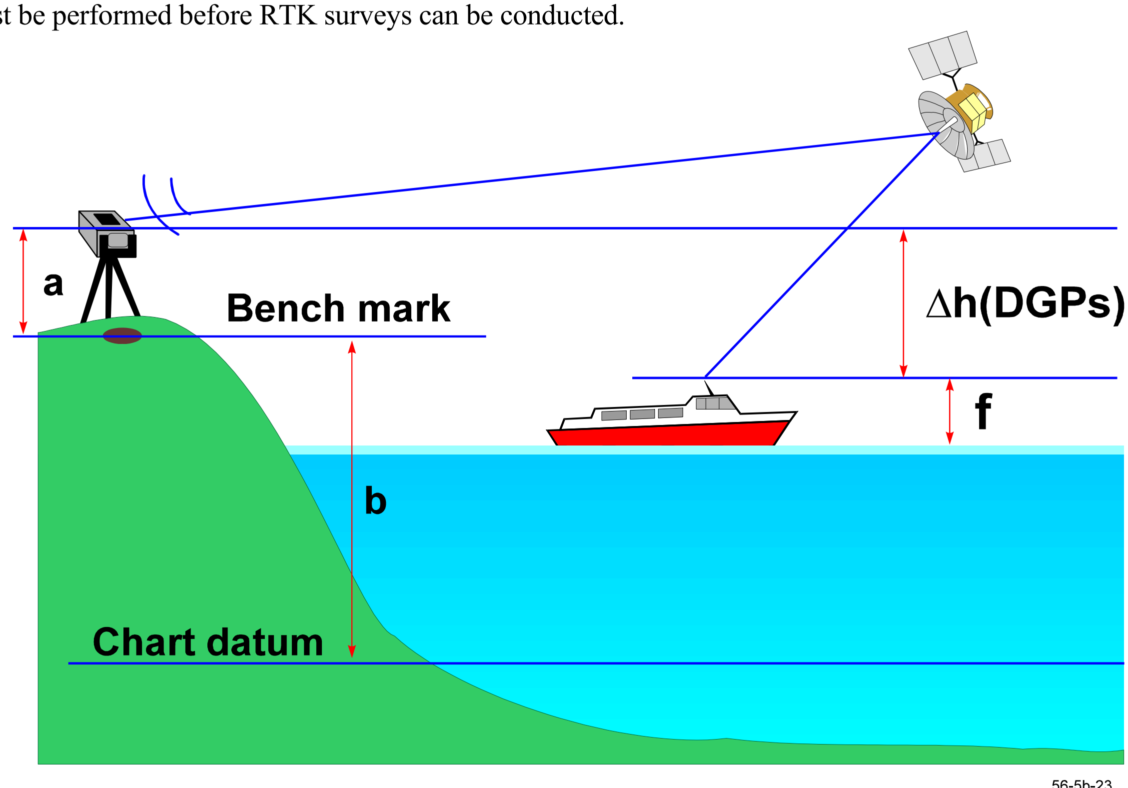
Chapter 16
Real-Time Kinematic Differential GPS Surveys

16-1. Real-Time Carrier Phase DGPS Technology

The DGPS carrier phase is capable of yielding decimeter accuracy on a moving dredge or survey boat--both horizontally and vertically. This technology can provide real-time elevations of survey vessels. If adequate motion compensation equipment is used, and project tidal datum modeling has been accomplished, accurate, real-time elevations (depths) can be directly obtained without observing tidal or river stage data--see Figure 16-1. A real-time kinematic (RTK) DGPS positioning system is based on DGPS carrier phase technology similar to the kinematic techniques currently used for static GPS geodetic surveys where millimeter level accuracies are achieved. RTK procedures allow for the movement of a GPS receiver after the initial integer ambiguity (i.e., whole number of wavelengths) between satellites and receiver has been resolved, as was outlined in Chapter 7. This chapter outlines the procedures for performing hydrographic surveys using RTK DGPS. It focuses on a deep-draft coastal navigation project as an example of the initial geoid modeling that must be performed before RTK surveys can be conducted.



$$b = (\Delta h + f - a)$$

Figure 16-1. Principle of Real-Time Kinematic DGPS elevation determination

16-2. Reference Station

The carrier phase positioning system is very similar to the current code phase tracking technology described in Chapter 7. A shore GPS reference station must be located over a known survey monument; however, the reference station must be capable of collecting both pseudo-range and carrier phase data from the GPS satellites. The reference station will consist of a carrier phase, dual frequency, full wavelength L1/L2 with cross-correlation technique during times of P-code encryption tracking, using a GPS receiver with its associated antenna and cables, high-speed processor, and communications link. The receiver should be capable of a 1-sec update rate. The location of the reference station will be the same as for a code phase tracking DGPS system. The processor used in the reference station will compute the pseudo-range and carrier phase corrections and format the data for the communications link. The corrections will be formatted in the RTCM SC-104 v.2.1 format for transmission to the remote user.

16-3. Communications Link

The communications link for a RTK positioning system differs from the code phase tracking DGPS system in the amount of data that has to be transmitted. The RTK positioning system may require a minimum data rate of 4800 baud, as compared to a baud rate of 300 for the code phase tracking DGPS system. This high data rate eliminates many of the low-frequency broadcast systems and limits the coverage area for high-frequency broadcast systems. VHF and UHF frequency communications systems are well suited for this data rate.

16-4. User Equipment

A desktop computer will be needed to process the hydrographic survey data. Currently, laptop computers are used separately to process the satellite information into the proper broadcast formats (RTCM SC-104 v2.1). One laptop resides at the reference station (master), and a second laptop resides on the survey vessel (remote). This arrangement may change as GPS receivers build the format capability into the receiver units. Two GPS receivers (master and remote) are needed for positioning. These receivers must meet the requirements to process real-time carrier phase tracking information. The proposed user equipment on the survey vessel or dredge consists of a carrier phase dual-frequency full-wavelength L1/L2 with cross-correlation technique during times of P-code encryption tracking GPS receiver. A communications link is needed to transfer corrections to the dredge or survey vessel. Frequency approval may be necessary for communication link broadcasts using a power source in excess of 1 watt. RTK technology should normally not be used for surveys in excess of 20 km from the master station. The position output for the helmsman is code phase tracking using pseudo-ranges (accurate at the meter level) for vessel navigation in real time. Alternatively, a USCG radiobeacon signal may be used for vessel navigation. The decimeter-level carrier phase DGPS data will be timed/tagged to allow for recording the true vessel position needed for survey processing. The minimum update rate from the reference station to the vessel(s) is 1 sec.

16-5. Kings Bay Entrance Channel Tidal Modeling for RTK Surveys

This section details the measurements of a tidal datum in the Saint Mary's Entrance Channel for the purpose of dredging and surveying. The channel is located at the boundary between the States of Florida and Georgia and provides access to the Kings Bay FBM Submarine Base, Georgia. The Entrance Channel is maintained to a project depth of 46 feet--out to the east channel limit eight miles offshore--Figure 16-2. The project has an approximate tide range of 7 feet and has always been difficult to survey due to uncertain tidal modeling.

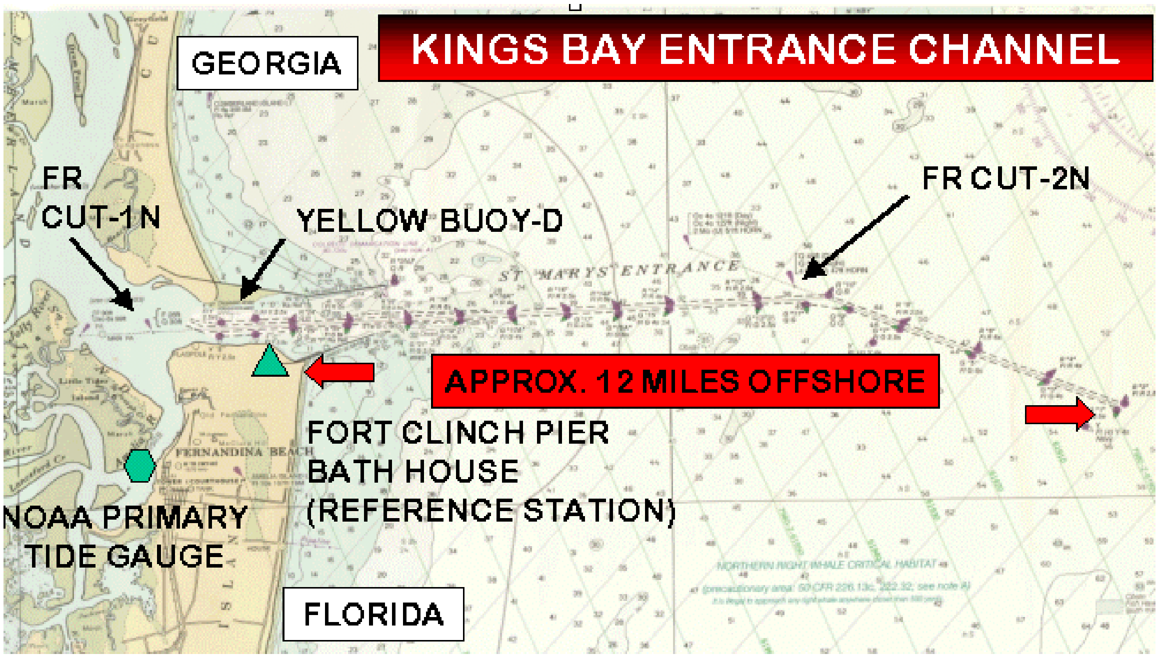


Figure 16-2. Kings Bay (St. Mary's) Entrance Channel

a. In May 1997, the Jacksonville District contacted the US Army Topographic Engineering Center (USATEC) to establish a tidal datum in the Saint Mary's Entrance Channel. The purpose was to update the entrance channel to reference the MLLW Datum. In addition, the Jacksonville District wanted to implement RTK DGPS technology to allow hydrographic surveys to be performed without using tide gages. The Jacksonville District began the actual field work by performing wide area GPS static surveys during the later part of 1997. Two acoustic tide gages were installed in Cut 1N between December 1997 and January 1998. The tidal datums at these two gage sites were computed by NOAA using four months of data. In order to mesh GPS water measurements and conventional tide gage measurements, the Jacksonville District's Survey Vessel Florida performed GPS tidal measurements between March and June 1998. The Surveyboat Florida anchored six times for 25 hour periods to provide intermediate datum points in the channel and correlate conventional tide gage methods to the GPS tidal datum method. The vessel anchored twice at tide gage locations to check the change in ellipsoid heights received on-board from the GPS reference station (kinematic mode) against the ellipsoid heights at the tide gages (static mode) over a tide cycle. A software configuration in the hydrographic survey package developed by Coastal Oceanographics, Inc. allows for the ellipsoid separation values to MLLW to be used to compute tide measurement from the waterline of the survey vessel.

b. The entire project depended on the tidal measurements from the primary NOAA tide gage located in the Amelia River at Fernandina, Florida, two miles south of the Saint Mary's Entrance Channel. This gage was the primary tide gage used to measure the Mean Lower Low Water (MLLW) in the Saint Mary's Entrance Channel. A reference was needed to incorporate tidal datum measurements along the channel made relative to the Fernandina Gage. Two vertical references were used, the GPS ellipsoid and the North American Vertical Datum of 1988 (NAVD 88). The Jacksonville District accomplished the vertical references by performing the GPS static survey over the entire project area. The GPS survey included two offshore range lights used to guide submarines into port.

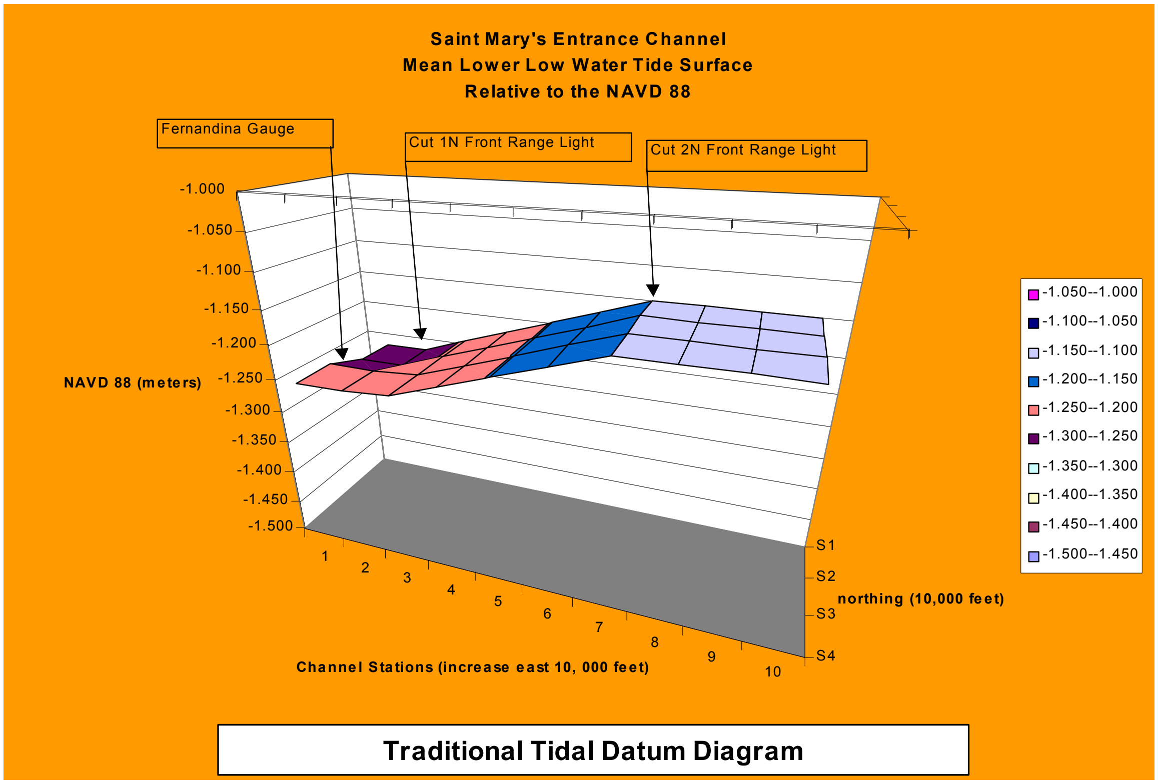
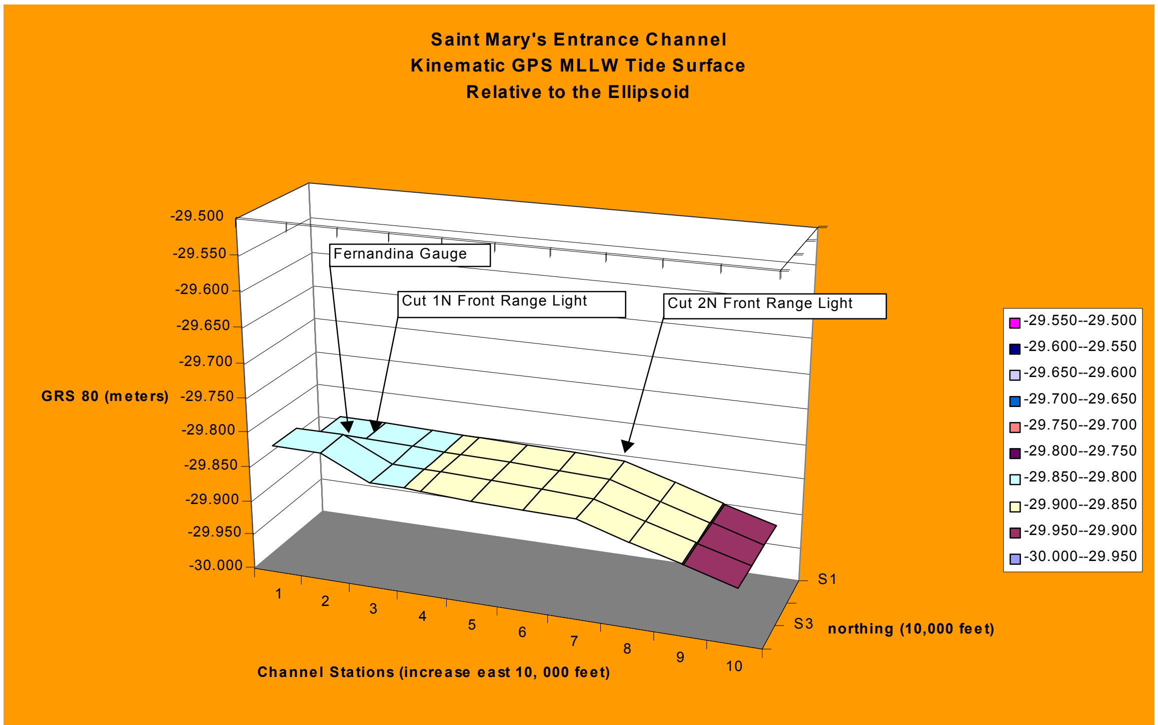


Figure 16-3. Traditional tidal diagram for Kings Bay Entrance Channel

16-6. Tidal Datum Diagram

A traditional tidal relationship for the Entrance Channel is shown in Figure 16-3 above. The primary focus of modeling a project for RTK surveys is to develop the ellipsoidal tidal datum diagram shown in Figure 16-4. The results shown on the tidal datum diagram provide the MLLW reference for the Saint Mary's Entrance Channel well within acceptable tolerances for dredging applications. This diagram uses the geodetic reference of NAVD 88. The mean sea level values on the diagram should theoretically be parallel to geodetic reference surface; however, the currents generated by the water moving through the inlet may help explain why the height values drop five centimeters (0.16 feet) from the ocean through the inlet to the confluence with the Amelia River. Ellipsoid height values can be plotted that map the relationship between the computed MLLW and the ellipsoid. These values and the GPS reference station used to measure the ellipsoid-MLLW separation allows Kinematic GPS hydrographic surveys without tide gages.



Ellipsoid Height Surface used for Hydrographic Surveys
NO TIDE GAUGES

Figure 16-4. Tidal model of Kings Bay Entrance Channel

16-7. GPS Reference Station

A permanent GPS reference station (Figure 16-5) was established at Fort Clinch for future hydrographic surveys in the Saint Mary's Entrance Channel. An antenna height of (-) 20.015 meters should be entered into the GPS receiver during GPS hydrographic surveys. If the GPS reference station antenna is moved, the value is invalid. If the antenna must be moved, the vertical difference between the bottom of the antenna and the reference benchmark must be remeasured--and to confirm that the benchmark is (20.015 + 3.645 = 23.660 meters) below the ellipsoid. Run levels through the old antenna location and the new antenna location starting from the benchmark.

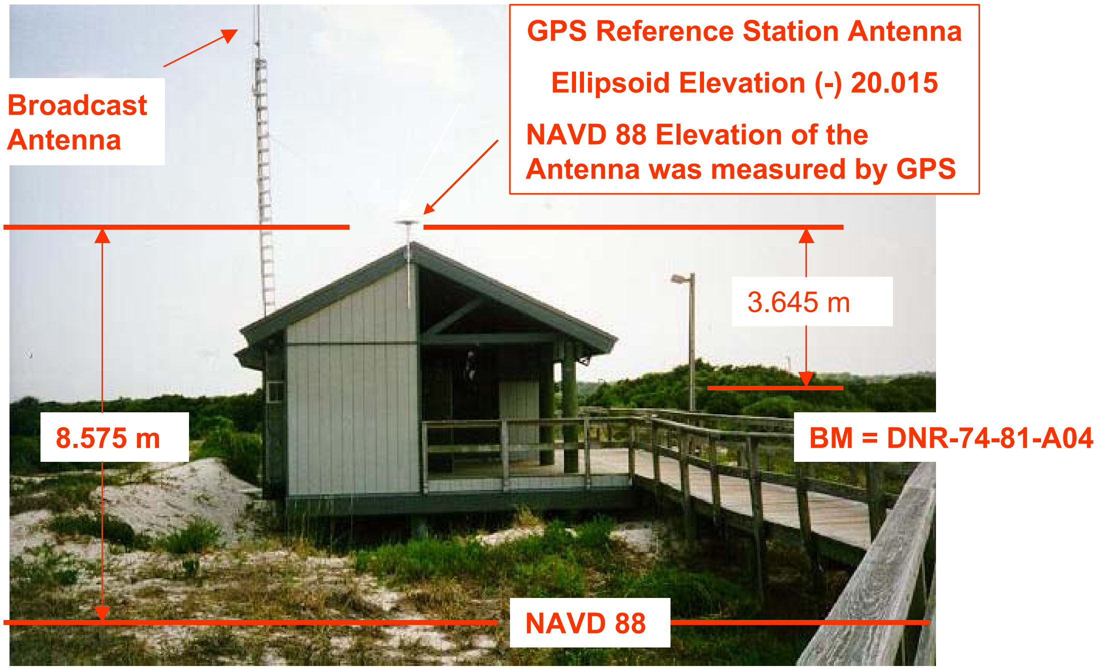


Figure 16-5. RTK DGPS reference station parameters

16-8. Resultant RTK DGPS Elevation Accuracy

The target accuracy for real-time RTK elevations was ± 0.25 feet. The resultant absolute project accuracy is estimated to be ± 0.22 feet (7 cm). The absolute accuracy refers to the MLLW relative to the geodetic reference datum, NAVD 88. No local project modeling of the ellipsoid-geoid separation was attempted for the project. Geoid 96, a computer program written by the National Geodetic Survey, was used by entering the surveyed horizontal positions to compute the NAVD 88 /ellipsoid separations.

a. The relative accuracy of points in the channel is estimated to be ± 0.13 feet (4 cm). This includes the accuracy of RTK DGPS between the boat and the reference station. The relative accuracy excludes the NAVD 88 monuments and the MLLW datum. A centimeter difference between adjusted GPS static vectors and uncertainty variations of two or three centimeters in DGPS water levels observations using extremely short data series were the most difficult issues to resolve in modeling the project. The errors are insignificant for dredging. Of all the estimated vertical errors, only the GPS static survey provides a standard error of the actual measurements.

b. Hydrographic surveys for dredge payment volumes are associated with relative accuracies from the GPS reference station or relative accuracies from a tide gage. Use ± 0.13 feet (4 cm) for RTK GPS as set up for this particular channel or use ± 0.2 feet (6 cm) at best by interpolating from the acoustic tide gages. Using only one tide gage, expect the accuracy to drop to at least ± 0.4 feet (12 cm). Accuracy is a range not a number. This information can be used as part of the error budget associated with the accuracy of a group of soundings from a particular survey (e.g. a Mean Square Error).

16-9. Survey Vessel

The most important vertical measurement on the survey vessel is the GPS antenna phase zero measurement down to the water line of the vessel. In a static measurement condition, the measurement is as shown in Figure 16-6. Underway the vessel speed through the water will change this measure. The nautical term for this phenomenon is called 'squat.' The vessel squat is not entered as a correction in the survey system in that the transducer depth is reduced by the same amount the antenna height is reduced.

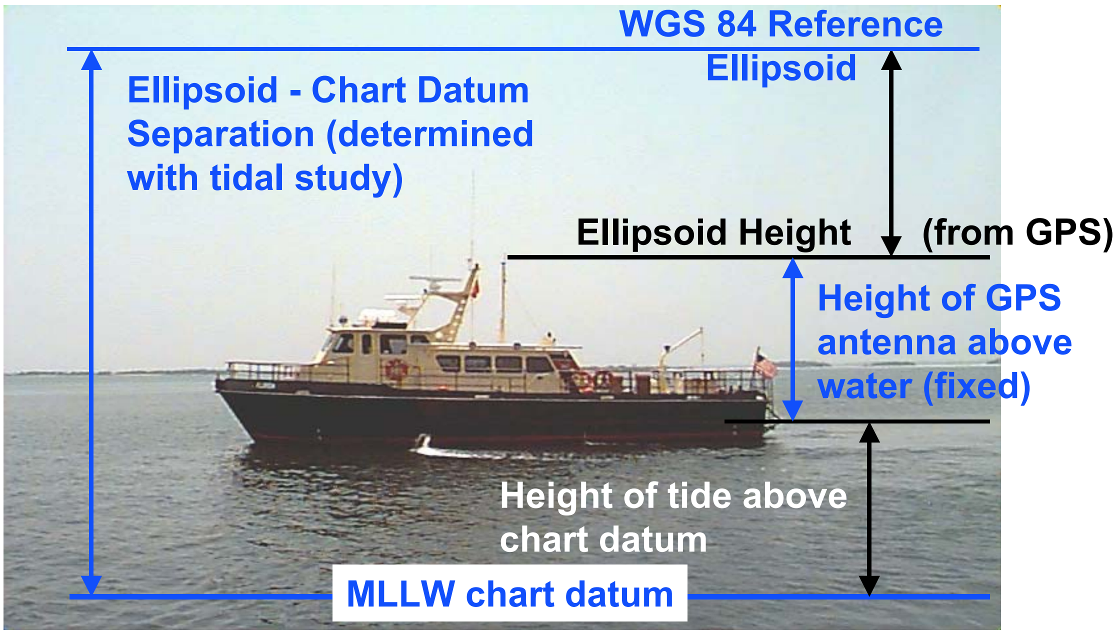


Figure 16-6. RTK measurements on survey vessel

16-10. RTK DGPS Hydrographic Survey Procedures

Two survey methods are available in the Saint Mary's Entrance Channel. The traditional method will be discussed first. Two acoustic tide gages are currently running in Cut 1N on the front range light structure. The gage located on the east range light offshore has a Geostationary Operational Environmental Satellite (GOES) uplink. This data can be retrieved three hours later over the Internet as well as the Fernandina gage data. The data sets will produce a six minute time series. The inside gage is operated by the US Army Corps of Engineers (USACE) and must be downloaded by USACE personnel. The data from these acoustic tide gages should be interpolated to the station numbers in the channel where surveys are being conducted. Both gages should be used to eliminate actual time differences in the channel from average time differences between the gages. Using one gage and surveying four miles from it can result in errors to 0.4 feet (12 cm) on average. The gages are separated by 8.5 nautical miles. Using both gages, surveys conducted on different days should overlay on the outside portions of the cross-sections unless dredge material has settled on the outside areas. The second method precludes the use of a tide gage during the hydrographic survey. This tidal datum diagram was used to build a MLLW surface in the Coastal Oceanographics, Inc. program HYPACK. The HYPACK manual explains the procedure. The survey vessel must have equipment to receive specific GPS information from the USACE reference station. The Jacksonville District uses Trimble 4000 SSi RTK GPS equipment and a 25 watt (joules per second) radio transmitter that broadcasts carrier corrections every second on a frequency of 164.200 MHz. To implement this technology on a survey vessel, refer to the Survey Vessel Section. Levels must be performed on the survey vessel to obtain the vessel information.

16-11. Test Results

The first test of the RTK GPS Tides separation values (ellipsoid minus MLLW) was conducted on 29 June 1998. A matrix of the separation values was constructed in the Coastal Oceanographics hydrographic survey program called HYPACK. The Surveyboat Florida ran twenty cross-sections at 100 foot spacing in Cut 1N midway between the acoustic tide gages 8.5 miles apart. The personnel then traveled to the gages and downloaded the tides for that day. Both tide gages were interpolated to establish a tide curve time series midway between the acoustic tide gages. The interpolation method was tested and found to work in this particular channel. The survey vessel ran lines of channel cross-sections in the mid-channel area under normal survey conditions. The survey was then processed in two ways: the conventional method and the GPS method. The conventional method uses the horizontal GPS coordinates but not the vertical coordinate. The tide gage data was then used to reduce the raw soundings into reduced depths relative to the MLLW. The same survey was then processed by RTK GPS. The first depth and last depth of each line was selected for a comparison with the GPS depths differenced relative to the tide gage reduced depths.

16-12. Scope of Work for Modeling Kings Bay Entrance Channel (Jacksonville District)

The following scope of work was designed to develop a DGPS tidal model for the Kings Bay Entrance Channel. It was developed jointly by the Jacksonville District and the US Army Topographic Engineering Center. This scope is representative of the modeling required in a navigation project.

SCOPE OF WORK

Tidal Datum for Dredging
Saint Mary's Entrance Channel

0. Background:

0.1 The US Army Engineer District, Jacksonville has identified a need to establish a new tidal datum for the Saint Mary's Entrance Channel. Mr. Fran Woodward of the Jacksonville District (CESAJ-CO-OM) and Mr. Brian Shannon of the US Army Topographic Engineering Center (CEERD-TS-G) assessed the effort necessary to establish a tidal datum in the Saint Mary's Entrance Channel on the Florida-Georgia state boundary during a two day period beginning 20 May 1997. They inspected the project aboard the SV Florida and also visited primary National Oceanic and Atmospheric Administration (NOAA) tide gages in the vicinity of the navigation channel.

0.2 A plan was developed to use both conventional tide gages and On-The-Fly (OTF) Global Positioning System (GPS) to measure the tide. The benefit of the GPS will be to eliminate the need for tide gage readers during hydrographic surveys as the boat can be used as a water level record as soundings are being collected. A second benefit of GPS is to use a heavy boat as a tide gage to develop a datum point at any location adjacent the navigation channel as needed. This eliminates the uncertainty of tide phase measurements between gages at the boat marina and tide phase at the boat location. Mr. Shannon proposed a target tidal accuracy between a vertical reference on shore and a measured datum point in the channel to be 0.25 feet (8 cm) for this channel using direct relative GPS ellipsoid measurements to measure the height of Mean Lower Low Water (MLLW).

1. Description of Work:
1.1 The tidal datum for the cut "1N" will have 5 tidal station measurements as a minimum to insure a MLLW along the reach to an accuracy of 0.25 feet. The five tidal station locations selected for this reach are shown in Figure __. The locations from west to east are: 1) Cut 1N Front Range Light Structure, 2) Yellow "D" Buoy, 3) Red #20 Buoy, 4) Red #16 Buoy, and 5) Cut 2N Front Range Light Structure. A sixth point, 6) Red #6 Buoy, at the midpoint of Cut 2N, will be

selected for tidal measurements. A combination of traditional tide gauging and OTF GPS methods will be used to measure the MLLW at these six points. Land GPS surveys, postprocessing, project management, report writing and CESAJ-CO-OM tide gage installation and maintenance training are included in this scope of work. Final MLLW determination along the channel will be coordinated with the NOAA, Silver Spring, Maryland. Coordination for tide gage installation and training will be through the State of Florida, Department of Environmental Protection (FLDEP), Tallahassee. The CESAJ-CO-OM will provide boat transportation for FLDEP as needed.

1.2 The tidal project will begin 10 November 1997. Field work will continue through December 1997.

2. Survey Control
2.1 A minimum of 2 horizontal marks and 3 vertical marks from the National Spatial Reference System (NSRS) plus the GPS reference station will be used for survey control for this project. The survey marks selected for GPS occupation will have a vertical tolerance not to exceed 0.05 feet (1.5 cm). The primary vertical datum of the marks will be the North American Datum of 1988 (NAVD 88). The marks selected will list corrections to the National Geodetic Vertical Datum of 1929 (NGVD 29). The NGVD 29 correction shall be listed as ADJUSTED or ADJ UNCHANGED. A tidal benchmark is recommended to be used as one of the marks if the benchmark is within the relative vertical tolerance. The Jacksonville District will select the survey control and perform a GPS static survey on the survey control before 10 November 1997.

2.2 The CESAJ-CO-OM will install three monuments on both structures before 3 November 1997. Beginning 10 November 1997, GPS vectors from the selected survey control on the land to the range light structures will commence. Only one monument per structure will be occupied with the GPS receiver. Two GPS sessions with a change in antenna height over the mark on each range light structure will be measured from the survey control.

3. Tide Gauging
3.1 The two acoustic tide gages will be mounted on existing range light structures for channel navigation. Photographs of the structures are shown in Figure __. The gages will be mounted by FLDEP such that the transducer is at the height of the top platform. FLDEP will then level to the gage zero mark. These tide stations will have a minimum uninterrupted time series of 30 days and both stations will be measured concurrently. The gages will run for a period between 60 and 90 days following installation. The tidal datum point for the west project limit (Cut 1N Front Range Light Structure) will be computed relative to the Fernandina Gauge (NOAA). Figure __ depicts the 3 NOAA gages close to the project. The tidal datum point for the east location limit (Cut 2N Front Range Light Structure) may be computed relative to both the Jacksonville Pier (30 miles) and the Saint Augustine Pier (55 miles). NOAA may have other data to improve the tidal datum computations at the project limits and will do so as needed.

3.2 Tide gage installation may be done with the technical assistance of Mr. Randy Harrel of FLDEP. CESAJ-CO-OM will provide vessel accommodations, materials, and personnel to assist and be trained in tide gage installations. FLDEP will provide the essential materials to install the gages. The USACE personnel and vessel will need to be available for at least one week, including a Saturday. Eight days will be scheduled for the installation.

3.3 The FLDEP will download the gage data on a monthly basis. The CESAJ-CO-OM will provide transportation for FLDEP to the range light structures.

4. Tide Gauge Removal
4.1 The FLDEP will dismantle the tide gages. Before the gages are dismantled, FLDEP will perform levels on the gages and turn through the three benchmarks on the top of each structure. The stilling wells, brackets, and other materials necessary for a future gage installation will be abandoned by CESAJ-CO-OM intact. The FLDEP intends to place their own tide gages at these locations to develop a longer tidal series for the St. Mary's Entrance Channel.

5. OTF GPS
5.1 The three middle tidal datum points will be measured by precise OTF GPS methods. A heavy vessel will be needed for the GPS platform. The SV Florida is recommended. The CESAJ-CO-OM will outfit the survey vessel to measure OTF GPS information as well as heave, pitch, and roll data. Computers on board the vessel must be capable of storing and downloading large amounts of data as necessary to insure the 2 second data rate GPS information is preserved for post processing. Daily download and backup is recommended. An electronics technician from the CESAJ-CO-OM will

be available to install and troubleshoot equipment during this project. The ship should anchor (one anchor only) outside the channel at the depicted locations in good weather to obtain a tidal series over a 25 hour period. Measurements will not be conducted during weather front passage. Five of these periods are required to obtain a datum point at each location. The 25 hour periods do not have to be consecutive but consecutive periods are recommended. The data must be collected while the gages on the light range structures are operational (NOTE: This will not be necessary for future additional datum points.). The ship may pay out as much chain as needed; the vertical GPS component is the only required data to be used for computation.

5.2 Concurrent with ship GPS activity, a GPS reference station will be operating at the "bath house" on Fort Clinch near the fishing pier. This GPS receiver will be downloaded on a daily basis by CESAJ-CO-OM while the survey vessel is collecting GPS signals in the channel.

6. Postprocessing
6.1 Postprocessing of the GPS data will be necessary for the static survey. Postprocessing of data will be assessed at a rate equal to the time spent in the field collecting GPS data. The same GPS data will be processed by CESAJ-CO-OM. Copies of all GPS data will be mailed to TEC within 30 days of collection. The data will be sent to:

US Army Topographic Engineering Center
ATTN (CEERD-TS-G, Shannon)
7701 Telegraph Road
Alexandria, Virginia 22315-3864

7. Computer Programming
7 .1 The CESAJ-CO-OM wants to compute the tidal datum relative to the ellipsoid in order to bypass the national geodetic vertical datums and the need for tide gage readers during hydrographic surveys. No computer programming is necessary for this option following a phone call to Pat Sanders, President, Coastal Oceanographics Incorporated, 29 May 1997. The HYPACK program can interpolate the MLLW as a function of the vessel's present position during a survey and subtract the correct distance from a sounding to obtain a reduced depth. A data base of six ellipsoid heights relative to the GPS reference station will be entered into the HYPACK Computer Program for the project (Saint Mary's Entrance Channel). NOTE: Be advised OTF GPS will be needed on the survey vessel as well as an operating GPS reference station with radio broadcast during survey operations if this option is executed.

7.2 Tide Data Programming: TEC will develop a computer program to average the 2-second GPS data into a 6-minute data series using all NOAA requirements necessary to enable sufficient tidal datum results from the NOAA Data Processing Analysis Subsystem (DPAS) program. TEC will process all CESAJ-CO-OM tide data into the 6-minute tidal series and submit the files to NOAA for processing.

8. Project Management Tasks for the project management will be divided among TEC, CESAJ, and NOAA. The tasks and the agency responsibilities include: writing memorandums of agreement (TEC), writing scopes of work (TEC), developing cost estimates (TEC), coordination of project schedules (CESAJ), obtaining permits (CESAJ), coordinating field effort (CESAJ, TEC), computing tidal datums (NOAA), constructing the tidal datum diagram (CESAJ, TEC), and report writing (CESAJ, TEC).

16-13. Mandatory Requirements

Geoidal-ellipsoidal modeling and tidal modeling procedures described in this chapter are mandatory if elevations are obtained through the use of RTK DGPS techniques.