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Water depth (MTL) at the deep edge of seagrass meadows in Tampa Bay measured by GPS carrier-phase processing: Evaluation of the technique

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WATER DEPTH (MTL) AT THE DEEP EDGE OF SEAGRASS MEADOWS IN TAMPA BAY MEASURED BY GPS CARRIER-PHASE PROCESSING: EVALUATION OF THE TECHNIQUE

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ABSTRACT

The Tampa Bay Estuary Program (TBEP) has selected seagrass restoration target depths for each major bay segment at which adequate light conditions (20.5% of subsurface PAR irradiance) shall be maintained to ensure seagrass growth and the long-term Tampa Bay seagrass restoration goal of 15,400 ha. To evaluate the progress towards the goal, information on today's seagrass depth distribution is needed. Specifically, a need exists to accurately determine the water depth at the deep edge of the meadows for each seagrass species in different sections of the bay.

A relatively simple technique that provides elevation measurements, related to the mean tide level (MTL), of Tampa Bay seagrass meadows is described and evaluated. The technique uses mapping grade differential Global Positioning System (GPS) carrier-phase processing equipment that is currently owned by several TBEP partners.

The elevation of a specific seagrass location is determined by placing one GPS instrument as a base station at a surveyed benchmark with a known elevation above MTL and a second instrument at the seagrass site to be surveyed. Tests of measurement errors indicate that the technique yields elevation measurements with an error that is less than ±10 cm for survey sites located up to 10 km from bench mark sites.

Field evaluations of the technique that included measurements in the four major bay segments and the deep edge of the three major Tampa Bay seagrass species, *Halodule wrightii*, *Thalassia testudinum,* and *Syringodium filiforme,* were conducted at ten Tampa Bay seagrass study sites.

The depth of the measured deep edges ranged from about -0.30 m MTL for *H. wrightii* meadows in the upper section of Hillsborough Bay to near -2.0 m MTL for *S. filiforme* meadows on the southwestern side of Middle Tampa Bay. All sites surveyed had deep edge elevations shallower than the TBEP seagrass restoration target depth for the respective bay segment.

The estimated average percent of subsurface incident light available at the deep edges of the surveyed seagrass meadow ranged from 59.8% to 28.9% for *H. wrightii*, from 19.0% to 16.9% for *T. testudinum,* and from 16.7% to16.2% for *S. filiforme*.

The differential GPS carrier-phase processing technique was field practicable and measured seagrass elevations with acceptable quality. The field measurements provided an important first step in understanding the current depth distribution of the major Tampa Bay seagrass species. However, many more elevation measurements should be obtained to yield a more complete understanding of the seagrass depth distribution in the bay.

INTRODUCTION

The Tampa Bay Estuary Program (TBEP) has adopted a long-term Tampa Bay seagrass restoration goal of 15,400 ha, which is approximately 95% of the estimated Tampa Bay seagrass cover present in 1950. Protection of the 10,400 ha existing in 1994 and the restoration of an additional 5,000 ha will be accomplished primarily through management of external nitrogen loadings and bay water quality.

The Tampa Bay seagrass restoration goal was established through a multistep process that included the identification of specific seagrass restoration areas from comparisons of ca. 1950 and 1990 high altitude aerial photography. Areas that had lost seagrass over the 40-year period and that had not been physically altered to prevent future seagrass recolonization were selected for restoration (Janicki and Wade 1996). It was further determined, through field studies conducted in Lower Tampa Bay, that *Thalassia testudinum* required a minimum of 20.5% of sub-surface irradiance to ensure healthy growth (Dixon 2000). This finding was adopted by the TBEP as an overall Tampa Bay seagrass light requirement target. Subsequently, water quality conditions and external nitrogen loading rates required to sustain a minimum of 20.5% of subsurface irradiance at the seagrass restoration areas in the major bay segments were determined from empirical models (Janicki and Wade 1996).

To link the seagrass restoration areas with the water quality and nitrogen loading based light target, it was necessary to determine to what depth seagrass grew in 1950. The 1950 seagrass depth distribution was estimated from apparent seagrass areas visible on ca.1950 high altitude vertical photographs that were overlaid on NOAA National Ocean Survey (NOS) sounding data collected between 1947 and 1958. The soundings were corrected to mean tide level (MTL) (Janicki and Wade 1996).

Estimates of the 1950 seagrass depth distribution were then used to develop bay segment specific seagrass target depths for Tampa Bay (Janicki and Wade 1996). The adopted approximate target depths were: -1.0 m (MTL) for Hillsborough Bay, -2.0 m (MTL) for Old Tampa Bay, -1.6 to -2.4 m (MTL) for Middle Tampa Bay (depending on sub-segment), and -2.5 m (MTL) for Lower Tampa Bay (see Figure 1 for location of bay segments). The Tampa Bay seagrass restoration goal will be accomplished when the deep edges of the seagrass meadows, delineated from the Southwest Florida Water Management District (SWFWMD) high altitude aerial photography, eventually extend to these depths in the respective bay segments.

The estimated 1950 Tampa Bay seagrass depth distribution was important for the development of the TBEP seagrass restoration and protection goal. Likewise, information on today's seagrass depth distribution is needed to evaluate the progress of the seagrass restoration process. Present-day depth information would yield a comparison to the estimated seagrass depth distribution in 1950. However, more importantly, the present seagrass depth information combined with light attenuation data from routinely conducted water quality monitoring programs could be used to calculate the percentage of subsurface irradiance available for different seagrass species found in the different bay segments. This information would relate current water quality conditions to the TBEP seagrass restoration goal and serve as a check on the Tampa Bay resource-based management plan (Johansson and Greening 2000). Also, seagrass depth measurements could be used to estimate specific seagrass species light requirements in the major bay segments, and therefore, complement the *T. testudinum* light requirement studies in Lower Tampa Bay (Dixon 2000). Finally, seagrass elevation measurements would also complement the cooperative Tampa Bay permanent seagrass transect monitoring program by providing elevation reference points on the transects (see City of Tampa 2000 and Avery et al. in prep). These reference points could be used for detailed measurements of seagrass elevations and also to measure potential sediment losses or gains along the transects.

The present study evaluated a relatively simple and practical field technique to

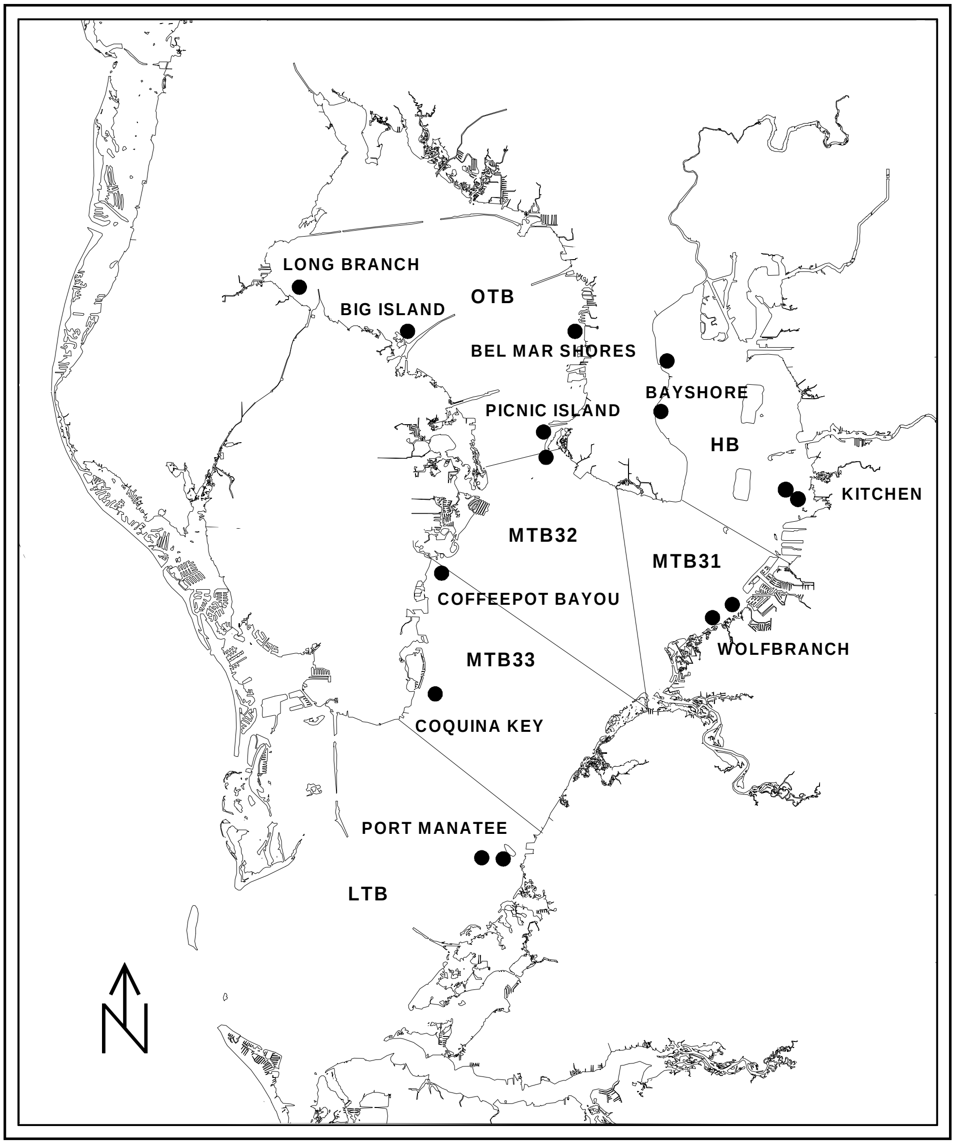

Figure 1. Locations of seagrass elevation survey sites in Tampa Bay. Also shown are major bay segments (HB=Hillsborough Bay; OTB=Old Tampa Bay; MTB=Middle Tampa Bay [including sub-segments]; and LTB=Lower Tampa Bay).

measure the depth to which seagrass meadows extend in Tampa Bay. The technique uses mapping grade differential Global Positioning System (GPS) equipment (Trimble Pathfinder PRO XR) to measure elevations related to a defined tidal datum (MTL). The current cost of the system is approximately $11,000 and several TBEP partners have purchased the system. The study included evaluations of measurement errors and numerous field surveys that measured seagrass elevations in the four major bay segments and for the three major Tampa Bay seagrass species, *Halodule wrightii*, *T. testudinum*, and *Syringodium filiforme.* Further, numerous benchmark locations were inspected and evaluated near the periphery of the bay for suitability as GPS base station locations.

METHODS

Determination of Measurement Errors

Trimble specifications for the GPS Pathfinder PRO XR system with carrier-phase processing reports the accuracy of position determinations, expressed as root mean square error (RMS), as 10cm + 5 ppm with 20 minutes of satellite tracking (occupation time). The 5 ppm error is caused by the distance between the base and the rover stations (baseline) and equals 0.5 cm of error for each kilometer of separation. To achieve 10 cm + 5 ppm accuracy, a minimum of 5 satellites should be tracked. PDOP (position dilution of precision), which is a measure of the current satellite geometry, should be less or equal to 6; the signal to noise ratio, which is a measure of the of the strength of the satellite signal relative to the background noise, should be less or equal to 6; and the satellite elevation mask, which excludes satellites low on the horizon, should be set at 15 degrees. Further, optimal accuracy is obtained by collecting data in an environment that has a clear view of the sky and that is devoid of large reflective surfaces, such as buildings, that extend above the satellite elevation mask.

The Trimble specifications do not differentiate between horizontal and vertical accuracy levels for carrier-phase processing. However, a report that characterizes the accuracy of the Trimble PRO XR receiver (Trimble 1997) states that the vertical error for carrier-phase processing solutions is similar to the horizontal error. The report also shows that the accuracy increases with increasing occupation time. As shown in Figure 2, modified from Trimble (1997), an error of less than 5 cm RMS can be expected with an occupation time of 30 min. For these tests, Trimble used a relatively short baseline (less than 1 km), 5 or more satellites, a maximum PDOP of 4, and the satellite elevation mask set at 15 degrees for the rover station and at 10 degrees for the base station.

Thirty-five tests were conducted over several days on the roof of the City of Tampa Bay Study Group (COT) laboratory to specifically test the vertical measurement performance of the PRO XR system (Fig. 3). This location provided a clear view of the sky and lacked potentially interfering reflective surfaces. Two PRO XR instruments were placed on the roof at a location with a known MTL elevation. The phase centers (the location within the antenna where the receiver detects the GPS signal) of the two antennas were located at near identical elevations and separated less than 1.0 m horizontally. One instrument was used as a base station and the other as a

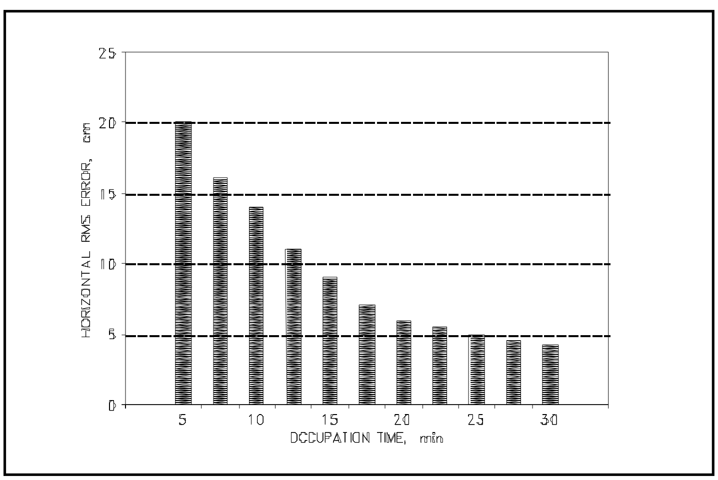

Figure 2. Performance of the Trimble Phase Processor v.2 software with the GPS Pathfinder PRO XR system according to Trimble (1997). Figure modified from Trimble (1997). Horizontal errors are shown; however, Trimble (1997) states that vertical and horizontal errors are similar for phase processed solutions.

Figure 3. Trimble Pathfinder PRO XR instruments located on the roof of the City of Tampa Bay Study Group laboratory during tests of vertical measurement errors.

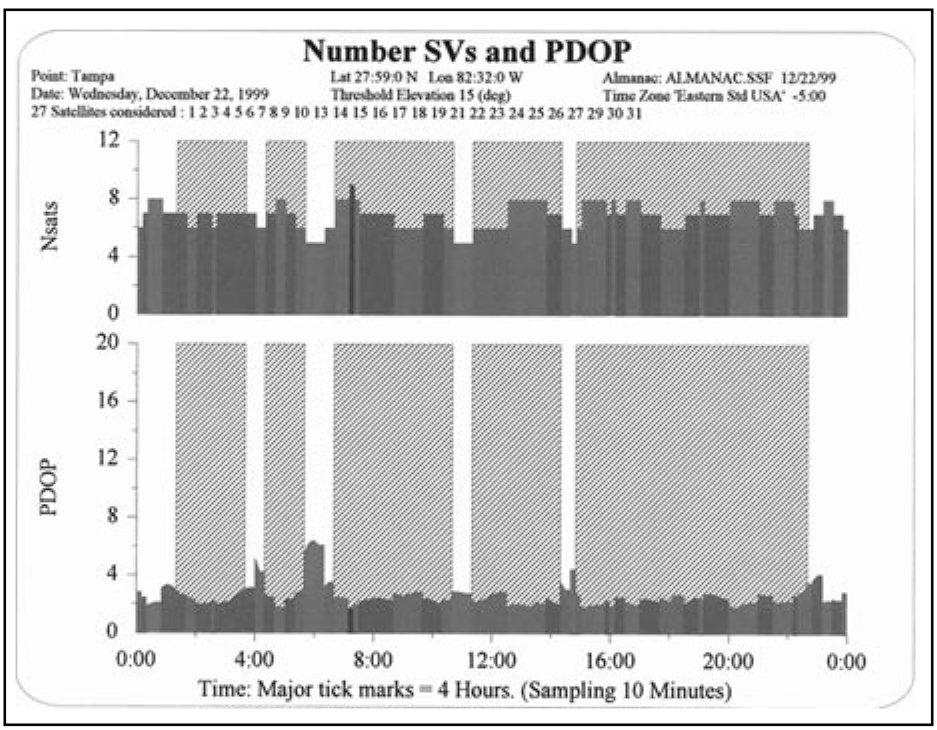

Figure 4 Example of quick plan graph from Trimble Pathfinder Office v.2.1. Excellent data collection windows (minimum of 6 satellites [SV] and maximum PDOP of 3) are shown as hatched bars.

rover station. The instruments were configured to the Trimble recommendations (see above and Trimble 1996). As recommended in the Trimble manual, the base station instrument had the satellite elevation mask set at 10 degrees. Further, predicted daily satellite schedules were examined prior to testing to ensure optimum data collection periods (Fig. 4). Generally, periods with a minimum of 6 available satellites and a PDOP of less than 3 were selected for data collections. These requirements should provide measurements with an accuracy comparable to that reported by Trimble (1997). The satellite data collection period for the 35 tests ranged from 30 to 41 minutes.

The potential baseline errors affecting the seagrass elevation measurements in the current study were not tested specifically (see below). This error was assumed to be 5 ppm, or 0.5 cm for each kilometer of separation between the base and rover stations, as specified by Trimble (1997).

Seagrass elevation measurements were replicated with n>2 at four specific seagrass sites to estimate the variability of field measurements, including variations caused by GPS errors and other errors, such as antenna height measurements. At one of these sites, measurements were repeated on two separate dates with the base station located at two different benchmark locations.

Measurements of Seagrass Elevations

A total of 38 seagrass elevation measurements were performed in Tampa Bay between October 1999 and February 2000 (Table 1). Measurements were conducted at ten general areas in the four major bay segments (Fig. 1). Most study areas were located at, or close to, an established Tampa Bay fixed seagrass transect (see Avery 2000; Avery et al. in prep; City of Tampa 2000) and included different seagrass species when present. Two study areas were located in Hillsborough Bay, four in Old Tampa Bay, three in Middle Tampa Bay, and one in Lower Tampa Bay. Of the 38 measurements, 21 were conducted on *H. wrightii*, 8 on *T. testudinum*, and 9 on *S. filiforme*. Twenty-nine measurements were conducted at distinctive deep edges of either large seagrass areas (meadows) or isolated smaller areas (patches) that were visible on recent, most often 1999, aerial photographs. The remaining nine measurements were done in seagrass areas other than the defined deep edge. These included measurements near the center of *H. wrightii* and *T.*

Table 1. Location of GPS seagrass elevation survey sites in Tampa Bay, including the number of measurements conducted for each surveyed seagrass species (see Fig. 1 for locations of study sites).

LOCATION	BAY SEGMENT	SEAGRASS SPECIES (number of surveys)
Bayshore	HB	*H. wrightii* (4)
Kitchen	HB	*H. wrightii* (9)
Long Branch	OTB	*H. wrightii* (1)
Big Island	OTB	*H. wrightii* (2)
Bel Mar Shores	OTB	*S. filiforme* (1); *T. testudinum* (1)
Picnic Island	OTB	*S. filiforme* (2); *T. testudinum* (1)
Wolf Branch	MTB	*H. wrightii* (4); *T. testudinum* (4)
Coffeepot Bayou	MTB	*S. filiforme* (mixed with sparse *T. testudinum)* (2)
Coquina Key	MTB	*S. filiforme* (2)
Port Manatee	LTB	*H. wrightii* (1); *S. filiforme* (2); *T. testudinum* (2)

testudinum patches; and at the shallow edge of a *H. wrightii* meadow in Hillsborough Bay.

Prior to conducting the field measurements at the selected seagrass areas, suitable benchmarks had to be located, preferably within 5 km of the survey sites in order to minimize the baseline error. Several publications and sources of benchmarks were examined; however, NOS tidal benchmarks were the primary type used (see www.opsd.nos.noaa.gov). The NOS benchmarks are referenced to mean lower low water and mean high water; however, the MTL elevation can easily be calculated from the tide station data provided for each set of benchmarks. The NOS benchmarks are not directly referenced to the National Geodetic Vertical Datum (NGVD)-29 datum, although, several tide stations (e.g. St. Petersburg and Ballast Point) have been tied to NGVD-29. The lack of a direct reference to NGVD-29 for some of the tidal benchmarks used was not of concern since the purpose of the study was to estimate the depth of the water above the seagrass meadows at the MTL.

After the selection of a suitable benchmark location, it was necessary to visit the benchmark site and locate (recover) the specific marker to be used and also to determine that the location was suitable for GPS observations (i.e. a relatively open area with a clear view of the sky and with no large reflective surfaces nearby). Most benchmark locations were not directly useable for GPS observations and a suitable location for the base station had to be marked and offset from the benchmark by using standard level (Carl Zeiss Ni2) and rod surveying techniques. All offset distances were relatively short (<200m) and all level readings were duplicated.

Elevation measurements at the ten selected seagrass study sites (Fig. 1) followed the establishment of base stations. Figure 5 is an aerial photograph of the Kitchen area of Hillsborough Bay that is shown as an example of the seagrass study sites. The photo shows the approximate locations of the seagrass elevation measurements. The specific locations to be measured within each seagrass study site (most often the deep edge of the meadow), were determined in the field by comparing aerial photographs of the area with on-site observations. The majority of the deep edge seagrass study sites had a very distinct and easily defined deep edge of the meadow, but several sites had sparse (low shoot density) seagrass coverage that extended from the edge of the meadow into deeper waters. This sparse seagrass coverage was not considered to be part of the defined meadow.

Typical set-ups of the GPS instruments for measurements of the deep edge of seagrass meadows are illustrated in Figures 6 and 7. The base station was placed with its antenna vertically above the benchmark and the rover station was placed on a tripod above the sea surface with its antenna vertically above the seagrass edge to be measured. As illustrated in Figure 6, the base station antenna height (A), i.e. the distance between the antenna phase center and the center of the benchmark, was measured using a weighted metric tape measure, and recorded. Similarly, the rover station antenna height (C), i.e., the distance between the antenna phase center and the top of the sediment at the seagrass site, was also measured and recorded. The instruments were configured to Trimble recommendations (Trimble 1996) and the daily satellite schedule was examined prior to data collections to ensure optimum data collection periods (see above). Static satellite observations were conducted for a period sufficiently long to ensure that the two stations collected at least 30 minutes of overlapping data (see addendum for an updated and more efficient method of satellite data collections).

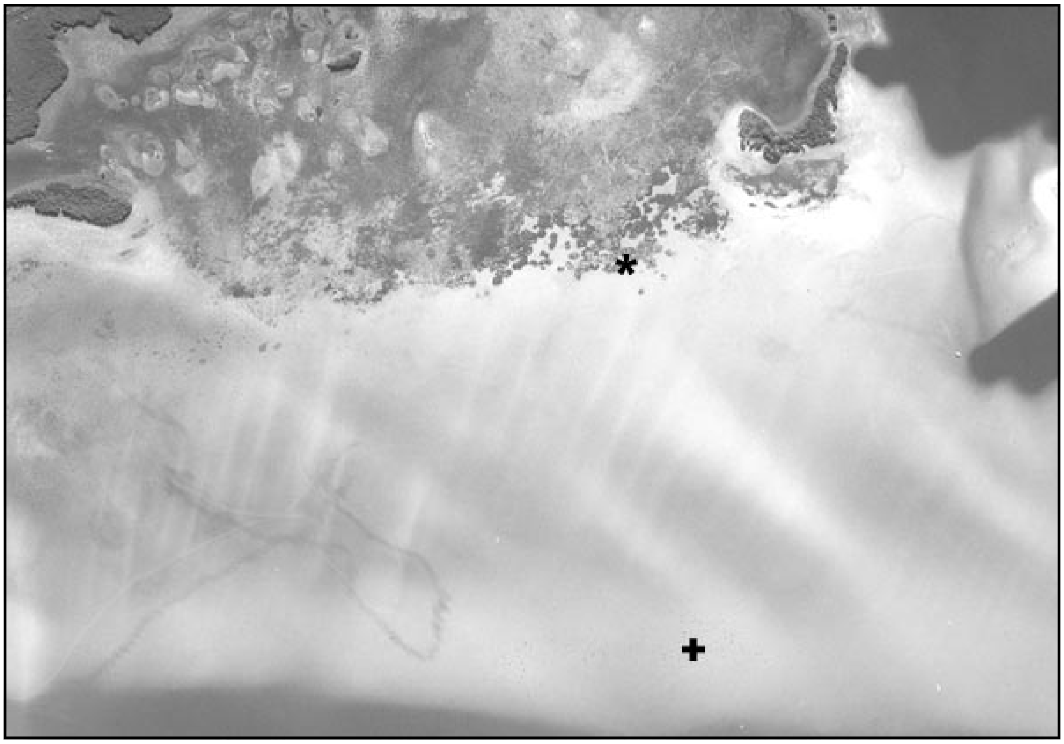

Figure 5. Vertical photograph of the Kitchen area in Hillsborough Bay taken on October 26, 1999. The symbols show the approximate locations of the GPS seagrass elevation survey sites.

The collected satellite data was analyzed using the Trimble software products Pathfinder Office v.2.1 and Phase Processor v.2. The software calculated the relative elevation difference between the two antennas (D in Fig. 6). Since the MTL elevation of the benchmark (B) was known and the antenna heights (A and C) had been measured in the field, the MTL elevation of the deep edge of the seagrass meadow (X) could easily be calculated using the equation shown in Figure 6.

RESULTS

Measurement Errors

Results from the 35 tests conducted on the roof of the laboratory to determine elevation measurement errors of the PRO XR system are shown in Figure 8. As previously discussed, the two instruments were assumed to be at identical elevation during all tests, i.e. the true elevation difference was 0 m. Measured elevation differences ranged between +6.0 cm to -2.7 cm. The average difference of the 35 tests was 0.2 cm (STD 2.1 cm). The 95% confidence interval ranged from 0 to 0.9 cm, suggesting that the confidence interval contains the actual elevation 95% of the time.

The baseline error introduced during these tests was near zero since the two antennas were separated by less than 1.0 m. However, the potential baseline error must be considered during field measurements. Trimble reports this error to be 0.5 cm for each kilometer of separation between the base and rover stations. The baseline distance should, therefore, be kept as short as possible. Baseline distances used during the seagrass elevation study ranged from 0.12 km to 10.6 km, resulting in potential baseline errors ranging from 0.1 cm to 5.3 cm. The average baseline distance of the 38 field measurements was 3.5 km.

Results from the replicated seagrass elevation measurements with n>2 are discussed below.

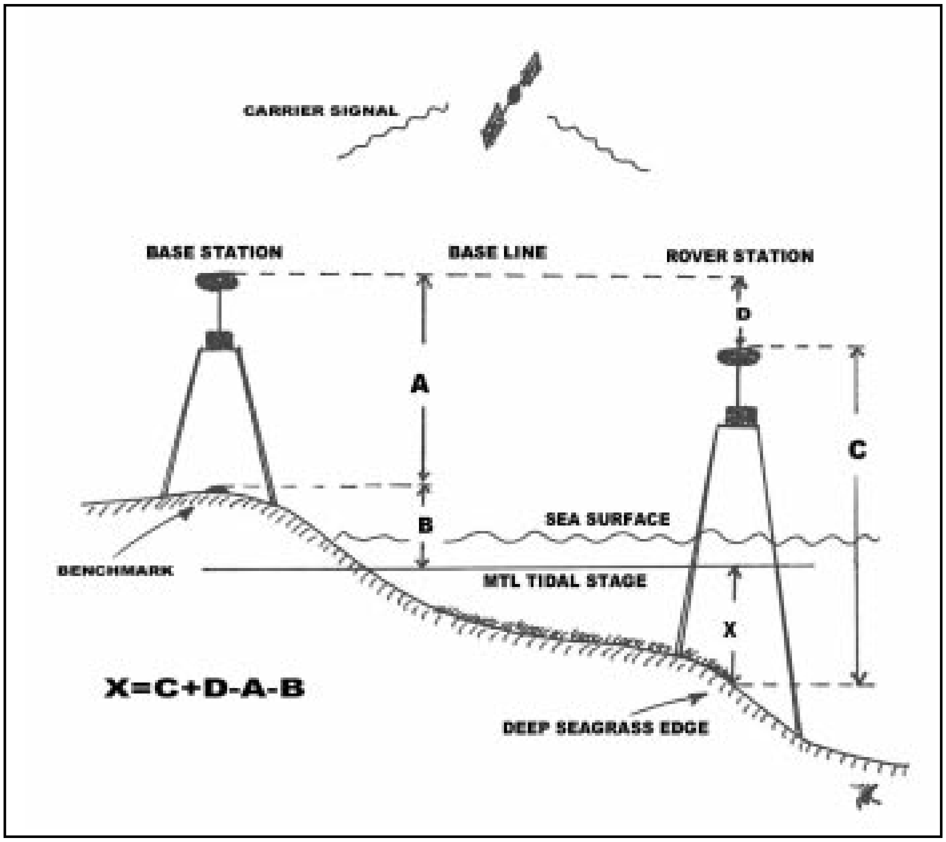

Figure 6. Schematic of typical GPS stations set-up during elevation measurements. A = base station antenna height; B = benchmark elevation above MTL tidal stage; C = rover station antenna height; D = Relative elevation difference between base station and rover station antennas; X = Calculated elevation of the deep seagrass edge.

Figure 7. Field set-ups of base (A) and rover (B) stations during GPS seagrass elevation measurements in Tampa Bay.

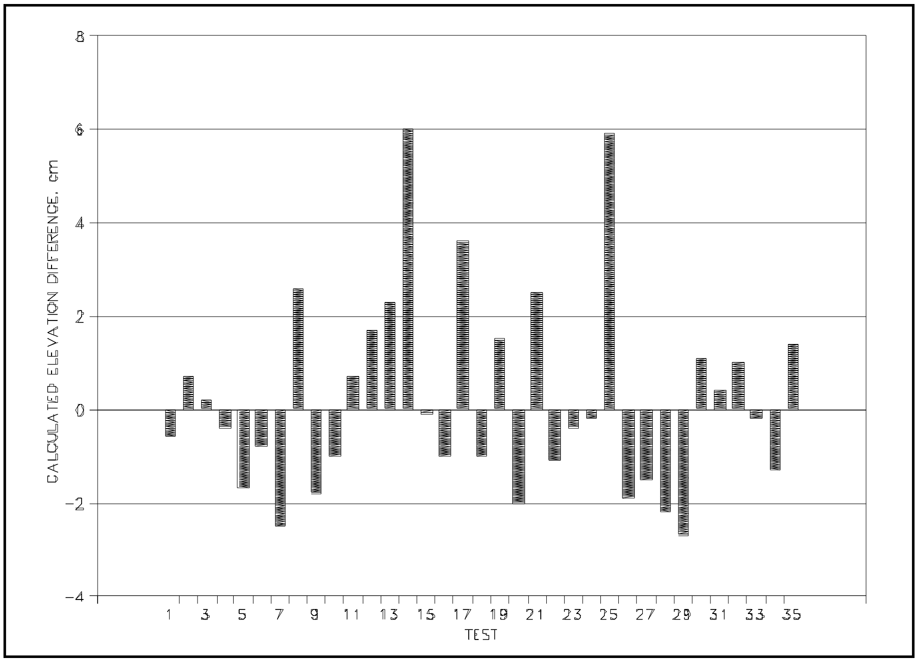

Figure 8. Results from 35 tests of vertical measurement errors conducted on the roof of the City of Tampa Bay Study Group laboratory using two Pathfinder PRO XR instruments. The true elevation difference between the instruments was 0 cm.

Seagrass Elevations

Results from the 38 seagrass elevation measurements at the ten selected seagrass study sites are shown in Table 2. The shallowest deep edge of the *H. wrightii* meadows was in the upper section of Hillsborough Bay (-0.30 to -0.34 m MTL) and at intermediate depths in the lower Hillsborough Bay and the northeastern area of Middle Tampa Bay, just south of Hillsborough Bay (-0.48 to -0.58 m MTL). The deepest *H. wrightii* surveyed was found at similar depths at Big Island in Old Tampa Bay and at Port Manatee in Lower Tampa Bay (-0.71 to -0.76 m MTL). Deep edges of *T. testudinum* meadows occurred at similar depths at Bel Mar Shores in eastern Old Tampa Bay and at Port Manatee. Depths for these edges ranged from -1.53 m MTL at Bel Mar Shores to -1.73 m MTL at Port Manatee. Isolated patches of *T. testudinum* located on the shallow sandbar at Picnic Island and the Wolf Branch area were found at considerably shallower elevations (-0.53 to -0.90 m MTL). Deep edges of *S. filiforme* meadows also occurred at similar depths at the sites in eastern Old Tampa Bay and at Port Manatee. Depths of these edges ranged from -1.19 to -1.46 m MTL. However, the deepest *S. filiforme* edges were measured at the two sites on the western side of Middle Tampa Bay. At Coffeepot Bayou the deep edge was between -1.79 and -1.81 m MTL and at Coquina Key between -1.93 and -1.96 m MTL. The latter depths were the deepest seagrass elevations measured in this study.

Results from the four seagrass sites with replicated (n>2) elevation measurements (Table 2) show that the standard deviation of the determined elevations ranged from 3 to 4 cm. The coefficient of variation for these measurements ranged from 4.1% to 7.7%. At one of these sites, the offshore bar in the Kitchen in southeastern Hillsborough Bay, four measurements were conducted in the center of different *H. wrightii* patches. Two of these measurements were performed with the base station located in Simmons Park, approximately 10.6 km

Table 2. Results of GPS seagrass elevation measurements conducted for different seagrass species in different sections of Tampa Bay. Elevation expressed as mean tide level (MTL).

SEAGRASS SPECIES LOCATION	BAY SEGMENT	NUMBER of SURVEYS	ELEVATION (MTL) (m) Average	Range	STD
***H. WRIGHTII* :**					
Bayshore North; Deep Edge of Meadow	HB	1	-0.30		
Bayshore South; Deep Edge of Meadow	HB	1	-0.34		
Bayshore South; Patch Offshore Bar	HB	1	-0.65		
Bayshore South; Shallow Edge of Meadow	HB	1	-0.20		
Kitchen; Deep Edge of Meadow	HB	5	-0.52	-0.48 to -0.58	0.04
Kitchen; Patches Offshore Bar	HB	4	-0.73	-0.69 to -0.77	0.03
Long Branch; Deep Edge of Meadow	OTB	1	-0.65		
Big Island; Deep Edge of Meadow	OTB	2	-0.74	-0.71 to -0.76	
Wolf Branch; Deep Edge of Meadow	MTB	4	-0.52	-0.50 to -0.57	0.03
Port Manatee; Deep Edge of Meadow	LTB	1	-0.72		
T. TESTUDINUM:					
Bel Mar Shores; Deep Edge of Meadow	OTB	1	-1.53		
Picnic Island; Deep Edge of Patch	OTB	1	-0.90		
Wolf Branch; Deep Edge of Patch	MTB	1	-0.76		
Wolf Branch; Center of Patches	MTB	3	-0.57	-0.53 to -0.59	0.03
Port Manatee; Deep Edge of Meadow	LTB	2	-1.6	-1.54 to -1.73	
S. FILIFORME:					
Bel Mar Shores; Deep Edge of Meadow	OTB	1	-1.42		
Picnic Island; Deep Edge of Meadow	OTB	2	-1.33	-1.19 to -1.46	
Coffeepot Bayou; Deep Edge of Meadow	MTB	2	-1.80	-1.79 to -1.81	
Coquina Key; Deep Edge of Meadow	MTB	2	-1.95	-1.93 to -1.96	
Port Manatee; Deep Edge of Meadow)	LTB	2	-1.2	-1.14 to -1.27	

from the seagrass site. The other two measurements were performed on a different date and with the base station located on Hillsborough Bay spoil island 3-D, approximately 2.7 km from the seagrass site. The seagrass patch elevations based on the Simmons Park benchmark were -0.73 and -0.77 m MTL; elevations based on the 3-D benchmark were -0.69 and -0.73 m MTL.

DISCUSSION

Technique Evaluation

Results from tests of measurement errors conducted by Trimble (Trimble 1997) and the present study suggest that the technique using PRO XR instruments and Phase Processor software will yield seagrass elevation measurements with an error less than ±10 cm for survey sites located up to 10km from benchmark sites.

Further, the field evaluation of the technique, which included measurements of the deep edge of the three major Tampa Bay seagrass species, *H. wrightii*, *T. testudinum*, and *S. filiforme* in the four major bay segments, found the method to be practical. Excellent replication of elevations was obtained when several measurements were taken in the same general area and also when different benchmarks were used.

Seagrass Elevations

First, it should be recognized that the present study was primarily designed to evaluate the GPS carrier-phase processing technique and that seagrass elevation measurements were conducted at a limited number of Tampa Bay seagrass sites. Although deep edge elevation measurements were conducted in all four major Tampa Bay segments and measurements included the three major seagrass species, a much more intensive effort is required before comprehensive conclusions should be formulated about the Tampa Bay seagrass depth distribution. Elevation measurements should be conducted at most, if not all, of the nearly 60 seagrass monitoring transects included in the Tampa Bay cooperative seagrass monitoring program. However, recognizing the limitations of the present study, several interesting findings warrant further discussion.

The deep edge elevations of the measured seagrass meadows ranged from -0.30 m MTL for *H. wrightii* in the upper portion of Hillsborough Bay to -1.96 m MTL for *S. filiforme* near Pinellas Point in Middle Tampa Bay. Further, all sites visited in the present study had deep edge elevations shallower than the TBEP seagrass restoration target depth for the respective bay segment. The greatest deviation from the target depth was found at the Long Branch and Big Island sites in western Old Tampa Bay, where the deep edges of the *H. wrightii* meadows were about 1.30 m shallower than the -2.0 m MTL target depth selected for this bay segment. The least deviation was found at three sites: the *H. wrightii* meadow in the Kitchen in southeastern Hillsborough Bay; the *T. testudinum* meadow at Bel Mar Shores in eastern Old Tampa Bay; and the *S. filiforme* meadow at Coquina Key in southwestern Middle Tampa Bay. These three areas had deep edges that were approximately 0.50 m shallower than the respective bay segment targets.

Similar deep edge depths were found for all three seagrass species at the Old Tampa Bay sites and the Port Manatee site in Lower Tampa Bay. This was surprising, considering the distance of these areas from the mouth of Tampa Bay. The Old Tampa Bay sites are approximately 50 km from the mouth of the bay, while the corresponding distance for the Port Manatee site is only about 20 km. It could be expected that water quality and light attenuation at the Port Manatee site would be superior due to its relative closeness to the Gulf of Mexico, and therefore, would allow seagrass to grow deeper at this site. Analysis of Hillsborough County Environmental Protection Commission (HCEPC) water quality monitoring data, averaged over the last six years, generally supports this hypothesis. Light extinction (Secchi Disk depth), chlorophyll *a* concentrations, and water color were all considerably lower near the Port Manatee site as compared to the Old Tampa Bay sites. However, turbidity was slightly higher near the Port Manatee site.

Additional elevation measurements of Lower Tampa Bay seagrass meadows may find deeper seagrass edges in this bay segment. Dixon (2000) conducted light requirement studies at *T. testudinum* sites in Lower Tampa Bay that ranged in depth from -1.98 to -2.37 m MTL. These depths, which were estimated from sea surface observations, are approximately 0.3 to 0.6 m deeper than the *T. testudinum* meadows surveyed at the Port Manatee site.

Light Availability

Light attenuation measurements of the water column directly above the deep edges of seagrass meadows in Tampa Bay are scarce. Light measurements are most often collected at deeper Tampa Bay sites during routine water quality monitoring. Light attenuation at the seagrass survey sites was therefore estimated from deeper site data. This method was previously used by the TBEP to establish the Tampa Bay seagrass restoration target (Janicki and Wade 1996; also see Giesen et al. 1990). In our study, monthly HCEPC Secchi Disk depths for the period 1994–99 collected near the seagrass elevation survey sites were converted to light attenuation (K_{dPAR}) values using bay segment-specific factors derived from concurrent Secchi Disk depth and PAR measurements by the COT at deep sites for the same six-year period (Table 3 and Fig. 9).

Table 3. HCEPC and COT water quality monitoring stations that were used to estimate the average water column light attenuation at the seagrass elevation survey sites in Tampa Bay for the six year period 1994–99.

HCEPC WATER QUALITY STATIONS	COT SECCHI DEPTH and PAR STATIONS	BAY SEGMENT	SEAGRASS SURVEY LOCATION
6 and 7	4, 12, 17, 18, 19, and 20	HB	Bayshore
73	4, 12, 17, 18, 19, and 20	HB	Kitchen
65	40	OTB	Long Branch
66	40	OTB	Big Island
50 and 51	40	OTB	Bel Mar Shores
33 and 36	40	OTB	Picnic Island
81	13 and 23	MTB	Wolf Branch
32	13 and 23	MTB	Coffeepot Bayou
28	13 and 23	MTB	Coquina Key
90	95	LTB	Port Manatee

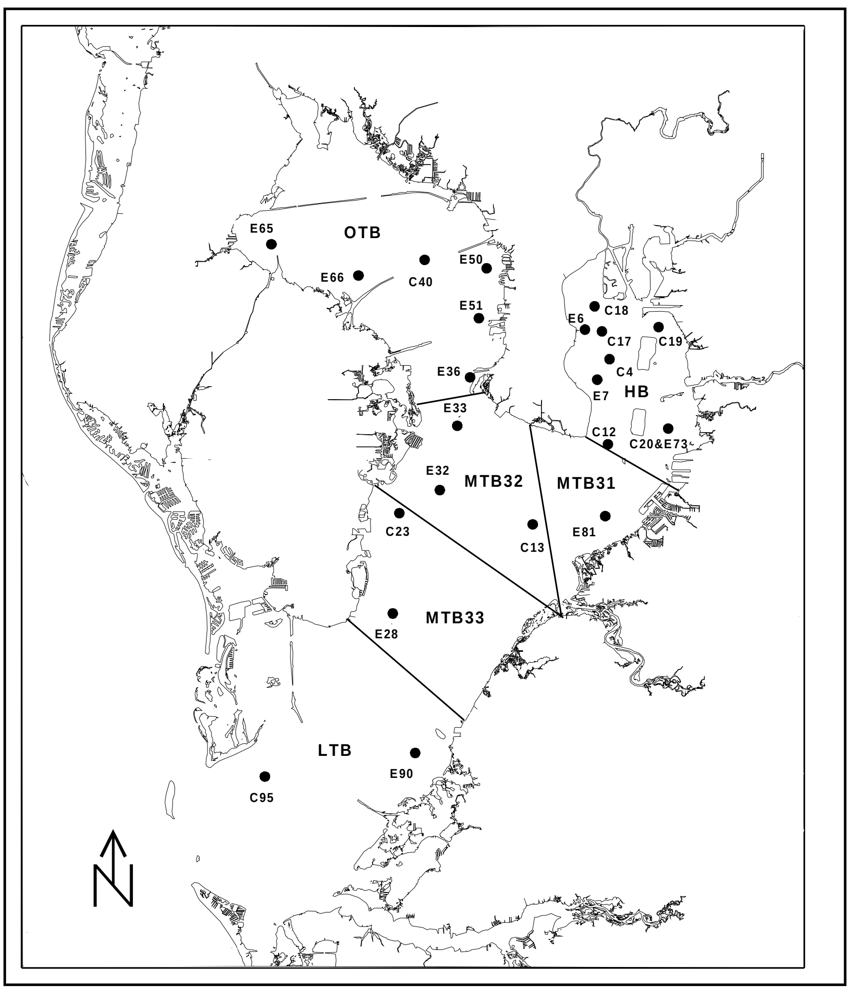

Figure 9. Location of HCEPC water quality monitoring stations (E) located near seagrass elevation survey sites (see Fig. 1). Also shown are COT stations (C) that, since 1994, have concurrently measured PAR attenuation coefficient and Secchi disk depth information.

The percentage of subsurface light remaining at the sediment surface at the deep edge of the seagrass meadows can be estimated from K_{dPAR} and the seagrass elevation measurements using the Lambert-Beer equation:

$$I_Z = I_0 * e^{-kz}$$

where I_Z = the incident light at depth z; I_O = the incident light just below the surface; k = the diffuse PAR light attenuation coefficient; and z = the depth (as m MTL) at I_Z.

The estimated average percent of subsurface incident light available at the deep edges of the seagrass meadows over the six-year period 1994–99 for the different seagrass survey sites and seagrass species is shown in Table 4. The available light at the deep edges of *H. wrightii* meadows in all four bay segments ranged from 59.8% to 28.9% of subsurface incident light and was substantially above the adopted TBEP seagrass restoration light target of 20.5%. Deep edges of *T. testudinum* at Bel Mar Shores in Old Tampa Bay and Port Manatee in Lower Tampa Bay appeared to receive less light than the target, 19.0% to 16.9%. The deep edges of *S. filiforme* meadows at Coquina Key and Coffeepot Bayou in Middle Tampa Bay received the least amount of light of all study sites, 16.7% and 16.2%, respectively.

As discussed above, the estimated light availability at the deep edge of the seagrass meadows was calculated from Secchi disk depth and PAR light attenuation data from the HCEPC and COT routinely conducted water quality monitoring programs at deep

Table 4. Estimated percentage of annual average subsurface irradiance (PAR) remaining at the sediment surface at the deep edge of seagrass meadows (or patches in areas lacking larger meadows) in Tampa Bay. The light attenuation coefficient (K_{DPAR}), used to calculate subsurface irradiance (%PAR), was estimated from the average 1994–99 Secchi disk depth at HCEPC water quality monitoring stations located near seagrass study sites and the COT bay segment specific light attenuation measurements for the same period.

SEAGRASS SPECIES LOCATION	BAY SEGMENT	ANNUAL AVERAGE ATTENUATION COEFFICIENT (K_{PAR}) (m^{-1})	PERCENT OF SUBSURFACE PAR REMAINING AT SEDIMENT SURFACE (%PAR)	
			Average	Range
***H. WRIGHTII*:**				
Bayshore North	HB	-1.72	59.8	
Bayshore South	HB	-1.72	55.4	
Kitchen	HB	-1.59	44.0	39.9 to 46.8
Long Branch	OTB	-1.91	28.9	
Big Island	OTB	-1.54	32.3	30.9 to 33.7
Wolf Branch	MTB	-1.13	55.6	52.4 to 57.1
Port Manatee	LTB	-1.02	47.8	
T. TESTUDINUM:				
Bel Mar Shores	OTB	-1.16	16.9	
Picnic Island (patch)	OTB	-1.10	37.1	
Wolf Branch (patch)	MTB	-1.13	42.5	
Port Manatee	LTB	-1.02	19.0	17.1 to 20.9
S. FILIFORME:				
Bel Mar Shores	OTB	-1.16	19.2	
Picnic Island	OTB	-1.10	23.6	20.0 to 27.1
Coffeepot Bayou	MTB	-1.01	16.2	16.0 to 16.4
Coquina Key	MTB	-0.92	16.7	16.5 to 16.9
Port Manatee	LTB	-1.02	29.4	27.3 to 31.4

water sites. A limited amount of water quality information is available for the shallow nearshore areas in Tampa Bay that can be used to evaluate the assumption that water quality of the shallow areas is similar to the deep areas. The COT has measured chlorophyll *a* and turbidity at five sites located on the nearshore sandbars in Hillsborough Bay on a monthly schedule since 1995. Three of these sites are located near deeper water quality monitoring stations. A comparison between the shallow and deeper sites showed no consistent difference in chlorophyll *a* concentrations. Turbidity, on the other hand, was often higher and more variable at the shallow sites. Turbidity peaks in the shallow areas were often associated with strong wind events. The limited comparison from Hillsborough Bay suggests that the shallow and deeper water column light climate may at times be substantially different. Therefore, the use of water quality data from deep sites for estimating water column light attenuation at the seagrass meadows needs to be evaluated further by additional deep and shallow water quality comparisons.

The average percent of subsurface incident light available at the deep edges of the seagrass meadows shown in Table 4 may not correspond to the minimum light requirement for maintaining sustained growth of the different Tampa Bay seagrass species. Determination of minimum light requirements for Tampa Bay seagrass species was beyond the scope of this study. Additional work is required to resolve uncertainties about extrapolating light availability data to seagrass light requirements. These uncertainties include, but are not limited to:

1. Light attenuation of the water column over the seagrass meadows may be different than that estimated from deep water data (see above).
2. The time period (six years) selected for calculating the average light attenuation of the water column above the seagrass meadow in this study may not properly reflect the lag-time of seagrass growth response to changes in light availability. The time-lag may be shorter or longer.
3. Seasonal light availability, specifically during the active seagrass growing season, may be more appropriate for estimating minimum seagrass light requirements than annual averaged values.
4. Epiphytic growth on the seagrass blades may have caused additional reductions in light availability.

Recommendations for Future Studies

Recently, seagrass recovery has stagnated in several areas of Tampa Bay, despite ambient water quality and light availability conditions that appear adequate to support continued seagrass expansion. As shown above, the deep edges of the *H. wrightii* meadows in the Kitchen in southeastern Hillsborough Bay and the Wolf Branch area in eastern Middle Tampa Bay were estimated to receive an average 44% and 57% of the incident light, respectively. These light levels are considerably greater than the 20.5% light target adopted by the TBEP; however, no expansion of these meadows into deeper water have occurred over the last three to four years.

Many factors may limit seagrass expansion in Tampa Bay in addition to water quality. Lewis et al. (1985) discussed the importance of an offshore unvegetated sandbar that separates the main seagrass meadow from the open bay waters, to protect the seagrass meadow by reducing wave impacts from storms and ship traffic. Destabilization and the ultimate loss of the bar may result in the shoreward migration of the seagrass meadow. However, studies examining the dynamics of the shallow sand bars and their interaction with the development of seagrass meadows are lacking for Tampa Bay.

Additional elevation measurements are recommended to learn more about the seagrass depth distribution and the dynamics of the shallow sandbars in Tampa Bay. The GPS carrier-phase processing technique could be used at most, if not all, of the 60+ baywide seagrass monitoring transects included in the cooperative Tampa Bay seagrass monitoring program to accurately and quickly determine the transect depth profiles (see addendum). Further, deep edge elevation measurements for the different seagrass species found on each transect could easily be included during the depth profile measurements.

The proposed periodically conducted elevation measurements will provide important information to complement the biennial high altitude aerial seagrass photography conducted by SWFWMD and the annual cooperative Tampa Bay seagrass transect monitoring program. Combined, the three programs would become a powerful tool for evaluating the progress of the Tampa Bay water quality and seagrass restoration effort.

CONCLUSIONS

Evaluations of measurement errors suggest that the GPS carrier-phase processing technique will yield seagrass elevation measurements with an error less than ±10 cm for survey sites located up to 10 km from benchmark sites. Further, repetitive elevation measurements (n>2) conducted at four specific seagrass areas resulted in a standard deviation of the determined elevations that ranged from 3 to 4 cm and a coefficient of variation that ranged from 4.1% to 7.7%.

Elevation measurements at ten Tampa Bay seagrass study sites found relatively shallow deep edges of *H. wrightii* meadows in the upper section of Hillsborough Bay (-0.30 to -0.34 m MTL) and at intermediate depths in the lower Hillsborough Bay and at the Wolf Branch area in northeastern Middle Tampa Bay, just south of Hillsborough Bay (-0.48 to -0.58 m MTL). The deepest *H. wrightii* surveyed was at Big Island in western Old Tampa Bay and at Port Manatee in eastern Lower Tampa Bay (-0.71 to -0.76 m MTL). Deep edges of *T. testudinum* meadows ranged from -1.53 m MTL at Bel Mar Shores in eastern Old Tampa Bay to -1.73 m MTL at Port Manatee. Isolated patches of *T. testudinum* located on the shallow sandbar at Picnic Island in southeastern Old Tampa Bay and the Wolf Branch area were at considerably shallower elevations (-0.53 to -0.90 m MTL). Deep edges of *S. filiforme* meadows in eastern Old Tampa Bay and Port Manatee ranged from -1.19 to -1.46 m MTL. However, the deepest *S. filiforme* edges were found outside the well-developed offshore sandbars at Coffeepot Bayou and Coquina Key on the western side of Middle Tampa Bay. The depth of these edges ranged between -1.79 and -1.81 m MTL at Coffeepot Bayou and between -1.93 and -1.96 m MTL at Coquina Key. The latter measurements were the deepest seagrass elevations recorded in this study.

All survey sites had deep edge elevations shallower than the TBEP seagrass restoration target depth for the respective bay segment. The greatest deviation from the target depth was found in western Old Tampa Bay, where the deep edges of the *H. wrightii* meadows were about 1.30 m shallower than the -2.0 m MTL target depth selected for this bay segment. The least deviation was found at three sites: the *H. wrightii* meadow in southeastern Hillsborough Bay; the *T. testudinum* meadow at Bel Mar Shores in eastern Old Tampa Bay; and the *S. filiforme* meadow at Coquina Key in southwestern Middle Tampa Bay. These three areas had deep edges that were approximately 0.50 m shallower than the respective bay segment targets.

The average percent of subsurface incident light available at the deep edges of *H. wrightii* meadows ranged from 59.8% to 28.9% and was substantially above the adopted TBEP seagrass restoration light target of 20.5%. Deep edges of *T. testudinum* at Bel Mar Shores and Port Manatee appeared to receive less light than the target (19.0% to 16.9%). The deep edges of *S. filiforme* meadows at Coquina Key and Coffeepot Bayou received the least amount of light of all study sites, 16.7% and 16.2%, respectively.

The field evaluation of the GPS carrier-phase processing technique provided an important first step in understanding the current depth distribution of the major Tampa Bay seagrass species. However, many more elevation measurements should be conducted to yield a more complete understanding of the seagrass depth distribution in the bay.

Recently, seagrass recovery has stagnated in several areas of Tampa Bay, despite ambient water quality and light availability conditions that appear adequate to support continued seagrass expansion. One theory proposed for the poor expansion focuses on the importance of the offshore unvegetated sandbar to protect the main seagrass meadow from wave action and to allow seagrass to expand into deeper waters. However, studies examining the dynamics of the shallow sand bars and their interaction with the development of seagrass meadows are lacking for Tampa Bay.

Additional elevation measurements are recommended to learn more about the seagrass depth distribution and the dynamics of the shallow sand bars in Tampa Bay. The GPS carrier-phase processing technique could be used at most, if not all, of the 60+ bay-wide seagrass monitoring transects included in the cooperative Tampa Bay seagrass monitoring program to accurately and quickly determine the transect depth profiles. Further, deep edge elevation measurements for the different seagrass species found on each transect could easily be included during the depth profile measurements.

The proposed elevation measurements will provide important information to compliment the biennial high altitude aerial seagrass photography conducted by SWFWMD and the annual cooperative bay-wide seagrass transect monitoring program conducted by the TBEP partners. Combined, the three programs would become a powerful tool for evaluating the progress of the Tampa Bay water quality and seagrass restoration effort.

ADDENDUM

Trimble recently distributed an upgraded version of the Pathfinder Office software (version 2.70), which includes software that calculates "Post-Processed Kinematic GPS" solutions. The upgraded software, in contrast to that used for processing the data in the current study (Phase Processor v.2), does not require that the GPS rover receiver remains static during the satellite data recording period. Horizontal and vertical positions can therefore be collected "on-the-fly", which allows for much more productive field surveys. For example, instead of obtaining a single elevation measurement during a static 30-minute data collection period (as used in the current study), the new technique can provide 360 measurements (with a sampling interval of 5 s) during the same time period.

The "on-the-fly" technique is currently being tested for measurement errors by the COT. However, preliminary results agree with Trimble specifications, which state that the kinematic method is as accurate as the static method.

The greatly increased number of data points that can be collected in the field with the "on-the-fly" method will allow for much more efficient and productive seagrass elevation studies, as well as for other studies requiring highly accurate vertical and/or horizontal position information. For example, seagrass species zonation with depth and elevation profiles of the permanent seagrass transects can easily and quickly be determined.

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