + \frac{\sin^2(R)}{\sin^2(P)}}\right)\frac{\sin(R)\cos(P)}{\sin^2(P)}\right| + \delta D. \quad (46)$$

Again, substituting values for the survey conditions and $0.5°$ for $\delta D$ provided by the compass manufacturer, $\delta V_{x,y} = 1.89°$.

$\delta X_0$ and $\delta Y_0$ are conservatively estimated to be equal to $\delta Z_0$, which for this analysis is 1.2 cm as derived from the beach cross-over analysis. (GPS horizontal positioning is actually expected to be more precise than vertical positioning.) Substituting these values and the survey conditions (including the average heading of $87.8°$ to compute the average $V_{x,y}$) into (37) and (39) yields $\delta X = -0.34$ cm and $\delta Y = 2.95$ cm, hence the expected horizontal positioning error ($E_{hp}$) of the sounding point is

$$E_{hp} = \sqrt{\delta X^2 + \delta Y^2} = 3.0 \text{ cm}. \quad (47)$$

The above analysis assumes that the SOS is constant and that all data are perfectly synchronized. Of course this was not the case during the lake survey, but the analysis does indicate the limit of precision we may expect to obtain when combining the various devices for the specific survey conditions.

## DISCUSSION AND CONCLUSIONS

In constant and uniform speed-of-sound conditions, HARBSS can repeatedly measure the height of the same location on a lake/ocean bottom to within 5.2 cm (mean error). We estimate the horizontal repeatability to be within 10 cm. Comparison with a conventional survey indicates that the vertical accuracy is the same as the repeatability. This accuracy can be achieved from a small boat that is rolling, pitching, heaving, or listing. Estimate of the combined error of the separate instruments suggests that we should be able to decrease the error by about one half. This must be achieved by better synchronization and interpolation of the various data streams.

Although the test survey was conducted in a lake, there were factors of the test that made it more difficult to achieve accuracy compared to an open-ocean nearshore setting. The roll of 8 to $10°$ was the same as in an actual Gulf of Mexico survey when 1-m high waves were encountered. The period of induced roll motion in the lake, however, was much shorter at 2 s than the natural roll period of about 5 s in the Gulf of Mexico. This made any error in the synchronization of the data more critical during the test survey than it would be during an actual nearshore survey. In addition, the bottom of the lake had scattered cobbles causing local, small-scale relief of several centimeters. This irregular relief is expected to cause more scatter in the data compared to uniform and sandy nearshore conditions.

HARBSS is a single-beam system designed for precise, high-resolution surveying along a transect. Multibeam systems record a swath of data the width of which is about twice the height of the transducer above the bottom. In shallow water, therefore, multibeam systems loose some of their advantage in spatial coverage. The U.S. Army Corps of Engineers have developed the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system. This system is mounted on a helicopter and uses Light Detection and Ranging (LIDAR) technology to determine the depth of water. SHOALS can survey 8 km$^2$ with depth soundings 4 m apart in one hour. Horizontal accuracy is 3 m and vertical accuracy is $\pm15$ cm (LILLYCROP et al., 1996). Depths must be corrected for water level variations. The essentially continuous coverage that SHOALS provides is highly desirable for coastal research. The accuracy, however, is not good enough for some applications, and low-water clarity inhibits its use (ESTEP et al., 1994). It may be advantageous to combine data from an airborne scanning system, such as SHOALS, with more accurate transect data, such as obtained by HARBSS. The transect data could be used to calibrate the airborne data.

The HARBSS vertical positions are GPS-derived ellipsoidal heights in the WGS-84 reference frame. Although the ellipsoidal heights are adequate for detecting change between surveys, they are not related to tidal datums. The elevations of

morphological features such as nearshore bars and berms are largely controlled by local water levels, which are affected by Earth's gravitational field, the hydraulic character of the basin, and meteorological factors. Thus for the scientific study of beach and nearshore features as well as the production of navigation charts, it is desirable to convert the ellipsoidal heights to orthometric heights and to relate these heights to a local tidal datum.

In another study, we used GPS to measure, within the WGS-84 reference frame, profiles of dune, beach, and nearshore features along 150 km of the southeast Texas coast (GUTIERREZ et al., 1996; MORTON et al., 1995). WGS-84 ellipsoidal heights can be converted to orthometric heights using a high-resolution geoid model (TORGE, 1980). We applied the National Geodetic Survey's GEOID93 model to convert the profile survey data. GEOID93 is a 3-minute by 3-minute gridded geoid for North America and is constructed from The Ohio State University's OSU91A geopotential model plus 1.8 million terrestrial and shipboard gravity measurements. Our interpretation of the orthometrically adjusted beach features is that once converted to orthometric heights, variations in beach morphology can be analyzed with respect to a reference surface that closely approximates mean sea level (GUTIERREZ et al., 1996). Specifically, orthometric adjustment vertically aligned the berm crests and nearshore bar crests along the coast. Future surveying of coastal tide gauges using the GPS will facilitate the conversion of ellipsoidal heights to orthometric heights relative to local tidal datums.

The distance of the boat from the onshore reference GPS station during the lake survey was only about 200 m. During a nearshore survey, distances of 10 km or more will commonly occur. As described previously, we have obtained centimeter-scale repeatability during fully kinematic beach surveys. The rover during these surveys moved as much as 1 km from the reference station. More testing is required to determine precision and accuracy of the GPS positions for longer baselines. Also, at the beginning of the lake survey, we collected data in a static mode. This was required to solve the initial GPS phase ambiguities. Static initialization, however, would be difficult or impossible for many situations. To overcome this problem, we are developing software that will solve phase ambiguities "on-the-fly" (OTF). It is also important to know during a survey if data for precise GPS positioning is being obtained. For this reason and to reduce post processing time, we are also developing software and incorporating radio modems for real-time kinematic solutions. FRODGE et al. (1993) and DELOACH et al. (1994) reported on a real-time OTF system developed for the U.S. Army Corps of Engineers. DELOACH et al. (1994) reported vertical accuracy of about 2 cm on a 20-m long vessel, and FRODGE et al. determined the range for ambiguity resolution to be at least 20 km. Motion of a small ($<7$ m long) boat, such as the one used during the lake test reported here, is probably more dynamic than what was encountered during their tests.

In the past, echo sounder survey error was caused mostly by short (waves) and long-term (tides and meteorological changes) water-level fluctuations. With the advent of precise GPS vertical positioning and electronic motion sensors, the greatest source of error is determining the sounding range with the echo sounder. This error involves the determination of the SOS as discussed previously, as well as the characteristics of the echo sounder, the water column, and the bottom. HARBSS uses a 200 kHz transducer with a beam width of 5.5°. For shallow, turbulent water this configuration is thought to be the best compromise for resolution and minimizing water column returns. GALLAGHER et al. (1996) deployed stationary, 1 MHz sonar altimeters in the surf zone that were successful in obtaining accurate bottom heights despite suspended sediment and air bubbles. They found, however, that as many as 70% of the sonar returns could be erroneous, and they had to rely on post processing of the data to obtain accurate measurements every 32 s. The fact that the altimeters were stationary allowed their post processing algorithm to successfully detect the bottom among the erroneous data, but the problem is more difficult for a bathymetric survey. Lower frequency sonar pulses should decrease the number of water column returns caused by suspended sediment, but the lower frequency sonar energy may significantly penetrate the sediment-water interface. In uniform sandy conditions, a 200 kHz sonar pulse will reflect off the sediment water interface, but where fluid mud or vegetation is present, the level at which the sonar energy is reflected may vary. Improvements in signal processing within echo sounders and other strategies for obtaining consistent soundings on vegetated and muddy bottoms will improve the surveying of coastal environments.

Other work currently underway includes developing methods for incorporating CTD data and more work on the construction of an instrument mast designed to keep the transducer as close to the bottom as practicable, as described previously. We are also considering mounting HARBSS on a vehicle such as the CRAB (BIRKEMEIER and MASON, 1984) or on a remotely operated vehicle such as the Surf Rover (DALLY et al., 1994). These vehicles can traverse the surf zone where a boat cannot travel. This would allow surveying in the surf zone while maintaining the resolution obtainable from an echo sounder.

## ACKNOWLEDGEMENTS

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