Evaluation of Hydrographic Survey Techniques Used for Channel Mapping by the Grand Canyon Monitoring and Research Center in The Colorado River Ecosystem, Grand Canyon, Arizona

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Abstract

In 1999 we conducted a comparison of three different hydrographic survey methods. Two of these, tagline and singlebeam surveys, are currently used for monitoring changes in channel bed elevation in the Colorado River ecosystem below Glen Canyon Dam. A multibeam, or swath survey system was evaluated to determine if this type of hydrographic survey system was feasible for use in the Colorado River, and to compare the multibeam surveys with a singlebeam survey in terms of resolution, cost and effectiveness.

A comparison of tagline cross-sections and cross-sections generated from a singlebeam survey surface model shows that both methods produce similar cross-sections. Channel bed morphology was similar in both profiles and cross-sectional areas at eight different profiles averaged 3.9 % ± 2.7 %. However, both methods were not collected on the same day at the same time and sediment storage changes due to Paria River input could not be discounted as a possible factor influencing these results.

A multibeam system tested on a river trip in February 1999. Surveys were completed in five separate reaches. However, some problems were encountered with the rented system. In particular the transducer mounting system required slower boat speed and decreased data quality in certain areas.

Comparison of multibeam and singlebeam surveys in the Tanner reach show that a multibeam system can collect more data in a shorter amount of time. The multibeam system was used to map 1.2 km of channel in approximately 4 hours, whereas the singlebeam system covered 0.6 km of channel in about 6 hours. In addition, the density of points collected by the multibeam system was greater than the 10 x 10 m grid coverage of the singlebeam system. Surface models are a generalization of the actual channel bottom based on the interval of recorded data, thus a greater density of points produces a more accurate the surface model. Post-processing time, and therefore cost, is slightly higher for a multibeam system. Singlebeam data require approximately 30-60 minutes to process per survey, whereas multibeam surveys requires about 40-100 minutes of processing per survey, depending on the area covered.

Multibeam technology offers the best, most efficient way to collect hydrographic data. The system evaluated in this study worked well in main channel, eddy, and riffle environments. The Grand Canyon Monitoring and Research Center (GCMRC) survey department has the infrastructure to support a multibeam system and only two components are needed to be operational - a multibeam transducer/processing unit and a dynamic motion compensator. The software, electrical system, boat, gyro compass, computers, cables, and logistical support items have already been purchased by GCMRC. Given the survey department's task of producing a system-wide channel map and the critical nature of sediment monitoring in the ecosystem, we feel that a multibeam system is the best tool for the job.

INTRODUCTION

The accurate measurement of channel bed elevation and morphology is a fundamental aspect of monitoring the sediment resources of the Colorado River ecosystem below Glen Canyon Dam. Historically, the tagline method of measuring topographic cross-sections was used to define channel bed elevation changes at streamflow gaging stations (Burkham, 1986), and in the Glen Canyon Reach to measure bed elevation changes following construction of Glen Canyon Dam (Pemberton, 1986). In 1990, the U.S. Geological Survey (USGS) established a network of monumented cross-sections for monitoring sand storage changes and for model development (Graf et al., 1995, 1997; Wiele et al., 1996). During preparation of the Glen Canyon Dam-Environmental Impact Statement, a method of determining the spatial distribution of sediment at the pool and reach-scale was needed. In 1993, Glen Canyon Environmental Studies developed a singlebeam hydrographic survey system that provides coverage of the entire channel. This system was first used on a Northern Arizona University sand bar monitoring trip in April 1993 following floods from the Little Colorado River in January and February, 1993 (Kaplinski et al., 1995). During the 1996 Controlled Flood, hydrographic surveys provided information on the pre-, during, and post- flood sediment distribution at several study sites (Andrews et al., 1999; Hazel et al., 1999; Weile, et al., 1999).

In February 1999, the Grand Canyon Monitoring and Research Center (GCMRC) survey department initiated a test of a multibeam hydrographic mapping system. Multibeam, or swath hydroacoustic (sonar) surveying uses an angular array of transducers to collect bed elevations in a broad strip or belt, whereas singlebeam sonar collects data along a profile. For any given point in time, a singlebeam system collects only one depth, whereas a multibeam system will record as many depth records as there are transducers. Multibeam technology has been used for years to survey large tracts of the ocean floor from large vessels. Through advances in microcomputer processing and storage, multibeam systems are now available for smaller, shallow-water operations. Multibeam hydrographic surveying can potentially improve the efficiency of data collection and provide better coverage of channel features. In this report we outline the methodology of tagline, single beam and multibeam surveying and compare these techniques in terms of resolution, cost, labor, and effectiveness in a variety of river environments.

Description of Hydrographic Surveying Methods

This section includes descriptions of each hydrographic survey method evaluated in this study. It is not intended to be a comprehensive technical manual, but rather a brief outline of the equipment and techniques used. The interested reader is referred to the U.S. Army Corps of Engineers hydrographic survey manual for a more detailed description of survey procedures (USACOE, 1994; IHO, 1998).

The Tagline Method

The tagline methodology involves stringing a kevlar line with flags at 6.1 m intervals across the river between section endpoints. The USGS cross-section data collection and analysis are described in detail by Graf et al. (1995). Endpoints are typically bolts that have been implaced into bedrock or large immovable boulders. Locations of endpoints have been surveyed and tied to the GCMRC control network in the Arizona State Plane Coordinate System, Central Zone Format (Table 1; Graf et al., 1995). Ten passes under the tagline are typically required for one measurement. A 200 Khz sonar depth sounder was used to measure bed topography. This system uses a 15 degree beam-width and a sound velocity of 1,500 m/s. Graf et al. (1995) state that the precision of the depth sounder is 0.03 m and the accuracy 0.5% of the measured depth. Marks were placed on the depth sounder paper chart as the boat passed under each flag. Each pass was digitized from the graphical record. The data were digitized and the mean of the 10 passes computed. Points were selected or generated from the mean trace at 0.25-m intervals across the channel, based on the distance of each point from the left bank endpoint (as viewed looking downstream). Error in this method is caused by depth sounder accuracy, uncertainty in boat position under the tagline, and changes in water-surface elevation during the 10 passes. Although changes in water surface elevation are mostly negligible during the 20-30 minutes required for each cross-section measurement, considerable error in terms of comparison to other methods is introduced because the water surface elevation for each cross-section was typically measured at only one local reference point. As a result, the method does not account for water surface slope and the water surface elevation is nearly the same for all cross-sections.

Common Elements of Singlebeam and Multibeam Methods

Both the singlebeam and multibeam survey techniques evaluated used several common system components. These components include: 1) GCMRC's hydrographic survey vessel; 2) electrical power system; 3) a range-azimuth navigation system; 4) Hypack software; and 5) SDI environmental computer and helmsman displays. Each of these system components was designed for hydrographic surveying.

GCMRC Hydrographic Survey Vessel

The hydrographic boat was developed by GCMRC specifically for surveying and hydrographic mapping applications. The boat design consists of a rigid aluminum frame strapped to twin 18 ft "snout" tubes (Figure 1). The twin flotation tube design provides a stable work platform that significantly reduces naturally occurring heave, pitch, and roll error, and is ideal for safely navigating the world-class rapids of the Colorado River. The boat is equipped with two fuel tanks with the fuel capacity to easily handle

Figure 1. Photograph of GCMRC's 18' hydrographic survey boat at the mouth of the Little Colorado River.

repetitive transects. It is also equipped with an aluminum equipment box and decking to accommodate survey crew and equipment. Additionally, the boat is equipped with mounting hardware for the hydrographic "swivel mast" assembly (Figure 2). This adjustable mast is designed to house a positioning laser target or GPS antenna on top and a submerged transducer or remote-sensing device on the bottom. With the combination of high boat tube buoyancy and an adjustable transducer draught, the boat can collect depths as shallow as one foot below water surface. This craft is also ideal for conventional survey applications because it combines the mobility of a sport boat with the ability to carry a large payload of survey equipment and crew. Routine hydrographic survey applications usually require one boatman, one surveyor, and one to two assistants. Deployment of a hydrographic rig requires one truck and one trailer. Equipment assembly usually requires one full day of loading at the warehouse, two to four hours to rig, and one to two hours to set up and configure hydro equipment and instruments.

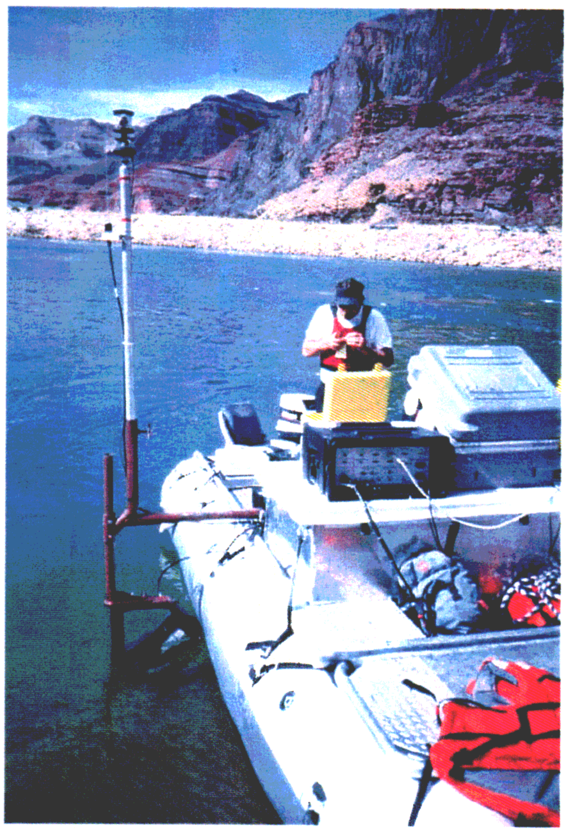


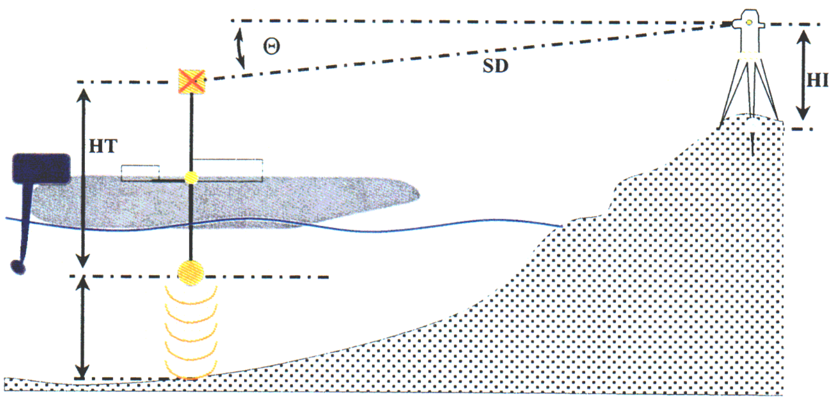
Figure 2. Photograph of swivel mast assembly with target mounted on top of mast and multibeam transducer head mounted directly below.

Electrical Power System

The electrical power system was also specifically designed to meet the requirements of operating within the Grand Canyon while meeting the power requirements of the survey equipment. The electrical system is comprised of a generator, battery, inverter-charger system, and a power connection box. All the power components have been mounted away from the sensors on the rear starboard deck-plate. A submerged marine ground plate has been mounted on the bottom of the transom to ensure a good grounding connection. The ground plate is connected to a large copper welding cable that runs the perimeter of the bilge so that all electronic devices have easy access to the ground connection. The other end of the ground cable connects directly to the outboard motor to reduce electric noise caused by static build up. The grounding system results in an improved signal to noise ratio in the UHF radio transmissions of positional data from the robotic tracking station to the boat. Prior to use of the grounding system, data transmissions fade at about 400 meters. With the grounding system, we successfully operated at a distance greater than 800 meters with no data loss.

Range-Azimuth Navigation System

GPS positioning systems are not viable options for hydrographic surveying in most Grand Canyon environments. Within the deeper, narrower sections of the canyon, GPS positioning systems are not reliable due to variations in the geometric integrity (PDOP) and multipath errors created by movement of the vessel. GPS systems can be used for hydrographic mapping in wider reaches of the river, such as the Tanner or Granite Park areas. However, a range-azimuth navigation system was chosen for use in the Grand Canyon because of its ability to provide highly accurate positioning information in all sections of the river corridor. A range-azimuth system uses a shore station located at a known benchmark to track a target on the boat and transmit the horizontal and vertical angle, and slope distance information back to the survey vessel. This information is time-tagged and simultaneously stored on a microcomputer with the time-tagged depth data. GCMRC has purchased a Geodimeter ATS-PT to track the survey vessel. The Geodimeter ATS-PT provides a combined tracking and measurement accuracy at 1,000 meters of 2 cm horizontal, 1.5 cm vertical, and 0.8 cm distance STD (Standard Deviation). The synchronization of measured angles and distances are within five milliseconds. The ATS-PT updates measurements at a rate of up to 5 Hz. Both the horizontal and vertical components of the tracking system are referenced from the established benchmark. Utilizing the benchmark as a reference point eliminates the need for independent stage-water surface data to reference depth values. The water surface elevation is measured as an independent data set. Figure 3 outlines the geometric calculations for calculating bed and water surface elevations.



BOTTOM ELEVATION =
BM + HI + (SIN Θ(SD)) – HT – DEPTH

H_2O SURFACE =
BM + HI + (SIN Θ (SD)) – HT + DRAUGHT

Figure 3. Schematic diagram illustrating the range-azimuth navigation system and the calculations used to determine river bottom and water surface elevation.

Hypack Software

Hypack software by Coastal Oceanographics, Inc was used to receive, display, store, and process the survey information. All input devices for the survey are configured and interfaced to the Hypack software. Hypack is very effective in receiving hydrographic hardware device inputs and time tagging and positioning the data. The operator and the boatman have a real-time display on the computer monitor of all data sets, including a dynamic representation of the channel, boat position, and survey lines. As the operator selects the sequence of transect lines, the boatman has a graphic, left-right indicator for precise navigation. Hypack is also used for editing and processing data. A thorough working knowledge of Hypack by the surveyor is extremely important to the integrity of the data. All data collection and processing are accomplished in Hypack unless otherwise noted. There are many hydrographic software packages to choose from, however, the programmers at Coastal Oceanographics have developed and supported modules and drivers that are unique to this canyon-river applications. For example, a unique application is the collection and processing of data in elevation mode instead of depths below sea level. Since this application does not provide a reliable water surface datum, depths must be referenced from ground control and converted to elevations. Multibeam data is edited and processed in a module called Hysweep. A software flowchart of procedures to follow for the multibeam survey in Hypack is provided in Appendix A.

Environmental Computer and Helmsman Displays

The SDI environmental computer was also used for both singlebeam and multibeam surveys. The PC based system is designed as a waterproof, shockproof, environmentally sealed system for outdoor use. It features a sealed 15" TFT flat panel display with a 1500 nit light output making it easily viewable in direct sunlight. The computer is equipped with eight COM ports to receive input from all survey devices. Both the computer housing and the monitor are designed with internal cooling fans that direct heat to external heat sink plates. The motherboard and hard drives are shock mounted to withstand severe vibration as well as sudden impacts caused by rough water or other hazards. Laptop computers are also carried as backups.

The 3LCD1 helmsmen's display is a configurable LCD panel that provides the boatman with important navigation information. As Hypack is receiving positions from the tracking system, the coordinates are translated into navigation data in the form of a real time left/right indicator. Given this data, the boatman can precisely maintain the vessel position on pre-established survey tracts. Following pre-determined tracts is essential for accurately repeating surveys for change detection. The boatman can also view depth and distance down line.

Singlebeam Surveying

As the name implies, this system collects a single profile of depth information along pre-set transect lines (Figure 4). A 200kHz innerspace 448 echosounder, with 2 degree beamwidth has been typically used to collect the soundings. Navigation is provided by the range-azimuth system described above.

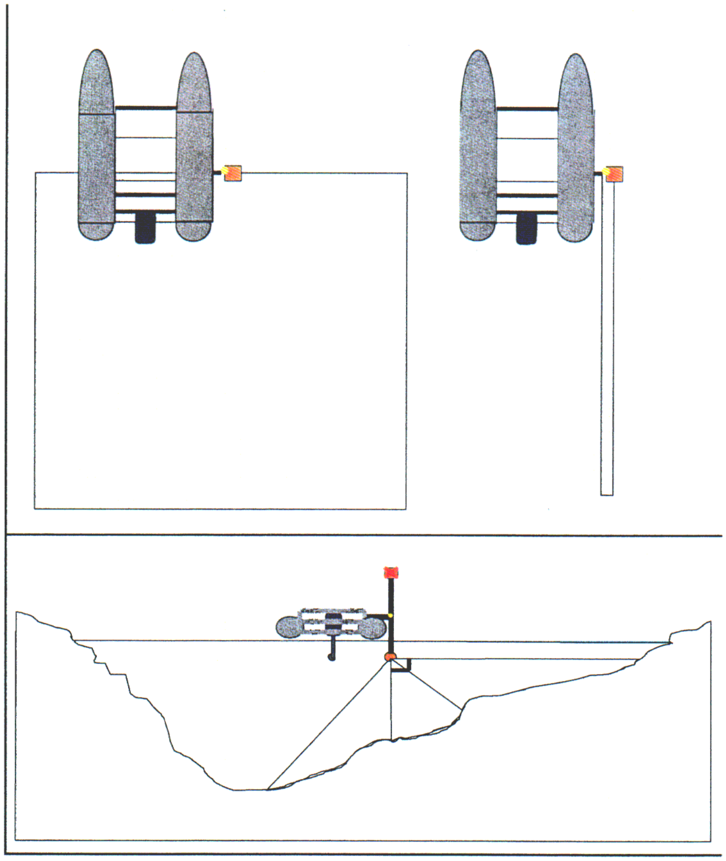


Figure 4. Schematic diagram showing A) multibeam and singlebeam "footprints", and B) 45-degree mounting and 90 degree swath coverage used in this study.

The first step in conducting a singlebeam survey is the equipment and software setup of the system. Depending on site-specific logistics and unexpected errors with the interfacing, this procedure takes approximately 15-30 minutes. First, the geodimeter tracker and backsight setups are deployed to the control benchmarks. The individual components of the system are then connected to the SDI computer (typically packed away for navigating rapids) and all components powered up. For each survey site, computer files containing the navigation control coordinates, pre-set transect lines, and referencing files (typically water's edge lines or a scanned air photo of the site) are stored on the SDI computer. Files pertaining to the local survey are loaded into HYPACK as defaults for the survey. Once the navigation control files are retrieved, communication between the boat and geodimeter tracking station is interfaced and the control coordinates of the tracing station are verified. Once the navigation system is verified and all system components are operating, data collection begins. The protocol for sediment and modeling studies requires the boat to follow a 10-meter by 10-meter grid of planned lines as a minimum coverage. Once a planned line is selected, the boat operator will follow the line using the helmsman's display. The HYPACK display typically consists of a plan-view plot of the survey area showing planned lines, referencing background views, and a cursor showing the location of the boat. Below the plan view, the left-right indicator that displays how far left or right the boat is from the planned line selected. The skill of the boat operator in the data collection phase is critical. In order to follow planned lines, the operator is required to react and perform on-the-fly course corrections based on the screen display data as well as changing current direction and velocity. Free form lines are also run near shorelines or in areas such as eddies to assure complete coverage. Following data collection, data files are backed up on two different disks and the system is disassembled and packed in water-tight boxes for travel. Post-survey processing involves editing the data files for erroneous bottom picks, compiling the individual data files and developing a surface model of the area. Editing and compilation of individual data files is conducted within the HYPACK software and requires approximately 15-30 minutes per survey, depending on the size of the survey. We use Triangulated Irregular Networks (TIN) to construct surface models from hydrographic survey. TIN models are used to calculated areas and volumes, and to compare to previous and subsequent surveys. Cross-sections can also be generated from the TIN model for analysis.

Singlebeam Survey Equipment List

- Innerspace 448 echosounder
- Marimatech E-Sound echosounder (back up)
- Super-Hydro range azimuth tracking station (back up)
- Lasertrak 5000 range azimuth tracking station (back up)
- Geodimeter ATS-PT robotic tracking station
- KVH ADGC gyrocompass
- SDI environmentally sealed computer
- Hypack software
- Power connection box and cables

Multibeam Surveying

Multibeam hydrographic surveying utilizes an array of transducers to collect a swath of hydrographic information beneath the survey vessel (Figure 4). The width of the swath depends on the transducer geometry and water depth. Transducer configurations are commercially available with arrays ranging from 90 to 210 degrees of coverage. Multibeam systems require extremely accurate positioning and motion compensation to successfully map the river bottom at centimeter resolution. Additional sensors are required to provide the level of accuracy needed as well as the multibeam transducer head and processor. A few modifications to the boat hardware for power supply and mounting considerations were required prior to deployment. The setup procedure for a multibeam survey is similar to the singlebeam system setup. However, additional time is needed to set up and interface the additional devices. Excluding the patch test and calibrations, multibeam setup requires about 20-40 minutes. Data collection for a patch test needs to be collected at the beginning of a survey trip, but not before every survey, as the mounting angles of the equipment should not change.

Multibeam System

A Reson 9001multibeam system was used in this test. The Reson 9001 consists of the transducer head, multibeam processing unit and display screen (Figure 5). The transducer head projects a 90-degree swath, using an array of 60 transducers. Each beam is 1.5 by 1.5 degrees, and when combined with a 455 kHz frequency which results in very high-resolution bottom detection. The 9001 has a range resolution of 5 cm of accuracy at the transducer head and an update rate of 15 per second (15Hz), which results in a data collection rate of 900 points per second. The 9001 processing algorithm analyzes the amplitude of the incoming signal to generate bottom picks for each transducer head. Multibeam systems are now available, such as the RESON 8000 series, that have a narrower beamwidth, range resolutions of 1.25 cm, wider swaths (up to 210 degrees!), and up to 90 transducers. In addition, the newer model multibeam systems include both amplitude and phase detection of the incoming transducer signals. The addition of phase detection increases the rated "side-looking" limit from 30-50 m to over 100 m.

A mounting plate was constructed to align the 9001 transducer head XYZ axis point directly underneath the laser diode tracking target axis. This reduced potential systematic error caused by the limitation of accurately measuring the horizontal offset. The mast was then set horizontal with a hand level and set with a pin. It is important that the mast orientation return to the exact same position every time so that the same offset and latency values from the patch test or calibration procedure are used.

The 90-degree swath translates into a footprint width of 2 times the water depth. Although ideal for a deep-water environment, this results in very narrow strips of coverage in shallow areas of the river system. This problem was resolved by mounting the transducer head pointing 45 degrees away from the boat on the "swivel mast assembly" (Figure 6). This places the starboard beam at nadir and the port beam running parallel with the water surface. This side scanning technique would also help better define sub-aqueous shoreline features such as cliff walls and undercut ledges. An issue of consideration with this method is that the coverage may be very dense at nadir and progressively sparse as the beam pattern disperses to the side. This is especially true in shallow environments, such as gravel bars and eddies.

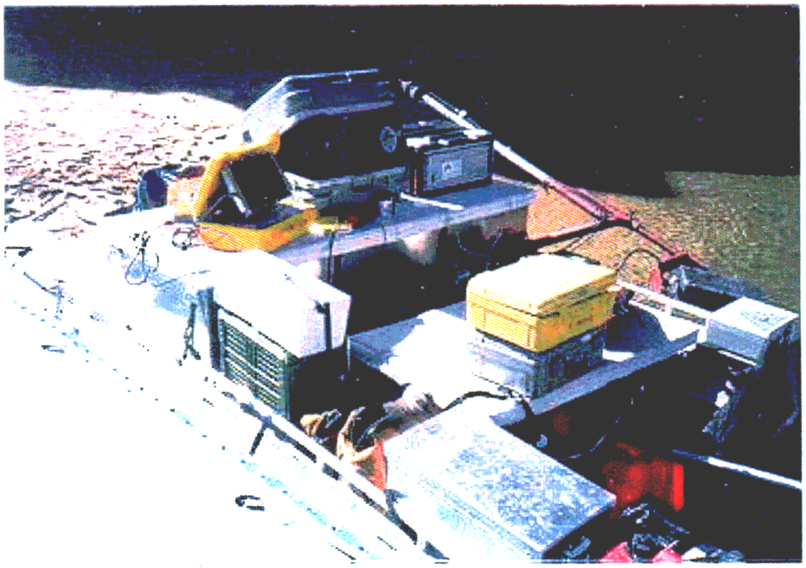


Figure 5. Photograph of multibeam survey boat equipment. The multibeam processing unit, display, and SDI environmental computer are located on the top deck, electrical system along the port rail, motion sensors along the starboard rail, and environmental equipment cases containing the helmsman display and cabling on the lower deck.

Figure 6. Photograph of multibeam transducer head mounted on the swivel mast assembly.

Motion Compensation

Motion compensation is one of the most important and complex areas of multibeam operations. The Reson 9001 multibeam system has a range resolution of 5cm, which is designed to meet International Hydrographic Organization standards (IHO, 1998). Without accurate positioning in combination with precise motion compensation, this standard cannot be achieved. The sensors selected for this operation were carefully specified for the desired mapping accuracy.

Four variables of motion are corrected for heave, pitch, roll, and yaw (Figure 7). The MRU (motion reference unit) TSS DMS-05 measures heave, pitch, and roll. The KVH ADGC (azimuth digital gyrocompass) measures yaw or vessel attitude. Hypack software applies these corrections along with sensor mounting offsets and data latency to the final multibeam solution. The TSS DMS-05 motion sensor was mounted on a rigid aluminum plate as close as possible to the mast-transducer assembly mount to reduce the possibility of any frame flex between the sensors. Once the DMS-05 was mounted, it would remain in place for the entire survey portion of the trip as not to change the offset and latency values.

The pitch and roll corrections measured by DMS-05 angular with a resolution of 0.05 degrees with an update rate of up to 100Hz. Pitch is the front to back rocking motion of the vessel and roll is the side-to-side rocking motion. Hypack software calculates pitch and roll motion in two stages. Given the sensor mounting offsets, the laser target XYZ position is reduced down to the rotation axis of the vessel. Then the vessel axis position is reduced down to the XYZ transducer axis. From there the multibeam processor reduces the soundings and sends them to Hypack.

The heave component of motion compensation is measured by the DMS-05 as an up and down motion with a resolution of 0.1 cm. The heave compensation is designed to correct for the up and down wave motion typical on a large body of water or offshore environment. The measured heave value is added and subtracted to the measured depth values. The average elevation of this wave motion is set as zero and is used as the depth reference datum. Hypack software stores this reference datum and adjusts the elevation according to whatever tide data is recorded or predicted in the form of a tide file. However, in a canyon-river environment where the water surface is continuously sloping, the heave sensor will continuously re-zero the reference datum. When used in combination with the elevation measurements from the

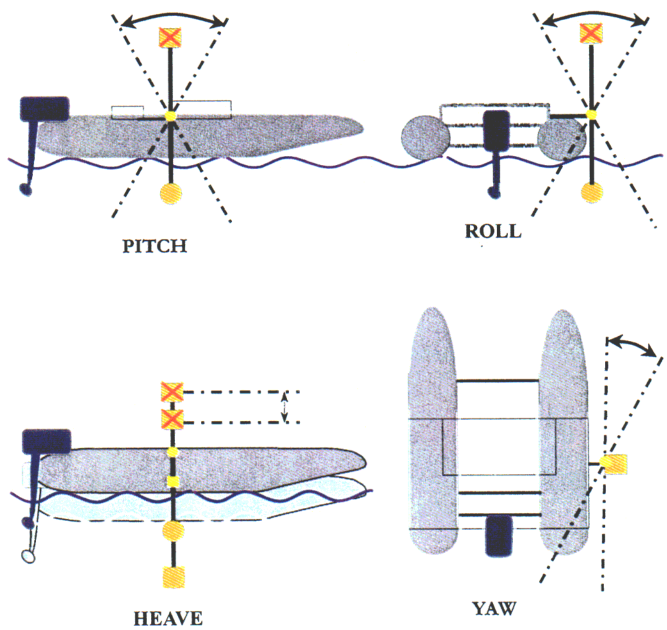


Figure 7. Schematic diagram illustrating the geometry of the heave, pitch, roll, and yaw corrections.

ATS-PT robotic tracker, the heave sensor produces double corrections of the transducer's vertical movement. To correct this problem, we specified, with Coastal Oceanographic's Hypack, the development of a device driver that reduces the elevation data from ATS-PT and generates an elevation version of the tide file. The software uses the actual measured elevations as vertical anchors. Between the measured elevation updates, the program fits the heave data to predict the change in vessel movement. Then during post-processing, the heave data is only used to apply corrections to intermittent vertical motion in-between vertical measurements from the ATS-PT.

An important portion of the hydrographic motion correction is the "D" in DMS-05, which stands for "Dynamic". When a vessel is turning, pushed by wave motion or experiences any type of lateral acceleration or deceleration, an artificial heave artifact is created by the MRU. The DMS-05 is capable of removing this erroneous data by taking in GPS position updates and gyrocompass data to determine vessel movement. Then the artificial heave measurements can be removed from the motion compensation solution. The problem in the canyon river environment is that we do not use GPS geographic coordinates (Latitude, Longitude). We are using SPC (State Plane Coordinate) Cartesian grid coordinates in association with the existing GIS-survey control network. To resolve this problem, we specified the development of a device driver within Hypack to translate the SPC data to geographic coordinates then output them to the DMS-05. The gyrocompass data feeds directly into the DMS-05 without any modification. These two data sets result in full utilization of the DMS-05 dynamic correction capability.

The KVH ADGC gyrocompass was mounted approximately 1m in back from the DMS-05. This position was required because it had to maintain a minimum distance of 1 m to any magnetic or electronic source. This location was the only place with the minimum required distances to the motor, battery, generator, computer, and mast-transducer assembly. The ADGC is a fluxgate compass to measure yaw or vessel attitude and is affected by local magnetic attraction. The yaw corrections measured by the ADGC are required because, unlike a singlebeam transducer, the multibeam transducer measures a swath. The Angle of the vessel is measured by the ADGC with a resolution of 0.5 degrees at an update rate of 10Hz. The directional sensor is a gimbal mounted fluxgate compass, which is sensitive to magnetic attractions on and around the boat. These local attractions must be calibrated out of the solution. This is done at the beginning of every survey as a routine calibration procedure.

Sound Velocity

Any hydro-acoustic measurement requires an accurate sound velocity calibration when used in survey applications. Factors such as temperature and salinity significantly affect the speed sound travels in water. Since a depth measurement from an echosounder is based on a time-distance relationship, conductivity of sound in the water column has to be accurately measured. A simple method of calibration is the bar check method. A bar or plate with an accurately graduated cable is lowered underneath the transducer at a full range of depths. The speed of sound is adjusted on the echosounder until the depth matches the cable measurement. This method is usually sufficient for most singlebeam applications as long as the depths do not substantially exceed the bar check cable length. With a multibeam survey the velocity changes in the water column cause refraction in the outer beams (ray bending). Therefore, the speed of sound in the water column must be very accurately measured with a sound velocity profiler. A sound velocity profiler is a probe that is lowered into the water column and measures the speed of sound independently of the echosounder using the "time of flight" method. We used the Odom Digibar profiler to measure speed of sound. We measured a sound velocity of 1,444 m/s at all surveys, with no variations in the water column.

Multibeam Survey Equipment List

- Reson 9001 multibeam transducer head and processor
- TSS DMS-05 motion sensor
- KVH ADGC gyrocompass
- Geodimeter ATS-PT robotic tracking system
- SDI environmental computer
- Odom Digi-bar velocimeter
- Trace 1112SB inverter/charger power controller
- Sun-X-tender 8D 250 AH battery
- Odom Digibar sound velocity profiler
- 3LCD1 helmsmen's display
- Hypack software

A Comparison of Tagline and Singlebeam Surveys For Measuring Cross-sections

Data Collection and Processing

The USGS cross-sections utilized for the comparison are p1-8, located downstream from the mouth of the Paria River (see Table 1 and Figure 4 in Graf et al., 1995 for locations). P1-3 and p5-6 were surveyed by the USGS on August 4, 1997. P4 and p7-8 were surveyed by the USGS on August 5, 1997. GCMRC conducted a singlebeam survey of the entire length of channel encompassing the profiles on August 5, 1997, beginning about 1 pm. As determined at the USGS streamflow gaging station at Lees Ferry (09380000), the mean daily flow on August 4 was 603 m^3/s, and the fluctuation range was 595 to 613 m^3/s. The mean daily flow on August 5 was 598 m^3/s, and the fluctuation range was 583 to 611 m^3/s. Thus, the flows were very similar on the two days of measurements. However, Paria River discharge (USGS streamflow gaging station 09382000) on August 5 increased from 0.3 m^3/s to 1.8 m^3/s at 11:45 am, prior to the hydrographic survey. Flow data from the Paria River on August 4 was not available because of a gage malfunction (G. Fisk, pers. comm., 1999). Therefore, we cannot discount changes in channel bed elevation as a result of discharge and sediment inputs from the Paria River on August 4 or 5, 1997.

The tagline data was obtained from the USGS after the data was converted to mean bed elevation at 0.25 m intervals (M. Flynn, USGS, written communication, 1999). The position and depth data collected during the singlebeam survey were verified and points were sorted at 2 m intervals (K. Kohl, GCMRC, written communication, 1998). The point file obtained from GCMRC contained 4,845 points. These points were used to create a surface model of the channel using the triangulated irregular network (TIN) method of surface modeling. Cross-sections were then generated at the same 0.25 m interval across the surface model at the USGS monumented cross-section locations (Figure 8). It is important to note that this hydrographic survey was not collected with the intent of direct comparison to tagline data. As a result, singlebeam data were collected with no regard for proximity to tagline cross-section locations. This provides an opportunity to examine the relative accuracy of a hydrographic survey of a long stretch of channel (~1000 m) to detailed cross-sections measured at specific locations. The overlap of data collected by the two methods was sufficient to examine 83 to 95% of the cross-section data collected by the USGS (Table 1).

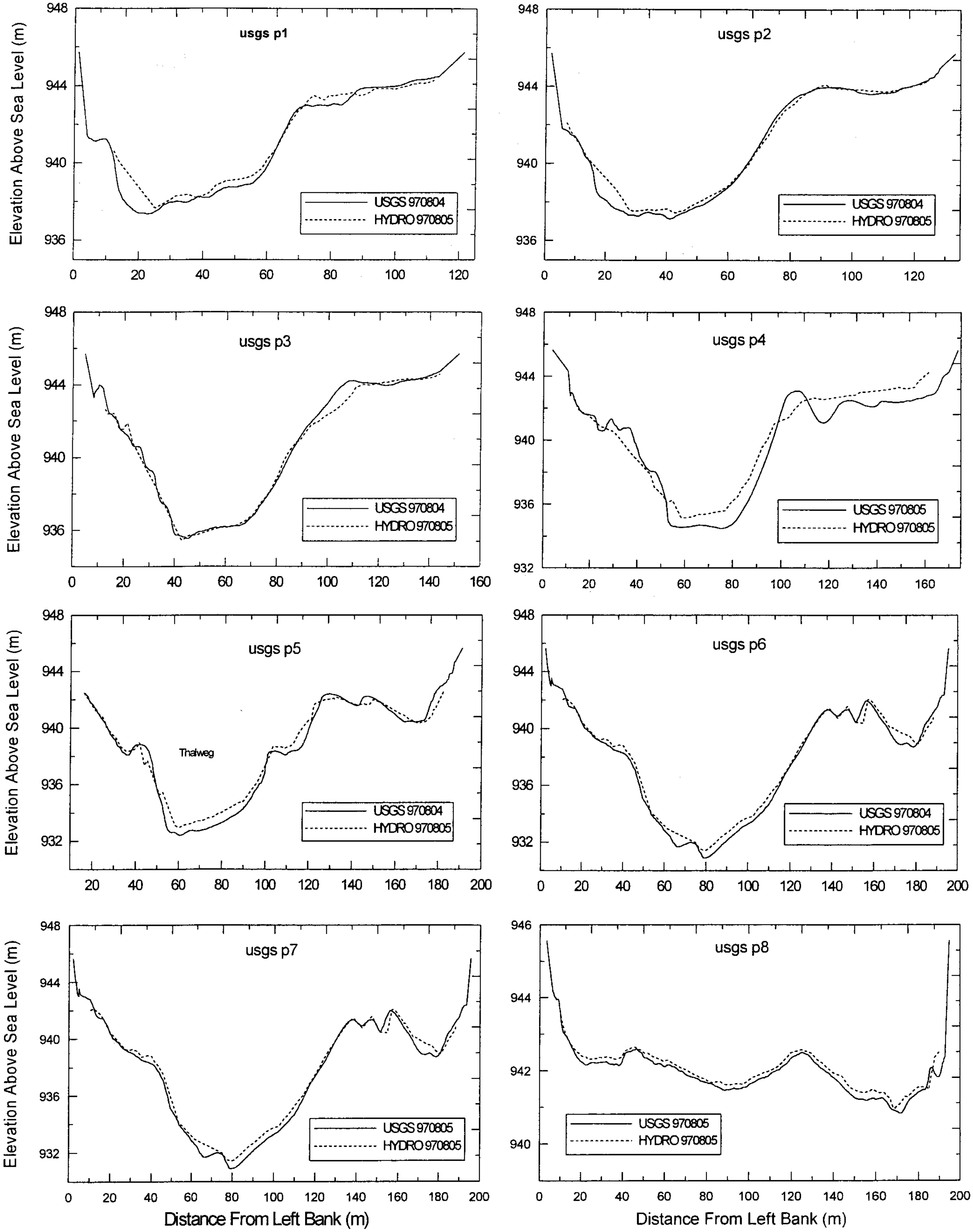


Figure 8. Plots of USGS cross-sections downstream of the Paria River confluence. Each profile displays the tagline cross-sections and cross-sections generated from a TIN model of singlebeam data.

Table 1. Tagline vs. Singlebeam Comparison

x-section	period eval. (yymmdd)	Fraction Tested	Diff. In Point Elev. (m)	std. dev	Diff. in Area (m)	%
p1	970804-970805	83	-0.26	0.45	26.1	6.3
p2	970804-970805	89	-0.14	0.32	16.9	3.4
p3	970804-970805	89	0.09	0.31	-11.4	-1.9
p4	970805-970805	87	-0.43	0.8	63.9	8.1
p5	970804-970805	95	-0.21	0.53	34.4	3.1
p6	970804-970805	92	-0.26	0.33	46.2	3.3
p7	970805-970805	93	-0.21	0.15	40	4.5
p8	970805-970805	94	-0.13	0.09	24	4.3
Ave		**90**	**-0.19**	**0.37**	**30.0**	**3.9**
Std.		**3.8**	**0.14**	**0.21**	**20.8**	**2.7**

The tagline method developed by the USGS to convert measured depths to bed elevations does not account for changes in water-surface elevation between cross-sections. Water-surface elevation is surveyed at one stage reference point and applied to all other cross-section measurements within the reach. Therefore, we devised a method to compare the tagline data to the singlebeam data, which is collected independent of the water surface elevation. The singlebeam system also records the water surface elevation at the time of each data point collection. Because the singlebeam survey was conducted during the afternoon (in about 3 hours) on August 5, during the peak release from Glen Canyon Dam (relatively steady for most of the day), changes in water surface elevation were probably very small. The average water surface elevation at the top of the pool was subtracted by the elevation at the downstream end of the pool, and this value was divided by the distance between the top and bottom of the pool. This yields a water surface slope of 0.000353, which results in a change in water surface elevation of about 0.18 m between profiles 1 and 8 (Table 1). The water surface elevation of individual taglines was adjusted by multiplying the relative distance between the USGS stage discharge reference point (located near p9 at river mile 1.5) and each tagline by the computed water surface slope and added to the water surface elevation used by the USGS at the tagline. We then computed point to point and cross-sectional area differences between the two data sets. Point to point differences in elevation were computed at each 0.25 m increment. Cross-sectional areas were computed only for the overlapping sections of the two cross-sections.

Results

The cross-section comparisons are graphically depicted in Figure 8. The average difference in point elevation and standard deviation and differences in cross-sectional area and the percentage difference are shown in Table 1. Differences between the two data sets of 1 to 2 m were found in areas of high relief such as steeply sloping banks. The average difference in point elevation was -0.19 ± 0.14 m. The standard deviation varied considerably between cross-sections and was largest at p4, where complex eddy bed topography observed in the tagline measurement was not evident in the hydrographic measurement. The average difference in point elevation was negative at 7 of the 8 cross-sections. This systematic difference suggests that the datum correction (described above) is not accurate or some other source of error prevents a more accurate comparison. Other possible sources of error include differences in depth-sounder frequency, possible inaccuracy of the stage discharge relation used at p9, inaccurate measurement of the transducer depth beneath the survey vessel, and measurement of the distance between the USGS reference point to the water surface.

Relatively large standard deviation is typically observed from the mean of 10 passes in the tagline technique; typically less than 0.1 m but can be 1.0 m or more (Graf et al., 1995). This suggests that the point to point comparison between the two techniques may be within the range of standard deviation from the mean of the passes. Further field work is required to adequately determine if the datum shift used in this analysis was correct.

Differences in cross-sectional area varied between $+63.9$ m^2 and -11.4 m^2 (Table 1). The average area difference was 30.0 ± 20.8 m^2. This means that the mean bed elevation for each measurement technique was not equal. However, the percentage difference in cross-sectional area for each method averaged 3.9%. These area differences are small relative to the changes that have been observed at these cross-sections during previous monitoring (Graf et al., 1995; 1997; Konieczki et al., 1997). In addition, there is no way of determining whether there was significant bed change during the interval of time between the two measurements (3 to 24 hours). Considerable short-term change can occur in eddies on the order of hours because of rapid redistribution of sand (Cluer, 1995; Andrews et al., 1999).

These results indicate that although bed elevations determined from each method were different, changes in overall channel geometry (as determined from the area comparison) were within 5%. Future data collected with the single beam system can likely be compared to previous collected Tagline data providing that a proper datum shift correction is computed for USGS stage reference points.

Multibeam Data Collection and Processing

The objectives of this phase of the project were to: 1) process multibeam data collected in February 1999; 2) generate surface models of multibeam data; 3) develop an integrated DEM of ground topography and multibeam data at one of the sites; 4) evaluate the validity of the multibeam data for use in the Colorado River.

All of the multibeam data collected in the protocol evaluation river trip (February 1999) were completely processed and TIN models generated. An integrated DEM of ground topography generated photogrammetrically and multibeam hydrographic data were generated for the Tanner reach. Ground topography was collected from 1990 aerial photographs. The multibeam and photogrammetric data integrated well along the rocky shorelines. However, significant gaps exist along shoreline dominated by sand deposits because of erosion and/or deposition of sediment that has altered the geometry of the shoreline. These data products have been delivered to GCMRC.

Data Collection

A test of the multibeam system described above was conducted from February 14-26, 1999. Five separate reaches were surveyed with this system (Figure 9). Data were processed and surface models generated from six of these reaches. One survey was conducted in Glen Canyon, but software driver problems precluded the use of this survey and it was dropped from our analysis. Surveys were successfully completed at the remaining reaches. Depending on the local channel geometry, approximately 0.5 km to 2 km of channel was surveyed.

Several problems were encountered during data collection. The main problem was cavitation created by the bulky, non-hydrodynamic profile of the transducer and mounting which decreased the speed of data collection, particularly on upstream planned lines, thus affecting data quality (Figure 6).

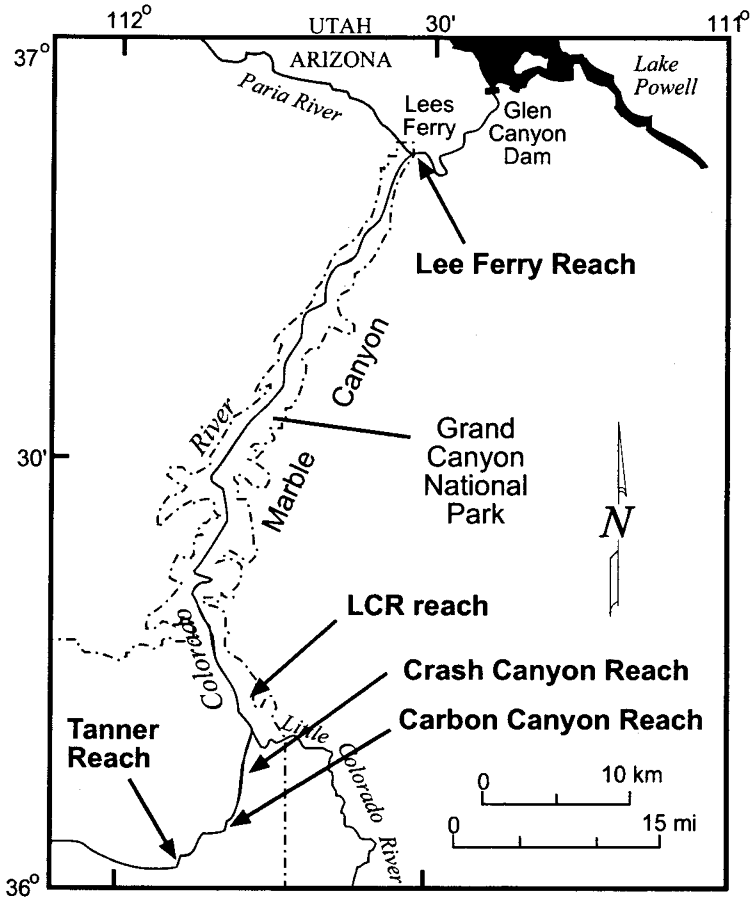


Figure 9. Location map of the Colorado River from Glen Canyon Dam to about river mile 75 showing the locations of the study reaches.

The drag on the transducer also made maneuvering the boat along planned lines difficult. Because of the cavitation, the multibeam processor unit was unable of interpret the incoming transducer signal at speeds greater than 0.6 knots while traveling upstream and approximately 3 knots in a downstream direction. Problems were also encountered with interfacing the radio links between the geodimeter tracking station and the boat. This issue was solved by decreasing the update rate from 5Hz to 4Hz. Apparently, the update rate specifications for this particular machine were listed as 5Hz, when they were actually set at 4Hz. An additional issue was related to the 45-degree transducer angle. Despite these obstacles, a good data set was collected at five reaches in a variety of pool, riffle, and eddy environments.

Data Processing

We identified six steps in processing raw multibeam data. These steps, in chronological order, are: 1) conduct patch tests; 2) apply patch test corrections to raw data; 3) edit individual data files for false bottom picks; 4) create matrix files of edited data; 5) generate TIN models from matrix files; and 6) edit data points based on visual inspection of TIN model.

Patch Test

The first step in processing multibeam data is a patch test. A patch test is a system calibration procedure that automatically determines correction factors for mounting angles of the various system components, and positioning system latency. This correction should only need to be run once a trip because the test calculates corrections based on the equipment setup. Patch test lines are run separately before the actual survey is started.

Patch test lines are run over specific bottom terrain in a specific order. The roll angle is tested first by locating an area where the bottom is smooth and flat, then surveying lines in both directions at normal boat speed. The positioning latency is tested next by running a line twice up a bank, once at maximum survey speed then again as slowly as possible. Running reciprocal lines across the bank at normal survey speed then tests pitch angle. Yaw is tested last by running offset lines in the same direction. After the data have been collected, the HYSWEEP Patch Test program automatically calculates the correct roll, pitch and yaw mounting angles and positioning system latency.

Patch tests were conducted independently on two data sets in order to insure proper calibration of the system components. The first was collected at Lee's Ferry at the beginning of the trip, and the second was collected before the Tanner survey on the last day of surveying. Both patch tests produced the same results (Table 2). Raw values of time (latency), compass heading (Yaw), heave, pitch, and roll were adjusted based on the results of the patch test. The adjusted versions of the data files were used in the editing process. The entire patch test process was completed in approximately one hour. In the future, this test should be completed on-site so that patch test adjusted data files can be edited in the field.

Table 2. Patch test results

Correction	Lee's Ferry	Tanner
Roll	2.0 degrees	2.0 degrees
Pitch	2.0 degrees	2.0 degrees
Heave	0.0 degrees	0.0 degrees
Yaw	8.0 degrees	8.0 degrees
Latency	-0.3 seconds	-0.3 seconds

Editing

The data editing process involves presorting the adjusted data, inputting the presorted data into the data editor, then scrolling through each individual collection line and deleting incorrect bottom picks. Based on recommendations from Coastal Oceanographics personnel, data were presorted to remove beam angles on excess of 80 degrees. Bottom picks (picks) were automatically chosen by the multibeam signal-processing unit. The data editing screen is split into two views: a view showing 50 to 100 cross-sections displayed pseudo-three dimensionally, and a view that shows the individual cross-section where the cursor is located (Figure 10a). Incorrect picks (< 10%) were easily identified by visually identifying the pick grossly out of line with the rest of the survey. However, some sections of the surveyed area were completely deleted due to the scarcity of picks in the region (Figure 10b). Because of the scarcity of picks, no visual comparison with "good" data was possible and the entire region was deleted. Sections that were deleted correspond to portions of the planned line where boat velocities exceeded the speeds at which the multibeam processor was able to interpret the return signals. As discussed above, cavitation caused by the transducer mount is the most likely cause of these deleted areas. Each survey required approximately 15 to 60 minutes to process, depending on size.

Once an entire survey was edited, these files were combined into a matrix that sorts the data based on a user-defined interval. For this study, we chose a sort interval of 0.5m. These files were then used to generate TIN models of the survey area.

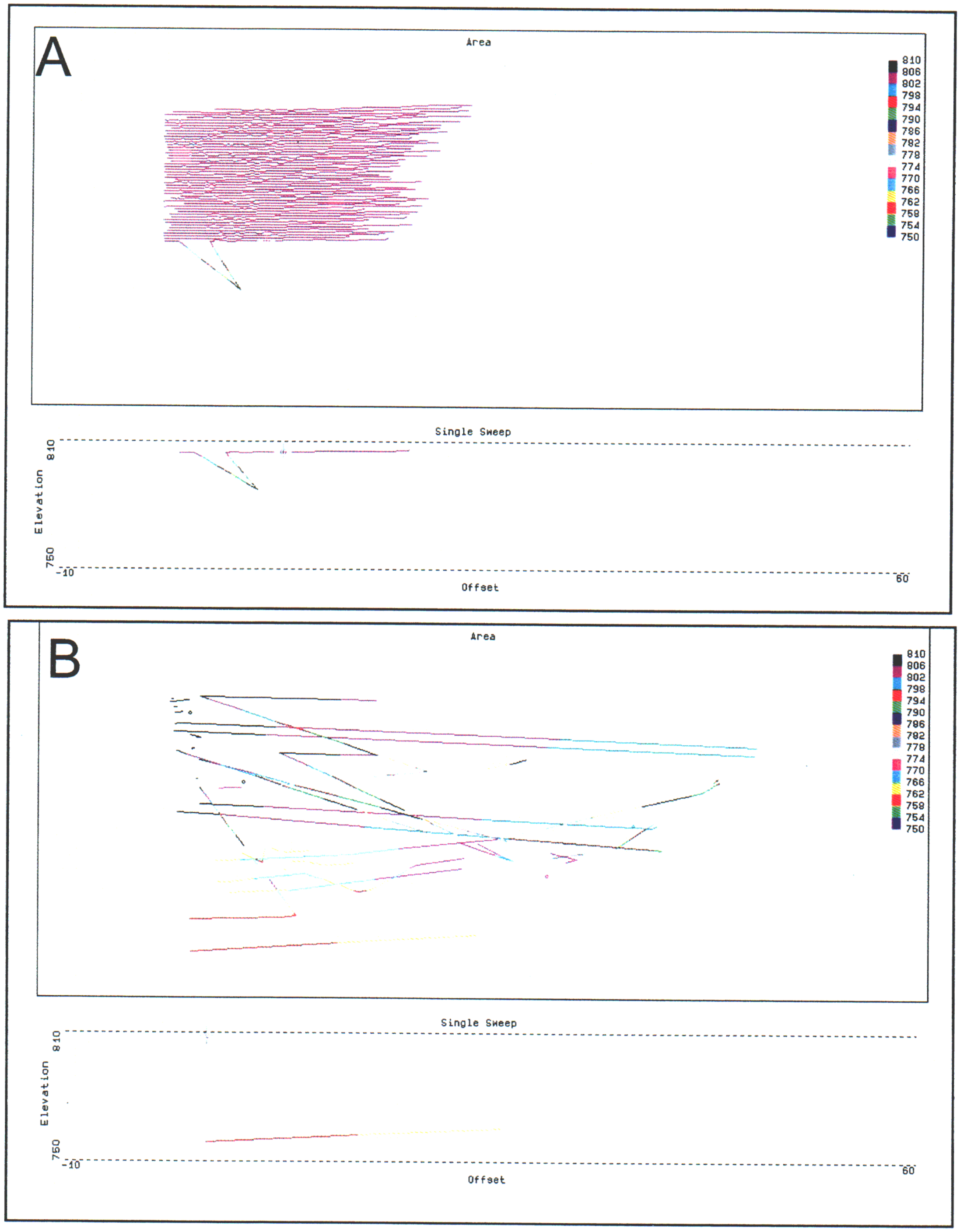


Figure 10. Plot of multibeam data editing screen showing: A) a typical data set with one "spike" that was subsequently deleted; and B) a section of the survey that was completely deleted. Cavitation due to the transducer head assembly was identified as the most likely cause of the poor data quality.

Comparison of Singlebeam and Multibeam Hydrographic Surveys

The multibeam surveys were analyzed for their extent of coverage, resolution, time and cost in comparison to singlebeam surveys. Unfortunately, a direct comparison of the two methods was not possible. Multibeam and singlebeam surveys were not collected at the same site on the same day and, as discussed above, the assumption of no change between surveys is not valid in the Colorado River. However, a comparison of the spatial resolution, extent of coverage, and associated costs of the two survey methods was possible. Multibeam and singlebeam surveys of the Tanner reach are used here to demonstrate the capabilities of each method in the same reach. Within this reach, pool, riffle, and eddy channel environments were surveyed by each method. The multibeam survey was conducted on February 12, 1999 and the singlebeam survey was conducted on May 11, 1999.

Our results show that the point density collected by multibeam surveys exceeds that of singlebeam surveys. Figure 11 show the point distribution collected in the same, approximately 30 m^2 area from both surveys. The multibeam survey point distribution is much denser than the 10x10 m singlebeam collection grid. Contour lines on a map are a generalization based on the interval of recorded data, thus the closer the sampling interval, the more accurate the portrayed data. The greater point density of multibeam surveys allows for a higher resolution surface model.

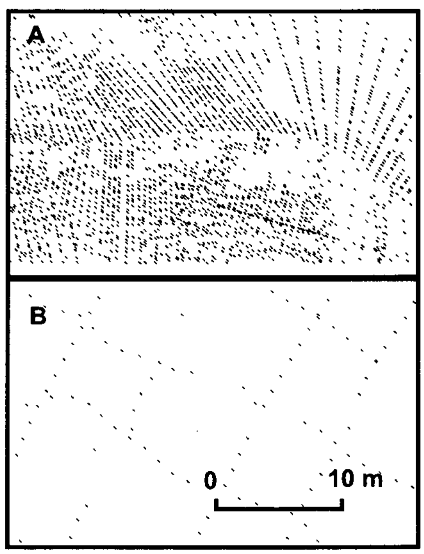


Figure 11. Plot of data points collected within a 30 m area in the Tanner reach. A) multibeam data points. B) singlebeam data points.

The denser point coverage acquired by multibeam is reflected in the spatial resolution of bottom features. Shaded perspective views of the TIN models generated from these two surveys shows how the increased point density of the multibeam survey creates a higher resolution surface model (Figure 12). Shaded perspective views from other reaches highlight the ability of increased spatial resolution in detecting bottom features. Figure 13 shows a perspective view of the Lee's Ferry reach TIN model. In this view, bedforms located along the channel bottom are easily identified. In Figure 14, a plot of a TIN model from the reach above the Little Colorado River reveals individual rocks along the channel bottom. The fanned array of transducers used in multibeam surveys can also resolve vertical features along the banks of the river. Figure 15 displays a plot from the HYPACK data-editing screen. In this pseudo-three dimensional view from the Crash Canyon reach, submerged rock ledges of Tapeats sandstone can be discerned on the right-hand side of the plot. Unfortunately, three-dimensional modeling software was not available to produce surface models that include undercuts and ledges along the river.

The extent of coverage acquired by multibeam surveys exceeds that collected by singlebeam surveys. In the Tanner reach, we compared the spatial extent of coverage from multibeam and singlebeam surveys (Figure 16). From initial arrival at the site to completion of the survey (including setup and breakdown of equipment), the multibeam survey covered approximately 1.2 km of channel in approximately 4 hours. The singlebeam survey covered approximately 0.6 km of channel in approximately 6 hours. Thus, at this site, multibeam provided about twice the survey coverage in about two thirds of the time.

In terms of operational cost, multibeam and singlebeam surveys are approximately the same. However, if operational expense is assessed on a per km of channel surveyed basis, multibeam costs are about half as expensive as singlebeam. Personnel costs for initial setup and processing time are slightly higher for multibeam (30-60 minutes per survey for singlebeam, versus 35-100 minutes per survey for multibeam). The most expensive aspect of multibeam is the price of the equipment. Purchase price for the multibeam transducer and processor range from $100,000 to 200,000 dollars and dynamic motion compensators run about $50,000, whereas a singlebeam unit costs approximately $10,000.

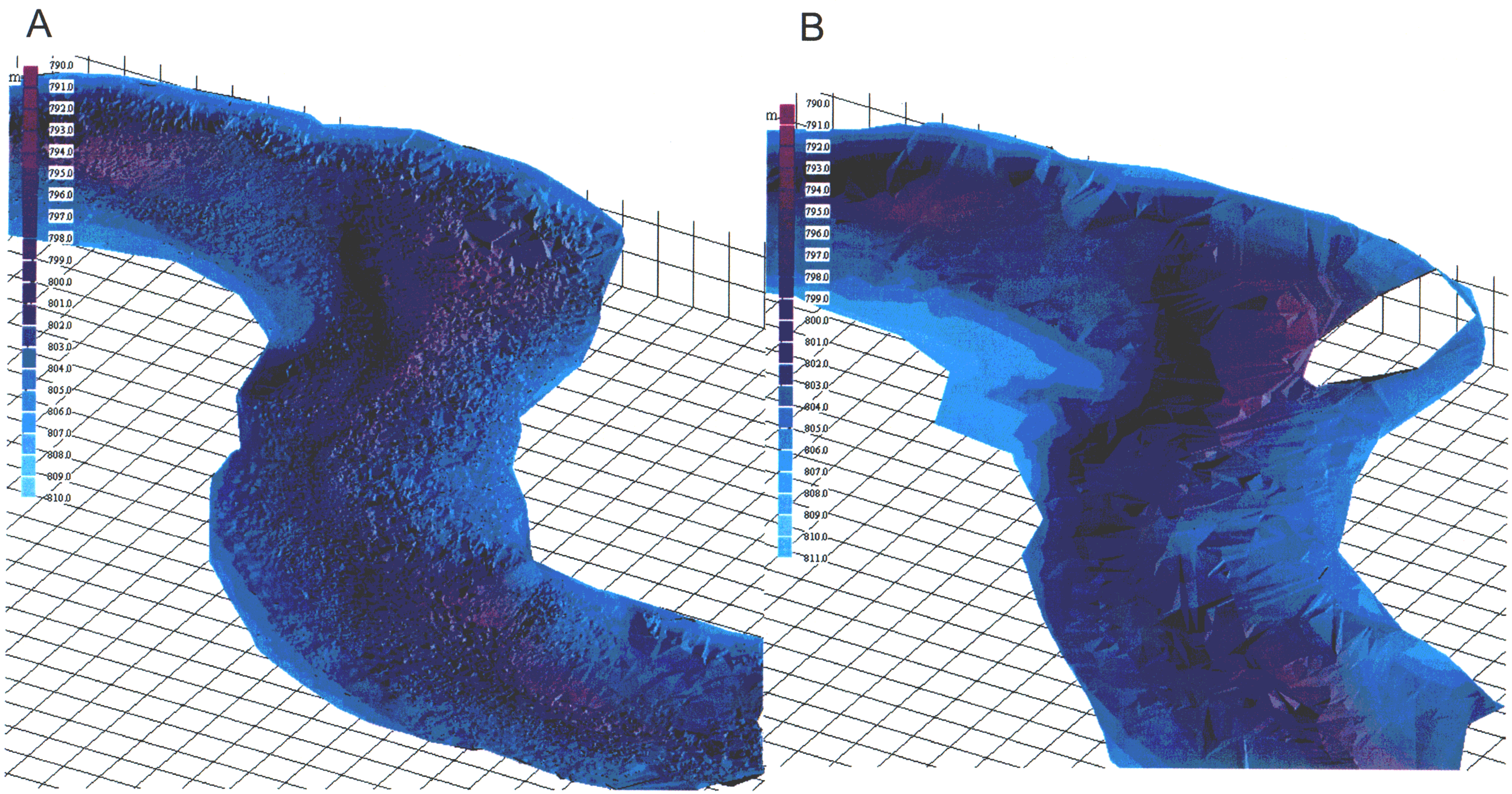


Figure 12. Shaded perspective views of the TIN models generated from A) multibeam data, and B) singlebeam data in the Tanner Reach.

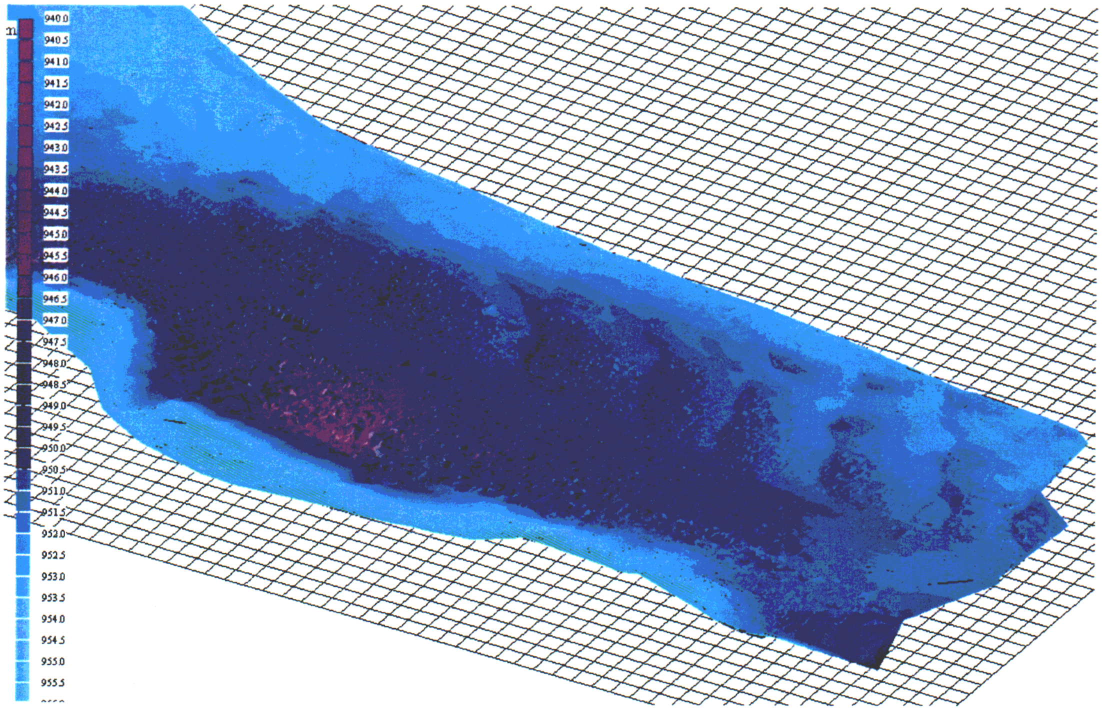


Figure 13. Shaded perspective views of the TIN surface model generated from multibeam data in the Lee's Ferry reach. Note the large bedforms along the channel.

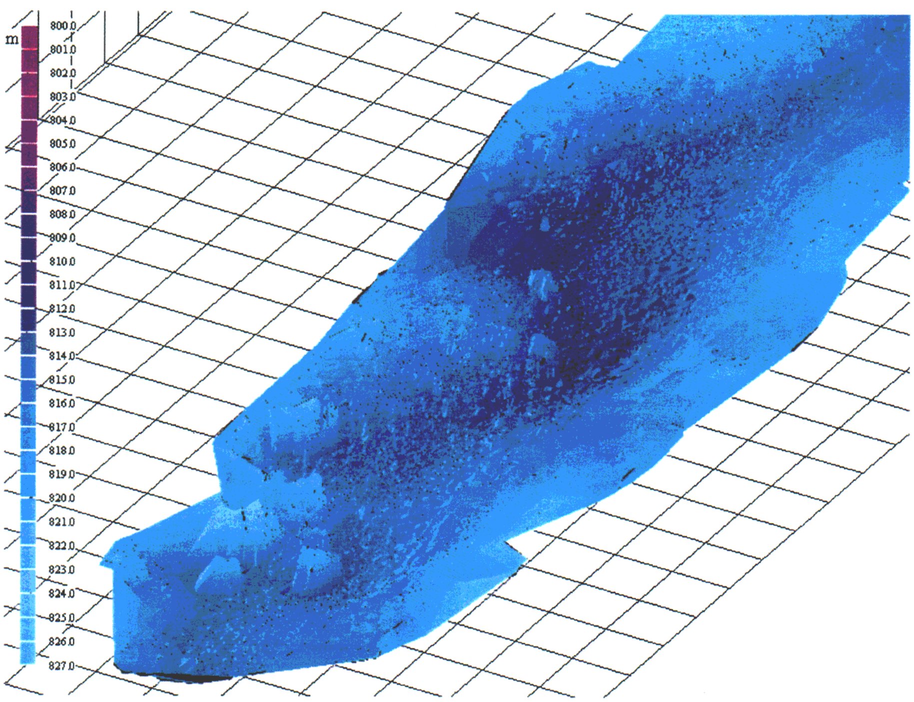


Figure 14. Shaded perspective views of the TIN surface model generated from multibeam data in the Little Colorado River reach. Note the large boulders in the center and bottom of plot.

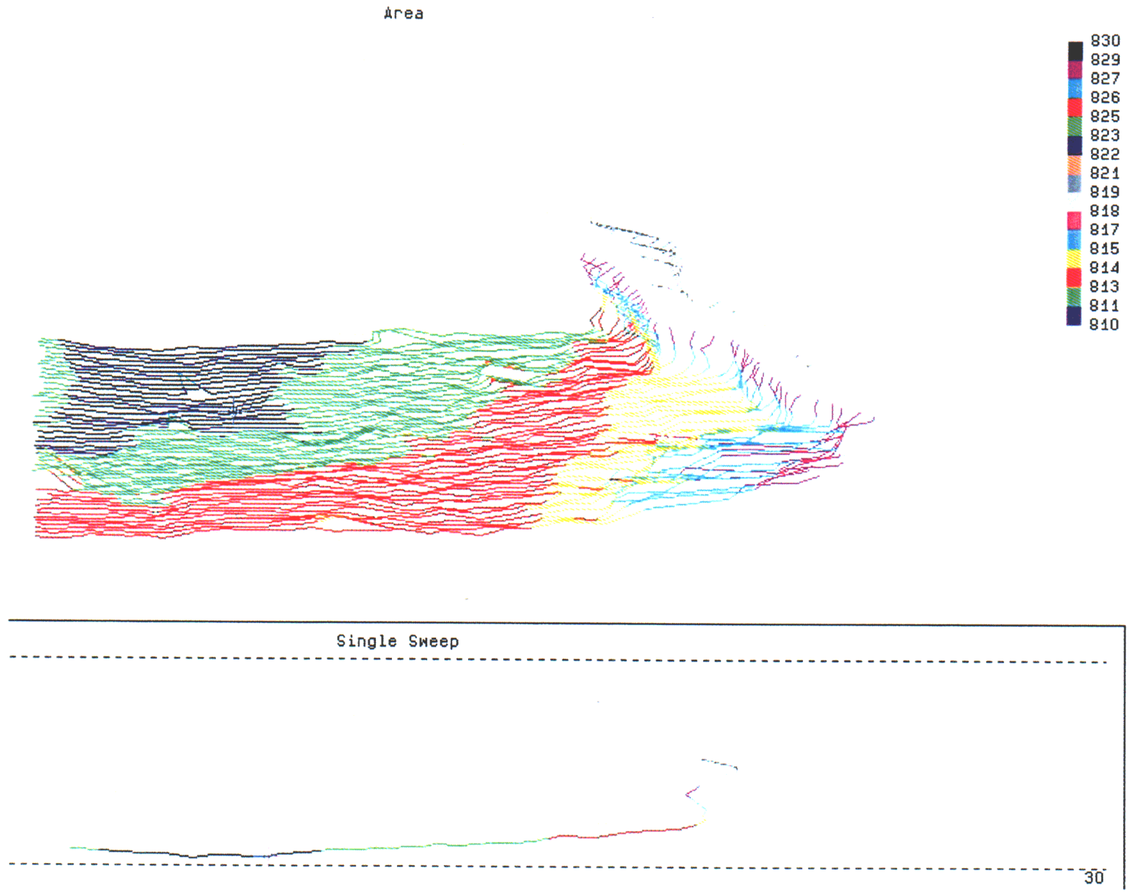


Figure 15. Plot of Hysweep multibeam data editing screen showing data collected in the Crash Canyon reach. The vertical features on the right side of the plot are submerged ledges of Tapeats Sandstone.

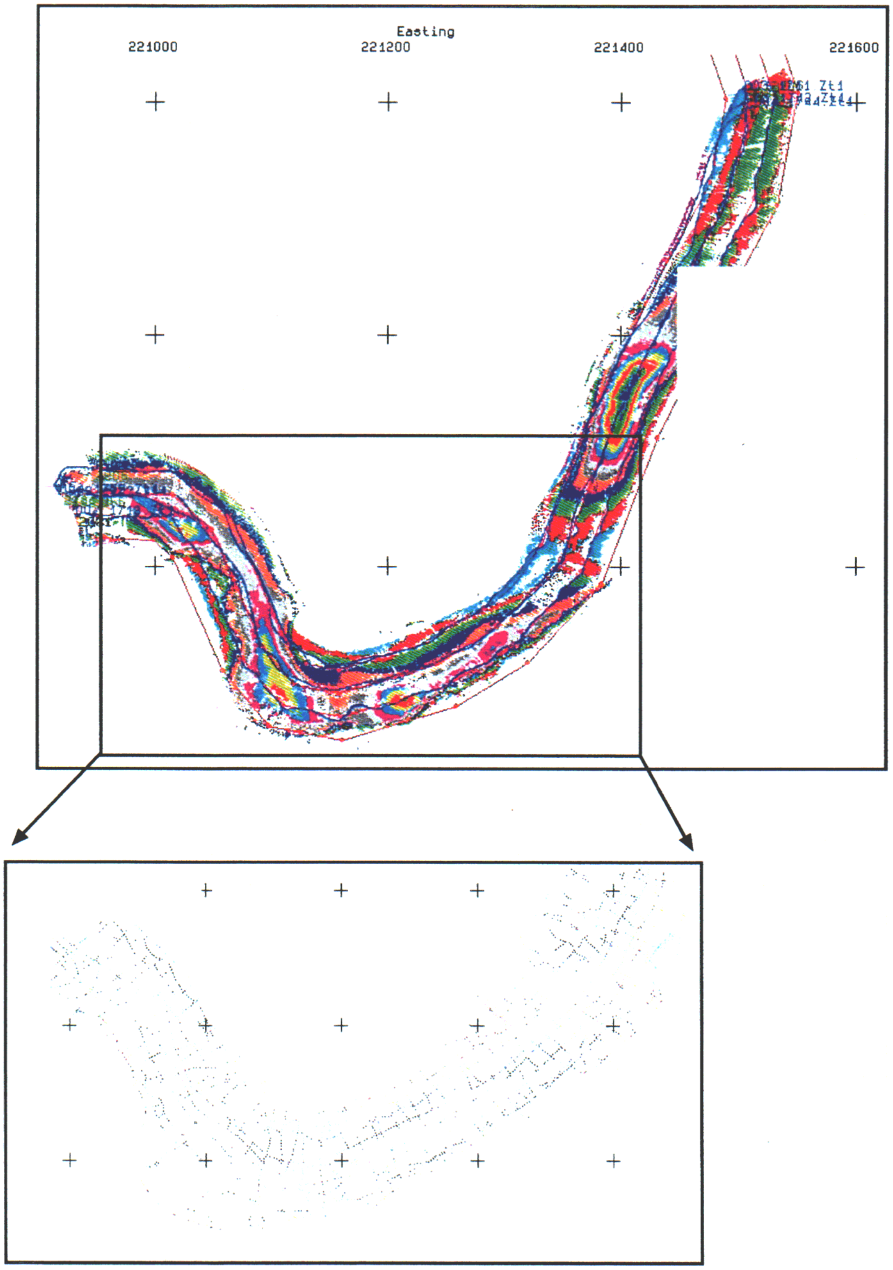


Figure 16. Spatial extent of coverage provided by multibeam and singlebeam surveys in the Tanner reach. The upper plot shows the multibeam coverage collected in approximately 4 hours. The bottom plot shows the singlebeam coverage collected in approximately 6 hours.

Conclusions

Tagline vs. Singlebeam

- Both methods are relatively accurate.
- Both methods require about the same number of personnel, but singlebeam collection is more cost effective because the data are collected in approximately ½ the time.
- The data resolution of this survey was not as good with singlebeam but resolution can be increased with more passes if required.
- Singlebeam produces cross-sections that depict relatively similar channel shape.
- Maps of channel geometry are more useful in the development of flow- and sediment transport models

Multibeam Evaluation

One of the main objectives of the initial protocol evaluation was to determine if multibeam sonar technology would actually work in the Colorado River environment. The data analyzed in this study show that multibeam worked well in the Colorado River. Multibeam covers more area in less time with a greater point saturation (and therefore greater resolution) for about the same price of operation. Time (and therefore cost) of post-processing is only slightly higher for multibeam. The initial purchase price is higher.

Lessons Learned

This evaluation was limited by a lack of direct comparisons (all methods used at the same site on the same day) between all methods. The data collection phase of future protocol evaluations should be carefully planned so that all methods can be tested in the same area on the same day.

The lessons learned from this evaluation should be applied to a new system. A new system should include a more hydrodynamic transducer head and mounting system. Cavitation caused by the transducer array used in this study slowed the speed at which data was collected and caused some gaps in coverage due to poor data quality. A new system should also include a transducer array angle of at least 120 degrees. Commercial systems are now available with array angle up to 210 degrees. A larger transducer array angle would reduce the number of passes needed to cover the entire channel, thereby increasing the amount of area surveyed. A new system should also be required to have a processing unit with a signal phase and amplitude processor. Phase and amplitude processing can increase the distance with which return signals can be detected from approximately 40 m to over 100 m.

Recommendations

Multibeam technology offers the best, most efficient way to collect hydrographic data. The system evaluated in this study worked well in main channel, eddy, and riffle environments. A new system with the recommended improvements would be beneficial to the GCMRC program. The GCMRC survey department already has the infrastructure to support a multibeam system and only two components are needed to be operational, a multibeam transducer/processing unit and a dynamic motion compensator. The needed software, electrical system, boat, gyro compass, computers, cables, and logistical support items have already been purchased by GCMRC. Given the survey departments' task of producing a system-wide channel map and the critical nature of sediment monitoring in the ecosystem, we feel that out of the three systems tested, the multibeam system is the best tool for the job.

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Appendix A: Hydrographic Survey Preparation and Procedures using Hypack

1) Set the geodetic control parameters in the **Geodetic Parameters** program.
    - Select "Arizona State Plane Coordinate"(SPC) system, "Central Zone", WGS84 projection.
2) Make the planned lines in the **Design** program.
    - Make the planned lines to cover the extent of the survey limits in the specific reach of river. The two major considerations in the length and frequency of the survey lines are range and visibility of the ATS-PT tracking operation and the swath to depth ratio ensuring 100% coverage of the bottom.
    - Make planned lines to cover patch test calibration procedure.
3) Define the system hardware in the **Hardware** program.
    - Set up the driver for the ATS-PT in elevation mode.
        1. Input the control coordinates.
        2. Specify COM port and communication parameters.
        3. Set up the Geodimeter ATS-PT on the selected control point as you would a conventional total station. Select and set up a target on a backsight reference point. Calculate the inverse azimuth between the instrument and backsight and input the value into the ATS-PT driver configuration menu. This orients the survey to the SPC grid system.
    - Set up the device driver for the 9001 multibeam transducer head and processor.
        1. Set transducer head roll offset by 45 degrees.
        2. Set all other transducer offset values to zero, all other devices will reference transducer axis point.
        3. Specify COM port and communication parameters.
    - Set up the device driver for the TSS DMS-05.
        1. Set mounting offsets referencing the transducer head axis.

2. Configure NMEA driver for SPC input to geographic coordinate output.
3. Specify COM port and communication parameters.

- Set up the device driver for the KVH ADGC gyrocompass.
    1. Set mounting offsets referencing the transducer head axis.
    2. Specify COM port and communication parameters.
- Set up the device driver for the Coastal Oceanographic 3LCD1 helmsmen's display.
    1. Select left/right indicator, depth, and distance down line as the display information.
    2. Specify parallel port and communication parameters.
- Connect a direct RS232 serial cable from the ADGC to the DMS-05.
- Check all other communication cables so that they correspond to the device driver configurations.

4) Make a directory for raw data files in **Data Directories**.

5) Start **Survey** program.
    - Select a directory and tag for your raw data files.
    - Select your planned survey lines.
    - Select a background file.
        1) Select a GIS shoreline layer in DXF format.
        2) Select a reference control point file in DXF format.

6) Power up sequence.
    - Check power connections and voltage meter on power box.
    - Slide grounding plate into stern bracket and ensure that it is in the water.
    - Check generator fuel and start.
    - Check inverter-charger relay switch and charging indicator light
    - Power up remaining hardware.

7) Begin Survey.
    - Initialize ATS-PT robotic tracking sequence.
        1. Configure radio modem for remote control of the ATS-PT.

2. Set at 4 Hz update rate.
3. Set for automatic search sequence if target is lost.
4. Check that laser tracking diode light is blinking.
5. Verify positional data string input on screen.

- Calibrate the KVH ADGC for local magnetic attraction.
  1. Run 3 large calibration loops.
  2. Verify that navigation data looks correct during calibration.

8) Set 9001 multibeam settings to water conditions.
   - Take velocity profile readings.
     1) Generate and save a velocity profile file.
   - Set speed of sound.
   - Set display range and resolution.
   - Adjust power and gain settings to optimize depth measurements.
9) Run Patch test for survey grade offset calculations.
   - Make sure that all hardware is mounted properly in their permanent positions.
   - Run a line on a sloped bottom both directions for latency and pitch calibration.
   - Run a line on a flat bottom both directions for roll offset angle calibration.
   - Run opposing lines that measure a common target for yaw offset angle calibration.
10) Start and end survey lines until coverage is complete.
11) Replay data in Hypack to verify coverage.
12) Back up data.
13) When necessary to traverse a hazard such as a white water rapid, all components must be disassembled and put away in waterproof boxes. A copy of the backed up data should be transferred to another boat. All equipment must be sealed and well tied down in the case of a flip.
14) After the hazard has been safely navigated, repeat the aforementioned procedures.
15) End of day.
    - Set up power system for small battery recharging, from reserve battery, not generator.
    - Set up computer for editing and processing of the day's data in Hysweep.