Lower Duwamish Waterway Group

Port of Seattle / City of Seattle / King County / The Boeing Company

LOWER DUWAMISH WATERWAY BATHYMETRIC SURVEY

For submittal to:

The US Environmental Protection Agency
Region 10
Seattle, WA

The Washington State Department of Ecology
Northwest Regional Office
Bellevue, WA

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Acronyms

ASCII	American Standard Code for Information Interchange
CTD	conductivity, temperature, and depth
DEA	David Evans and Associates, Inc.
DGPS	differential global positioning system
DTM	digital terrain model
DXF	Drawing interchange format
DWG	AutoCADD drawing format
EPA	US Environmental Protection Agency
GIS	geographic information system
GPS	global positioning system
HIPS	hydrographic information processing system
LDW	Lower Duwamish Waterway
LDWG	Lower Duwamish Waterway Group
MLLW	mean lower low water
NAD	North American datum
NAVD	North American vertical datum
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
PDF	Portable Document File
PID	Permanent Identifier
POS/MV	Position and orientation system for marine vessels
QAPP	Quality Assurance Project Plan
RI	Remedial investigation
RM	River Mile
RTK	real-time kinematic
SPCS	State Plane Coordinate System
TBM	Temporary benchmark
TGO	Trimble Geomatics Office
TIFF	Tagged image file format
USACE	US Army Corps of Engineers
Windward	Windward Environmental LLC
WGS84	World Geodetic System of 1984
WSDOT	Washington State Department of Transportation
XTF	Extended triton format

1.0 Introduction

This report presents results from a high-resolution multibeam bathymetric survey conducted in the Lower Duwamish Waterway (LDW) from August 25 to August 29, 2003 by David Evans and Associates, Inc. (DEA). The objective of this survey was to produce an accurate, up-to-date bathymetric dataset containing bank-to-bank data (where possible) for the LDW study area, as part of the Phase 2 Remedial Investigation (RI) for the LDW. The survey was conducted from RM 0.0 (the southern end of Harbor Island) to the bridge at RM 4.8 (Figure 1). Results of the survey may be used to support the following RI activities: 1) placement of additional sediment sampling locations, 2) evaluation of fish and wildlife habitat, 3) analysis of bottom substrate composition, 4) evaluation of potential sediment transport conditions, and 5) preparation for remedial activities.

The field procedures used to conduct these surveys are described in detail in the Quality Assurance Project Plan (QAPP) for the bathymetric survey of the LDW (Windward 2003), and are also described in Section 2.0 below. In addition to this report, deliverables from DEA include contour and hill-shade maps (hard copy and AutoCAD files), ArcView shape files of contours, georeferenced TIFF (tagged image file format) files of imagery, AutoCAD files of survey tracklines, ASCII files of 1-meter binned data sets, and metadata for digital data.

2.0 Methods

The purpose of the LDW bathymetric survey was to collect high-resolution data in the LDW study area using multibeam sonar, which allows for the collection of data with up to 100% coverage of the riverbed. The multibeam data were used to create a digital terrain model of the riverbed morphology from which hill-shade images and contours were generated.

The survey was conducted during August 25 to August 29, 2003, which was the earliest date the survey could be initiated following acceptance of the QAPP by EPA and Ecology. Although tidal conditions were not optimal, it was necessary to conduct the survey during this period to avoid conflicts with net fishing conducted by the Muckleshoot tribe. The opening for the Muckleshoot fishery was scheduled from September 10, 2003 to an unknown date in February 2004.

Bathymetric coverage across the waterway was developed by running multiple lines parallel to the shoreline. Several perpendicular crosstie lines were also surveyed to confirm system calibration and document accuracy.

Figure 1. Coverage of bathymetric survey of the Lower Duwamish Waterway

2.1 CONTROL NETWORK

A geodetic control survey was conducted to establish a control network for the project. Monuments and temporary benchmarks (TBM) were set at strategic locations along the waterway to provide horizontal and vertical control for the survey, provide redundant observations for quality assurance, and reference the bathymetric data for future studies. The horizontal datum for this survey is the North American Datum of 1983 through the 1991 adjustment (NAD83/91), State Plane Coordinate System (SPCS), Washington North Zone, measured in US Survey Feet. The vertical datum for this survey is mean lower low water (MLLW) established from the relationship between MLLW and the North American Vertical Datum of 1988 (NAVD88) published on the U.S. Army Corps of Engineers web site using stations: 93 – Seattle; 92A – Lockheed Shipyard; and 92 - Duwamish Waterway (USACE 2003). The relationship between NAVD88 and MLLW was interpolated between Station 92A at the Lockheed Shipyard and Station 92 near 8th Street at RM 2.7. The relationship at Station 92 was held for the remainder of the project from RM 2.7 to RM 4.8, as there are no data available to develop the relationship above RM 2.7 and little change is anticipated over this reach.

Prior to the multibeam survey, monuments were established along the LDW corridor and a geodetic control survey was conducted using static and fast-static GPS techniques. Six control points were placed in the project corridor from its northern extent at RM 0.0 to its southern extent at RM 5.0 (Figure 1). The placement of the control points required ties to existing monuments for which NAVD88 elevations and NAD83/91 positions were published.

GPS observations were made using Trimble dual frequency receivers on August 21 and 22, 2003. Baselines were processed and adjusted using Trimble Geomatics Office (TGO), version 1.50 software. GPS data were initially adjusted using least squares on August 25, 2003. In that adjustment, the network was constrained horizontally to three National Geodetic Survey (NGS 2003) and two Washington State Department of Transportation (WSDOT 2003) control points. It was also constrained vertically to the same three NGS points and one of the WSDOT points. Raw real-time kinematic (RTK) GPS checks were made to network control points and existing staff gauges as part of the project's quality control plan during multibeam data logging. Larger than expected vertical differences were noted. The RTK base receiver remained at point DEA2005 during the course of the multibeam survey, and positions relating to WGS84 were collected.

Upon detailed analysis of the redundant comparisons of the RTK GPS elevation data, the original control network adjustment was reevaluated to see if a better solution could be obtained in the adjustment. On November 20, 2003, two least squares re-adjustments were made to the GPS observations (see Appendix D for Minimally Constrained and Final Adjustment Reports.) A summary of the adjustments is presented in Table 1. In the first, a minimally constrained adjustment, the network was constrained horizontally and vertically on the NGS Permanent Identifier (PID) SY0290. This adjustment confirmed the internal consistency in the GPS baselines. In the final adjustment the network was constrained horizontally on five points: NGS PIDs SY0290, SY4354 and SY4595 and WSDOT Monument ID's 2672 and 142. (These five points also were held as horizontal and/or vertical control points in the August 25, 2003 adjustment.) The final adjustment was also constrained vertically on NGS PID SY0290, a NOAA Tidal Benchmark and a First Order – Class 1 NAVD88 benchmark. The record NGS and WSDOT horizontal positions are based on the NAD 83/91 horizontal datum. Final adjusted coordinates were generated using the WGS84 ellipsoid and GEOID99 models. The November 20, 2003 adjusted orthometric elevation of point DEA2005 is 0.12 ft higher than its August 25, 2003 adjusted elevation (see Table 2). The horizontal change at DEA2005 was minimal. Section 3.2, Data Quality, shows results and daily position checks at control point DEA2000 and the staff gauge comparisons to RTK GPS water surface elevations. The re-adjustment of the GPS network and subsequent shift of RTK points relative to the new coordinates at DEA2005 improved the results of the quality control checks. The November 20, 2003 adjusted network elevations provide a better reference to the multibeam survey for future efforts in the LDW.

Table 1. Lower Duwamish Waterway Control Network final adjustment

Lower Duwamish Waterway Geodetic Control Network					
Horizontal Datum: NAD 83/91	State Plane Coordinate System: Washington North Zone				
Vertical Datum: NAVD88 and MLLW (1960 - 1978 tidal epoch)					
Units: U.S. Survey Feet					
Station Identification	**Northing**	**Easting**	**NAVD88 Elevation (ft)**	**Adj. To MLLW (ft)**	**MLLW Elevation (ft)**
DEA2000	211485.40	1266932.88	14.85	2.48	17.33
DEA2001	201180.01	1269372.12	14.26	2.43	16.69
DEA2002	196266.87	1274614.30	11.99	2.42	14.41
DEA2003	190503.62	1276767.29	16.51	2.42	18.93
DEA2004	190035.21	1278752.42	11.79	2.42	14.21
DEA2005	198924.13	1272394.71	13.75	2.42	16.17
SY0290	223868.84	1269078.99	16.06	2.52	18.58
SY4354	211760.04	1284004.86	21.12		
SY4595	220964.25	1256980.24	17.24		
W142	194806.38	1254939.34	21.35		
W2672	180009.76	1289038.99	236.42		

Table 2. Vertical differences between the November 20, 2003 and August 25, 2003 adjustments

STATION IDENTIFICATION	11/20/03 ADJ. NAVD88 (ft)	8/25/03 ADJ. NAVD88 (ft)	DIFFERENCE (ft)
DEA2000	14.85	14.73	0.12
DEA2001	14.26	14.11	0.15
DEA2002	11.99	11.96	0.03
DEA2003	16.51	16.54	-0.03
DEA2004	11.79	11.83	-0.04
DEA2005	13.75	13.63	0.12
SY0290	16.06	16.06	0.00
SY4354	21.12	21.00	0.12
SY4595	17.24	17.06	0.18
W142	21.35	21.40	-0.05
W2672	236.42	236.49	-0.06

Staff gauging sites were established approximately 1 to 2 miles apart within the study area. Temporary benchmarks (TBM) were set on the staff gauge pile and an elevation was established by running closed differential loops from the control network monuments. Elevations were computed based on the August 25, 2003 network adjustment for each TBM and were used for the placement of new staff gauges. Adjustments to the elevations were made during the November 20, 2003 final adjustment of the network. Table 3 presents the TBM locations and elevations based on the November 20, 2003 adjustment from which staff gauge conversions were generated.

Table 3. Temporary benchmark locations and elevations

TEMPORARY BENCHMARK	RIVER MILE	DESCRIPTION	MLLW ELEVATION (ft)	NAVD88 ELEVATION (ft)
TBM #1	0.0	Railroad spike in north pile of gangway	13.60	11.12
TBM #2	2.0	Railroad spike in pile on old pier	13.15	10.72
TBM #3	3.4	Railroad spike set in pile next to existing staff gauge.	13.01	10.59
TBM #4	4.6	Railroad spike set in pile on old pier	17.53	15.11

When possible, staff gauges were installed on MLLW based on the August 25, 2003 adjustment report. However, there were instances where this was not possible due to insufficient water depth or use of an existing staff gauge. Further, adjustments to the staff gauge observations needed to be made based on the November 20, 2003 final adjustment to the control network. Adjustments to MLLW were computed, which allowed for comparison to adjusted RTK GPS-derived water surface elevations. Table 4 presents the final adjustments used at each staff gauge location to obtain

MLLW (1960-1978 tidal epoch). During data processing, the November 20, 2003 final network adjustment to the RTK GPS base station was applied.

Table 4. Staff gauge locations and adjustments

CONTROL POINT	RIVER MILE	ADJUSTMENT FROM NAVD88 TO MLLW (ft)	TIDE STAFF	MLLW ADJUSTMENT (ft) (STAFF READING + ADJ. = MLLW)
DEA2000	0.0	2.48	New Staff	0.12
DEA2001	2.0	2.43	New Staff	+1.15
DEA2005	2.7	2.42	None	N/A
DEA2002	3.4	2.42	Existing Staff	-0.22
DEA2003	4.6	2.42	New Staff	-0.03
DEA2004	5.0	2.42	None	N/A

2.2 POSITIONING

Horizontal positions were acquired with an Applanix® Position and Orientation System for Marine Vessels (POS/MV) differential global positioning system (DGPS) and inertial navigation system. This system integrates two GPS receivers with a motion reference unit. Additionally, RTK GPS positions were input into the system to improve horizontal positioning accuracy to better than 0.5 m (1.6 ft). The advantage of this system is that it not only provides motion information (i.e., heading, roll, pitch, and heave) to compute X, Y, Z data from the multibeam sonar measurements, but also provides accurate inertial navigation through GPS outages for up to 30 seconds. The combined GPS and inertial system is a major improvement in positioning over conventional GPS equipment. These systems are preferred because the use of conventional equipment under bridges and alongside ships, a typical environment in the LDW, causes satellite signals to be blocked and/or reflected from these structures (multipath), resulting in position jumps or large drifts in position, which can exceed survey tolerances.

Position data were used in real-time to provide navigation information to the vessel operator. A preliminary coverage plot was generated in real-time to show multibeam swath coverage. The helmsman was presented with a plan view of the survey area with the vessel position and track. A color-coded swath of the multibeam coverage was painted to the screen and used to navigate the survey vessel to fill the area. Daily position checks were performed daily on control point DEA2000 at the Harbor Island Marina to check the accuracy of the positioning system and confirm that the geodetic parameters used in the real-time projection to the NAD83/91, SPCS Washington North Zone coordinate system were correct.

2.3 WATER SURFACE OBSERVATIONS

Bathymetric data were time-tagged and recorded relative to the water surface. To reduce the data to MLLW, accurate water surface observations in the vicinity of the survey are required to account for water level changes. Water surface measurements were obtained by RTK GPS with on-the-fly (OTF) ambiguity resolution. An RTK GPS base station was deployed at monument "DEA2005" to provide RTK GPS correctors to the rover GPS receiver aboard the survey vessel. RTK correctors were applied to the shipboard GPS for logging of water surface elevations at a rate of five hertz (Hz). An ellipsoid separation model was developed and used in Hypack MAX software for OTF conversion from the WGS84 ellipsoid (ellipsoid from which GPS heights are derived) to MLLW elevations. During processing, RTK GPS water level observations were graphically viewed and edited for outliers, artifacts from multipath, or loss of satellites. Data were removed if there were fewer than 5 satellites, spikes in the water surface elevation, or other irregularities that would not be characteristic of a short-term water surface elevation change. Spikes are most likely caused by satellite signal multipath. Longer period irregularities are most often the result of temporary loss of the satellite signal being used in the solution due to an obstruction (e.g., passing under a bridge or running alongside a ship). After editing, a 60-second average of RTK GPS observations was used for correcting multibeam soundings to MLLW elevations. All soundings for this survey were reduced to MLLW elevations in the delivered data set.

2.4 MULTIBEAM DATA ACQUISITION

Soundings were acquired with the Reson SeaBat 8101 multibeam bathymetric sonar. Using a frequency of 240 kHz and a standard deployment, the SeaBat sonar illuminates a 150° (75° to starboard and 75° to port) by 1.5° swath along the riverbed, perpendicular to the ship's track, and resolves a slant-range measurement to the riverbed every 1.5° along the swath. This system results in 101 soundings along a swath perpendicular to the vessel track over seven times the water depth in a single sonar ping. Sonar swaths were recorded at a minimum rate of 8 Hz as the vessel would transit along the survey track line. Additionally, the SeaBat 8101 used during the survey had the optional stick projector as well as the sidescan sonar imagery output option. The stick projector on the 8101 improves the system performance in shallow water (depths less than 165 ft [50 m]), which was ideal for the LDW survey because the deepest area surveyed was only 52 ft (16 m) below MLLW. Sidescan imagery was recorded in Extended Triton Format (XTF) with the multibeam data and was displayed during editing.

Multibeam data were collected by running lines parallel to the shoreline. This is a standard survey practice for multibeam data acquisition and is the most efficient when running parallel to contours. The multibeam sonar head was mounted in a modified position from the standard deployment, with a 15° offset angle for horizontal orientation of the outer starboard beam. This position enabled swath coverage every 1.5° over a range from nadir (beam number 41, straight down) to 90° starboard (beam number 101, horizontal) and 60° from nadir to port (beam number 1). This configuration allowed shoreline data to be collected as far up the bank as possible, on a steep bank, by making shoreline runs with the starboard side toward shore. Survey lines offshore of the shoreline runs were clipped at 60° from nadir on the starboard side (beam numbers 82 through 101).

Running with a 120° swath (60° to port and starboard with beam numbers 1 through 81), the system still provided swath coverage at 3.5 times the water depth in a single pass. The POS/MV system enabled the survey vessel to run near ships at berth and under bridges with minimal loss of positioning integrity. In addition to several parallel lines down the channel, crosstie lines were run over the main scheme lines to confirm system calibration and document the accuracy of beam numbers 1 through 81 used for the survey. In addition, to document the accuracy of the outer beams (beam numbers 82 through 101) single beam (vertical echosounding) comparison lines were run at high tide along the outer limits of the multibeam coverage in shallow water along the shore.[1] The most vital measurements in a multibeam survey are pitch and roll angles. The Applanix® POS/MV motion reference sensor was used to account for vessel heave (vertical movement) pitch and roll. The POS/MV system was also used to record vessel heading (yaw) from which the sonar beam orientation is derived. The POS/MV provides a higher degree of accuracy for heading measurements than a conventional gyrocompass.

Multibeam data were acquired simultaneously on two acquisition systems. The primary system, Triton-Elics Isis, provided precise time-tagging of the sensor data and real-time data displays for quality control. The secondary acquisition system, Coastal Oceanographics HYPACK MAX, was used for navigation and survey control. Both systems acquired and time-tagged all sensor data, including multibeam sonar, position, heading, heave, pitch, and roll. The navigation system provided navigation output to the vessel operator's monitor, and managed the survey. The acquisition systems were also used to replay survey data so that the coverage and quality of the data could be reviewed prior to demobilization from the site.

Detailed measurements of the sound velocity profile through the water column are crucial in multibeam surveys. Changes in the sound velocity profile not only affect acoustic distance measurements, but also cause refraction or bending of the sonar path as it passes through layers in the water column at different velocities. The Sea-Bird SBE 19 SeaCat CTD profiler was used to measure conductivity (from which density is determined), temperature, and depth (CTD) at one-second intervals as the probe was lowered to the riverbed. The CTD measurements were used to compute an accurate sound velocity profile, which was applied to the data during processing. To account for temporal variation in sound velocity, CTD casts were taken and reviewed in the field; the frequency of these casts was generally hourly, but on occasion was extended

[1] The *Preston* can collect single beam data in 3 ft of water under optimal conditions (i.e., smooth, gradual bottom with no obstructions).

during periods of minimal tidal exchange. The time between casts during data collection never exceeded 2 hours. The LDW was divided into half-mile subsections prior to beginning survey operations. Spatial changes were addressed by taking CTD casts at the upstream and downstream end of the subsection in which data were being acquired.

A patch test was conducted to confirm alignment of the sensor data with the sonar swath, and to verify delay times applied to the time-tagged sensor data. A patch test is a series of lines run in a specific pattern that are used in pairs to analyze roll, pitch, and heading alignment angles with the sonar swath, as well as latency (time delays) in the time-tagging of the sensor data. Bar check and lead line checks were conducted to confirm the draft of the sonar head. These tests were conducted at the beginning and end of the survey. A third roll test was run during the survey to confirm roll alignment following the swinging up of the sonar head.

2.5 DATA PROCESSING

Caris® HIPS multibeam analysis and presentation software was used to process the multibeam data. The patch test data were analyzed and alignment corrections were applied to the survey data prior to editing. The Caris® HIPS system allowed for simultaneous viewing of the sidescan and multibeam data to analyze anomalies on the riverbed during post-processing. Water-level data were applied to adjust all depth measurements to MLLW. A sound velocity profile was generated from CTD measurements taken in the field and used to correct slant range measurements and compensate for ray path bending.

Processing began with the review of each survey line using Caris® swath editor. Water surface correctors were verified based on a comparison to staff gauge observations, a comparison to NOAA tide values, and a review for anomalies (spikes and irregularities). These correctors were applied to the data set at that time. Position and sensor data were reviewed and edited if erroneous data were observed. Sounding data were reviewed and edited for data flyers such as bottom multiples, returns from pilings, and passing vessel wakes, that were identified during graphical editing in Caris HIPS relative to surrounding data, field notes, and comparison to aerial imagery. These data points were rejected and were not used as part of the final data set. Piles and seawalls were removed from the data set so that all soundings represent the sediment line of the LDW. Sounding data, including sonar beams reflecting from suspended particles in the water column or noise due to aeration in the water column, were carefully reviewed to ensure that all fliers were rejected. In each case, rejected data were not eliminated from the file, but recoded so that it was possible to re-accept data later in the editing process.

After swath editing, all data were reviewed through the Caris® HIPS subset editing program to ensure that all flyers had been removed from the data set, or to re-accept data previously flagged in the swath editor. The Caris® subset editor allowed a set of adjacent lines to be reviewed together for line-to-line comparison to ensure agreement to one another. A series of subsets were made to cover the entire survey area to ensure all data were reviewed.

Caris® HIPS was used to create 1-m (3.3-ft) resolution weighted mean surfaces from the high-resolution multibeam data. A surface was produced for each area defined by the five LDW sheets. The gridding process used both inverse distance weighting and beam grazing angle algorithms to create the mean surface (Caris 2003). The weighted surfaces were then used to create hill-shaded geo-referenced TIFF images as well as 1-m (3.3-ft) gridded ASCII data sets.

The hill-shade images were reviewed for survey coverage and analyzed to guarantee that no subtle artifacts were present in the data set. Upon finalization of the survey processing, the 1-m (3.3-ft)ASCII data were imported into TerraModel® software. Within Terramodel, the data were factored by a negative 1.0 to make sounding data negative (sounding data are output from Caris as positive values for charting purposes) and the final network adjustment to the RTK GPS base station was applied (+0.12 ft). A digital terrain model (DTM) was created from the resultant data set. The DTM was used to generate contours at a two-foot interval. The georeferenced hill-shaded TIFF images and the contours were imported into AutoCAD® version 2002 for final presentation and plotting. Figure 2 presents a flowchart illustrating the data flow from acquisition to production of deliverables.

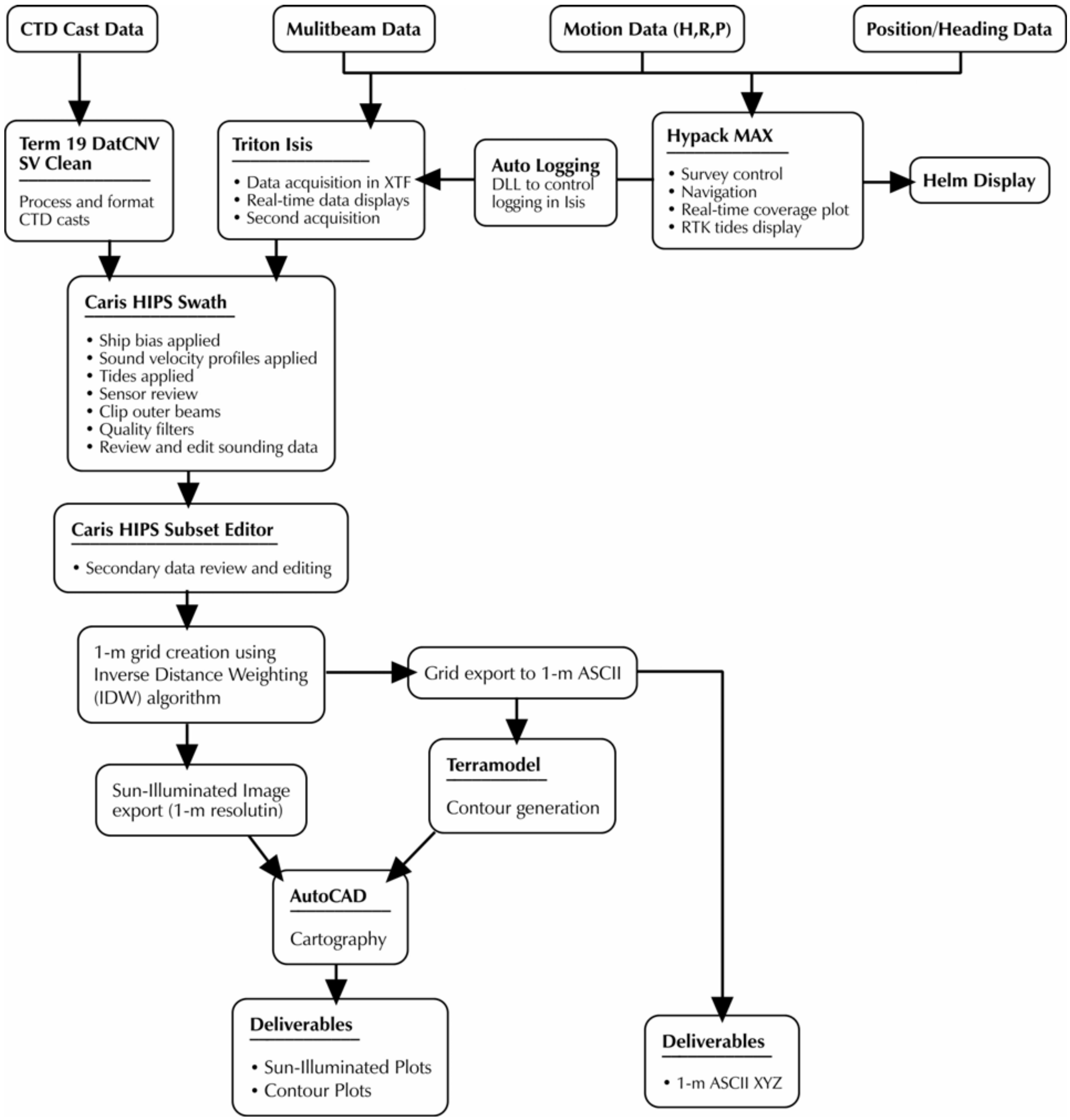

Figure 2. Multibeam data acquisition and processing flowchart

2.6 QUALITY CONTROL

The acquisition system and survey protocols were designed with some redundancy to demonstrate that the required accuracy was being achieved during the survey and to provide a backup to primary systems. Data integrity was monitored throughout the survey by redundant system comparisons and checks against known values. All raw data were recorded to allow for adjustments to be made to any of the data during processing based on the results of comparisons and checks.

As part of the survey plan, checks were performed routinely to ensure data quality control. These checks included:

Positioning. Prior to the bathymetric survey, a geodetic control survey was conducted to provide positions for monuments within the study area. A position confidence check was conducted daily on the monument DEA2000, which was located at the Harbor Island Marina. The check consisted of placement of the vessel RTK GPS antenna over the control monument. The obtained RTK GPS position and elevation data were compared to the control network adjusted values to assure the target horizontal and vertical accuracies were being obtained. Following the daily position confidence check, the RTK GPS antenna was returned to a fixed bolt on the vessel. The antenna height remained constant relative to the sonar head throughout the survey.

Tides: RTK GPS derived heights were evaluated daily with multiple checks. The first check was performed during the morning position check. Valid elevations on the control point confirmed that the RTK heights were correct. In addition, staff gauge observations were made and compared to RTK GPS derived water elevations twice per day. As a final check, RTK derived water levels were checked during the survey by way of a comparison to predicted tides.

Sonar draft:

- A bar check was conducted at the beginning and end of the project to confirm single beam and multibeam sonar draft below the water line. A bar was lowered below the sonar to a depth of 6.0 m (19.7 ft) below the water surface using calibrated marks on the attached chain. Data were then logged with the acquisition system and compared to the bar depth of 6.0 m (19.7 ft).
- Sonar draft marks were observed with the vessel trimmed to zero roll angle to confirm the static draft of the sonar.
- Leadline depth observations were made at the beginning and the end of the project to confirm single beam and multibeam sonar draft and sound velocity observations. Changes in draft were accounted for in the Caris® vessel configuration file, which used date- and time-stamped draft offset values.
- A comparison of multibeam and single beam depth soundings was performed.

Motion sensor, positioning system latency, and vessel heading calibration: A patch test was conducted at the beginning and end of the project to confirm that the sensor mounting angles and timing bias were correctly applied to multibeam sonar data.

Metric-English unit conversions: Multibeam data were collected in metric units and were converted to US survey feet after data were exported from Caris® HIPS. The U.S. Army Corps of Engineers' Corpscon software (ver 5.11.08) was used to automate these conversions.

Cross-line analysis: A cross-line analysis was conducted across the full width of the survey, where there was sufficient water depth, to confirm that the beams used met target accuracy. Caris® GIS was used to perform this analysis, which involved an automated comparison between data from a cross-line that was run during the survey and a reference DTM that was created from the multibeam survey data. The standard tolerances of the comparison were modified so the 95% confidence within 0.5-feet survey requirements could be evaluated.

In addition, single beam comparison lines were run in shallow water along the shoreline to confirm accuracy of outer beams.

Hill-Shade analysis: A sun-illuminated (hill-shade) image was generated from the DTM of the accepted bathymetric data set. The image was reviewed for anomalous data and consistency between adjacent sonar swaths.

3.0 Results

3.1 BATHYMETRIC DATA PRESENTATION

Project drawings were prepared on 34″x 22″ D size plots at a scale of 1″=200′. The LDW survey area (RM 0.0 – RM 4.8) was divided into five sections, each covering approximately one mile of the LDW. Contour plots and hill-shaded imagery plots were created for each of the 5 sections. Smaller, half size, 11″x 17″ versions of the project drawings are presented in Appendix E and are also provided as PDF files in the digital deliverables.

Project drawings were prepared using AutoCAD® version 2002 software and saved in dwg format. All hill-shaded images were saved in TIFF format with a tfw worldfile for georeferencing. Contours files were also saved in ESRI shapefile (shp) format for use with GIS software. A digital data catalog is included in Appendix A.

3.2 DATA QUALITY

Positioning. All daily position checks were well within the target horizontal accuracy of 3 ft and the target vertical accuracy +/- 0.5 ft. See Table 5 for results of this check.

Table 5. Position check results

Observation Date	Control Point	NAD 83 WA North		Raw RTK MLLW (ft)	Adj. RTK MLLW (ft)	Horizontal Distance Off (ft)	Vertical Distance Off (ft)
		Northing US (ft)	Easting US (ft)				
8/25/2003	DEA2000	211485.57	1266932.93	17.21	17.33	0.18	0.00
8/26/2003	DEA2000	211485.27	1266932.96	17.28	17.40	0.15	-0.07
8/27/2003	DEA2000	211485.47	1266932.98	17.25	17.37	0.12	-0.04
8/28/2003	DEA2000	211485.45	1266932.91	17.25	17.37	0.06	-0.04
8/29/2003	DEA2000	211485.45	1266933.08	17.25	17.37	0.20	-0.04
					Average	0.14	-0.04
					St dev	0.06	0.02

Tides: RTK water levels were compared to the staff gauge every morning prior to the start of survey operations. See Table 6 for RTK GPS water elevation comparison to staff gauge readings. No systematic errors were found during any of the tide checks and all checks were within the error budget for the survey.

Table 6. Staff gauge comparison to RTK GPS water surface elevations

Date and Time	RM	Location	Raw Staff Gauge (ft)	Staff Adj. (ft)	Adj. Staff Gauge (ft)	Raw RTK (ft)	Adj. RTK (+0.12) (ft)	Adj. Staff Minus Adj. RTK (ft)
8/26/2003 8:51	0.0	DEA2000	1.30	0.12	1.42	1.27	1.39	0.03
8/26/2003 9:34	3.4	DEA2002	-0.1	0.03	-0.07	-0.13	-0.01	-0.06
8/26/2003 20:05	2.0	DEA2001	9.95	0.15	10.10	9.91	10.03	0.07
8/27/2003 8:53	0.0	DEA2000	3.00	0.12	3.12	2.99	3.11	0.01
8/27/2003 14:46	2.0	DEA2001	5.10	0.15	5.25	5.05	5.17	0.08
8/27/2003 16:56	2.0	DEA2001	10.30	0.15	10.45	10.40	10.52	-0.07
8/28/2003 9:01	0.0	DEA2000	4.78	0.12	4.90	4.73	4.85	0.05
8/28/2003 13:59	4.6	DEA2003	1.80	-0.03	1.77	1.70	1.82	-0.05
8/28/2003 14:18	3.4	DEA2002	2.47	0.03	2.50	2.40	2.52	0.02
8/29/2003 5:19	0.0	DEA2000	10.25	0.12	10.37	10.15	10.27	0.10
8/29/2003 7:23	4.6	DEA2003	10.25	-0.03	10.22	10.10	10.22	0.00
8/29/2003 10:46	4.6	DEA2003	2.50	-0.03	2.47	2.30	2.42	0.05

Sonar draft: Several checks were carried out to ensure that sonar draft was recorded accurately.

- A bar check was taken at the beginning and end of the survey. A data file was logged while a metal bar was lowered 6.0 m (19.7 ft) below the water surface to confirm that draft settings were properly applied in the processing system. The processed data matched the bar depth within 0.03 meters. This error is within the accuracy of this test and the difference was attributed to the 6 meter chain mark fluctuating at the water surface. Actual draft measurements were a better indicator of sonar head draft.

- Sonar draft marks were observed each morning as part of the daily system check routine and logged in the daily survey log. The sonar draft values changed slightly under varying vessel loading, but no unusual changes in draft were observed.
- Leadline depth observations were made at the beginning and at the end of the project to verify single beam and multibeam sonar draft as well as the sound velocity measurements. These checks verified that draft readings were read and recorded accurately. Table 7 presents results of the leadline checks.

Table 7. Single beam and leadline comparison to multibeam

DATE	LEADLINE (ft)	MB DEPTH (ft)	SB DEPTH (ft)	DIFFERENCE (ft)
8/26/2003	34.2	34.2		0.0
8/26/2003	34.2		34.2	0.0
8/29/2003	34.5	34.5		0.0
8/29/2003	35.6		35.6	0.0

Motion sensor, positioning system latency, and vessel heading calibration: A patch test was conducted at the beginning and end of the project to ensure that the sensor mounting angles and timing bias were correctly applied to multibeam sonar data. The patch test confirmed that mounting angles did not change during the survey. The latency test found 0.0-sec latency, which is the standard value with the system setup that was used during the survey. See Table 8 for the results of the patch test.

Table 8. Patch test results

ROLL	PITCH	YAW	LATENCY
-0.21°	-0.65°	-2.1°	0.0 sec

To confirm the patch tests values, data were evaluated using Caris® HIPS software. Individual sonar swaths (passes) were color coded and evaluated by cutting cross-sections through the data set. Figure 3 is a cross-section perpendicular to the vessel track. Data points are assigned a different color for each individual pass from lines run in opposing directions. The good agreement from independent passes from opposing directions verifies the roll and yaw values obtained from the patch test.

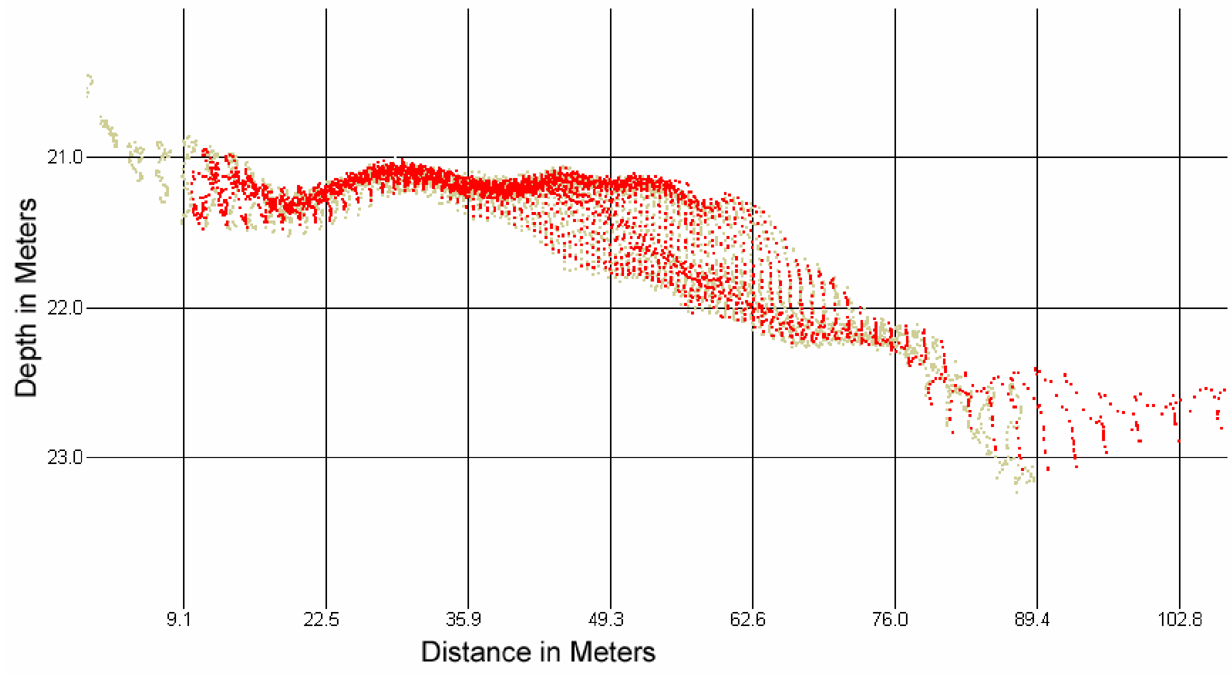

Figure 3. Roll and yaw alignment verification

Pitch and latency values were verified by comparing a profile of data along survey tracks from lines run in opposing directions up and down a slope. Figure 4 shows the profile of opposing lines directly beneath the survey track. The good agreement verifies the pitch and latency values obtained from the patch test.

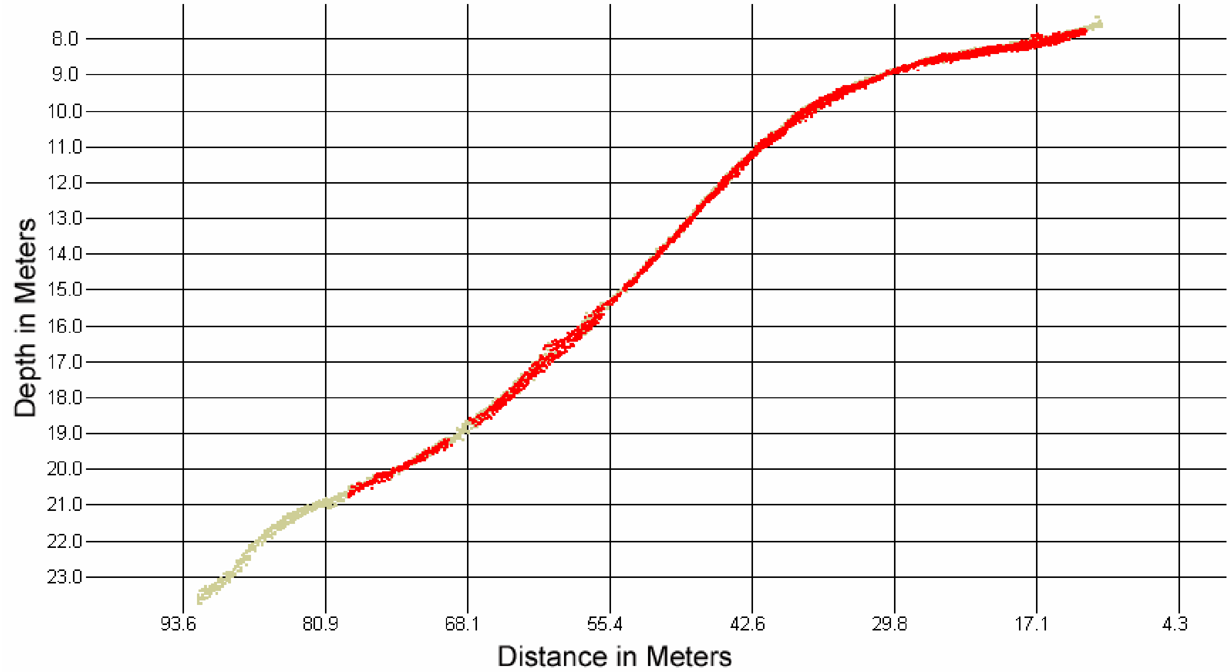

Figure 4. Pitch and latency alignment verification

Metric-English unit conversions: Multibeam data were collected in metric units and were converted to US survey feet after data were exported to ASCII from the multibeam processing software. Corpscon coordinate conversion software was used to automate these conversions. A check on unit conversions included a comparison of converted control monument horizontal and vertical locations to their known locations in feet. These checks verified that metric to English unit conversions were performed correctly for all transformations.

Comparison to prior surveys: A dxf file of the major contours was overlaid on NOAA chart 18450, 15th Edition, to compare adjusted data to NOAA surveys. Figure 5 is a screen grab of the comparison at the north end of Kellogg Island. The chart and contours were registered to NAD83, Washington North Zone using Coastal Oceanographics HYPACK Max software. Red contours are from the multibeam survey conducted by DEA. The multibeam contours match the chart contours reasonably well when taking into account the methodology and date for each survey. The 30-foot contour on the west side of the waterway and the 0-foot contour on the north end of Kellogg Island match extremely well to the charted contours. This comparison documents that there are no blunders in conversions or adjustments.

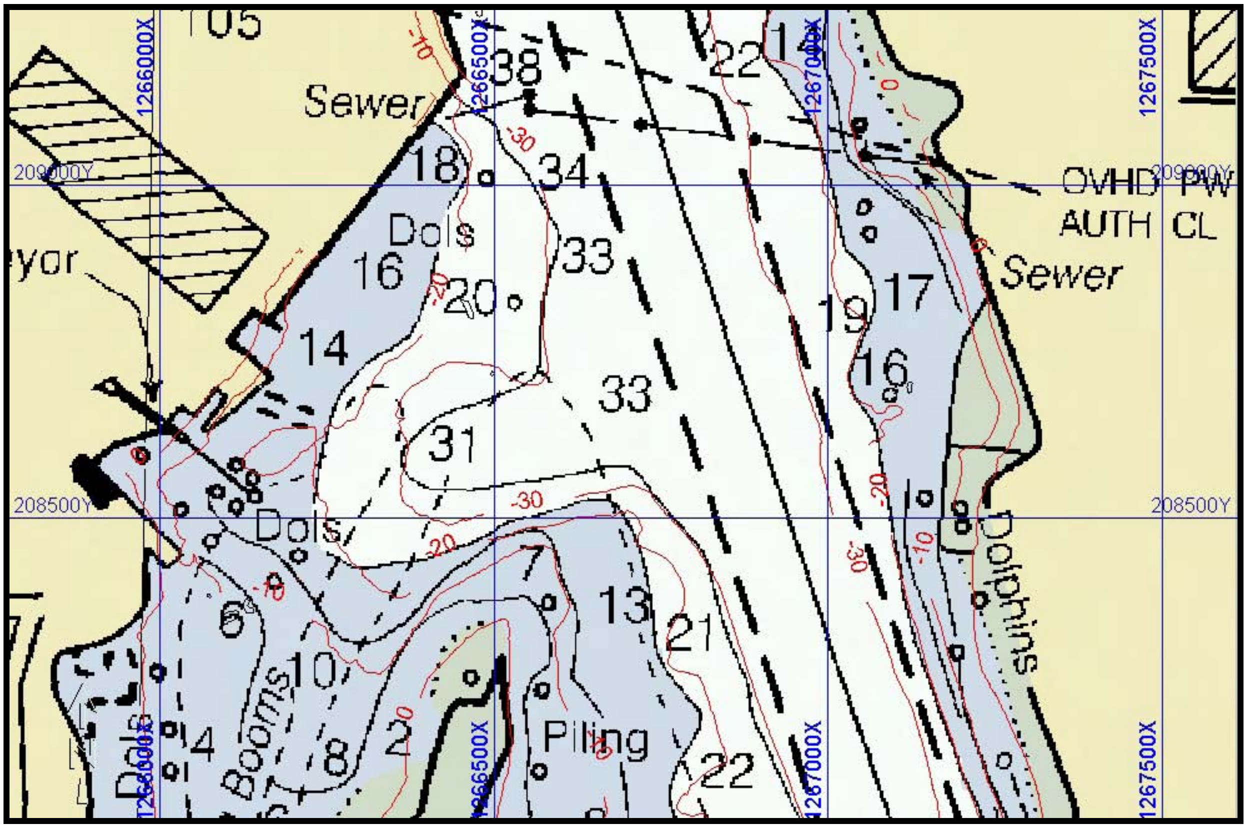

Figure 5. Comparison of multibeam contours to NOAA chart

Cross-line analysis: A cross-line analysis was conducted to confirm that sonar beams used to create contours and hill-shaded images met the target vertical accuracy of ±0.5 ft. Caris GIS was used to perform this analysis, which involved an automated comparison between data from a cross-line that was run on a flat bottom during the survey and a reference DTM that was created from the multibeam survey data. The output of the comparison was a text file that displayed beam number, the number of each beam that passed and failed the 0.5–foot criteria, and the percent within the 0.5-foot requirement. A histogram of the results is presented in Figure 6.

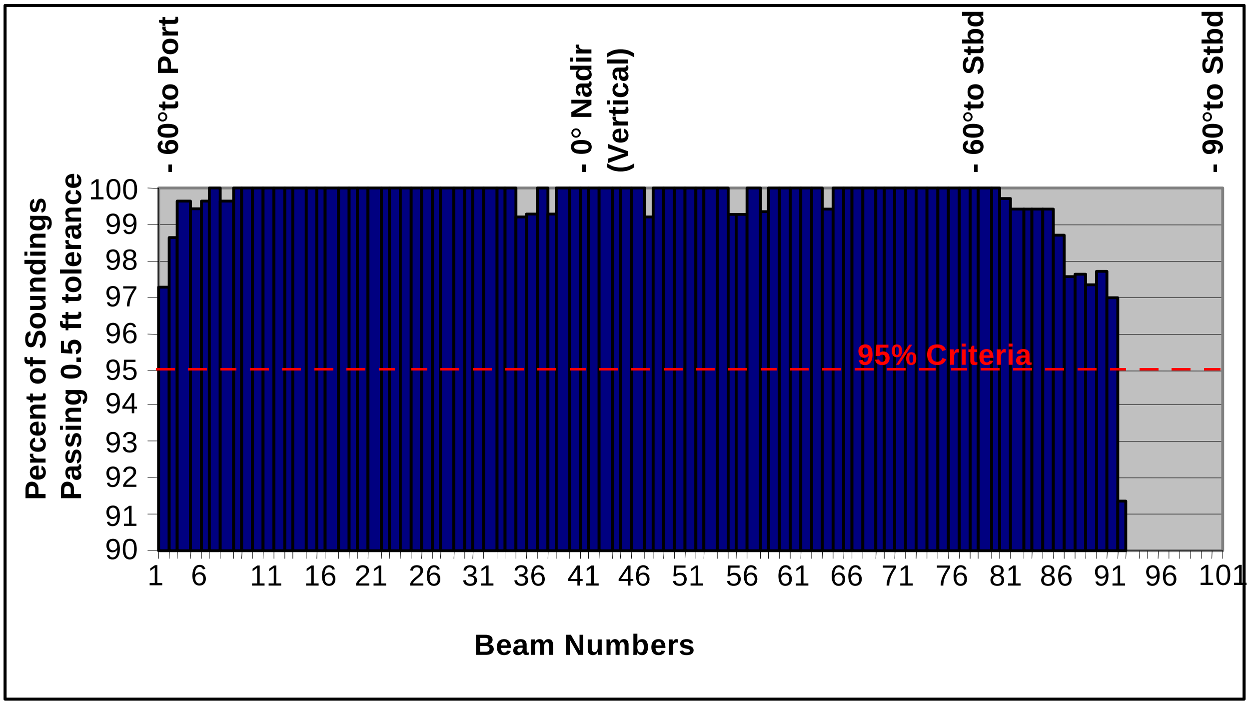

Figure 6. Cross-line analysis using a 0.5 ft tolerance at a 95% confidence level

All beams within the 60° multibeam swath (beams 1- 81) that were used in the final mapping passed the vertical accuracy requirement. Some starboard beams outside of the 60° swath, which were used for shoreline mapping, failed the 95% test due to a low angle of incidence in the data used for this test.

A single beam to multibeam comparison was performed along the shoreline to confirm accuracy of outer beams that did not pass the cross-line analysis. Single beam (vertical) soundings were directly compared to the DTM surface at the southwest side of Kellogg Island with 98.8% depths within the 0.5-ft project requirement. As expected, outer multibeam depths were slightly higher than vertical beam data on the gradual slope but met the 0.5-foot vertical tolerance requirement. Results of the single beam comparison are presented in Figure 7.

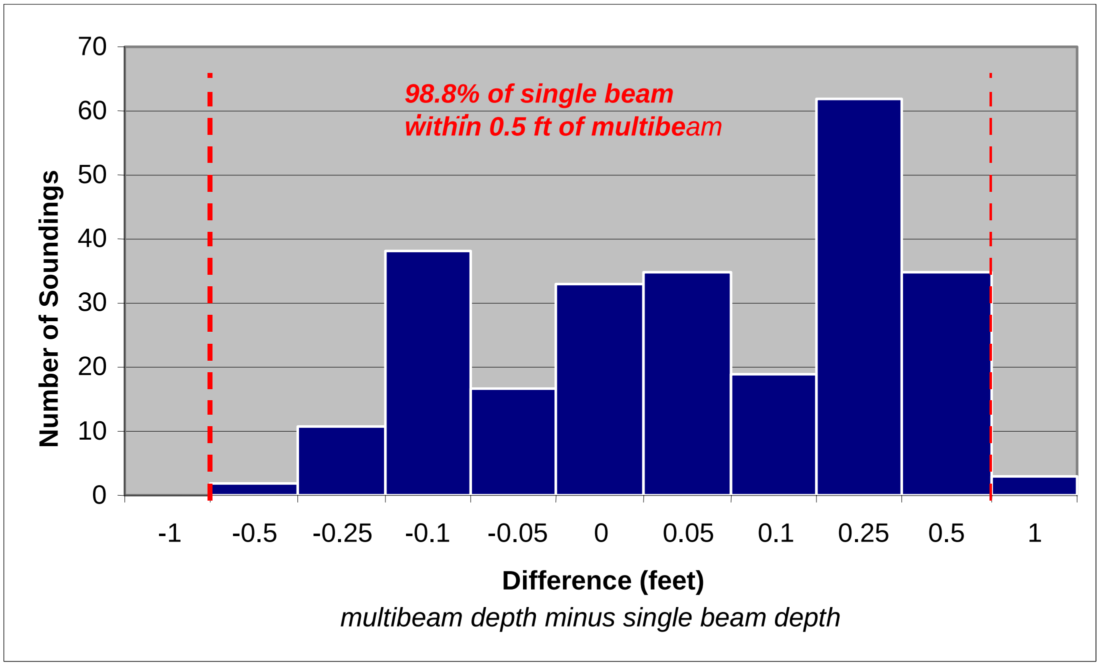

Figure 7. Results of single beam comparison to outer multibeam data

Hill-Shade analysis: Sun-illuminated images (hill-shade) were generated from the DTM surfaces of the accepted bathymetric data sets. The images were reviewed and no anomalous data or inconsistencies between adjacent sonar swaths were found.

Survey completeness: Survey coverage met most of the requirements specified in the Quality Assurance Project Plan (QAPP). As expected, there are some data gaps. The survey vessel was not able to navigate under the bridge at S 102nd St. due to low clearance, which excluded RM 4.8 – 5.0 from the survey area.

In order to complete the survey before the opening of the Muckleshoot tribal fishing season, the LDW survey was conducted during a spring tide with extremely low tides during survey hours. The tide cycle at the time of the survey limited the ability to collect all shoreline data during a tide stage above the targeted 5-ft MLLW as stated in the QAPP. Shoreline data collection was timed to collect data during the highest possible tide stage.

Other data gaps, which were expected, are present where obstructions such as docks, vessels, or pilings restricted safe vessel operations.

With these issues excluded, the LDW multibeam bathymetric data set is complete and accurate.

4.0 References

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